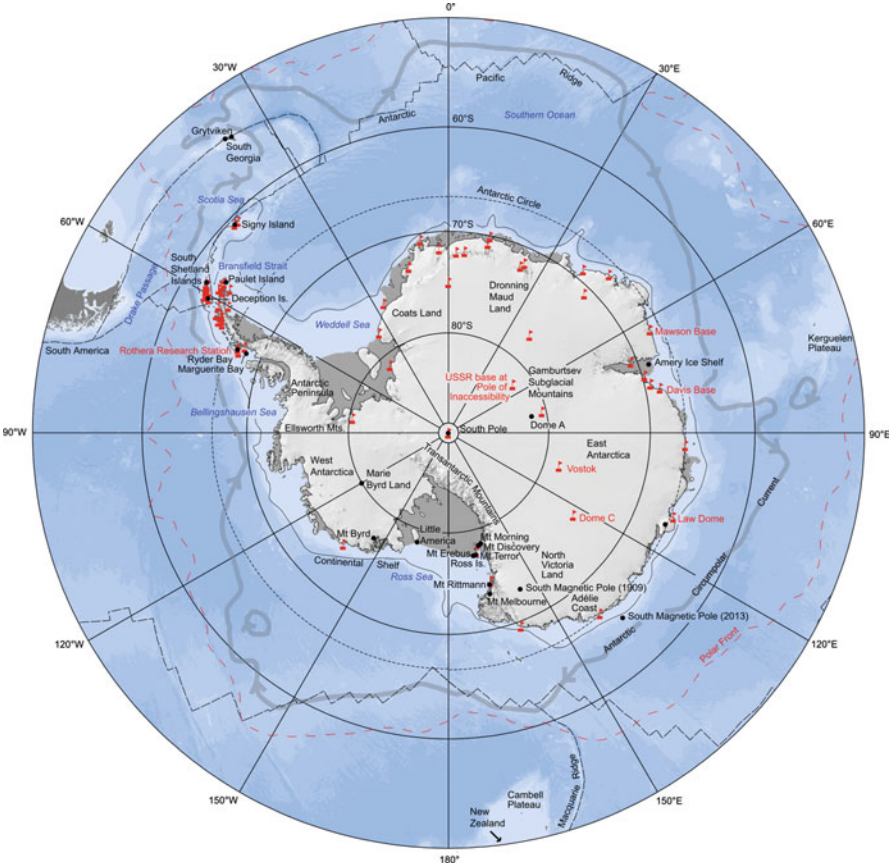
Daniela Liggett
Bryan Storey
Yvonne Cook
Veronika Meduna
*Editors*

# Exploring the Last Continent

## An Introduction to Antarctica

Springer

Exploring the Last Continent


0°
30°W
30°E
60°W
60°E
90°W
90°E
120°W
120°E
150°W
150°E
180°
60°S
70°S
80°S
Pacific
Ridge
Antarctic
Southern Ocean
Antarctic Circle
Grytviken
South
Georgia
Scotia Sea
Signy Island
South
Shetland
Islands
Bransfield Strait
Paulet Island
Deception Is.
Drake Passage
South America
Rothera Research Station
Ryder Bay
Marguerite Bay
Antarctic
Peninsula
Bellingshausen Sea
Weddell Sea
Coats Land
Dronning
Maud
Land
Mawson Base
Amery Ice Shelf
Davis Base
Kerguelen
Plateau
USSR base at
Pole of
Inaccessibility
Gamburtsev
Subglacial
Mountains
Dome A
South Pole
Ellsworth Mts.
East
Antarctica
Vostok
West
Antarctica
Marie
Byrd Land
Transantarctic Mountains
Dome C
Law Dome
Mt Byrd
Little
America
Mt Morning
Mt Discovery
Mt Erebus
Mt Terror
Ross Is.
North
Victoria
Land
Continental
Shelf
Ross Sea
Mt Rittmann
South Magnetic Pole (1909)
Mt Melbourne
Adélie
Coast
South Magnetic Pole (2013)
Circumpolar
Current
Antarctic
Polar Front
Cambell
Plateau
New
Zealand
Macquarie
Ridge

Daniela Liggett • Bryan Storey • Yvonne Cook
Veronika Meduna
Editors

# Exploring the Last Continent

## An Introduction to Antarctica

Springer

*Editors*
Daniela Liggett
Gateway Antarctica
University of Canterbury
Christchurch, New Zealand

Bryan Storey
Gateway Antarctica
University of Canterbury
Christchurch, New Zealand

Yvonne Cook
School of Earth and Environmental Science, James Cook University
Townsville, QLD, Australia

Veronika Meduna
Radio NZ House
Wellington, New Zealand

ISBN 978-3-319-18946-8 ISBN 978-3-319-18947-5 (eBook)
DOI 10.1007/978-3-319-18947-5

Library of Congress Control Number: 2015947821

Springer Cham Heidelberg New York Dordrecht London


Cover image: The picture is showing the sea ice edge in McMurdo Sound, Antarctica, (looking ENE towards Mt. Erebus) in late January 2015. Photo by R. Eisert.

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

# Acknowledgements

This book has been an incredible and enlightening journey for the authors, editors and publishers and would never have come to fruition without the support, encouragement and enthusiasm of a wide range of people and organisations.

We owe sincere gratitude to Michelle Rogan-Finnemore for her generosity, good advice and help in moving this book project along. Sam Elworthy, the Director of Auckland University Press, was instrumental in supporting the development of the book project from early ideas and draft chapters into a coherent academic text. Margaret Deignan and Takeesha Moerland-Torpey at Springer were helpful, understanding and patient with us and gave us sufficient time and support to fine-tune the final product.

We gratefully acknowledge the crucial funding that led to the production of this book. Funding was provided by the Foundation for Research Science and Technology in support of the International Polar Year through contract UOCX0806 to Gateway Antarctica (University of Canterbury) entitled "Providing gateways for Antarctic and Southern Ocean education".

We wish to thank Paul Bealing at the Department of Geography, University of Canterbury, for producing the Antarctic map featured in this book and Kurt Joy at Gateway Antarctica, University of Canterbury, for drawing a range of geological images. Andy Reisinger's help with converting file formats and producing figures was invaluable.

A number of New Zealand and international artists gave us the kind permission to include some of their work in this book, and in particular, we wish to extend our gratitude to Nigel Brown, Margaret Elliot, Fieke Neuman, Robert Nicholls and Clare Plug. Many individual researchers, writers, modellers and technicians generously allowed us to reuse their photos, drawings or diagrams and find mention in the respective figure captions throughout the book. We acknowledge and thank each of them for their generosity in this regard.

Reasonable attempts have been made to secure copyright permissions. If any have been overlooked, we apologise and ask the concerned individuals or groups to contact us in this regard.

Finally, we are very grateful for having had the opportunity to work with a wonderful team of extremely knowledgeable, talented and accommodating authors, without whom we could not have produced this multidisciplinary and multifaceted introduction to Antarctica, Antarctic research and current issues surrounding human engagement in Antarctica. We appreciate their support, patience and enthusiasm for this project throughout and beyond a very long gestation period.

Chapter authors would also like to thank the following: Dave Barnes, Eugene Murphy, Inigo Eversen, Pete Bucktrout, Chris Gilbert, Geraint Tarling and John Turner for providing figures, comments and discussions about Chap. 12. This work is part of the research sponsored by the Foundation for Science and Technology (Portugal), Institute of Marine Research of the University of Coimbra and by the Polar Science for Planet Earth (PSPE) programme of the British Antarctic Survey (United Kingdom).

# Contents

# Chapter 1
# Exploring the Last Continent

## An Introduction to Antarctica

**Daniela Liggett, Bryan Storey, and Yvonne Cook**

**Abstract** This brief chapter outlines how Antarctica captured humankind's imagination over the centuries, culminating in a flurry of expeditions during the Heroic Age and, more recently, in endeavours to better understand this continent and its importance for the global system through science.

**Keywords** Exploration • Imagination • Science • Climate change • Governance

Having crossed the Antarctic Circle for the first time in 1774 and ventured further south than any of his contemporaries, Captain James Cook painted a bleak picture of the Antarctic continent and questioned not only the feasibility of exploring it any further but also its value for humanity.

> It is however true that the greatest part of this Southern Continent (supposing there is one) must lay within the Polar Circle [sic] where the sea is so pestered with ice, that the land is thereby inaccessible. The risk one runs in exploreing [sic] a coast in these unknown and Icy Seas, is so very great, that I can be bold to say, that no man will ever venture farther than I have done and that the lands which may lie to the South will never be explored. (Captain James Cook, as quoted in Beaglehole 1974:431)

Cook further wrote in his diary:

> Should anyone possess the resolution and the fortitude to elucidate this point by pushing yet further south than I have done I shall not envy him the fame of his discovery, but I make bold to declare that the world will derive no benefit from it. (Captain James Cook, as quoted in Frank 1957)

D. Liggett (✉) • B. Storey
Gateway Antarctica, University of Canterbury, Christchurch, New Zealand
e-mail: daniela.liggett@canterbury.ac.nz; bryan.storey@canterbury.ac.nz

Y. Cook
School of Earth and Environmental Science, James Cook University, Townsville, QLD, Australia
e-mail: yvonne.cook@jcu.edu.au



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_1

Despite Cook's pessimistic assessment of the role Antarctica was to play in the history of geographic exploration, the unmapped spaces of the Southern Ocean and its promising bounty of marine wildlife exerted an unmistakable pull on explorers, sealers, whalers, scientists and cartographers. Sealers soon ventured to the islands of South Shetland and the Antarctic Peninsula and hunted for fur seals at first and then, after 1820, when the fur seal colonies around South Georgia were practically depleted, for elephant seals. Whalers were also drawn to the Southern Ocean, and whaling dominated human activity in the Antarctic region by the early twentieth century.

In the meantime, pursuing imperial and resource interests as well as following the quest of mapping, science and adventure, the United Kingdom, the United States of America, Russia and France sent expeditions to the Antarctic in the first part of the nineteenth century (Dodds 2012; Walton 2013). Stimulated by these early expeditions, scientists around the world began to show increasing interest in Antarctica. In 1895, Georg von Neumayer, in his position as the director of the Deutsche Seewarte, called for further Antarctic exploration, which resonated with a number of governments and individual explorers (Walton 2013). An era of almost frantic and competitive exploration in the Southern Ocean and beyond the coastlines of the Antarctic continent followed and later became known as the 'Heroic Age'. In that era (1898–1916), numerous expeditions originating from the Northern Hemisphere (primarily from Europe and North America but also Japan) were pushing further inland on the Antarctic continent. Captain Robert Falcon Scott's and Roald Amundsen's race to the South Pole in 1912 are among the expeditions of the Heroic Age most commonly cited.

The Heroic Age also marked the time when states began manifesting their interest in Antarctica by colonising parts of the continent. Although Argentina was the first state to pursue and achieve permanent presence in Antarctica, the UK was the first state to officially submit a claim to Antarctic territory through a 1908 Letters Patent (Dodds 2012). Encouraged by the UK, New Zealand took on the administration of the Ross Sea region in 1923, followed by France submitting a claim to Adélie Land in 1924. Australia was the third Commonwealth state announcing its claim to a large sector of land, the Australian Antarctic territory; and Norway put forth a claim to Dronning Maud Land in 1939. Norway was the only state claiming a section in the Antarctic without following the sector principle. Argentina and Chile were the last states to make claims to territory in Antarctica (Argentina in 1940, Chile in 1943). Yet, it was these claims, which overlapped with the British claim in the Antarctic Peninsula region, that instigated the serious and expensive 'Antarctic Problem'. The latter saw subtle and growing agitation by Argentina, Chile and the UK as well as increasingly blatant statements of 'ownership', represented by flag raisings, the installation of plaques, the issuance of Antarctic stamps along with the establishment of post offices, the erection of signposts and overall attempts to further the respective titles to territory (Dodds 2012).

This situation was slightly diffused by the negotiation of a governance agreement for Antarctica. Motivated by the successful scientific collaboration during the 1957/1958 International Geophysical Year (IGY), the USA invited the seven claimant states as well as the five other states that had established bases in the Antarctic during the IGY to a Washington-based conference on the future of the continent. The 1959 Antarctic Treaty was borne out of this conference and entered into force in 1961. While not solving the sovereignty problem in Antarctica, the Antarctic Treaty froze all territorial claims and established a platform for the 12 IGY states to peacefully collaborate in the Antarctic. Over the last half century, the Antarctic Treaty developed into a system of associated conventions, which had an increasingly conservationist focus, culminating in the 1991 Protocol on Environmental Protection to the Antarctic Treaty, which entered into force in 1998.

While systemically unable to dissolve the Antarctic Problem, the Antarctic governance regime has successfully resulted in higher levels of environmental protection and has ensured that the main human activity on the Antarctic continental landmass continues to be science and science support. Increasingly, Antarctica's linkages with the global system are one of the focal points of Antarctic science, and Antarctic science informs, and is at the forefront of, climate change research. The unique character of the Antarctic continent, which is surrounded by the vast, nutrient-rich Southern Ocean, plays an important role in its appeal as a climate change laboratory.

Antarctica is the coldest place on Earth, with average summer temperatures of 0 °C in coastal areas and −30 °C in the interior and average winter temperatures ranging from −15 °C near the coast and −65 °C in the interior of the continent (Cassano 2013). Similarly, Antarctica is the windiest place on Earth which, in conjunction with its remoteness and extremely low temperatures, proved to be a great challenge to many early explorers as well as modern-day adventurers. A famous quote by Sir Douglas Mawson (1915, p 88) expressed how destitute a place Antarctica was considered to be:

> We dwelled on the fringe of an unspanned continent, where the chill breath of a vast, polar wilderness, quickening to the rushing might of eternal blizzards, surged to the northern seas. We had discovered an accursed country. We had found the home of the blizzard.

The vast Antarctic ice sheets covering approximately 98 % of the Antarctic continent make Antarctica the highest continent on Earth and contribute to the low temperatures experienced on the continent. The majority of the sunlight reaching the Antarctic ice sheets is reflected back into space. Furthermore, the high elevations of the Antarctic ice sheets in the continent's interior result in Antarctica being considerably colder than the Arctic, which is largely situated at sea level at the highest latitudes (Cassano 2013). The extremely low temperatures in Antarctica result in the absolute amount of water vapour that can be held in the atmosphere being very low, making Antarctica the driest continent on Earth, with on average just over 100 mm of precipitation annually in the continent's interior (Cassano 2013).

Approximately 90 % of the world's ice and 70 % of the world's freshwater are stored in the West and East Antarctic ice sheets. The Transantarctic Mountains, one of the continent's most dramatic features, separate Antarctica into what is referred to as East and West Antarctica with their respective ice sheets. Resting on the solid continental landmass, the East Antarctic Ice Sheet is larger and thicker than the West Antarctic Ice Sheet, which is grounded below sea level in a rift system that represents the last stage in the breakup of Gondwana. As the stability of the Antarctic ice sheets is in part controlled by the underlying bedrock topography on which they sit, the East Antarctic Ice Sheet is more stable than the West Antarctic Ice Sheet. In recent years, a significant loss of mass of the West Antarctic Ice Sheet has been observed and is speculated to be forced by an upwelling of warmer ocean water leading to melting of the base of floating ice shelves (Thoma et al. 2008). Any loss in the mass of the Antarctic ice sheets will result in sea level rise.

The effects of climate change in Antarctica have a direct and significant bearing on the rest of the world. It is now being recognised that Antarctica is not as stable as it was deemed to be and climate science undertaken on the continent reports rapid changes in snow accumulation, sea ice extent and ice mass balance every year (Dodds 2012).

How fast Antarctica will warm and how long the West Antarctic Ice Sheet will remain in a warming world is very uncertain at present. Our long-term instrumental climate record, going back to the International Geophysical Year 1957/1958, shows that Antarctica is not warming in a systematic manner; the Antarctic Peninsula represents one of the global hotspots, having warmed approximately 3.5 °C over the past 50 years, whereas other parts of East Antarctica may have been cooling. Antarctic scientists have suggested that the significant springtime decrease in stratospheric ozone over the Earth's polar regions, commonly referred to as the ozone hole and discovered by systematic ozone measurements undertaken at Halley Station by British Antarctic Survey scientists (Farman et al. 1985), is the most important control on Antarctic climate at the present time, resulting in variable climatic changes across the continent. The thinning of the ozone layer in springtime is likely to become less pronounced, and potentially stop altogether, in about 50 years due to international agreements that are in place, restricting the release of chlorofluorocarbons (CFCs) into the atmosphere. As a thinner layer of ozone over Antarctica allows more of the solar radiation to escape back out to space, a more systematic warming of Antarctica is anticipated as the effects of ozone destruction in the stratosphere become less pronounced.

How the currently observed and anticipated changes in Antarctica impact the rest of our global system is an unanswered scientific question. Based on our knowledge of the geological evolution of Antarctica, we understand that Antarctica has not always been the cold isolated polar continent that it is today. It was once part of the Gondwana supercontinent that drifted south over time, traversing different climatic belts and inhabited by a diverse range of flora and fauna, before it became isolated from the once neighbouring Gondwana landmasses of South America, Africa, India, Australia and New Zealand. The current shape of the Antarctic continent reflects those geological processes, and the previous connection of

Antarctica to continents that have rich mineral reserves and offshore oil deposits has led to speculation about the mineral and oil potential of Antarctica. Although mineral resource activity is currently prohibited under the Protocol of Environmental Protection to the Antarctic Treaty, Antarctica's mineral resource potential remains a contentious issue into the future.

It was the final separation of Antarctica from South America that led to the development of the circumpolar current, which thermally isolated the continent, resulting in the cooling of Antarctica and in the subsequent development of unique ecosystems and species. This thermal isolation is most distinct in the Antarctic convergence, an approximately 30–50 km wide boundary zone in the Southern Ocean (between the 48th and 61st southern latitudinal lines), where cold, dense, northward flowing Antarctic waters push underneath warmer and less saline subtropical waters. Processes of mixing and upwelling of nutrient-rich water within this zone result in very high marine productivity. Despite its high productivity and biomass, the marine ecosystem of the Southern Ocean is among the simplest in the world. Subjected to extensive sealing and whaling exploitation in the past, the Southern Ocean is now affected by Japanese scientific whaling, commercial krill extraction and other fisheries (through legal as well as illegal operations). Attempts to eliminate illegal fishing or to protect certain areas of the Southern Ocean more comprehensively, e.g. through Marine Protected Areas, are currently receiving much media and political attention.

In contrast to the high biomass of the marine ecosystem, the terrestrial Antarctic ecosystem has much more restricted flora and fauna. Although there are no terrestrial vertebrates, it has become apparent that the soils in the McMurdo Dry Valley regions of Antarctica contain a large biomass of microorganisms. As is the case with the marine ecosystems, humankind and climate change pose the greatest risks to the terrestrial ecosystem. While its flora and fauna are not directly exploited, human activity on the continent – be it through science, tourism or other activities – can have significant adverse effects on the environment, from the introduction of diseases and alien species to the contamination of soils and Antarctic ponds, streams and lakes, just to name a few. It remains to be seen if the marine and terrestrial communities can adapt to a changing world and if we can keep invasive species from becoming established in Antarctica.

The following contributions by eminent Antarctic researchers from a range of disciplines will shed light on some of these issues. The first part of this book discusses Antarctica's physical systems over time – the continent's geological evolution, its climate, weather and atmosphere as well as its distinctive oceanographic, hydrographic and glaciological features. In the second part of the book, authors look at Antarctica's marine and terrestrial ecosystems. The third part of the book is devoted to human endeavours in Antarctica over time and the politics behind human activities in the Southern Ocean and on the continent. The final part of the book weaves together insights in the physical, social and human sciences to illuminate a discussion of current issues, such as climate change, bioprospecting, science collaboration, environmental management and Antarctic politics.

## References

Beaglehole JC (1974) The life of Captain James Cook. Stanford University Press, Stanford

Cassano JJ (2013) Climate of extremes. In: Walton DWH (ed) Antarctica: global science from a frozen continent. Cambridge University Press, Cambridge, pp 102–160

Dodds K (2012) The Antarctic: a very short introduction. Oxford University Press, Oxford, p 160

Farman JC, Gardiner BG, Shanklin JD (1985) Large losses of total ozone in Antarctica reveal seasonal ClOx/NOx interaction. Nature 315(6016):207–210

Frank R Jr (1957) Ice island: the story of Antarctica. Available from the Library of Congress (USA) through www.archive.org

Mawson Sir D (2010, original edition 1915) The home of the Blizzard – an Australian hero's classic tale of Antarctic discovery and adventure. National Library of Australia, Canberra

Thoma M, Jenkins A, Holland D, Jacobs S (2008) Modelling Circumpolar Deep Water intrusions on the Amundsen Sea continental shelf, Antarctica. Geophys Res Lett 35(18):1–6

Walton DWH (2013) Discovering the unknown continent. In: Walton DWH (ed) Antarctica: global science from a frozen continent. Cambridge University Press, Cambridge, pp 1–34

# Part I
# Physical Sciences

# Chapter 2
# A Continent Under Ice

## The Geological Setting of Antarctica

**Yvonne Cook and Bryan Storey**

**Abstract** Today Antarctica is the stage for active volcanoes, rising mountains and the formation of deep marine basins. Amidst the arid desert landscape of the McMurdo Dry Valleys, geological processes operate that are similar to those on Mars and other planets. Yet entire mountain ranges and one of the world's largest volcanic provinces disappear completely under the smooth Antarctic ice sheets, and geologists need to use geophysical and remote-sensing techniques to visualise the topography and describe the physical properties of the continent under ice. The shape of the continent, its mountain ranges and landforms directly reflect the underlying geology and plate tectonic processes of the past and present. The Transantarctic Mountains divide the continent into two geological provinces, East and West Antarctica. Each of these unequal parts has its own geological history which resulted in distinct crustal properties. While East Antarctica's crust is thick and continuous, the West Antarctic crust is thinner and varies in thickness, which means that a large part of it and the ice sheet that sits above lie below the surface of the ocean.

**Keywords** Transantarctic Mountains • Plate tectonics • Seafloor spreading • Subduction • Continental rifting • Volcanic activity • Extra-terrestrial geology

---

Y. Cook
School of Earth and Environmental Science, James Cook University, Townsville, QLD, Australia
e-mail: yvonne.cook@jcu.edu.au

B. Storey (✉)
Gateway Antarctica, University of Canterbury, Christchurch, New Zealand
e-mail: bryan.storey@canterbury.ac.nz



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_2

## 2.1 Deciphering the Past

For geologists, rocks are like history books. Each tells a story about Earth's ancient past, when tectonic shifts and mountain-building forces worked together to create unique rock types and landforms. Yet in Antarctica today, exposed rocks are a rare phenomenon. Thick ice sheets cover most of the continent and create a formidable barrier to interpreting the geological information preserved underneath.

Less than 1 % of Antarctica is free of ice, but despite this paucity of exposed rocks, some general topographical and geological features are unmistakable. The mountains of the Antarctic Peninsula and offshore islands rise shear from the ocean and have been built by a succession of volcanic eruptions; the collection of volcanoes that make up Marie Byrd Land represents one of the largest landforms of this kind in the world. The largely non-volcanic Transantarctic Mountains that divide the continent into two geological provinces and span the length of East Antarctica are visible from the moon.

All of these mountain ranges are fundamentally different and, along with the shape of the continent, directly reflect the underlying geology and plate tectonic processes. In addition, geophysical and remote-sensing techniques, including airborne magnetic and gravity surveys, over-snow seismic techniques and ice-penetrating radar, help scientists to visualise the topography and describe the physical properties of the land below the ice.

Water, ice and wind are the main carving tools that shape Antarctica's surface landscapes, resulting in unusual features that provide the closest analogue on Earth of Martian conditions. In turn, Antarctica's slow-moving ice sheets are one of the most favourable locations for finding extra-terrestrial material on Earth.

## 2.2 Antarctica's Geological Features

The differences in size and shape of the two main geographical domains of the Antarctic continent, East and West Antarctica (Fig. 2.1), reflect fundamental differences in their geological histories (Chap. 3) that have resulted in distinct crustal properties. The crust of East Antarctica is thick and continuous, and much of East Antarctica sits above sea level. In contrast, the crust of West Antarctica is thinner and varies in thickness, which means that a large part of this section of the continent lies below the surface of the ocean (Fretwell et al. 2013) and the West Antarctic Ice Sheet is grounded below sea level (Chap. 5). Underneath this smaller ice sheet lies a collage of crustal segments that form a landscape of several geologically distinct islands, archipelagos and small landmasses (Fig. 2.2).

The Transantarctic Mountains separate East and West Antarctica. Stretching 3,500 km from the northern reaches of North Victoria Land to the western margin of Coats Land and up to 200 km in width, with peaks as high as 4,500 m, these mountains are not only the most prominent range in Antarctica but also one of the

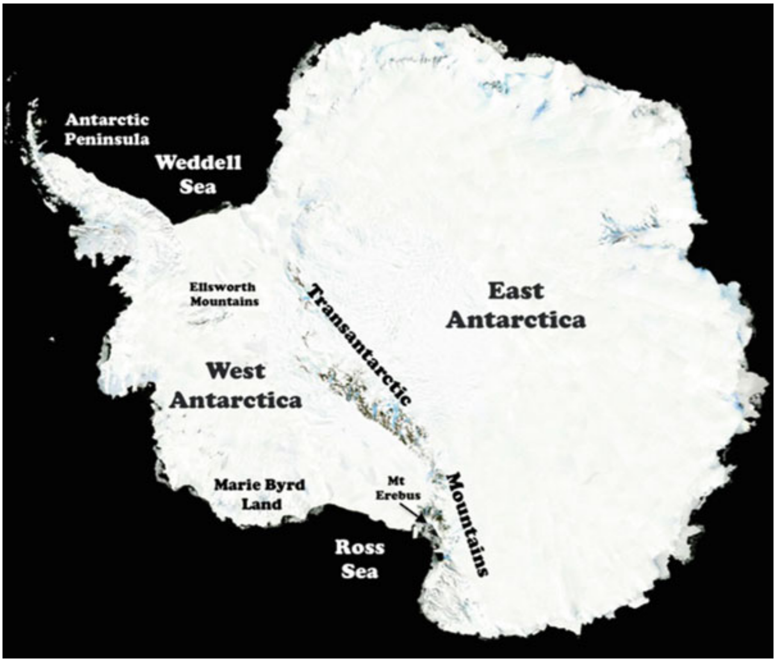



**Fig. 2.1** This Landsat image mosaic shows some significant topographical features of Antarctica: the Transantarctic Mountains separating East from West Antarctica, Mount Erebus, the Ellsworth Mountains within West Antarctica, Marie Byrd Land, and the mountainous Antarctic Peninsula (With kind permission from USGS)

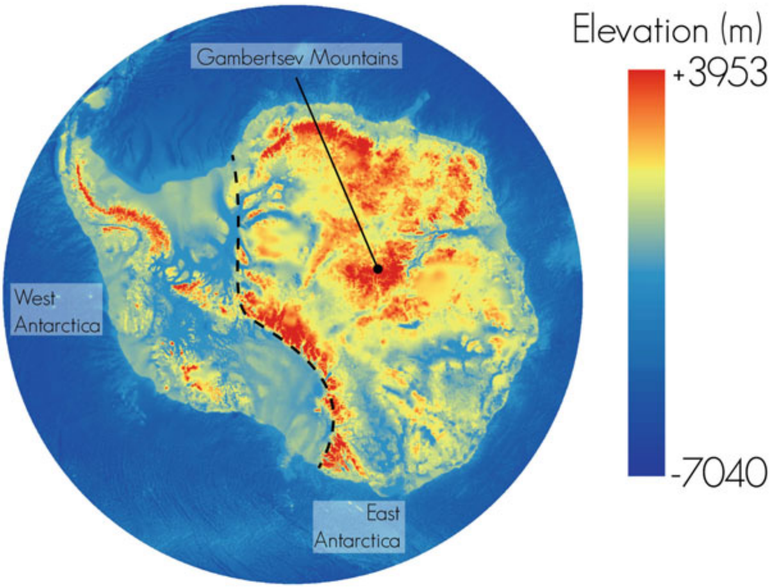



**Fig. 2.2** Antarctic sub-ice topography, showing the boundary between East and West Antarctica and regions below present sea level in *blue* (With kind permission from Fretwell et al. 2013)

highest and longest on Earth (ten Brink et al. 1997). East Antarctica features many other mountain ranges, most of which emerge only as nunataks, or isolated outcrops, through the East Antarctic Ice Sheet. The Gamburtsev Mountains are completely covered by ice (Box 2.1, Fig. 2.3).

West Antarctica is persistently mountainous. The spectacular Ellsworth Mountains host the highest summit in Antarctica (Vinson Massif, 4897 m) and the mountains of the Antarctic Peninsula form the second longest range in Antarctica. Even under vast areas of ice, such as in Marie Byrd Land, a mountainous landscape is apparent.

Volcanoes are active in three main areas. Deception Island, off the Antarctic Peninsula, is the caldera of an active volcano and the seafloor of the Bransfield Strait is strewn with vents; Ross Island in the western Ross Sea is perhaps best known for its steaming landmark, Mount Erebus; and on the eastern side of the Ross Sea, in Marie Byrd Land, a mountain range features several under-ice volcanoes. Other volcanoes exist elsewhere, but these are either dormant or extinct.

Despite the presence of large mountain ranges, Antarctica is relatively free of earthquakes. Many tremors detected in Antarctica are caused by movements within the flowing ice and not the rocks themselves, and other tremors are associated with volcanic activity rather than with major displacements in the Earth's crust.

**Box 2.1: Subglacial Gamburtsev Mountains**

The Gamburtsev Mountains have puzzled geologists for decades. These jagged peaks lie completely buried under the highest part of the East Antarctic Ice Sheet, known as Dome A. The range is about the same size as the European Alps, about 1200 km long and 3400 m from the base to the highest point, but its highest summits remain 600 m beneath the surface of the 4 km-thick ice sheet.

Major mountain ranges are generally pushed up at the edge of tectonic plates, but the Gamburtsev Mountains rise from the middle of the Antarctic plate. The most common explanation for mountain ranges that have formed at a plate centre is volcanic activity that has been caused by a so-called hotspot. Yet, there is no evidence of any volcanoes in the Gamburtsev Mountains. Another possible explanation is that this range might be hundreds of millions of years old, a remnant from a time when an ancient plate boundary ran through the continent and gave rise to the mountains. However, if this was the case, it is unusual that the mountains have not eroded and become rounded and much smaller. The height of this range and its location in the centre of the continent, away from warming sea air, suggests that the Gamburtsev Mountains may well be the place where the East Antarctic Ice Sheet first started to form 35 million years ago. The relationship between mountain formation and ice development could be crucial to determining the rate and type of glaciation that occurred as the East Antarctic Ice Sheet grew.

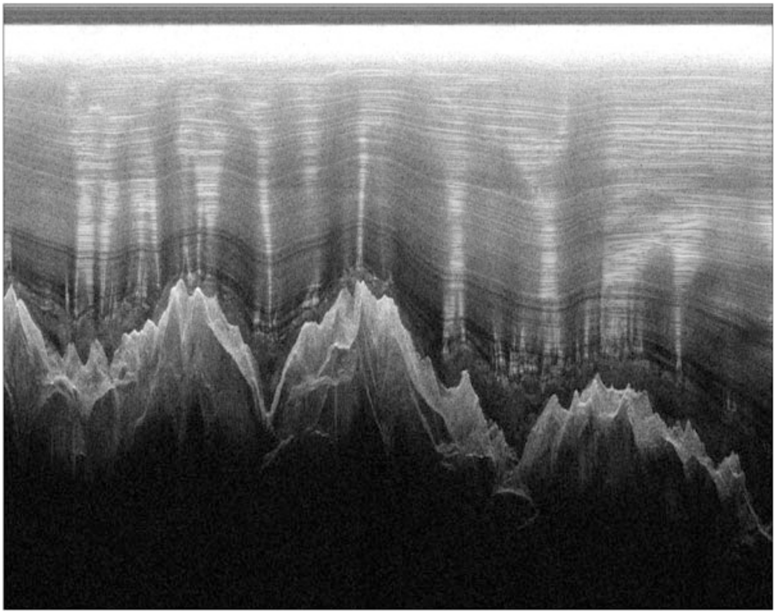


**Fig. 2.3** A radar image of the Gamburtsev Mountains showing the jagged mountain range covered in layers of ice (With kind permission from the AGAP project, Lamont-Doherty Earth Observatory of Columbia University)

## 2.3 Antarctica's Tectonic Environment

Plate tectonics drives processes that give rise to mountains, volcanic activity and deep-ocean valleys, and generally shapes the Antarctic continent and the surrounding Southern Ocean. The entire Antarctic landmass and its associated islands, with the exception of the South Shetland Islands, are part of the Antarctic plate (Torsvik et al. 2008). In addition to the thick continental crust material, this plate also includes the surrounding thin and dense oceanic crust that lies beneath the Southern Ocean (Box 2.2, Fig. 2.4).

**Box 2.2: The Inner Earth**

Earth has several distinct layers (Marshak 2011). The outer layer, the crust, is made up of two components. Continental crust is 35–70 km thick and relatively buoyant; it forms continental landmasses and tends to sit higher than sea level. Oceanic crust is 5–10 km thick and dense; it forms depressions on Earth's surface that are filled by the oceans, and is usually not exposed above sea level. The crust is divided into plates that can comprise oceanic or continental crust, or a mixture of both. The Earth's plates move apart from

(continued)

**Box 2.2** (continued)
each other, towards each other or slide past each other. In each of these cases, the geological response is very different and distinctive rocks are produced.

Tectonic plates sit on a layer of semi-molten mantle, where much of Earth's internal heat is located. Here, large-scale convection cells circulate and distribute this heat from the inner core to the crust. These convection cells are a fundamental part of plate tectonics.

Earth's inner layer is the core. It is separated into the liquid outer core, which contains mainly nickel and iron, and the solid inner core, composed of iron. The liquid outer core drives Earth's magnetic field.


**Fig. 2.4** The Antarctic continent sits within a large Antarctic plate (shown in *grey*). The Antarctic plate is separated by a spreading ridge from the African, Australian, Pacific, Nazca and South American plates. A series of small plates occurs between the Antarctic plate and the South American plate (With kind permission from Steven Dutch)

The Antarctic plate borders five other major plates and four small plates (Fig. 2.4) and it is undergoing four different types of plate tectonic processes: seafloor spreading, subduction, back arc extension and continental rifting. These processes are inherited from a major geological reorganisation of the southern hemisphere continents that started about 180 million years ago and resulted in the breakup of the supercontinent Gondwana into the present-day tectonic plates (Chap. 3). Three of the four tectonic processes acting on the Antarctic plate occur around its edge, while the fourth happens within the plate itself, between East and West Antarctica.

### *2.3.1 Seafloor Spreading: The Southern Ocean*

Most of the Antarctic plate boundary is marked by a spreading ridge (Fig. 2.5), which is generally found where the oceanic crusts (Box 2.2) of two tectonic plates are moving apart. Magma, or molten rock, sits just below the contact zone between the two plates and, as the plates move apart, new volcanic rock (basalt) fills the gap and is added to the edge of the plates, forming new ocean crust. As a result, the plates grow at their edges, forming what is known as a constructive or diverging plate boundary. This formation of new ocean crust is known as seafloor spreading. As it happens at the edge of the plate, a long way from the Antarctic continent itself, it means that Antarctica experiences fewer earthquakes and little volcanic activity, with the exception of active volcanoes near the tip of the Antarctic Peninsula, in the Ross Sea and in Marie Byrd Land.

During seafloor spreading, variable rates of spreading cause differential movement, which results in transform faults that offset the plate boundary. Along the edge of the Antarctic plate transform faults are often more extensive than sections of the spreading ridge itself, resulting in parts of the Antarctic plate moving sideways relative to its neighbouring plate (Fig. 2.5).

### *2.3.2 Subduction: The Impact on South America*

The Antarctic plate is moving towards the South American plate along the Patagonian sector of South America (Fig. 2.4). This convergence causes the thin, dense oceanic crust of the Antarctic plate to be forced down beneath the less dense continental crust at the edge of the South American plate. The result is what geologists call a destructive plate boundary. The process is known as subduction, and the resulting compression pushes the land up into mountain ranges (Fig. 2.5). The down-going section of the Antarctic plate melts as it is exposed to higher temperatures and pressures in the Earth's interior. This molten material is less dense than the surroundings and rises to the surface, producing volcanoes within the

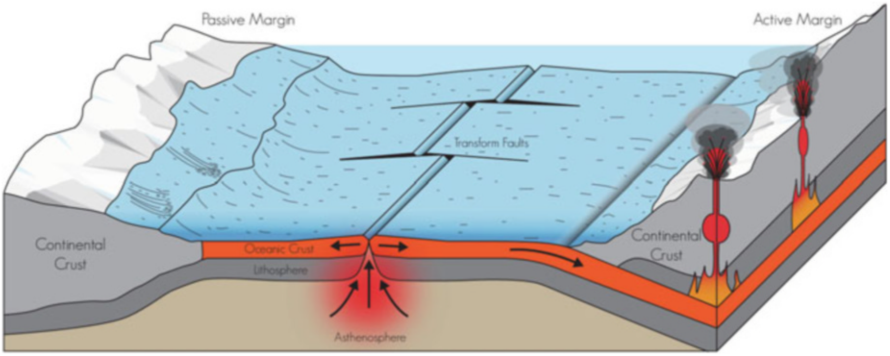



**Fig. 2.5** This block diagram shows a simple spreading ridge where two plates are moving apart with offsetting transform faults. The diagram also shows a subduction zone where one plate is going beneath a continental margin (active margin), and a passive margin where the oceanic crust is joined to the continent (Adapted from Earth: Portrait of a Planet 2011, with kind permission from Kurt Joy)

mountain range that tend to have explosive eruptions. The volcanic Andes mountains lie more or less parallel to the subduction zone.

### *2.3.3 Subduction and Formation of a Back Arc Basin: The Antarctic Peninsula, South Shetland Islands and Bransfield Strait*

The Patagonia region of South America split from the Antarctic Peninsula during the last stages of the Gondwanan breakup (Chap. 3), and several new tectonic plates were produced as a result. Today, near the top of the peninsula, four small tectonic plates are caught up between the bigger Antarctic and South American plates (Barker et al. 1991). One of these small plates, the Drake plate, is the last remaining part of what was once a much larger plate subducting beneath the entire western margin of the Antarctic Peninsula, in a process that was associated with the earliest formation of the Patagonian Andes. This subduction built the mountain range on the peninsula and produced many volcanoes. Today, the Drake plate is being subducted only beneath the South Shetland Islands (Fig. 2.6) and the only remaining volcanic activity is steaming fumaroles on Bridgeman Island.

Another tectonic process resulted in the formation of back arc extension to the east of the subduction zone, and led to the creation of a new plate, the Shetland plate. The back arc basin formed as extension and splitting of the crust occurred behind the line of volcanoes that formed during the subduction. The extension progressed, forming the new plate boundary, and some of the original volcanic rocks were forced west, away from the remainder of the Antarctic Peninsula. These now form the South Shetland Islands. During this process, a marine basin, the

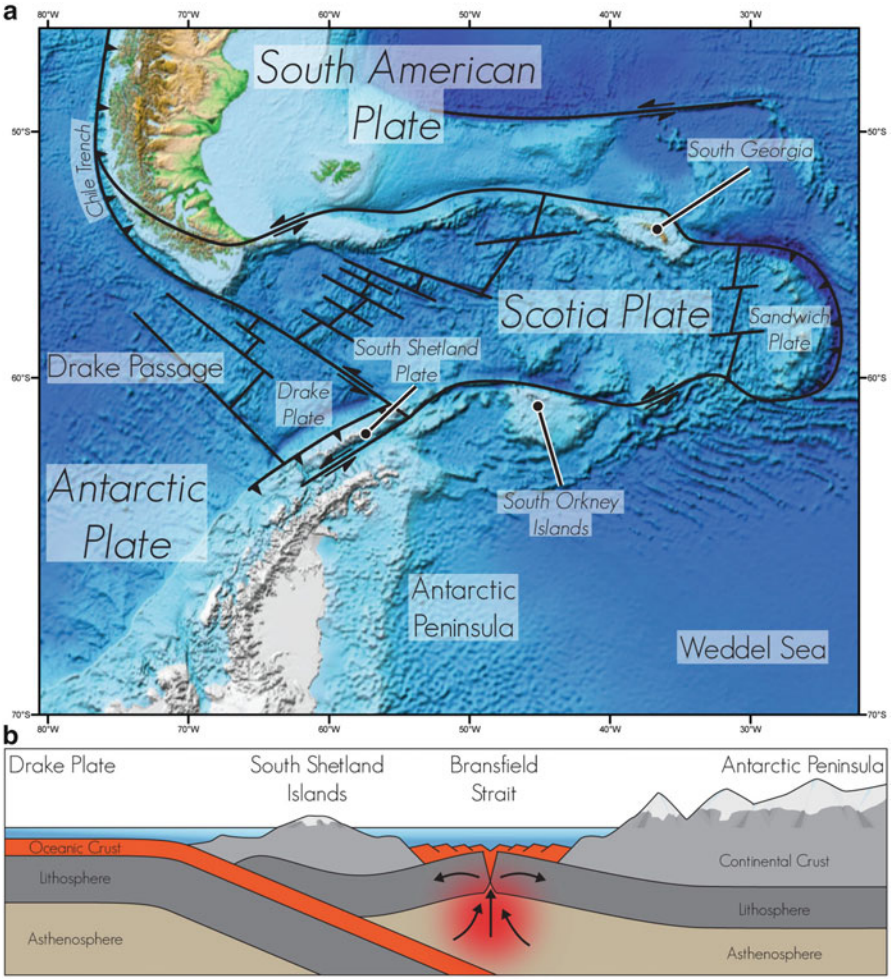



**Fig. 2.6** (**a**) This map shows four small plates, Drake, Shetland, Scotia and Sandwich, that exist between the large South American and Antarctic plates. Spreading ridges are shown by *thick black lines*, subduction zones by the toothed symbol and transform margins by the single *black lines* with *arrows* showing the direction of movement in some cases (With kind permission from Kurt Joy). (**b**) A cross section showing the subduction of the Drake plate and the resulting back arc basin that formed Bransfield Strait (Adapted from Earth: Portrait of a Planet 2011, with kind permission from Kurt Joy)

Bransfield Strait (Fig. 2.6b), formed at the point of extension between the Shetland plate (containing the South Shetland Islands), and the Antarctic plate (containing the Antarctic Peninsula). This zone of extension is still active and Deception Island, the site of one of the two most active volcanoes in Antarctica, sits above it (Smellie et al. 2002) (Box 2.3).

**Box 2.3: Deception Island**

Deception Island is almost crescent shaped, about 13 km in diameter. Its highest point is more than 500 m above sea level. Most of the island formed about 10,000 years ago during an explosive eruption. Thirty cubic km of molten rock was ejected, and the summit of the volcano collapsed to form a caldera which has since been partially flooded by the sea.

The volcano was particularly active again during the eighteenth and nineteenth centuries, and also between 1906 and 1910. A 1967 eruption formed three small new craters and an island, and led to temporary evacuation of research personnel. In 1969, a fissure erupted in the ice on the caldera wall, destroying a Chilean base and severely damaging a nearby British base, with personnel again having to be evacuated by ship. A string of small craters was formed in a 1970 eruption.

The caldera forms a protected harbour with a very narrow entrance. It has been used for shelter since the first whalers arrived in the region. Today, it is a destination for tourists and research personnel.

However, Deception Island is not extinct. In 1992, seismic activity resulted in ground deformation and increased water temperatures. Currently, the floor of the caldera is rising by a small but significant amount. It contains the only geothermal lagoon in Antarctica and extreme microclimates exist around steaming fumaroles and geothermally heated water (up to 70 °C). These features make the island a site of interest for geological and biological research, although the relatively warm microclimate means that introduced species, inadvertently brought to the island by visitors, have a better chance of establishing (Chap. 27).

### *2.3.4 Continental Rifting and Volcanic Activity: The West Antarctic Rift System*

Continental rifting takes place within the Antarctic plate itself, between East and West Antarctica. On one side of the rift system, in the McMurdo Volcanic Province in the western Ross Sea, volcanic activity began about 40 million years ago (Kyle 1990; Rocchi et al. 2002). This area hosts Antarctica's most active volcano, Mount Erebus (Box 2.4) and several extinct volcanoes, including Mount Terror and Mount Bird on Ross Island, and Mount Discovery and Mount Morning on the mainland. Although Mount Erebus does not sit on a plate boundary, the volcanic activity exists because of tension and extension within the Antarctic plate that remain as a result of the breakup of Gondwana (Chap. 3). As the Antarctic plate extended, forming a continental rift (Behrendt et al. 1991), the continental crust gradually thinned to the point that hot magma from the mantle could rise through and produce volcanic activity (Fig. 2.7). Associated volcanism has occurred along the

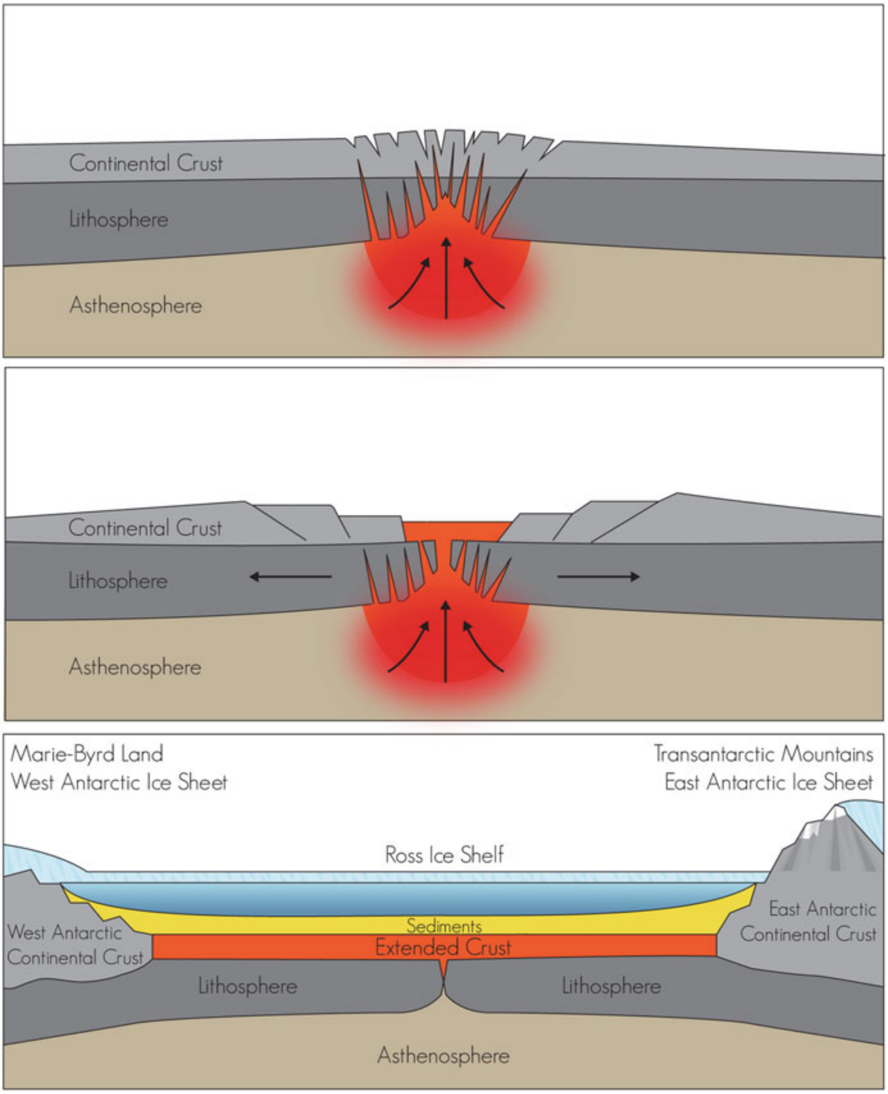



**Fig. 2.7** This block diagram shows the formation of the West Antarctic Rift System and the uplift of the Transantarctic Mountains on one side of the rift (Adapted from Earth: Portrait of a Planet 2011, with kind permission from Kurt Joy)

Transantarctic Mountains as far north as Victoria Land. Today, the volcanic Mount Melbourne has warm ground, and an ash layer exposed in ice on the volcano's flank suggests an eruption less than 200 years ago. Fumaroles also occur on Mount Rittmann.

**Box 2.4: Mount Erebus**

Mount Erebus (3,794 m) forms part of Ross Island, in the south west corner of the Ross Sea. The last significant eruption of Mount Erebus occurred in 1985, but it has been continuously active since at least 1972. Mount Erebus is one of few volcanoes on Earth to contain a permanent lake of magma in its crater, and small fountains of lava erupt up to several times a day as gasses continually escape from the magma lake. Almost always, a plume of water vapour and other gases rises from a separate vent within the crater, and fumaroles near the summit are constantly active. Mount Erebus produces an unusual volcanic rock called kenyte, which is found only in one other place on Earth, on Mount Kenya in the East African Rift. These two volcanoes produce the same rock type because they both formed in a similar, continental rift setting.

Mount Erebus was first climbed by members of Ernest Shackleton's party in 1908 (Chap. 15). Ross Island is now home to New Zealand's Scott Base and McMurdo Station, one of three United States bases, and Mount Erebus is relatively accessible for monitoring and research. Any fluctuations, for example in the chemistry of gases or in seismic activity, may indicate significant changes within the volcano, possibly marking the onset of a larger eruption. Research involves monitoring sulphur dioxide and carbon dioxide emissions, determining the age and sequence of lava flows, monitoring seismic activity, using Global Positioning Systems to monitor the shape of the volcano, and determining the overall impact of the volcano on Antarctica and the global environment.

Volcanism in Marie Byrd Land (West Antarctica) marks the opposite side of the continental rift and began at least 36 million years ago (Hart et al. 1995; Kyle 1994). There are more than 18 large volcanoes and 30 small volcanic centres, but most are covered in snow with their bases buried beneath the West Antarctic Ice Sheet. Many more may exist under the ice (Box 2.5). At 4181 m, Mount Sidley is the tallest volcanic peak. It rises 2200 m above the surrounding ice level.

**Box 2.5: Marie Byrd Land Volcanic Province**

The craters that emerge from the ice sheet in Marie Byrd Land show distinctive volcanic forms (Fig. 2.8). However, volcanism extends far beyond the few partially visible summits, and the Marie Byrd Land volcanic province is one of the largest such landforms on Earth (LeMasurier and Rex 1989; Hart et al. 1995).

Ice-penetrating radar has shown that a volcano now completely covered by the West Antarctic Ice Sheet, erupted about 2,300 years ago. The eruption is

(continued)

**Box 2.5** (continued)

**Fig. 2.8** The Marie Byrd Land volcano Mount Hampton is visible above the West Antarctic Ice Sheet and the clouds (John Smellie, previously published in *Antarctica*: *Global Science from a Frozen Continent* 2013, with kind permission from Cambridge University Press) (Walton 2013)

thought to have blown a hole in the ice sheet and produced a plume of ash and gas 12 km high. It would have covered an area of 20,000 km$^2$. This is probably the biggest eruption in Antarctica during the last 10,000 years. The volcano remains active today and molten rock erupts under the ice. Mount Berlin is also considered active as it has an underlying ice cave with higher air temperatures and a steaming fumarole that produces a tower of ice as the steam freezes on contact with the air. It is not known how many similar volcanoes exist beneath the ice of Marie Byrd Land.

## 2.4 The Transantarctic Mountains

The Transantarctic Mountains (ten Brink et al. 1993) are also a product of the crustal tension that formed the West Antarctic Rift System. During the initial part of continental extension, Antarctica's surface bulged upwards, raising elevation over a wide area before the eventual rift. The Marie Byrd Land sector of West Antarctica gradually separated from East Antarctica leaving behind the Transantarctic Mountains, which have steep escarpments on the side of the rifting (Fig. 2.9). There is no corresponding escarpment on the West Antarctica side of the rift because West

**Fig. 2.9** The Transantarctic Mountains formed on the uplifted flank of the West Antarctic rift system (Bryan Storey, previously published in *Antarctica*: *Global Science from a Frozen Continent* 2013, with kind permission from Cambridge University Press) (Walton 2013)

Antarctica is made of several smaller landmasses, allowing the extension to be distributed over a much wider area within West Antarctica itself.

## 2.5 Ross Sea Rift Basins

As the continental crust extended and thinned, it subsided and was flooded by seawater, resulting in deep marine basins under the Ross Sea (Davey et al. 1983). The difference in height from the top of the Transantarctic Mountains to the Ross Sea basins is about 7 km, and a steady supply of sediments, eroded from the neighbouring Transantarctic and West Antarctic mountains is continually filling the basins. Geologists have drilled into these thick sequences of sedimentary rock and retrieved two cores, unearthing a record of the advances and retreats of the Antarctic ice sheets and the changing Antarctic climate over the past 35 million years (Chap. 4).

The older deposits in these rift basins date to a period when life was abundant in Antarctica. Organic matter was transported to the basins and incorporated within the sediments. Such deposits are a potential source of hydrocarbons, and the sedimentary basins of the Ross Sea are one location in the Antarctic region where oil and gas reservoirs might exist (Chap. 23).

## 2.6 Consequences of the West Antarctic Rift System

As the continental crust extended and thinned and the various crustal blocks of West Antarctica separated, some regions sank below sea level. As a consequence, the base of the West Antarctic Ice Sheet is grounded below sea level and, as ocean temperatures rise, it is more likely to melt (Chaps. 5 and 25). In contrast, the East Antarctic Ice Sheet sits on a single, thick landmass, most of which is above sea level.

The Transantarctic Mountains obstruct the flow of ice from the Polar Plateau to the coast. The presence of this barrier within the extraordinary Antarctic environment results in surface processes that have shaped the unique geomorphology of the McMurdo Dry Valleys, the largest stretch of ice-free land on the continent. This arid desert landscape provides a range of habitats for terrestrial organisms, but it also represents the closest analogue on Earth for Martian conditions and geological processes on other planets.

Some of the rocks found in Antarctica are extra-terrestrial themselves. The moving ice sheets obscure the mountains of the continent itself but they make Antarctica one of the best places in the world to find meteorites.

## 2.7 McMurdo Dry Valleys

Ice-free areas are rare in Antarctica. The largest stretch of bare rock and soil is found in a sequence of valleys west of McMurdo Sound known as the McMurdo Dry Valleys (Fig. 2.10). Glaciers advancing from the Polar Plateau to the Ross Sea originally carved these valleys and filled them with ice, but now much of that ice has gone, exposing bedrock and moraine. In this region, glaciers now rarely manage to breach the Transantarctic Mountains and the flow of ice to the Ross Sea is limited. Dry katabatic winds (Chap. 6) that sweep down from the Polar Plateau cause glacial ice that has entered the valleys to sublimate (turn directly into water vapour rather than melting into liquid water). The valleys themselves receive very little direct snowfall and because of the mountain barrier, the supply of new ice does not keep pace with sublimation. As a result, the volume of ice decreases.

This process has been occurring for several million years, and during this time, permanently ice-covered saline lakes, ephemeral summer streams, bare soil, sand dunes and permafrost features have developed. Collectively, these elements now form part of a landscape that may be close to 5 million years old, one of the oldest on Earth. Moraines form part of this landscape (Chap. 5) and indicate that the McMurdo Dry Valleys have been exposed to the advances and retreats of ice from three sources. Firstly, the East Antarctic Ice Sheet has thickened and expanded to produce glaciers extending east into the valleys. Secondly, alpine glaciers that remain today have advanced and retreated, and lastly, ice from an expanded and thickened Ross Ice Shelf has been forced to spread inland and upstream, bringing

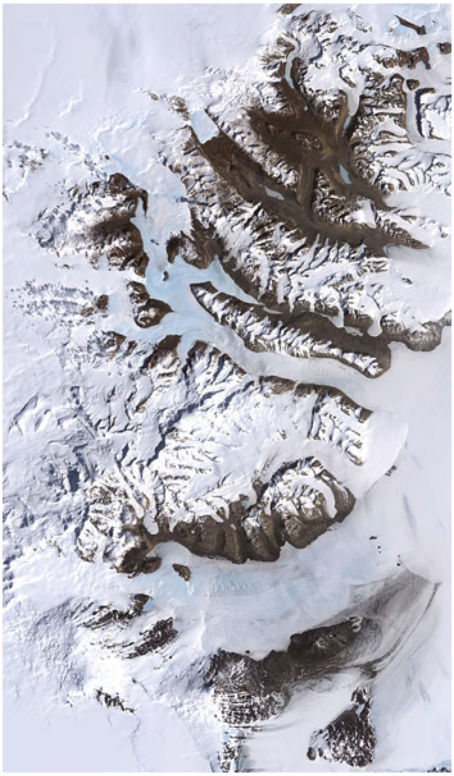


**Fig. 2.10** The McMurdo Dry Valleys are the conspicuous ice-free areas on the left in this photograph. Large lakes can be seen within the valleys (With kind permission from NASA)

with it distinctive moraines from the volcanic rocks on Ross Island that lies to the east. Determining the age and extent of these ice advances is key to understanding past climate conditions (Chap. 4).

The valleys provide a unique Antarctic environment for studying a range of physical processes, and local variations in temperature, humidity and soil moisture provide an array of microclimates that generate extraordinary habitats for terrestrial life (Chaps. 10 and 11).

## 2.8 Antarctica and Extra-Terrestrial Geology

Antarctica provides clues about the universe and our solar system for two main reasons: the extremely cold, dry and ice-free McMurdo Dry Valleys are the closest analogues we have for surface processes occurring on other planets, and the ice of the Polar Plateau supplies extra-terrestrial material, in the form of meteorites.

Antarctica and Mars are both dry and cold with low snow and ice accumulation, slow ice movement, low sublimation rates and little energy for ablation (Chap. 5). Under these conditions, unique topography can develop. Where the McMurdo Dry

**Fig. 2.11** A large sand dune formed by blowing sand (from *right* to *left*) in Victoria Valley, McMurdo Dry Valleys (With kind permission from Charlie Bristow)

Valleys have sand and gravel on the valley floors, the winds have piled the debris into scattered sand dunes (Fig. 2.11). These sand dunes contain ice at their centres, which gives the dunes a distinctive shape and determines how they move across the valleys as the sand grains are blown by the wind.

Dunes on Mars, which have been studied using remote-sensing techniques, are also thought to contain ice at their centres. This may have provided a suitable habitat for life in the past.

Rock weathering is also distinctive in the McMurdo Dry Valleys. Any moisture in the atmosphere breaks down rock, causing cracks, which are then enlarged by ice and sand to produce highly cavernous rocks known as tafoni. Wind-blown sand is instrumental in wearing down and polishing faceted stones known as ventifacts. The layers of sand and gravel deposited on the floor of the valleys are subject to permafrost, and the melting and freezing in the active layer produces unusual patterns known as sublimation polygons. All these features also appear to have analogues on Mars, and by understanding their formation and comparing them with Martian images, planetary scientists hope to increase their understanding of extra-terrestrial processes.

## 2.9 Rocks from Outer Space

Meteorites land randomly all over Earth. In Antarctica, however, they are easy to spot. In the centre of East Antarctica, where the continent's ice cover is at its thickest, the closest terrestrial rocks are embedded 3,000 m beneath the ice. Any rocks found on the surface are likely to have fallen there from space. Meteorites are dark in colour and prominent on white snow or blue ice, and in Antarctica, they are not obscured by vegetation. The ice they land on is flowing down from the Polar Plateau towards the Ross Sea. The Transantarctic Mountains obstruct these glaciers as they move over or around the mountains. Sometimes, slow-moving eddies are formed in the glaciers. Meteorites are carried in or on the ice to these slower moving areas, where dry katabatic winds speed across the surface for long periods of time, resulting in extensive sublimation. As the ice disappears, the meteorites emerge.

More than 1500 meteorites have been found in a relatively small (3 km by 7 km) patch of exposed, slow-moving blue ice on the Beardmore Glacier, and in total, over 16,000 samples have been recovered from Antarctica. Meteorites found in Antarctica are less weathered than those found in temperate climates and, because industrial pollution is low, they remain relatively uncontaminated. Even though the meteorites may have dropped from space tens of thousands or millions of years ago, they remain fresh and clean.

This large collection of Antarctic meteorites has improved our understanding of the early history of our solar system and the origin of asteroids, comets, the moon and planet Mars. Many rare and unusual meteorites have been found which add to the diversity of known extra-terrestrial rock types.

## References

Barker PF, Dalziel IWD, Storey BC (1991) Tectonic development of the Scotia Arc region. In: Tingey RJ (ed) The geology of Antarctica. Clarendon, Oxford, pp 215–246

Behrendt JC, LeMasurier WE, Cooper AK, Tessensohn F, Trehu A, Damaske D (1991) Geophysical studies of the West Antarctic rift system. Tectonics 10(6):1257–1273

Davey FJ, Hinz K, Schroeder H (1983) Sedimentary basins of the Ross Sea, Antarctica. N Z J Geol Geophys 27(4):405–412

Fretwell P et al (2013) Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. Cryosphere 7(1):375–393. doi:10.5194/tc-7-375-2013

Hart SR, Blusztajn J, Craddock C (1995) Cenozoic volcanism in Antarctica: Jones Mountains and Peter I Island. Geochim Cosmochim Acta 59(16):3379–3388

Kyle PR (1990) McMurdo volcanic group Western Ross embayment. Introduction In: LeMasurier W, Thompson J (eds) Volcanism of the Antarctic plate and Southern Ocean. Antarct Res Ser Am Geophys Union 48:18–25

Kyle PR (1994) Volcanological and environmental studies of Mount Erebus. Antarct Res Ser Am Geophys Union 66:162

LeMasurier WE, Rex DC (1989) Evolution of linear volcanic ranges in Marie Byrd Land, West Antarctica. J Geophys Res 94(6):7223–7236

Marshak S (2011) Earth: portrait of a planet, 4th edn. W.W Norton & Company, New York

Rocchi S, Armienti P, D'Orazio M, Tonarini S, Wijbrans JR, Di Vincenzo G (2002) Cenozoic magmatism in the western Ross Embayment: role of mantle plume versus plate dynamics in the development of the West Antarctic rift system. J Geophys Res 107(B9):2195
Smellie JL, Lopez-Martinez J et al (2002) Geology and geomorphology of Deception Island, BAS Geomap Series. British Antarctic Survey, Cambridge
ten Brink US, Bannister S, Beaudoin BC, Stern TA (1993) Geophysical investigations of the tectonic boundary between East and West Antarctica. Science 261(5117):45–50
ten Brink US, Hackney RI, Bannister S, Stern TA, Makovsky Y (1997) Uplift of the Transantarctic Mountains and the bedrock beneath the East Antarctic ice sheet. J Geophys Res Solid Earth 102 (B12):27603–27621
Torsvik TH, Gaina C, Redfield TF (2008) Antarctica and global paleogeography: from Rodinia, through Gondwanaland and Pangea, to the birth of the southern ocean and the opening of gateways. In: Cooper AK, Barrett PJ, Stagg H, Storey B, Stump E, Wise W (eds) Antarctica, a keystone in a changing world. Proceedings of the 10th International symposium on Antarctic Earth Sciences. The National Academies Press, Washington DC
Walton DWH (2013) Antarctica: global science from a Frozen Continent. Cambridge University Press, Cambridge

# Chapter 3
# A Long Journey South

## Unravelling Antarctica's Geological History

**Bryan Storey and Yvonne Cook**

**Abstract** Millions of years ago, Antarctica broke free from a giant supercontinent and began its transformation from a land of lush forests that harboured dinosaurs to a frigid continent at the bottom of the world. Evidence of the geological processes acting on the continent is preserved in the many different types of rock in Antarctica. The rocks tell a complex tale of a continent that has experienced a wide range of climates, seen a variety of life forms and hosted mountain ranges that are now completely eroded away. Although exposed rocks are rare in Antarctica, their diversity provides enough information to chart the continent's history from one of the oldest rocks found on Earth to the present day.

**Keywords** Rodinia • Gondwana • Ross orogeny • Mass extinction • Gondwanan breakup • Cooling of Antarctica

## 3.1 Reading Rocks

When a search party discovered Captain Scott's final tent in November 1912, some 8 months after he and his four companions had perished on their return journey from the South Pole, they found meteorological logs, diaries, letters, rolls of film and 16 kg of fossil-bearing rocks.

Several of the fossils were of a plant with feather-like veined leaves, collected by Edward Wilson from a coal seam in the Beardmore Glacier. Wilson – doctor, artists and scientist on the ill-fated Terra Nova expedition – was the first to study these

B. Storey (✉)
Gateway Antarctica, University of Canterbury, Christchurch, New Zealand
e-mail: bryan.storey@canterbury.ac.nz

Y. Cook
School of Earth and Environmental Science, James Cook University, Townsville, QLD, Australia
e-mail: yvonne.cook@jcu.edu.au



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_3

coal shales and to recognise them as geological signposts from a time when Antarctica must have been much warmer and covered in lush vegetation. Scott's men didn't know at the time that they had discovered the first Antarctic specimen of Glossopteris, an ancient seed fern which had also been found in South America, Africa and India. But they knew that their find was significant. As they struggled to make their way back from the pole, they abandoned much of their gear in an effort to reduce their sledging load, but they continued to carry the rocks to their icy grave.

It was only once the fossils were identified and confirmed as Glossopteris that it became clear that the men's final effort had contributed important evidence and added weight to the idea of a southern supercontinent and the theories of plate tectonics and continental drift.

Geology works slowly but relentlessly. Evidence of geological processes acting over billions of years is preserved in the many different rock types in Antarctica, and geologists have learned to decipher these traces of information, much like forensic detectives reconstructing a crime from fragments left behind at the scene. The diversity of Antarctic rocks provides enough information to establish general and detailed pictures of Antarctica's history, from a 3.93 billion-year-old mineral, representing one of the oldest rocks found on Earth, to the present day.

The composition and structure of rocks, and their relative age all indicate the geographic and tectonic environments that existed when they formed. Sedimentary rocks are good indicators of geography, pointing to the existence of ancient rivers, lakes, marine basins, mountains, lowland plains and swamps, and sometimes even providing enough information to determine temperature and humidity (Box 3.1). In contrast, igneous rocks are more indicative of past plate tectonic processes (Box 3.2).

**Box 3.1: Sedimentary Rocks (Fig. 3.1)**

Sedimentary rocks are made from the eroded fragments of pre-existing rocks. The pieces are transported by wind and water and as they accumulate and build up in layers, they are buried and compressed, eventually turning into a solid rock. The size and shape of the fragments indicate the environment in which the rocks formed. Sandstone is made of small, rounded fragments that have been in a high-energy environment, such as a river or a beach, where constant movement knocks edges off the pieces and makes them rounder and smaller. Mudstone forms in low-energy environments such as lakes, where only small particles can be carried in the water and eventually sink and accumulate. Sedimentary rocks sometimes contain fossils, for example of marine or freshwater fish, which provide information about environmental conditions at the time. Occasionally, rocks such as some types of limestone are made entirely from animal remains and, in some circumstances, sedimentary rocks are not derived from pre-existing rocks but precipitate directly from water.

(continued)

**Box 3.1** (continued)

**Fig. 3.1** The layered sequence of sedimentary rocks shows interbedded pale coloured sandstones and dark coloured mudstones in the Transantarctic Mountains. Note the people for scale (© Bryan Storey)

The composition of the rock fragments can also provide geologists with clues about the tectonic environment at the time the fragments were being eroded.

**Box 3.2: Igneous Rocks (Fig. 3.2)**

The word igneous comes from the Latin word *ignis* for fire. Igneous rocks are derived from magma, molten rock that forms in the extreme heat in the inner Earth. The magma gradually makes its way towards the surface where it erupts from a fissure or vent and forms a volcano. If it reaches the Earth's surface, for example as a lava flow, it cools quickly and forms an igneous rock with small crystals, such as basalt. If it doesn't, it cools and hardens slowly, forming an igneous rock with large crystals, such as granite. Granite and similar rocks can be thought of as the root of a volcano. The chemistry of igneous rocks holds clues about the tectonic environment at the time they formed. For instance, magma chemistry differs depending on the location

(continued)

**Box 3.2** (continued)

**Fig. 3.2** This photograph shows a columnar jointed basalt unconformably overlying an eroded pale coloured granite in Marie Byrd Land. The cliff face is approximately 30 m high (© Bryan Storey)

where it first formed and the extent of contamination by surrounding rocks as it rose to Earth's surface. Volcanic rocks formed in areas of plate collision are chemically different from those that formed in areas of plate divergence.

Sometimes, volcanic rocks also hold information about geographical conditions at the time of their deposition.

The tectonic movement of plates is the main driver for Earth's complex and constantly changing topography, which in turn influences circulation in the atmosphere, physical processes on the surface, as well as biological habitats and, ultimately, the evolution of life.

Ancient rocks that formed on Earth's surface can be compared directly with those forming today and the environment in which they were created can be interpreted with reasonable accuracy. However, some rocks were formed deep within Earth before being uplifted and exhumed (eroded and exposed at the surface) and the high temperatures and pressures that created these rocks need to be taken into account and correlated with processes on Earth's surface before their origin can be described with any certainty. The older the rocks, the more opportunity they have had to be eroded away, metamorphosed (Box 3.3) or covered by younger rocks, reducing the quality of information they supply.

**Box 3.3: Metamorphic Rocks (Fig. 3.3)**

Metamorphic rocks are formed from any pre-existing rock that has been forced below Earth's surface, where high temperatures and pressures caused it to change structure and composition. A combination of the original rock type and the temperature and pressure reached during metamorphism determines the final metamorphic rock type and gives an indication of the tectonic environment. Schist and marble are examples of metamorphic rocks.

**Fig. 3.3** The granite gneiss at Haag Nunataks is typical of many of the metamorphic basement rocks in East Antarctica (© Bryan Storey)

Rocks in Antarctica tell a tale of a continent that has experienced a wide range of climates, has seen a variety of life forms and has hosted mountain ranges that are now completely eroded away. The rocks of East Antarctica originated in the Northern Hemisphere and came to be part of a huge supercontinent that moved across the globe before breaking up and positioning Antarctica as an isolated continent at the South Pole. The rocks of West Antarctica have a variety of origins and most of them are relatively young additions to the continent. Those of the Antarctic Peninsula are related to rocks of Patagonian South America.

## 3.2 Antarctica Within Ancient Supercontinents

### *3.2.1 Rodinia*

Scientists speculate that 1100 million to 750 million years ago East Antarctica was joined to the western side of North America in a continent called Rodinia (Fig. 3.4) (Moores 1991; Dalziel 1997). This reconstruction is based on the alignment of rocks of similar composition, structure and age. In particular, a distinctive stretch of metamorphic rocks, which represents the roots of an ancient mountain range known as the Grenville belt, is present in North America and East Antarctica. The configuration of the continents in Rodinia allows for continuity of this ancient mountain range.

North America is thought to have split from East Antarctica in a continental rift (Chap. 2) approximately 750 million years ago. As the two parts separated, ocean crust started to form along a spreading ridge, resulting in the formation of the earliest, or proto, Pacific Ocean.

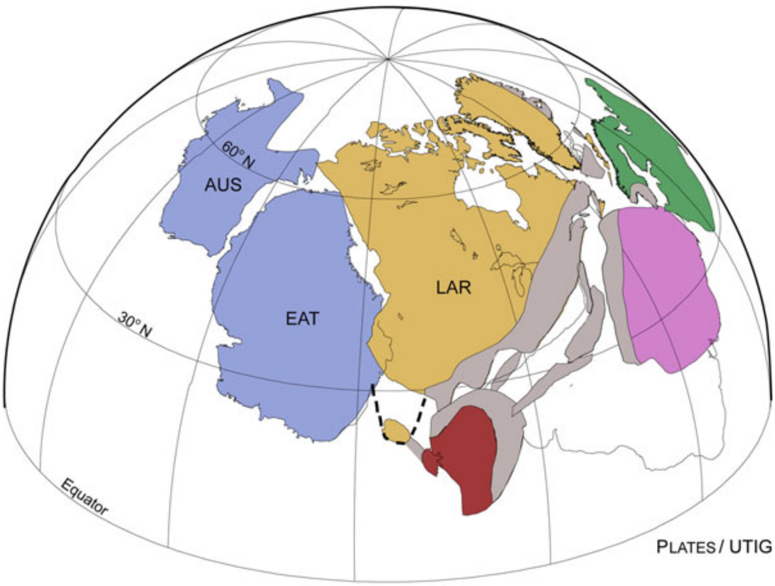



**Fig. 3.4** This reconstruction shows East Antarctica (EAT) and Australia (AUS) joined to North America (Laurentia, LAU) in an ancient supercontinent called Rodinia. The Grenville belt of metamorphic rocks is coloured grey in this figure (Adapted from *Antarctica*: *Global Science from a Frozen Continent* 2013, with kind permission from Cambridge University Press)

### 3.2.2 Gondwana

As these newly formed continents continued to move, North America rotated away from East Antarctica and collided with the western margin of South America (Dalziel 1997). This collision caused scattered continental blocks, including the rocks of East Antarctica, to come together to form another supercontinent called Gondwana, about 550 million years ago (Fig. 3.5).

Where the continental blocks collided, Himalayan-sized mountain ranges arose. In Antarctica, these have now been eroded, exposing their roots, which are found in the scattered nunataks protruding through the East Antarctic Ice Sheet. The fossil record built up during the formation of Gondwana indicates a time of rapid evolution of multi-cellular plants and animals. When Gondwana eventually broke apart (Torsvik et al. 2008), the continents and landmasses of Antarctica, South America, India, Africa, Australia and New Zealand were formed (Fig. 3.6).

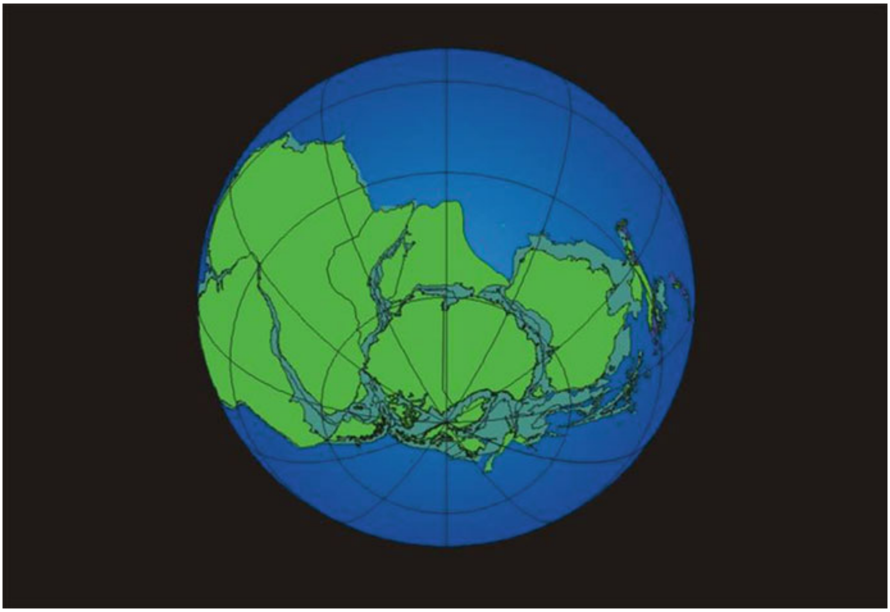


**Fig. 3.5** The continents of South America, Africa, India, Australia and New Zealand were joined together in a supercontinent called Gondwana from about 550 to 180 million years ago (Bryan Storey, previously published in *Antarctica*: *Global Science from a Frozen Continent* 2013, with kind permission from Cambridge University Press)

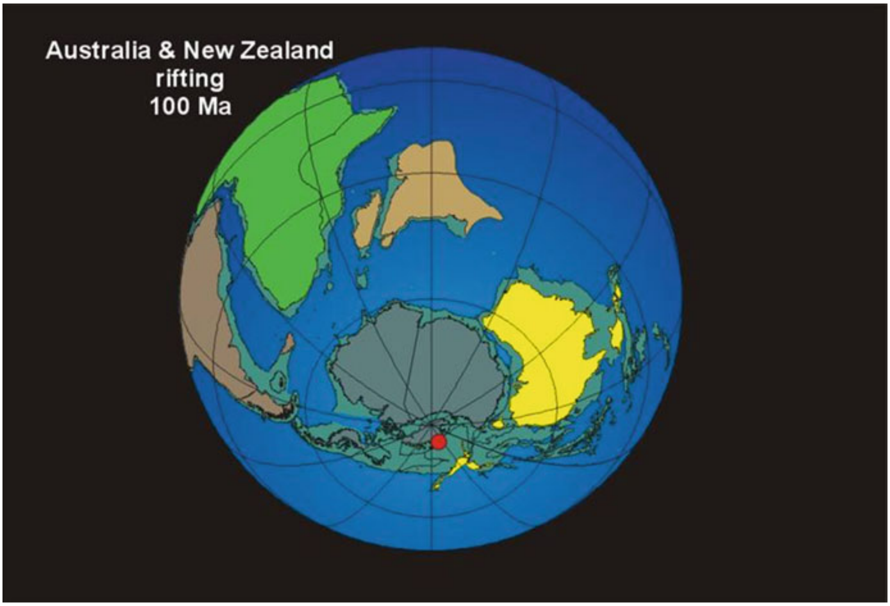



**Fig. 3.6** By 100 million years ago, South America, Africa and India had separated from Antarctica. Australia and New Zealand rifted away from Antarctica soon after. The *red dot* shows the location of a possible mantle hot spot that may have contributed to the separation of New Zealand from Antarctica (Bryan Storey, previously published in *Antarctica*: *Global Science from a Frozen Continent* 2013, with kind permission from Cambridge University Press)

### *3.2.3 An Active Tectonic Environment*

From 550 to 450 million years ago, during the Cambrian and Ordovician periods, the Pacific Ocean subducted (Chap. 2) beneath Gondwana along what is now the edge of East Antarctica, resulting in a volcanic mountain range 3000 km in length. This mountain-building episode is known as the Ross Orogeny (Stump 1995) and ended most likely because a mass of continental crust on the subducting plate collided with East Antarctica and stopped the subduction process.

The Ross Orogeny brought deep-level rocks to the surface, including granite, the solidified roots of volcanoes, and metamorphic rocks, the roots of mountain ranges formed deep in Earth's crust during subduction. Once subduction had stopped, erosion of the mountains produced an extensive flat surface, known as the Kukri Peneplain, which cuts through the igneous and metamorphic roots of the Ross Orogeny (Fig. 3.7).

**Fig. 3.7** This photograph shows the horizontal erosion surface called the Kukri Peneplain that is underlain by igneous rocks formed by subduction during the Ross Orogeny and overlain by sedimentary rocks after subduction ceased (With kind permission from Margaret Bradshaw)

## 3.3 Geography and Biology of Gondwana

Over 300 million years of Gondwana's history, a 2.5 km thick sequence of sedimentary rocks known as the Beacon Supergroup (Barrett 1991) was deposited on the Kukri Peneplain in Antarctica. During that time, Gondwana experienced climatic variations that affected the whole globe, and which are reflected in the fossil record and the rock compositions. In addition, Gondwana crossed different climatic regions as it moved from the equator towards the South Pole, which led to a constantly evolving flora and fauna.

### *3.3.1 Rivers, Shallow Seas and Fishes*

The oldest rocks at the base of the Beacon Supergroup show that the East Antarctic segment of Gondwana supported large meandering rivers and was partly covered in lakes and shallow seas during the Silurian and Devonian periods. The Devonian period saw rapid evolution of fishes across the world and the rivers of Antarctica were no exception. Fossils of various fishes, including primitive lungfish and the armour-plated Placoderm fish, are preserved in sedimentary rocks throughout the Transantarctic Mountains (Fig. 3.8a, b).


**Fig. 3.8** (**a**, **b**) Mid-Devonian Antarctic fish. (**a**) The fossilised lower jaw of the large *Notorhizodon mackelveyi* and (**b**) a reconstruction of *Donnrosenia* based on fossilised skeletal remains (With kind permission from Stilwell and Long 2011)

### *3.3.2 A Temporary Polar Landscape*

The Beacon Supergroup rocks also suggest that about 300 million years ago the climate changed and Gondwana became partially covered by a large ice sheet during the Carboniferous period (Fig. 3.9). This ice sheet advanced and retreated, depositing glacial moraines that are now solidified and preserved in the Transantarctic Mountains as large thicknesses of till. As the ice moved, boulders frozen within it cut furrows and grooves in the underlying rock surface that are still visible today and record the passage of the ice sheet.

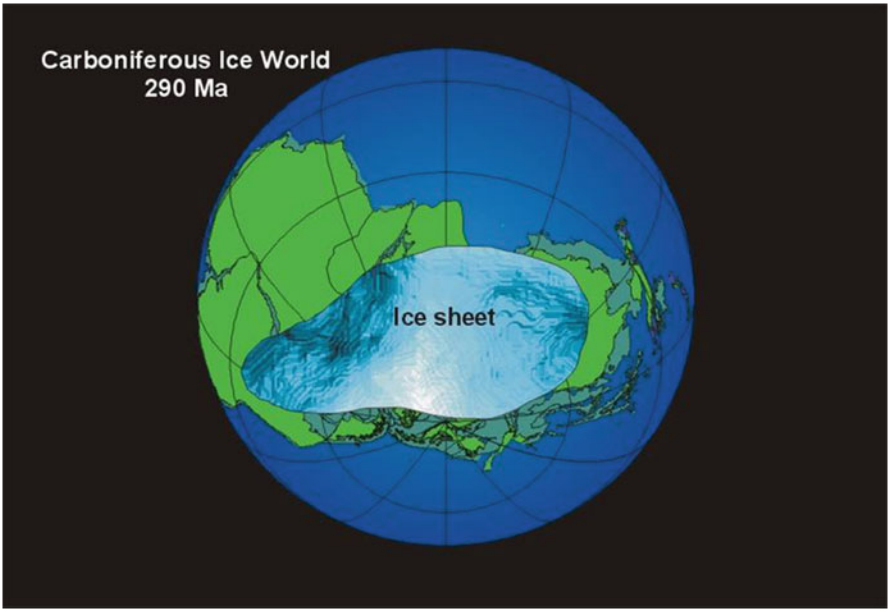



**Fig. 3.9** An ice sheet covered part of Gondwana about 300 million years ago, forming a temporary polar landscape during the Carboniferous period (Bryan Storey, previously published in *Antarctica*: *Global Science from a Frozen Continent* 2013, with kind permission from Cambridge University Press)

### *3.3.3 Swamps, Coal and Conifers*

After the Carboniferous glaciation, the climate warmed gradually and plants that thrived in extensive cool-temperate swamps evolved quickly during the Permian period. This swamp vegetation eventually turned into coal deposits, now seen as thick seams at several places in the Transantarctic Mountains (Fig. 3.10).

Edward Wilson was the first person to study these coal seams, as he climbed the Beardmore Glacier on his way to the South Pole with Captain Scott in 1911. He noticed fossil leaves in the coal, which showed that Antarctica had not always been the barren, icy place he was experiencing. The most characteristic fossils were later identified as Glossopteris (Fig. 3.11), the largest and best-known genus of an extinct order of seed ferns.

During Scott's time, the idea that crustal fragments should move around on the surface of the globe was far from accepted, and the discovery of Glossopteris in East Antarctica as well as South America, Africa, Australia and India added weight to the concept of Gondwana and the theories of plate tectonics and continental drift. Other plant fossils identified in East Antarctica include Ginkgo and conifer species, which colonised the drier hillsides, and tree ferns similar to those alive today.

**Fig. 3.10** A 4–5 m thick coal bed within sedimentary rocks in the Transantarctic Mountains (Bryan Storey, previously published in *Antarctica*: *Global Science from a Frozen Continent* 2013, with kind permission from Cambridge University Press)

## 3.4 Mass Extinction, Renewed Evolution

Approximately 250 million years ago, at the end of the Permian period, up to 96 % of all marine species, and 70 % of land vertebrate species died out during Earth's most extreme extinction event. Many plants were also affected, including Glossopteris. The initial triggers of the extinction were probably gradual environmental changes such as dropping sea levels, the development of anoxic conditions in the oceans, and increased aridity on land. A later catastrophic event, such as a large meteor impact (Kaiho et al. 2001) which would have led to increased volcanism or a sudden release of methane hydrates from the seafloor, may have acted on this already stressed ecosystem and made the extinction so devastating.

Certain groups, including some conifers, ferns and ginkgos, survived the extinction. They became part of the next burst in evolution during the warm and wet Triassic period which produced many plants that are widely represented in South America, Australia and New Zealand today. This new flora was characterised by Dichroidium, a seed fern with forked fronds, podocarps and horsetails. As the Triassic progressed, the climate became increasingly hot and dry and many plants evolved drought-resistant adaptations.

Reptiles were common (Vickers-Rich and Hewitt Rich 1999). Lystrosaurus was a vegetarian mammal-like reptile, with two tusks, which fed on fluvial flood plains across Gondwana (Fig. 3.12).

**Fig. 3.11** Fossil Glossopteris leaves approximately 10 cm long (With kind permission from Margaret Bradshaw)

Myosaurus was a very small, rare mammal-like reptile found only in South Africa and Antarctica, and Thrinaxodon was a stoat-sized carnivore that also lived in South Africa. This was the time when the first primitive ancestors of modern lizards evolved. The Temnospondyls were semi-aquatic amphibians the size of a large crocodile with skulls nearly 1 m in length.

As dinosaurs evolved and spread across the world during the Jurassic period, they also colonised the East Antarctic sector of Gondwana. *Cryolophosaurus ellioti*, known as the frozen crested reptile, was unique to Antarctica, 7 m long and carnivorous with an unusual bony display crest on top of its skull (Fig. 3.13).

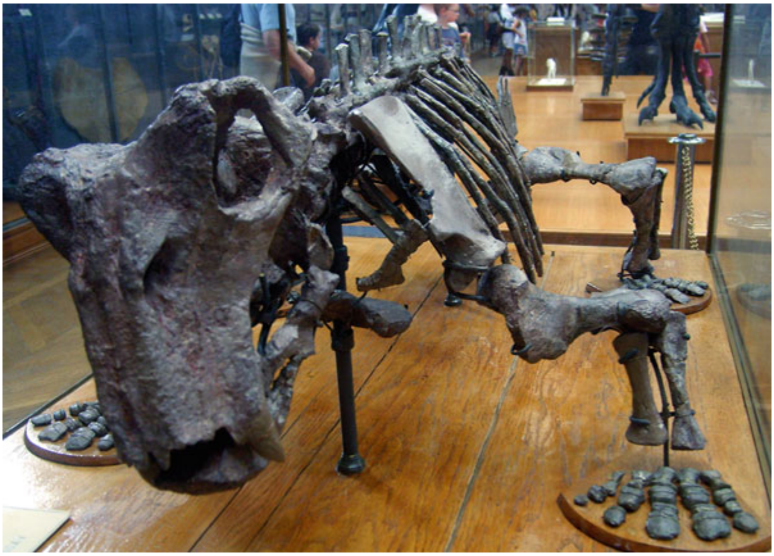


**Fig. 3.12** A *Lystrosaurus murrayi* skeleton, at the Museum national d'histoire naturelle, Paris. Fossils of this 1 m long reptile were found within sedimentary rocks in the Transantarctic Mountains. The reptiles roamed the river banks during the Triassic period, 250 million years ago (With kind permission from Wikimedia Commons)

**Fig. 3.13** A cast of the head of *Cryolophosaurus elliota*, Royal Ontario Museum, Toronto, Ontario, Canada (With kind permission from D. Gordon, E. Robertson, Wikimedia Commons)

Large, long-necked reptilian herbivores such as Apatosaurus and Brachiosaurus, and flying reptiles, the Pterosaurs, were also present. This rapid success of dinosaurs is associated with a change in climate and with vegetation dominated by conifers (Rich and Rich 1993).

## 3.5 Breakup of Gondwana and Isolation of Antarctica

### *3.5.1 Ferrar Large Igneous Province*

Gondwana started to break into smaller fragments about 183 million years ago, during the Jurassic period. The breakup was marked by intensive volcanism that lasted less than a million years. The volcanic activity spanned Gondwana from what is now Africa, through East Antarctica along the Transantarctic Mountains, and into Tasmania and New Zealand, a distance of over 4000 km. Most volcanoes and vents that formed during this period have since been eroded. However, just below Earth's surface a network of vertical sheets (dykes) and horizontal layers (sills) of igneous rock formed that originally supplied magma to the volcanoes. This structure is now solidified and preserved, and has been uplifted to Earth's surface and exposed by erosion. It is known as the Ferrar Dolerite (Elliot 1992) and the wider volcanic activity across East Antarctica as the Ferrar Large Igneous Province (Storey and Kyle 1997) (Fig. 3.14). Similar volcanic rocks in southern Africa are known as the Karoo Province (Cox 1988) and are similar to those found in Dronning Maud Land in East Antarctica.

The Ferrar and Karoo igneous rocks may have been derived from an abnormally large, hot part of Earth's mantle, called a plume. Plumes appear to be associated

**Fig. 3.14** The prominent black layers are basalt sills, crystallised from hot liquid magma that was injected into sedimentary rock along the Transantarctic Mountains 183 million years ago just prior to the initial breakup of Gondwana in the Jurassic period (With kind permission from Antarctica New Zealand)

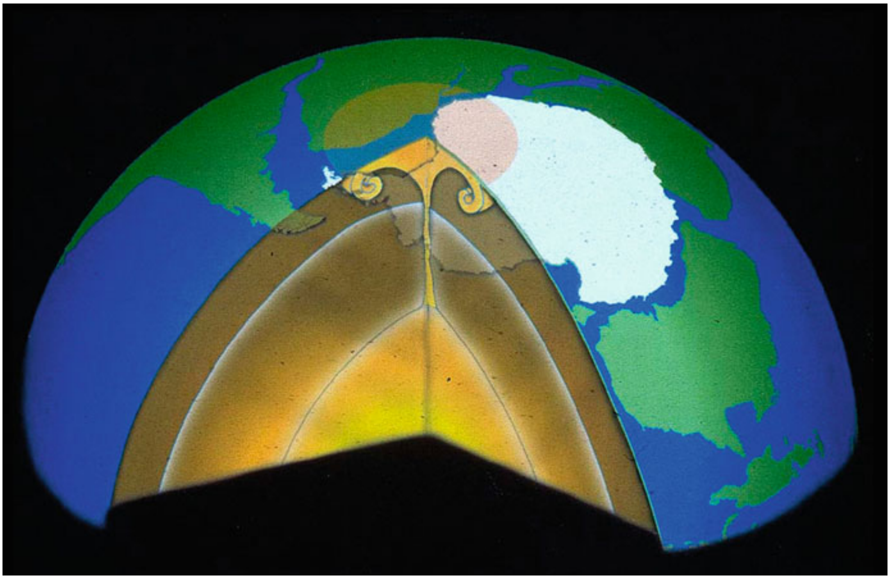


**Fig. 3.15** This figure illustrates a plume of hot magma that may have originated from the Earth's core beneath Gondwana and contributed to its breakup, forming the large volume of igneous rocks across Gondwana (Bryan Storey, previously published in *Antarctica*: *Global Science from a Frozen Continent* 2013, with kind permission from Cambridge University Press)

with unusually large-volume volcanic events and can also be linked with continental rifting (Storey 1995). The location of the Karoo Province coincides with the point where East Antarctica split from Africa during Gondwana's breakup. Several plumes may have been associated with the splitting of Gondwana (Fig. 3.15), but all of the Ferrar magma may have come from just two plumes found in what is now the South Atlantic.

The volcanic islands of Marion and Bouvet may be their present-day expressions. If this is the case, magma has flowed for thousands of kilometres through the dykes and sills that are preserved today.

In southern South America, geologists have identified a large area of volcanic rocks that are of a similar age, but differ in composition from those of the Ferrar and Karoo provinces. However, these are also related to the breakup of Gondwana. The difference in their composition most likely means that the magma came from a different location in the Earth's mantle and was exposed to other processes as it rose to the surface.

The extensive volcanic activity associated with the breakup of the Gondwanan supercontinent had a major effect on other Earth systems, influencing atmospheric composition, climate, flora and fauna.

### 3.5.2 Stages of Gondwana Breakup

The breakup of Gondwana (Storey 1995) started either at the same time or just after the outburst of Ferrar volcanic activity in the Jurassic period and led to a thinning of the continental crust and the sea encroaching between West Gondwana (South America and Africa) and East Gondwana (East Antarctica, Australia, India and New Zealand). As rifting progressed, new tectonic plates formed in what are now East Africa and the Weddell Sea, ocean crust formed and seafloor spreading developed.

The second stage of the breakup happened about 130 million years ago (early Cretaceous), when the South American plate separated from a combined African-Indian plate, which in turn was splitting from the combined Antarctic-Australian plate (Lawver et al. 1998). From 90 to 100 million years ago (late Cretaceous), New Zealand and Australia started to separate from Antarctica, and by approximately 32 million years ago the breakup of Gondwana was almost complete. The final stage was the separation of the tip of South America from the Antarctica Peninsula, which opened up the Drake Passage (Fig. 3.16).

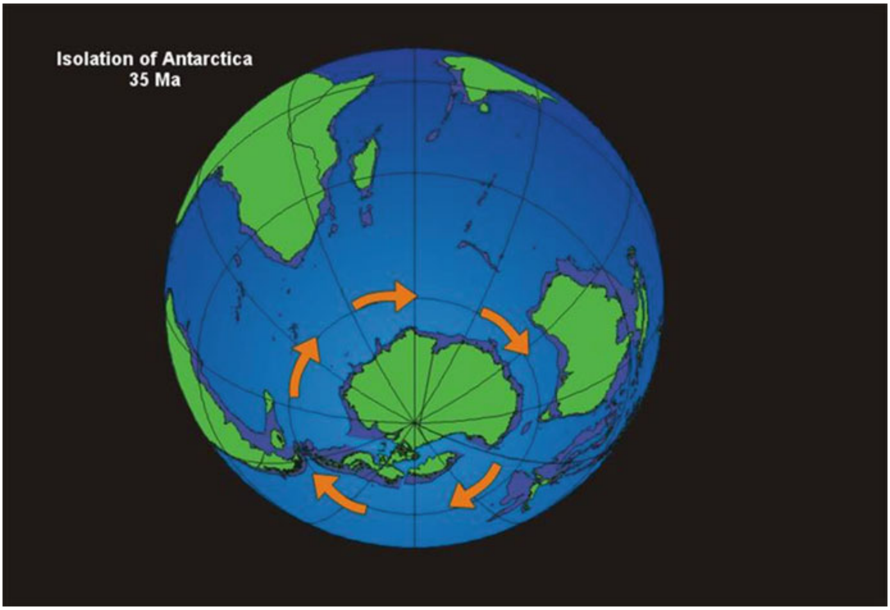



**Fig. 3.16** The final separation of South America from Antarctica lead to the opening of the Drake Passage, the formation of the circumpolar current and the final isolation of Antarctica (Bryan Storey, previously published in *Antarctica*: *Global Science from a Frozen Continent* 2013, with kind permission from Cambridge University Press)

### 3.5.3 The Pacific Ocean and the Antarctic Peninsula

As Gondwana was breaking apart, the Pacific Ocean floor was continually being subducted beneath the supercontinent in the regions that are now New Zealand, the Antarctic Peninsula and the west coast of South America. This resulted in the formation of a volcanic mountain chain and also in sedimentary material being scraped off the subducting Pacific plate and accreted (added) to the western margin of Gondwana. This subduction was the first stage in the emergence of the Antarctic Peninsula (Storey and Garret 1985). The eroded remnants of these volcanoes and the accreted sediment remain today.

The subduction process has now ceased along most of the peninsula region of the Antarctic plate because the spreading ridge between the Antarctic and Nazca plates collided with the subduction zone and brought the process to a halt (Larter et al. 2002). However, in a small region in the northern part of the Antarctic Peninsula, the subduction that was initiated during the breakup of Gondwana continues today (Chap. 2).

### 3.5.4 The Cooling of Antarctica

By approximately 45 million years ago, Tasmania had moved northward, away from East Antarctica, creating a significant seaway. This seaway initiated the thermal isolation of Antarctica and resulted in the cooling that produced, through feedback mechanisms, the first ice sheets on the continent. The separation of the tip of South America from the Antarctica Peninsula and the opening up of the Drake Passage completed this isolation process when the Antarctic Circumpolar Current formed (Barker and Thomas 2004) (Chap. 7). This massive current encircles Antarctica and provides an effective barrier to the transfer of heat from more northerly latitudes. Ultimately, this contributed to the extensive cooling of Antarctica and the growth of the major ice sheets (Chap. 4).

### 3.5.5 Rotated Microplates and East Antarctica

The formation of new tectonic plates and the large southern hemisphere continents were not the only results of the Gondwanan breakup. Some small fragments, or microplates, (Fig. 3.17) were also created, particularly in the South Atlantic region, and their movements help explain some apparently anomalous geological features of Antarctica (Dalziel and Elliot 1982; Grunow et al. 1987). The Ellsworth Mountains of West Antarctica consist of Ross Orogeny and Gondwanan rocks like those

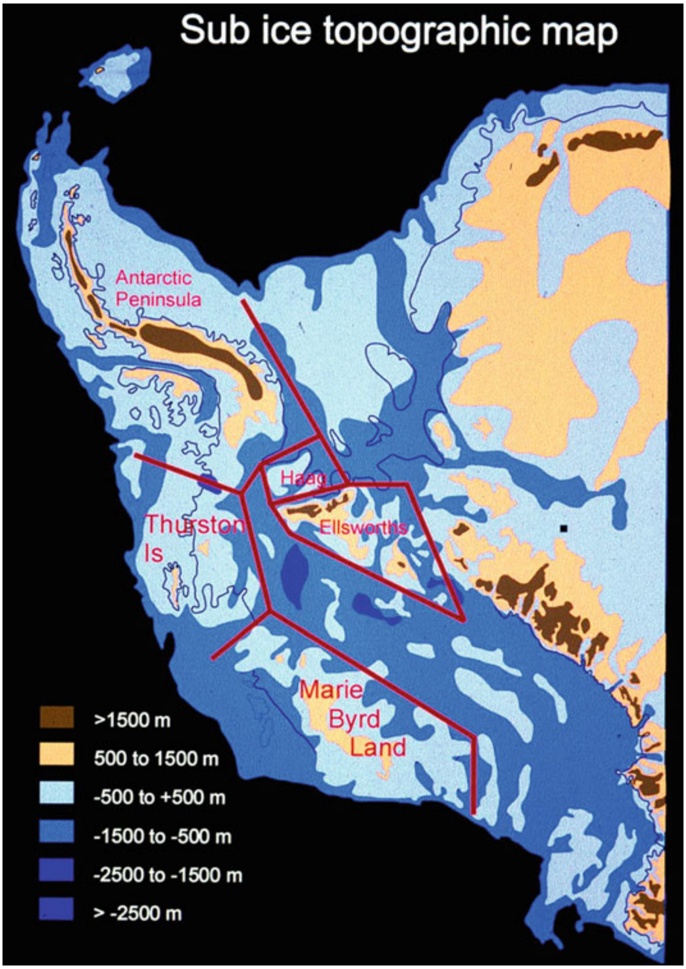



**Fig. 3.17** A sub-ice topography map of West Antarctica showing the Haag and Ellsworth Mountains microplates, which formed during the breakup of Gondwana. The areas in blue are below sea level and indicate that deep marine basins separate the microplates (Chap. 2) (© Bryan Storey)

of the Transantarctic Mountains, rather than like the younger volcanic rocks typical of the rest of West Antarctica. These rocks form the Ellsworth microplate, which was part of East Antarctica but has now moved some distance away from the Transantarctic Mountains and is oriented more or less at a right angle to them. The Haag Nunataks are also a microplate of 1200-million-year-old metamorphic rocks from East Antarctica, which now forms part of West Antarctica.

### 3.5.6 Rotated Microplates and West Antarctica

Displaced microplates are also a significant component of the final separation of the South American plate from the Antarctic Peninsula and the creation of the Drake Passage. The South Georgia block (now part of the South American plate) moved from a location much closer to southern South America to its present position, and the South Orkney block (on the Antarctic plate) moved away from the northern tip of the peninsula to form Powell Basin (Chap. 2, Fig. 2.6a). The South Shetland Islands (on the Shetland plate) are now separated from the peninsula by the Bransfield Strait (Chap. 2).

A further consequence of the breakup was the initiation of the West Antarctic Rift System. The rifting is thought to be part of a process that initially led to the separation of New Zealand from Antarctica but which continues today with the separation of East and West Antarctica. The mountain ranges and volcanoes arising from this rifting are described in Chap. 2.

## 3.6 Consequences of Antarctica's Gondwanan Heritage

For close to 300 million years the southern hemisphere continents shared part of their geological history as components of the Gondwana supercontinent. Regions of volcanic activity, mountain ranges, rivers, flora and fauna may not have been universally distributed across Gondwana but their boundaries crossed what are now the margins of continents and tectonic plates. As a result there are fundamental geological similarities between Antarctica and its immediate Gondwanan neighbours. These similarities have not only led to the recognition of Gondwana, which in turn led to the theory of plate tectonics, but also have implications for targeting geological research in regions of Antarctica that are hidden by ice. These similarities also encourage speculation when discussing the potential economic resources Antarctica might contain (Chap. 23).

## References

Barker PF, Thomas E (2004) Origin, signature and palaeoclimatic influence of the Antarctic Circumpolar Current. Earth Sci Rev 66:143–162

Barrett PJ (1991) The Devonian to Jurassic Beacon Supergroup of the Transantarctic Mountains and correlatives in other parts of the world. In: Tingey RJ (ed) The geology of Antarctica. Clarendon, Oxford, pp 120–152

Cox KG (1988) The Karoo province. In: MacDougall JD (ed) Continental flood basalts. Kluwer Academic Publishers, Dordrecht, pp 239–271

Dalziel IWD (1997) Neoproterozoic-Paleozoic geography and tectonics: review, hypothesis, environmental speculation. Geol Soc Am Bull 109:16–42

Dalziel IWD, Elliot DH (1982) West Antarctica: problem child of Antarctica. Tectonics 1:3–19

Elliott DH (1992) Jurassic magmatism and tectonism associated with Gondwanaland break-up: An Antarctic perspective. In: Storey BC, Alabaster T, Pankhurst RJ (eds) Magmatism and the causes of continental breakup. Geological Society, London, vol 68, pp 165–184
Grunow AM, Kent DV, Dalziel IWD (1987) Evolution of the Weddell Sea basin: new palaeomagnetic constraints. Earth Planet Sci Lett 86:16–26
Kaiho K, Kajiwara Y, Nakano T, Miura Y, Kawahata H, Tazaki K, Ueshima M, Chen Z, Shi GR (2001) End-Permian catastrophe by a bolide impact: evidence of a gigantic release of sulfur from the mantle. Geology 29:815–818
Larter RD, Cunnigham AP, Barker PF (2002) Tectonic evolution of the Pacific margin of Antarctica. 1. Late Cretaceous reconstructions. J Geophys Res 107:23–45
Lawver LA, Gahagan LM, Dalziel IWD (1998) A tight fit-early Mesozoic Gondwana, a plate reconstruction perspective. Mem Natl Inst Polar Res Spec Issue 53:214–229
Moores EM (1991) The south west U.S. – East Antarctica (SWEAT) connection: a hypothesis. Geology 19:425–428
Rich PV, Rich TH (1993) Wildlife of Gondwana. Reed Books, Chatswood
Stilwell J, Long J (2011) Frozen in time: prehistoric life in Antarctica. CSIRO Publishing, Collingwood, Victoria, Australia, p 248
Storey BC (1995) The role of mantle plumes in continental breakup: case histories from Gondwanaland. Nature 377(6547):301–308
Storey BC, Garrett SW (1985) Crustal growth of the Antarctic Peninsula by accretion, magmatism and extension. Geol Mag 122:5–14
Storey BC, Kyle PR (1997) An active mantle mechanism for Gondwana breakup. S Afr J Geol 100 (4):283–290
Stump E (1995) The Ross orogen of the Transantarctic Mountains. Cambridge University Press, Cambridge
Torsvik TH, Gaina C, Redfield TF (2008) Antarctica and global paleogeography: From Rodinia, through Gondwanaland and Pangea, to the birth of the southern ocean and the opening of gateways. In: Cooper AK, Barrett PJ, Stagg H, Storey B, Stump E, Wise W (eds) Antarctica, a keystone in a changing world. Proceedings of the 10th international symposium on Antarctic Earth sciences, The National Academies Press, Washington DC

# Chapter 4
# Looking Back to the Future

## Palaeoclimate Studies in Antarctica

**Cliff Atkins**

**Abstract** Antarctica has not always been a frozen continent covered in large ice sheets. It has experienced vastly different climates, ranging from tropical to polar, over hundreds of millions of years. As climate changed, so did the types of plants and animals, the amount of ice, the composition of the air and water, and the geological processes depositing sediments. Traces of these changes became preserved in layers of rock and ice that accumulated over time. Detailed studies of these layers allow scientists to produce a picture of, or to reconstruct, environments and climate conditions that existed in the past and piece together how and why they changed.

**Keywords** Palaeoclimate • Climate proxies • Isotopes • Fossils • Greenhouse • Icehouse • Milankovitch cycles • Climate models • Groundtruthing

## 4.1 Modelling the Past

Palaeoclimate studies show a long-term progressive cooling of Antarctica from a generally warm 'greenhouse' climate without ice sheets that existed before 35 million years ago, to the colder 'icehouse' conditions that we see today. Superimposed on the overall cooling trend are many shorter-term fluctuations in climate. These glacial-interglacial fluctuations occurred over tens to hundreds of thousands of years, causing large changes in Earth's temperature, albedo and the size of ice sheets, which in turn affected global sea level and ocean circulation, highlighting the complex but important role Antarctica plays in the global climate system.

Sophisticated computer programmes can be used to model how the various components of the climate system such as oceans, atmosphere and ice interact to produce different climate conditions through time. The models use information on the timing and scale of past climate changes derived from palaeoclimate studies. Furthermore, the accuracy of the models is assessed by using the palaeoclimate evidence to evaluate or

C. Atkins (✉)
School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand
e-mail: cliff.atkins@vuw.ac.nz



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_4

'groundtruth' how well a model simulates past climates (Box 4.1). Some climate models are now used to predict future climate change scenarios and include indications of how the large ice sheets in Antarctica will respond. Predicting future scenarios is becoming important as levels of greenhouse gases and global temperatures rise, and as scientists become increasingly concerned about the stability of the Antarctic ice sheets.

**Box 4.1: Groundtruthing**

Climate models contain many assumptions and estimates about the components of the climate system and how they interact. These can produce uncertainties or errors in the model. Groundtruthing is the process of using direct scientific evidence such as fossils, rocks or sediments (rather than assumptions and estimates) to provide real measured data, or 'truth', which can be used to constrain the uncertainties in the models. For example, certain plant fossils may indicate a specific temperature or rainfall that existed at a point in the past, or sediments and marine fossils may indicate water depth and chemistry of ancient oceans. The climate conditions predicted by the model can then be compared to the 'groundtruths' to test how well the model simulates what actually happened.

## 4.2 Studying Palaeoclimate: The Proxy

The term palaeoclimate refers to the study of climate during the geological past, before the instrumental record, and examines evidence preserved in natural archives (Bradley 1999). Natural archives are the traces of a wide range of natural occurrences that are influenced by climate and have become preserved in the geological record (Shuman and Scott 2007). Examples include plants and animals preserved as fossils in sedimentary rocks, or bubbles of air frozen in layers of ice. Although natural archives do not directly record climate, they reflect biological, chemical and geological responses to climate which vary as the climate changes, providing a substitute measure, or proxy record.

Proxies provide information about the patterns, magnitude, timing and mechanisms of climate change. The relationship between climate and the response of the proxy is determined by comparing and calibrating the proxy with the equivalent modern processes. For example, fossil plants are compared with related modern plants to determine their likely environmental and climate preferences and tolerances. Statistical methods are used to interpret the proxy and provide measurable data such as temperature or precipitation. This provides a view of the past at the time the proxy formed and enables a detailed picture of the climate conditions to be reconstructed. There are several commonly used proxy records in Antarctica.

### *4.2.1 Isotopes*

Isotopes are variations of the same chemical element. Elements are made up of atoms and each atom has a nucleus containing protons and neutrons. Although an atom always has the same number of protons (atomic number), some elements, such as oxygen, can have a variable number of neutrons (Box 4.2). This results in various isotopes of an element each having a slightly different atomic mass. The different isotopes of an element can co-exist but the ratio of one isotope to another is often determined by characteristics of the physical environment, such as temperature. As temperature changes, the ratio of one isotope to another also changes. The isotopic ratios can be preserved in the fossil record in various ways, such as in fossil shells or bones of animals. Measuring the ratios of different isotopes incorporated into fossil material provides a proxy measure of the climate when the organism lived (Jansen et al. 2007).

**Box 4.2: Oxygen Isotopes**

Oxygen atoms have eight protons, but the number of neutrons can be eight, nine or ten, resulting in three isotopes with different mass numbers of $^{16}O$, $^{17}O$ and $^{18}O$. This difference in atomic mass means that water vapour ($H_2O$) evaporated from the oceans has a slightly higher amount of the lighter $^{16}O$ isotope relative to $^{18}O$. As the water vapour rises and is transported toward the poles, it cools and the heavier $^{18}O$ precipitates out as rain at mid-latitudes while the $^{16}O$ is transported farther, precipitating as snow at high latitudes. During colder climates such as glacials, there is a larger volume of snow and ice on land at the poles, trapping the $^{16}O$ in the snow, effectively raising the ratio of the heavier $^{18}O$ in the oceans. During warmer interglacials, the ice and $^{16}O$ is released back to the oceans, balancing the ratio (Fig. 4.1). Although

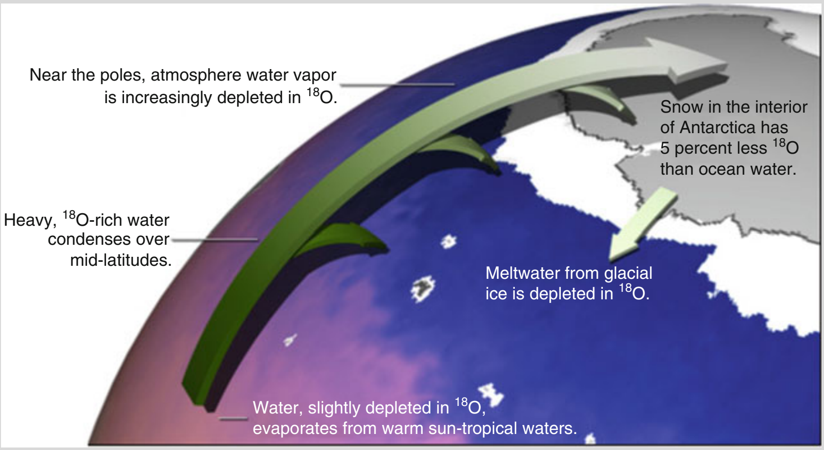



**Fig. 4.1** This illustration shows how the differentiation of oxygen isotopes in the oceans and ice sheets occurs. The different ratios can be used in palaeoclimate studies to estimate past temperatures and ice volume (With kind permission from Robert Simmon, NASA GSFC)

(continued)

**Box 4.2** (continued)
this description is somewhat simplified, it illustrates how oxygen isotopes provide a proxy measure of global ice volume and temperature through time. This relationship can be used for palaeoclimate studies by analysing the shells of microscopic marine creatures called foraminifera. Oxygen is precipitated from seawater into the calcium carbonate ($CaCO_3$) shells of the foraminifera. The ratio of $^{16}O$ to $^{18}O$ reflects the temperature of the water at the time of precipitation, so by analysing the oxygen composition in the shells, fossil foraminifera from ancient sediments can be used to measure the temperature of the water and also the relative volume of polar ice at the time they lived.

### *4.2.2 Sedimentary Rocks*

Layers of sedimentary rock provide a proxy record of past environments. Sedimentary layers contain rock fragments that have been transported and deposited by rivers, glaciers and ocean currents. The size and shape of the fragments, the pattern of structures such as ripples and cross bedding combined with the type of fossils in the rock reflect the processes that occurred during deposition. For example, thick deposits of angular boulders with scratched surfaces mixed with finer sediment are characteristic deposits of glaciers, whereas layers of mudstone with marine fossils indicate the slow settling out of sediment in the ocean. Geologists can therefore interpret the environment that each layer of sediment was deposited in and quantify conditions such as water depth or proximity to glaciers. The associations of different layers in the rock record then allow geologists to estimate how the depositional processes and environmental conditions changed through time.

### *4.2.3 Fossils*

A wide variety of plant and animal fossils are preserved in Antarctic sediments. These include large fossils like wood, leaves, animal bones and shells, but also extremely small microfossils like pollen grains and plankton. Features of individual fossils, such as leaf size and shape or the assemblage of different fossils from a particular sedimentary layer, can be compared with modern examples. This gives an idea of past environmental and climate conditions that existed when the organisms were alive and can provide very specific palaeoclimate data, including past precipitation or temperature ranges (Box 4.3).

**Box 4.3: Fossil Case Study**

Outcrops of sedimentary rock on Alexander Island on the Antarctic Peninsula contain a rich record of fossil material including leaves, pollen, wood and flowers that existed about 85 million years ago during the Cretaceous Period. The assemblage of fossils and sediment types allowed scientists to reconstruct an accurate picture of a forest environment that existed on a river floodplain at the time. Statistical analysis of the number of fossil plant types identifies a forest canopy comprising mainly conifer, ginkgos and podocarp trees with an understory of ferns, liverworts, mosses and shrubby angiosperms. An artist's impression of this environment is shown is Fig. 4.2. A comparison of fossil leaf size and shape with related modern species indicates mean annual temperatures of up to 20 °C and rainfall greater than 2500 mm during the growing season, i.e. the fossil plants lived in a warm and humid sub-tropical climate (Francis et al. 2008).


**Fig. 4.2** A reconstruction of the forests on Alexander Island, Antarctica, 100 million years ago during the warm climate of the Cretaceous Period based on the analysis of plant fossils. The reconstruction is based on the work of Jodie Howe (University of Leeds) and Jane Francis (formerly University of Leeds, now BAS) and geologists from the British Antarctic Survey (With kind permission from the artist Robert Nicholls, © 2009, of Paleocreations.com)

### 4.2.4 Ice Layers

Cores of ice retrieved from ice sheets in Antarctica provide an important climate proxy. As annual layers of snow become buried and compressed into ice, air in the snow becomes trapped in gas bubbles within the ice. These bubbles provide a precise record of past atmospheric compositions, including greenhouse gases such as carbon dioxide ($CO_2$) and methane ($CH_4$), global dust levels, volcanic aerosols and also isotopic ratios of oxygen and deuterium (Chap. 5), which provide proxy measures of past temperatures. Ice cores provide high-resolution records – sometimes annual variation can be determined – but ice cores are limited because they extend back in time by only about 800,000 years.

## 4.3 Past Antarctic Climate

### 4.3.1 Greenhouse Conditions

Sedimentary rock in the Transantarctic Mountains and on the Antarctic Peninsula contains evidence of climate change over millions of years as the Antarctic plate drifted from equatorial latitudes toward the South Pole (Chap. 2). Reconstructions based on this evidence reveal that shallow seas, rivers, lakes and forests existed in warm climates during the Devonian to Early Carboniferous (400–340 million years ago), followed by cold conditions and wide-spread glaciation during the Carboniferous to Early Permian (340–280 million years ago). After the glaciation, warmer climates created extensive swamps, river systems and forests supporting a wide range of flora and fauna, culminating in a sub-tropical climate at polar latitudes in the Cretaceous (85 million years ago) (Box 4.3, Fig. 4.2) (Francis et al. 2008). The Cretaceous warm period in Antarctica's history is commonly referred to as the greenhouse climate.

### 4.3.2 Greenhouse to Icehouse

Isotope records from sedimentary rocks retrieved in deep-sea drill cores far from Antarctica show long-term changes in global temperature and carbon dioxide ($CO_2$) levels. Oxygen isotopes preserved in calcareous ($CaCO_3$) fossils in the sedimentary rock provide a proxy for past ocean temperatures. Similarly, carbon isotopes from marine plankton fossils reflect past $CO_2$ concentrations of the water and this can then be used to infer the $CO_2$ concentration in the atmosphere (e.g. Pagani et al. 2005). The level of $CO_2$ in the atmosphere is important because it is a major greenhouse gas and is closely linked to temperature. The isotope record shows a progressive decline in global temperature and atmospheric $CO_2$ from the

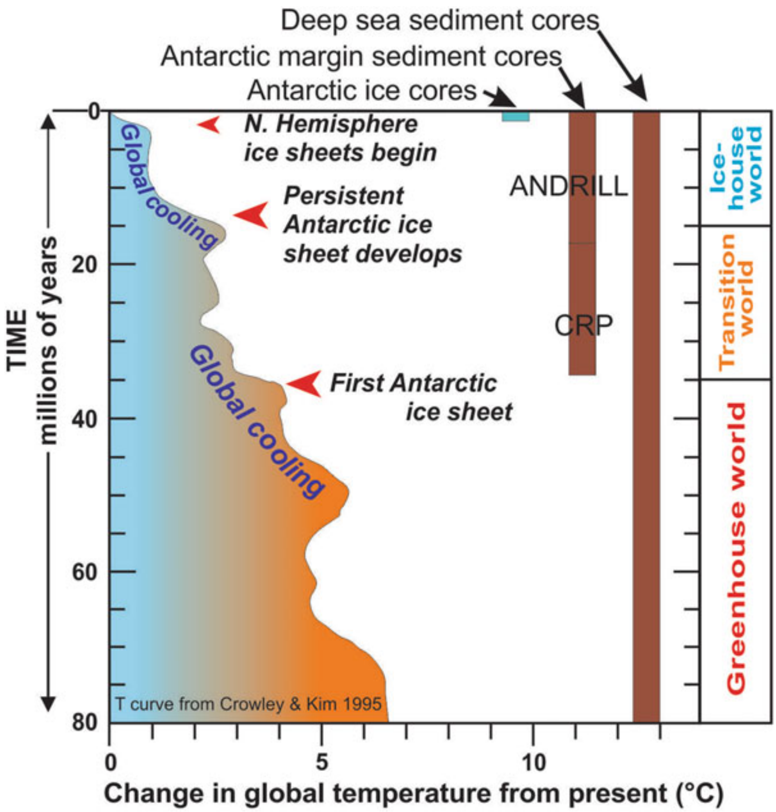



**Fig. 4.3** A time-temperature graph for the last 80 million years showing: (**a**) an irregular global cooling curve and the development of Antarctic ice sheets; (**b**) *vertical colour bars* indicating time intervals represented in drill cores recovered from the deep sea, Antarctic margin (Cape Roberts Project-CRP, ANDRILL) and ice cores. Collectively, the drill-core records contain palaeoclimate evidence of the transition from warm greenhouse conditions prior to 35 million years ago through a transition to cold icehouse conditions we see today (Temperature curve reprinted from Crowley and Kim 1995, modified from Barrett 2009, with kind permission from Elsevier)

warm greenhouse climates before 35 million years ago, through a transition period to cold icehouse conditions after 15 million years ago, when ice sheets became more persistent in Antarctica. Further global cooling intensified the icehouse conditions leading to the continental-scale Antarctic ice sheets we see today and the development of ice sheets in the Northern Hemisphere over the last 2.5 million years (Fig. 4.3).

The cause of the global cooling has been the subject of much research. Several reasons for the change have been suggested including continental drift and changes in the ocean circulation around Antarctica, fluctuations in solar energy input, the amount of aerosol in the atmosphere, and changes in greenhouse gas concentrations. The answer may be a combination of several factors, but the close relationship between temperature and $CO_2$ records indicates that the fall in $CO_2$ levels was a major factor (e.g. DeConto and Pollard 2003; IPCC 2013).

The geological record of the transition from greenhouse to icehouse conditions is only exposed in a few outcrops on the Antarctic Peninsula and the Transantarctic Mountains. However, a more complete record is well preserved in layers of sedimentary rock that accumulated in marine basins around the margin of the continent. Much of this record has been recovered through a series of drilling projects such as the Cape Roberts Project (CRP) and ANDRILL (Fig. 4.3).

### *4.3.3 Into the Icehouse*

Drill cores from the Victoria Land Basin in the western Ross Sea record the time period between 34 and 1 million years ago (Barrett 2009; Hodgson et al. 2009). Sedimentary rock layers and fossils from the drill cores provide proxy records of past climate conditions, such as temperature, ice volume and sea level, close to Antarctica. These records confirm the overall global climatic cooling with the first continental-scale ice sheets appearing at about 34 million years ago, and the establishment of permanent ice sheets at about 15 million years ago. The data also reveal many shorter-term changes in ice sheet size and global sea level superimposed on the overall cooling trend, and these short-term changes are related to alternating glacial-interglacial climate conditions (Naish et al. 2001, 2009).

Each sediment layer represents a specific depositional environment. Layer by layer analysis reveals a cyclic pattern, reflecting changes in the depositional environment and climate through time. Typically, each sedimentary cycle shows the following: a layer of coarse-grained, poorly-sorted sediment (diamictite) deposited directly by glaciers, overlain by layered sandstone with pebbles that have melted out of ice floating in the ocean, overlain by mudstone or fine-grained sediment made up exclusively of marine diatom fossils (diatomite) deposited in deeper, open ocean.

The diamictite layers represent colder glacial climates when sea level fell and the ice sheets expanded onto the exposed continental shelf, depositing glacial debris as moraines over the area which is now the drill site. The overlying layered, pebbly sandstones formed in warming climates. As the ice sheets and ice shelves began melting, sea level rose over the shelf and floating ice bergs dropped stones to the seafloor. The mudstones and diatomite formed in open ocean conditions, indicating retreat of the ice, higher sea level and warm interglacial climates. Each cycle of sediments represents the advance and retreat of Antarctica's ice sheets and ice shelves in conjunction with rises and falls in sea level, as a result of global-scale, glacial-interglacial cycles (Fig. 4.4).

Dating the drill cores using microfossils, palaeomagnetic signals in the sediment and volcanic ash layers shows that the sedimentary cycles usually occurred on 40,000-year and sometimes 100,000-year timescales (Naish et al. 2001, 2009). This periodicity closely matches the timing of cyclic variations in Earth's rotation on its axis and its orbit around the sun, called Milankovitch cycles. These orbital variations influence the amount of solar radiation received at different latitudes and are

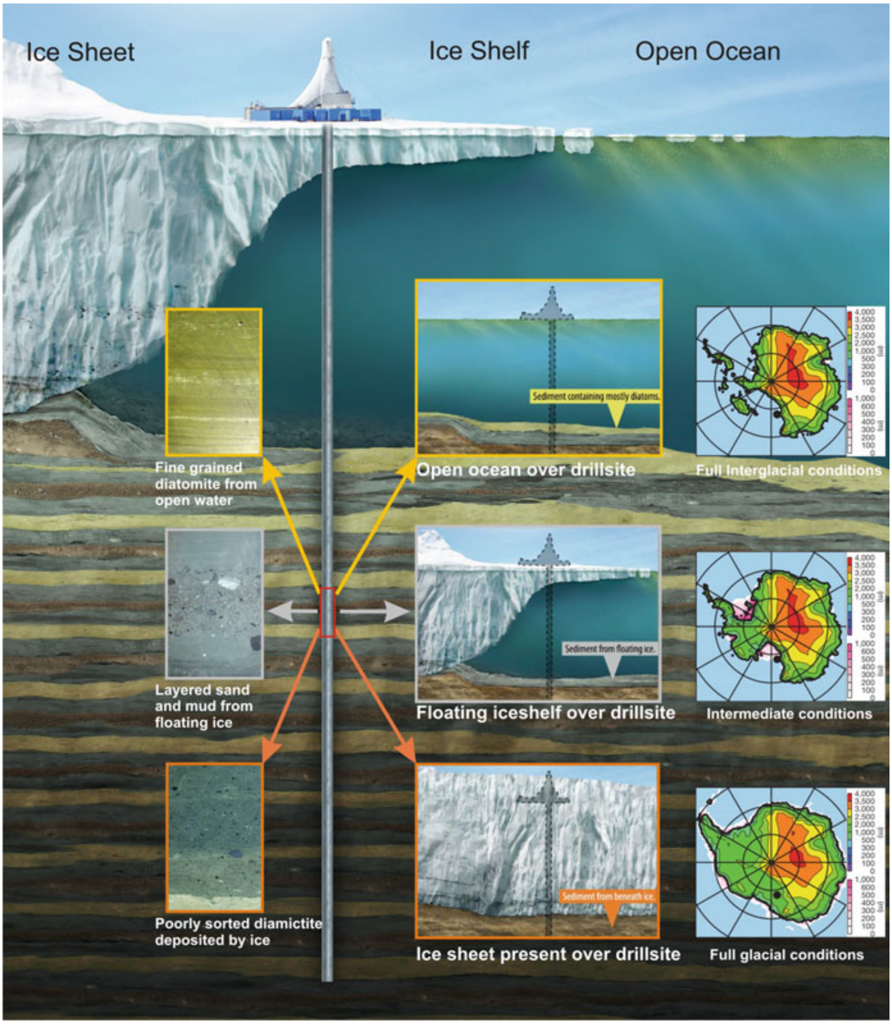



**Fig. 4.4** This diagram of the AND-1B drill core recovered from beneath the Ross Ice Shelf shows: *1* various sediment types found in repeated sedimentary cycles (diamictite, stratified pebbly sandstone and diatomite); *2* associated environment and climate reconstructions (ice sheet overriding, ice shelf retreat and open ocean); *3* modelled ice sheet-climate interpretations, (full glacial, intermediate and full interglacial). Ice sheet and ice shelf thickness in meters indicated on the coloured scale and drill core location is marked by the *black dot* on the maps (Modified from ANDRILL flexibit poster, climate models from Pollard and DeConto 2009, with kind permission from ANDRILL/University of Nebraska State Museum)

widely accepted as the primary mechanism of triggering a change in climate between glacial to interglacial conditions (Box 4.4).

The palaeoclimate record from drill cores at Cape Roberts shows that from 34 to 15 million years ago, Antarctica's ice sheets waxed and waned on predictable

Milankovitch controlled timescales (Naish et al. 2001). After 15 million years ago, global temperature and $CO_2$ continued to fall, resulting in Antarctica's ice sheets becoming permanent. However, the ice sheets and global climate continued to oscillate on 40,000-year Milankovitch timescales. This is well recorded in a drill core (AND-1B) recovered from beneath the floating Ross Ice Shelf by the ANDRILL project.

The Ross Ice Shelf is the world's largest ice shelf and is fed by glaciers draining from the West Antarctic Ice Sheet, which is considered to be inherently unstable because much of the ice rests on a downward sloping seafloor well below sea level. Importantly, the floating Ross Ice Shelf provides a buttressing effect for the ice sheet, preventing it from expanding outward and disintegrating. Therefore, if the Ross Ice Shelf melts, it has a major impact on the stability of the West Antarctic Ice Sheet (e.g. Jenkins et al. 2010; Pritchard et al. 2012). At the AND-1B drill location, the diatomite layers in each cycle indicate that during the warmest interglacial conditions, open ocean existed and the Ross Ice Shelf had completely disappeared. This occurred several times during the Early Pliocene (5–3 million years ago). The important palaeoclimate implication is that the Ross Ice Shelf and possibly the whole West Antarctic Ice Sheet disappeared in the past, raising global sea level, when temperatures were known to be only 2–3 °C higher than present (Naish et al. 2009; McKay et al. 2012).

**Box 4.4: Milankovitch Cycles and Climate Change**

Milankovitch cycles are periodic variations in the spin of Earth on its axis and the orbit of Earth around the sun. These variations change the amount of solar radiation (insolation) reaching different latitudes on Earth and therefore influence climate (Fig. 4.5). Three principle cycles occur on different periodicities:

1. A 100,000-year cycle, referred to as eccentricity, which relates to the variation of Earth's orbit around the sun.
2. A 40,000-year cycle known as obliquity, which occurs due to Earth's tilt on its axis varying between 22 and 24°. This influences the contrast between seasons.
3. A 21,000-year cycle called precession caused by Earth wobbling on its axis, altering the orientation of the hemispheres in relation to the sun and changing the timing of the seasons.

The change in solar insolation caused by the interplay of the three Milankovitch cycles is small, but it is enough to trigger changes in the climate (e.g. Zachos et al. 2001). Complex feedback mechanisms within the climate system then amplify the changes and cause climate to vary between glacial and interglacial conditions.

(continued)

**Box 4.4** (continued)

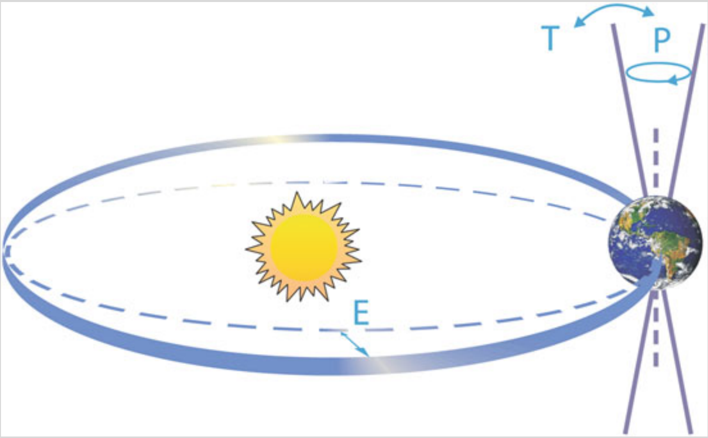



**Fig. 4.5** This diagram illustrates Earth's various orbital cycles (Milankovitch cycles) that influence the amount of solar radiation reaching different latitudes. *E* refers to the eccentricity of Earth's orbit around the Sun (100,000-year period), *T* denotes obliquity caused by the changes in the tilt of Earth's axis (40,000-year period) and *P* refers to precession due to wobbles in the tilt of the axis (21,000-year period) (Adapted from Rahmstorf and Schellnhuber 2006, with kind permission from IPCC 2007)

For example, cooler temperatures at polar latitudes due to obliquity cause a slow build-up of ice over tens of thousands of years, increasing the albedo of the Earth and reflecting more solar radiation, which in turn contributes to further cooling. A lower water temperature allows the oceans to absorb more $CO_2$, reducing the greenhouse effect and generating further cooling.

The change from glacial to interglacial climate is faster, typically occurring over thousands of years. As $CO_2$ is released from warming oceans, the greenhouse effect is increased, resulting in further temperature increases, a reduction in ice volume and rising sea levels.

### *4.3.4 Climate Change Over Last 800,000 Years*

Overlapping with the youngest part of the sediment drill-core record is the ice-core record. Ice cores recovered from Antarctica's ice sheets provide a continuous, high-resolution record of global climate over the last 800,000 years (Jouzel et al. 2007; Bertler and Barrett 2010 for review). Analysis of gases trapped in bubbles in the ice shows a clear record of glacial-interglacial cycles and a strong relationship between greenhouse gases and temperature (e.g. Petit et al. 1999; Jansen et al. 2007) (Chaps. 5 and 8). The record shows that the periodicity of the climate cycles changed from 40,000-year obliquity to 100,000-year eccentricity controlled Milankovitch timescales about 700,000 years ago. The climate cycles show an asymmetric saw-tooth pattern indicating a slow fall in $CO_2$ levels, temperature and sea level as ice sheets build up over tens of thousands of years, followed by relatively rapid warming, along with a rise in $CO_2$ and sea level as ice sheets melt over thousands of years. During interglacial conditions temperatures were 2–5 °C warmer and sea level 4–6 m higher than present. During glacial conditions, temperatures were about 5 °C colder and sea level was up to 120 m lower than present (Jansen et al. 2007). The large change in sea level was primarily due to the expansion and contraction of the large Northern Hemisphere ice sheets, whereas Antarctica's ice sheets likely contributed only 10–20 m of the global sea level change (Hodgson et al. 2009).

## 4.4 Climate Models

Palaeoclimate studies have provided a large amount of the proxy data used in detailed reconstructions of past climates. In the last three decades, the numerical data have been used in increasingly sophisticated computer models of ice sheet configuration and climate conditions. The models examine the interaction between the various components of the climate system such as ocean temperature, sea ice conditions, ice sheet size, land-ice albedo, atmospheric greenhouse gases, solar radiation and orbital forcing (Milankovitch cycles) (Bartlein and Scott 2007). By altering one or more of these variables, the models can simulate different climate regimes and help identify cause and effect relationships between the different variables. The degree of fit between the model simulation and the reconstruction based on proxy records provides the groundtruthing, or test, of how well the model simulates the conditions that actually existed and how well it might predict future changes.

### *4.4.1 Ice Sheet Behaviour*

Modelling the behaviour of the Antarctic ice sheets is important for understanding global climate. Early models clearly showed the link between temperature, ice volume and changes in sea level (e.g. Huybrechts 1993) but did not have fine enough resolution to model specific regions or timeframes. As palaeoclimate reconstructions improved and computer technology increased, larger datasets have been used in models. These can now simulate key climate events hundreds to millions of years ago (Mock and Scott 2007). For example, DeConto and Pollard (2003) used a climate-ice sheet model to show that atmospheric $CO_2$ helped control air and ocean temperature and therefore the inception and size of Antarctica's early ice sheets. More recently, Pollard and DeConto (2009) constructed a model of the growth and decay of the Ross Ice Shelf and the closely related West Antarctic Ice Sheet over the last 5 million years. Their model used changes in solar radiation caused by Milankovitch cycles, global $CO_2$ levels derived from deep-sea isotope records, and proximity of the ice derived from the sedimentary layers in the AND 1B drill core. The model simulations suggest that the Ross Ice Shelf repeatedly retreated under conditions only slightly warmer than today, removing its buttressing effect on the West Antarctic Ice Sheet, and leading to a near complete melting of the West Antarctic Ice Sheet in only a few thousand years, contributing up to 7 m of global sea level rise. This scenario was verified (groundtruthed) by the palaeoclimate record in the AND-1B drill core which confirms that the Ross Ice Shelf did collapse as indicated in the model (Fig. 4.4) (Naish et al. 2009; McKay et al. 2012). The implication is that the Ross Ice Shelf (and therefore the West Antarctic Ice Sheet) is sensitive to small changes in temperature of the order likely to be reached this century.

### *4.4.2 Modelling the Future*

Palaeoclimate studies and climate modelling have improved our understanding of how the climate system works on a range of timescales. In particular they have established the links between atmospheric greenhouse gases, orbital variations, global temperatures, ice sheets and sea level, and have highlighted the importance of Antarctica in the global climate system. The insight gained from looking back at the past is now providing the knowledge to begin looking forward into the future. In view of rapidly rising levels of greenhouse gases, several ocean-atmosphere-ice climate models are being used to produce scenarios of future climate change. Some of these scenarios are presented in the report of the Intergovernmental Panel on Climate Change (IPCC 2013). These scenarios all predict increases in $CO_2$ and average global temperature along with rising sea level over the coming decades and centuries. For the Antarctic region, specific predictions are still limited by sparse data and uncertainties regarding ice sheet dynamics. The various models produce a wide range of predictions but indicate there will be an average continental warming of about 2 °C and sea surface temperature warming of about 1 °C by the year 2100, which is slightly less than the global mean rate of increase. This is likely to be associated with an increase in precipitation, but the magnitude and spatial distribution is uncertain. There is also likely to be changes in the dominant atmospheric circulation patterns such as the Southern Annular Mode and El Niño Southern Oscillation impacting the extent of sea ice and the strength of the circumpolar westerlies. Such changes will affect both marine and terrestrial environments and ecosystems. Although the increase in precipitation will cause net snow accumulation in some areas of East Antarctica, it is outweighed by the outflow of ice, primarily from West Antarctica, therefore contributing to a sea level rise. However, a major limitation of the predictions is that they are only beginning to account for the possibility of accelerated melting due to a rapid retreat of the ice shelves that buttress the continental ice sheets, as suggested by some palaeoclimate studies and models (e.g. Pritchard et al. 2012; Pollard and DeConto 2009). This dynamic behaviour is known to have occurred in the past when temperature was not much higher than today, indicating that the model predictions may seriously underestimate the potential ice loss and sea level rise from Antarctica. Further high-resolution palaeoclimate studies on a range of geological timescales from key locations in Antarctica are needed to constrain the uncertainties in the models and to provide more accurate predictions of likely future climate changes.

## References

Barrett P (2009) A history of Antarctic Cenozoic glaciation – view from the continent. In: Florindo F, Siegert M (eds) Antarctic climate evolution, vol 8, Developments in earth and environmental sciences. Elsevier, Amsterdam, pp 33–82

Bartlein PJ, Scott AE (2007) Paleoclimate, time scales of climate change. In: Elias S (ed) Encyclopaedia of quaternary science. Elsevier, Oxford, pp 1873–1883

Bertler NAN, Barrett PJ (2010) Vanishing polar ice sheets. In: Dodson J (ed) Changing climates, earth systems and society, 1st edn. Springer, Dordrecht, pp 49–83

Bradley R (1999) Palaeoclimatology, reconstructing climates of the quaternary. Academic, San Diego

Crowley TJ, Kim K (1995) Comparison of longterm greenhouse projections with the geologic record. Geophys Res Lett 22:933–936

DeConto RM, Pollard D (2003) Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric $CO_2$. Nature 421:245–249

Francis J, Ashworth A, Cantrill DJ, Crame JA, Howe J, Stephens R, Tosolini A-M, Thorn V (2008) 100 million years of Antarctic climate Evolution. In: Cooper AK, Barrett PJ, Stagg H, Storey B, Stump E, Wise W, and the 10th ISAES editorial team (eds) Antarctica: a keystone in a changing world. Proceedings of the 10th international symposium on Antarctic Earth sciences. The National Academies Press, Washington DC

Hodgson DA, Abram NJ, Anderson J, Bargelloni L, Barrett P, Bentley MJ, Bertler NAN, Chown S, Clarke A, Convey P, Crame A, Crosta X, Curran M, di Prisco G, Francis JE, Goodwin I, Gutt J, Masse G, Masson-Delmotte V, Mayewski PA, Mulvaney R, Peck L, Portner H-O, Rothlisberger R, Stevens MI, Summerhayes CP, van Ommen T, Verde C, Verleyen E, Vyverman W, Wiencke C, Zane L (2009) Antarctic climate and environment history in the pre-instrumental period. In: Turner J, Bindschandler R, Convey P, di Prisco G, Fahrbach E, Gutt J, Hodgson D, Mayewski PA, Summerhayes CP (eds) Antarctic climate change and the environment. Scientific Committee on Antarctic Research, Cambridge, pp 115–182

Huybrechts P (1993) Glaciological modelling of the Late Cenozoic East Antarctic ice sheet: stability or dynamism? Geogr Ann 75A(4):221–238

IPCC (2007) Climate change 2007. The physical science basis. Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge/New York, 996p

IPCC (2013) In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, in press

Jansen E, Overpeck J, Briffa KR, Duplessy J-C, Joos F, Masson-Delmotte V, Olago D, Otto-Bliesner B, Peltier WR, Rahmstorf S, Ramesh R, Raynaud D, Rind D, Solomina O, Villalba R, Zhang D (2007) Palaeoclimate. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis.

Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Jenkins A, Dutrieux P, Jacobs S, McPhail S, Perrett J, Webb A, White D (2010) Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat. Nat Geosci 3:468–472

Jouzel J, Masson-Delmotte V, Cattani O, Dreyfus G, Falourd S, Hoffmann G, Minster B, Nouet J, Barnola JM, Chappellaz J, Fischer H, Gallet JC, Johnsen S, Leuenberger M, Loulergue L, Luethi D, Oerter H, Parrenin F, Raisbeck G, Raynaud D, Schilt A, Schwander J, Selmo E, Souchez R, Spahni R, Stauffer B, Steffensen JP, Stenni B, Stocker TF, Tison JL, Werner M, Wolff EW (2007) Orbital and millennial Antarctic climate variability over the past 800,000 years. Science 317:793–796

McKay R, Naish T, Carter L, Riesselman C, Dunbar R, Sjunneskog C, Winter D, Sangiorgi F, Warren C, Pagani M, Schouten S, Willmott V, Levy R, DeConto R, Powell RD (2012) Antarctic and Southern Ocean influences on Late Pliocene global cooling. Proc Natl Acad Sci 109(17):6423–6428

Mock CJ, Scott AE (2007) Paleoclimate, introduction. In: Elias S (ed) Encyclopaedia of quaternary science. Elsevier, Oxford, pp 1867–1873

Naish T, Woolfe KJ, Barrett PJ, Wilson GS, Atkins C, Bohaty SM, Bucker C, Claps M, Davey F, Dunbar G, Dunn A, Fielding CR, Florindo F, Hannah M, Harwood DM, Watkins D, Henrys S, Krisseck L, Lavelle M, van der Meer JJP, McIntosh MC, Niessen F, Passchier S, Powell R, Roberts AP, Sagnotti L, Scherer RP, Strong CP, Talarico F, Verosub KL, Villa G, Webb P-N, Wonik T (2001) Orbitally induced oscillations in the East Antarctic ice sheet at the Oligocene/ Miocene boundary. Nature 413:719–723

Naish T, Powell R, Levy R, Wilson G, Scherer R, Talarico F, Krissek L, Niessen F, Pompilio M, Wilson T, Carter L, DeConto R, Huybers P, McKay R, Pollard D, Ross J, Winter D, Barrett P, Browne G, Cody R, Cowan E, Crampton J, Dunbar G, Dunbar N, Florindo F, Gebhardt C, Graham I, Hannah M, Hansaraj D, Harwood D, Helling D, Henrys S, Hinnov L, Kuhn G, Kyle P, Läufer A, Maffioli P, Magens D, Mandernack K, McIntosh W, Millan C, Morin R, Ohneiser C, Paulsen T, Persico D, Raine I, Reed J, Riesselman C, Sagnotti L, Schmitt D, Sjunneskog C, Strong P, Taviani M, Vogel S, Wilch T, Williams T (2009) Obliquity paced Pliocene West Antarctic ice Sheet oscillations. Nature 458:322–328

Pagani M, Zachos JC, Freeman KH, Tipple B, Bohaty S (2005) Marked decline in atmospheric carbon dioxide concentrations during the Palaeogene. Science 309:600–603

Petit J-R, Jouzel J, Raynaud D, Barkov NI, Barnola J-M, Basile I, Bender M, Chappellaz J, Davis M, Delayque G, Delmotte M, Kotlyakov VM, Legrand M, Lipenkov VY, Lorius C, Pépin L, Ritz C, Saltzman E, Stievenard M (1999) Climate and atmospheric history of the past 420,000 years from the Vostok Ice Core Antarctica. Nature 399:429–436

Pollard D, DeConto RM (2009) Modelling West Antarctic ice sheet growth and collapse through the past five million years. Nature 458:329–332

Pritchard HD, Ligtenberg SRM, Fricker HA, Vaughan DG, van den Broeke MR, Padman L (2012) Antarctic ice-sheet loss driven by basal melting of ice shelves. Nature 484:502–505

Rahmstorf S, Schellnhuber HJ (2006) Der Klimawandel. Beck Verlag, Munich, p 144

Shuman B, Scott AE (2007) Paleoclimate reconstruction, approaches. In: Elias S (ed) Encyclopaedia of quaternary science. Elsevier, Oxford, pp 1942–1948

Zachos J, Pagani M, Sloan L, Thomas E, Billups K (2001) Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292:686–693

# Chapter 5
# An Ice-Bound Continent

## Antarctica's Cryosphere and Hydrological Systems

**Kate E. Sinclair**

**Abstract** In the introduction to his epic *The Ice*, Stephen Pyne describes Antarctica as "a maelstrom of ice . . . fused together, as a continent, by ice". Indeed, ice covers 99.6 % of the continent and this immense ice cap is the single largest solid object on the surface of Earth. Antarctic snow and ice, the cryosphere, contain around 90 % of the world's ice and around 80 % of all freshwater, which is frozen in the East and West Antarctic ice sheets and the ice caps and glaciers of the Antarctic Peninsula. It has grown and diminished over ice ages and warm periods, but is currently about twice as big as Australia, and makes Antarctica the highest, driest, coldest and windiest continent on Earth. Up to 4800 m thick in places, the weight of the ice sheet is enough to deform Earth's crust below. Every year new snow accumulates on the surface of the continent, and due to the very low annual temperatures, this does not melt. Instead, it builds up over time and is compressed by the weight of new snowfall and turns into ice, preserving a rich and detailed climate record spanning nearly a million years.

**Keywords** Ice sheets • Ice caps • Ice sheet mass balance • Ice cores • EPICA • Roosevelt Island ice core project • Ice streams • Glaciers • Subglacial hydrology • Ice shelves • Sea ice

## 5.1 Ice in Motion

Antarctica's ice flows relentlessly from the interior of the continent towards the coast, channelled by glaciers and ice streams. This glacial conveyor belt transports 200 billion tonnes of ice per year to the continental margin, where ice flows into floating ice shelves. Once part of an ice shelf, the ice travels across the ocean surface, eventually breaking off as icebergs and drifting away from the continent into the currents of the Southern Ocean. Every year, during the winter, when the ocean around Antarctica congeals into frozen sea ice, the continent becomes virtually inaccessible.

K.E. Sinclair (✉)
GNS Science, Wellington, New Zealand
e-mail: sinclair.kate.e@gmail.com



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_5

The freshwater stored in, and released from the Antarctic cryosphere, is in delicate balance between accumulation from snowfall and loss of ice into the Southern Ocean (Chap. 7). The release of this freshwater plays a major role in controlling the world's oceans and climate, and the way that these systems respond to future warming will profoundly affect all physical and biological systems.

## 5.2 Antarctic Ice Sheets

The ice sheets that cover Antarctica currently have an area of 13.7 million square kilometres. Their average thickness is 2.3 km and, in some areas, the ice is more than 4 km above sea level, making Antarctica the highest continent on Earth (Vaughan 2007). The Transantarctic Mountains stretch from the Ross Sea to the Weddell Sea and separate the East Antarctic and West Antarctic ice sheets. The geological record from the continent, and from offshore marine sediments, shows that these ice sheets not only have contrasting physical characteristics, but that they respond to climate change in very different ways (Chap. 4).

### *5.2.1 East Antarctic Ice Sheet*

The East Antarctic Ice Sheet (EAIS) contains around 88 % of Antarctica's ice and mostly lies above sea level (Fig. 5.1). In some deep basins, however, the underlying continental crust is pressed below sea level by the weight of the ice above, and if the ice sheet were removed, this underlying rock would slowly rebound over thousands of years. In many areas, the ice of East Antarctica is frozen at the base to the underlying rock, so its flow towards the coast is slow relative to other parts of the continent where there is a layer of water at the ice-rock boundary that lubricates the ice and accelerates the flow rates.

### *5.2.2 West Antarctic Ice Sheet*

The West Antarctic Ice Sheet (WAIS) is much smaller than EAIS and, instead of sitting on a single piece of continental crust, it covers a series of islands that are made of rock thinner and younger than that of East Antarctica (Chap. 2). Most of the ice sheet sits on rock that is below sea level and reaches a depth of more than 1000 m in places (Fig. 5.1). Unlike EAIS, the bedrock beneath WAIS would not rebound if the ice were removed and, for this reason, the West Antarctic Ice Sheet is known as a marine-based ice sheet (Alley and Bindschadler 2001). Due to its low elevation and position below sea level in many areas, the WAIS is generally warmer than EAIS, and the base of the ice is at melting point across large areas.

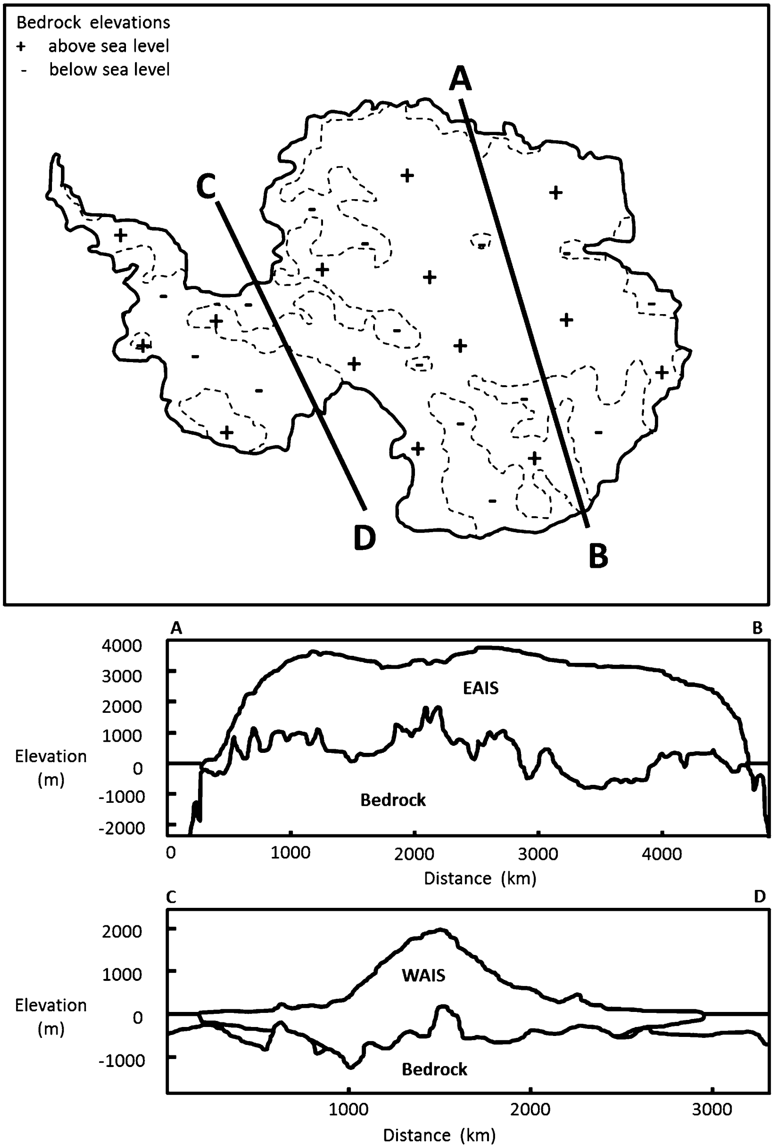



**Fig. 5.1** Cross sections through the (***A–B***) West and (***C–D***) East Antarctic Ice Sheets (With kind permission from Rob DeConto)

**Box 5.1: West Antarctic Ice Sheet Disintegration**

As most of the West Antarctic Ice Sheet (WAIS) sits below sea level, any thinning of the ice could cause it to float and quickly melt as the relatively warm ocean water is allowed access to the base of the ice. This makes WAIS more sensitive to climate change than its East Antarctic counterpart and geological

(continued)

**Box 5.1** (continued)

records and climate models show that the WAIS has in fact grown and shrunk many times in the past (Pollard and DeConto 2009) (Chap. 4). However, current ice sheet models and computer simulations are not yet able to predict the rate at which any future ice sheet collapse could occur, and uncertainties about future projections of greenhouse gas concentrations and temperature rise make this very difficult to predict. It is known, however, that if the WAIS were to disintegrate, that this would raise global sea level by 4.8 m (Bamber et al. 2009).

The WAIS has warmed by more than 0.1 °C per decade in the last 50 years. This trend is strongest in winter and spring and the greatest warming has been observed on the Antarctic Peninsula (Steig et al. 2009). Indications that the WAIS is losing mass at an increasing rate in response to this warming come from the Amundsen Sea sector. Glaciers such as the Pine Island, Thwaites and Smith Glaciers are thinning and losing more ice than is being replaced by snowfall (Pritchard et al. 2009, Fig. 5.2). There is growing evidence that this trend is accelerating, and there has been a 75 % increase in Antarctic ice mass loss in the 10 years from 1996 to 2006 (Rignot et al. 2008).

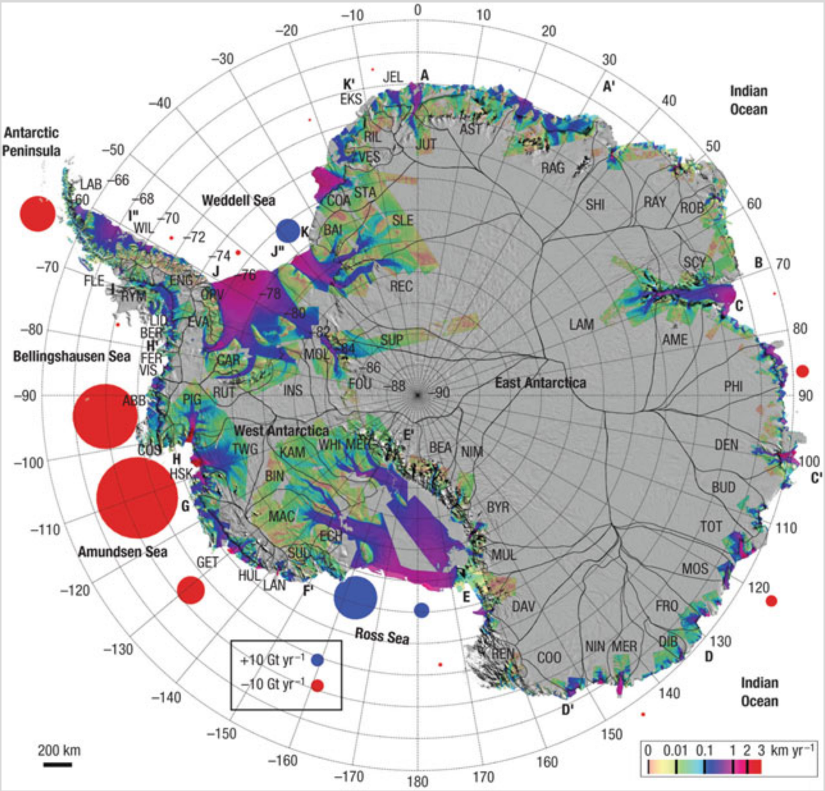



**Fig. 5.2** Rate of ice loss around the Antarctic coastline in giga-tonnes per year (Gt year$^{-1}$). The size of the *dots* in the legend shows the equivalent of 10 Gt year$^{-1}$ and the *colour bar* shows the ice flow speed in km per year (km year$^{-1}$) (Reprinted with kind permission from Macmillan Publishers Ltd: Nature Geoscience, Rignot et al. 2008)

### 5.2.3 Ice Caps

The ice on the Antarctic Peninsula consists of smaller, thinner ice caps than either EAIS or WAIS. Covering the length of the mountainous spine of the Peninsula, and extending north into the circumpolar westerly winds, these ice caps and glaciers are fed by marine weather systems and receive high volumes of snowfall. Recent warming of the Peninsula has led to rapid retreat of these ice caps, and dramatic collapses of the ice shelves into which they flow (see Sect. 5.8).

### 5.2.4 Ice Sheet Mass Balance

The mass balance of the two Antarctic ice sheets is a fundamental indicator of the response of the continent to climatic changes. It is a measure of how much ice mass is gained or lost from the ice sheet over a given time period. If completely in balance, the ice sheet would be in equilibrium; neither growing nor shrinking.

The ice sheet gains mass from snow accumulation, and loses mass mainly from iceberg calving, although other contributing factors are melt from the base of ice shelves and the loss of snow from the surface due to sublimation (direct evaporation of the snow into the atmosphere). The ice sheet mass balance is positive if the amount of ice accumulating on the continent exceeds the amount of ice that is lost at the coastal margins. If the reverse is true (the amount lost at the coast exceeds accumulation), the mass balance is negative. The mass balance of Antarctica is closely linked to global sea level because the loss of ice into the Southern Ocean can result in large volumes of freshwater being released from the continent. Monitoring Antarctic mass balance is therefore crucial for predictions of future sea level rise.

It is almost impossible to measure the mass balance of the entire continent simultaneously because of the variability in the behaviour of individual drainage basins and glaciers. However, estimates of the mass changes from satellite data have revolutionised our ability to monitor the Antarctic cryosphere (Box 5.2). Since the launch of satellites in the 1960s, surface elevation, surface temperature, ice flow rates and surface properties have been monitored, so that patterns of change are beginning to emerge.

**Box 5.2: ICESat and Cryosat**
The Ice, Cloud and Land Elevation Satellite (ICESat) was launched by the United States National Aeronautics and Space Administration (NASA) in 2003. This satellite used lasers to measure small changes in surface elevation of ice in Greenland and Antarctica, with accuracies better than 1 cm per year (Zwally et al. 2002). Alongside ice sheet mass balance, it also measured sea ice thickness, cloud and aerosol heights, as well as land topography and

(continued)

**Box 5.2** (continued)
vegetation characteristics. ICESat gathered data for 7 years before being retired after the last of three lasers on the satellite's Geoscience Laser Altimeter System (GLAS) ceased emitting light in October 2009. NASA is planning to launch a follow-on mission, ICESat-II, to continue studying polar ice changes from 2015. For the period of time in between the two satellites NASA's operation ICE Bridge is using a DC-8 aircraft to measure ice thickness over Antarctica.

The European Space Agency (ESA) also began monitoring Antarctic mass balance changes in April 2010, with the launch of CryoSat-2. From an altitude of just over 700 km and reaching latitudes of 88°, the CryoSat-2 satellite uses radar to monitor precise changes in the thickness of the polar ice sheets and floating sea ice. This provides valuable information about the behaviour of coastal glaciers around Antarctica that are experiencing rapid thinning.

## 5.3 Snow Accumulation

The ice that covers Antarctica has been formed from the gradual build-up of snow. Moisture that evaporates from open water is carried in the atmosphere to the continent, where it cools, condenses and freezes on tiny nuclei, such as rock dust or organic matter. The frozen particles gather more water droplets, and form snowflakes that fall to the surface and settle.

Coastal areas are regularly battered by storms from a band of large low-pressure systems. These systems track around the continent in the circumpolar westerly winds, and sweep marine moisture on to coastal areas (Chap. 6). As this moisture reaches higher-elevation areas, such as the Transantarctic Mountains, the air is forced to rise and cool and snow is formed. Some parts of coastal Antarctica consequently receive more than 2 m of snow per year. The storm tracks rarely penetrate into inland Antarctica, and instead, across much of EAIS, moisture falls as tiny granules of ice, known as diamond dust, that drift down through the atmosphere and settle on the surface of the ice sheet. At the South Pole, only 2–5 cm of snow accumulates each year, which is equivalent to the amount of rainfall in the Sahara desert.

## 5.4 Ice Formation

Across most of Antarctica, summer temperatures remain below zero, which means that snow does not melt, but becomes buried and compacted by new snow above. As it moves further below the surface, the snow gradually turns into ice due to the weight of new snow pushing down from above. As the snow becomes compacted, in a process known as sintering, the individual crystals become more rounded and spherical and the air that was trapped in their structure is squeezed between them. At this stage, the snow is known as firn.

When the firn is compressed even more, the snow loses most of its original structure, the rounded crystals are pressed together, and the air is sealed into individual pockets, or pores. This forms bubbly ice at the firn-ice transition, which occurs somewhere between 50 m (near the coast) and 110 m depth (inland), depending on the density (weight) of the snow above (Craven 2007). Containing about 10 % air, the bubbly ice seals in tiny samples of the atmosphere at the time it was frozen into the ice.

**Box 5.3: Why Is Ice Blue?**
As with water, the blue colour associated with compressed glacial ice is caused by the absorption of both red and yellow light. This only leaves light at the blue end of the visible light spectrum to be reflected back to our eyes. From the surface, snow and ice seem uniformly white. This is because almost all of the visible light striking the surface is reflected back. As this light travels into the snow or ice, it is scattered and, as it moves deeper into the ice, most colours are filtered out so that only the blue light can be transmitted.

## 5.5 Ice Cores

By drilling down vertically into ice sheets and ice caps, scientists can extract a record of past climates (Box 5.4; Fig. 5.3). As scientists drill deeper, they extract older ice that contains a record of past climates from air trapped in tiny bubbles and from the chemistry of the frozen water in the ice core (Chap. 7). This is a crucial part of understanding climate change; by unravelling past climates, we can begin to understand how the current rate of global warming compares to past cycles of warming and cooling. Some of the deepest ice cores retrieved from Antarctica, such as the Vostok Ice Core and the EPICA (Dome C) Ice Core, are over 3000 m long and cover up to 800,000 years of climate history (Jouzel et al. 2007).

**Box 5.4: The EPICA/Dome C Ice Core**
The European Project for Ice Coring in Antarctica (EPICA) was a multinational drilling project, based on the EAIS at the Franco-Italian Concordia research station Dome C. The site at Dome C was chosen for its exceptionally thick ice and is a bitterly cold environment, with temperatures ranging from −50 °C at the start of the season to −25 °C in the middle of the Antarctic summer. Over eight consecutive seasons the team drilled further into the ice and completed the core extraction in 2004. At 3190 m, this ice core reveals a climate history that spans more than 800,000 years (EPICA 2004).

(continued)

**Box 5.4** (continued)

The time period covered by the EPICA core spans eight full glacial-interglacial cycles and confirms that Antarctica has seen recurring warm and cold phases at about 100,000-year intervals (Chap. 4). These results confirm the climate discoveries made from the Vostok ice core (Petit et al. 1999), drilled about 500 km from the Dome C site, which covered four glacial cycles (about 400,000 years). Both cores highlighted the link between historical greenhouse gas concentrations and temperature variability.

Although the EPICA core was a huge success, the project was not without problems. In the 1998–1999 drilling season, ice chips formed in the drilling mechanism, jamming it in place. This forced the team to abandon the hole and start again. At depths of more than 3 km, the drill took more than an hour to haul to the surface, making the final stages of the drilling extremely time consuming (Walker 2004).

**Box 5.5: Roosevelt Island Ice Core**

The New Zealand Ice Core Programme is focused on extracting ice cores from areas of very high snow accumulation in the coastal Ross Sea region. These cores cover much shorter time periods than the deep cores extracted from the EAIS, but due to the high rates of snowfall, they give a very detailed view of climatic variability in this region. From the ice-core geochemistry, scientists have been able to reconstruct not only temperature change but also learn more about such things as sea ice, phytoplankton productivity in the southern Ross Sea and storm tracks across the region.

The most recent and ambitious ice core extraction project has been on Roosevelt Island in the Ross Sea. This is a small island embedded into the Ross Ice Shelf with an ice cap that is approximately 750 m thick. In late 2012, after two drilling seasons, the team was finally able to drill through the full depth of the ice cap. The core will give an unprecedented record of past fluctuations of the Ross Ice Shelf, a major drainage pathway from the WAIS. It is expected to cover approximately 20,000 years and will therefore extend back to a time when global temperatures were about 6 °C higher, global sea level rose by approximately 120 m and the ice shelf retreated more than 1000 km. Knowledge of the past response of the ice shelf to global warming will therefore provide unique insights into the way that temperature change may affect this region and global sea level in the future.


**Fig. 5.3** A team from the New Zealand Ice Core Programme working in the Roosevelt Island drill trench (With kind permission from Nancy Bertler)

### 5.5.1 Dating Ice Cores

A range of chemistry measurements are made in order to interpret the climate history preserved in ice cores. The most common measurements are the stable isotopes of oxygen and hydrogen, which can be used as indicators of past temperatures. They can also show changes in atmospheric circulation, such as changes in storm tracks, and the effects of climate phenomena such as El Niño on the climate of Antarctica.

Oxygen has two common isotopes, $^{18}O$ and $^{16}O$, and the stable isotopes of hydrogen are $^{1}H$ and $^{2}H$ ($^{2}H$ is deuterium, also referred to as D). The heavier isotopes, $^{18}O$ and $^{2}H$, contain extra neutrons, which makes them react differently in the hydrological cycle. As temperature decreases, there is more separation between the isotopes; the heavier isotopes are removed more quickly so that the moisture in the atmosphere contains more light isotopes. This ratio of heavy to light isotopes is recorded in snow as it falls on the surface of Antarctica, and is compared to an international standard for ocean water, to give $\delta^{18}O$ and $\delta D$ values. Because of the direct relationship between these delta values with the temperature of the atmosphere when the snow was formed, scientists can use the isotopes as a proxy for past temperatures.

Stable isotopes can also be used to help identify summer (relatively warm) and winter (relatively cold) layers in an ice core and this is one of the simplest ways to mark out individual years and date the ice.

Layers of volcanic ash, carried high in the atmosphere to Antarctica from major volcanic eruptions, are also used to help date the age of ice in an ice core. The layers of ash are identified either visually (because they appear as dark bands in the ice core) or by measuring sulphates, nitrates and electrical conductivity (or acidity) in the ice and then correlated with known volcanic eruptions.

### 5.5.2 Chemistry and Dust Measurements in Ice Cores

Measurements of trace elements (such as sodium, aluminium, magnesium etc.), major ions (such as nitrates and sulphates) and the dust that is trapped in ice cores preserve information about many types of environmental indicators. These include marine biological productivity and sea ice extent, atmospheric circulation and industrial pollution (Legrand and Mayewski 1997). Many trace elements also have a seasonal cycle. Sodium trapped in Antarctic snow, for example, usually increases in summer months because of the open water around the continent. For this reason, looking at the record of trace elements over time can help scientists find annual layers in the ice-core record. It can also show differences between marine elements, such as sodium, and terrestrial (land-based elements), such as aluminium. The relative changes between these elements can then show shifts in dominant weather patterns that brought moisture to an ice-core site.

Extracting dust from melted water samples from an ice core is a powerful indictor of windiness. There is a direct relationship between the dust record from ice cores and cold/warm climate episodes (glacials and interglacials). In glacial times, more freshwater is locked up in ice caps and glaciers, so that the remaining land tends to be relatively dry and arid. Winds also tend to be stronger because of the larger temperature difference between the equator and the poles. This results in more dust (with larger grain sizes) being swept up and deposited in ice-core records.

### *5.5.3 Greenhouse Gases*

It is also possible to extract greenhouse gases trapped in tiny air bubbles within the ice to give us a precise picture of how greenhouse gas concentrations have varied over time (Chap. 8). Ice-core records have shown us that cycles of increasing and decreasing greenhouse gas concentrations correspond directly with changes in the Earth's surface temperature. They have also shown us that greenhouse gas concentrations have not exceeded the present day values for hundreds of millennia (Petit et al. 1999). These measurements give us baseline information to help predict how human emissions of greenhouse gases will affect the temperature and climate of the planet in the future (Chap. 8).

## 5.6 Ice Streams and Glaciers

### *5.6.1 Ice Flow*

Viewed from space, the ice that covers Antarctica looks permanent and static. It is, however, a very dynamic and fluid system that changes rapidly and flows much like a river system that drains an upstream basin. Ice flows mainly by deforming plastically downslope under its own weight in the direction of maximum slope (Paterson 1994). Plastic deformation occurs at a microscopic scale due to individual ice crystals sliding past each other. On a larger scale, the ice appears to flow and, somewhat like pouring sauce over a pudding, it spreads outward from the centre of Antarctica and thins as it flows downslope. The highest part of the ice sheet, about 4100 m above sea level, is not at the South Pole but in the middle of EAIS at about latitude 80 S and longitude 77°E. This is the major drainage divide and from here ice flows out radially towards the coast (McGonigal and Woodworth 2001).

Moving relatively slowly near the centre of the ice sheet, the ice accelerates as it flows towards the edge of the continent guided by the topography of the underlying drainage basins. The ice also moves fastest at the surface, and more slowly in deeper layers near the bedrock due to the friction produced by ice shearing against the underlying topography. For this reason, horizontal layers in the ice sheet move past each other at different rates, and range in speed from a few metres to several hundred metres per year. The ice that is lost from the edges of the ice shelves and glaciers is constantly replenished by ice flowing from the interior of the continent.

### *5.6.2 Ice Streams*

Ice streams were discovered only recently when satellite images of the surface of the ice sheet became available. Scientists studying these images noticed that giant rivers of ice cut through the ice sheet, fringed on each side by wide zones of crevasses. These fractured zones represent areas of ice extension, or shearing, which indicate that the ice streams flow much faster than surrounding ridges of ice. This was one of the biggest glaciological discoveries in the history of Antarctic science and these ice streams have since become one of the most studied features of the Antarctic cryosphere.

Ice streams can flow 10–100 times faster than the surrounding ice. Like a river, they flow fastest in the centre and more slowly at the edges, where the ice is impeded by the slow-moving ice sheet. The flow rates in ice streams are too rapid to be explained by plastic deformation alone, and so glaciologists drill bore holes and send cameras and instruments to the base of the ice streams to monitor processes beneath the ice and determine the basal conditions. They have found that the ice is underlain by water-saturated sediment, known as till. The water at the base is produced by pressure melting, which occurs when the weight of the overlying ice is sufficient to cause melting at the base. This melt water flows into the sediment, creating a slurry that increases the water pressure and lubricates the base of the ice streams.

The basal conditions beneath ice streams play a fundamental role in the future stability of the West Antarctic Ice Sheet by governing the amount of ice that can be funnelled away from the interior of the continent. Ice streams, such as those around the Siple Coast in the Ross Sea (Fig. 5.4), appear to respond very rapidly to changing ice thickness, along with pressures and temperatures beneath the ice, although rapid ice-stream flow is still not fully understood and streams can start and stop for reasons that are unclear. About 150 years ago, Kamb Ice Stream simply switched off and became dormant probably due to a change in subglacial water pathways, but the nearby Whillans Ice Stream still flows at rates of about 600 m per year near the entry to the Ross Ice Shelf (Joughlin et al. 2002; Pritchard et al. 2009, Fig. 5.5).

Discharge through the ice streams on the Amundsen Sea Coast of West Antarctica is strongly out of balance with the rest of the ice sheet. Ice thinning and acceleration have resulted in the rapid loss of mass from some of the largest glaciers, such as Pine Island Glacier and Thwaites Glacier. These ice streams have grounding lines (see below) much closer to the ocean than the Ross Sea ice streams, and are vulnerable to rapid melting (Wingham et al. 2009).

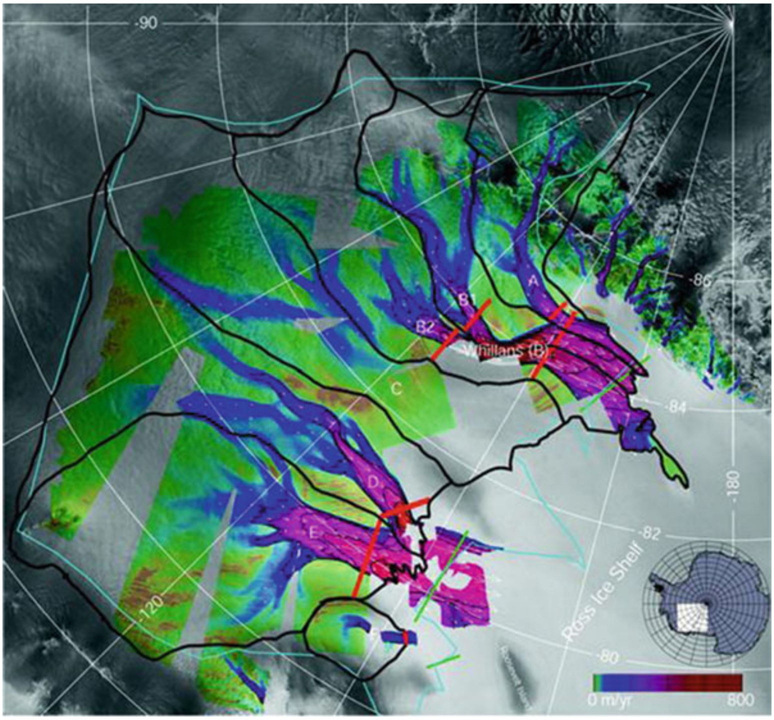



**Fig. 5.4** Velocity map for ice streams on Siple Coast of West Antarctica (With kind permission from Ian Joughin)

### *5.6.3 Glaciers*

Glaciers in Antarctica can be classified as outlet, alpine or dry-based glaciers. Outlet glaciers behave in a similar way to ice streams and can drain vast quantities of ice from the interior of the ice sheet (Fig. 5.6). In fact, more than 40 % of the ice that is lost from the continent flows through the 20 largest outlet glaciers and ice streams (Vaughan 2007). Unlike ice streams, which cut a path through the ice sheet, outlet glaciers flow through mountain ranges, where the valley topography channels ice into distinct flow paths. Many of the largest outlet glaciers flow through the Transantarctic Mountains, and allow ice to escape from the East Antarctic Ice Sheet. One such glacier, the Lambert, is one of the world's largest glaciers; about 400 km long and 200 km wide where it meets the ocean, it drains an area of approximately 1 million square kilometres and flows into the Amery Ice Shelf. Early explorers such as Captain Robert Falcon Scott, travelling via the Beardmore Glacier on his bid to reach the South Pole, used these outlet glaciers as a means to cross the Transantarctic Mountains en route to the Polar Plateau.

Dry-based glaciers have no subglacial water and are frozen to the rock and sediment beneath them. Although they make up a very small proportion of the

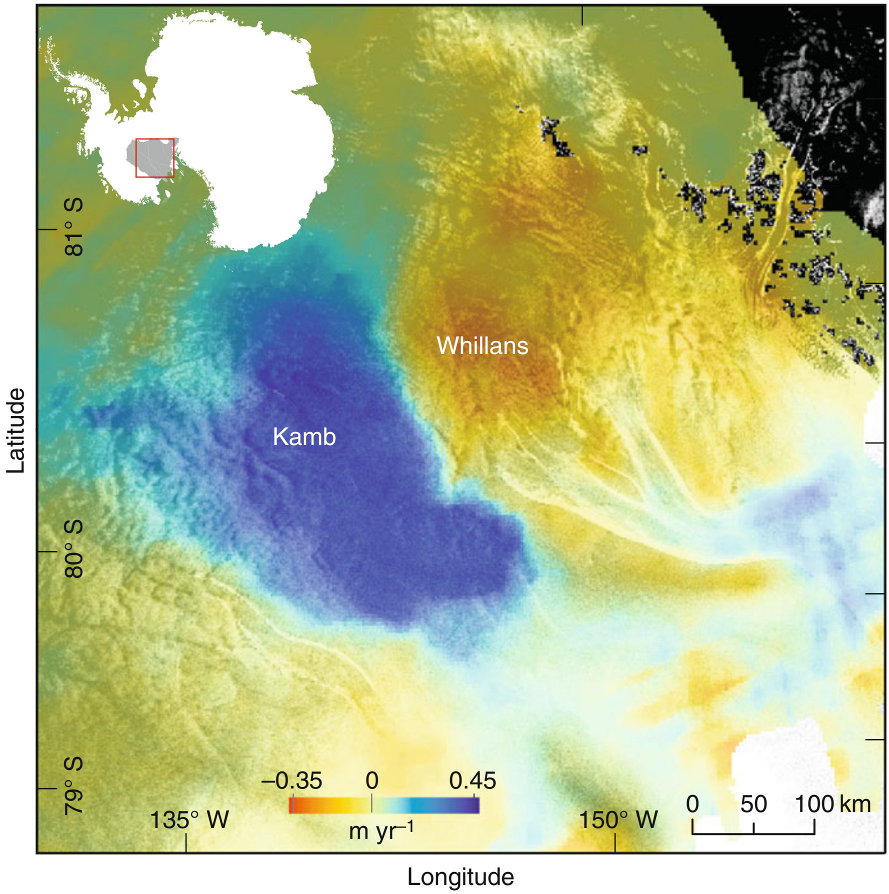



**Fig. 5.5** The rate of change of ice thickness (in metres per year) of the Kamb and Whillans Ice Streams, Siple Coast, Antarctica. The Kamb Ice Stream has stagnated and is thickening, while the neighbouring Whillans is flowing rapidly and thinning (Reprinted with kind permission from Macmillan Publishers Ltd: Nature, from Pritchard et al. 2009)

Antarctic cryosphere, dry-based glaciers are some of the most unique features on the continent because they owe their existence to a specific set of environmental conditions, such as extremely low annual temperatures and precipitation.

The McMurdo Dry Valleys contains numerous dry-based glaciers, many of which drape down valley walls and terminate in near-vertical ice cliffs (Fig. 5.7). Some of the larger glaciers, such as the Commonwealth and Taylor Glaciers, extend out on to the valley floors. They move very slowly, due to the lack of basal sliding, but contain very old ice and sediment-rich basal ice layers that have been intensively studied by glaciologists to learn more about their unusual behaviour and dynamics.

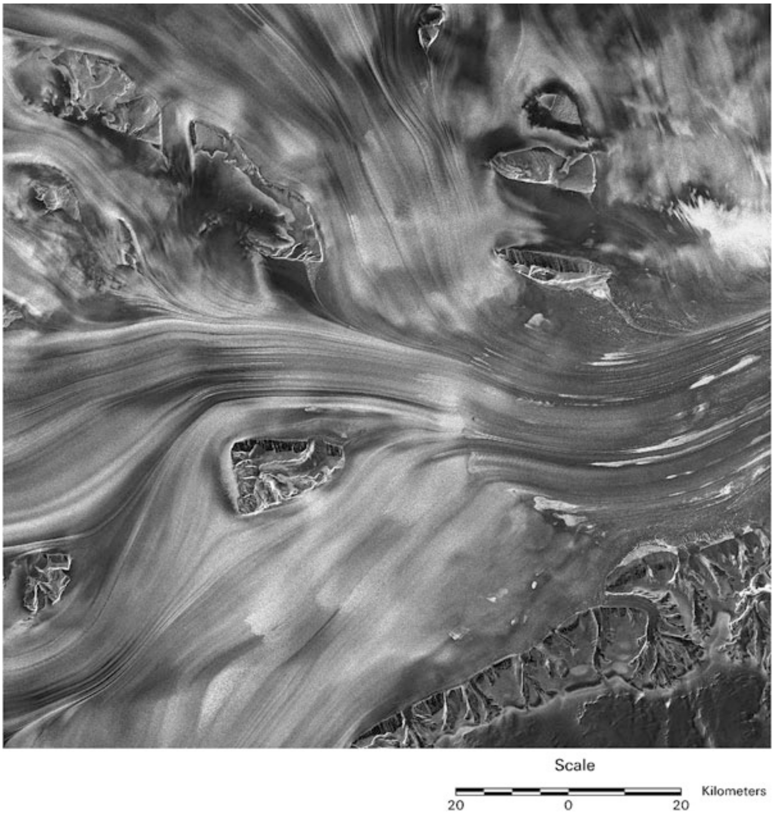



**Fig. 5.6** A satellite (RADARSAT) image of the Lambert Glacier (With kind permission from the National Snow and Ice Data Center, University of Colorado, Boulder)

Glaciers on the Antarctic Peninsula behave more like alpine glaciers in other parts of the world. They have shaped the topography of this mountainous region and now occupy valleys and cirques. Most of these glaciers have been retreating rapidly in recent decades in response to the temperature increase along the Peninsula.

## 5.7 Subglacial Hydrology

There are five major drainage basins in Antarctica, and each is made up of a complex network of ice streams, glaciers, subglacial drainage systems and lakes (Fig. 5.8). The existence of lakes beneath the ice was discovered by scientists in the late 1960s. These liquid bodies of water exist just above freezing point due to the input of geothermal heat from the continent below and the pressure from the weight of the overlying ice (Siegert 2000).

**Fig. 5.7** View of the dry-based Stocking Glacier in the Taylor Valley, Antarctica (With kind permission from Hinrich Schaefer)

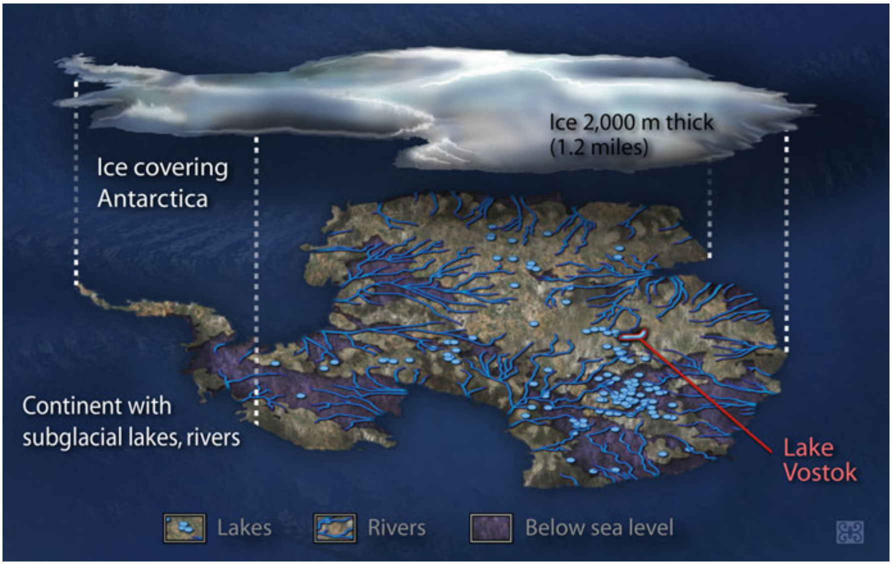



**Fig. 5.8** An artist's representation of the drainage systems beneath the Antarctic ice sheet (With kind permission from Zina Deretsky/NSF)

There are more than 150 subglacial lakes in Antarctica and scientists think that they are connected, at least temporarily. Differences in water pressure between individual lakes mean that large sub-surface rivers may form quickly and allow water to discharge from one lake to another. For example, during a period of 16 months on the EAIS, 1.8 km$^3$ of water was transferred over 290 km from lake to lake (Wingham et al. 2006). If large lakes, such as Lake Vostok (Box 5.5) or Lake Concordia, are under sufficient pressure, this water may flow as far as the Antarctic coast. This has implications for ice sheet velocities and mass balance because the movement of this water may reduce the pressure at the base of the ice sheet, and trigger accelerated ice flow (Bell 2008).

**Box 5.6: Lake Vostok**

Lake Vostok is about 250 km long and up to 50 km wide and sits in a giant subglacial trench 4000 m beneath the East Antarctic Ice Sheet (Fig. 5.9). Russian and British scientists mapped the outline of the lake in 1996 using airborne ice-penetrating radar imaging and spaceborne radar altimetry (Box 5.2). In the 1990s, the Vostok ice core was drilled above the lake and came within 200 m of the lake surface. Further coring stopped while scientists tried to develop a way of investigating the lake without contaminating the water.

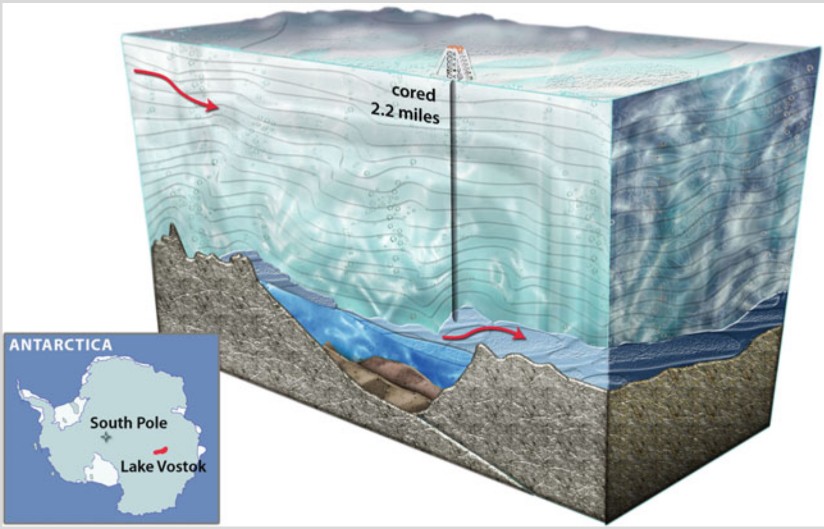



**Fig. 5.9** An artist's cross-section of Lake Vostok, the largest known subglacial lake in Antarctica. Liquid water is thought to take thousands of years to pass through the lake, which is the size of North America's Lake Ontario (With kind permission from Nicolle Rager-Fuller/NSF)

(continued)

**Box 5.6** (continued)

The water in the lake has been isolated from Earth's atmosphere for up to 35 million years and is divided into two deep basins. The northern basin is about 400 m deep, the southern basin is about 800 m deep and the average water temperature is around −3 °C. The water remains liquid below the normal freezing point (0 °C) because of high pressure from the weight of the ice above it. Geothermal heat from Earth's interior also warms the bottom of the lake and the ice sheet itself insulates the lake from cold temperatures on the surface.

The water is not as old as the lake itself; it is continuously being recycled by freezing on to the base of the ice. This refrozen ice is then carried away by the flow of the ice sheet above. Based on an analysis of the buckling patterns in the ice, scientists have been able to reconstruct the pattern of ice flow across the lake and estimate the average residence time of the water to be 13,300 years.

Analysis of the ice from the base of the Vostok core revealed a high number of microbes. This suggested that the lake water itself supports simple but ancient life forms that have been isolated from the Earth's atmosphere for perhaps 500,000 years. The oxygen levels in the lake are about 50 times higher than Earth's atmosphere due to the pressure of the ice above. Any organisms that exist in this environment would therefore need to have developed specialised adaptations to survive. In early 2012, a Russian team was able to drill close to the surface of the lake. Once the drill was removed, this lowered the pressure of the hole so that water from the lake moved upwards and froze. In this way, the team was able to extract the first samples from Lake Vostok. Analysis of the samples has so far identified more than 3500 unique gene sequences mostly from bacteria.

## 5.8 Ice Shelves

Ice shelves are floating rafts of ice that fringe about 45 % of Antarctica. They fill coastal embayments, and so generally are connected to the coast with one seaward margin. Ice shelves appear to be flat and featureless but, although their surface slopes at a very low angle, they also have very little friction at their base where they are in contact with the ocean. For this reason, they are the fastest moving component of the Antarctic cryosphere, reaching speeds of several kilometres a year in places.

The largest ice shelves are the Ross, the Ronne-Filchner and the Amery, but there are many other smaller ice shelves around the coast of the continent. They are fed by the flow of ice from inland, and also gain mass by seawater freezing on to the base and from snowfall above. Ice shelves lose mass mainly by shedding icebergs off their seaward margins into the ocean, in a process known as calving. This

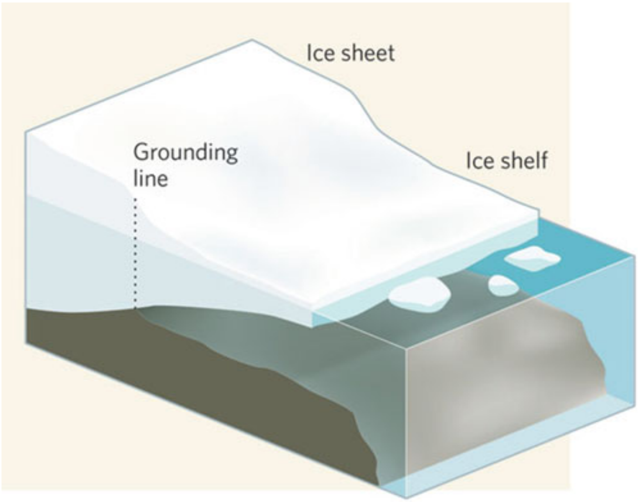



**Fig. 5.10** The main features of an Antarctic ice shelf (Reprinted with kind permission from Macmillan Publishers Ltd: Nature, from Huybrechts 2009)

creates near-vertical cliffs at the seaward edge of ice shelves. Around the Ross Ice Shelf these impenetrable cliffs are about 50 m high, which prompted early explorers to name it the Ross Barrier.

Ice shelves originate on land and connect with the seafloor until the grounding line, at which point they gain enough buoyancy to begin to float on the ocean surface (Fig. 5.10). The thickest ice is generally found at the grounding line, and the ice thins as it spreads out over the ocean. The position of the grounding line is sensitive to climate change; in cold climates, when the ice sheet expands, the grounding line will move further into the ocean, and the reverse occurs when the climate warms and the ice retreats. Any ice inland of the grounding line will contribute to sea level rise if it is lost to the ocean. Ice that is seaward of the grounding line is already floating, so does not contribute to sea level rise, but may play a crucial role in slowing down the loss of ice through ice shelves by obstructing the flow of the inland ice as it moves towards the ocean.

Spectacular collapses of ice shelves around the Antarctic Peninsula are driven by warmer ocean waters and surface melt water and have sparked much discussion in the scientific community and media. Ice shelves are fed by glaciers and ice streams flowing from the interior of the continent so the loss of the barrier provided by the ice shelf has allowed rapid acceleration of the tributary glaciers as they adjust to the new conditions (Rignot et al. 2004). If this is an analogue for the processes that would take place if ice shelves disintegrated around the entire continental margin of West Antarctica, it is possible that there would be a runaway release of ice from the continent. The role of the ice shelves as an obstacle to ice movement is still poorly understood and is the focus of much current glaciological research in Antarctica.

## 5.9 Icebergs

Icebergs are formed at the edge of ice shelves along lines of weakness, where stresses from ocean currents and waves cause large areas of ice to fracture away from the edge of the floating ice shelf. The largest bergs are tabular icebergs that may be greater than 300 m thick and contain enough frozen water to supply a city of a million people for 3 years. Tabular icebergs have characteristically flat surfaces and are carried across the ocean surface by ocean circulation. They tend to follow westerly currents around coastal Antarctica before moving north and getting caught in the easterly flow (West Wind Drift) further out to sea. By the time icebergs meet the Antarctic Convergence, stress fractures from waves and warmer temperatures generally cause them to disintegrate quickly, although on rare occasions they have travelled as far north as 35° into the Indian and South Atlantic Oceans.

**Box 5.7: Antarctic Iceberg Off the New Zealand Coast**

In the summer of 2009, large tabular icebergs that had drifted north from Antarctica were sighted off the southern coast of New Zealand. The largest was about 2 km long and about 50 m above sea level, which implies a total thickness of about 350 m. It is unclear where they originated from exactly, but they were likely to be part of a much bigger iceberg that had calved off the Ross Ice Shelf. The last time a large Antarctic iceberg travelled this far north was after large calving events in the Ross Sea in 2000 and 2002. Typically, these bergs can take 2 or more years to work their way out of the Ross Sea circulation and into the Southern Ocean, so there is a large time lag before they travel as far north as New Zealand.

The world's largest recorded iceberg, B-15, calved off the Ross Ice Shelf in 2000. With an area of over 11,000 km$^2$, it was larger than the island of Jamaica, but broke into several pieces in 2002 and 2003. The largest of these pieces, B-15A, was 122 km long, and on 10 April 2005 it impacted the Drygalski Ice Tongue, breaking off an 8 km$^2$ section and changing the shape of the Ross Sea coastline. This giant iceberg prevented ocean currents and winds from breaking up summer sea ice in McMurdo Sound, causing not only an obstacle to the annual return of icebreakers that resupply research stations, but also a decline in penguin populations due to the extra distances that parents had to cover to reach their chicks from open water.

## 5.10 Sea Ice

In winter, the surface of the ocean around Antarctica freezes as far as 1000 km from the coast over an area of about 20 million square km. In May and June, the sea ice front advances outward from the continent by up to 4 km a day. As it develops outward it also thickens by the addition of new snowfall on the surface and the refreezing, or accretion, of water at the base. The maximum sea ice extent occurs in September and October, when the ice can be 3–4 m thick. It then thins and recedes to a minimum of around 3 million square km by the end of February each year.

The sea ice surrounding Antarctica is not continuous, but instead groups into floes. The floes move and join at pressure ridges, or are rafted over each other as ocean currents and winds move them across the surface of the ocean. The ice floes are separated by open water areas know as polynyas, which are semi-permanent features that tend to occur in the same location for long periods of time. They are kept open by surface ocean circulation, water upwelling from the ocean below and katabatic winds that blow from the continent out to the ocean. Polynyas are zones of intense biological productivity. The Ross Sea Polynya, for example, is the most southerly location in the Antarctic where phytoplankton growth is initiated in early summer (mid-November), and it supports the largest production of phytoplankton biomass of any region in the Southern Ocean (Smith and Gordon 1997).

The yearly cycle of sea ice formation and decay has a dramatic effect on the Antarctic climate. In spring, when the sun returns to the southern polar regions, the brightness, or albedo, of the surface of the sea ice reflects much of the incoming solar radiation back into the atmosphere. This cools the surface and slows the rate of warming and sea-ice melt. The ice also acts like a blanket over the ocean and prevents the evaporation of moisture into the atmosphere. This is one of the key reasons why the Antarctic continent is so dry, especially in winter months. In summer, when the sea ice has retreated, the atmosphere around Antarctica is more humid, and coastal regions receive more snowfall from the marine moisture that is swept inland from the ocean. The increased open-water area also allows more light to penetrate into the water column. This increases biological productivity in the oceans and phytoplankton growth, which is a crucial building block in the Antarctic food chain (Chap. 12).

Sea ice formation around Antarctica also plays a critical role in ocean circulation. Large ocean currents that circulate around the globe, often referred to as the ocean conveyor belt, are partly driven by the formation of Antarctic bottom water. This dense, cold and salty water is produced when less saline, relatively fresh water is frozen into the sea ice. The saltier, denser water is pushed below the surface and sinks deep into the Southern Ocean where it is transported away by ocean currents (Chap. 7).

Recent temperature data from the Southern Ocean has shown that the ocean around Antarctica has warmed (Böning et al. 2008). This could have a major effect on sea ice formation and ocean circulation in the future. If less sea ice forms, the albedo of the Southern Ocean will also decrease, meaning that less solar radiation is reflected. This, in turn, will accelerate warming of the ocean surface and further slow the formation of sea ice and Antarctic bottom water.

**Box 5.8: Types of Sea Ice**

Sea ice takes many different physical forms, but the most basic distinctions are between new, first-year and multi-year ice. New ice has relatively high salinity, but as the ice ages, the salty brine trapped between crystals drains down through the ice structure and increases the salinity of the sea water below. Multi-year ice, or ice that has survived more than one winter, therefore has a lower salinity and can even be melted for drinking water. It also has the lowest density because of the empty brine pockets near the surface.

The first ice to form every winter season is known as frazil ice. This begins as small needles, which then become a delicate layer of tiny ice plates. When this thickens, it resembles an icy sludge that is known as grease ice. If conditions are calm, this ice can grow rapidly into solid sheets called nilas, but this can be rapidly broken up in stormy seas and rammed together into pancake ice. Once the pancake ice solidifies and thickens it forms floes, which eventually thicken and grow into first-year sea ice. If ice is frozen to the continent, it is known as fast ice, but if it rests on open ocean it is called pack ice.

## 5.11 Conclusions

The ice in Antarctica plays a crucial role in Earth's physical environment. It is a major link in the ocean circulation system and affects the climate of the entire planet. The giant Antarctic ice sheets are over 4 km thick in some parts and contain most of Earth's freshwater resources. This ice also contains an unprecedented history of the Earth's climate over the past 800,000 years, with secrets still to be discovered from the depths of subglacial lakes, such as Lake Vostok. The relentless flow of ice towards the coast from the interior makes the continent a dynamic and continually changing environment. Vast ice streams and outlet glaciers feed ice shelves, which eventually shed ice into the Southern Ocean. The ice lost from this glacial conveyor belt is replaced by new snowfall in inland areas, which is compacted into glacial ice. The way the ice in Antarctica responds to climate change in the future will have a profound effect on all life on Earth, and it is crucial that we continue to study and monitor the rapid changes taking place on the continent.

## References

Alley RN, Bindschadler RA (eds) (2001) The West Antarctic ice sheet – behaviour and environment. American Geophysical Union, Washington, DC

Bamber JL, Riva REM, Vermeersen BLA, LeBroq AM (2009) Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet. Science 324:901. doi:10.1126/science.1169335 (Supporting online material)

Bell RE (2008) The role of subglacial water in ice-sheet mass balance. Nat Geosci 1:297–304. doi:10.1038/ngeo186

Böning CW, Dispert A, Visbeck M, Rintoul SR, Schwarzkopf FU (2008) The response of the Antarctic circumpolar current to recent climate change. Nat Geosci 1:864–869. doi:10.1038/ngeo362

Craven M (2007) Firn compaction. In: Riffenburgh B (ed) Encyclopedia of the Antarctic, vol 1. Routledge, New York, pp 398–399

EPICA Community Members (2004) Eight glacial cycles from an Antarctic ice core. Nature 429:623–628. doi:10.1038/nature02599

Huybrechts P (2009) Global change: west-side story of Antarctic ice. Nature 458:295–296. doi:10.1038/458295a

Joughlin I, Tulaczyk S, Binschadler RA, Price SF (2002) Changes in the West Antarctic ice stream velocities: observation and analysis. J Geophys Res 107(B11):2289. doi:10.1029/2001JB001029

Jouzel J et al (2007) Orbital and millennial Antarctic climate variability over the past 800,000 years. Science 317:793–796. doi:10.1126/science.1141038

Legrand M, Mayewski P (1997) Glaciochemistry of polar ice cores: a review. Rev Geophys 35:219–243

McGonigal D, Woodworth L (2001) Antarctica – the complete story. Random House, Auckland

Paterson WSB (1994) The physics of glaciers. Elsevier, Oxford/New York/Tokyo, 480pp

Petit J-R et al (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399:429–436

Pollard D, De Conto RM (2009) Modelling West Antarctic ice sheet growth and collapse through the past five million years. Nature 458:329–332. doi:10.1038/nature07809

Pritchard HD, Arthern RJ, Vaughan DG, Edwards LA (2009) Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. Nature 461:971–975. doi:10.1038/nature08471

Rignot E, Casassa G, Gogineni P, Krabill W, Rivera A, Thomas R (2004) Accelerated ice discharge from the Antarctic Peninsula following the collapse of the Larsen B ice shelf, Antarctica. Geophys Res Lett 31:L18401. doi:10.1029/2004GL020679

Rignot E, Bamber JL, van den Broeke MR, Davis C, Li Y, van de Berg WJ, van Meijgaard E (2008) Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. Nat Geosci 1:106–110. doi:10.1038/ngeo102

Siegert M (2000) Antarctic subglacial lakes. Earth Sci Rev 50(1–2):221–236

Smith WO Jr, Gordon LI (1997) Hyperproductivity of the Ross Sea (Antarctica) polynya during austral spring. Geophys Res Lett 24:233–236

Steig EJ, Schneider DP, Rutherford SD, Mann ME, Comiso JC, Shindell DT (2009) Warming of the Antarctic ice-sheet surface since the 1957 international geophysical year. Nature 457:459–462. doi:10.1038/nature07669

Vaughan DG (2007) Antarctic ice sheet: definitions and description. In: Riffenburgh B (ed) Encyclopedia of the Antarctic, vol 2. Routledge, New York, pp 56–59

Walker G (2004) Paleoclimate: frozen time. Nature 429:56–59. doi:10.1038/429596a

Wingham DJ, Siegert MJ, Shepherd A, Muir AS (2006) Rapid discharge connects Antarctic subglacial lakes. Nature 440:1033–1036. doi:10.1038/nature04660

Wingham DJ, Wallis DW, Shepherd A (2009) Spatial and temporal evolution of pine island glacier thinning 1995–2006. Geophys Res Lett 36:L17501. doi:10.1029/2009GL039126

Zwally HJ et al (2002) ICESat's laser measurements of polar ice, atmosphere, ocean and land. J Geodyn 34:405–455

# Chapter 6
# Weather and Climate

## Antarctica's Role in the Global Atmospheric System

**Ian Owens and Peyman Zawar-Reza**

**Abstract** The difference between weather and climate is time. Weather refers to the atmospheric conditions over a short period of time, from hours to a few days, whereas climate is the long-term pattern or average of weather in an area, region or across the globe. The weather and climate of Antarctica play an integral part in the global atmospheric system. This system produces a wide belt of low pressure surrounding Antarctica, which creates the westerly winds that drive atmospheric circulation over the Southern Ocean. Global circulation also produces a region of high atmospheric pressure over the South Pole, which leads to East Antarctica being dominated by cloudless skies and very little snow fall. By contrast, the coastal regions of Antarctica are relatively warm, cloudy and receive the most snow fall; they are sometimes exposed to easterly winds or the low-pressure systems that originate from the low-pressure belt that hugs the margin of the continent. The long, narrow Antarctic Peninsula extends the farthest north of any point of the continent. It reaches the region of persistent, strong westerly winds, which combined with the Peninsula's maritime environment, produce weather and climate conditions quite distinct from those of East Antarctica.

**Keywords** Coriolis force • Automated weather stations • Greenhouse effect • Albedo • Radiation • Conduction

## 6.1 Continent of Extremes

Extreme cold, extreme wind and extreme dryness are the features that most characterise the Antarctic atmospheric environment. They result from a combination of Antarctica's polar position, its topography and surface characteristics. Much of the East Antarctic plateau is more than 3000 m above sea level, and gives Antarctica the highest average elevation of all the continents (Fig. 6.1). This cold, high interior of Antarctica causes the dryness of the air and also gives rise to

I. Owens • P. Zawar-Reza (✉)
Department of Geography, University of Canterbury, Christchurch, New Zealand
e-mail: peyman.zawar-reza@canterbury.ac.nz

 
D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_6

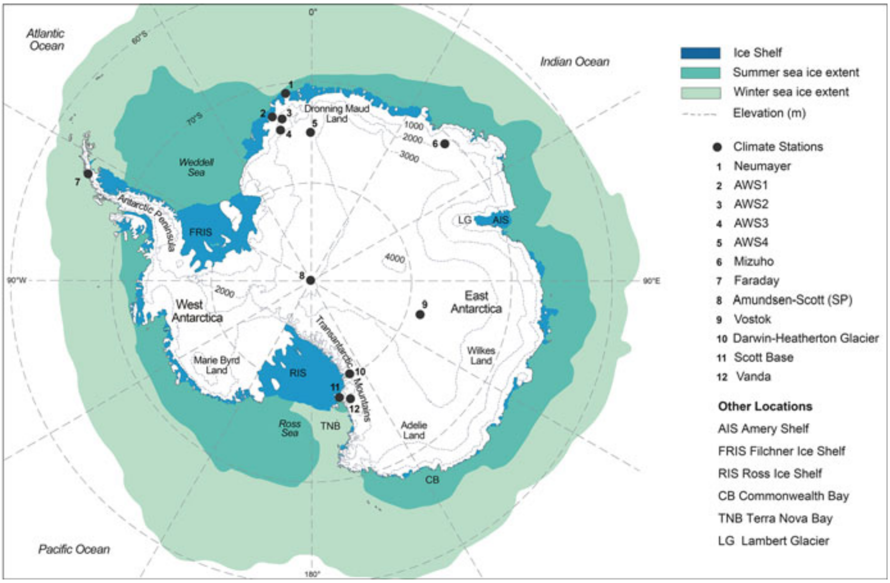



**Fig. 6.1** This map shows Antarctica's topography. Average sea ice extent and locations are referred to in the text (© Ian Owens and Peyman Zawar-Reza)

gravity-driven winds. Snow covers almost the entire continent, with only 0.3 % of rock (Frezzotti 2007) and 2 % of blue ice (van den Broeke et al. 2006) exposed. These surface characteristics affect the amount of the sun's radiation that is reflected back to the atmosphere, which in turn influences temperature and wind patterns. In addition, the surface area of snow and ice doubles seasonally due to the formation and melting of sea ice (Fig. 6.1), resulting in a marked seasonality in the reflection of the sun's radiation above the Southern Ocean.

The remoteness of Antarctica, along with its inhospitable environment, makes gathering weather and climate data challenging. Little more than a dozen climate stations have operated since the International Geophysical Year in 1957, and all but two, Vostok and Amundsen-Scott, are coastal stations (Box 6.1). Since the 1970s, the situation has improved markedly and there are now over 130 weather stations operated by at least 13 countries (listed on the University of Wisconsin-Madison's automatic weather station website). There are probably many more weather stations associated with specific research projects, but nevertheless their total distribution is sparse. Apart from land-based weather stations, considerable advances in remote sensing techniques have been made, and measurements of the upper atmosphere occur on a regular basis using weather balloons in a few locations (Chap. 8).

**Box 6.1: Automatic Weather Stations (AWSs)**
A weather station contains instruments that measure some of the most important weather related parameters, such as wind speed and direction, temperature, relative humidity, pressure and solar radiation. Generally, most weather stations have been automated recently, which means that the data are either logged on a local device for downloading manually or telemetered via satellite links. AWSs need to be maintained, especially in the harsh conditions of Antarctica and often dug out of snow. In Antarctica, temporarily installed AWSs also provide data for specific field campaigns, but the short duration of data makes them unsuitable for long-term climate analysis. AWS data is often freely available for anyone interested in researching Antarctic's weather and climate.

## 6.2 General Circulation of the Atmosphere

The low temperature of Antarctica means that it is a heat sink (a large absorber of heat) compared to the tropics, which are a heat source. Redistribution of heat energy in the atmosphere is influenced by Earth's rotation, which produces the Coriolis force. As air moves to transport heat horizontally from areas of high atmospheric pressure (colder air) to areas of low atmospheric pressure (warmer air) across the globe, the Coriolis force influences wind direction so that air does not flow directly from high to low pressure (Fig. 6.2). Wind direction is also influenced by the position of oceans and continents, which may block or channel the wind, and may also cause moisture levels in the air to increase or decrease. This general circulation of the atmosphere results in air rising near the equator and producing heavy precipitation. At latitudes of 30° North and South (approximately), where the world's hot deserts are found, air is sinking, and drying as it does so (Box 6.2). At mid-latitudes, the Coriolis force helps produce strong westerly winds (flowing from west to east and shown by closely spaced isobars), unimpeded by land, giving rise to the regions known as the Roaring Forties and Furious Fifties (Fig. 6.2).

General circulation results in two important features of Antarctic weather. Firstly, just to the north of Antarctica, between 60°S and 65°S, there is a zone of rising air and low pressure with embedded cyclonic weather systems called the circumpolar trough (Fig. 6.2). Here winds are westerly, and regular storms bring warm moist air from the middle latitudes towards the continent. Secondly, an area of sinking air and high pressure occurs over central East Antarctica resulting in airflows from south to north (southerlies) that are influenced by cold air drainage processes (see katabatic wind below). The Coriolis force deflects this airflow to create a narrow zone of easterlies near the edge of the continent.

Antarctic climate can be broadly broken into two regimes: continental plateau (high and low elevation), and maritime (low elevations near the coast and Antarctic Peninsula). The proximity to the Southern Ocean and low elevation typically

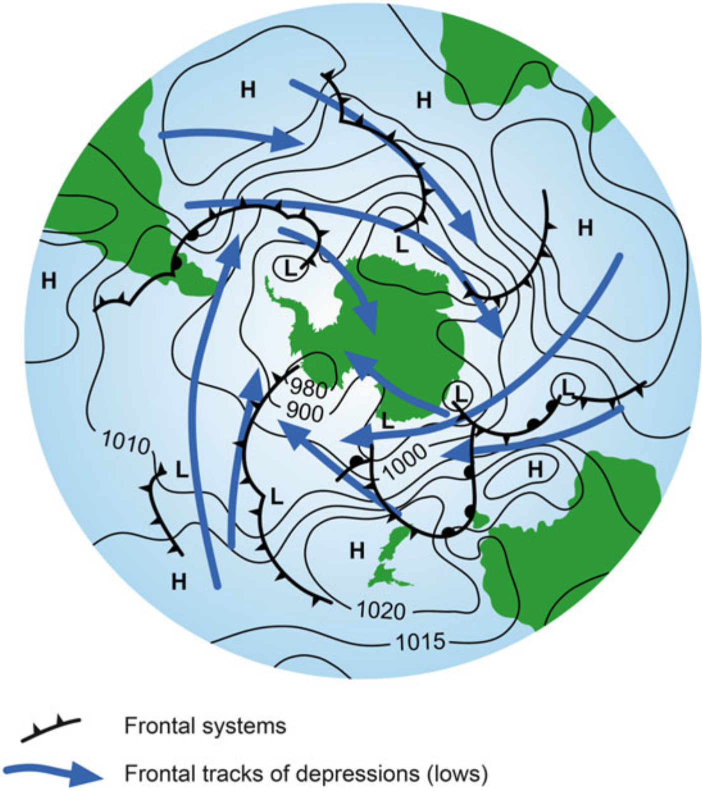



**Fig. 6.2** This weather map shows characteristics of the general circulation around and to the north of Antarctica. The location of the circumpolar trough is indicated by the presence of low pressure systems near the edge of Antarctica (Adapted from Reader's Digest 1985)

support the maritime type environment where the weather produced by the westerly belt brings relatively moist warm air into the region. The continental zones have much harsher temperatures and are drier with very little precipitation of any form.

**Box 6.2: Ascending and Descending Air**

When a parcel of air is forced to rise, it encounters lower pressure and expands. This expansion causes the parcel to cool down. If there is enough moisture in the air parcel, it will start condensing because of the lower temperature possibly resulting in cloud formation and precipitation. Low pressure systems or cyclones cause large scale upward motion of the atmosphere, which is why they are often associated with poor weather. On the other hand, if a parcel of air is forced to go down in the atmosphere, it will encounter higher pressures and compress. Compression causes warming of

(continued)

**Box 6.2** (continued)
the parcel, so if there were any clouds, they will evaporate. High pressure systems or anti-cyclones therefore characterise fair settled weather.

A parcel of air can be forced to rise or fall if forced by a barrier, such as a mountain range. If air descends down the slope, compression will increase its temperature, which is why Föhn winds (winds in the lee of topographic barriers) are relatively warm. This mechanism has been suggested as a possible contributing factor to the warming of the Larsen Ice Shelf region. When the katabatic wind drops into the McMurdo Dry Valleys from the Polar Plateau, the same compression heating can increase its temperature.

## 6.3 The Coldest Continent

The extreme cold near the surface of Antarctica is a result of the energy transfers described in Box 6.3 and discussed in more detail in this section.

### *6.3.1 Radiation*

Radiation plays a major role in surface energy transfers at the surface of Antarctica and is strongly influenced by the continent's polar location and surface characteristics.

**Box 6.3: Heat Transfer and the Greenhouse Effect**
There are three main ways to transfer heat energy: radiation, convection and conduction, and of these radiation is the most important for Antarctic weather. When studying weather and climate, two main types of radiation are identified on the basis of wavelength; short wave and long wave.

The hotter the radiating body, the shorter the wavelength. The sun (at more than 5700 °C) emits shortwave radiation (including the UV rays that people protect themselves against with sunscreen), while Earth (between about −3 and 27 °C) emits longwave radiation (the infrared that is detected by night vision glasses).

An atmosphere with no clouds is reasonably transparent to shortwave radiation and a portion of radiation that reaches Earth's surface is reflected back into space. The reflectivity of the surface is known as the albedo and is the ratio of reflected over incoming shortwave radiation. The shortwave radiation that is absorbed at the surface but not reflected increases the temperature of the surface, which then influences the amount of longwave

(continued)

**Box 6.3** (continued)
radiation emitted from the surface into the atmosphere. The atmosphere, particularly when cloudy, absorbs and re-emits longwave radiation back to Earth and plays a crucial role in determining the atmospheric temperature near Earth's surface. This phenomenon is known as the greenhouse effect and without it the Earth would be much colder (by more than 30 °C on average) and would be an ice planet.

The total of all of these radiation transfers at Earth's surface is the net radiation. The net radiation is available for redistribution to or from the atmosphere by convective or turbulent transfer, and to or from the ground surface by conduction.

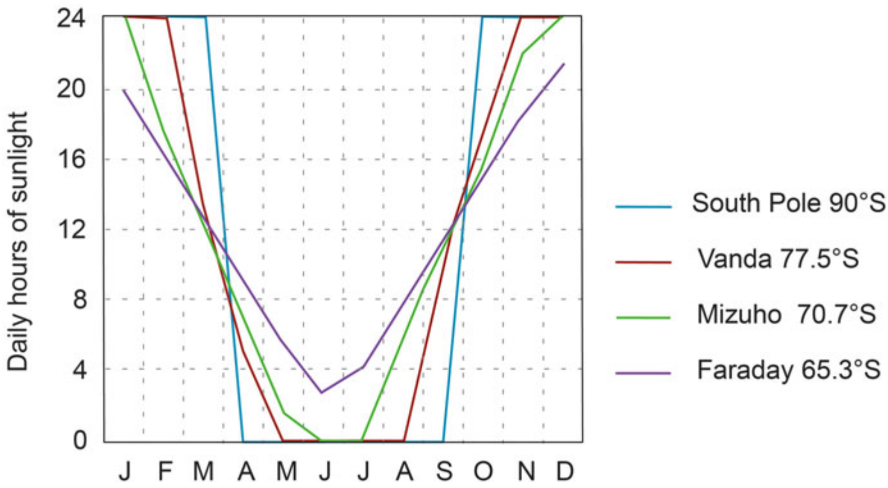



**Fig. 6.3** Monthly variation of hours of sunlight at selected Antarctic stations (© Ian Owens and Peyman Zawar-Reza)

Earth's axis of rotation is tilted at 23.5° to the plane of its orbit around the sun, causing extreme seasonal variation in the duration and intensity of shortwave radiation in polar latitudes. At the South Pole there are almost 6 months of 24-h sunlight in summer and 6 months of 24-h darkness in winter (Fig. 6.3). These periods of sunlight and darkness decrease to the north such that beyond the Antarctic circle (66.5°S), for example at Faraday Station (now called Vernadsky Station), no periods of 24-h sunlight or darkness occur.

The maximum angle of the sun above the horizon at noon (the maximum solar elevation angle) for each month shows that at the South Pole, the sun is never more than 23° above the horizon (Fig. 6.4). Further north, the elevation angles are higher but even at Faraday, the summer elevation angle is still less than 50°. This slanting sunlight reduces the solar radiation intensity on a horizontal surface because the

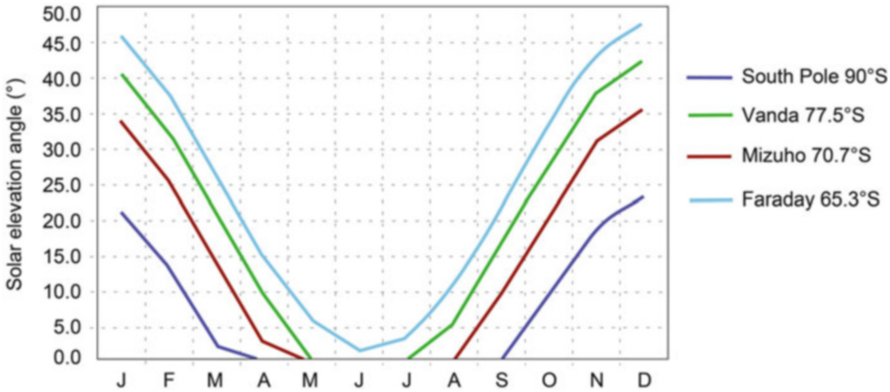



**Fig. 6.4** Monthly variation of the solar elevation angle at noon for selected Antarctic stations (© Ian Owens and Peyman Zawar-Reza)

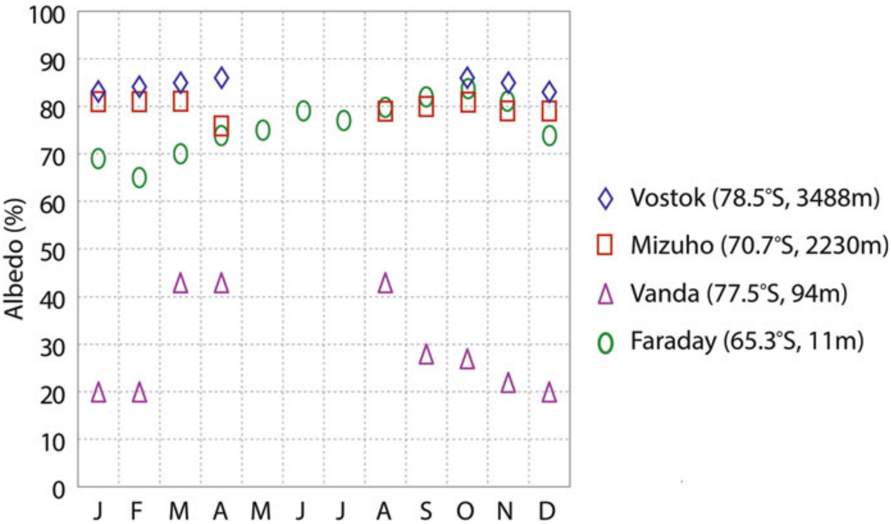



**Fig. 6.5** Variation of albedo at Antarctic stations (Adapted from King and Turner 1997; Schmidt and König-Langlo 1994)

sun's rays are spread over a larger area than they are at lower latitudes. This solar geometry is the primary reason Antarctica (and also the Arctic) acts as a heat sink.

Despite the low solar elevation angles, the long sunlight hours mean that solar radiation on a horizontal surface at the top of the atmosphere in mid-summer over Antarctica is greater than that at the equator. However, the low angle means that sunlight takes a longer path through the atmosphere, providing more opportunity for reflection and absorption. In addition, as most of the continent, and the seasonally occurring sea ice, is snow covered, much of the solar radiation is reflected back into the atmosphere due to the high albedo (Chap. 4). Albedo varies with location and season (Fig. 6.5). It is highest when large areas are covered in snow and ice, with snow having the highest albedo (the most reflective) followed by ice, rock and the ocean (which is the most absorbent) (Table 6.1).

The greatest amount of incoming shortwave radiation is at the high elevation stations of Vostok and Mizuho (Fig. 6.6). At these elevations the atmosphere above is thinner, so more solar radiation passes through (the atmosphere can filter some solar radiation), and these regions are also less cloudy because of the high pressure system. All stations experience negative longwave (L*) radiation throughout the year. Net radiation (Q*) is negative from March to October for most stations and for longer periods for the plateau stations Vostok and Mizuho. Except for Vanda station, which is representative of the small area of ice-free land, the annual totals of net radiation are negative which is why the continent as a whole is a heat sink.

**Table 6.1** Albedo of different surface types

| Surface type | Albedo (α) | |
|---|---|---|
| Ocean | 0.02–0.20 | Least reflective |
| Rock | 0.10–0.40 | |
| Blue ice areas | 0.56–0.7 | |
| Snow | 0.50–0.959 | Most reflective |

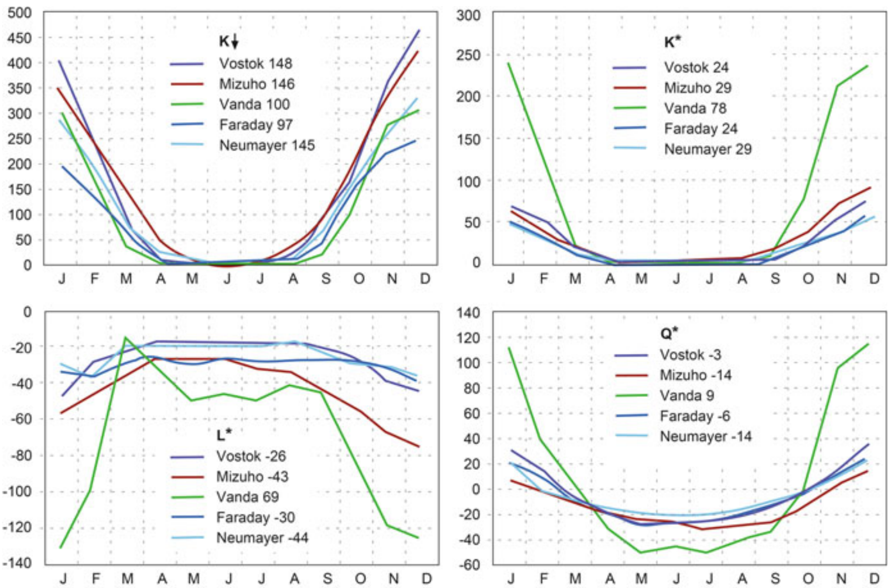



**Fig. 6.6** Monthly variation and annual totals of radiation fluxes for selected Antarctic stations. K↓ is solar radiation received by the ground, K* is the amount of solar radiation that is absorbed by the ground after reflection is considered. L* is the total amount of thermal radiation available at the surface. Q* is the difference between K* and L* and is known as the net radiation (Adapted from Schwertdfeger 1984; Schmidt and König-Langlo 1994)

### 6.3.2 *The Surface Energy Balance*

Because the annual totals of net radiation at the surface of the continent as a whole are negative, other transfers are required to achieve the surface energy balance. If this does not occur on a year-to-year time scale, the surface would either continue to heat up or cool down. As with radiation transfers, the other fluxes in the energy balance are substantially smaller than the same processes elsewhere in the world.

### 6.3.3 *Turbulent Transfer*

At individual sites, the most significant turbulent transfer is sensible heat exchange which is a mirror image of the mainly negative radiation exchange at the surface (Fig. 6.7). This exchange is most pronounced in areas of strong katabatic winds which are discussed in more detail in Sect. 6.4.3. The lower atmosphere over most of the Antarctic continent is characterised by a surface inversion (an increase of temperature with height), and this means that turbulent transfers from the surface to the atmosphere and vice versa are inhibited. Strong winds promote mixing and overcome this effect. In winter there is significant downward transfer of heat from the relatively warm atmosphere to the cold surface. Latent heat transfers (Box 6.4) are near zero for most of the year and play a minor role in determining surface temperature. However, they are significant in the short summer season when some radiation is available for sublimation (the direct transition from snow to water vapour) which is the cold climate version of evaporation and which thus plays a role in net snow accumulation (see Sect. 6.5). In addition, at low elevations near the continent edge, where temperatures in summer are at or above freezing, surface melt may occur.

**Box 6.4: Latent Heat and Sensible Heat**

Heat that causes a change in temperature in a substance is called sensible heat. For example, when water is heated, its temperature rises until it reaches boiling point. This increase in temperature is due to sensible heat. The heat removed from the water as its temperature falls to freezing point is also sensible heat.

The heat absorbed or released as the result of a phase change is called latent heat. There is no change in temperature of the substance because all energy is used for the phase change rather than to increase temperature. For example, once the boiling point of water has been reached, the temperature remains at 100 °C until all the water has turned to vapour, regardless of how much heat is added to the water (how vigorously it boils). Latent heat is required for all phase changes such as from ice to water during melting, ice to water vapour during sublimation, and water to ice during freezing. As air rises, for example over the Southern Ocean, water vapour begins to condense and form clouds. As this vapour freezes and turns into ice, it releases latent heat, which adds to the energy of a storm.

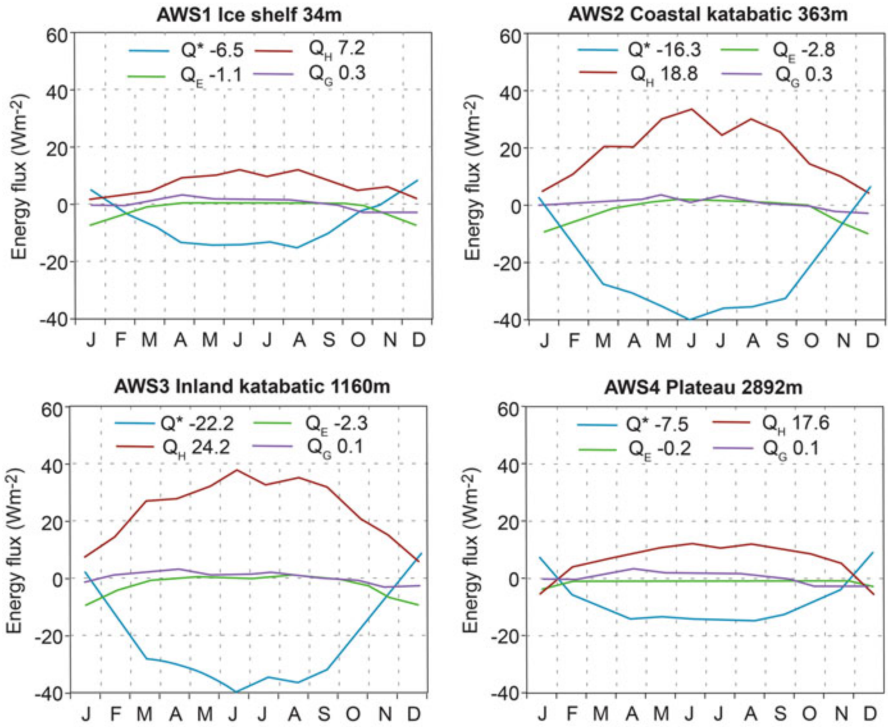



**Fig. 6.7** Surface energy fluxes on a transect across climatic zones in Dronning Maud Land showing the effect of katabatic winds on turbulent transfer magnitude. Q* is the net radiation, $Q_H$, sensible heat flux, $Q_E$ latent heat flux and $Q_G$ subsurface heat flux. Note that the vertical scales are identical to allow comparison between sites (Adapted from van den Broeke et al. 2005)

At a broader scale heat loss is balanced by warm air being transported from northerly regions at upper atmospheric levels, as high pressure over central Antarctica causes air to sink and flow outwards near the surface, forming a circulatory cell. In addition to this general circulation pattern, the wind movement cyclonic systems around the continent results in horizontal transfer of heat (advection). Warm moist air is moved towards the pole on their forward side, and cold dry air towards the equator behind the cold fronts (Box 6.5). Turbulence is an effective process for distributing sensible heat and latent heat.

**Box 6.5: Atmospheric Stability, Clouds and Temperature Inversions**

For most parts of the Earth, for most of the time, air temperature in the lowest part of the atmosphere decreases with height above the surface. When this change of temperature with elevation is rapid, the lower atmosphere is said to be unstable and vertical movement of parcels of air is enhanced, often leading to cloud formation and precipitation. Where the change of temperature with elevation

(continued)

**Box 6.5** (continued)
above the surface is not very fast, the atmosphere is said to be stable and vertical air movement is dampened. There is a lack of surface heating in Antarctica, so the atmosphere is usually stable and vertical air movement is suppressed. Consequently, cloud types related to vertical movement (i.e. cumulus type clouds) are relatively uncommon in Antarctica except where vertical air uplift occurs at fronts, and layer-type clouds are most common.

Although a decrease of temperature with elevation above the surface is the rule, exceptions to this occur. These conditions invert the normal change of temperature with elevation, and are referred to as temperature inversions. In Antarctica, the temperature inversions are much stronger than those at mid latitudes, particularly during the Southern Hemisphere winter and at high elevations on the East Antarctic Plateau. Figure 6.8 shows that in winter, the strength of temperature inversions averages 25 °C over large areas of the Polar Plateau and generally decreases towards the coast.

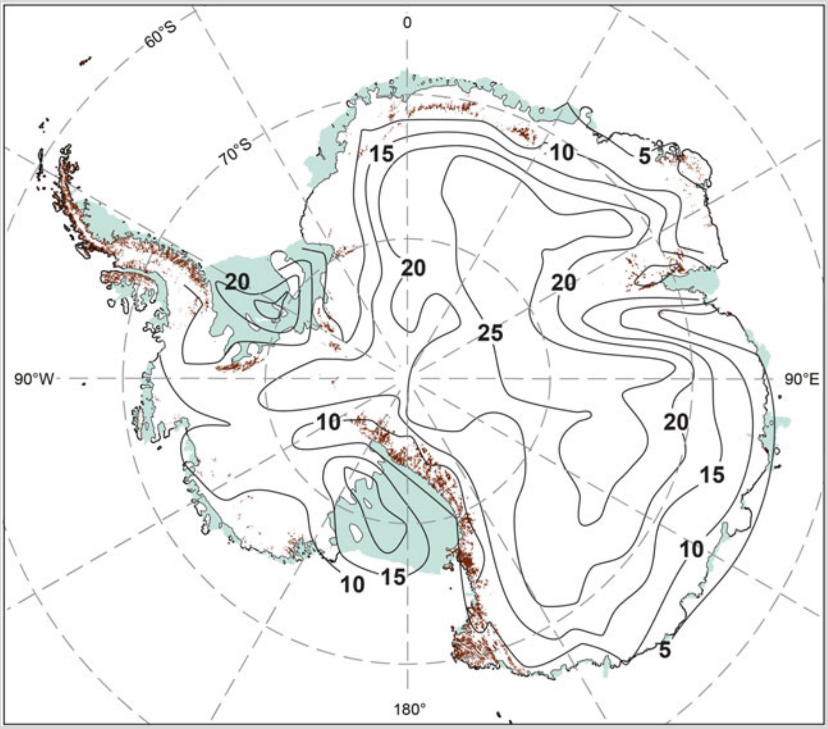



**Fig. 6.8** Average inversion strength over Antarctica in July (Adapted from Connolley 1996, with kind permission from Wiley)

### *6.3.4 Conduction*

Conduction plays a minor role in heat transfer at the surface and is close to zero throughout the year.

### *6.3.5 Effects of Elevation*

Elevation influences temperatures in Antarctica in two main ways. Firstly, similar to other locations on Earth, temperature decreases with elevation as a result of decreasing pressure, which leads to very low temperatures on the high Polar Plateau (Fig. 6.9). Secondly, low elevations near the continent's edge are strongly influenced by horizontal movement of heat (advection) by cyclonic systems.

The cyclonic systems embedded in the low pressure zone immediately north of the continent edge travel from west to east. Their influence on temperature at higher inland elevations is limited because the latitudes around 70°S are a cyclone 'graveyard' as cyclones lose energy and do not penetrate further towards the pole (Simmonds and Keay 2000).

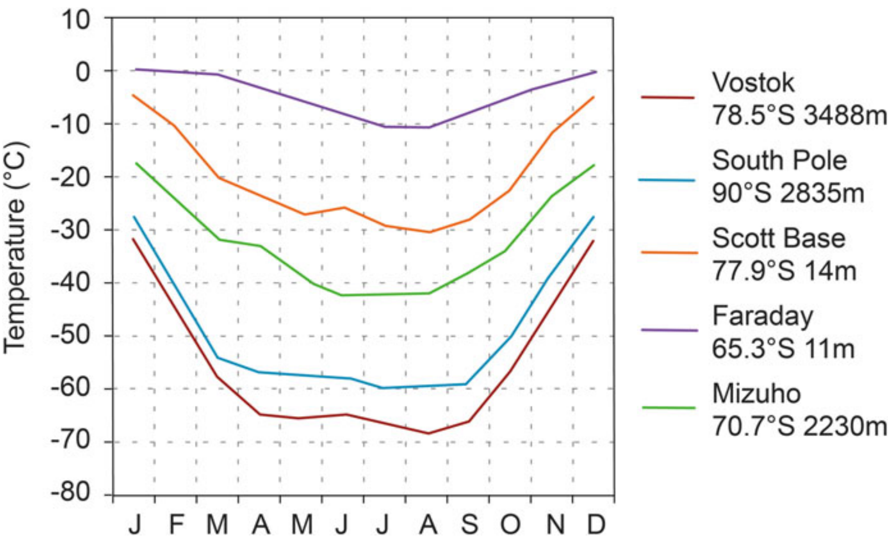



**Fig. 6.9** Annual temperature regimes for selected Antarctic stations, showing the effect of elevation and the coreless winter and short peaked summer temperatures except for Faraday on the Antarctic Peninsula. The graph also depicts the effect of latitude (e.g. Scott Base compared to Faraday) and elevation (e.g. Vostok compared to South Pole) (Based on data obtained from the READER project available at http://www.antarctica.ac.uk/met/READER/)

### 6.3.6 Annual Temperature Regime

Most parts of the world exhibit a sinusoidal annual temperature curve (i.e. a sideways S-shape) with a clear minimum in the coldest month. This temperature pattern does not apply near the equator, or in Antarctica. Near the equator there is almost no difference in temperature across the seasons. In Antarctica, the annual change in temperature (Fig. 6.9) reveals a phenomenon known as the 'kernlose' or coreless winter at all stations except Faraday (now called Vernadsky Station), which is relatively far north on the Antarctic Peninsula. In most parts of Antarctica, temperatures reach their lowest value in April, stay more or less constant, and then rise rapidly from September onwards. There is no clear minimum marking the coldest month. The coreless winter is particularly marked on the East Antarctic plateau because the significant negative net radiation in the winter months is balanced by downward sensible heat transfer, and latent and ground energy transfers are minimal (Fig. 6.7). It has also been suggested that the longwave radiation emitted by Earth at such cold temperatures shifts to longer wavelengths which are more easily absorbed by the atmosphere. Therefore the temperature loss at the Polar Plateau decreases (Bromwich and Parrish 1998). During summer there is a rapid increase before the summer peak temperature, followed by a decrease afterwards, resulting in a short, peaked summer period. It is likely that the rapid decrease of temperature at the end of summer played a role in the demise of Scott's polar expedition (Solomon and Stearns 1999).

### 6.3.7 Distribution of Temperature Across Antarctica

There is a distinct temperature distribution pattern across summer and winter in Antarctica (Fig. 6.10). In winter, a significant portion of the East Antarctic plateau has a monthly temperature of less than −50 °C, and even in summer much of this area is below −30 °C. In summer, there is a rapid increase of temperatures towards the continental margins (shown by closely spaced isotherms), the main feature being the position of the 0 °C isotherm, which is close to the edge of the continent in East Antarctica but further offshore in the Weddell and Ross Sea areas. This occurs because relatively warm air moves across the ocean. The ocean temperature varies little because it has a high heat capacity, i.e. large amounts of energy are required to change its temperature, and because mixing distributes any temperature changes. In winter and well into spring, however, sea ice extends well north of the continent's edge which negates the atmospheric warming influence of the thermally conservative ocean. Consequently, there is a much more even change of temperature to the north with temperatures at the continent edge about −20 °C while the 0 °C isotherm is well north at about 60°S latitude.

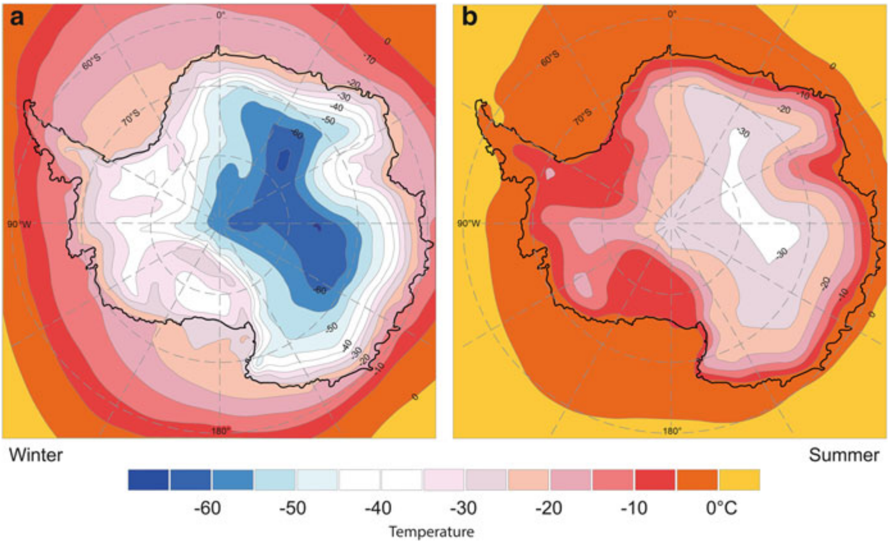



**Fig. 6.10** Distribution of mean monthly temperature for (**a**) winter and (**b**) summer. The stippled area depicts the extent of sea ice for each period (Adapted from Dudeney 1987, with kind permission from Cambridge University Press)

## 6.4 The Windiest Continent

### *6.4.1 Surface Winds in Antarctica*

Although the entire atmosphere can be 1000 km thick, most of its mass resides within the first 8 km above the ground (Chap. 7). The surface winds are intimately connected to the winds that blow some distance above the ground. This interaction can be very complex and is still under intense research. In this chapter we will only look at the winds just immediately above the ground since they are of far greater importance for operational safety and have an immediate impact on life in the continent.

### *6.4.2 Scales of Atmospheric Motion*

Weather forecasting, particularly of intense wind storms, has been a major challenge. Several countries invest heavily into research that can lead to better forecasts, and although Antarctica presents its own unique challenges, and the weather forecasts are not as reliable as those in other parts of the globe, the forecasts have improved dramatically.

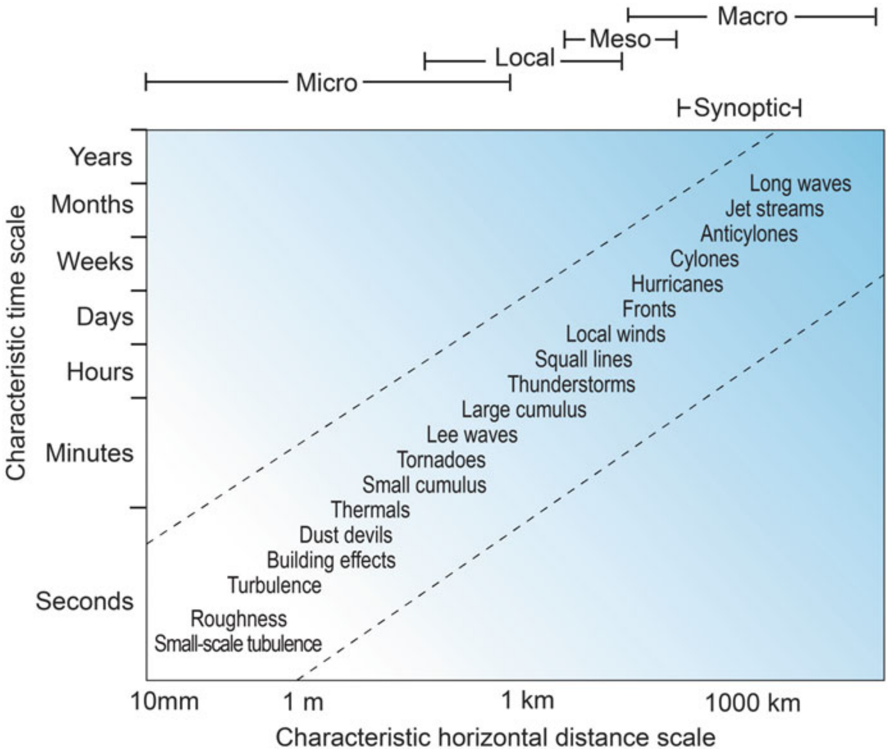



**Fig. 6.11** Scales of atmospheric motion (Adapted from Oke 1987)

The weather experienced at any location can be either generated by local conditions or be part of a much wider continental-scale pattern. Both need to be understood for accurate forecasting (Box 6.6). Meteorologists typically break down atmospheric motions into micro, meso or macro scales. Figure 6.11 illustrates such a classification, whereby well known phenomena are matched with their typical size and lifespan.

The type of cyclone (or low pressure system) we usually associate with rainy and stormy weather (snowy if it is cold) is typically a macro-cyclone. These last for more than a day and influence large areas, often several thousand kilometres wide. Cold and warm fronts are embedded in such systems and form clear lines (fronts) where the majority of weather activity is concentrated.

Satellites recently discovered that polar regions can also produce low pressure systems (cyclones) that are much smaller and compact. They fall into the meso-category. Meso-cyclones are typically less than 1000 km wide and frequently affect the margin of the continent. Their small size means that they remain below detection levels for conventional ground-based methods and can therefore only be studied on satellite images. These systems are generally not as intense and destructive as the polar lows of the Northern Hemisphere, but they can still complicate logistical operations. Lifetimes of about 12 h and wind speeds of about 10 $ms^{-1}$ have been reported for some of the smaller meso-cyclones, but greater intensities can occur. Meso-cyclones also increase the exchange of momentum and heat between polar and subpolar regions but they do not usually intrude into the interior of the continent; instead they contribute significant precipitation to the continental margins.

**Box 6.6: Weather and Logistical Operations at McMurdo Station and Scott Base**

Severe weather presents one of the gravest hazards to operations in Antarctica. Providing better forecasts is an important lifeline for flight operations, but it remains an ongoing challenge in a place where sparse weather measurements on the ground hamper understanding storm behaviour. Satellite monitoring and computer-based weather models are increasingly helpful in this regard. Intense winds are associated with turbulence and low visibility (blowing snow) which can prevent landing and take-off from the ice-based runways. If the storm is severe enough, McMurdo Station and Scott Base may shut down (when visibility becomes less than 31 m, or wind chill temperatures become colder than −73 °C, or winds exceed 28 m/s).

### *6.4.3 Katabatic Winds*

Radiative cooling of the air directly above the Antarctic ice sheet produces very cold, dense (heavy) air that flows downhill, away from elevated areas to the coastal regions (Fig. 6.12). The resulting katabatic (gravity driven) winds accelerate, enhanced by the confines of valley walls, and blow with great consistency over their area. Once at the coast, there is little change in elevation and the winds lose their driving force, dissipating offshore at some distance depending on how fast they are. Weaker katabatic events propagate on the flat surface of the ocean or the ice shelves for much shorter distances than their stronger counterparts.

The air that replaces that which is moved by the katabatic wind comes from aloft, as air transported from the tropics at altitude flows towards the edge of the continent, making the influence of Antarctica really far reaching. There is no analogue for such a system in the Northern Hemisphere since the topography is largely flat over the polar region.

Near the Antarctic coast, low pressure systems can interact with katabatic winds to increase their strength. Resulting wind speeds can exceed 100 km/h for days at a time, and gusts can be well over 200 km/h. Conversely, katabatic winds can force the creation of low pressure systems (cyclogenesis), particularly in the Ross Sea Region (Carrasco and Bromwich 1993). Even though cyclones and katabatic winds are produced by different mechanisms, they still influence each other in a way that makes prediction of weather in Antarctica very challenging.

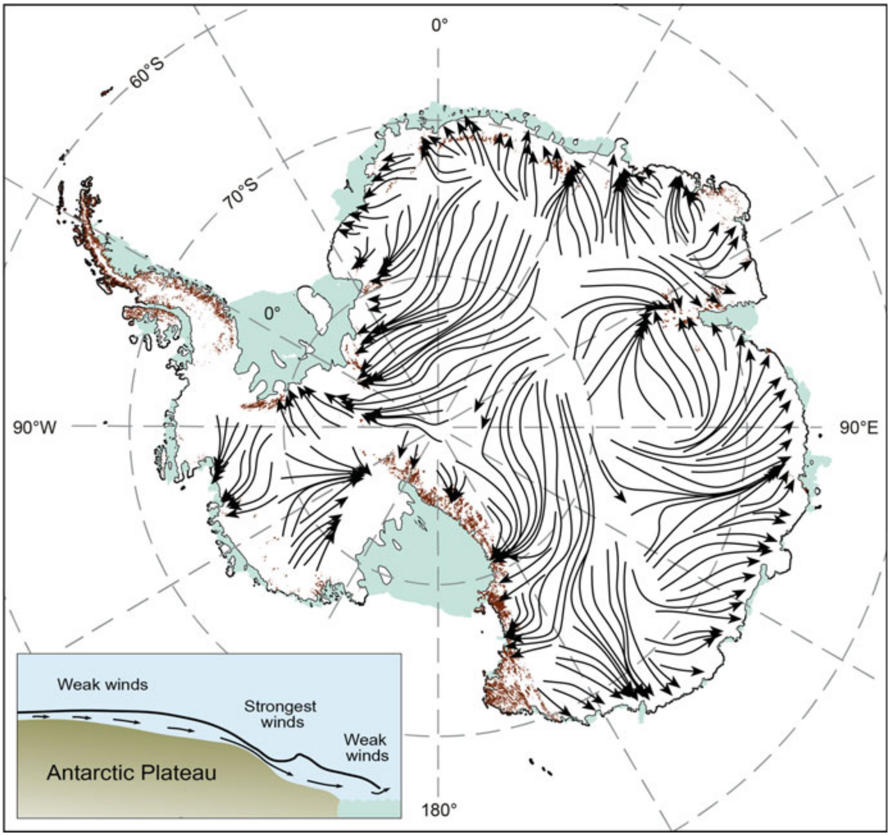



**Fig. 6.12** Katabatic winds in Antarctica showing drainage from high points (mainly on the East Antarctic Plateau). Wind flow streamlines are shown by arrows which are approximately perpendicular to the contours. Channelling occurs in valleys where streamlines combine to form zones of very high winds such as Terra Nova Bay, the Lambert Glacier valley and Commonwealth Bay which the Australian explorer Mawson called 'home of the blizzard'. The inset shows a cross section from gentle slopes on the Antarctic plateau to steeper slopes near the continent edge (Adapted from Bromwich and Parish 1998, with kind permission from the American Meteorological Society)

Katabatic conditions in general are warmer than non-katabatic conditions, but the level of warming depends on the season. For example during the summer in the McMurdo Dry Valleys, the smallest difference in average monthly values (average temperatures during katabatic winds minus temperatures during non-katabatic conditions) occurs in summer (4 °C) (Nylen et al. 2004).

Turbulent mixing results in downward transport of warm air during katabatic conditions so that the lowest layer of a katabatic current can be detected as a warm signature by remote sensing studies. This technique can be used to show that once katabatic winds flow out onto the Ross Ice Shelf, they can propagate for hundreds of kilometres on the ice shelf and over the sea.

Katabatic intensity is weaker during the summer period, from December to February, over nearly the entire continent because the surface warms due to solar radiation. Smaller-scale katabatic winds, similar to those occurring almost anywhere else in the world where the terrain is sloped, have been detected over glaciers in the McMurdo Dry Valleys. However, these localised katabatic winds are less intense and cover a much smaller geographical area because the source of cold air is from a much more limited region (Obleitner 1994; Nylen et al. 2004).

### 6.4.4 Anabatic Winds and Sea Breezes

Anabatic winds flow upslope. In some of the valley systems in the McMurdo Dry Valleys, where most of the surface is not covered by snow and ice, these are the most common winds in summer, flowing from the Ross Ice Shelf towards the interior. Formation is partly due to the influence of the sea which produces a sea breeze circulation. Sea breezes form when temperature differences between the warm land and cold water create a pressure difference which forces higher pressure, cooler air from the sea to move inland.

The adjacent terrain, especially if it is covered by a glacier, can generate its own small-scale katabatic. Weather stations on the Commonwealth and Canada glaciers in the Taylor Valley have registered glacier-induced katabatic winds in summer. Stations on the Darwin-Hatherton Glacier show a prominence of small-scale katabatic winds when the sun is close to the horizon and the surface heating is minimal. The katabatic winds can push the anabatic winds back, producing a bimodal wind pattern (Nylen et al. 2004). Figure 6.13 provides examples from three weather stations placed approximately 20 km apart in a triangular formation over the Darwin-Hatherton Glacial System in the Transantarctic Mountains. Two of the stations clearly show that when the solar radiation is weak (early mornings and late afternoons), the flow tends to be down the slope, either large-scale or local-scale katabatic. But the tendency is for the flow to be up the slope (anabatic) when the sun has had a chance to warm the surface. At the third station, the bimodality is not as clear. This may be due to the fact that this station is at a higher elevation. This illustrates that the strong katabatic flow is not the only type of circulation pattern and that a variety of weather types is possible over this mostly ice-covered landmass.

### 6.4.5 Barrier Winds

Barrier winds are jets of rapidly moving air produced when cold air piles up against steep topography. They flow parallel to the topographic barrier. Such conditions can exist over the Ross Ice Shelf and Antarctic Peninsula, but they have also been observed in other cold-climate regions with significant topography, such as

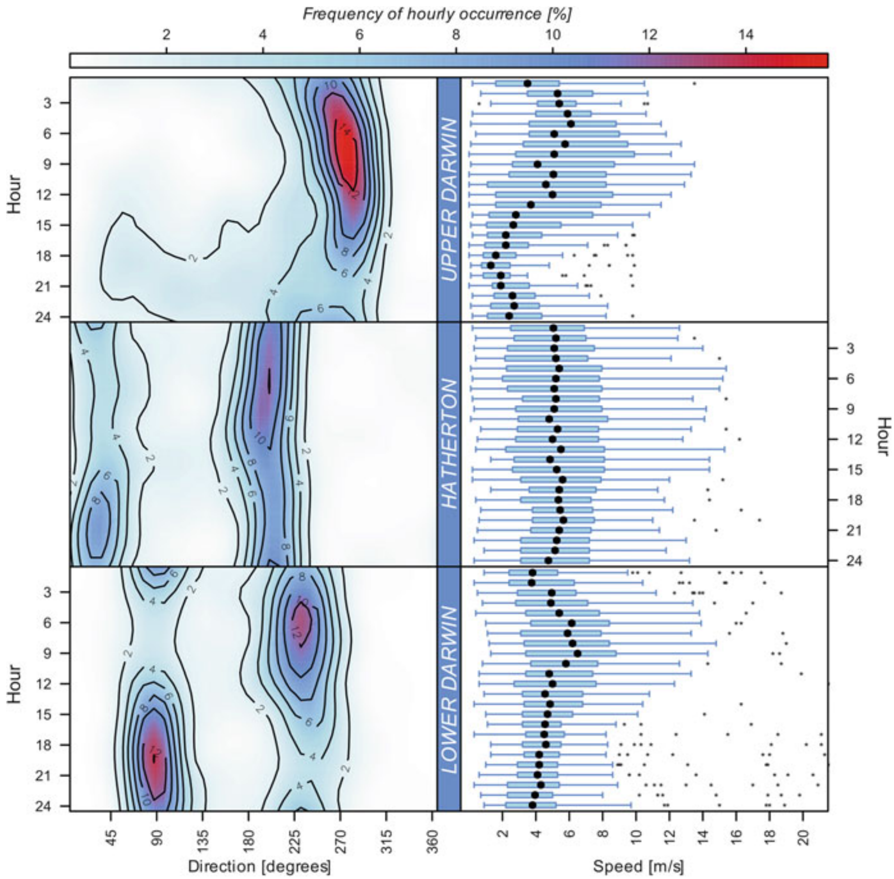



**Fig. 6.13** Summertime frequency distribution of hourly wind direction (*left panel*) and statistics of hourly wind speed. The box-and-whisker plots are for median, first and third quartile; the 1.5 quartile distance is indicated by the bar. The katabatic blows from the north-west quadrant at *Upper* Darwin, and more westerly quadrants at *Lower* Darwin and Hatherton (Reprinted from Zawar-Reza et al. 2010, with kind permission from Cambridge University Press)

Greenland. Forecasting barrier winds is important for operational reasons since their intensity can be problematic.

## 6.5 The Driest Continent

### *6.5.1 Precipitation*

Measuring precipitation in Antarctica is critical for determining the volume of ice and its role in global sea-level change. However, the density of climate stations with reasonably long records is low in Antarctica and standard rain gauges are not suitable for measuring snowfall in windy environments. Alternative methods have been developed for assessing the amount of precipitation based on glaciological and meteorological techniques and remote sensing, usually using satellites. For both of these methods, the precipitation accumulation is usually expressed in terms of depth of water equivalent (e.g. mm w.e.a$^{-1}$ for annual totals), and less commonly, as the weight per unit area of accumulation (kg m$^{-2}$). Very little falls as liquid precipitation except at the northern extent of the Antarctic Peninsula.

### *6.5.2 Glaciological and Satellite Methods*

The measurement of the depth and density of layers of snow allows the calculation of the water equivalent. This technique is usually applied to annual accumulation by using stakes as markers, or by using chemical and physical changes to identify annual layers in snow pits, in a similar manner to identifying layers in ice cores (Chap. 5).

Sublimation, which occurs during the relatively short summer period is significant enough to affect the record of accumulation (Fig. 6.14). The final measure is the net surface mass balance. The sampling is at rather irregular intervals so passive microwave remote sensing and ground-penetrating radar have been used to fill in the gaps. Since the early 1990s, satellite radar altimetry data have provided accumulation data for most of Antarctica (Zwally et al. 2005).

### *6.5.3 Meteorological Method*

With advances in computer technology and our understanding of the laws that govern the behaviour of the atmosphere, it is now possible to simulate weather and climate in Antarctica. The computer simulations can in most cases realistically generate data about such things as surface winds and precipitation, even if we do not have measured data at all locations. The use of computers allows precipitation to be approximated in places where it is difficult to obtain measurements, and the models can be verified with data from locations where measurements are available. Further improvements continue to be made through advances in computer technology and our understanding of how the atmosphere works (Fig. 6.15).

### *6.5.4 Distribution of Surface Accumulation*

Fortunately, the results of these two approaches to precipitation measurement agree in broad terms and show that the majority of the east Antarctic plateau receives less than 50 mm w.e.a$^{-1}$ while the areas of largest accumulation are concentrated near

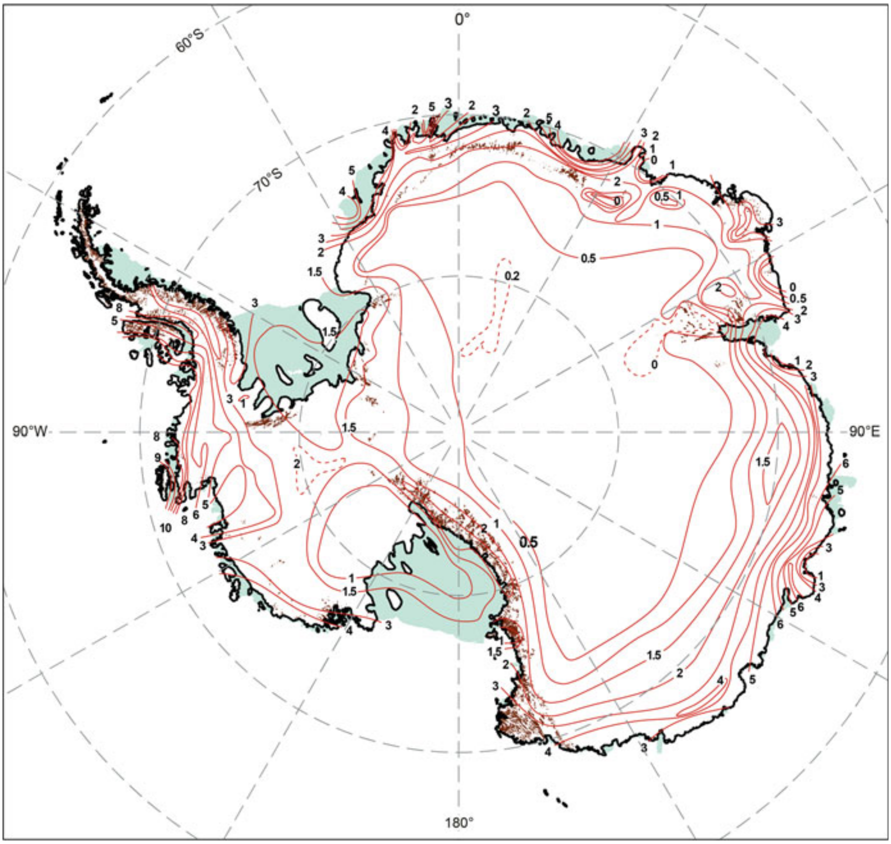



**Fig. 6.14** Snow accumulation in Antarctica in 100 mm w.e.a$^{-1}$ (Adapted from Giovinetto and Bentley 1985, with kind permission from the US National Science Foundation)

the coast especially on the Antarctic Peninsula and the coast of west Antarctica to the west of the peninsula. In a few small areas, for example the Lambert Glacier Valley (shown in grey on Fig. 6.15) and in the McMurdo dry valleys, where the Vanda station is located, accumulation is negative because the potential for sublimation exceeds the precipitation amount.

## 6.6 Conclusions

Antarctica's climate and weather are determined by its geographical location and its significant topography. Being positioned at the South Pole means that the amount of solar radiation and hence the heat the continent receives are much smaller than other regions of the planet. This is the primary reason the continent has a frigid climate and is covered by ice and snow, which subsequently cool the environment

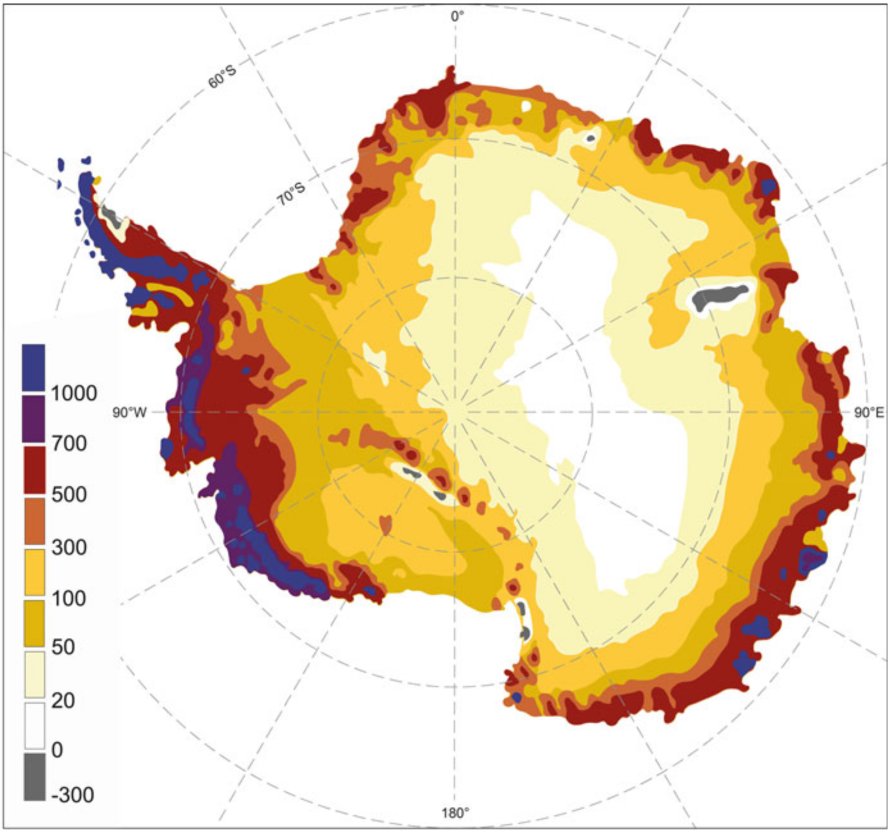



**Fig. 6.15** Modelled surface mass balance (mm w.e.a$^{-1}$) for Antarctica for the period 1958–2002 (Adapted from van de Berg et al. 2005, with kind permission from the International Glaciological Society)

even further by reflecting the solar radiation back into space. Most of the continent lies at high elevations, contributing further to the harshness of the climate, but the low temperatures in this case are because high altitude regions are typically colder due to the lower air pressure. As well as severe cold, the earth-sun geometry contributes to a distinctive coreless annual temperature regime while the seasonal expansion and contraction of sea ice produces distinctly different spatial distributions of temperature.

The sloping terrain provides a conduit for dense cold air to drain towards the coasts leading to the formation of katabatic winds. The katabatic winds funnel through topography and their intensity builds up near the coasts where the terrain becomes steep. Beyond Antarctica, the general weather patterns across the Southern Ocean are largely influenced by hemispheric temperature differences between the tropics and the South Pole, which create the wide band of westerly winds containing most of the weather-producing pressure systems (low and the high pressure systems, or cyclones and anti-cyclones). These weather systems often invade the coastal margins of Antarctica, bringing in relatively milder air masses and the associated precipitation. Therefore the lower coastal regions and the Antarctic Peninsula have a moderate maritime climate, whereas the continental dome has drier and colder air masses. As most of the continent experiences intense wind systems, measuring precipitation has remained a challenge, but remote sensing and computer modelling technologies have aided in providing a rough distribution of precipitation patterns. Precipitation tends to be far higher near the coasts and the Antarctic Peninsula, and generally relatively insignificant in East Antarctica.

## References

Bromwich DH, Parrish TR (1998) Meteorology of the Antarctic. In: Karoly DJ, Vincent DG (eds) Meteorology of the southern Hemisphere. American Meteorological Society, Washington, DC, pp 175–200

Carrasco JF, Bromwich DH (1993) Mesoscale cyclogenesis dynamics over the southwestern Ross Sea. Antarct J Geophys Res 98(D7):12973–12995

Connolley W (1996) The Antarctic temperature inversion. Int J Climatol 16(12):1333–1342

Dudeney JR (1987) The Antarctic climate today. In: Walton D (ed) Antarctic science. Cambridge University Press, Cambridge, pp 209–221

Frezzotti M (2007) Surface features. In: Riffenburgh B (ed) Encyclopedia of the Antarctic. Routledge, New York, pp 972–973

Giovinetto MB, Bentley CR (1985) Surface balance in ice drainage systems of Antarctica. Antarct J US 20:6–13

King JC, Turner J (1997) Antarctic meteorology and climatology, vol xi, Cambridge atmospheric and space science series. Cambridge University Press, Cambridge, p 409

Nylen TH, Fountain AG, Doran PT (2004) Climatology of katabatic winds in the McMurdo dry valleys, southern Victoria land, Antarctica. J Geophys Res 109. doi:10.1029/2003JD003937

Obleitner F (1994) Climatological features of glacier and valley winds at the Hintereisferner (Ötztal Alps, Austria). Theor Appl Climatol 49(4):225–239

Oke T (1987) Boundary layer climates, 2nd edn. Methuen, London

Reader's Digest (1985) Antarctica: great stories from the frozen continent. Reader's Digest Services, Sydney, p 319

Schmidt T, König-Langlo G (1994) Radiation measurements at the German Antarctic station Neumayer 1982–1992. Ber Polarforsch 146:66

Schwerdtfeger W (1984) Weather and climate of the Antarctic. Elsevier, Amsterdam, p 261

Simmonds I, Keay K (2000) Mean Southern Hemisphere extratropical cyclone behavior in the 40-year NCEP–NCAR reanalysis. J Clim 13:873–885

Solomon S, Stearns CR (1999) On the role of the weather in the deaths of R. F. Scott and his companions. Proc Natl Acad Sci 96:13012–13016

van de Berg WJ, van den Broeke MR, Reijmer CH, van Meijgaard E (2005) Characteristics of the Antarctic surface mass balance, 1958–2002, using a regional atmospheric climate model. Ann Glaciol 41:97–104

Van den Broeke M, Reijmer C, Van As D, Van de Wal R, Oerlemans J (2005) Seasonal cycles of Antarctic surface energy balance from automatic weather stations. Ann Glaciol 41(1):131–139

van den Broeke M, van de Berg WJ, van Meijgaard E, Reijmer C (2006) Identification of Antarctic ablation areas using a regional atmospheric climate model. J Geophys Res 111. doi:10.1029/2006JD007127

Zawar-Reza P, George S, Storey B, Lawson W (2010) Summertime boundary layer winds over the Darwin-Hatherton glacial system, Antarctica: observed features and numerical analysis. Antarct Sci 22(6):619–632

Zwally HJ, Giovinetto MB, Li J, Cornejo HG, Beckley MA, Brenner AC, Saba JL, Yi D (2005) Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise 1992–2002. J Glaciol 51:509–527

# Chapter 7
# The Southern Ocean

## Antarctica's Northern Boundary

**Michael J.M. Williams**

**Abstract** The Southern Ocean totally surrounds Antarctica and, with its cold waters and partial covering of sea ice, it is the maritime component of greater Antarctica. The range of water temperatures in the Southern Ocean is large. Near Antarctica, water can be colder than −2 °C, while at the ocean's northern limits temperatures can reach 10 °C or more. In contrast, there is a small change in salinity across the ocean, but the slight changes in temperature and salinity are enough to set up density gradients that, along with the wind, drive the Southern Ocean currents. The dominant current is the eastward flowing Antarctic Circumpolar Current, the world's largest current, but smaller westward flowing currents fringe the Antarctic continental shelf. Density gradients also drive vertical circulation where cold, salty, dense waters sink around the margins of Antarctica. This dense water then slowly flows north and is found globally at the bottom of the world's oceans. This process helps to establish the global ocean circulation that transports heat, moisture and dissolved compounds such as carbon dioxide and oxygen over thousands of kilometres. This chapter explores the significance of the Southern Ocean and its role in global ocean transport and circulation, as they contribute to the global climate system.

**Keywords** Southern Ocean • Ocean currents • Water masses • Fronts • Bottom water • Heat transfer • Gas transfer

## 7.1 Water Transport in the Southern Ocean

Distinct bodies of water, and the dissolved gases and nutrients they contain, are transported huge distances through the Southern Ocean by currents. This transport influences living conditions for marine life and the world's climate through the exchange of heat, moisture and chemicals between the ocean and the atmosphere. Currents flow in complex patterns primarily driven by wind, the water's salinity and

M.J.M. Williams (✉)
National Institute of Water and Atmospheric Research Ltd, Wellington, New Zealand
e-mail: Mike.Williams@niwa.co.nz



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_7

temperature, and are also influenced and steered by seafloor topography and the Earth's rotation (Talley et al. 2011). This leads to water redistribution around the globe.

## *7.1.1 Drivers of Ocean Currents*

### 7.1.1.1 Wind

There is a balance between wind, the Coriolis force (caused by the Earth's rotation, Box 7.1) and friction between layers in the ocean. These three forces are in balance in the upper layer of the ocean known as the Ekman Layer and result in a current over the top 100 m or so of the ocean that flows 90° to the left of the wind in the Southern Hemisphere. Ocean currents and winds have different naming conventions, with currents named for the direction they are going, and winds for the direction they are coming from, which means that a westerly wind and an easterly current are going in the same direction (from west to east). With a westerly wind, as is common in the Southern Ocean (coming from the west and going to the east), the current in the Ekman Layer is to the north. Close to Antarctica winds from the continent are easterly, driving southward surface currents. Hence as the winds shift form westerlies to easterlies with latitude the surface currents diverge, driving upwelling from the ocean interior.

**Box 7.1: Coriolis Force**
The Coriolis force is an apparent force that explains how an object moving in a straight line in space will appear to move in a curve when viewed from the rotating Earth. The Coriolis force is small and relevant only over large distances in the ocean and atmosphere. In the Southern Hemisphere, it causes ocean currents and air masses to turn to the left, while in the Northern Hemisphere it causes them to turn to the right. It is the balance between the Coriolis force and the other relevant forces, e.g. friction, that determines how far to the left (Southern Hemisphere) or right (Northern Hemisphere) they turn.

### 7.1.1.2 Density Gradients

Variations in density drive currents within the ocean because denser (heavier) water moves to sit below less dense water. The density gradients depend on a combination of water pressure, temperature and salinity. Changes in water pressure cause the largest changes in density, with density increasing as pressure increases deeper in the ocean. However, it is not this vertical change that is most important for ocean currents, but the horizontal density gradients that are mostly caused by changes in temperature and salinity (Talley et al. 2011).

Cold, salty water is denser than warm, fresh water, although the effects of temperature and salinity are variable. Below 0 °C, seawater density is mainly caused by changes in its salinity. However, as water gets warmer, changes in salinity become less important, and for most of the global ocean, temperature is the main determinant of density. The Southern Ocean density gradients are always small as the density varies by less than 0.5 % from the mean (average) density.

#### 7.1.1.3 Temperature and Salinity

Over most of the Southern Ocean, temperature and salinity are modified by interaction and exchange between the ocean and the atmosphere. Temperatures at the ocean's surface are linked to heat distribution in the atmosphere, with oceans at the poles being colder than those at the tropics. Despite extremely low air temperatures, seawater around Antarctica doesn't cool much below its freezing temperature. The freezing temperature varies with salinity, but is approximately −1.9 °C at the ocean surface. Below this temperature sea ice forms and, as it thickens, insulates the ocean beneath, preventing it from cooling further (Wadhams 2000).

Salinity in the Southern Ocean has a small range, from around 33.8 g $kg^{-1}$ to more than 35 g $kg^{-1}$. Across the open ocean, changes in surface salinity are controlled by two factors: the amount of precipitation, made up of rain and snow, and the amount of evaporation of ocean water into the atmosphere. Sea ice and ice shelves act as barriers to these processes. When sea ice forms, approximately 85 % of the salt is expelled from the ice into the water immediately below, resulting in higher salinity in the water underneath sea ice (Chap. 5). During summer, when the ocean is warm enough to melt the sea ice, the ocean surface freshens because of the low salinity of melted sea ice.

#### 7.1.1.4 Pressure Gradients

The pressure gradient within the ocean results from a combination of water density and the uneven surface of the sea. The higher the sea surface the greater the pressure in the water below. Due to differences in atmospheric pressure, the Southern Ocean sea surface usually slopes downwards from north to south by about 1.5 m, resulting in higher pressure in the north (Sokolov and Rintoul 2009). This, along with density gradients in the water column, sets up horizontal pressure gradients. These gradients set the water flowing from regions of high pressure to regions of low pressure. However, the presence of the Coriolis force (Box 7.1) modifies this water movement and results in currents flowing along isobars (lines of equal pressure) like winds on a weather map. This is known as geostrophic flow and occurs when the horizontal pressure gradient and the Coriolis force are close to being in balance. Within the ocean this results in currents flowing along density gradients because density variation has the largest local effect on pressure gradients. In the Southern Hemisphere, high pressure is to the left of the direction of flow.

### 7.1.2 *Water Masses and Fronts*

Temperature and salinity vary not just at the surface, but also throughout the entire water column. This gives rise to water masses, bodies of water that have physical and chemical properties such as temperature, salinity, silicates, nitrates or dissolved oxygen that are distinct from the surrounding water (Talley et al. 2011) (Box 7.2).

**Box 7.2: Water Masses in the Southern Ocean**

Antarctic Surface Water: found at the surface between the Antarctic continent and the Polar Front.

Antarctic Intermediate Water: cold, with relatively low salinity and found mostly at intermediate depths (around 1000 m). It is formed along the Subantarctic Front, and has its largest source in the eastern South Pacific Ocean.

Circumpolar Deep Water: relatively warm and saline, penetrates the continental shelves and occurs all around Antarctica. It is often separated into two, Upper and Lower Circumpolar Deep Water. It forms most of the water circulating in the Antarctic Circumpolar Current.

Antarctic Bottom Water: formed around Antarctica and as the densest water is found at the bottom of the ocean.

North Atlantic Deep Water: water mass that forms in the North Atlantic Ocean and can be traced into the Southern Ocean, where it mixes to become part of Circumpolar Deep Water.

At the ocean surface, interaction with the atmosphere and the formation of sea ice result in the largest changes in temperature and salinity in the ocean. The ocean's top few tens of metres are stirred by the wind to form the mixed layer. Once below the mixed layer, the properties of a water mass remain more or less consistent for long periods of time, and can be distinguished over large distances, although they gradually erode through mixing with adjacent water masses.

Along the northern parts of the Southern Ocean the temperature and salinity of the interior water masses are set during autumn and winter, when the cold atmosphere cools the surface water enough to remove the summer stratification. This winter mixed layer is, however, not dense enough to enter the ocean interior alone. It is pushed in, or injected, by Ekman pumping driven by atmospheric low pressure systems.

Closer to Antarctica the surface waters do not warm sufficiently in winter to keep surface waters light. Instead the combination of a cold atmosphere, and salt rejected when sea ice forms can make surface waters denser than the waters underneath. This drives a process known as convection where the dense water sinks and mixes with the waters underneath, until the mixture is not dense enough to sink further (Talley et al. 2011).

With water masses remaining near constant from year to year, their properties can be measured in the ocean interior and the pathways from their source regions can be mapped through the ocean, even though each parcel of water may have traveled for many years (Box 7.3).

**Box 7.3: Measuring the Properties of the Southern Ocean**
Global-scale ocean circulation can be measured in real time by Argo floats. These floats measure ocean temperature and salinity by drifting with the currents usually at a depth of 1000 m and are of use particularly in the Southern Ocean, which is distant from shipping routes and sees relatively little traffic. Every 10 days, the float drops to 2000 m before, a small pump inflates a bladder with oil, increasing the buoyancy of the float. As the float rises, it records the water temperature and salinity. Once the float reaches the sea surface, the information is relayed via satellite to researchers on land. The pump then deflates the bladder and the float sinks back to 1000 m to begin another cycle. Each float lasts for about 4 or 5 years, sending back up to 180 vertical profiles of ocean conditions.

Once pushed into the interior of the ocean, water masses flow along surfaces of constant density, called isopycnals. The isopycnals generally slope down through the ocean from the Southern Ocean towards the tropics. The effects of this flow can be seen in the vertical slices of temperature and salinity shown in Fig. 7.1.

Fronts mark abrupt changes in ocean properties between different water masses (Box 7.4). Changes either side of a front can be substantial, such as the temperature change of around 3 °C across the Subantarctic Front (Orsi and Whitworth 2005).

**Box 7.4: Fronts in the Southern Ocean**
Subtropical Front (STF): the boundary between warm, salty subtropical waters and fresher, cooler subantarctic waters. It is often considered the northern boundary of the Southern Ocean.

Subantarctic Front (SAF): marks the northern boundary of the Antarctic Circumpolar Current. It typically forms three branches, northern, main, and southern, which tend to follow the bathymetry, converging where there are ocean ridges and diverging over the deep ocean.

Polar Front (PF): separates polar waters from the relatively warm and salty sub-polar water. Like the Subantarctic Front it has multiple branches that are steered by the ocean bathymetry.

Southern ACC Front (SACCF): marks a change in properties below the surface layer, but has no surface signature. The subsurface changes have a dynamic effect on the ACC.

(continued)

**Box 7.4** (continued)

Southern Boundary of the ACC (SB): southern limit to the Antarctic Circumpolar Current. This lies along the southern limit for Circumpolar Deep Water.

Antarctic Slope Front: situated by the shelf break of the Antarctic continental shelf, and separates shelf and oceanic waters.

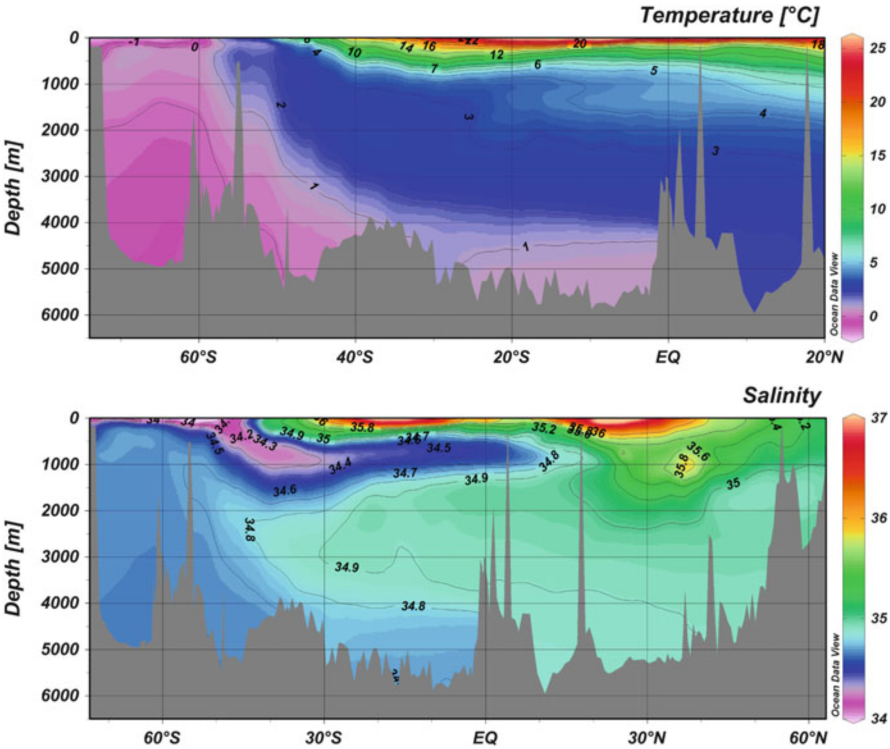



**Fig. 7.1** Vertical temperature (in degrees Celsius; *upper panel*) and salinity (in g kg$^{-1}$; *lower panel*) along south to north sections from Antarctica (*left*) through the Southern Ocean, into the Atlantic Ocean. Data combined from multiple years and different seasons. The ocean floor is coloured *grey*. Easily identifiable water masses are the cold Antarctic Bottom Water near the Antarctic Coast (coloured *pink* on the *upper panel*; *blue* on the *lower panel*), and relatively fresh Antarctic Intermediate Water (coloured *dark blue* on the *upper panel*; *pale green* on the *lower panel*) (© Michael J. M. Williams)

Differences in temperature and salinity across a front give rise to waters of different density. The less dense water stands higher than the denser water and this is reflected in a change in height of the ocean surface across the front. This height change can be located and measured by satellite-based altimeters and used to map the location of fronts (Sokolov and Rintoul 2009). The mean (average) positions of

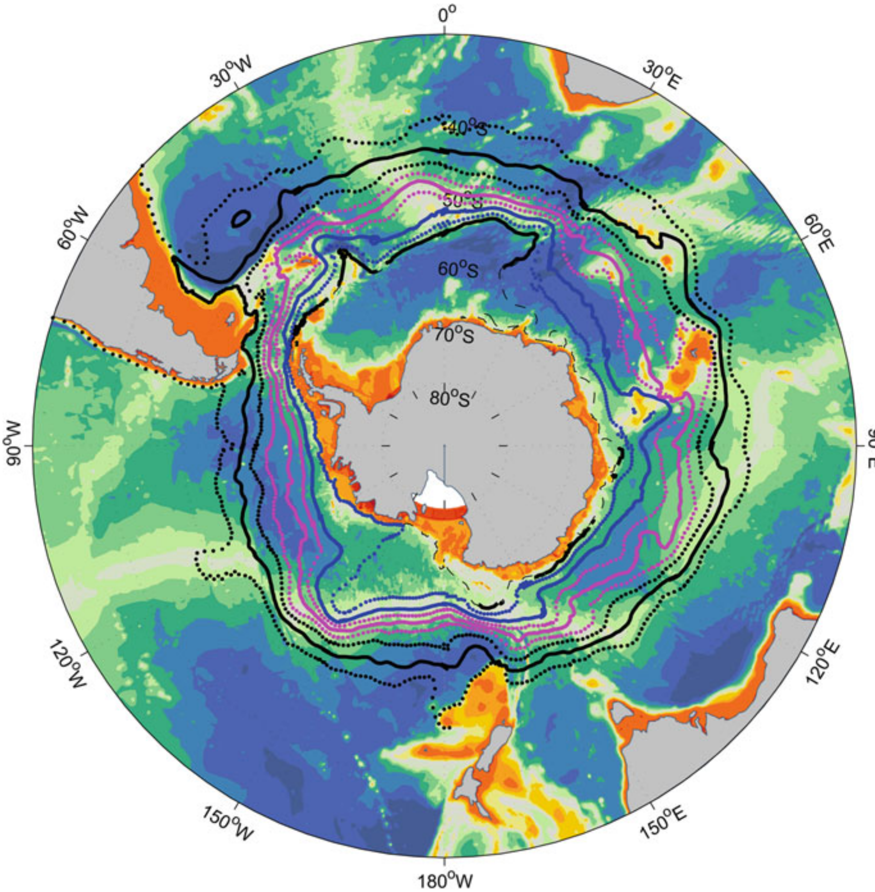



**Fig. 7.2** The Southern Ocean fronts are colour coded from south to north as follows: SB *black*, SACCF (-S and -N) *blue*, PF (-S, -M, and -N) *magenta*, SAF (-S, -M, and -N) *black*. The middle branches of the fronts are shown by *solid lines*, while the northern and southern branches (where applicable) are show by *dotted lines*. In the case of the SACCF, the northern branch is shown by a *solid line* and the southern branch is shown by a *dotted line*. The 2000 m bathymetric contour is shown by a *thin black line*. The deepest water is *dark blue*, grading through *dark green*, *light green* and *orange* as the water depth decreases (© Serguei Sokolov, modified from Sokolov and Rintoul 2009)

the main fronts in the Southern Ocean are shown in Fig. 7.2. However, the location of fronts is dynamic because density gradients across fronts help drive the ocean currents, which in turn influence the positions of the fronts.

### 7.1.3 Vertical Circulation and Formation of Bottom Water

Density differences and wind, through Ekman forcing drive, vertical as well as horizontal movement of water masses. The vertical movement is connected to the global ocean circulation. This transports the surface water of the Southern Ocean into the deep ocean. The surface water contains dissolved gases such as oxygen and carbon dioxide as well as heat received from the atmosphere. Measurements of the temperatures and salinities of water masses can be used to follow their movement through the ocean and map the ocean circulation.

In the Southern Ocean, vertical circulation can be described as two overturning cells: a southern cell close to Antarctica and a northern cell (Fig. 7.3). The position of the boundary between the northern and southern cells is linked to the location of the velocity maximum in the westerly wind. The northern cell is driven by the westerly winds that move water near the surface north in the Ekman Layer. The southern cell is driven by dense water, particularly Antarctic Bottom Water (see below), sinking off the continental shelf towards the ocean floor. In both cells, Circumpolar Deep Water (Box 7.2) rises to replace the surface waters that are being moved north and south.

Antarctic Bottom Water is cold and relatively salty and is the densest water in the ocean. It flows north from Antarctica in trenches and passages in the deepest parts of the ocean, before reaching and filling the deep basins of the Indian, Pacific

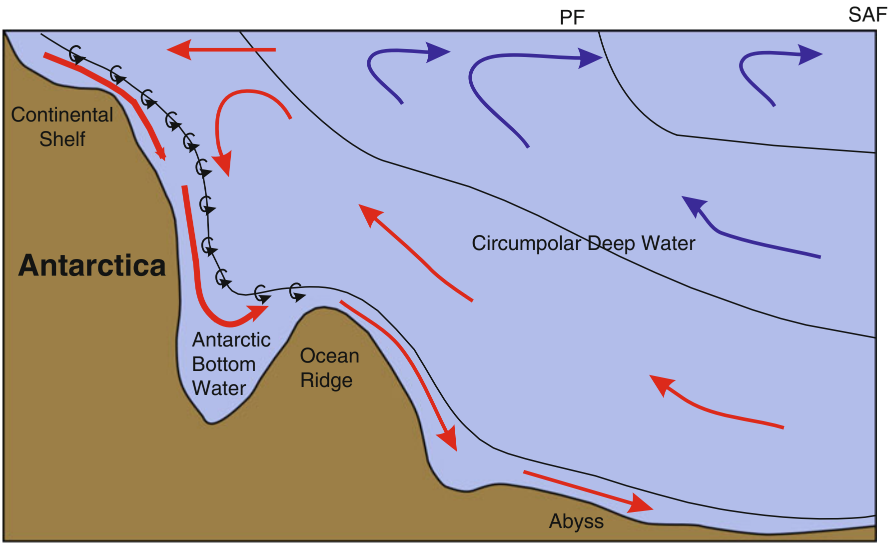



**Fig. 7.3** The meridional overturning circulation in the Southern Ocean can be broken into two cells. The northern cell is primarily driven by northward transport in the Ekman Layer, while the southern cell is primarily driven by Antarctic Bottom Water formation near the Antarctic continent. For both cells the return flow comes from Circumpolar Deep Water (© Michael J. M. Williams, modified from Speer et al. 2000)

and Atlantic Oceans (Figs. 7.1 and 7.3). The exact mechanisms of bottom water formation around Antarctica are active areas of research, but there are basic processes that drive it. Initially, water on the continental shelf is too light to sink, becoming dense only by accumulating salt from sea-ice formation during winter. Generally, this is insufficient to make the water dense enough to flow off the continental shelf, so it needs to be trapped in areas were salt can build up further, such as over a basin on the continental shelf or under a polynya (an area where sea ice is absent, Chap. 5).

With this increased density, water is able to flow off the continental shelf as a gravity-driven plume that slides under less dense water in the deep ocean (Talley et al. 2011). As it sinks this plume expands by incorporating the surrounding lighter water. When two parcels of water mix, a new parcel is formed that has a temperature and salinity intermediate between the two constituents. In some circumstances, a process known as caballing occurs where this mixture is denser than both of the original water parcels. Caballing allows the plume mixture to sink further, entraining more water until the plume reaches either water with the same density or the ocean floor. Although this process occurs around much of Antarctica, only a few places have been found where it is dense enough to reach the bottom: the Weddell Sea, the Ross Sea, along the Adélie Land Coast and off Cape Darnley (Ohshima et al. 2013).

### *7.1.4 Currents*

The dominant current in the Southern Ocean is the easterly flowing Antarctic Circumpolar Current (ACC). The ACC transports several water masses and is the largest current in the world's oceans. It connects and supplies water to the Atlantic, Pacific and Indian ocean basins (Fig. 7.4). The ACC is driven by both geostrophic processes and the wind. Wind acts over the whole ACC, although this effect is greatest at around 50°S where the westerly winds are strongest. Density differences across fronts produce and concentrate most of the flow in the ACC. The two most important fronts are the Subantarctic Front and the Polar Front (Box 7.4, Fig. 7.2). Unlike most ocean currents, the ACC reaches from the surface to the ocean floor. Here friction produced by the ocean floor is important for counteracting the continual driving action of the wind and density gradients and for keeping the speed of the current approximately constant over time (Rintoul et al. 2001).

The speed of the ACC varies, with the fastest flow occurring at fronts where the density gradients drive the geostrophic flow. Here currents can be up to 75 cm $s^{-1}$, while away from the fronts the current speed is typically less than 20 cm $s^{-1}$ (Stanton and Morris 2004). The amount of water carried by the ACC, known as the transport, is calculated as the flow through a defined area. In the Drake Passage, between South America and the Antarctic Peninsula, transport reaches 134 million cubic metres per second ($134 \times 10^6\ m^3\ s^{-1}$), but it is thought to increase by up to another $13 \times 10^6\ m^3\ s^{-1}$ south of Australia where the broader area allows more flow

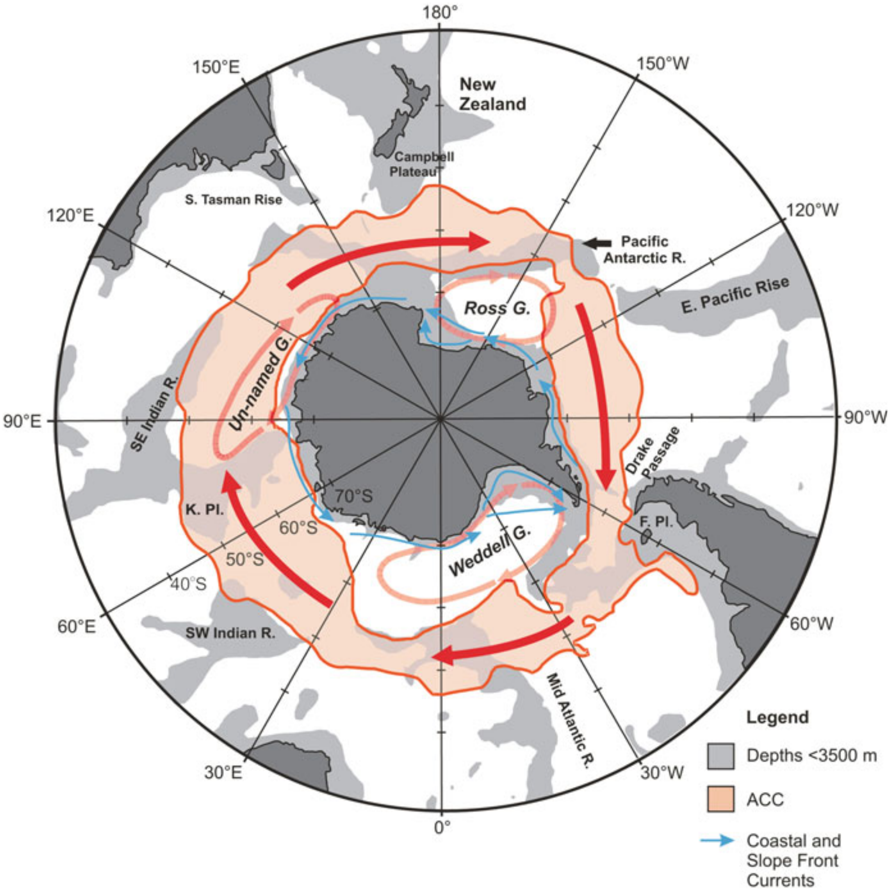



**Fig. 7.4** Currents of the Southern Ocean, including the dominant Antarctic Circumpolar Current (ACC), the Antarctic Coastal Current (closest to Antarctica) and the Antarctic Slope Front Current. Also indicated are the three gyres. F.Pl.: Falkland Plateau, K.Pl.:Kerguelen Plateau, G.:Gyre, R.:Ridge (© Michael J. M. Williams, modified from Carter et al. 2009)

(Rintoul et al. 2001). The ACC can transport such a large volume of water because the current is very wide, up to 2000 km, and has a large vertical range from the surface to the seafloor, up to 4000 m in places.

The path of the ACC is heavily influenced by land and seafloor topography and these cause fronts in the ACC to merge and diverge around Antarctica. Figure 7.2 shows sharp changes in the position of fronts where the ACC crosses the shallow bathymetry of the mid-ocean ridges and where it flows through major choke points. In the Drake Passage and near the Kerguelen Plateau, fronts are pushed together, and south of New Zealand the ACC is directed south by the Macquarie Ridge and the Campbell Plateau (Fig. 7.4).

South of the Southern Boundary Front lies the Antarctic Slope Front. This sits close to the shelf edge and is the offshore limit of the colder and fresher waters that lie on Antarctica's continental shelf.

Associated with the Antarctic Slope Front is the westward flowing Antarctic Slope Front Current, which is a westward flowing current driven by geostrophic processes (Heywood et al. 2004). The Antarctic Coastal Current is a fast, shallow current that lies over the continental shelf close to the large ice shelves, and is driven by the easterly wind belt that follows the Antarctic coast. Although the Antarctic Slope Front and Coastal Currents are normally distinct and are driven by different mechanisms, in areas where the continental shelf is narrow the two currents are difficult to separate (Heywood et al. 2004). This led early researchers to consider them as a single current named the East Wind Drift.

In the Ross and Weddell seas, the ACC is deflected northward by the Antarctic-Pacific Ridge and the Antarctica Peninsula, respectively. This northward deflection combined with the extensive southern reach of both embayments leads to the formation of local gyre circulations. In addition, a similar as yet unnamed feature has also been reported along the Antarctic coast south of Australia (Fig. 7.4; Bindoff et al. 2000). The lateral extent of all three gyres is poorly known, but generally they are likely to be limited by bottom topography.

## 7.2 Global Ocean-Atmosphere Interaction

The oceans and the atmosphere work together to distribute heat and regulate climate around the globe. There is an exchange of freshwater, momentum, heat and gases between the ocean and the overlying atmosphere (Chap. 8). Freshwater exchange occurs mainly in the form of evaporation from the ocean and precipitation from the atmosphere. Momentum exchange occurs primarily through the action of wind and water currents. Gases from the atmosphere enter the ocean mainly through direct air-sea exchange (Chester 2000).

### *7.2.1 Heat Transfer*

The vast amount of heat stored in the ocean is transported by the ocean circulation, but the ocean also has significant temperature inertia, or resistance to change. This means the ocean is slow to release heat to the atmosphere and as a result moderates the climate on land near to the ocean. Vertical circulation carries heat from the surface down into the interior of the ocean. As the Earth warms, this transported excess heat causes sea level to rise through thermal expansion (warm water is less dense than cold water, so takes up more space, raising the ocean surface), and contributes to the regional distribution and rate of sea-level rise in the Southern Hemisphere (Purkey and Johnson 2010).

### 7.2.2 Gas Transfer

Oxygen and greenhouse gases are exchanged during the establishment of a chemical equilibrium between the atmosphere and the ocean, and the ocean is both a source and sink of gases. For example, the vertical circulation maintains oxygen levels in the deep ocean by transporting oxygen-rich surface water into the ocean interior.

The ocean contains a significant amount of carbon in the form of organic material and as dissolved gases. Biological processes, such as photosynthesis in phytoplankton, turn carbon dioxide into organic material and when organisms die, they sink, carrying carbon into the ocean (some carbon is used in biological processes) (Chester 2000).

Gas exchange between the ocean surface and the atmosphere, and between the upper ocean and the deep ocean, is fundamental to climate change and is a complex process that is dependent on differences in the air-sea gas concentrations gradient, wave breaking and the ocean temperature (Chester 2000). In the Southern Ocean, the cold surface water allows carbon dioxide from the atmosphere to dissolve more readily. Low surface concentrations persist as Southern Ocean vertical circulation continually transports carbon dioxide absorbed in the surface water deep into the ocean.

### 7.2.3 Global Implications

Approximately one third of anthropogenic carbon dioxide is accumulating in the world's oceans (Siegenthaler and Sarmiento 1993), slowing the rate of climate change. Some of this is being sequestered in the Southern Ocean. Disruption of the ocean's circulation may mean the ocean becomes a source of carbon rather than a sink, and atmospheric carbon dioxide levels could rise much higher than they are now.

The Southern Ocean, with the associated Antarctic Circumpolar Current, is the only ocean that encircles the globe and this gives it a key role in the global climate system. The ACC is instrumental in the exchange of water, heat and other components such as carbon dioxide and oxygen, between all of the Southern Hemisphere ocean basins. This global redistribution of heat and carbon dioxide influences Earth's climate and means that changes happening now may influence global climate in years to come.

## 7.3 Conclusions

The oceanography of the Southern Ocean is complex, being influenced by seafloor topography, sea ice, the atmosphere and interactions with Antarctica's ice shelves. The Antarctic Circumpolar Current connects the Southern Hemisphere ocean basins, putting the Southern Ocean and the ACC at the centre of the global ocean circulation. The formation of dense waters, such as Antarctic Bottom Water, and their ability to transport gases, which either oxygenate the deep ocean or bury carbon dioxide within the ocean, make the Southern Ocean a key component in the global climate system.

## References

Bindoff NL, Rosenberg MA, Warner MJ (2000) On the circulation and water masses over the Antarctic continental slope and rise between 80 and 150°E. Deep Sea Res 47:2299–2326

Carter L, McCave IN, Williams MJM (2009) Circulation and water masses of the southern ocean: a review. In: Florindo F, Siegert M (eds) Developments in earth and environmental sciences, vol 8, Antarctic climate evolution. Elsevier, Amsterdam, pp 85–114

Chester R (2000) Marine geochemistry. Blackwell Science, Oxford, p 506

Heywood KJ, Garabato ACN, Stevens DP, Muench RD (2004) On the fate of the Antarctic slope front and the origin of the Weddell Front. J Geophys Res 109(C0621):1–13

Ohshima KI, Fukamachi Y, Williams GD, Nihashi S, Roquet F, Kitade K, Tamura T, Hirano D, Herraiz-Borreguero L, Field IM, Aoki S, Wakatsuchi M (2013) Antarctic bottom water production by intense sea-ice formation in the Cape Darnley Polynya. Nat Geosci 6:235–240

Orsi AH, Whitworth T III (2005) Hydrographic atlas of the world ocean circulation experiment (WOCE). In: Sparrow M, Chapman P, Gould J (eds) Southern ocean, vol 1. International WOCE Project Office, Southampton. ISBN 0-904175-49-9

Purkey SG, Johnson GC (2010) Warming of global abyssal and deep southern ocean waters between the 1990s and 2000s: contributions to global heat and sea level rise budgets. J Climate 23:6336–6351

Rintoul SR, Hughes CW, Olbers D (2001) The Antarctic circumpolar current system. In: Siedler G, Church J, Gould J (eds) Ocean circulation and climate observing and modelling the global ocean. Academic, London, pp 271–302

Siegenthaler U, Sarmiento JL (1993) Atmospheric carbon dioxide and the ocean. Nature 395:119–125

Sokolov S, Rintoul SR (2009) Circumpolar structure and distribution of the Antarctic Circumpolar Current fronts: 1. Mean circumpolar paths. J Geophys Res 114:C11018. doi:10.1029/2008JC005108

Speer K, Rintoul SR, Sloyan B (2000) The diabatic Deacon cell. J Phys Oceanogr 30:3212–3222

Stanton BR, Morris MY (2004) Direct velocity measurements in the Subantarctic Front and over Campbell Plateau, southeast of New Zealand. J Geophys Res 109:C1. doi:10.1029/2002JC001339

Talley LD, Pickard GL, Emery WJ, Swift JH (2011) Descriptive physical oceanography. Academic, London, p 555

Wadhams P (2000) Ice in the ocean. Gordon and Breach Science Publishers, London, p 351

# Chapter 8
# From Ice to Space

## The Antarctic Atmosphere

**Rhian A. Salmon and Anna E. Jones**

**Abstract** The atmosphere over Antarctica is pristine, dry and isolated. This is because it is very far from all sources of manmade emissions, is extremely cold and completely surrounded by the enormous Southern Ocean. It is, however, home to unusual chemical and physical processes that have a global significance. In this chapter, we start by considering some fundamental concepts used to describe the Earth's atmosphere. We then focus on measurements of past and present carbon dioxide concentrations from Antarctica, the stratospheric ozone hole, and atmospheric chemistry occurring near ground level. Finally, we consider some connections between these apparently distinct phenomena in order to illustrate the critical role the Antarctic atmosphere plays in connecting global land, ice and oceans, as well as different geographical areas of the Earth.

**Keywords** Antarctic atmosphere • Troposphere • Stratosphere • Mesosphere • Thermosphere • Aurora • Carbon dioxide • Stratospheric ozone hole • Polar vortex • Polar stratospheric clouds

## 8.1 Introduction to the Antarctic Atmosphere

Atmospheric science involves the study of the chemistry, composition and physical properties of the air both now and in the past. By combining this information, we are able to better predict the characteristics of the atmosphere in the future. Antarctica is an excellent location for understanding the composition of 'pristine' air and processes that are currently occurring in the atmosphere. In addition, tiny bubbles of ancient air that are trapped in the ice provide a window on the past. Antarctica's icy cap therefore holds an archive of past atmospheric conditions,

R.A. Salmon (✉)
Victoria University of Wellington, Wellington, New Zealand
e-mail: rhian.salmon@vuw.ac.nz

A.E. Jones
British Antarctic Survey, Cambridge, UK
e-mail: aejo@bas.ac.uk



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_8

which can be connected to present day measurements. The combination of data collected from ice cores and measurements of the air over the past 50 years has been invaluable in discovering how the composition of the atmosphere has changed over the last centuries and millennia, and has been fundamental to our understanding of the changing climate (Chaps. 4 and 25).

Regular observations of meteorology and the Antarctic atmosphere have been carried out since the International Geophysical Year in 1957/1958 (Chap. 28). In many cases, measurements were made because they were accessible, innovative and of interest to scientists who were trying to better understand the Earth's systems. Ozone measurements are one such example. Only in the last few decades have we discovered processes that deplete ozone at different heights in the polar atmosphere. The longer-term ozone data from the 1950s have been critical for determining whether these newly discovered processes are manmade (such as the ozone hole discussed below) or natural (such as tropospheric ozone depletion, also discussed below).

## 8.2 Physical Structure and Characteristics of the Atmosphere

In order to understand processes occurring in the Antarctic atmosphere, we first require a general understanding of the structure and characteristics of the atmosphere everywhere. Atmospheric science is the study of chemical and physical properties of air, as well as connections between the two. From a chemical perspective, the atmosphere consists of nitrogen (78.1 %), oxygen (20.9 %), argon (0.9 %) and a wide range of trace gases such as carbon dioxide and methane (Box 8.1).

The Earth's atmosphere is an oxidising system because of the abundance of oxygen and its associated gases. Oxygen occurs in three different forms in the atmosphere (Fig. 8.1): atomic oxygen (O), which is extremely reactive; molecular oxygen ($O_2$), which is very stable and by far the most common form in air; and ozone ($O_3$), which is discussed in detail later.

**Box 8.1: Chemical Composition of the Atmosphere**

The global atmosphere is primarily composed of nitrogen (78.1 %) and oxygen (20.9 %). The concentration of argon is at just over 0.9 %, making the total for these three gases over 99.9 % of our atmosphere. Gases such as carbon dioxide ($CO_2$), water vapour, hydrogen, helium and methane ($CH_4$) are called trace gases because they are found in tiny concentrations. Collectively, they add up to less than 0.1 % of the atmosphere and are measured in parts per million (ppm) and parts per billion (ppb). This means that if, for

(continued)

**Box 8.1** (continued)
example, there was 1 ppm of gas X in the atmosphere, there would be exactly one molecule of that gas in every million molecules in the air. Ozone is often quantified using a different unit. Because it is important as a filter of solar ultra-violet radiation, what matters is how much ozone the radiation has passed through on its way to the Earth's surface. A Dobson Unit (DU) is a way of describing the total amount of ozone in the atmosphere over a particular point. One DU is defined as 0.01 × the thickness of ozone (in mm) at standard temperature and pressure (STP). Putting this differently, if the total ozone through the atmosphere over your house measured 300 DU, then if all the molecules were brought down to the Earth's surface, at a temperature of 0 °C and 1 atmosphere pressure, and piled up on top of each other, they would form a pile that was 3 mm high. Since most of this ozone is concentrated in the stratosphere, the total ozone column gives a good indication of stratospheric ozone concentrations.

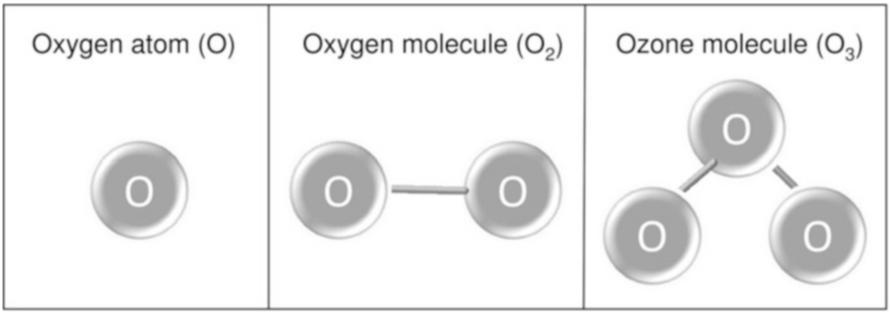



**Fig. 8.1** A molecule of ozone ($O_3$) contains three oxygen (O) atoms bound together. Oxygen molecules ($O_2$), which constitute 20.9 % of the gases in Earth's atmosphere, contain two oxygen atoms bound together

One way to understand the atmosphere from a physical perspective is to consider how it changes with height (Fig. 8.2). The Earth's atmosphere can be thought of as a series of layers, which are distinguished from one another by their thermal characteristics. The heights of these layers vary with latitude and season, but an average overview is given in Fig. 8.2 and the different regions are discussed below.

### *8.2.1 The Troposphere*

The lowest layer of the atmosphere (within which we live) is the troposphere. The air in the troposphere is warmest close to the ground and temperature generally

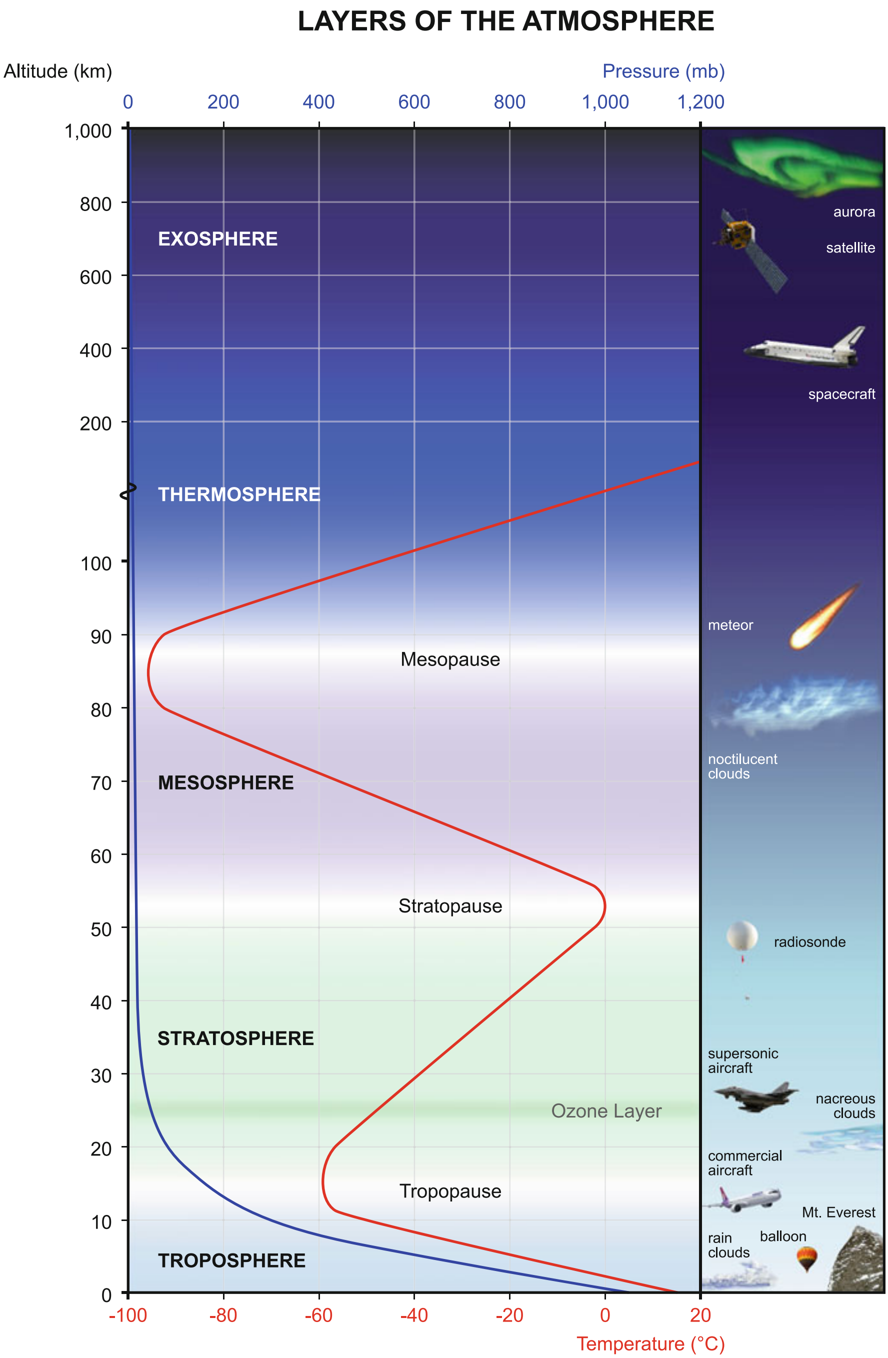



**Fig. 8.2** This graphic shows a vertical profile of the atmosphere, including changes in temperature (With kind permission from J. Oliver/BAS)

decreases with height (it gets colder as you go up a mountain). When warm air is overlain by colder air, the warmer air rises, and it is this convective motion that fundamentally drives our weather systems (Chap. 6). Almost all of the atmosphere's water vapour is found in the troposphere, so this is where we find most clouds, and all of the rain and snow. Another effect of this convection is that gases emitted at the ground, either through pollution or from natural emission, can be mixed rapidly to considerable altitudes within the troposphere. About 80 % of all the mass of the atmosphere is held within the troposphere.

### *8.2.2 The Stratosphere*

The tropopause separates the troposphere from the layer above – the stratosphere. Within the stratosphere, temperature increases with height. For this to occur, there must be a source of heat within the stratosphere, and indeed there is. A suite of chemical reactions involving the three forms of oxygen (Fig. 8.1) generate a steady concentration of ozone known as the ozone layer (Box 8.3). These reactions also generate heat and provide an example of the intricate link between atmospheric chemical composition and temperature. As a result of the stratospheric temperature profile, there is very little vertical mixing of air in the stratosphere.

### *8.2.3 The Mesosphere and Thermosphere*

Above the stratopause is the mesosphere, a region with no source of heat, so that, again, temperatures decrease with altitude. Convective processes once again operate in the mesosphere, driving vertical air motion, so that the mesosphere is another relatively well-mixed region of the atmosphere.

The upper boundary of the mesosphere, called the mesopause, sits at around 85 km altitude, above which temperatures rise rapidly with altitude. This next layer is the thermosphere. The chemical composition of the thermosphere is very different to that at lower altitudes, with a much larger concentration of atomic oxygen relative to molecular $O_2$ and $N_2$. Here, highly energetic solar radiation is absorbed by molecular and atomic constituents, which then release heat. A particular feature of the thermosphere, which can be observed from the ground at high latitudes, is the display of the aurora (Box 8.2). Charged particles from the sun bombard atoms and molecules in the thermosphere, resulting in emission of visible light and the fantastic light displays that occur sporadically (Fig. 8.3).

**Fig. 8.3** An aurora can occur at any time of day or night, but, like stars, can only be seen at night (With kind permission from S. Burrell/BAS)

**Box 8.2: The Aurora**

Incredible light displays observed at night time at high latitudes are known in the Northern Hemisphere as Aurora Borealis (or northern lights) and in the Southern Hemisphere as Aurora Australis (or southern lights). They occur in a range of colours, most commonly greens or pinks and reds, and also take a variety of forms. They can look like moving patches or scattered clouds of light, like rippling curtains, shooting rays, or mysterious arcs.

An aurora occurs as a result of the interaction between solar wind and the Earth's magnetic field. Energy released from this process is transferred to charged particles, which travel along the magnetic field lines around the Earth, towards both polar regions. The light display is observed because these excited atoms, molecules or ions release energy at discrete wavelengths. As examples, excited oxygen atoms at lower and higher altitudes emit green and red light, and an excited form of nitrogen produces a violet colour. The combination and overlay of these emissions, observed from the ground, can result in a range of changing colours.

At the top of the thermosphere, which may occur anywhere between 500 and 1000 km, is the edge of the Earth's atmosphere and the beginning of space. Already, we see that the atmosphere is a collection of subtle and complex processes which determine its behaviour. In the next few sections, we look at some of the processes that are particularly characteristic for the Antarctic atmosphere.

## 8.3 Atmospheric Carbon Dioxide, Past and Present

Carbon dioxide, $CO_2$, is the most well-known greenhouse gas. Greenhouse gases absorb infrared radiation that is reflected from the surface of the Earth, and re-emit it as heat, in all directions. This is critical to the sustainability of life on Earth as we know it: if there were no greenhouse gases in the troposphere, the Earth's temperature would be $-17\ ^{\circ}C$, all water on Earth would be frozen, and life as we know it would not exist. It follows that any change in the concentration of carbon dioxide and other greenhouse gases will have an impact on Earth's climate. We are therefore very interested in studying carbon dioxide concentrations in the air, known as ambient $CO_2$ concentrations, as well as inferring these concentrations in the past, in order to better predict the Earth's climate in the future (Chap. 4).

### *8.3.1 Direct Measurements of Carbon Dioxide in the Air*

The first measurements of ambient $CO_2$ in Antarctica started during the International Geophysical Year, in 1957, and have continued ever since. The first panel of Fig. 8.4 shows that since 1975 there has been a continuous and steady increase in $CO_2$ concentrations measured at the Amundsen-Scott South Pole station.

The variability that is superimposed on the general trend line (seen as 'wobbles' in the line) results from the annual 'breathing' of the Earth's atmosphere. This is predominantly controlled by processes in the Northern Hemisphere because that is where the majority of the Earth's landmass, and therefore vegetation, is found. During the spring and summer, $CO_2$ is removed from the atmosphere as plants grow and photosynthesise. In contrast, during the autumn and winter, with the dominance of respiration over photosynthesis and decay over growth, $CO_2$ is released from the biosphere into the atmosphere. Measurements from remote areas such as Antarctica give us excellent information on the background concentrations of carbon dioxide in the Earth's atmosphere.

### *8.3.2 Connecting Atmospheric with Ice-Core Data*

The steady increase of $CO_2$ that has been measured over the last 50 years raises questions about why its concentration is rising, and what the $CO_2$ baseline for the Earth has been in the past. In order to understand this, we need to turn to palaeoclimate data obtained from ice cores (Chaps. 4 and 5).

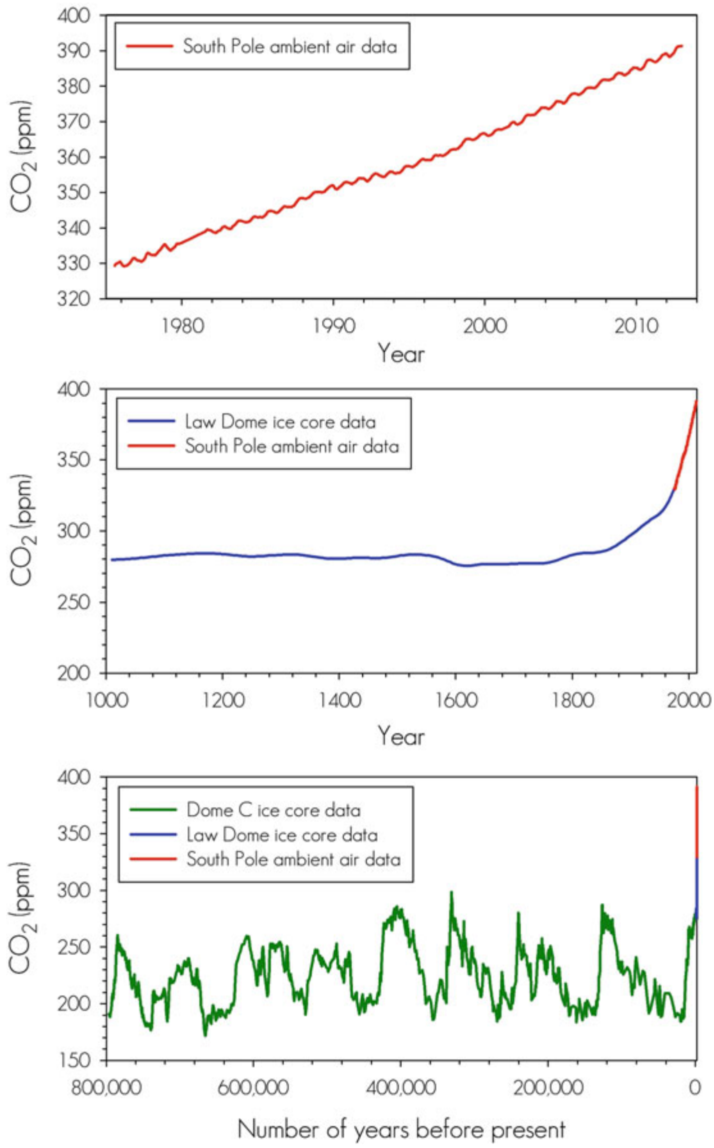



**Fig. 8.4** Concentration of carbon dioxide measured in air and ice cores. The first panel shows $CO_2$ concentrations obtained from surface air since 1975 at Amundsen-Scott South Pole station. (NOAA Earth System Research Laboratory, Global Monitoring Division). The second panel shows $CO_2$ concentrations obtained from a shallow ice core at Law Dome, Antarctica, which takes us back 1000 years (Etheridge et al. 1996). The third panel shows data from the EPICA deep ice core in Antarctica, discussed in greater detail in Chap. 5, which takes us back 800,000 years (EPICA Community 2004). In order to appreciate the change in timescale, the data shown in the first two panels are also shown in the third panel. The impressive agreement and fit between these three unique datasets gives us confidence in ice-core measurements, and the information that they provide about past climates (Adapted from Etheridge et al. 1996; MacFarling Meure 2004; MacFarling Meure et al. 2006; Lüthi et al. 2008, with kind permission from NOAA Earth System Research Laboratory, Global Monitoring Division)

Unlike most other areas of the Earth, the Antarctic atmosphere is separated from the rocky surface of the continent by a layer of ice and snow. Close to the surface is a layer of firn, porous ice and snow through which air can flow freely to and from the open atmosphere. The deepest ice is formed by compaction of hundreds or thousands of years of snowfall. Bubbles of air trapped inside this ice therefore contain a snapshot of older atmospheres. By drilling into this ice, and carefully extracting an ice core, we can therefore learn about the chemical composition of the atmosphere in the past.

The second panel in Fig. 8.4 shows ambient $CO_2$ concentrations that were derived from a relatively shallow ice core, obtained at Law Dome in Antarctica that dates back 1000 years. This graph has two features worth noting. First, the overlap between measurements of $CO_2$ obtained from ambient measurements (in red) compared with data obtained from the ice core (in blue) is excellent. This gives us confidence that we can accurately derive concentrations of $CO_2$ in the past from ice cores. Secondly, it can be seen that ambient $CO_2$ concentrations over the past 50 years (shown by the red line in both panels A and B, but on axes with different scales) was consistently higher than it has been at any point in the last 1000 years.

### 8.3.3 *Carbon Dioxide Concentrations in Deep Ice Cores*

In order to put things into a longer-time perspective, we need to consult data obtained from deep ice cores. The third panel in Fig. 8.4 shows data from the EPICA Dome C ice core, which was retrieved from central Antarctica and dates back to 800,000 years before present. Data obtained from Law Dome (blue, panel B), and ambient measurements from the South Pole (red, panel A) are also shown on this graph. Given that $CO_2$ in the atmosphere today has reached ~400 ppm in some places, this figure clearly shows that our present-day $CO_2$ is at higher concentrations than at any time in the previous 800,000 years.

The third panel in Fig. 8.4 also shows the natural fluctuations of atmospheric $CO_2$ concentrations in the past. These have been found to correlate with variations in the Earth's temperatures, as shown in Fig. 8.5. The two lines show how closely past $CO_2$ and temperature have tracked one another over the past 800,000 years. There are clear, repeatable and significant oscillations that occur roughly every 100,000 years. These are the cold, glacial periods, characterised by lower concentrations of $CO_2$, and the warm, interglacial periods, characterised by higher concentrations of $CO_2$. These oscillations are understood to be initiated by Milankovitch cycles – changes in the Earth's orbit relative to the Sun, but the temperature signal is amplified by the changing $CO_2$.

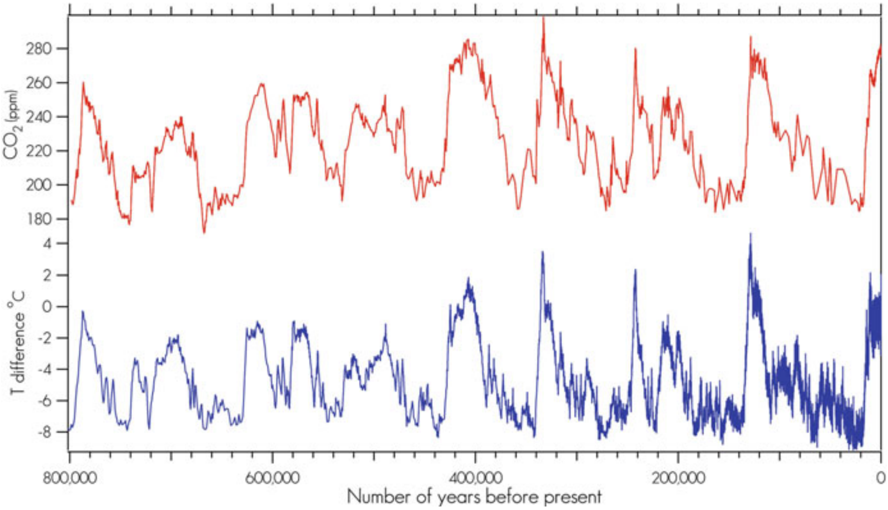



**Fig. 8.5** Ice-core data show that there is a very close connection between the concentration of carbon dioxide and temperature (which is determined from oxygen isotopes; Chaps. 4 and 5). This graph presents data from the EPICA Dome C ice core, Antarctica, and shows how these parameters have varied over the past 800,000 years. The temperature scale is a comparison to today's temperature (With kind permission from Jouzel et al. 2007 (temperature data), Lüthi et al. 2008 ($CO_2$ data))

### *8.3.4 Relevance of Ice-Core Data*

The information obtained from ice cores supports our understanding of the greenhouse gas properties of carbon dioxide, and the critical role it plays in enabling life on Earth.

Information obtained from ice cores identifies two important points. The first is the regular oscillation of $CO_2$ concentrations that correlate with the natural cycles of the Earth's orbit (Chap. 4). The second is that these changes remain within a fairly clear range of about 190–290 ppm. Some combination of ocean, atmosphere and terrestrial vegetation, superimposed on the orbital influence, kept the pre-industrial global carbon system within that range. Today, after about 150 years of human use of fossil fuels, atmospheric carbon dioxide concentrations have reached 400 ppm, significantly outside this range. Concentrations of this greenhouse gas are thus much higher than at any time in the past 800,000 years. An additional concern is the rate of increase: in the past when the Earth moved from a glacial period to an interglacial period, atmospheric $CO_2$ increased by about 70 ppm over 10,000 years; as a result of anthropogenic emissions, we are now witnessing an equivalent increase over the past ~150 years.

In this section we have focused on a very limited number of ice core parameters, namely $CO_2$ and temperature. Ice cores also hold a wealth of information about other atmospheric trace gases, for example methane and nitrous oxide. As a result, they also hold the potential to tell us about environmental changes during the past, such as variations in sea-ice extent, or changes in atmospheric transport patterns. Teasing out this information from ice-core data is no easy task and is the subject of intense, ongoing scientific research.

## 8.4 The Antarctic Stratospheric Ozone Hole

The ‘hole’ in the ozone layer is not only one of the most famous examples of atmospheric chemistry known to the general public, but is also an example of the importance and impact of a good relationship between science, the public and international politics.

Ozone has the capacity to absorb solar radiation (Box 8.3). It can do this at several wavelengths, but the most important for life on Earth is absorption of ultra-violet (UV)-B radiation at short wavelengths (<315 nm). The reason that this is so important is because this is exactly the part of the solar spectrum where DNA absorbs, so DNA can be critically damaged if it absorbs UV radiation.

Considering the critical role it plays for life on Earth, ozone concentrations in the stratosphere are surprisingly small. There are approximately between three and eight ozone molecules for every million other air molecules in the ozone layer (the precise number depends on latitude and season). The ozone layer is therefore not only a crucial but also a potentially vulnerable component of our Earth’s system.

**Box 8.3: Stratospheric Ozone**

To understand the importance of ozone for the stratosphere, and indeed, for life on Earth, we need to look at the reactions that generate it, and also ozone’s capacity to absorb solar ultra-violet radiation.

The reactions that generate ozone ($O_3$) involve molecular oxygen ($O_2$), atomic oxygen (O), a ‘third body’ (needed to absorb excess energy and prevent the reaction products splitting apart again), and solar radiation ($h\nu$). The third body is referred to below as ‘M’ but in fact is often nitrogen. The following sequence of reactions occurs in the stratosphere. Together, these reactions maintain a steady concentration of stratospheric ozone:

Ozone production reactions:

1. $O_2 + h\nu \rightarrow 2O$
2. $O + O_2 + M \rightarrow O_3 + M$

(continued)

**Box 8.3** (continued)
Ozone loss reactions:

3. $O + O_3 \rightarrow 2O_2$
4. $O_3 + h\nu \rightarrow O + O_2$

Different molecules in the atmosphere absorb radiation in different parts of the solar spectrum. Molecular oxygen is a very stable gas, and it requires very energetic radiation to split it into its component atoms (reaction 1). It takes less energy to split ozone molecules apart (reaction 4), and frequently ozone absorbs more energy than it needs, with the ‘left-over’ being released as heat. Reaction 2 also produces heat, and these two processes are important sources of heat to the stratosphere.

### *8.4.1 Halogens in the Stratosphere*

Chemical species are often categorised according to shared properties and characteristics. Members of one such group, collectively known as halogens, are central to processes that cause stratospheric ozone depletion. The most common halogen species are fluorine (F), chlorine (Cl), bromine (Br), and iodine (I).

Stratospheric ozone depletion has occurred as a result of emissions of manmade halocarbons. These are organic molecules that contain one or more halogen atom. They were first developed in the 1890s and used industrially from the 1930s onwards. The most potent of these in terms of ozone destruction are chlorofluorocarbons (CFCs), halons, methyl chloride and carbon tetrachloride, which all contain either chlorine or bromine atoms. The key characteristics of these compounds, which make them so attractive to industry, are that they are non-flammable, non-reactive, non-toxic, odourless and are gases at room temperature and below. This made them an excellent replacement for toxic chemicals such as ammonia, chloromethane and sulfur dioxide, which were used as early refrigerants. Some halocarbons were also used during the Second World War for extinguishing fires, and were later used widely in air conditioning, foam blowing, aerosol propellants, the production of industrial solvents and for cleaning electronic components.

Unfortunately, the exact characteristics that made halocarbons so attractive, and prolific, in industry are central to their role in stratospheric ozone depletion. The extreme non-reactivity of CFCs and halons in the lower atmosphere means that all emitted CFCs will, ultimately, be transported up to the stratosphere by global circulation patterns. Eventually, the chlorine and bromine they carry is released, and can result in the destruction of the ozone layer that is observed over Antarctica each spring – the Antarctic ozone hole.

**Box 8.4: Discovery of Antarctic Stratospheric Ozone Hole**

The potential danger posed by halocarbons to atmospheric ozone was recognised quite early. In 1974, Mario Molina and Sherwood Rowland published a paper in *Nature* suggesting that CFCs could damage ozone at around 40 km altitude, across the whole globe. According to chemical reactions known at that time, they calculated that between 5 and 10 % of ozone at this altitude would be destroyed over a period of 100 years. It turns out that Roland and Molina were correct in anticipating the danger to ozone posed by chlorine, but did not predict the specific threat to the ozone layer above Antarctica because their model did not include the heterogeneous processes that occur on polar stratospheric clouds. Many years later, their work on ozone, as well as that of another scientist, Paul Crutzen, was recognised with the Nobel Prize.

Stratospheric ozone has been monitored at various stations in Antarctica since the 1950s. In the early 1980s, scientists realised that ozone concentrations over Antarctica each spring were rapidly declining, and were considerably lower than earlier observations. In 1985, three scientists from the British Antarctic Survey (Joe Farman, Brian Gardiner and Jonathan Shanklin) published a paper in *Nature* reporting the extraordinarily low ozone over Halley station, Antarctica. They correctly linked the decline in ozone to an increase in the use of CFCs, and therefore an increase in reactive chlorine in the stratosphere. Soon afterwards, satellite observations confirmed springtime ozone depletion across Antarctica that had been occurring since the early 1980s and was centred over the South Pole. A major investigation was implemented in 1987 that included the use of special high-altitude aircraft, satellites, radar and lasers to probe activity in the stratosphere. The combination of these research methods confirmed that the ozone layer was being destroyed, and that the agents responsible were primarily chlorine and bromine atoms that had originated as industrial halocarbons.

### *8.4.2 Halogen Reservoir Gases*

Halogen atoms are extremely reactive, but the products of their reactions are much more stable molecules. Therefore, molecules that contain halogens, such as CFCs and halons, are often quite unreactive. As a result, common atmospheric gases do not break them down. Indeed, the only effective way of breaking these particular halocarbons down is with high-energy radiation, such as the UV-B light that is present in the stratosphere above the ozone layer.

The light-induced chemical breakdown (photolysis) of CFCs and halons in the stratosphere produces highly reactive chlorine and bromine atoms, which immediately undergo various chemical reactions with other gaseous species in the air. They form relatively stable products such as hydrogen chloride (HCl) and chlorine nitrate ($ClONO_2$), which do not react directly with ozone. These products are referred to as 'reservoir gases' because they provide an effective means of distributing halogens throughout the stratosphere, including in the polar regions.

### *8.4.3 The Polar Vortex and Polar Stratospheric Clouds*

The Antarctic winter lasts for several months, is extremely cold and completely dark. The vast winter temperature difference between the equator and the South Pole drives strong winds that circle the Antarctic continent. Known as the polar vortex, this circulation system effectively prevents air moving either into, or out of, the polar stratosphere. Stratospheric air containing halogen reservoir gases is thus essentially isolated during the Antarctic winter.

The polar vortex that establishes over Antarctica in winter is central to stratospheric ozone depletion. The extremely cold temperatures of the stratosphere during the polar winter enable the development of polar stratospheric clouds (PSC) (Box 8.5). These clouds have two important properties: they contain certain impurities, and they provide surfaces, which allow a very specific suite of chemical reactions to proceed. The most important of these reactions is:

$$ClONO_2(g) + HCl(s) \rightarrow Cl_2(g) + HNO_3(s)$$

The (s) in the equation refers to 'solid' and the (g) means the molecule is in the gas phase. Such reactions proceed on solid PSC surfaces throughout the months of the polar night, converting halogen reservoir gases (such as $ClONO_2$) into photo-labile forms (such as $Cl_2$), which are stable in the dark but which can be split apart easily by sunlight. The lack of sunlight means that there is a steady build-up of these photo-labile compounds inside the polar vortex during the polar winter. At the end of the winter, the sun returns to the Antarctic stratosphere, triggering photolysis reactions that rapidly release halogen atoms. What follows next is massive ozone destruction.

**Box 8.5: Polar Stratospheric Clouds**

Until the advent of measurements from space, it was thought that the very dry stratosphere did not often contain clouds. This view changed dramatically following the launch of the Stratospheric Aerosol Measurement (SAM) II instrument on the Nimbus 7 spacecraft in October 1978. Although the

(continued)

**Box 8.5** (continued)
instrument was designed to measure how much light was attenuated by aerosols above the polar regions, unexpected results that were observed when the stratospheric temperature was extremely low led to the discovery of polar stratospheric clouds (PSCs).

PSCs form during the polar winter and early spring, between about 60°S latitude and the South Pole, and between 10 and 25 km altitude. The clouds are classified into Types I and II according to their particle size and formation temperature. Type I PSCs form slightly above the ice frost point (about −83 °C) and are composed mostly of hydrated drops of sulfuric and nitric acid. Type II clouds are composed of ice crystals and form below the ice frost point. PSCs play a central role in the formation of the ozone hole. They contain impurities that react with halogen reservoir gases, and provide surfaces upon which these reactions take place. The reactions produce photolabile halogen gases. When PSCs occur inside the polar vortex, these gases are isolated and build up in concentration. When the sun arrives in spring, photolysis rapidly produces active halogen atoms that destroy ozone molecules (Fig. 8.6).

**Fig. 8.6** This image shows a 'mother-of-pearl' polar stratospheric cloud, enhancing a dramatic sunrise at McMurdo Station as work crews prepare Pegasus Ice Runway for incoming flights in early September (With kind permission from Jack Green/NSF)

### 8.4.4 Chemical Reactions in the Polar Vortex

The halogen atoms (Cl and Br), which are produced by photolysis inside the polar vortex, initially react with ozone via standard reactions to form ClO or BrO:

$$Cl + O_3 \rightarrow ClO + O_2$$
$$Br + O_3 \rightarrow BrO + O_2$$

While such reactions may also occur at lower latitudes, the subsequent pathways do not. Because of the containment of air within the vortex, concentrations of ClO can increase to unusually high levels, and at these very high concentrations different reaction pathways become important. The ozone destruction cycles operative within the Antarctic vortex are shown below:

Polar Ozone Destruction Cycle 1

$$ClO + ClO \rightarrow (ClO)_2$$
$$(ClO)_2 + \text{sunlight} \rightarrow ClOO + Cl$$
$$ClOO \rightarrow Cl + O_2$$
$$2(Cl + O_3 \rightarrow ClO + O_2)$$
$$\text{Net} : 2O_3 \rightarrow 3O_2$$

Polar Ozone Destruction Cycle 2
Either:

$$ClO + BrO \rightarrow Cl + Br + O_2$$

Or:

$$ClO + BrO \rightarrow BrCl + O_2$$
$$BrCl + \text{sunlight} \rightarrow Br + Cl$$

Then:

$$Cl + O_3 \rightarrow ClO + O_2$$
$$Br + O_3 \rightarrow BrO + O_2$$
$$\text{Net} : 2O_3 \rightarrow 3O_2$$

The cycles are catalytic, which means they destroy ozone while regenerating the halogen atoms. With these reaction mechanisms, ozone is rapidly destroyed and within a matter of a few weeks the ozone hole is formed.

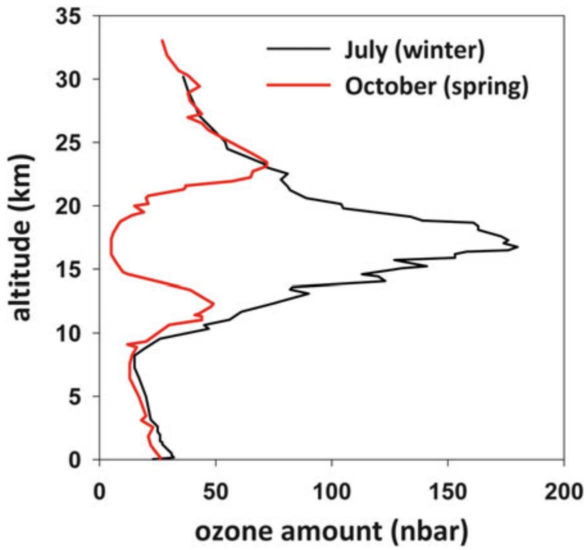



**Fig. 8.7** This figure shows measurements made by instruments carried on balloons that are used to probe the concentrations of ozone at various heights. The *black line* shows the profile of ozone measured in July (i.e. during the winter) above Halley Research Station, Antarctica. The *red line* shows the ozone profile in early October. This is only a few weeks after the sun has returned. The difference in the measurements shows that within the space of a few weeks, nearly all of the ozone in the ozone layer has been destroyed (Jones 2008, and with kind permission from BAS)

### *8.4.5 Stratospheric Ozone Depletion*

Key ingredients for stratospheric ozone depletion in Antarctica are the formation of the polar vortex, the presence of gases that contain chlorine and bromine atoms, the presence of polar stratospheric clouds and the arrival of sunlight following a long, cold polar winter. An important factor that makes this chemical and physical cocktail so potent is the fact that PSCs form at the same altitudes as the heart of the ozone layer, so the associated chemistry has a high impact (Fig. 8.7).

Towards the end of the Antarctic spring, as the atmosphere warms, the vortex breaks down, flushing in air from lower latitudes that are rich in ozone. Concentrations of stratospheric ozone over Antarctica return to normal for the rest of the year, until the following winter, when the vortex forms and the atmosphere is primed for rapid ozone depletion once again.

### *8.4.6 The Montreal Protocol*

Although the potential for halocarbons to have an effect on the stratospheric ozone layer was first raised in the 1970s, it was only in the 1980s that a definite ozone hole over Antarctica was identified and investigated (Box 8.4).

In 1987, the Montreal Protocol was drawn up to limit the production and use of substances that deplete the ozone layer, including CFCs. The protocol was followed up by a series of amendments, such that all developed countries agreed to phase out production of CFCs by the year 2000. By the end of 2009, all UN member states had signed the basic protocol and all CFC production anywhere should have stopped by 2010. The Montreal Protocol is hailed as one of the most successful examples of international agreement and interaction between science and international policy, and it was used as an example of best practice in the development of policy about a different global environmental concern many years later: climate change.

In response to the Montreal Protocol, CFCs have been replaced by other compounds including hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs). These have similar properties to CFCs but cause less damage to the ozone layer (although they are greenhouse gases and so have other implications). The success of the Montreal Protocol has meant that the amount of ozone-depleting substances in the stratosphere is now starting to decrease. There has so far not been any clear evidence to suggest that the ozone hole is recovering, or becoming smaller. However, the continued increase in the size of the ozone hole that occurred through the 1990s seems to have ceased. This can be ascribed to the fact that most of the ozone in the core of the vortex, at the key altitude and temperatures where the reactions occur, is now being destroyed. There is therefore little opportunity for further destruction. Recovery of the ozone hole back to its natural levels is, however, predicted to occur, but not until roughly 2070–2080. Figure 8.8 shows how the ozone hole has developed and changed since the start of measurements in the 1970s.

### *8.4.7 Linkages Between Climate and Stratospheric Ozone*

The relationship between stratospheric ozone and climate is complex and still the subject of much research. Anthropogenic (manmade) climate change, and stratospheric ozone depletion are two separate issues, which have both come about due to societal developments since the industrial revolution. Both phenomena, either directly or indirectly, are having an impact on the global climate system.

The increase of $CO_2$ and other greenhouse gases in the troposphere has had the effect of warming the troposphere. This has been most clearly demonstrated by a global average increase in surface temperature, an increase in sea level and a reduction in the extent of snow and ice over the past century (IPCC AR5, Summary for Policy Makers) (Chaps. 4 and 25).

The increased absorption, or trapping, of infrared radiation by greenhouse gases in the troposphere means that less of this radiation is available for absorption in the stratosphere. The result is a cooling effect in the stratosphere.

This stratospheric cooling is compounded by the existence of the ozone hole. Ozone in the stratosphere absorbs incoming solar radiation, so an additional effect of a loss of ozone is a cooling of the stratosphere. Indeed, observations of

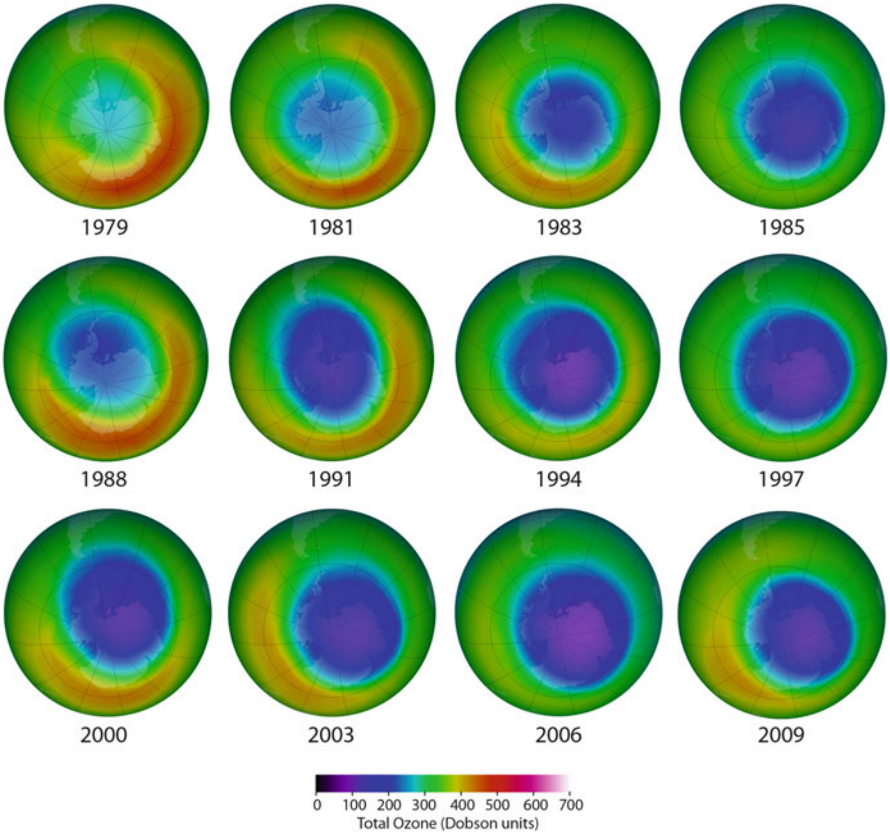



**Fig. 8.8** Long-term changes in Antarctic total ozone are demonstrated with this series of total ozone maps derived from satellite observations. Each map is an average during October, the month of maximum ozone depletion over Antarctica. Please note that the ozone maps in the first line are 2 years apart, while the interval changes to 3 years thereafter (With kind permission from NASA Ozone Watch)

stratospheric temperatures over 30 years have shown that the stratosphere is cooling. This is likely to be due to the combination of effects from both tropospheric warming and stratospheric ozone depletion.

Although we anticipate a recovery of stratospheric ozone over the next 60 years or so, emissions of greenhouse gases are likely to increase and will continue to cool the stratosphere. Stratospheric temperatures are thus likely to remain suppressed, and their coupled influence on tropospheric circulation patterns is likely to pervade well into the future.

As a further impact, a cooler stratosphere encourages the formation of polar stratospheric clouds. Indeed, the amount of PSCs that have formed during the Antarctic winter has increased over the past 30 years. Since PSCs are central to ozone-depleting processes in the vortex, an increase in PSCs may therefore delay the ultimate recovery of the ozone hole, even if the concentration of chlorine and bromine in the stratosphere is decreasing (as a result of the Montreal Protocol).

Like all clouds, PSCs absorb outgoing radiation from the Earth, resulting in a warming effect below their height, and a cooling effect above. The increased frequency of PSCs during the Antarctic winter could therefore increase temperatures in the mid-troposphere at that time of the year, and explain the increased warming in this area that has been observed.

Another implication of the Antarctic ozone hole on climate is the impact of the replacements for ozone-depleting substances (ODSs). CFCs and halons are damaging to the atmosphere both because of their potential to destroy ozone, but also because they are greenhouse gases. The Montreal Protocol has banned the use of many ODSs, and by doing so, has made a significant contribution towards tackling climate change. However, some of the ODS replacements, such as HFCs and HCFCs are themselves potent greenhouse gases, and therefore have a warming effect on the climate.

Anthropogenic stresses on the troposphere and stratosphere are therefore not independent of each other. However, because these two regions of the atmosphere have very different physical and chemical properties, the two effects have complex repercussions. The intricate relationship between the chemical composition of the air in different regions and physical circulation patterns are studied with the use of complex global climate models and verified through a comparison between these simulations and real-time measurements. Further discussion about the interconnectivity of atmospheric processes, including wider implications of the ozone hole, is covered at the end of this chapter.

## 8.5 Chemical Phenomena in the Antarctic Troposphere

Tropospheric chemistry is strongly influenced by emissions of trace gases from the Earth. These might be emitted from the oceans (marine emissions), from living organisms (biogenic emissions), or from manmade (anthropogenic) sources. Such emissions often comprise relatively reactive trace gases, and therefore add some complexity and diversity to the mix of chemical reactions. Although the Antarctic troposphere is pristine relative to the rest of the world, several interesting processes are occurring as a result of chemicals that are produced during freezing and thawing of sea ice, or which are imported from lower latitudes.

### *8.5.1 Measurement of Trace Gases in Antarctica*

Because Antarctica is remote from most sources of emissions, it has been historically assumed that the chemistry of the Antarctic troposphere would be relatively dull, dominated by stable chemicals, and with few interesting processes.

Furthermore, the anticipated very low concentrations of trace gases would be a real challenge to measure. As a result, the Antarctic troposphere remained relatively unstudied until the 1990s when instruments with the necessary sensitivity to measure low concentrations were developed. Exploration of the Antarctic troposphere was also encouraged by studies in the Arctic troposphere that had started to reveal some interesting results.

Contrary to expectations, the chemistry of the Antarctic troposphere has proved to be complex. The key to the unanticipated chemistry is that trace gases are emitted directly into the Antarctic troposphere, from sources that had not previously been thought of: namely, from the snow itself, and from the sea ice surrounding the continent.

Many chemical reactions that occur in the troposphere involve very fast oxidation processes driven by trace gases that include oxygen. An important example is the hydroxyl radical (OH), which is produced in the atmosphere by the natural interaction of oxygen, water vapour and light. It is a major driver behind many oxidation processes in the Antarctic troposphere.

Recent studies have shown that the hydroxyl radical is also produced as a result of emissions from the snowpack. Snow is not just made up of frozen water, but contains small amounts of natural impurities. The action of sunlight on these impurities generates trace gases that are released to the atmosphere. Many of these trace gases are in turn sources of the hydroxyl radical, a crucial oxidant in atmospheric chemistry.

The other suite of chemicals that act as powerful oxidants is the halogen family. The halogens that drive chemistry in the Antarctic troposphere are predominantly bromine and, to a lesser extent, iodine. The main source of these halogens in the troposphere is the ocean and the sea ice around Antarctica. The following sections discuss the relationship and interplay between these two types of oxidants in the Antarctic troposphere.

### *8.5.2 Surface Ozone and Ozone Depletion Events*

Ground level ozone, or ‘surface ozone’, has been measured at a number of Arctic and Antarctic stations for several decades. Analysis of these year-round records shows that there are occasions during spring, at coastal stations, when surface ozone is depleted and sometimes almost completely destroyed. These tropospheric ozone depletion events (ODEs) were originally observed in the Arctic and thought to be associated with northern hemisphere pollution. Scientists then measured in unpolluted coastal Antarctica, where they also found ODEs. These Antarctic measurements confirmed that ODEs were natural phenomena, driven by natural processes. This was an important step in determining the processes involved.

We now know that this ozone depletion is driven by bromine chemistry, in a suite of reactions that are completely natural. This is an important distinction from stratospheric ozone depletion, which was discussed earlier.

Bromine is released to the atmosphere from sea-ice surfaces in a series of reactions referred to as the 'bromine explosion'. Each year, sea ice grows around the coast of Antarctica during the cold months of autumn, winter and early spring. With the warmth of the sun, the ice melts, and then re-forms the following year. The annual maximum in sea-ice area is roughly 18 million $km^2$, compared with the minimum of roughly 2.5 million $km^2$. There is thus a vast coverage of sea ice, and also an enormous amount of new sea ice forming each year.

Sea ice forms by the process of seawater freezing. As seawater cools, pure (salt-free) ice starts to form, and salts in the seawater are expelled both downwards, to the water below, and also upwards, creating pools of very saline solution (brine). Although the exact processes are not fully understood, it is clear that this salty environment of the sea-ice zone is a source of reactive bromine to the atmosphere. We will focus specifically on bromine because this dominates halogen-driven oxidation in the troposphere.

Springtime in the polar coastal regions has a unique combination of melting and reforming sea ice, low temperatures and sunlight, which are central to the processes that release halogens. This has been confirmed by measurements showing that the highest concentrations of bromine trace gases in Antarctica are found during the spring.

### *8.5.3 Impact of Bromine in the Antarctic Troposphere*

There are two major influences of bromine chemistry in the Antarctic troposphere. The first is its influence on ground level ozone, and the second is its influence on mercury chemistry.

Bromine that is released during the bromine explosion reacts with ozone. It is the primary agent responsible for tropospheric ozone depletion events discussed above. During these events, the normal chemical composition of the troposphere becomes distorted. Instead of ozone and its chemical relations driving oxidation processes, halogens dominate these processes. This results in different reactions, with different molecules, at different speeds, and with very different outcomes.

One such example is mercury. Gaseous elemental mercury, which is relatively passive, is converted by bromine compounds to a form that deposits to the snow surface. During the spring melt, this mercury is flushed into the ocean where it can enter the food web. This is a serious concern because mercury is extremely toxic. While there are various natural sources of mercury to the global atmosphere, such as volcanoes and forest fires, a significant fraction comes from recent anthropogenic sources (e.g. chemical, industrial and power plants). Global circulation patterns then carry this gaseous mercury towards the polar regions. It has been estimated that about half of the mercury deposited in the Arctic has recent anthropogenic sources.

Particularly high concentrations of mercury have been found in marine mammals and people living in the Arctic. This has triggered an extremely difficult debate about the health of people living in the Arctic, and the impossible decision about whether or not to eat traditional food from the sea, which is full of essential nutrients and fats but which also contains poisonous mercury. Antarctica is located further from sources of mercury than the Arctic and therefore has lower concentrations of gaseous mercury – about 60 % of amounts found in the Arctic. However, soils, lichens and mosses downwind of a polynya, i.e. open water, in Antarctica have still been found to contain higher concentrations of mercury than those found far from the open water and sea ice.

Thus, although the Antarctic troposphere is relatively unpolluted, emissions from the cryosphere – the sea ice and the snowpack – drive a broad and complex suite of chemical reactions. By studying processes that are occurring in this pristine, and relatively simple, environment, we are better able to understand processes that are occurring in more polluted regions of the Earth, including the Arctic, as well as the interconnectivity of the whole Earth System.

## 8.6 Connectivity of Atmospheric Processes

The global atmosphere provides a critical connection between all surfaces on Earth: from ice and snow in the polar regions, to desert dust, tropical forests and industrialised areas with high human populations.

The physical properties of the atmosphere are essential for life on Earth. In the stratosphere, the ozone layer protects the surface from incoming UV radiation that would harm living matter. In the troposphere greenhouse gases absorb outgoing IR radiation and warm the atmosphere such that the temperature of the Earth has water in a liquid state.

Chemical processes in the atmosphere break down anthropogenic pollution and biogenic emissions through a series of oxidation reactions that maintain a stable atmospheric composition. Changes to either the physical or chemical properties of the atmosphere therefore have the potential to affect global processes in unforeseen ways. This has been observed in the case of halocarbons triggering catalytic destruction of stratospheric ozone, and anthropogenic greenhouse gas emissions having an impact on global climate. The study of past atmospheres as well as the present-day atmosphere in polluted and unpolluted areas is therefore central to our understanding of the entire Earth system.

In this chapter, we have explored the Antarctic atmosphere by considering past and present carbon dioxide concentrations in the troposphere, ozone depletion in the stratosphere, and spring-time tropospheric chemistry. The processes described are subtle and complex, and, significantly, are also interlinked. They also interact with other physical and chemical processes that are described elsewhere in this book.

Tropospheric warming and stratospheric ozone depletion, for example, both have a cooling effect on the stratosphere (Sect. 8.4.7). This, in turn, has an impact on atmospheric circulation patterns with the result that the westerly winds that define the springtime stratospheric vortex have accelerated (Chap. 6). The increases in these Southern Ocean westerly winds have been associated with changes in oceanic circulation patterns (Chap. 7). The Southern Ocean is an important sink for anthropogenic $CO_2$ so the result of these circulation changes could have a significant effect on global climate.

In addition, stratospheric and tropospheric wind patterns are interlinked such that stratospheric ozone loss has been found to be influencing the Southern Annular Mode and its associated climatic influence (Chap. 25).

An understanding of atmospheric chemistry is also critical for the interpretation of ice-core data (Chap. 5). This data can only be unraveled with an understanding of chemical and physical processes that occur in the air and snow in Antarctica prior to becoming trapped in an air bubble in the ice. A considerable amount of research is therefore carried out into present-day air-snow-ice processes.

The atmosphere is extremely fluid, and responsive to change, and it provides a critical link between the more geographically restricted regions of the Earth such as land, ice and oceans. Atmospheric science therefore focuses not only on processes occurring within the air, such as stratospheric ozone depletion, but also on the interconnectivity with the rest of the Earth system. Given these complex interactions, the way Antarctica responds to, or has an effect on, changes in global climate is extremely complex and remains a critical area for future scientific research.

## Bibliography

British Antarctic Survey, The Ozone Hole (2012). http://www.antarctica.ac.uk/about_bas/publications/bas_the_ozone_hole.pdf

Carlisle R (2004) Scientific American inventions and discoveries. Wiley, New York, p 351. ISBN 0-471-24410-4

EPICA Community Members (2004) Eight glacial cycles from an Antarctic ice core. Nature 429:623–628

Etheridge DM, Steele LP, Langenfelds RL, Francey RJ, Barnola J-M, Morgan VI (1996) Natural and anthropogenic changes in atmospheric $CO_2$ over the last 1000 years from air in Antarctic ice and firn. J Geophys Res 101:4115–4128

Farman JC, Gardiner BG, Shanklin JD (1985) Large losses of total ozone in Antarctica reveal seasonal ClOx/NOx interaction. Nature 35:207–210

Grannas AM, Jones AE, Dibb J, Ammann M, Anastasio C, Beine HJ, Bergin M, Bottenheim J, Boxe CS, Carver G, Chen G, Crawford JH, Dominé F, Frey MM, Guzmán MI, Heard DE, Helmig D, Hoffmann MR, Honrath RE, Huey LG, Hutterli M, Jacobi HW, Klán P, Lefer B, McConnell J, Plane J, Sander R, Savarino J, Shepson PB, Simpson WR, Sodeau JR, von Glasow R, Weller R, Wolff EW, Zhu T (2007) An overview of snow photochemistry: evidence, mechanisms and impacts. Atmos Chem Phys 7:4329–4373. doi:10.5194/acp-7-4329-2007, http://www.wmo.int/pages/prog/arep/gaw/ozone_2010/ozone_asst_report.html

IPCC (2013) Summary for policymakers. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge (in press)

Jones AE (2008) The Antarctic ozone hole. Phys Educ 43(4):358–366, www.iop.org/journals/physed

Jouzel J et al (2007) Orbital and millennial Antarctic climate variability over the last 800,000 years. Science 317:793–796

Lüthi D, le Floch M, Bereiter B, Blunier T, Barnola J-M, Siegenthaler U, Raynaud D, Jouzel J, Fischer H, Kawamura K, Stocker T (2008) High-resolution carbon dioxide concentration record 650,000–800,000 years before present. Nature 453:379–382

MacFarling Meure C (2004) The natural and anthropogenic variations of carbon dioxide, methane and nitrous oxide during the Holocene from ice core analysis. PhD thesis, University of Melbourne

MacFarling Meure C, Etheridge D, Trudinger C, Steele P, Langenfelds R, van Ommen T, Smith A, Elkins J (2006) The law dome $CO_2$, $CH_4$ and $N_2O$ ice core records extended to 2000 years BP. Geophys Res Lett 33(14):L14810. doi:10.1029/2006GL026152

Molina MJ, Rowland FS (1974) Stratospheric sink for chlorofluorocarbons: chlorine atom-catalysed destruction of ozone. Nature 249:810–814

Pfaffhuber KA, Berg T, Hirdman D, Stohl A (2012) Atmospheric mercury observations from Antarctica: seasonal variation and source and sink region calculations. Atmos Chem Phys 12:3241–3251

Salmon RA, Carlson DJ (2007) International polar year – the poles and the planet. In: Stewart C, Green A (eds) EcoScience: the 34th Harry Messel International Science School. Science Foundation of Physics within the University of Sydney, Sydney, pp 146–161

Simpson WR, von Glasow R, Riedel K, Anderson P, Ariya P, Bottenheim J, Burrows J, Carpenter LJ, Frieß U, Goodsite ME, Heard D, Hutterli M, Jacobi H-W, Kaleschke L, Neff B, Plane J, Platt U, Richter A, Roscoe H, Sander R, Shepson P, Sodeau J, Steffen A, Wagner T, Wolff E (2007) Halogens and their role in polar boundary-layer ozone depletion. Atmos Chem Phys 7:4375–4418. doi:10.5194/acp-7-4375-2007

Steffen A, Douglas T, Amyot M, Ariya P, Aspmo K, Berg T, Bottenheim J, Brooks S, Cobbett F, Dastoor A, Dommergue A, Ebinghaus R, Ferrari C, Gardfeldt K, Goodsite ME, Lean D, Poulain AJ, Scherz C, Skov H, Sommar J, Temme C (2008) A synthesis of atmospheric mercury depletion event chemistry in the atmosphere and snow. Atmos Chem Phys 8:1445–1482. doi:10.5194/acp-8-1445-2008

Turner JT, Lachlan-Cope TA, Colwell S, Marshall GJ, Connolley WM (2006) Significant warming of the Antarctic winter troposphere. Science 311:1914–1917

Turner, J, Bindschadler, R, Convey P, di Prisco G, Fahrbach E, Gutt J, Hodgson D, Mayewski P, Summerhayes C (2009) Antarctic climate change and the environment. SCAR, Cambridge, http://www.scar.org/publications/occasionals/acce.html

Turner JT, Comiso JC, Marshall GJ, Lachlan-Cope TA, Bracegirdle T, Maksym T, Meredith MP, ZZhaomin W, Orr A (2009) Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent. Geophys Res Lett 36:L08502. doi:10.1029/2009GL037524

Von Glasow R (2008) Recent developments in tropospheric halogen chemistry. Science features, IGACtivities. http://www.uea.ac.uk/~fkd06bju/papers/vonGlasow_IGAC_2008.pdf

World Meteorological Organization, Scientific Assessment of Ozone Depletion (2010) Global ozone research and monitoring project, report 52, Geneva, Switzerland, p 516

# Part II
# Life Sciences

# Chapter 9
# Remote Ocean Outposts

## Biological Diversity of the Subantarctic Islands

**Peter W. Carey**

**Abstract** The subantarctic zone is a largely oceanic region found roughly within the latitudes of 40 and 60° South. This region is the threshold of Antarctica, a zone where the climate is less harsh than that found on the frozen continent itself, resulting in greater biological diversity. The landmass in this region is limited, consisting only of the southern cone of South America, and a handful of small, widely scattered islands. The terrestrial fauna of these remote islands is markedly poor when compared with that found on continental mainlands, and there is also considerable variability between island groups. Larger islands, and those closer to continents tend to host more species than smaller, more remote islands. Invasive species also have an enormous impact on the biodiversity of subantarctic islands.

**Keywords** Subantarctic • Biodiversity • Biosecurity • Invasive species • Conservation

## 9.1 Sovereignty

Lying north of 60° South, the subantarctic islands are not within the realm of the Antarctic Treaty. None of the 18 island groups is an independent country; all are claimed and administered as part of developed nations found in lower latitudes. New Zealand has the most extensive subantarctic portfolio with six island groups, followed by France (4), the United Kingdom (4), Australia (2), and South Africa (2). Argentina claims the Falkland Islands (and knows them as Islas Malvinas), and South Georgia, but these claims are generally not recognised outside Latin America.

Only the Falkland Islands, Chatham Islands, and Tristan da Cunha support permanent human communities. All the other island groups are uninhabited except for small numbers of researchers and support staff. These latter islands are administered as reserves and landing permits are required for anyone wishing to visit. Some allow strictly controlled tourist visits, while landings on others are completely prohibited (Fig. 9.1).

P.W. Carey (✉)
SubAntarctic Foundation for Ecosystems Research (SAFER), Christchurch, New Zealand
e-mail: peter@subantarctic.com; http://www.subantarctic.com



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_9


**Fig. 9.1** This map shows the location of subantarctic islands (Modified from Peat 2003, with kind permission from the New Zealand Department of Conservation)

What makes an island a subantarctic island? The very name ‘subantarctic’ tells us the islands are found at latitudes immediately below Antarctic latitudes. However, latitude alone does not define a subantarctic island. More crucial is the temperature of the water surrounding it. Strictly speaking, subantarctic islands are those that lie between the Subtropical Convergence zone, and the Polar Front (Antarctic Convergence). The water here ranges from 2 to 10 °C.

A few islands that fall just outside these oceanic boundaries are usually included in this category as they have much in common with the true subantarctic islands, while being quite dissimilar from land in any other zone (Table 9.1). The northern

**Table 9.1** Some components of the fauna of individual island groups

| Island groups | Latitude/ Longitude | Oceanic zone | Sovereignty | Number of breeding land birds | Number of breeding seabirds | Number of introduced mammals |
|---|---|---|---|---|---|---|
| St Paul | 38º 43'S 77º 31'E | north of Sub-tropical | France | 0 | 10 | 1 |
| Amsterdam | 37º 50'S 77º 33'E | north of Sub-tropical | France | 1 | 9 | 4 |
| Tristan da Cunha | 37º 07'S 12º 16'W | north of Sub-tropical | United Kingdom | 6 | 19 | 8 |
| Prince Edward | 46º 38'S 37º 56'E | north of Polar | South Africa | 1 | 28 | 0 |
| Marion | 46º 54'S 37º 44'E | north of Polar | South Africa | 1 | 26 | 2 |
| Macquarie | 54º 30'S 158º 55'E | north of Polar | Australia | 4 | 22 | 0 |
| Auckland | 50º 50'S 166º 00'E | north of Polar | New Zealand | 19 | 27 | 3 |
| Snares | 48º 00'S 166º 33'E | north of Polar | New Zealand | 10 | 19 | 0 |
| Campbell | 52º 30'S 169º 10'E | north of Polar | New Zealand | 10 | 19 | 0 |
| Antipodes | 49º 42'S 178º 45'E | north of Polar | New Zealand | 8 | 21 | 1 |
| Bounty | 47º 45'S 179º 01'E | north of Polar | New Zealand | 0 | 7 | 0 |
| Chatham | 44º 00'S 176º 30'E | north of Polar | New Zealand | 36 | 28 | 11 |
| Falkland / Malvinas | 51º 48'S 59º 25'W | north of Polar | United Kingdom | 41 | 22 | 11 |
| Gough | 40º 19'S 9º 56'W | north of Polar | United Kingdom | 2 | 20 | 1 |
| Crozet | 46º 24'S 51º 45'E | north of Polar | France | 1 | 36 | 4 |
| Kerguelen | 49º 18' S 70º 00'E | south of Polar | France | 2 | 33 | 7 |
| Heard | 53º 06'S 73º 33'E | south of Polar | Australia | 1 | 17 | 0 |
| South Georgia | 54º 20'S 36º 40'W | south of Polar | United Kingdom | 4 | 24 | 3 |

Data in this table are from the following references: (British Antarctic Survey 2004; Chown et al. 1998; Clark and Dingwall 1990; Crawford et al. 2003; Frenot 2007; Green and Woehler 2006; Headland 1992; Jouventin et al. 1984; Lebouvier and Frenot 2007; Macquarie Island Management Plan 2001; Miskelly et al. 2001, 2006; Parkes and Murphy 2003; Peat 2003; Reid 2007; Ryan 2007; Selkirk 2007; Tennyson et al. 2002; Warham and Bell 1979; Weimerskirch et al. 1989; Woods and Woods 2006)

**Fig. 9.2** Home to millions of seabirds, the soil on Snares Island is honeycombed with petrel burrows which are easily destroyed by visitors. Hence, like on most subantartic islands, special permits are required to land here (© Peter W. Carey)

outliers, lying on or just north of the Subtropical Convergence, are Tristan da Cunha, Amsterdam, St Paul, Snares and Chatham. These islands all have (or had) naturally occurring trees and other woody plants but they are also populated by fur seals, penguins, albatrosses and burrowing petrels (Fig. 9.2).

The southern outliers, lying just south of the Polar Front in Antarctic waters, are Kerguelen, Heard and South Georgia. All of these also support albatrosses, burrowing petrels, penguins and fur seals and all are partially glaciated. Islands closer to the Antarctic continent (e.g. South Shetland and South Orkney) are not included here as they are almost devoid of vegetation and are surrounded by frozen seas in winter. They are truly part of Antarctica. The term 'peri-Antarctic' is used by some authors (Headland 1989; Reid 2007) to denote all islands that lie north of the Antarctic continent, regardless of oceanic zone. However, this collating term does not allow for precise discussions of biological differentiation.

## 9.2 Limits to Biodiversity

Biologists have long noted the relative simplicity of island ecosystems. Most islands support far fewer species of plants and animals than are found on continental landmasses. In addition to this limited biodiversity, island organisms also show a high degree of endemism. Endemic species are those found exclusively in one particular place.

### 9.2.1 Isolation

Isolation from other landmasses is one of several factors that limit the number and variety of terrestrial species that inhabit subantarctic islands (Chown et al. 2000). In some cases, the islands are thousands of kilometres away from the nearest continent and these vast distances, over salt water – an extremely hostile environment for most land dwellers – are an insurmountable barrier to the natural immigration of most species.

Biodiversity is usually greater the closer an island is to a large landmass (Chown et al. 1998). For example, the southernmost portion of South America, Tierra del Fuego, has 545 species of native vascular plants (Moore 1983) compared with 171 on the Falkland Islands (530 km offshore), and 25 on South Georgia (2210 km away) (Chown et al. 1998). The distance also affects the type of plant that can bridge the gap, with species that have salt-tolerant seeds or associations with seabirds more likely to be successful. One example are the seeds of the small herb *Aceana magellanica*, which have hooked barbs that easily attach to feathers and have been observed stuck to the bodies of seabirds. This native of Patagonia is also found on the Falklands, South Georgia, and even Kerguelen Island in the Indian Ocean, over 7800 km away (Moore 1968).

### 9.2.2 Cool Climate

As small specks of land in a vast ocean, most subantarctic islands present no barrier to the moisture-laden winds that sweep strongly through these latitudes. The climate here is relatively cool, windy and wet. The more southerly groups will experience below-freezing temperatures in winter, but the mean annual temperatures on most islands are cool rather than cold (e.g. 5 °C at Macquarie) (Selkirk 2007). The temperature is stable, too, with little variance between winter and summer, e.g. $-1.5$ °C in winter and 5.6 °C in summer at South Georgia (Headland 1992). Precipitation is common in all months, as are the strong westerly winds that have led early mariners to christen these latitudes the Roaring Forties or the Furious Fifties. These cool conditions limit the number and types of species that can survive and many taxa are absent or poorly represented. Hence, any organism that somehow manages to cross a wide stretch of hostile ocean will still need to be able to cope with the island's harsh living conditions if it is to become established. This cool climate likely has a role in restricting the establishment of exotic species, although it is not enough to completely protect these islands from invasive plants and animals that have hitched a ride with human visitors (see below).

Biodiversity of plants and insects increases with temperature and some of the northerly islands such as Tristan da Cunha (64 plants, 38 insects) show about twice the species-richness found on southerly islands such as South Georgia (25 plants, 21 insects).

### *9.2.3 Glacial History*

Ten subantarctic island groups have been affected by glaciation at some point in their history, and four of these (Marion, Kerguelen, Heard and South Georgia) still bear some permanent ice cover. The remaining eight island groups have never been glaciated and therefore have potentially had a longer time with conditions suitable for colonisation and diverisfication. Some early research suggested that the extent of past glaciation had a strong influence on current biodiversity (Chown 1994; Kuschel 1971) but more detailed recent analyses do not support this (Chown et al. 1998).

### *9.2.4 Size*

Not surprisingly, larger islands often have more species since they have room for a greater variety of habitats (Clark and Dingwall 1990). Two neighbouring Indian Ocean islands illustrate this clearly: Amsterdam (55 ha) is only 90 km away from St Paul (8 ha). Both are volcanic in origin and both lie to the north of the Subtropical Convergence. Yet Amsterdam has 26 native species of vascular plants and 19 species of insects, while St Paul has only 9 plants and 13 insects.

## 9.3 Land Birds

While seabirds such as penguins and albatrosses are obvious residents of subantarctic islands, some island groups are also home to small numbers of terrestrial birds (Table 9.1). Birds have an advantage over more passive migrants like plants and insects since they are able to fly long distances, and can maintain a warm body temperature even in freezing conditions. Nevertheless, species numbers are low when compared with the number of seabirds on the same island, or, indeed, when compared with the number of land birds on continents. Among the subantarctic islands, the richest terrestrial avifauna is found on larger islands, and on islands closer to continents. The Falkland and Chatham Islands meet those conditions, and are the only two groups with more land birds than seabirds.

## 9.4 Land Mammals

Today, there are no native land mammals on any subantarctic island and, with only one arguable exception, land mammals have never naturally occurred on these remote islands. The one exception is the Falklands fox, or warrah (*Dusicyon* *antarcticus*), which was hunted to extinction in 1876. Its presence has long puzzled biogeographers and for many years the most plausible explanation suggested the warrah was brought to the islands in the canoes of the Yaghan people, residents of Tierra del Fuego, who were occasionally blown downwind onto the Falklands. However, recent evidence of an extinct close relative found on the Patagonian mainland now indicates the fox may have colonised the islands around 16,000 years ago, by walking across the frozen surface of the much narrower sea strait that then separated the Falklands from the continent (Austin et al. 2013).

## 9.5 Reptiles and Amphibians

There are no reptiles or amphibians found on any of the true subantarctic islands. As ectotherms they cannot regulate their body temperature from within and survival would be difficult in the cool conditions found on these islands. In continental South America, the world's most southerly lizards are found as far south as 53° (Scolaro 2005), but none have successfully colonised the remote islands of the Southern Ocean. However, as with many rules, there is an exception: one species of lizard (a skink, *Oligosoma nigriplantare nigriplantare*) is found on the Chatham Islands. Its presence there may be explained by the Chathams' relatively mild climate, as well as their position close downstream from the lizard-rich New Zealand mainland.

## 9.6 Seabirds

Marine birds are the most conspicuous animals found on subantarctic islands. They dominate the fauna in number of species as well as total population. Penguins are emblematic of the subantarctic and half of the world's species breed on the islands in the Southern Ocean (Fig. 9.3).

Albatrosses and petrels are also present in large numbers and most islands support several species of these wide-ranging foragers. Humans, as terrestrial beings, tend to view the vastness of the ocean as a barrier and a hostile environment. However, for penguins and petrels, these far-flung islands are conveniently located in the middle of their feeding grounds. The oceanic position gives them a central location on which to nest, while being close to the cold, productive waters where food is plentiful. For seabirds, the islands' locations are not a hindrance, but an advantage. Most islands are also home to near-shore seabirds such as gulls, skuas, terns and cormorants. On most island groups, the number of seabird species is vastly greater than the number of land bird species.

**Fig. 9.3** Thousands of breeding pairs of king penguins congregate at a colony on South Georgia. The fuzzy brown blobs are downy chicks (© Peter W. Carey)

### *9.6.1 Procellariiformes (Tube-Noses)*

Ranging in size from the 9 kg royal albatross to the 35 g storm petrel, the tube-noses all have distinctive tube-shaped nostrils which sit prominently on top of their bills. Most members of this group are long-distance foragers and some albatross species routinely cover thousands of kilometres in a single feeding trip. Petrels, shearwaters and albatrosses all have long, thin wings that are excellent for soaring in the windy open ocean (Fig. 9.4).

The royal, *Diomedea epomophora*, and wandering, *D. exulans*, albatrosses have the longest wingspan of any bird, with large individuals reaching 3.5 m from tip to tip. Using these glider-like wings, albatrosses exploit the wind and the way it deflects off ocean swells. These birds can easily cover 900 km in a day (Jouventin & Weimerskirch 1990). On the Crozet Islands, wandering albatrosses fitted with satellite tracking devices made foraging trips that averaged 5991 km (Weimerskirch et al. 1997). These long feeding trips occur during the incubation stage, when the birds do not yet have chicks to feed. In the initial stages after hatching, when the chick requires frequent feeding, the average round trip foraging flight drops to 'only' 500 km.

Another tube-nose that uses its narrow wings to record-setting effect is the sooty shearwater, *Puffinus griseus*, which has the longest measured annual migration of any animal. They nest in burrows on many subantarctic islands, but spend their

**Fig. 9.4** Southern royal albatrosses display near their nesting area on Campbell Island. Royal and wandering albatrosses have the longest wingspans of any birds, reaching up to 3.5 m (© Peter W. Carey)

winters in the north Pacific, near Alaska. The figure-of-eight migratory path they take means they fly over 64,000 km each year (Shaffer et al. 2006).

The smallest members of the Procellariiformes are the diving petrels and the storm petrels. These tiny birds lack the glider wings of the albatrosses, shearwaters and other petrels, and use their more modest appendages for feeding in a different way. The diving petrels, *Pelecanoides spp*., use their short, stubby wings to propel themselves underwater, 'flying' through a different medium than most birds. The storm petrels have large wings for their slight weight and are able to virtually hover on the surface, picking up copepods and other pelagic crustaceans while seemingly walking on water. The name 'petrel' comes from this behaviour, a reference to the Biblical account of St Peter walking on water.

In the subantarctic, all tube-nose species except the giant petrels and albatrosses, nest in underground burrows. Subterranean nesting provides them with shelter from bad weather and protection for the chicks from predators such as skuas. On many islands, the ground is so honey-combed with seabird burrows that visitors must be careful where they walk, lest they cave in the roof of a petrel burrow.

### *9.6.2 Penguins*

Well adapted for life in cold, harsh environments, penguins are found on all subantarctic island groups. Four species are endemic to the subantarctic: king, *Aptenodyptes patagonicus*, found on several island groups; erect-crested, *Eudyptes*

**Fig. 9.5** Rockhopper penguins return to Maqcquarie Island with food for their chicks. You can tell these birds have just returned from the sea because their feathers are not yet sullied with the mud and guano of the breeding colony (© Peter W. Carey)

*sclateri*, found only on Bounty and Antipodes; Snares crested, *E. robustus*, found only on Snares; and royal, *E. schlegeli*, found only on Macquarie.

Other species include the Magellanic penguin, *Spheniscus magellanicus*, the gentoo, *Pygoscelis papua*, the rockhoppers, *E. moseleyi* and *E. chrysocome*, macaroni, *E. chrysolophus*, and yellow-eyed, *Megadyptes antipodes*. A small population of chinstrap penguins, *Pygoscelis antarctica*, nests at the south end of South Georgia. This is the only place outside Antarctica where this species breeds (Fig. 9.5).

Penguins are very much at home in the water and are the best divers among all birds. Their flipper is a highly modified wing that works very effectively as a paddle, allowing penguins to 'fly' through the water to catch fish, squid, krill and other prey that is beyond the reach of other avian predators. Penguins need land only for nesting and moulting, and most species spend much of the year at sea. During the summer breeding season most subantarctic species nest in large colonies. For several species, colonies of over 10,000 pairs are not uncommon. The world's largest penguin colony is found on Cochon Island in the Crozet group, where 494,000 pairs of king penguins were counted in 1988 (Guinet et al. 1995).

## 9.7 Marine Mammals

Several species of fur seals live in densely-packed colonies on the islands of the subantarctic. Indeed, the commercial harvest of these animals was the driving force for much of the exploration of the region (Chap. 20). Fur seals were nearly

**Fig. 9.6** An Antarctic fur seal pup suckles from its mother on South Georgia. This species of fur seal nurse their pups for about 4 months, after which age they are on their own (© Peter W. Carey)

extripated from all the islands in the late 1700s and early 1800s, but after almost two centuries of legal protection and no hunting, their populations are once again thriving. Four species of fur seal inhabit the region. The Amsterdam fur seal, *Arctocephalus tropicalis*, predominates on the northerly islands in the Atlantic and Indian oceans, while the Antarctic fur seal, *A. gazella*, favours the southermost islands in all oceans. The New Zealand fur seal, *A. forsteri*, inhabits the islands south of that nation, and the South American fur seal, *A. australis*, is found in small numbers in the Falkland Islands (Fig. 9.6).

In addition, the South American sea lion, *Otaria flavascens*, is found on the Falklands and the New Zealand, or Hooker's, sea lion, *Phocarctos hookeri*, is found on Auckland, Campbell and Snares islands.

The largest seal in the world, the southern elephant seal, *Mirounga leonina*, breeds on many subantarctic islands. Males can reach lengths of over 5 m and weigh up to 3700 kg. Females are considerably smaller, topping out at 3 m and 800 kg. A small number of Weddell seals, *Leptonychotes weddelli*, breed at the southern tip of the southernmost subantarctic island, South Georgia, but this is the only place outside of Antarctica where they do so.

## 9.8 Introduced Mammals

With the exception of the strongly influential marine environment, nothing has had a bigger impact on the existing biodiversity of the subantarctic islands than the exotic mammals that have been introduced upon them. Only six island groups are without any introduced mammals, and the natural ecosystems on these islands are wonderfully intact (Table 9.1). Elsewhere, cattle, pigs, goats, sheep, reindeer, foxes, rabbits and even guanacos were deliberately brought ashore and established

**Fig. 9.7** Reindeer were brought from Norway and established on South Georgia to provide meat and sport for the whalers based there during the early twentieth century. While they don't bother fur seals, their grazing does destroy the fragile native vegetation and efforts are being made to eradicate them (© Peter W. Carey)

by men hoping to lay the groundwork for a reliable future food source or income (Fig. 9.7).

The negative impacts of these introduced species are obvious and dramatic. Omnivorous pigs chew through succulent endemic plants, dig petrels out of their burrows, and snack on albatross chicks as they sit in their nests. Cattle cause soil erosion as a result of their over-grazing, and their heavy hooves destroy petrel burrows wherever they walk.

Rats, *Rattus norvegicus* and *R. rattus,* are the most widespread of the introduced pests, and these opportunistic feeders have been responsible for the extinctions of many island birds. Rats, as well as mice, *Mus musculus*, were not deliberately introduced, but escaped to shore from many of the ships that visited the islands soon after discovery. Cats, *Felis silvestris catus*, originally brought to some islands to combat the mice and rats, found that ground-nesting seabirds were easier prey and therefore compounded the problem (Fig. 9.8).

Of the six mammal-free groups, four (Snares, Prince Edward, Bounty and Heard) have always been pristine. On the fifth and sixth, Macquarie and Campbell Islands, all introduced mammals have been deliberately eradicated by hunting and poisoning. In their absence, the native plants and animals have flourished, providing encouragement that, with proper management, the unique ecosystems of the subantarctic islands can be restored and preserved.

**Fig. 9.8** Rats are the most widespread invasive species in the subantarctic and their opportunistic feeding and prolific breeding has seen them cause the most damage to native species (© Peter W. Carey)

## 9.9 Biosecurity and the Management of Invasive Species

Biosecurity is the term used to describe efforts to limit the introduction and establishment of exotic species. On subantarctic islands, the need for biosecurity measures is well understood and most of the island groups have management plans that include specific protocols to prevent introductions. Efforts have also been made to remove species that were introduced in previous centuries, before the negative consequences of invasive species were fully understood. New Zealand's Campbell Island is an example of what can be achieved with proper planning, political will and a lot of money.

By the middle of the twentieth century, Campbell Island was home to exotics like sheep, cattle, cats and rats. The grazing of sheep and cattle had substantially altered the vegetation while the cats and rats actively preyed upon nesting seabirds, land birds and terrestrial invertebrates. Rats arrived before any naturalists did, and their rapid establishment meant they eradicated the Campbell Island snipe before anyone knew this bird existed. This inconspicuous land bird was accidentally discovered in 1997, when a party of scientists made the first landing on a small neighbouring islet. Jacquemart Islet is so steep-sided that rats could not establish there, even if they swam the short distance from the main Campbell Island. Hence, snipe thrived on Jacquemart Island in an ecosystem unaltered by exotic mammals.

In 1970, the first eradication efforts were made on Campbell Island with the shooting of sheep from one third of its area. In 1976, cattle were removed and in 1984 a second portion of the island was cleared of sheep. The last sheep were eradicated from the remainder of the island in 1990–1991, leaving the island free of introduced grazing animals for the first time since 1895 (Kerr 1976). The vegetation quickly recovered. About this same time, the cats disappeared. The cause of this is not known for certain, but it is presumed they died out as a result of the change in habitat caused by the newly lush vegetation (Miskelly and Norton 2008) (Fig. 9.9).

**Fig. 9.9** Endemic Campbell Island daisies, *Pleurophyllum speciosum*, are conspicuous now that grazing animals have been removed from Campbell Island (© Peter W. Carey)

Norway rats were the last exotic species to be removed from Campbell Island and this was done in 2001. New Zealand's Department of Conservation used helicopters to drop cereal baits laced with brodifacoum poison over the entire island. This managed to kill every rat on the 11,268 ha island. In the absence of rats, snipe have now colonised the main Campbell Island and are breeding there successfully.

Eradication efforts do not always go as smoothly as on Campbell Island and valuable lessons were learned about the interconnectedness of introduced species when cats were removed from Australia's Macquarie Island (Bergstrom et al. 2009). Located 715 km to the southwest of Campbell Island, Macquarie was home to cats, rats, mice and rabbits in the latter part of the twentieth century. In 2000, the last cat on the island was killed and with it, the last serious predator of rabbits. Rabbit populations, which had been held in check by cat predation and the myxoma virus, increased dramatically and their grazing has completely denuded the vegetation from large areas. It has highlighted the need to confront exotic species with a comprehensive eradication plan, rather than a gradual approach.

**Fig. 9.10** With considerable effort, feral cats were eliminated from Macquarie Island. In their absence, rabbit populations exploded, causing widespread overgrazing and erosion, inadvertantly illustrating the need for a comprehensive approach to invasive species control (© Peter W. Carey)

This will have major implications for how such work is funded, since comprehensive clearances will be much more expensive than the previously used step-by-step approach (Fig. 9.10). Using a broad, well coordinated approach, the remaining three species of pests were declared extinct on Macquarie in 2014.

With their milder climate and more frequent human visitors, subantarctic islands are more vulnerable to invasive species than the Antarctic continent (Chap. 27). However, the Deep South is not immune to invasion. In 1998, gnats of the genus *Lycoriella* were spotted in Australia's Casey station, on the Antarctic mainland. Confined to the warm interiors of buildings, these flies got to Antarctica as stowaways in the base's food supplies. Despite intensive eradication efforts in 2005, they have survived inside the water treatment plant and associated structures and are still present in a few buildings (Hughes et al. 2005). A similar species is also found inside buildings at the UK's Rothera base, on the Antarctic Peninsula. Both the UK and Australia have strict biosecurity measures in place to try to prevent such invasions, but clearly any human traffic carries with it some risk of unwanted stowaways. In some isolated cases, these unwanted species can survive outside the warmth of buildings. The grass *Poa annua* became established on Deception

Island, in Antarctica's far north, while *P. pratensis* still survives at Cierva Cove on the Antarctic Peninsula. In both cases, these grasses are growing adjacent to scientific stations, although they are exposed to the full force of the Antarctic climate. Careful monitoring for invasive species is likely to be a key component in the environmental management of Antarctica in the twenty-first century.

## References


Austin JJ, Soubrier J, Prevosti FJ, Prates L, Trejo V, Mena F, Cooper A (2013) The origins of the enigmatic Falkland Islands wolf. Nat Commun 4:1552–1559

Bergstrom DM, Lucieer A, Kiefer K, Wasley J, Belbin L, Pederson TK, Chown SL (2009) Indirect effects of invasive species removal devastate World Heritage island. J Appl Ecol 46:73–81

British Antarctic Survey (2004) Checklist of the wildlife at South Georgia, British Antarctic Survey, Cambridge

Chown SL (1994) Historical ecology of subantarctic weevils: patterns and processes on isolated islands. J Nat Hist 28:411–433

Chown SL, Gremmen NJM, Gaston KJ (1998) Ecological biogeography of Southern Ocean islands: species-area relationships, human impacts, and conservation. Am Nat 152:562–575

Chown SL, Gaston KJ, Gremmen NJM (2000) Including the Antarctic: insights for ecologists everywhere. In: Davison W, Howard-Williams C, Broady P (eds) Antarctic ecosystems: models for wider ecological understanding. New Zealand Natural Sciences, Chirstchurch, pp 1–15

Clark MR, Dingwall PR (1990) Conservation of islands in the Southern Ocean. Cambridge University Press, Cambridge

Crawford RJM, Cooper J, Dyer BM, Greyling MD, Klages NTW, Ryan PG, Petersen SL, Underhill LG, Upfold L, Wilkinson W, De Villiers MS, Plessis SD, Toit MD, Leshoro TM, Makhado AB, Mason MS, Merkle D, Tshingana D, Ward VL, Whittington PA (2003) Populations of surface-nesting seabirds at Marion Island, 1994/95–2002/03. Afr J Mar Sci 25(1):427–440

Frenot Y (2007) Crozet Island (Iles Crozet). In: Riffenburgh B (ed) Encyclopedia of the Antarctic. Routledge, New York, pp 316–317

Green K, Woehler E (2006) Heard Island: Southern Ocean Sentinel. Surrey Beatty & Sons, Chipping Norton

Guinet C, Jouventin P, Malacamp J (1995) Satellite remote sensing in monitoring change of seabirds: use of Spot Image in King Penguin population increase at Ile aux Cochons, Crozet Archipelago. Polar Biol 15:511–515

Headland R (1989) Chronological list of Antarctic expeditions and related historical events. Cambridge University Press, Cambridge

Headland R (1992) The Island of South Georgia. Cambridge University Press, Cambridge

Hughes KA, Walsh S, Convey P, Richards S, Bergstrom DM (2005) Alien fly populations established at two Antarctic research stations. Polar Biol 28:568–570

Jouventin P, Stahl JC, Weimerskirch H, Mougin J-L (1984) The seabirds of the French subantarctic islands and Adélie Land, their status and conservation. ICBP Techn Publ 2:609–625

Jouventin P, Weimerskirch H (1990) Satellite tracking of wandering albatrosses. Nature 343:746–748

Kerr IS (1976) Campbell Island, a history. A.H. Reed, Wellington

Kuschel G (1971) Entomology of the Aucklands and other islands south of New Zealand: Coleoptera: Curculionidae. Pac Insects Monogr 27:225–259

Lebouvier M, Frenot Y (2007) Conservation and management in the French sub-Antarctic islands and surrounding seas. Pap Proc R Soc Tasmania 14:23–28

Macquarie Island Marine Park Management Plan (2001) Environment Australia, Canberra, 70 pp
Miskelly CM, Norton B (2008) A further 1952 record of a *Coenocorypha* snipe on Campbell Island, New Zealand subantarctic. Notornis 55:165–168
Miskelly CM, Sagar PM, Tennyson AJD, Schofield RP (2001) Birds of the Snares Islands, New Zealand. Notornis 48:1–40
Miskelly CM, Bester AJ, Bell M (2006) Additions to the Chatham Islands' bird list, with further records of vagrant and colonising bird species. Notornis 53:215–230
Moore DM (1968) The vascular flora of the Falkland Islands. British Antarctic Survey scientific reports no. 60, London
Moore DM (1983) Flora of Tierra del Fuego. Anthony Nelson, Oswestry
Parkes J, Murphy E (2003) Management of introduced mammals in New Zealand. NZ J Zool 30:335–359
Peat N (2003) Subantarctic New Zealand: a rare heritage. Department of Conservation, Invercargill
Reid T (2007) Terrestrial birds. In: Riffenburgh B (ed) Encyclopedia of the Antarctic. Routledge, New York, pp 991–995
Ryan P (2007) Field guide to the animals and plants of Tristan da Cunha and Gough Island. Pisces Publications, Newbury
Scolaro A (2005) Reptiles patagonicos sur: una guia de campo. Universidad Nacional de la Patagonica San Juan Bosco, Trelew
Selkirk P (2007) Macquarie Island. In: Riffenburgh B (ed) Encyclopedia of the Antarctic. Routledge, New York, pp 607–608
Shaffer SA, Tremblay Y, Weimerskirch H, Scott D, Thompson DR, Sagar PM, Moller H, Taylor GA, Foley DG, Block BA, Costa DP (2006) Migratory shearwaters integrate oceanic resources across the Pacific Ocean in an endless summer. Proc Natl Acad Sci U S A 110033:12799–12802
Tennyson A, Taylor R, Taylor G, Imber M, Greene T (2002) Unusual bird records from the Antipodes Islands in 1978–1995, with a summary of other species recorded at the island group. Notornis 49(4):241–245
Warham J, Bell BD (1979) The birds of Antipodes Island, New Zealand. Notornis 26:121–169
Weimerskirch H, Wilson RP, Lys P (1997) Activity pattern of foraging in the wandering albatross: a marine predator with two modes of prey searching. Mar Ecol Prog Ser 151:245–254
Weimerskirch H, Zotier R, Jouventin P (1989) The avifauna of the Kerguelen Islands. Emu 89:15–29
Woods Robin W, Woods A (2006) Birds and mammals of the Falkland Islands. Wild Guides, Old Basing

# Chapter 10
# Life on Land

## Aquatic Ecosystems

**Paul A. Broady**

**Abstract** What lives in Antarctica? Often the immediate answer is penguins, seals and krill, but these are part of the marine ecosystem, being entirely dependent on the ocean for their food. People do not usually think of plants thriving in Antarctica or that life on the continent is dominated by microorganisms. Neither is it generally realised that there are animals on the continent and surrounding islands which never enter the ocean as their home is in streams, lakes and soils. These organisms and their environment are termed the terrestrial ecosystem. The following two chapters are devoted to life on land. This chapter overviews the range of organisms found on land and then focuses on the habitats where water is abundant – aquatic habitats. Chapter 11 then considers non-aquatic habitats where water is less freely available and long periods of dry conditions can be normal. It concludes with some thoughts about the reasons for performing research on life in these environments.

**Keywords** Aquatic habitats • Microbial mats • Cyanobacteria • Protozoa • Phytoplankton

### 10.1 Diversity of Life

In summer, ice-free ground in Antarctica covers 46,000 km$^2$, which is only about 0.35 % of the continent. The availability of water is the major factor determining where life occurs. Maritime Antarctica is generally moister than continental Antarctica where conditions become increasingly dry with progression inland and to higher altitude. In most ice-free areas, life is not immediately apparent. It is mostly a cold, dry desert. Only in favourable environments with a good water supply do rock and soil surfaces support readily visible growths of plants, lichens and algae. To see the most abundant life, it is necessary to look into ponds and lakes, but these are often thickly covered with ice. Elsewhere conditions are much less favourable and microbes retreat into hidden habitats where traces of water are conserved.

P.A. Broady (✉)
School of Biological Sciences, University of Canterbury, Christchurch, New Zealand
e-mail: paul.broady@canterbury.ac.nz



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_10

There are well over a thousand known species of organisms that live in Antarctica's terrestrial ecosystem (Table 10.1; Adams et al. 2006; Convey 2007; Rautio et al. 2008). However, we are still ignorant of the full number as many groups, especially of microorganisms (Tindall 2004), remain incompletely investigated.

The most advanced in terms of evolution are the two species of flowering plants and the animals. All of these are small, the flowering plants being ground-hugging herbs and the animals all being invertebrates (lacking an internal bony skeleton) no longer than 15 mm and usually considerably smaller. The most diverse, numerous and widespread are microorganisms, which contribute by far the most to the overall biomass.

Many species are found in either aquatic or non-aquatic habitats but some species occur in both. Each species belongs either to the primary producers, decomposers or consumers.

Primary producers are almost all photosynthetic, using the energy of sunlight to make sugars from carbon dioxide and, usually, water. This is the role of plants, lichens and algae. The sugars they make provide the carbon and energy which support the decomposers and consumers. Blue-green algae (cyanobacteria) are the dominant primary producers (Vincent 2000).

Decomposers secrete enzymes which digest the complex organic matter of dead organisms to simpler molecules that can be absorbed. Decomposers are the fungi, and many bacteria and archaea. Archaeans have hardly been investigated in Antarctica. Food for decomposers comprises mainly plants and algae but dead individuals from all other groups of organisms are also included.

Consumers actively search for, capture and ingest other organisms. Protozoa are single-celled consumers. They include flagellates, ciliates and amoebae, all of which include algae and bacteria as major components of their diet. The remaining consumers are invertebrate animals. The large majority of these have mixed diets of algae and decaying organic matter. The latter has associated populations of decomposer microorganisms.

A few animals are predators that consume other invertebrates. These include a tardigrade, a nematode, a few mites and a species of crustacean.

## 10.2 Life in Aquatic Habitats

Lakes, ponds, streams and rivers in Antarctica have unusual features. They form in basins or channels cut through rock, sediment or ice. They are often numerous in coastal ice-free areas and on melt zones of glaciers and ice shelves. Also, vast volumes of water occur below the continental ice sheets.

**Table 10.1** Characteristics of the different groups of organisms found in maritime and continental Antarctica

| Group of organisms | | Approximate length of individual adults (mm) | Occurrence[a] | Role[b] | Number of species[c] | | Figure number |
|---|---|---|---|---|---|---|---|
| | | | | | Maritime Antarctica | Continental Antarctica | |
| Plants | Flowering plants | 40–100[d] | N | P | 2 | 0 | 11.1a |
| | Mosses | 5–30 | N(A) | P | 100 | 25 | 11.1b, 11.4a, c, and 11.5a–c |
| | Liverworts | 5–10 (50[e]) | N | P | 25 | 1 | |
| Lichens[f] | | 2–450 | N | P | 250 | 150 | 11.4d and 11.9 |
| Microorganisms | Eukaryotic algae[g] | 0.001–100[h] | NA | P(C) | >600 | | 10.1d, f and 11.11f |
| | Blue-green algae[i] | 0.001–100[j] | NA | P | >100 | | 10.1b, 10.2c, 11.11c, d, 11.13f, and 11.14d |
| | Protozoa[k] | 0.005–0.150 | NA | C | 83 | 33 | 11.6 |
| | Fungi[l] | 0.005–1,000+[j] | N(A) | D | ? | 250 | 11.1b |
| | Bacteria | 0.001–0.01 | NA | D(P) | ? | ? | |
| | Archaea | 0.001–0.01 | N?A | DP | ? | ? | |
| | Viruses[m] | <0.0002 | N?A | – | ? | ? | |
| Animals | Rotifers[k] | 0.1–0.5 | NA | C | ? | 13 | 11.7c, d |
| | Tardigrades | 0.2–1.2 | NA | C | 26 | 20 | 11.7a |
| | Nematode worms[k] | 0.3–0.5 | NA | C | 40 | 10 | 11.7b |
| | Enchytraeid worms | 5–15 | NA | C | 3 | 0 | |
| | Collembola | 1–2 | N | C | 10 | 10 | 11.8a, b |

(continued)

**Table 10.1** (continued)

| Group of organisms | | Approximate length of individual adults (mm) | Occurrence[a] | Role[b] | Number of species[c] Maritime Antarctica | Continental Antarctica | Figure number |
|---|---|---|---|---|---|---|---|
| | Mites | 0.25–2 | N(A) | C | 36 | 29 | 11.8c–f |
| | Diptera (flies) | 4–5 | N(A) | C | 2 | 0 | 11.3 |
| | Crustaceans | 2–10 | A | C | 11 | 11 | 10.3b |

[a]Habitats: *N* non-aquatic, *A* aquatic, brackets indicate infrequent occurrence
[b]*P* primary producers, *D* decomposers, *C* consumers, brackets indicate a role of only a small number of species (in the case of eukaryotic algae, these are species which both photosynthesise and can consume bacteria)
[c]In many cases a proportion of species found in maritime Antarctica is also found in continental Antarctica while others occur only in one of these regions. ? no estimate has been made of species numbers
[d]Above ground stems and leaves
[e]Strap-like thalloid liverworts in maritime Antarctica. Others are smaller leafy liverworts
[f]Lichens consist of fungi and algae in a close and mutually beneficial relationship
[g]Eukaryotic algae are ones with complex cells that contain a nucleus and one or more chloroplasts. They include green algae, yellow-green algae, diatoms and dinoflagellates
[h]Large size applies to only a few colony-forming and sheet-like algae. Most are microscopic
[i]Blue-green algae are also called cyanobacteria
[j]Large size applies to visible colonies of the cyanobacterium *Nostoc* and to the rarely observed mushrooms (sexual spore-forming structures) of some fungi
[k]Large changes in numbers of species are likely with further research
[l]Single-celled yeasts to filamentous species. The latter can be extensive, branched networks of indeterminate total length.
[m]Usually not regarded as organisms as they do not have a metabolism of their own but take over that of a living cell in order to reproduce, and in so doing they kill their host cell.

### 10.2.1 Streams and Rivers

Antarctic streams and rivers are diverse and variable environments (Fig. 10.1). In summer, they are supplied with melt water from snow banks, ice fields and glaciers. Water flows for a few weeks to 5 months at the most and volumes vary from percolations a few millimetres deep to torrents of several cubic metres per second. In winter their channels are dry.

#### 10.2.1.1 Irrigated Rock Surfaces

The shallowest of water percolations down rocky cliff faces support the growth of thin black crusts of cyanobacteria (Fig. 10.1a, b). Commonly found is *Gloeocapsa*, the cells of which produce, and cluster within, brown, violet or red jelly-like material called mucilage. The pigmentation acts as a sunscreen. When water supply ceases, the mucilage retains moisture for a brief period but then the algae survive in a very dry condition.

In the McMurdo Dry Valleys, crusts of cyanobacteria are occasionally seen high up on the sides of valleys where snowfall is more frequent than at lower altitudes and subsequent melt stimulates algal growth (Broady 2005). At the Vestfold Hills, a 410 $km^2$ coastal area of low hills and valleys in continental Antarctica, crusts usually occur on rock faces sheltered from the strongest winds because this is where snow banks accumulate and then provide melt water (Broady 1986). Also, the rock shields crusts from abrasive wind-borne sand and ice crystals. When exposed to direct summer sun, crusts survive temperatures of up to 30 °C and in winter survive freezing to around −40 °C.

#### 10.2.1.2 Ice Walls of Glaciers

Thin films of water percolate over terminal walls of glaciers (Fig. 10.1c, d). In the McMurdo Dry Valleys, small sheets of the green alga *Prasiola* grow on gently sloping ice walls (Broady 2005). These sheets become caught on small projections of ice which prevent them from being washed from the glacier.

#### 10.2.1.3 Larger Streams and Rivers

Streams with well-defined channels run down sloping valley walls in many ice-free areas. In the base of valleys these streams merge to form flows large enough to be called rivers (Fig. 10.1e, f; McKnight et al. 1999). Valley-side streams have maximum summer flows ranging from a few litres to more than a cubic metre per second. Onyx River in Wright Valley, one of the main valleys of the McMurdo Dry Valleys, is 35 km long and the longest river in Antarctica. For about 2 months each year, it flows inland from the higher seaward end of the valley to where it discharges

**Fig. 10.1** Examples of flowing water habitats and some of the algae that inhabit these. (**a**) Thin films of melt water pass over rock in Garwood Valley, McMurdo Dry Valleys. Cyanobacteria dominate the dark crusts of algae (*scale line* is equivalent to 1 m). (**b**) The cyanobacterium *Gloeocapsa* is often an abundant component of the crusts. Its spherical cells are embedded in jelly-like mucilage. The mucilage is pigmented and this shields the cells from damaging intensities of solar radiation (*scale line* is equivalent to 1/40th of a millimetre). (**c**) Ice walls of the Joyce Glacier, Garwood Valley. In summer, melt water percolates down the slope and the green, sheet-like alga *Prasiola* grows there. (**d**) For the large part of the year, *Prasiola* survives frozen in the ice (*scale line* is equivalent to 1 cm). (**e**) Summer flows of the valley-bottom river in Garwood Valley. (**f**) Aggregates of hair-like filaments of green algae wrap around stones on the river bed (© Paul A. Broady)

into Lake Vanda. The maximum flow in warm summers is a substantial 30 $m^3$ per second. Flows are considerably lower during cloudy summers with less melt from glaciers. The diversity and abundance of algae can be determined by the duration and strength of water flow.

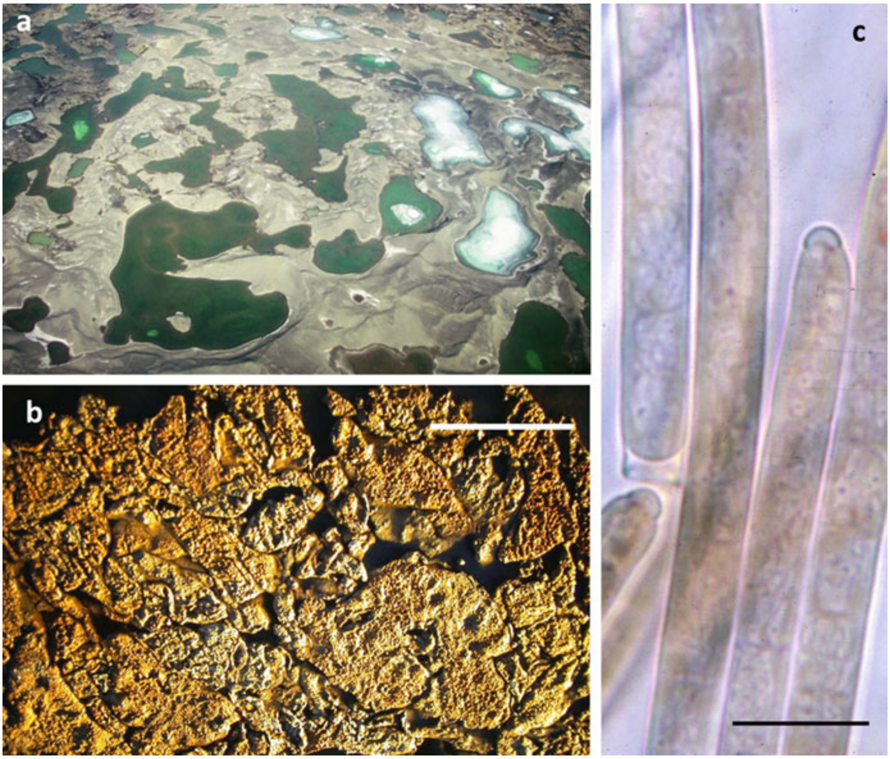



**Fig. 10.2** Microbial mats dominated by the filamentous cyanobacterium *Phormidium* comprise the most abundant photosynthetic life forms in Antarctica. They occur as extensive growths over stream beds and cover sediments of ponds and lakes. (**a**) An aerial view of ponds (up to about 100 m wide) on the McMurdo Ice Shelf, most of which contain microbial mats. (**b**) Close-up of the surface of a thick microbial mat (*scale line* is equivalent to 1 cm). (**c**) Filaments (chains of cells) of *Phormidium* viewed using a light microscope at 1,000 times magnification (*scale line* is equivalent to 1/100 mm) (© Paul A. Broady)

The term applied to algal communities that attach to underwater rock and sediment surfaces is periphyton. In Antarctica, these communities are usually dominated by cyanobacteria which form extensive mats containing many billions of individual microscopic filaments, interwoven and glued together by mucilage secreted by their cells. The cyanobacterium *Phormidium* is commonly the major component (Fig. 10.2) but other algae, as well as protozoa and invertebrate animals, live within the mats.

Mat surfaces are orange-brown in colour because cells accumulate pigments called carotenoids that protect them from damaging ultra-violet radiation and intense sunlight. Stones that protrude above mats are coated with black crusts of *Gloeocapsa* and *Calothrix*. These are more resistant to desiccation experienced during reduced flows. Dark brown to black colonies of the nitrogen-fixing cyanobacterium *Nostoc* grow along moist stream margins.

Tangles of filaments and narrow ribbons of green algae (phylum Chlorophyta) can also be abundant. They exhibit distinct patterns in their distribution on a range of scales. On the regional scale, different types occur in maritime Antarctica (*Zygnema*, *Mougeotia* and *Klebsormidium*; Hawes 1989) to those in the McMurdo Dry Valley streams (*Prasiola* and *Binuclearia*; Broady 1989). On Ross Island, some ice-free areas receive wind-borne sea spray from McMurdo Sound that results in salt-encrusted soils and brackish streams. A different filamentous green alga, *Urospora*, grows thickly in these (Broady 1988).

Along an individual stream, different species can occupy distinct reaches. For instance, ribbon-forming *Prasiola* occurs in upper reaches attached to under-surfaces of large stones where it is well-adapted to deep shade. In contrast, *Binuclearia* lies fully exposed over the stream bed of lower reaches.

Fast-flowing streams passing over unstable sandy beds can be turbid with up to a kilogram of suspended sediment in each cubic metre of water. The scouring effect of this prevents colonisation by algae except on the most protected downstream-facing surfaces.

Nutrient concentrations vary greatly. Streams passing through penguin colonies contain much higher concentrations than those away from birds. Often nutrient concentrations are greatest in the first flows of summer and then decrease. Also, they can vary over a single day. For example, the freezing of a stream in the shadow of a mountain followed by thaw when it is again exposed to the full sun results in higher concentrations in the first new flows. In the Onyx River, algal mats extract nutrients from the water so that by the time the river enters Lake Vanda nutrients are in very low concentrations.

The major environmental challenge experienced by stream life is deep-freezing and complete desiccation over winter. In continental Antarctica, freeze-dried algal mats are dormant in winter but are capable of regrowth. Maximum photosynthesis can be attained within a remarkable 10 min of rehydration of mats of the cyanobacterium *Nostoc*, but this takes over 10 days for mats of *Phormidium* (Hawes et al. 1992).

Growth rates of algae in continental Antarctic streams are slow compared with those in temperate regions. The important factor is low water temperatures which are usually close to freezing but can reach 11 °C on sunny days.

Algal mats can accumulate to a centimetre or more in thickness by slow growth each summer over many years. This is helped by their survival over winter, low rates of decomposition and few losses to grazing by protozoa, nematodes, tardigrades and rotifers. Most losses are due to strong winter winds blowing away desiccated mats and by vigorous summer flows peeling mats away from the streambed (Hawes and Howard-Williams 1998).

### *10.2.2 Lakes*

Lakes are relatively large, deep water bodies which, in contrast to ponds, do not dry out or freeze through, although a thick layer of ice can persist over summer. There are thousands of lakes in Antarctica which differ greatly in their environmental features (Fig. 10.3).

**Fig. 10.3** A selection of diverse Antarctic lakes. (**a**) Heywood Lake (the most distant of the two lakes in the left foreground) on Signy Island, South Orkney Islands, is a nutrient-enriched lake that is fertilised with the excreta of fur seals, several hundred of which occupy the lake catchment during summer. It is a small lake, 4.5 ha in area with a maximum depth of 6.4 m. (**b**) Two species of copepod crustaceans from Heywood Lake. The smaller (*Boeckella poppei*) feeds on phytoplankton and is eaten by the larger (*Parabroteas sarsi*) which is a predator. The *scale line* is equivalent to 2 mm. (**c**) Salt encrusts the ground downwind from a hypersaline lake at the Vestfold Hills. (**d**) A freshwater lake at the Vestfold Hills which contains rich growths of aquatic moss. (**e**) Releasing a water sampling bottle into a hole drilled through the 4-m thick ice cover of Lake Vanda, Wright Valley, McMurdo Dry Valleys. Below the ice the water is up to 70 m deep. (**f**) Permanently ice-covered Lake Fryxell in Taylor Valley, McMurdo Dry Valleys (© Paul A. Broady)

#### 10.2.2.1 Lakes in Maritime Antarctica

Lakes in maritime Antarctica contain a richer diversity of organisms than continental lakes, especially of invertebrate animals. Invertebrates include representatives of three groups of crustacean: copepods, cladocerans (water fleas) and a fairy shrimp (Fig. 10.3a, b; Gibson and Bayly 2007).

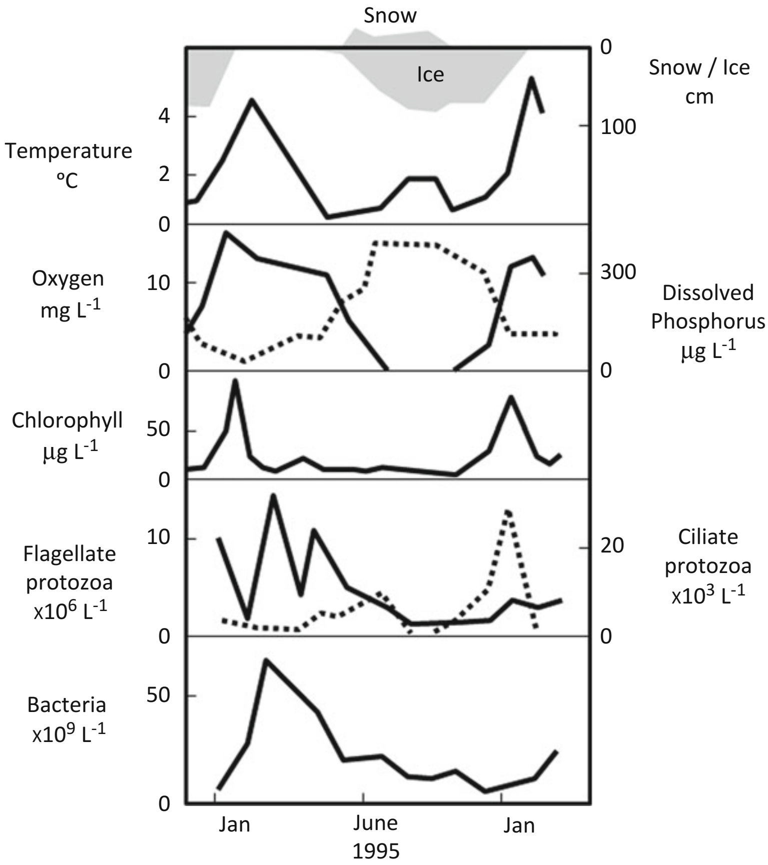



**Fig. 10.4** Changes in the water column of Heywood Lake (Fig. 10.3a; Signy Island, South Orkney Islands) over one annual cycle. The lake surface becomes ice-free during summer. In early summer a large population of phytoplankton develops (shown by the increase in the green pigment chlorophyll). Oxygen (*continuous line*) is produced during photosynthesis and also dissolves into lake water from the atmosphere. Phytoplankton use mineral nutrients including phosphorus (*dotted line*) in the form of phosphate. Flagellate (*continuous line*) and ciliate (*dotted line*), protozoa graze on phytoplankton and bacteria. Bacteria are involved with decomposition of organic matter produced by phytoplankton. This releases phosphate and other mineral nutrients back into the water. Decomposition continues over winter when the lake is capped by ice which results in the loss of oxygen from the water. The lake ecosystem includes three species of crustaceans that number up to 120 per litre in summer (Adapted from Butler 1999)

Most graze on algae and other microbes but one copepod is a predator of crustaceans. Larvae of midges (Hahn and Reinhardt 2006) and a relatively large oligochaete worm can be found amongst the periphyton. Periphyton includes cyanobacterial mats (Taton et al. 2006) and filamentous green algae. Sometimes mosses are abundant. Seasonal changes in the water column are marked with various groups of organisms waxing and waning in response to changes in physical and chemical conditions (Fig. 10.4).

In contrast, continental Antarctic lakes have few species. For instance, many lack copepods and cladocerans and when these are present, there is often just a single species. Plankton is dominated by microorganisms and the periphyton usually consists of cyanobacterial mats. However, abundant moss is known to occur in some coastal lakes in the form of pillars of up to 40 cm in diameter and 60 cm high (Imura et al. 1999).

#### 10.2.2.2 Diverse Lakes of the Vestfold Hills

The Vestfold Hills is an area that features about 150 lakes. These contrast greatly in their characteristics but are representative of lakes in other coastal ice-free regions.

An especially severe environment is found in hypersaline lakes (Fig. 10.3c). These formed when the land rose following ice retreat at the end of the last major glaciation about 8,000 years ago. Fjords became lakes of seawater trapped in inland basins. The lakes which received less water from snow and ice melt than evaporated from their surfaces became more saline than seawater (hypersaline). Deep Lake is about six times as saline as seawater. In winter, strong winds stir the lake so an even temperature is found throughout its full depth of 36 m (Ferris and Burton 1988). The water temperature drops to −17 °C but freezing is prevented by the high salinity (Fig. 10.5). In calmer, sunnier summer conditions the surface waters warm to

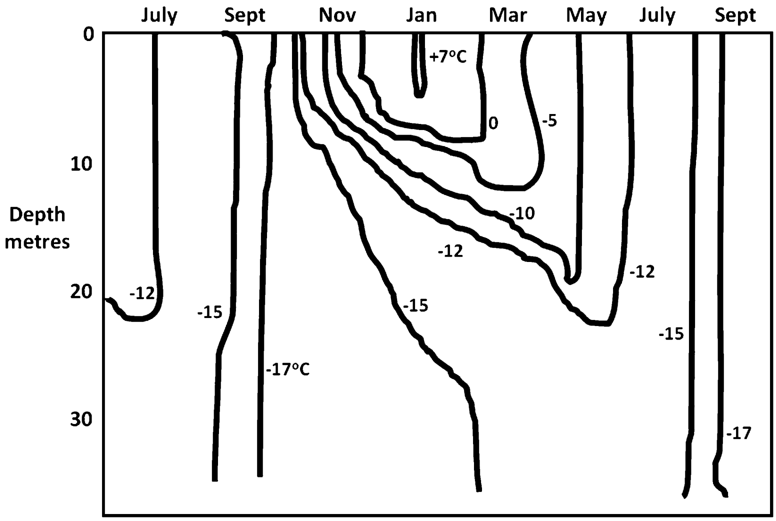



**Fig. 10.5** Water temperatures throughout the depth of hypersaline Deep Lake, Vestfold Hills, over a typical year. The *lines* in the diagram are called isotherms and are labelled with the water temperature that each isotherm represents. They function in a similar way to contours on a topographic map. Moving from *left* to *right* across the diagram shows how temperatures change over time while moving from *top* to *bottom* shows how temperatures change from the surface to the *bottom* of the lake. For instance, surface waters warm from a minimum of around −15 °C in winter to a maximum of around 7 °C in mid-summer, while waters at 30 m depth remain very cold all year (Adapted from Ferris and Burton 1988)

7–11 °C and float above deeper, denser waters that remain at −15 °C, well below the freezing point of pure water.

The phytoplankton in Deep Lake is dominated by a single-celled green alga called *Dunaliella*. Each cell bears two whip-like flagella that are used for swimming at temperatures as low as −14 °C. Cells accumulate a simple organic molecule, glycerol, to concentrations close to those of external salts. This functions as an anti-freeze and also prevents water being sucked from cells by the surrounding highly saline water.

One of the few records of archaea from Antarctica is of a salt-loving (halophilic) species found at Burton Lake. This is a tidal lake, as during high tides in summer it receives seawater through an ice-free channel linking it to the sea. Eventually the lake will become isolated due to continued uplift of the Vestfold Hills, but presently, its surface waters remain less saline than seawater due to inflows of fresh melt water. Denser water of seawater salinity lies below. The upper 10 m of water are well oxygenated and contain phytoplankton typical of other saline lakes. Deeper, more saline waters, down to 18 m, are anoxic and contain hydrogen sulphide. Light intensities at these depths are never greater than 0.5 % of those at the lake surface but even this dim light supports photosynthesis by a green sulphur bacterium called *Chlorobium* (Burke and Burton 1988). It produces sulphur as a by-product of photosynthesis in contrast to the oxygen produced by cyanobacteria.

Over winter there is insufficient light for growth and some cells survive in the dark presumably using stores of food accumulated over summer.

In contrast to the lakes described above, others contain very fresh water (Fig. 10.3d). For instance, Crooked Lake receives melt water that flows off a nearby glacier during summer. As with most Antarctic lakes that are not fertilised by seabirds or seals, there are extremely low concentrations of mineral nutrients available for growth of phytoplankton. This and cold water temperatures below 4 °C result in low growth rates which provide little organic food for decomposers and consumers. Most of the nutrients are cycled through a microbial food web (Fig. 10.6). They are released by the digestive processes of bacteria and protozoa and are then again available to be taken up by phytoplankton. Overall, plankton is very unproductive, at low abundance and represented by few species.

The phytoplankton is dominated by four species with flagella. Protozoa are represented by four flagellates and three ciliates. There is one species of planktonic animal, a cladoceran (water flea) called *Daphniopsis studeri*, but grazing by this has insignificant effects on planktonic microorganisms as only 10–20 individuals occur in each cubic metre of water.

An important strategy, termed mixotrophy (mixed feeding) has been adopted by certain phytoplankton species and ciliate protozoa (Laybourn-Parry et al. 2000). Mixed feeding allows them to obtain food both by photosynthesis and by feeding on other cells. For instance, mixotrophic phytoplankton can eat bacteria at times of darkness and very low light, when they cannot perform photosynthesis, as a supply of organic food. At times of higher light, when they can perform photosynthesis, nitrogen and phosphorus supply is enhanced by consuming bacterial cells.

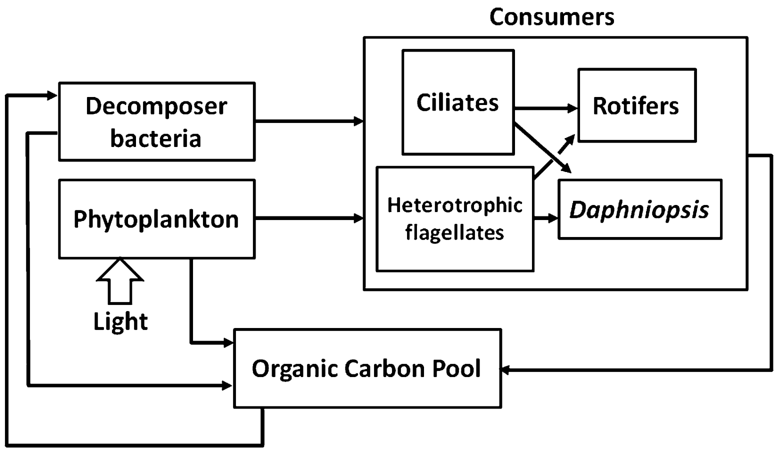



**Fig. 10.6** The simple microbial food web of Crooked Lake, a freshwater lake in the Vestfold Hills. Photosynthesis by phytoplankton produces organic material in the form of new phytoplankton cells. These are grazed by consumers that include flagellate and ciliate protozoa and invertebrate animals (rotifers and a crustacean called *Daphniopsis*). Bacterial cells are also a source of food for consumers. Both phytoplankton and bacteria release organic substances into the water when these leak out of healthy cells and when the cells are burst open by viral infections. Waste products from consumers also contribute to this organic carbon pool. This is used as an energy source by decomposer bacteria. Throughout these processes, carbon dioxide is released by respiration and mineral nutrients are returned to the water (Adapted from Laybourn-Parry 1997)

The ciliate feeds on phytoplankton and other microbial cells. However, instead of immediately digesting them it can maintain the chloroplasts (sub-cellular structures that perform photosynthesis) of some phytoplankton in a functioning state and benefits from the carbohydrates formed by their photosynthesis.

Viruses are likely to be important by infecting bacterial cells, causing them to burst when new viral particles are released (Säwström et al. 2008). Organic material released from burst cells is then used during growth of other bacteria.

#### 10.2.2.3 Permanently Ice-Covered Lakes of McMurdo Dry Valleys

There are about 12 large, deep lakes in the McMurdo Dry Valleys, all permanently capped by a layer of ice several metres thick (Fig. 10.3e, f). In summer, this melts only around the lake margin to form a moat of shallow water. All lakes have meltwater inflow but none has an outflow. Water is lost by evaporation from the ice. The balance between inflow and evaporation is very sensitive to climate change and lakes become deeper or shallower in response.

Mixing of lake waters is confined to an uppermost layer. Even here mixing is weak and driven by slow convection currents. More vigorous mixing is prevented by the upper layers being fresh and less dense than deeper more saline water and also by the water being protected from strong winds by the ice cap. This lack of mixing allows the water to stratify into layers, each of which has distinct characteristics. Different mat-forming and planktonic organisms respond to stratification by growing at the depth to which they are most suited (Hawes and Schwarz 1999; Sabbe et al. 2004; Burnett et al. 2006).

**Box 10.1: Lake Vanda, a Stratified Lake**

Lake Vanda in Wright Valley is a supreme example of stratified waters (Figs. 10.3e and 10.7; Vincent and Vincent 1982; Purdy et al. 2001). Below the 4-m thick ice cap, water is up to 70 m deep. The bottom water contains no dissolved oxygen, is three times the salinity of seawater and is warm, at about 24 °C. The origin of the salt is not completely understood but is likely to have been leached from rocks in the catchment. In contrast, freshwater just under the ice is at 0 °C and is super-saturated with oxygen. The surprising warmth of deep waters is due to solar heating over many years by the dim sunlight that penetrates to those depths. Because of strong winds, little snow gathers on the ice cap which is also largely free of fractures and bubbles. This clear ice allows about 10 % of sunlight to penetrate through to the water. By 60 m depth only about 1 % remains and the light is now blue-green as other colours of the spectrum have been absorbed.

Phytoplankton includes several types of single-celled flagellates and the smallest of single-celled cyanobacteria. Some flagellates prefer the colder, fresher, better illuminated waters while others, together with cyanobacteria, form a layer of greatest abundance in the very dim, blue-green light at about 60 m, just above the most saline, warmest waters. These deep phytoplankton species are well adapted as their cells contain large amounts of a reddish pigment that absorbs blue-green light. Maximum numbers are found at this depth because waters here are enriched in mineral nutrients while surface waters contain extremely low concentrations.

This mineral enrichment is due to dead organisms sinking down and being decomposed by bacteria in bottom waters. Mineral nutrients are released and these slowly diffuse upwards and supply the phytoplankton. The anoxic bottom water means that bacteria there are anaerobic (they grow without needing oxygen) and decomposition is anaerobic. A product of anaerobic decomposition is hydrogen sulphide which is used by photosynthetic bacteria that occur in the extremely dim light in the water layer just below the phytoplankton. Bacteria called chemoautotrophs grow at the interface between anoxic bottom waters, enriched in hydrogen sulphide, and oxygenated waters overlying these. These bacteria combine hydrogen sulphide with oxygen to make sulphate and water. This chemical reaction releases energy that is then used by the bacteria to make organic molecules from carbon dioxide.

(continued)

**Box 10.1** (continued)

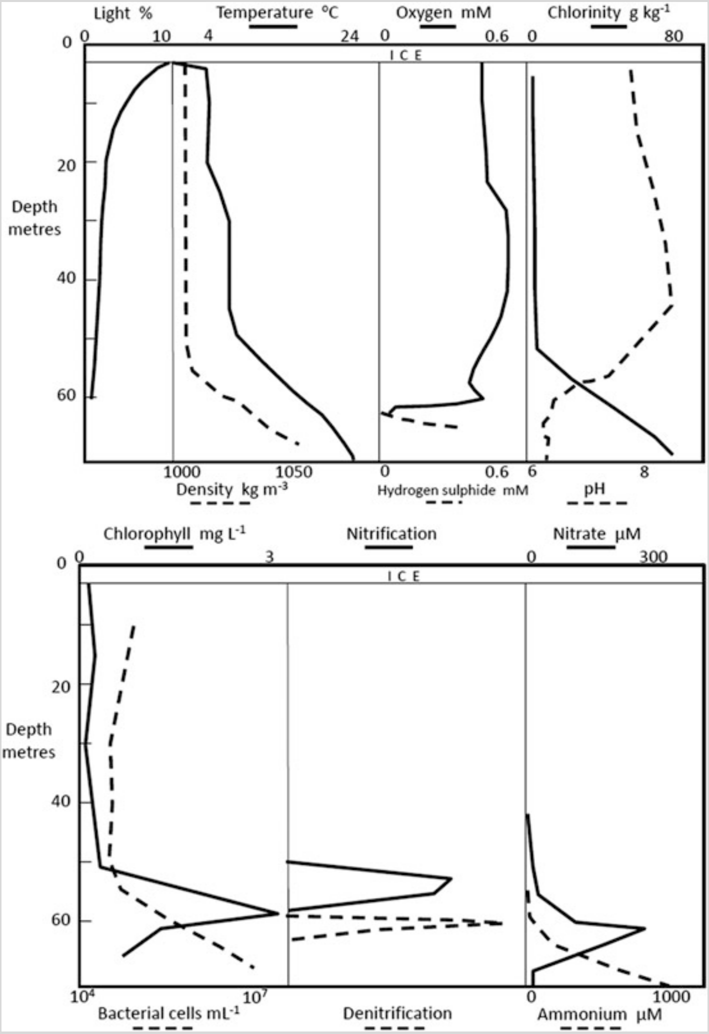



**Fig. 10.7** Lake Vanda in Wright Valley, McMurdo Dry Valleys, is strongly stratified in that diverse aspects of the physics, chemistry and biology of the water column change markedly with depth. Box 10.1 describes most of the features shown here. The green pigment chlorophyll is used as an indicator of the abundance of phytoplankton. Water density increases rapidly in deep water due to the increase in concentration of dissolved salts (shown here as chlorinity). Ammonium and nitrate are nutrient salts produced by decomposition and other microbial processes in deep water. Nitrification and denitrification are two of these microbial processes. Nitrifying bacteria oxidise ammonium to produce nitrate in the process of nitrification. The energy released is used to support their growth. Denitrifying bacteria remove oxygen from nitrate and use this when feeding on organic matter. The products of denitrification include the gases nitrous oxide and nitrogen (Adapted from Vincent et al. 1981; Takii et al. 1986; Priscu 1989; Voytek et al. 1999; De Carlo and Green 2002; Burnett et al. 2006)

(continued)

**Box 10.1** (continued)

Periphyton mats also change with depth. Nitrogen-fixing *Nostoc* grows only in shallow waters where the moat develops in summer. Below the ice, mats are dominated by *Phormidium* and contain more diatoms as well as intermingled moss. Deeper still, diatoms become abundant until the mats cease to develop where waters become anoxic.

Fragments of microbial mats become trapped within the ice cover of the lakes in the McMurdo Dry Valleys (Mosier et al. 2007). Fragments include those dislodged from dry stream beds which may be blown onto lake ice. In summer, this dark material is heated by the sun and melts down into the ice where the small pieces of mat lie in cavities filled with melt water. In winter they freeze to about −40 °C.

Other fragments come from mats covering sediments at the bottom of the lake. Small portions break away when buoyed with bubbles of oxygen produced during photosynthesis. These float to the under-surface of the ice and become enclosed when ice thickens during winter.

Cavities contain a wide diversity of bacteria but the abundance of different species is not the same as that in the original mat as they are now in a very different environment.

#### 10.2.2.4 Permanently Ice-Covered Lakes Associated with Nunataks

Nunataks are mountain peaks that protrude through ice sheets and glaciers. Lakes occur next to some nunataks with their outlets dammed by ice.

Lake Untersee (71°20′S 13°26′E) in Drønning Maud Land is the largest known (Wand et al. 2006) with an area of over 11 $km^2$ and water up to 167 m deep below a permanent 3 m thick layer of ice. Most inflow comes from melt of the ice dam and water is lost by ablation of the ice cover. The water column is layered with fresh oxygenated water at less than 1 °C, overlying saline anoxic water which warms to over 4 °C below 50 m deep.

In the upper layer of freshwater, sparse populations of phytoplankton grow slowly over summer using the very dilute mineral nutrients. As in most lakes, life is most abundant as mats of cyanobacteria covering sediments at the bottom of the lake.

The deep anoxic waters contain unusually high concentrations of methane. This is formed in two stages. First, bacteria decompose organic matter supplied as dead phytoplankton. This results in the production of carbon dioxide and hydrogen. Secondly, these gases are used for metabolism by certain archaea (methanogens) that produce methane as a by-product. Other bacteria can use methane as a source of energy. There are also bacteria that decompose organic matter by using oxygen taken from sulphate and produce hydrogen sulphide, ammonium and phosphate which accumulate to high concentrations in deep water. A temperature peak of 4.6 °C at around 80 m depth is thought to be due to energy release from some of these microbial activities.

#### 10.2.2.5 Epishelf Lakes

Epishelf lakes lie between land and a coastal ice shelf. Their freshwater is derived from melt streams flowing off the land. Several are known both along the Antarctic Peninsula and around eastern Antarctica. The great depth of the ice shelf acts as a dam to retain freshwater. Seawater lies under the floating ice shelf and its associated freshwater lake, both of which rise and fall with tides.

Beaver Lake is the largest epishelf lake with an area of 150 $km^2$. It lies adjacent to the Amery Ice Shelf (Laybourn-Parry et al. 2001) in eastern Antarctica. A permanent ice cover is 4 m thick and the upper layer of freshwater merges with underlying seawater at 220–260 m depth. The maximum water temperature is 2.3 °C.

Beaver Lake contains the sparsest life of any known Antarctic freshwater lake. The cold waters and extremely low nutrient concentrations must make it one of the most challenging freshwater lake environments on Earth. A small, slow-growing population of single-celled phytoflagellates provides organic food for low numbers of bacteria and flagellate and ciliate protozoa. Unexpectedly in a lake with such poor food supply, there is one species of copepod, *Boeckella poppei*. It is a dwarf form up to only 1.5 mm long, half the size attained in maritime Antarctica, and here it exists at the limit of its capabilities.

#### 10.2.2.6 Subglacial Lakes

Most freshwater in Antarctica lies below ice sheets where melt is caused by the immense pressure of the overlying ice and possibly by geothermal heat. About 300 subglacial lakes exceed 10,000 $km^3$ in total volume (Chap. 5). Some are connected by rivers below the ice. They contain more than 8 % of global lake water.

Lake Vostok lies below 3,740 m of ice and is the largest (14,000 $km^2$) and deepest (670 m). The lake could be up to 35 million years old, which is the approximate age of the overlying East Antarctic Ice Sheet. Any microbial life in the lake has evolved in isolation over long periods (Siegert et al. 2001).

Ice formed from lake water freezes to the under-surface of the ice sheet. This ice has been sampled, by a drill core, from a depth of 3,623 m (Karl et al. 1999; Priscu et al. 1999). DNA analysis has revealed diverse bacteria but cell numbers of

400–36,000 cells per ml are very low compared with the million or so cells that are normally found in a millilitre of lake water. Surprisingly, these include bacteria related to ones found elsewhere in hot springs. Perhaps dense populations of these grow at geothermal hot spots in the lake floor. As no light reaches down to the lake, these chemoautotrophic microbes could be the only ones to synthesise organic matter from carbon dioxide, using energy released by reactions of inorganic chemicals in water flowing from vents. A more recent re-analysis of this ice claims to have found genetic traces of more complex animals as well as diverse microbes (Schiermeier 2013c). However, this is very controversial as some researchers think the samples could have been contaminated with kerosene that was used as a drilling fluid.

In February 2012 Lake Vostok was penetrated and a sample of water taken for analysis (Schiermeier 2013b). Low numbers of bacteria were counted, numbering about 167 cells per ml, and these included what appeared to be a novel form. However, the controversy surrounding contamination still remains.

In January 2013, Lake Whillans was the first lake to be penetrated using a hot water drill that is very unlikely to introduce contaminants (Schiermeier 2013a). It lies below 800 m of ice on the inner edge of the Ross Ice Shelf and is just 2 m deep. Water samples and cores of sediment contain diverse microbes which number around 1,000 cells per ml of water.

This fascinating subglacial environment has so far provided only a glimpse of the organisms that it supports. Their diversity, interactions and roles will no doubt continue to be the focus of intense study.

#### 10.2.2.7 Lake Sediments as Archives of Environmental Change

Lakes are important sources of information about past environments. For instance, if bottom sediments are laid down year by year as a sequence of layers, then materials they contain can allow reconstruction of changes that have occurred within the lake or the lake catchment. These changes include those caused by variability in climate. Relative abundances of the remains of different organisms are often assessed at different depths along cores taken from sediments.

For example, diatoms in sediments of Anderson Lake, Vestfold Hills, have been used to assess changes in lake water salinity because different species have different salinity preferences (Fig. 10.8; Roberts and McMinn 1997). The shape and structure of diatom cell walls is characteristic for different species and is readily preserved. Microscopic examination of samples taken between the surface and 140 cm depth has shown changes in species with depth. Deep sediments from 8,500 to 7,000 years before present (yBP) contain freshwater species. This suggests Anderson Lake was receiving vigorous flows of fresh glacial melt water from the retreating East Antarctic Ice Sheet.

Marine diatoms appeared at 7,000 yBP and persisted for a millennium in response to a global rise in sea level which turned the lake into a marine inlet. Uplift of the land then isolated the lake from the sea. Evaporation exceeded inflow

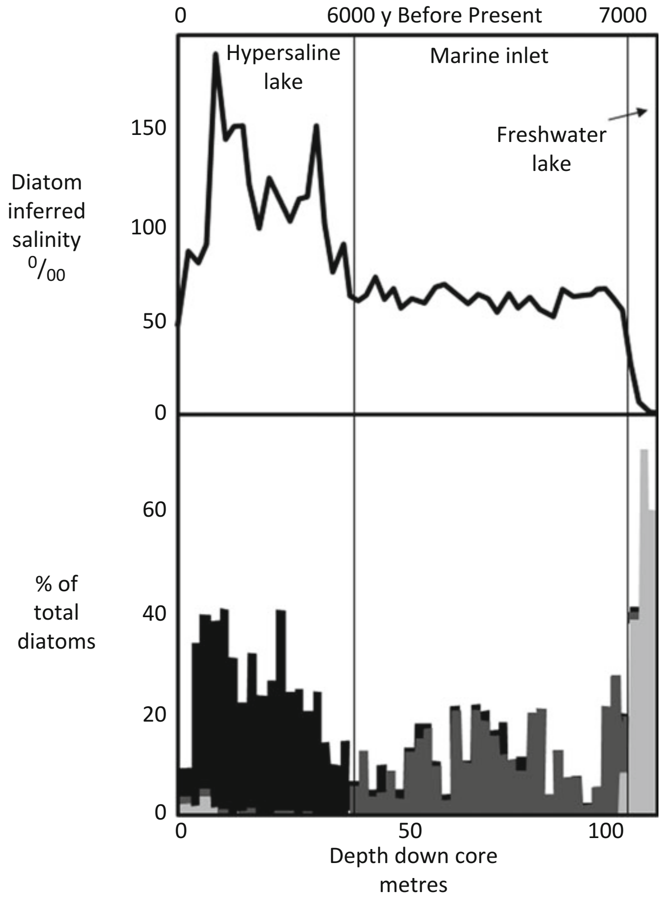



**Fig. 10.8** Understanding the history of a lake (Anderson Lake, Vestfold Hills) by identification and counts of diatoms found at increasing depth down a core sample of sediment removed from the bottom of the lake. *Top graph*: over about the last 7,000 years, the lake has changed from a freshwater lake to a marine inlet and then to a hypersaline lake (see text for details). Abundance estimates of three different species of diatoms are shown: *darkest shading*, *Navicula directa*, characteristic of salinities greater than seawater; *medium shading*, *Fragilariopsis cylindrus*, characteristic of seawater salinity; *lightest shading*, *Pinnularia microstauron*, characteristic of freshwater. Using the relative abundance of these and other diatoms, an assessment was made of past water salinities (diatom inferred salinity, shown as $^{o}/_{oo}$ = parts per thousand) (Adapted from Roberts and McMinn 1997)

and the lake became hypersaline. Diatoms with a preference for this condition have persisted until the present.

This and related studies at a variety of locations are improving our understanding of how Antarctica and its biota have changed in the past. Importantly, they also allow us to better predict how change might manifest itself in the future if a warmer climate prevails.

## *10.2.3 Ponds*

Ponds are small, relatively shallow water bodies which number in their millions throughout Antarctica. They span a wide range of environmental conditions and individual ponds can change greatly over a short period of time (Fig. 10.9; Healy et al. 2006).

### 10.2.3.1 Ponds on Ice-Free Ground

Ponds occur in depressions in rock and glacial till (Fig. 10.9a, c) in all but the smallest and steepest ice-free areas. Many become free of ice in summer while others remain frozen. Small ponds might evaporate completely and then refill early next summer with melt from snow banks which had accumulated over winter.

Pond waters distant from bird and seal colonies often contain low concentrations of mineral nutrients, which means that phytoplankton are sparse but cyanobacterial mats can develop. Mat algae absorb some nutrients from overlying layers of water. These are recycled within the mat when algae die and decompose and provide additional nutrients for more algal growth. Eventually the algal mat thickens and becomes a greater store of nutrients than the nutrient-depleted water.

Cyanobacterial mats occur in freshwater, brackish and hypersaline ponds (Healy et al. 2006). Several different salts such as sodium chloride, sodium sulphate and sodium nitrate cause elevated salinities. Different species of cyanobacteria and associated diatoms and other algae prefer different salinities.

Don Juan Pond (Samarkin et al. 2010), in the upper reaches of the Wright Valley, McMurdo Dry Valleys, has the greatest known salinity. Its waters remain unfrozen all year due to calcium chloride dissolved at salinities 14 times those of seawater. The pond surface is often encrusted with salt crystals. The salt is derived from the gradual leaching of rocks in the catchment. Active life has not been conclusively detected at these high salinities but is present in the few places where lower-salinity water percolates into the pond.

Spectacular green or purplish-red phytoplankton blooms occur in ponds fertilised by birds and seals (Fig. 10.9b). Phytoplankton growths are dense enough to prevent light penetration down to the bottom and algal mats cannot develop. A rotifer that occurs worldwide in waters polluted by wastes from farm animals is also found in these Antarctic ponds.

### 10.2.3.2 Ponds on Ice Surfaces

If between a millimetre and a few centimetres of sandy sediment sits on the surface of ice, summer solar radiation warms this dark material, which then melts the ice beneath to form ponds. Ponds can be numerous and extensive on glaciers and ice shelves. During summer, pond life grows at temperatures close to freezing and


**Fig. 10.9** Examples of ponds. (**a**) A pond amongst moraines adjacent to a glacier at Cape Bird ice-free area on Ross Island. Green phytoplankton is suspended in the water. (**b**) Small ponds that are fertilised by the wastes of birds and seals often develop dense growths of planktonic single-celled green algae. This coastal pond at Cape Geology, Granite Harbour, southern Victoria Land received additional nutrients from skuas that nested nearby. (**c**) A pond amongst the huts at Scott Base on Ross Island. It has been colonised by filamentous green algae. If human activity transports new algae to Antarctica, it is perhaps in habitats such as this that they will first grow. (**d**) Thousands of small cryoconite ponds cover the ablation zone of Joyce Glacier at the head of Garwood Valley, McMurdo Dry Valleys. Dark mineral material warmed by the sun melts into the ice. (**e**) Many thousands of ponds occur on moraines surrounding the nunataks of La Gorce Mountains. Despite air temperatures in mid-summer that are well below freezing, solar heating of pond sediments is sufficient to melt underlying glacial ice and maintain a few tens of centimetres of water below an ice cover. Sediments are coated by thin mats of the cyanobacterium *Phormidium*. (**f**) One of many thousands of ponds on the surface of the McMurdo Ice Shelf. This one is saline and is surrounded by dry crusts of salt. Pond life is dominated by orange mats of cyanobacteria. Sandy deposits are about 10 cm thick and overly the thick ice of the ice shelf (© Paul A. Broady)

survives frequent freeze-thaw cycles. In winter, ponds freeze completely and life processes all but cease.

These ponds could have been refugia during colder periods when ice sheets expanded over adjacent land. Cold-tolerant organisms could have survived there until ice retreated and ice-free habitats were again available for colonisation.

Cryoconite ponds are found on the lower ablation zone of glaciers (Fig. 10.9d). In the McMurdo Dry Valleys they cover up to 15 % of this zone (Porazinska et al. 2004). Cryoconite means "cold rock dust" and in Antarctica this dust is wind-blown or avalanche-derived and accumulates in small depressions in the ice. As the ice melts, dust becomes a thin layer of sediment at the base of pools which range from centimetres to over a metre in diameter and are typically 30–50 cm deep. Deeper melting leads to ponds becoming entombed within the ice where they alternately freeze and melt for years.

Cyanobacteria usually dominate microbial communities which also include archaea, bacteria, other algae, protozoa, tardigrades and rotifers. Food webs must be quite complex in such diverse communities. Most algae obtain mineral nutrients from the sediments. The nitrogen-fixing cyanobacterium *Nostoc* is sometimes abundant and is probably using nitrogen gas dissolved in the pond water.

These communities resemble those of aquatic habitats on adjacent ice-free land. There is constant transfer of living organisms between these habitats and cryoconite ponds. Wind-blown material from the edges of dry lake shores and stream beds is deposited on glacier surfaces and organisms are washed out of the ice into streams and lakes.

Thousands of ponds occur on ice surrounding nunataks at the most southerly latitudes, such as La Gorce Mountains (86°30′S 147°W), 420 km from the South Pole and at about 1,800 m altitude (Fig. 10.9e; Broady and Weinstein 1998). Despite mid-summer air temperatures around −14 °C, there are between 25 and 60 ponds within each hectare of thin, sandy moraine lying on glacier ice. Each pond is up to 15 m in diameter with 30 cm of ice covering about 25 cm of water. Thin mats of the filamentous cyanobacterium *Phormidium*, associated with a few other algae, coat the bottom sediments where temperatures are about 1 °C. Protozoa and micro invertebrates have not been observed and food webs must be amongst the simplest, perhaps comprising only primary producers and decomposers.

The McMurdo Ice Shelf has hundreds of thousands of ponds, many connected by streams, scattered over about 1,750 km$^2$ (Fig. 10.9f; Howard-Williams et al. 1990). Sediment that melts into the ice comes from two sources. Some is blown from adjacent ice-free land but much is of marine origin. Marine sediments stick to the base of the ice shelf and then over many years move up to the surface through 20–50 m of ice. This movement is caused by ice ablating from the surface but forming on the under-surface of the ice shelf.

Ponds range in area from less than 1 m$^2$ to about 3 ha and are a few centimetres to 4 m deep. They occupy depressions up to 20 m deep, which places some below sea level. Weddell seals can appear in ponds that are connected to the sea by tunnels in the ice.

More than 60 species of algae inhabit these ponds. Water salinity is a major determinant of which species occur in a particular pond. Ponds with extensive sediments up to 10 cm deep have thick mats of cyanobacteria and often host tardigrades, nematodes and rotifers (Suren 1989). The rotifer *Philodina gregaria* occurs at remarkable densities of up to 400,000 per square metre and forms vivid orange aggregates. Where ice is covered by only patches of thin sediment, ponds are smaller and fresher and have lower concentrations of mineral nutrients. In summer, vigorous melt causes the collapse of ice dams and pinnacles; some ponds disappear and new ones form. In these disturbed conditions, algae are less abundant, with diatoms and single-celled green algae usually dominant.

When pond waters freeze during winter, the environment is very challenging (Hawes et al. 1999; Wait et al. 2009). As ice on brackish ponds thickens, salts accumulate below the ice to form a concentrated brine with much reduced freezing points. In late winter, the temperature of the brine drops to $-22\,^{\circ}\mathrm{C}$ without freezing. The water becomes anoxic and hydrogen sulphide accumulates due to the continuing activity of decomposer bacteria. Less saline ponds freeze completely.

## 10.3 Future Research

Research over the last 50 years has provided considerably more detail than that outlined in this overview. However, much remains to be discovered and understood. This is as true for readily accessible habitats as it is for those that have barely been examined. The full diversity of life forms, and especially of microorganisms, has yet to be described and we are largely ignorant of growth rates, interactions amongst species and of species with their physical environment. Global environmental change will have as yet unknown effects as it increasingly impinges on Antarctic ecosystems. This is equally applicable to non-aquatic habitats which are the focus of the next chapter.

## References

Adams BJ et al (2006) Diversity and distribution of Victoria Land biota. Soil Biol Biochem 38:3003–3018

Broady PA (1986) Ecology and taxonomy of the terrestrial algae of the Vestfold Hills. In: Pickard J (ed) Antarctic Oasis. Academic, Sydney, pp 165–202

Broady PA (1988) Broadscale patterns in the distribution of aquatic and terrestrial vegetation at three ice-free regions on Ross Island, Antarctica. In: Vincent W, Ellis-Evans C (eds) High latitude limnology. Kluwer, Dordrecht, pp 77–95

Broady PA (1989) The distribution of *Prasiola calophylla* (Carmich.) Menegh. (Chlorophyta) in antarctic freshwater and terrestrial habitats. Antarct Sci 1:109–118

Broady PA (2005) The distribution of terrestrial and hydro-terrestrial algal associations at three contrasting locations in southern Victoria land, Antarctica. Algol Stud 118:95–112

Broady PA, Weinstein R (1998) Algae, lichens and fungi in La Gorce Mountains, Antarctica. Antarct Sci 10:376–385

Burke CM, Burton HR (1988) The ecology of photosynthetic bacteria in Burton Lake, Vestfold Hills, Antarctica. Hydrobiologia 165:1–11

Burnett L, Moorhead D, Hawes I, Howard-Williams C (2006) Environmental factors associated with deep chlorophyll maxima in dry valley lakes, south Victoria Land, Antarctica. Arct Antarct Alp Res 38:179–189

Butler HG (1999) Seasonal dynamics of the planktonic microbial community in a maritime Antarctic lake undergoing eutrophication. J Plankton Res 21:2393–2419

Convey P (2007) Biogeography. In: Riffenberg B (ed) Encyclopedia of the Antarctic, vol 1. Routledge, New York, pp 154–161

De Carlo EH, Green WJ (2002) Rare earth elements in the water column of Lake Vanda, McMurdo Dry Valleys, Antarctica. Geochim Cosmochim Acta 66:1323–1333

Ferris JM, Burton HR (1988) The annual cycle of heat content and mechanical stability of hypersaline Deep Lake, Vestfold Hills, Antarctica. Hydrobiologia 165:115–128

Gibson JAE, Bayly IAE (2007) New insights into the origins of crustaceans of Antarctic lakes. Antarct Sci 19:157–164

Hahn S, Reinhardt K (2006) Habitat preference and reproductive traits in the Antarctic midge *Parochlus steinenii* (Diptera: Chironomidae). Antarct Sci 18:175–181

Hawes I (1989) Filamentous green algae in freshwater streams on Signy Island, Antarctica. Hydrobiologia 172:1–18

Hawes I, Howard-Williams C (1998) Primary production processes in streams of the McMurdo Dry Valleys, Antarctica. In: Priscu JC (ed) Ecosystem dynamics in a polar desert: the McMurdo Dry Valleys, Antarctica, Antarctic research series 72. American Geophysical Union, Washington, DC, pp 129–140

Hawes I, Schwarz A (1999) Photosynthesis in an extreme shade environment: benthic microbial mats from Lake Hoare, a permanently ice-covered Antarctic lake. J Phycol 35:448–459

Hawes I, Howard-Williams C, Vincent WF (1992) Desiccation and recovery of antarctic cyanobacterial mats. Polar Biol 12:587–594

Hawes I, Smith R, Schwarz A, Howard-Williams C (1999) Environmental conditions during freezing, and response of microbial mats in ponds of the McMurdo Ice Shelf, Antarctica. Antarct Sci 11:198–208

Healy M, Webster-Brown JG, Brown KL, Lane V (2006) Chemistry and stratification of Antarctic meltwater ponds II: inland ponds in the McMurdo Dry Valleys, Victoria Land. Antarct Sci 18:525–533

Howard-Williams C, Pridmore RD, Broady PA, Vincent WF (1990) Environmental and biological variability in the McMurdo Ice Shelf ecosystem. In: Kerry KR, Hempel G (eds) Antarctic ecosystems – ecological change and conservation. Springer, Berlin, pp 23–31

Imura S, Saito S, Seto K, Kanda H (1999) Benthic moss pillars in Antarctic lakes. Polar Biol 22:137–140

Karl DM, Bird DF, Björkman K, Houlihan T, Shackelford R, Tupas L (1999) Microorganisms in accreted ice of Lake Vostok, Antarctica. Science 286:2141–2144

Laybourn-Parry J (1997) The microbial loop in Antarctic lakes. In: Lyons WB, Howard-Williams-C, Hawes I (eds) Ecosystem processes in Antarctic ice-free landscapes. Balkema, Rotterdam, pp 231–240

Laybourn-Parry J, Roberts EC, Bell EM (2000) Mixotrophy as a survival strategy among planktonic protozoa in Antarctic lakes. In: Davison W, Howard-Williams C, Broady PA (eds) Antarctic ecosystems: models for wider ecological understanding. University of Canterbury, New Zealand Natural Sciences, Christchurch, pp 33–40

Laybourn-Parry J, Quayle WC, Henshaw T, Ruddell A, Marchant HJ (2001) Life on the edge: the plankton and chemistry of Beaver Lake, an ultra-oligotrophic epishelf lake, Antarctica. Freshw Biol 46:1205–1217

McKnight DM, Niyogi DK, Alger AS, Bomblies A, Conovitz PA, Tate CM (1999) Dry Valley streams in Antarctica: ecosystems waiting for water. Bioscience 49:985–995

Mosier AC, Murray AE, Fritsen CH (2007) Microbiota within the perennial ice cover of Lake Vida, Antarctica. FEMS Microbiol Ecol 59:274–288

Porazinska DL, Fountain AG, Nylen TH, Tranter M, Virginia RA, Wall DH (2004) The biodiversity and biogeochemistry of cryoconite holes from McMurdo Dry Valley glaciers, Antarctica. Arct Antarct Alp Res 36:84–91

Priscu JC (1989) Photon dependence of inorganic nitrogen transport by phytoplankton in perennially ice-covered lakes. Hydrobiologia 172:173–182

Priscu JC, Adams EE, Lyons WB et al (1999) Geomicrobiology of subglacial ice above Lake Vostok, Antarctica. Science 286:2141–2144

Purdy KJ, Hawes I, Bryant CL, Fallick AE, Nedwell DB (2001) Estimates of sulphate reduction rates in Lake Vanda, Antarctica support the proposed recent history of the lake. Antarct Sci 13:393–399

Rautio M, Bayly IAE, Gibson JAE, Nyman M (2008) Zooplankton and zoobenthos in high-latitude water bodies. In: Vincent WF, Laybourn-Parry J (eds) Polar lakes and rivers. Limnology of Arctic and Antarctic aquatic ecosystems. Oxford University Press, Oxford, pp 231–247

Roberts D, McMinn A (1997) Palaeosalinity reconstruction from saline lake diatom assemblages in the Vestfold Hills. In: Lyons WB, Howard-Williams C, Hawes I (eds) Ecosystem processes in Antarctic ice-free landscapes. Balkema, Rotterdam, pp 207–219

Sabbe K, Hodgson DA, Verleyen E, Taton A, Wilmotte A, Vanhoutte K, Vyverman W (2004) Salinity, depth and the structure and composition of microbial mats in continental Antarctic lakes. Freshw Biol 49:296–319

Samarkin VA, Madigan MT, Bowles MW, Casciotti KL, Priscu JC, McKay CP, Joye SB (2010) Abiotic nitrous oxide emission from the hypersaline Don Juan Pond in Antarctica. Nat Geosci 3:341–344

Säwström C, Lisle J, Anesio AM, Priscu JC, Laybourn-Parry J (2008) Bacteriophage in polar inland waters. Extremophiles 12:167–175

Schiermeier Q (2013a) Lake-drilling team discovers life under the ice. Nat News. doi:10.1038/nature.2013.12405

Schiermeier Q (2013b) Russian scientist defends Lake Vostok life claims. Nat News. doi:10.1038/nature.2013.12578

Schiermeier Q (2013c) Claims of Lake Vostok fish get frosty response. Nat News. doi:10.1038/nature.2013.13364

Siegert MJ, Ellis-Evans JC, Tranter M, Mayer C, Petit J-R, Salamatin A, Priscu JC (2001) Physical, chemical and biological processes in Lake Vostok and other subglacial lakes. Nature 414:603–609

Suren A (1989) Microfauna associated with algal mats in melt ponds on the Ross Ice Shelf, Antarctica. Polar Biol 10:329–335

Takii S, Konda T, Hiraishi A, Matsumoto GI, Kawano T, Torii T (1986) Vertical distribution in and isolation of bacteria from Lake Vanda: an Antarctic lake. Hydrobiologia 135:15–21

Taton A, Grubisic S, Balthasart P, Hodgson DA, Laybourn-Parry J, Wilmotte A (2006) Biogeographic distribution and ecological ranges of benthic cyanobacteria in East Antarctic lakes. FEMS Microbiol Ecol 57:272–289

Tindall BJ (2004) Prokaryotic diversity in the Antarctic – "The tip of the iceberg". Microb Ecol 47:271–283

Vincent WF (2000) Cyanobacterial dominance in the polar regions. In: Whitton BA, Potts M (eds) The ecology of cyanobacteria. Kluwer Academic Publishers, Dordrecht, pp 321–340

Vincent WF, Vincent CL (1982) Factors controlling phytoplankton production in Lake Vanda (77°S). Can J Fish Aquat Sci 39:1602–1609

Vincent WF, Downes MT, Vincent CL (1981) Nitrous oxide cycling in Lake Vanda, Antarctica. Nature 292:618–620

Voytek MA, Priscu JC, Ward BB (1999) The distribution and relative abundance of ammonia-oxidising bacteria in lakes of the McMurdo Dry Valleys, Antarctica. Hydrobiologia 401:113–130

Wait BR, Nokes R, Webster-Brown JG (2009) Freeze-thaw dynamics and the implications for stratification and brine geochemistry in meltwater ponds on the McMurdo Ice Shelf, Antarctica. Antarct Sci 21:245–254

Wand U, Samarkin VA, Nitzsche H-M, Hubberten H-W (2006) Biogeochemistry of methane in the permanently ice-covered Lake Untersee, central Dronning Maud Land, East Antarctica. Limnol Oceanogr 51:1180–1194

## *General Books and Articles*

Bergstrom DM, Convey P, Huiskes AHL (eds) (2006) Trends in Antarctic terrestrial and limnetic ecosystems. Springer, Dordrecht, xiv + 369 pp

Broady PA, Vincent WF (1990) Life in land, ice and inland water habitats. In: Hatherton T (ed) Antarctica: the Ross Sea region. DSIR Publishing, Wellington, pp 176–194

Hawes I (2001) Aquatic habitats. In: Waterhouse EJ (ed) Ross Sea region 2001: a state of the environment report for the Ross Sea region of Antarctica. New Zealand Antarctic Institute, Christchurch, pp 4.58–4.80

Vincent WF (1988) Microbial ecosystems of Antarctica. Cambridge University Press, Cambridge, xiii + 304 pp

Vincent WF, Laybourn-Parry J (eds) (2008) Polar lakes and rivers. Limnology of Arctic and Antarctic aquatic ecosystems. Oxford University Press, Oxford, xviii + 327 pp

# Chapter 11
# Life on Land

## Non-aquatic Ecosystems

**Paul A. Broady**

**Abstract** Water availability is of primary importance in controlling the abundance of life in non-aquatic habitats (Kennedy 1993). Unlike aquatic habitats, there is no free-standing water but water may be found in the minute spaces between particles of rocks, soils and snow. Its supply decreases with progression from relatively warm and moist maritime Antarctica to colder continental Antarctica where conditions are often extremely dry. For example, in maritime Antarctica, green expanses of moss can cover more than a hectare of ground, and lichens thickly encrust surrounding rocky slopes, whereas in the McMurdo Dry Valleys no vegetation is immediately apparent and brown rock and soil surfaces dominate the landscape. Also important is the microclimate at ground level. In summer, solar heating of dark vegetation, rocks and soils stimulates growth and activity of organisms, and may also increase water supply by melting overlying and adjacent ice and snow. This chapter first discusses life found on and in soils and rocks in typical ice-free areas, in conditions progressing from the most favourable to the most severe. It then considers unusual habitats provided by soils warmed with heat from volcanoes, by snow and ice and by extensive wetlands thought to be present under the Antarctic ice sheets.

**Keywords** Flowering plants • Soils • Mosses • Liverworts • Lichens • Microbial life

## 11.1 Flowering Plants

Antarctica's two indigenous species of flowering plant are restricted to maritime regions (Smith 2003). Their greatest abundance is in the South Orkney and South Shetland islands. Antarctic hair grass, *Deschampsia antarctica*, is a short tufted grass and Antarctic pearlwort, *Colobanthus quitensis*, has low-lying cushion-like growths of densely packed leafy stems (Fig. 11.1a). An additional two small

P.A. Broady (✉)
School of Biological Sciences, University of Canterbury, Christchurch, New Zealand
e-mail: paul.broady@canterbury.ac.nz



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_11

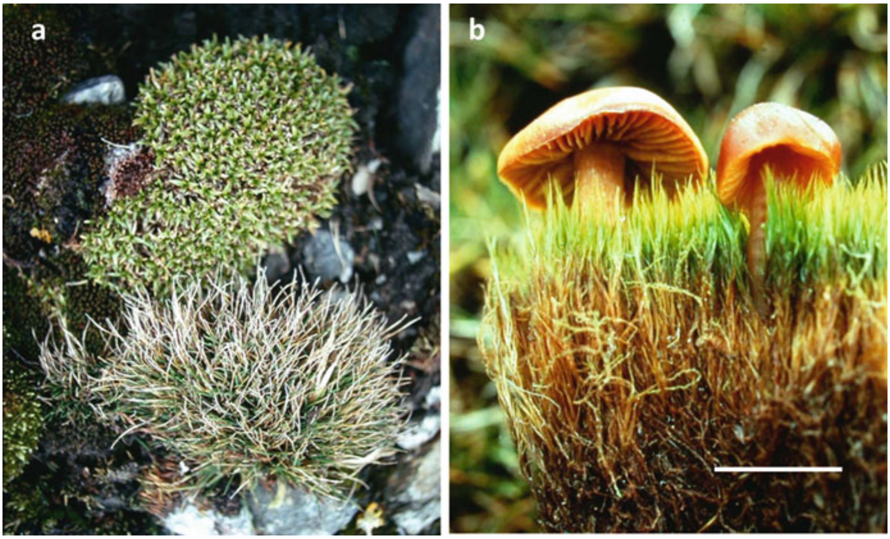



**Fig. 11.1** (**a**) The two indigenous Antarctic flowering plants growing on Signy Island, South Orkney Islands in the Maritime Antarctic region: *top*, *Colobanthus crassifolius* (pearlwort); *bottom*, *Deschampsia antarctica* (Antarctic hair grass). Both specimens are about 5 cm in diameter. (**b**) Sexual reproductive, spore-forming structures (basidiocarps, commonly called mushrooms) of a fungus emerge from a moss turf on Signy Island, South Orkney Islands. Basidiocarps are an unusual sight in maritime Antarctica. The green, healthy moss stems grow upwards and increasingly shade older parts which die and become brown peat deposits. These deposits can accumulate to depths in excess of 2 m. The fungus occurs predominantly as huge lengths of microscopic threads within the peat. It feeds on the peat during the process of decomposition. Decomposing peat is a major food source of collembola and mites. The *scale line* is equivalent to 2 cm (© Paul A. Broady)

herbaceous plants, *Nassauvia magellanica* and *Gamochaeta nivalis*, have recently been observed for the first time on Deception Island, South Shetland Islands (Hughes and Convey 2010). These could be either natural colonisers or introductions brought by visitors.

The pearlwort is much scarcer than the grass but both occur as far south as the Terra Firma Islands (68°43′S) off the west coast of the Antarctic Peninsula. Both species grow in South America from where it seems they were dispersed south across the Drake Passage to Antarctica by migrating birds.

Growth is best at sheltered, coastal sites less than 50 m in altitude. Dense grass typically covers ground sloping towards the north and receiving maximum sunlight, and can extend over several hundreds of square metres. On the calmest of cloudless summer days, temperatures among plants reach 25–30 °C and can occasionally be in excess of 40 °C. For 6–7 months over winter, plants are often insulated from the coldest temperatures by overlying deep snow. In summer, this melts and can provide a persistent water supply. The most luxuriant growths of grass are often fertilised with nutrients washed down from nesting birds on nearby cliffs. However, both the grass and pearlwort can be early colonists on recently exposed nutrient-poor mineral soils close to receding ice fields.

Both plants are adapted to minimise water loss. The effects of drying wind are reduced by their small ground-hugging size. Water loss from leaves is reduced by waterproof, thick waxy coatings and the grass can roll up its leaves along their length.

Abundant flowers are produced by the grass and its seeds, which take at least 18 months to mature, often fail to germinate if the summer is colder than usual and they are not exposed to several days of temperatures above freezing. Reproduction is probably best accomplished by rooted fragments of plants being dislodged, dispersed and establishing at new sites. Birds may have an important role as nesting material of skuas and Dominican gulls often contains plant fragments.

Warming of the regional climate in maritime Antarctica is allowing these plants to expand and to move into new sites. In monitored plots on Signy Island, South Orkney Islands, pearlwort plants increased in number by up to eight times between 1992 and 2000 (Smith 2003). Between 1985 and 2001, on the Fildes Peninsula on King George Island, South Shetland Islands, the number of sites with grass increased from about 14 to 160 and the first pearlwort plants became established (Fig. 11.2; Gerighausen et al. 2003).

### *11.1.1 The Most Highly Developed Antarctic Soils*

The soil below dense growths of grass is the most highly developed in Antarctica. It resembles fertile loam soils of temperate regions, although it is shallower at usually less than 20 cm in depth. Invertebrate animals and decomposer microorganisms feeding on decaying plant fragments stimulate the incorporation of organic matter into the soil. Testate amoebae, whose cells are contained within an outer shell, can occur at spectacularly high numbers of over 100,000 below each square centimetre of soil surface. At sites along the Antarctic Peninsula, soil animals include larvae of the wingless midge *Belgica antarctica* (Fig. 11.3; Chown 2007). Adults emerge at the soil surface during periods of calm, warm weather late in summer. Fungi closely associated with healthy grass roots are probably mycorrhizae which help the plant gather mineral nutrients from the soil while themselves gaining organic nutrients from the grass.

## 11.2 Mosses and Liverworts

Mosses and liverworts are collectively known as bryophytes and are the only other true plants in Antarctica (Lewis-Smith 2007a, b). Both usually have leaf-like lobes of tissue attached to thin stems up to 3 cm long. Moss leaves generally have a thickened midrib while liverworts do not. Neither has roots but produces rhizoids

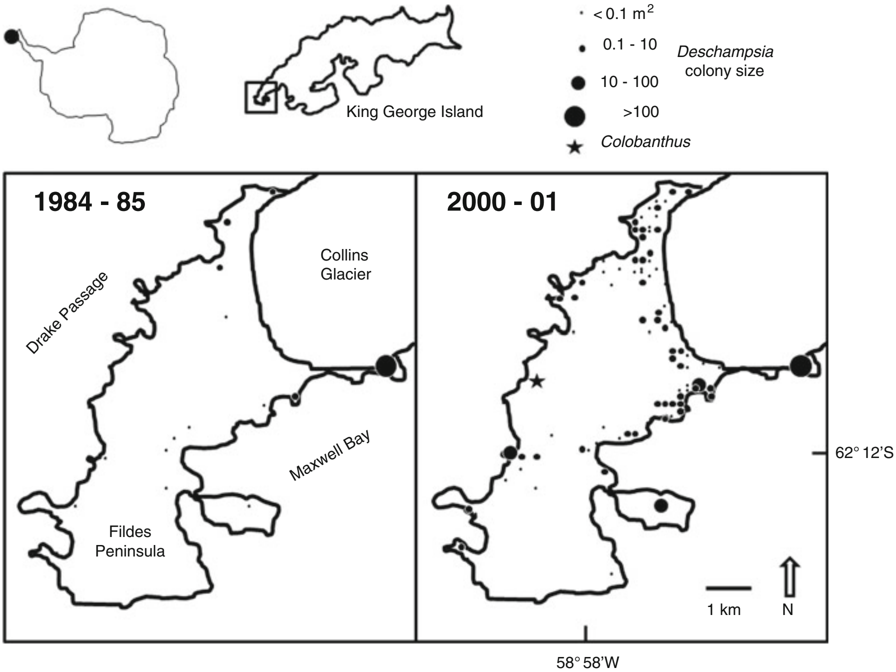



**Fig. 11.2** The increase in the abundance of the two indigenous Antarctic flowering plants on Fildes Peninsula, King George Island, South Shetland Islands, over 16 years. This is possibly due to regional warming of the climate. King George Island is located near the north-west tip of the Antarctic Peninsula and Fildes Peninsula is at the western end of the island. By 2000–2001, the number of colonies of the grass *Deschampsia antarctica* had increased considerably as had the size of many colonies present in 1984–1985. The pearlwort, *Colobanthus crassifolius*, had colonised for the first time by 2000-2001 (Adapted from Gerighausen et al. 2003)

which are fine, hair-like structures just one cell wide used for attachment to the substrate. The upper few millimetres of the plants are photosynthetic and usually green (Fig. 11.1b). One species of liverwort resembles branched flattened straps and is found only in northern maritime Antarctica.

Moss stems grow tightly packed or entwined to form small cushions. Each stem grows from its tip, by a few millimetres each year. As it extends upwards the lower portion becomes increasingly shaded until it loses its green pigments and eventually dies. This brown, organic material accumulates year by year to turn into a deposit known as peat.

Mosses and lichens (see below) form the most conspicuous vegetation in Antarctica (Figs. 11.4, 11.5, and 11.9). Liverworts are usually relatively minor inhabitants growing inconspicuously amongst moss stems in moist habitats. In total there are about 113 moss species and 27 liverwort species of which about 18 mosses and just one liverwort occur in continental Antarctica. South of 80°S, there are only five moss species, with the furthest southern record at 84°42′S. Many species of Antarctic moss and liverwort also occur in more temperate regions and some are

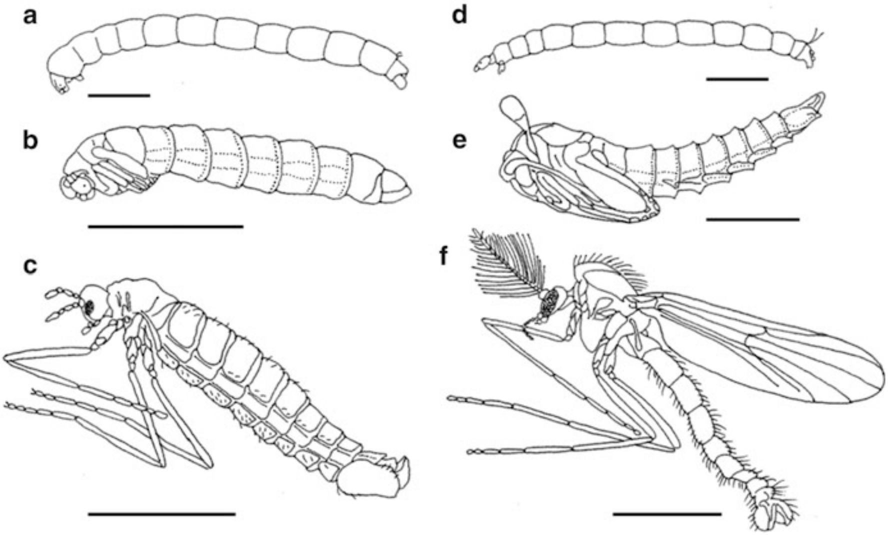



**Fig. 11.3** Two midges from maritime Antarctica. (**a**–**c**) *Belgica antarctica*; (**a**) larva, (**b**) pupa, (**c**) adult male. Adults of both sexes are flightless and have very reduced wings. (**d**–**f**) *Parochlus steinenii*; (**d**) larva, (**e**) pupa, (**f**) adult male. Adults have functional wings but only infrequently take to flight. Larvae of both species crawl over damp vegetation and are found in ponds. *Scale-lines* are equivalent to 1 mm (Adapted from Wirth and Gressitt 1967)

found in the Arctic. Like the flowering plants, these have probably been dispersed from the north during periods of reduced ice cover since the last ice age.

Mosses and liverworts occur in habitats with a good water supply. They readily absorb water and nutrients over their entire surface. Likewise water is easily lost but many species can survive in a dry condition for long periods. Growth requires a good supply of water for sufficient duration, and temperatures above 0 °C for photosynthesis. Depending on summer weather there may be between 5 and 15 weeks of favourable growth conditions at coastal locations in continental Antarctica. Over winter, individuals survive frozen and resume growth on thawing.

Growth rates are very slow (Selkirk and Skotnicki 2007). Mosses in coastal continental Antarctica have elongation rates of 1–5 mm per year at moist sites. At dry sites rates are a tenth of that. In maritime Antarctica, mosses can extend over more than 1 ha (Fig. 11.4a–c). At higher altitudes and on windswept, drier ground and throughout continental Antarctica mosses form small, sparsely scattered cushions to mats of a few square metres (Fig. 11.5).

Habitats with melt water seepages support different species compared with well-drained sites and exposed ground. Species in wet sites have underlying peat to a depth of 15 cm or less. In contrast, well drained rocky hillsides in northern regions of maritime Antarctica support two moss species which accumulate peat up to a depth of 2.5 m below the upper centimetre or so of upwardly growing stems. Below about 30 cm the peat is permanently frozen which prevents decomposition. Radiocarbon dating of the deepest peat shows it is up to 5,500 years old. At that time,

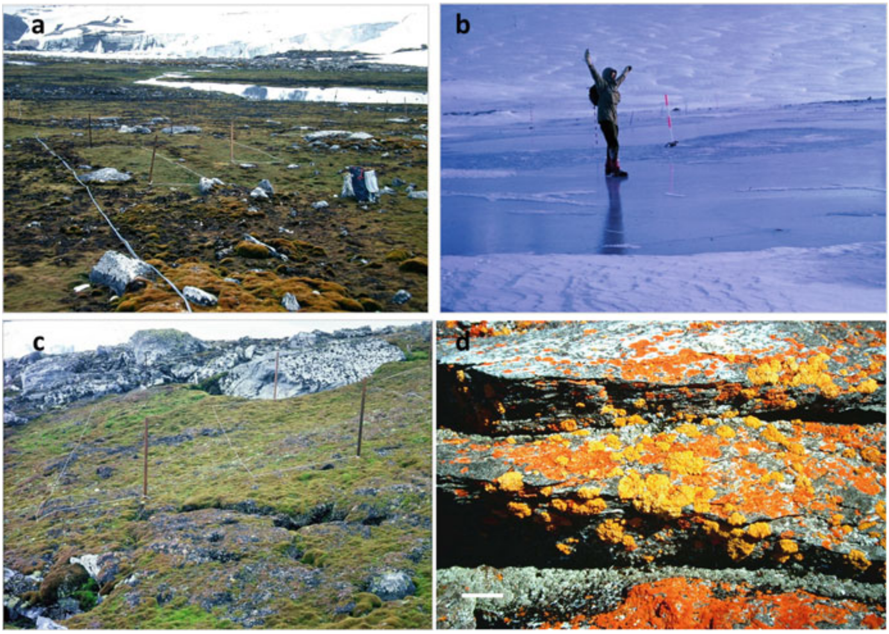



**Fig. 11.4** Moss and lichen in maritime Antarctica on Signy Island, South Orkney Islands. (**a**) A study site in an extensive area of moss carpet growing on boggy ground. (**b**) The same site as shown in (**a**) but in winter. The moss carpet is frozen under about 10 cm of ice for about 8 months. (**c**) A study site in an area of moss turf. This form of growth occurs on well-drained gently sloping hillsides. (**d**) Colourful lichens that encrust rocks in areas fertilised by birds. *Scale line* is equivalent to about 10 cm (© Paul A. Broady)

spores or small fragments of moss, probably dispersed by wind, first colonised ground exposed by retreating ice fields (Smith 1990).

On Signy Island, South Orkney Islands, what was once extensive, coastal moss has been heavily impacted by a huge increase in the population of fur seals over the last 35 years (Smith 1997). Prior to the mid-1970s, about 50 seals would be seen during summer. Since then numbers have increased to more than 20,000 in some years. The seals move easily over land and the vegetation has been trampled and poisoned by their wastes. Areas once dominated by mosses are now covered by a green alga, *Prasiola crispa*. The expansion of the seal population could be related to a warming climate with less ice around the islands in summer and to changes in marine food webs.

In continental Antarctica, most ground is too dry to support mosses. They mostly grow along stream edges (Fig. 11.5b) and on boggy ground, down-slope from melting ice fields and large snow banks (Schwarz et al. 1992). But even in these situations, algae generally dominate. Other habitats, even more restricted in extent, allow moisture enhancement and moss growth. One of these is below translucent stones resting on dry soil surfaces (see hypolithic communities). Another is where a few centimetres depth of sandy soil has been blown or washed over moss cushions


**Fig. 11.5** Moss growths at Cape Geology, southern Victoria Land, continental Antarctica. (**a**) Mosses are often restricted to very small patches where they receive water from melting snow banks. In this example, an area of less than 1 $m^2$ of scattered moss cushions is in the lee of a large boulder where snow would accumulate over winter before melting in early summer. Following complete melt of the snow, the mosses survive the remainder of summer in a desiccated condition. (**b**) More vigorous growths occur along the margins of summer melt streams. The dry exposed rocks to the side of the moss growths are stained white with salt deposits. The *scale line* is equivalent to 1 m. (**c**) Hummocky moss cushions grow amongst boulders where snow accumulates. The moss surfaces are darkly encrusted with microscopic blue-green algae. The *scale line* is equivalent to 10 cm (© Paul A. Broady)

and sufficient light penetrates for growth to continue. At this depth moisture is retained while it is rapidly lost at the surface. A third is close to the summits of volcanoes where steam condenses on geothermal ground (see below).

### *11.2.1 Life Among Moss Plants*

A wide range of organisms lives in air or water-filled tiny spaces among moss plants and the underlying peat. On sunny summer days this moist, warm environment exhibits considerable activity and the interactions of organisms can be described as a food web.

Details of life among mosses are best understood for maritime Antarctica (Davis 1981). Photosynthesis in mosses leads to the production of new organic material but this living moss tissue is a very minor source of nutrition for consumers. The organic component of the moss becomes available only after death and decomposition. The other primary producers, algae, are abundant as microscopic cells

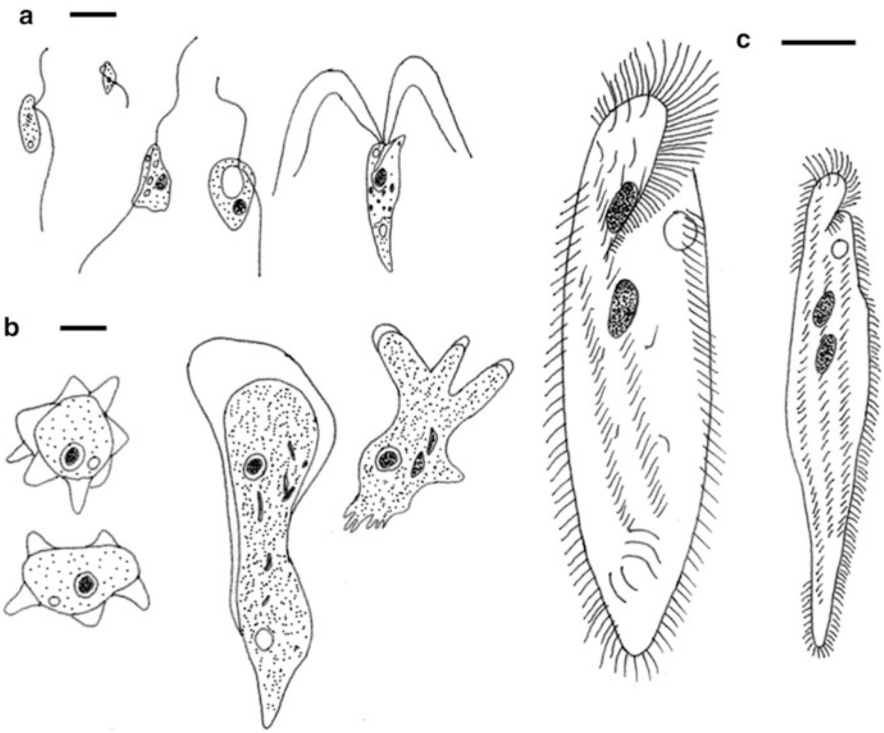



**Fig. 11.6** Protozoa are common in most aquatic and moist non-aquatic habitats. Three types are commonly recognised: (**a**) Flagellates which swim by means of whip-like flagella; (**b**) Amoebae which creep over substrate by pushing out pseudopodia (false feet); and (**c**) Ciliates which are the most actively motile due to possession of often hundreds of whip-like cilia. *Scale lines* are equivalent to: **a**, **b**, 1/100 mm; **c** 1/50 mm (Adapted from Smith 1978)

attached to moss surfaces. Up to five million cells of algae occur below each square centimetre of moss turf. These are the more important food source.

Small flagellate protozoa consume bacteria, and ciliates and amoebae eat bacteria and algae (Fig. 11.6). Rotifers and most species of tardigrades and nematodes (Fig. 11.7) have mixed diets of algae and fragments of dead moss that are being decomposed by bacteria, yeasts and filamentous fungi. Other nematodes are specialist feeders on either bacteria or fungi. The single species of collembolan and most species of mite also have a mixed diet (Fig. 11.8). The collembolan is also cannibalistic on carcasses of its own dead (Broady 1979).

There are a few predatory animals. One species of both tardigrade and nematode preys on other individuals of these groups. A species of rapidly moving mite captures collembola and mites and sucks the juices from their bodies. Several species of fungi are predators of nematodes and trap them using either a sticky glue or a ring of filaments that swells once a nematode has unwittingly entered (Gray and Smith 1984). The fungus then grows into the body of the nematode to digest it.

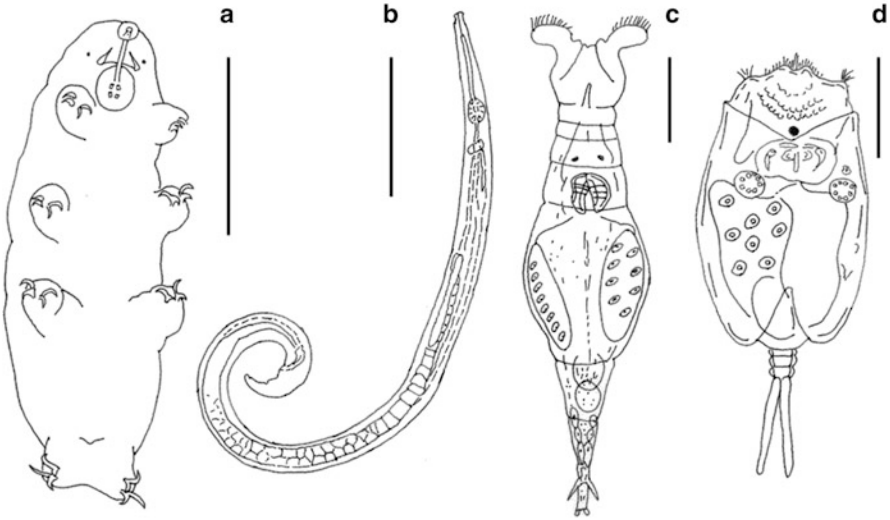



**Fig. 11.7** Invertebrate animals from aquatic and non-aquatic habitats. (**a**) A tardigrade showing its eight short legs, each tipped with curved claws that allow the animal to pull itself through vegetation such as mosses and filamentous algae. The feeding apparatus is used to pierce cells and suck out the cell contents. (**b**) A thread-like nematode. This is a male specimen of a species found among mosses in the South Orkney islands. (**c**) *Philodina gregaria* is a rotifer that is known only from Antarctica. It occurs throughout the region and is especially abundant in pools that are enriched by seal and penguin excreta. It can attain an abundance in excess of 50 million individuals per square metre. (**d**) This rotifer, *Euchlanis* sp., has a much more restricted distribution. It occurs in lakes in the South Orkney Islands. *Scale lines* are all equivalent to 0.1 mm (**a** Adapted from Dastych 1984; **b** Adapted from Maslen 1979; **c**, **d** Adapted from Dartnall and Hollowday 1985)

## 11.3 Lichens

Although many thousands of species of lichens have been described, each is in fact a combination of two very different types of organism, namely fungi and algae. When combined to form a lichen these species look very different to their appearance when growing separately. Lichens can grow in much harsher environments than their separate components growing individually.

The fungus (the mycobiont) is usually dominant and is associated with one or two species of algae (the photobionts). Their close relationship benefits both partners. The alga produces organic compounds by photosynthesis, providing a food supply for the fungus. The fungus envelopes and protects the alga from intense light and supplies it with water and mineral nutrients.

Most lichens grow in one of three ways (Fig. 11.9). Crustose lichens resemble splashes of paint, usually over rock surfaces. Foliose lichens are more loosely attached by hair-like outgrowths called rhizines that emerge from the under-surfaces of sheets that resemble crumpled cloth. Fruticose lichens are small bushes of branching hairs. Colours range from black and dull brown to the brightest of orange, yellow and white.

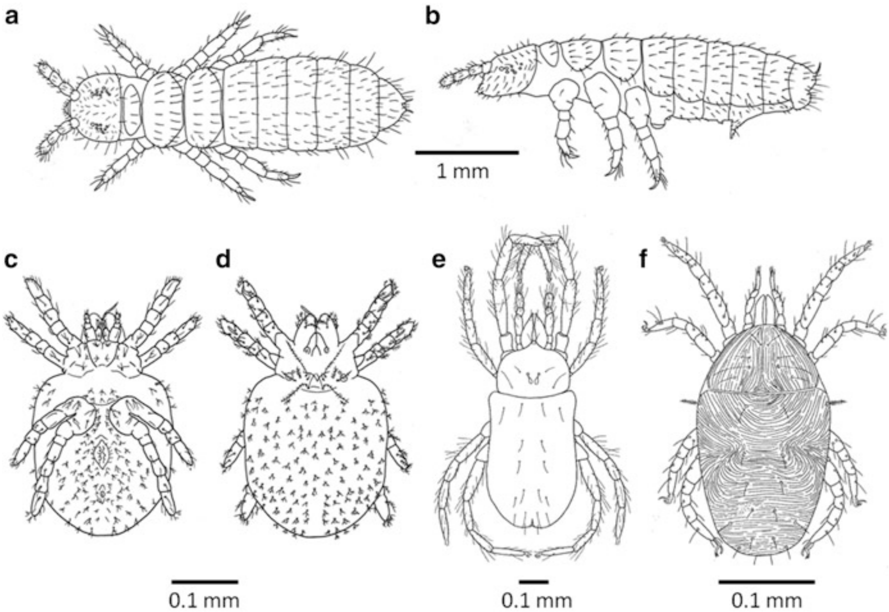



**Fig. 11.8** Collembola (**a**, **b**) and mites (**c**–**f**) are small invertebrate animals found among moss and algae and below stones resting on mineral soils. (**a**, **b**) *Gomphocephalus hodgsoni* occurs in southern Victoria Land and on Ross Island. (**c**, **d**) *Nanorchestes antarcticus* is a tiny red mite that is widespread from maritime Antarctic islands to nunataks far inland on continental Antarctica. Here it is viewed from below (**c**) and above (**d**). (**e**) *Coccorhagidia keithi* is a larger mite from the continent. (**f**) *Tydeus tilbrooki* is found in maritime Antarctica (**a**, **b** Adapted from Carpenter 1921; **c**, **d** Adapted from Womersley and Strandtmann 1963; **e**, **f** Adapted from Strandtmann 1967)

About 420 species have been described from Antarctica with about 75 % of these occurring in maritime regions (Lewis-Smith 2007c). Of the 90–100 species in continental Antarctica, about 50 % are endemic, i.e. they occur only in that region and nowhere else worldwide. Perhaps these lichens survived glaciations in the limited areas that remained ice-free, such as on nunataks. Over long periods of isolation in Antarctica they have evolved their unique characteristics which enable them to occupy very challenging habitats.

In maritime Antarctica, at favourable coastal locations, lichens can thickly cover several hectares of ground, with up to 2 kg of lichens occurring within each square metre. They grow on rock, soil and moss, as well as on concrete and wood structures. Even though they are not immediately apparent in the arid regions of continental Antarctica, such as the McMurdo Dry Valleys, they may occur hidden just below rock surfaces (see endolithic communities).

Lichens have been found in almost all areas where rock is exposed, although their altitudinal limit is around 2,500 m and only 15 species are known beyond 85°S. The most southerly occurrence is at La Gorce Mountains (86°29′S) at about 1,800 m altitude, where three species occur as minute surface growths (Fig. 11.9e, f; Broady and Weinstein 1998). The distribution of lichens is often patchy on the scale

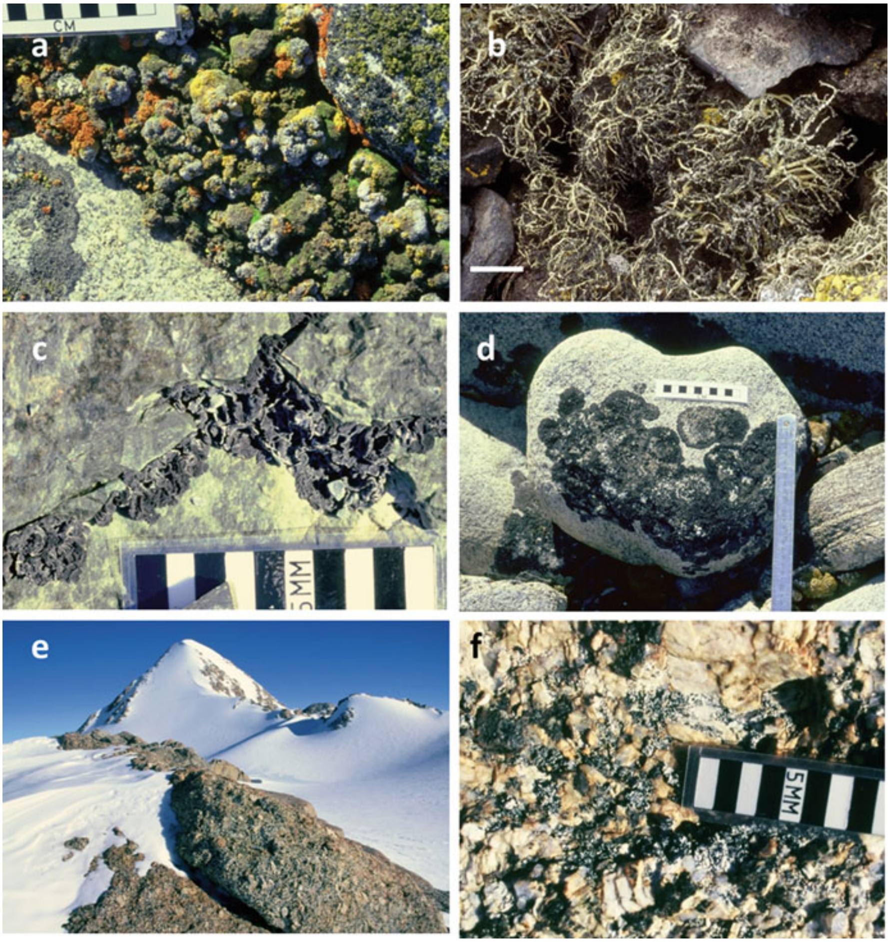



**Fig. 11.9** Lichens in continental Antarctica. (**a**) Moss cushions thickly encrusted by diverse lichens. (**b**) The fruticose lichen *Usnea* growing among large stones where it is sheltered from the damaging effects of strong winds. (**c**) Small specimens of the foliose lichen *Umbilicaria* growing along a crevice penetrating a rock surface. The moisture supply would be slightly enhanced in this microhabitat. Each division on the scale is 5 mm. (**d**) The crustose lichen *Buellia* on a small boulder at Cape Geology, Granite Harbour, southern Victoria Land. This same boulder was photographed by members of Scott's northern party in 1911. Careful comparison of the historical photograph with this recent image could detect no growth of these apparently healthy lichens over a period of 90 years (Schroeter et al. 1993). Growth rates must be very slow. (**e**) Mt. Roland in La Gorce Mountains is the site of the farthest south record of lichens (86°30′S). (**f**) The foreground rock face supported the sparse growth of two crustose species (© Paul A. Broady)

of centimetres to metres as conditions that support growth can be very localised. For example, freeze-thaw processes erode some rocks too rapidly for lichen colonisation and surfaces facing strong winds are abraded by wind-borne sand and ice crystals. Lichens are also greatly restricted in the wettest habitats where luxuriant growths of mosses dominate.

The availability of mineral nutrients influences lichen growth. Large supplies of nitrogen, in the form of ammonium, are associated with coastal and inland sea bird colonies and with individual bird nests. This stimulates growth of crustose, nitrophilous (nitrogen-loving) lichens such as vivid orange *Caloplaca* and *Xanthoria* (Fig. 11.4d). At the other extreme are nitrophobous (nitrogen-avoiding) crustose lichens such as *Acarospora*, which grow distant from these habitats.

Foliose species are mostly found close to the coast. In maritime Antarctica, *Umbilicaria* grows to a diameter of 45 cm in sheltered habitats but reaches only 1–2 cm in colder, more exposed positions. Exceptionally, some fruticose lichens grow to a length of over 40 cm.

*Usnea sphacelata* is a black fruticose lichen that tolerates extreme conditions in continental Antarctica. Its temperature may drop below −50 °C during winter on bare windswept mountain ridges where an insulating cover of snow is unlikely. In summer, water is supplied from moisture in clouds but clear days have intense solar radiation and it is extremely dry. Dark pigments provide protection from damaging ultra-violet radiation.

### *11.3.1 Photosynthesis and Growth*

Lichens can photosynthesise when their temperature is well below 0 °C, even as low as −17 °C in some continental species, although rates are very slow (Kappen and Schroeter 2002). In temperatures above 5 °C and in full sun, lichens undergo rapid drying and are subjected to intense radiation, both of which inhibit photosynthesis. Most can survive losing 95 % or more of their water content and will rapidly resume metabolic activity if remoistened. During the brief summer, lichens usually spend a large proportion of their time dry and inactive (Fig. 11.10). Conditions that allow growth occur for only 6–10 % of the year.

Even in the most favourable localities growth rates are very slow. In maritime Antarctica crustose lichens enlarge from their outer edge at about 0.01 to 0.7 mm per year (Hooker 1980). The few measurements made in continental Antarctica suggest rates at the lower end of this range or less (Brabyn et al. 2005). Most larger lichens are at least several centuries old and some have been estimated to be up to 5,000 years old.

## 11.4 Microbes in Soil

Most soils in Antarctica are lithosols (mineral soils) made of silt, sand and gravel produced by weathering and glacial erosion of rocks. Generally any organic material is very minor and most likely derived from microorganisms growing in the soil. Organic material can also be introduced through the erosion of rocks which harbour living organisms and by dried microbial mats being blown from stream beds and shore lines of lakes and ponds (Hopkins et al. 2006). More bizarre sources

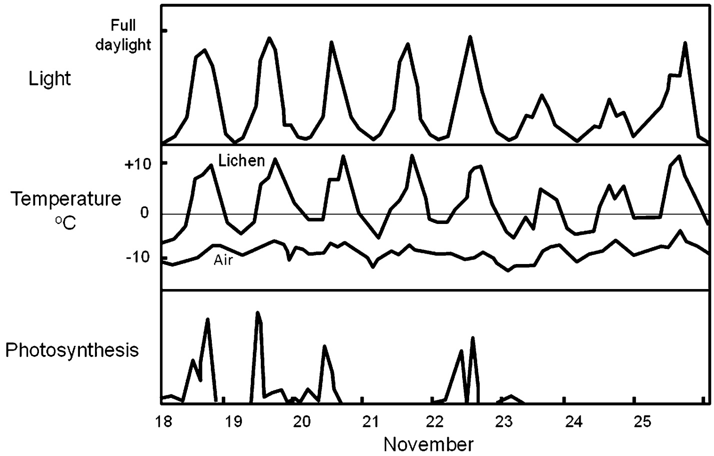



**Fig. 11.10** In early summer at Cape Geology, Granite Harbour, southern Victoria Land, solar heating can warm lichens encrusting rocks to temperatures well above freezing despite air temperatures remaining below freezing. However, photosynthesis occurs only when the lichens are hydrated following melt of a recent snowfall and when they receive melt water from adjacent snow banks (Adapted from Schroeter et al. 1997)

of organic material are the seals and penguins that become disorientated and wander into ice-free areas, die and mummify. These carcasses act as additional sources of nutrients.

Richly fertilised soils occur among nesting birds and on beaches where elephant seals congregate. These contain considerably more organic matter than lithosols. As both birds and seals feed at sea the result is a transfer of nutrients from the marine ecosystem to soils when animals release their wastes or die on land.

Soils of dry environments in continental Antarctica are often saline (Campbell 2000). Salts can form surface crusts or occur as interior layers. At high-altitude locations inland, nitrate salts are common because snowfall contains traces of nitrate and this remains following evaporation. Close to the coast the salt sodium chloride increases due to seawater droplets being blown inland. Also, salts originate from earlier periods when land was inundated by the sea. Yet other salts are derived from rock weathering.

In all these soils the abundance of life is usually determined by the availability of water.

### *11.4.1 Microbial Life in Moist and Wet Soils*

Some lithosols become saturated with melt water from snow banks and ice fields, and wetlands occur along the edges of streams, ponds and lakes (Fig. 11.12). Wet sites are less common with progression south and to higher altitudes. Mats and crusts of cyanobacteria cover between a few square metres and several hectares of

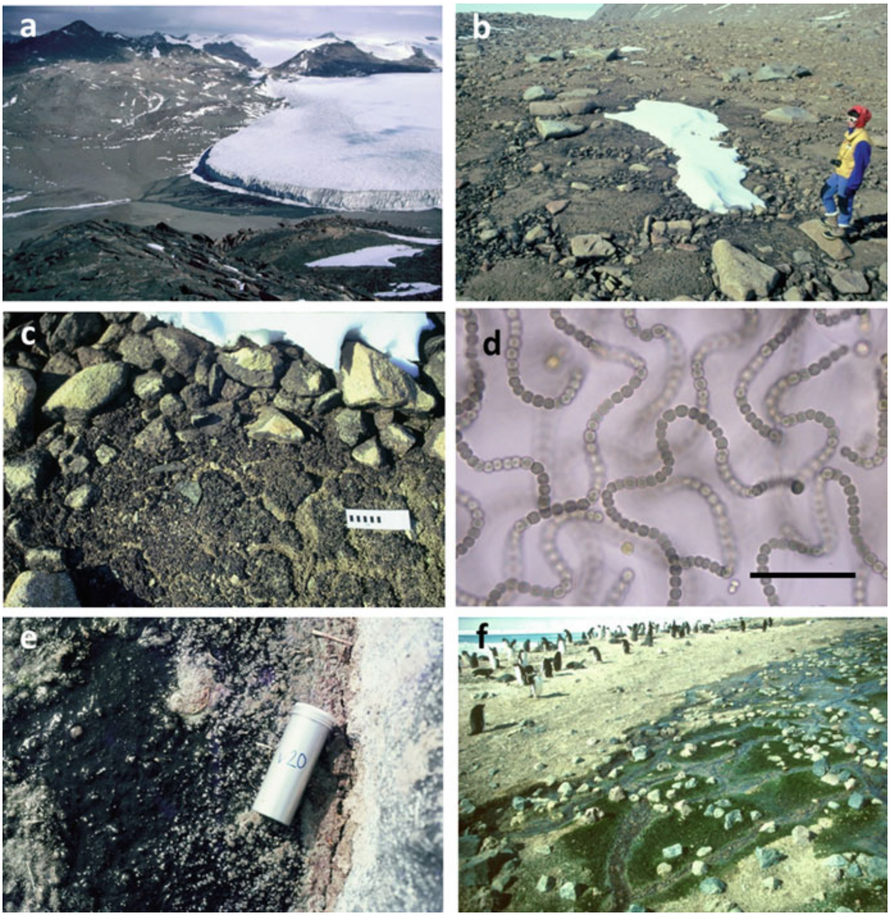


**Fig. 11.11** Algae growing on soils that receive a good supply of melt water during summer. (**a**) A distant view of boggy ground in front of the terminal ice walls of Joyce Glacier in Garwood Valley, southern Victoria Land. Several hectares are covered by black growths of the blue-green alga *Nostoc*. (**b**) Patterned ground at Cape Geology, southern Victoria Land. Colonies of *Nostoc* grow in channels containing large stones that lie between the small patches of sandy soil. Melt water percolates through the channels. (**c**) A closer view of colonies of *Nostoc*. The scale is equivalent to 10 cm. (**d**) Chains of cells (filaments) of *Nostoc* viewed at 400× magnification. The filaments are embedded in jelly-like mucilage that is secreted by the cells. The *scale line* is equivalent to 1/20th mm. (**e**) A thin mat of the blue-green alga *Phormidium* (see Fig. 10.2) growing on moist penguin guano at an Adélie penguin colony on Ross Island. (**f**) The sheet-like green alga *Prasiola crispa* growing on penguin guano in melt water percolations (© Paul A. Broady)

wet ground and comprise usually filamentous species, of which *Phormidium* is common (Fig. 11.11e), similar to mats in ponds and lakes. Jelly-like colonies of *Nostoc* can cover swampy ground in front of glaciers (Fig. 11.11a–d). Living within these mats are other algae including single-celled greens, yellow-greens and diatoms.

Where water supply is not persistent, algal crusts can still develop. In early summer in the McMurdo Dry Valleys, small, valley-side snow banks moisten underlying soil before they melt completely. Here, dark brown to black granular crusts are dominated by a filamentous cyanobacterium called *Microcoleus*.

Far south at the La Gorce Mountains an unusual habitat is provided below a few millimetres thickness of moist lithosol on the surface of glacier ice surrounding nunataks (Fig. 11.12e, f; Broady and Weinstein 1998). If the lithosol is brushed aside, brightly coloured patches of the green alga *Desmococcus* are revealed growing over the underlying ice. During summer, solar heating of the dark soil surface, to at least 7 °C, causes slight melting of the ice, and light reaches the alga by being scattered back upwards after shining into adjacent ice with no soil cover. These micro-environmental conditions support algal growth despite above-ground summer air temperatures of around −14 °C.

Heavily fertilised soils in the vicinity of bird and seal colonies support luxuriant sheet-like growths of the green alga *Prasiola crispa*, but only where melt water percolates and if the soil is not too disturbed by animals (Fig. 11.11f). This alga is evidently easily dispersed as it grows in coastal penguin colonies and also among petrels nesting on nunataks far inland (Ryan et al. 1989).

### *11.4.2 Microbial Life in Dry Soils*

In continental Antarctica, sparse populations of microscopic algae occur in dry soils. How active these are is unknown. They may be dispersed from elsewhere by wind and survive in an inactive state or perhaps grow during brief periods of increased moisture following occasional snow fall.

Moisture is slightly enhanced in some situations. For instance, patterned ground in the McMurdo Dry Valleys is made of furrows, about 30 cm deep, surrounding polygonal-shaped areas of ground (Fig. 11.12a, b). Beneath the surface, soil is cemented by permafrost. Following rare summer snowfall, snow persists in the shelter of furrows longer than it does over polygon surfaces from where it soon evaporates or blows away. Melting of snow in these furrows enhances moisture resulting in a greater abundance of the single-celled yellow-green alga *Botrydiopsis* (Broady 2005).

Despite only small populations of algae, the abundance of bacteria can be high even in the driest soils. Up to 100 million cells have been found in each gram of soil (Aislabie et al. 2008). There is gathering evidence that bacteria are diverse and differ considerably among different soil types (Cary et al. 2010). There also appears to be a high proportion of species that are unique to Antarctica while others are global in their distribution. A surprisingly small proportion is capable of maximum growth at temperatures below 15 °C (psychrophilic). Most can tolerate temperatures from 4 to 8 °C but grow best above 15 °C. In this capacity they seem adapted to the brief summer periods of warm micro-climates. For instance, in the Ross Sea

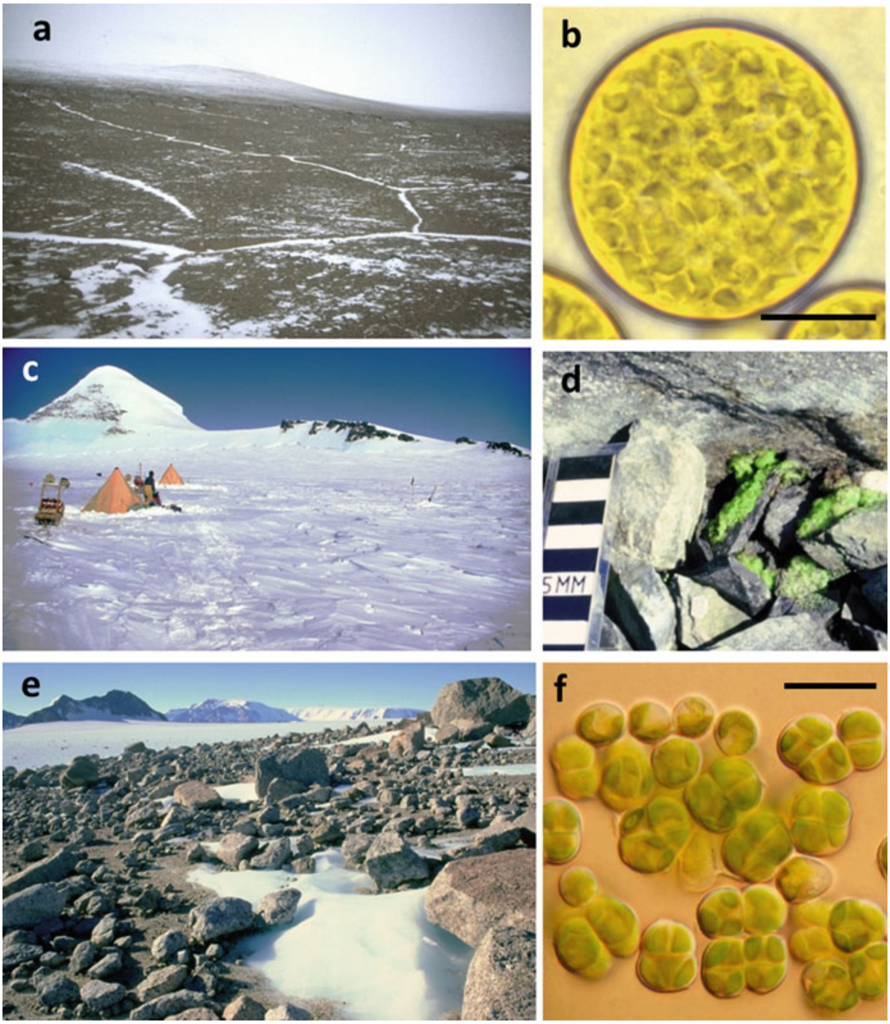



**Fig. 11.12** Algae growing in habitats of intermittent summer water supply. (**a**) Extensive areas in the McMurdo Dry Valleys consist of patterned ground. Shallow furrows surround each polygonal area. Infrequent snowfall results in snow accumulating in the furrows. Subsequent melt of this supplies additional moisture for growth of microscopic algae. In Victoria Valley, the microalgae are dominated by a single-celled yellow-green alga called *Botrydiopsis* (**b**); *scale line* is equivalent to 1/100th mm. (**c**) La Gorce Peak is a nunatak on Edward VII Peninsula. Small colonies of green algae (**d**) grow among stones on the rock exposures to the right of the camp site. (**e**) In the far south La Gorce Mountains, nunataks are flanked by areas of thin moraine covering the glacial ice. Where the moraine is sandy and only a few millimetres thick, patches of green algae can be revealed by brushing the sand off the underlying ice. The green alga, *Desmococcus*, forms clusters of cells (**f**), here viewed at 400× magnification, *scale-line* equivalent to 1/100th mm (© Paul A. Broady)

region the average annual soil temperature ranges from −15 to −40 °C, but in summer, when soil receives direct sunlight, surface temperatures can reach 20 °C.

Filamentous fungi and yeasts are also ubiquitous in dry valley soils (Connell et al. 2006). Although filamentous fungi prefer soils with slightly elevated moisture content, yeasts occur in even the driest soils. Little is understood about their functions and it is even possible that some might be relics from the past when climate was more conducive to reproduction.

### *11.4.3 Life on Geothermal Ground*

On Antarctic volcanoes, where heat is supplied by geothermal activity, soil surfaces can be warmed to temperatures well above those of the air (Fig. 11.13). Maximum soil surface temperatures ranging from 40 to 100 °C have been recorded (Broady 1993). A favourable environment is also provided by a reliable moisture supply from snow melt and condensation of steam. Unusual communities, unlike anything else found in Antarctica, develop.

In total these sites cover no more than a few hectares. Several locations, all below 550 m in altitude, occur in maritime Antarctica. Best known are those in the South Sandwich Islands and on Deception Island, South Shetland Islands. In continental Antarctica, sites are found at high altitudes of 2,250–3,750 m close to the summits of three heavily glaciated volcanoes: Mount Melbourne and Mount Rittmann in northern Victoria Land and Mount Erebus on Ross Island.

Geothermal soils have surface crusts and mats of algae, mosses and liverworts, which include species known only from such sites in Antarctica. For instance, 18 of the 36 species of mosses and liverworts known from the South Sandwich Islands are restricted to geothermal soils. The single moss species on the summits of Mount Erebus and Mount Melbourne is absent elsewhere in Antarctica but is well known in Australasia and South America (Skotnicki et al. 2001). All these species must be easily dispersed to Antarctica. For high altitude continental sites, dispersal is by wind, while in maritime Antarctica migrating birds are likely to play a role.

Surface temperatures are greatest within steam vents and reduce rapidly only a few centimetres from a vent. Soil temperatures also increase with depth. The warmest soils at above 40 °C contain thermophilic (heat-loving) bacteria (including cyanobacteria), archaea and fungi. Other algae, mosses and liverworts inhabit a zone further from vents where temperatures are cooler. On Mount Melbourne, this zone contains just one species of protozoan, a testate amoeba which is the sole grazer of microbes.

On Mount Erebus, the powerful techniques of molecular genetics have been used to reveal an unusual and diverse assemblage of bacteria and archaea (Soo et al. 2009). This is very similar to assemblages found on other continents in rocks deep beneath Earth's surface, leading to the suggestion that the Mount Erebus microbes might be derived from this deep-subsurface biosphere.

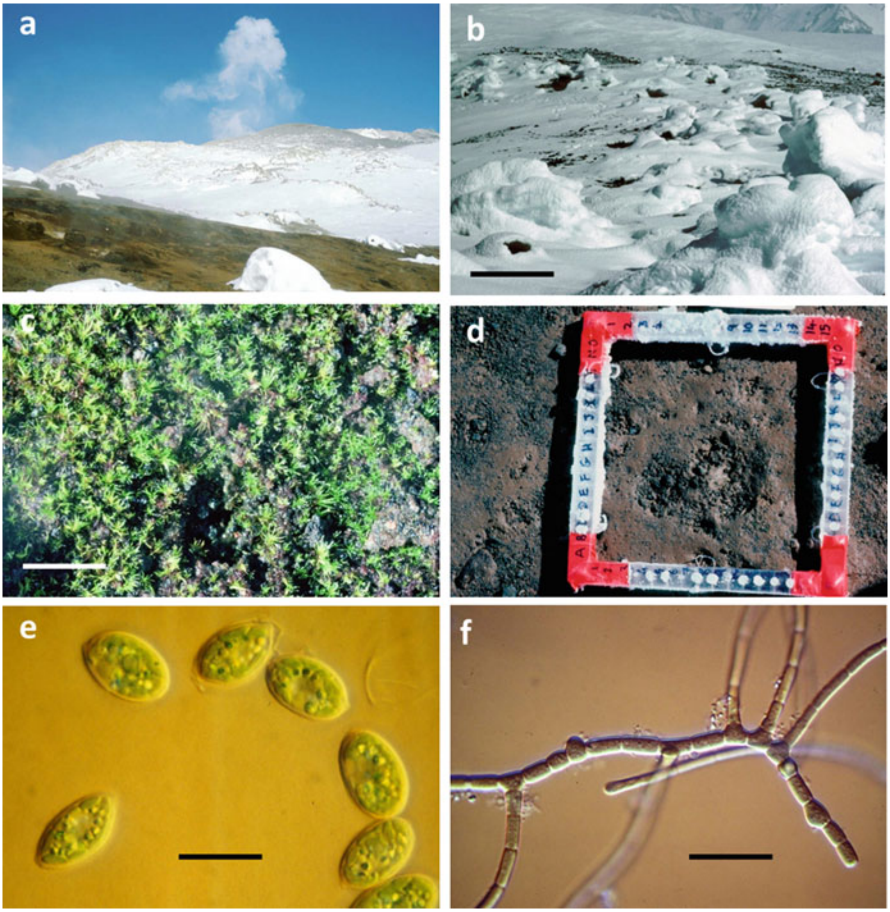



**Fig. 11.13** Life on geothermal ground close to the summit of two Antarctic volcanoes. (**a**) In the foreground is an area of open ground warmed by volcanic heat close to the summit of Mount Erebus, Ross Island. A small cloud of steam has just erupted from the summit crater. This area has been designated as an Antarctic Specially Protected Area because of the scientific importance of the site and the susceptibility of the microbial and moss community to disturbance and introduction of new organisms. (**b**) Geothermal ground on the edge of the ice-filled summit crater of Mount Melbourne, northern Victoria Land. Steam vents surrounded by exposed ground are partially covered by ice hummocks that are formed when steam emissions freeze. (**c**) The moss *Campylopus pyriformis* on geothermal soil on Mount Melbourne. This species also occurs on Mount Erebus but only as an immature form called protonema. The *scale line* is equivalent to 1 cm. (**d**) A thin mat of cyanobacteria on geothermal soil with a surface temperature of about 30 °C. The quadrat is 15 cm wide. (**e**) A single-celled green alga from Mount Erebus geothermal soil at a surface temperature of about 15 °C. (**f**) A thermophilic (heat-loving) blue-green alga, *Mastigocladus laminosus*, from Mount Erebus geothermal soil with a surface temperature of about 45 °C. (**e**) and (**f**) The *scale line* is equivalent to 1/100th mm (© Paul A. Broady)

## 11.5 Microbes Associated with Rocks and Stones

### *11.5.1 Life Below Stones: Hypolithic Communities*

Soil a few centimetres below the surface can be moistened by melting permafrost. If light reaches this moist sub-surface soil, photosynthetic organisms can grow. This combination of light and moisture occurs in the hypolithic (i.e. below a rock) habitat when light striking the upper, exposed surfaces of translucent stones passes through to underlying moist soil. Green and blue-green algae encrust the lower surfaces of the stones and, rarely, mosses and lichens grow there too. This habitat can be likened to a miniature greenhouse (Fig. 11.14a, b).

The Vestfold Hills is a region where the hypolithic habitat is widespread. Translucent quartz stones are extensively scattered over the desert soils (Broady 1986). Each square metre of ground has an average of 10 stones which cover about 66 $cm^2$. Algae live below these in dim light, typically about 1–3 % of the intensity at the soil surface. In summer, this radiation is sufficient to produce temperatures well above those of overlying air. For instance, at midday under a cloud-free sky when air is at −5 °C, the under-surface of a stone can reach 10 °C.

In the lower-altitude valleys of the McMurdo Dry Valleys region, the hypolithic environment hosts a wide range of organisms (Kahn et al. 2011). This community is distinct from that of surrounding soil. It includes blue-green and green algae, mosses, fungi, decomposer bacteria and archaea. Details of how all these organisms interact remain unknown.

### *11.5.2 Life Within Rocks: Endolithic Communities*

In continental Antarctica, the very dry environment greatly restricts the growth of vegetation on rock surfaces. However, if the rock is translucent, then lichens and algae are able to find a favourable habitat below the rock surface to a depth of a few millimetres. These communities are termed endolithic (i.e. inside a rock; Nienow and Friedmann 1993).

At Vestfold Hills and the McMurdo Dry Valleys, endoliths are the most extensive form of vegetation. Suitable rock types include granites and sandstones, both of which contain translucent crystals of quartz. Layers of differently coloured algae and lichens are revealed when these rocks are broken open with a hammer. In contrast, the dark, opaque, basaltic rocks of Ross Island completely lack endoliths. On the Antarctic Peninsula, endoliths have been found within crusts of gypsum (calcium sulphate) that form over boulder surfaces.

Endoliths are either chasmoendolithic or cryptoendolithic. Chasmoendoliths inhabit narrow cracks which penetrate into rock from its weathered surface, as in granites of the Vestfold Hills and lower-altitude regions of the McMurdo Dry Valleys (Fig. 11.14c–f). Cryptoendoliths grow in minute spaces between individual

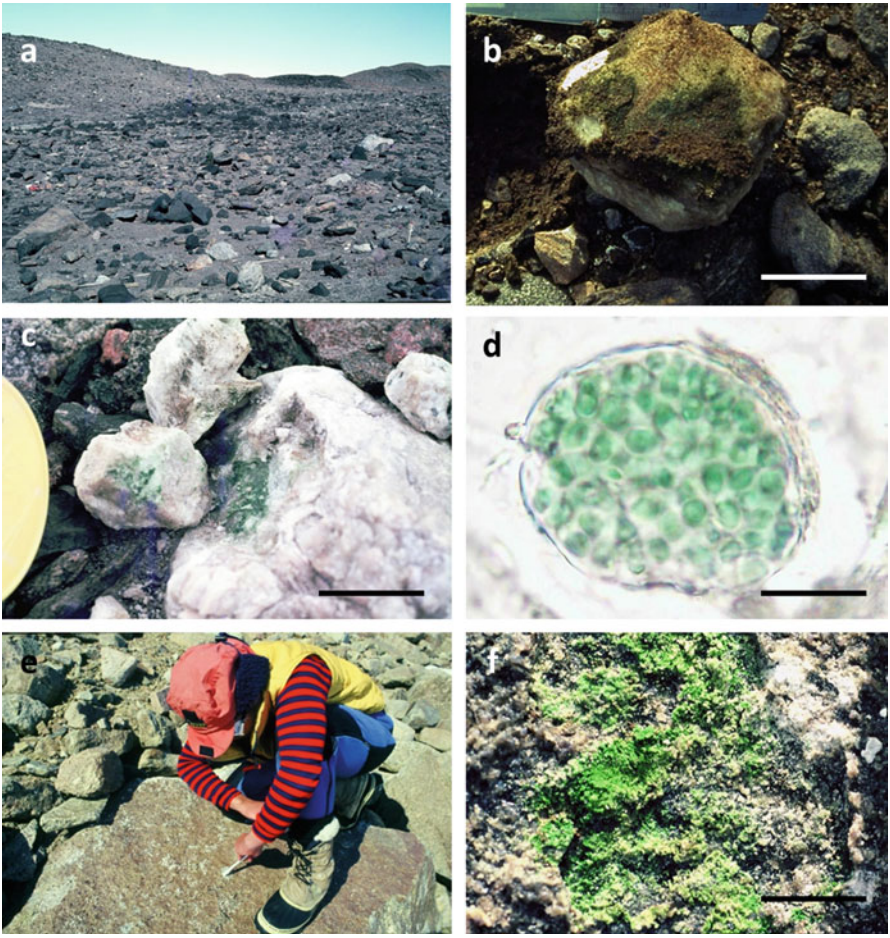



**Fig. 11.14** Algae associated with rocks and stones. (**a**) A typical dry desert landscape at the Vestfold Hills. A thin scattering of white quartz stones can be seen resting on the soil surface. It is below these that hypolithic microbial communities are found. (**b**) An overturned quartz stone with a thick mat of blue-green algae attached to its under-surface. A wide diversity of other microbes and possibly invertebrate animals will be associated with the mat. The *scale line* is equivalent to 10 cm. (**c**) A small quartz stone that has been broken open through a narrow crevice in order to reveal chasmoendolithic blue-green algae. The *scale line* is equivalent to 1 cm. This community is often dominated by *Chroococcidiopsis* (**d**). The *scale line* is equivalent to 1/100th mm. (**e**) Hammering a granitic boulder at Cape Geology, southern Victoria Land, in order to dislodge thin flakes of surface rock to reveal chasmoendolithic algae. (**f**) A chasmoendolithic crust consisting of both green and blue-green algae. The *scale line* is 1 cm (© Paul A. Broady)

crystals of more porous rocks such as sandstone. Additionally, they are usually sealed from the exterior by a thin crust that develops from fine dust blown into the rock surface.

Life in sandstones at high altitudes is dominated by cryptoendoliths. At 1,800 m altitude on Battleship Promontory, in the McMurdo Dry Valleys, inhabited rocks are next to those that lack life and at this boundary the limits for life on Earth are reached. At these sites, a small change in climate could result in local extinction. Such changes have occurred at sites where cryptoendoliths are now dead or fossilised.

Cryptoendoliths occupy a very shaded environment. When rock is moist, a maximum of 1 % of sunlight striking its surface can penetrate to the uppermost microorganisms. This rapidly reduces to 0.1 % a few millimetres deeper, at the bottom of the inhabited layer. When the rock is dry, sunlight intensities are a tenth of these.

Cryptoendoliths have the least requirement for water of any Antarctic microbial communities, but sufficient supply is still critical for their development. Often snow sublimates directly into the dry atmosphere or is blown away, but if rock surface temperatures exceed 0 °C, some melt will be absorbed into the rock. This is stored in the minute spaces between rock crystals. In summer, rock surfaces warmed by the midday sun can reach 15 °C when air temperatures are around −5 °C. Warming of the rock also boosts the metabolism of the inhabitants, as long as they are sufficiently hydrated to respond.

Another advantage for cryptoendoliths is that they are protected from abrasive ice and dust particles blown by strong winds, and from the frequent freeze-thaw cycles that can kill cells. Clouds shading the sun and cold wind gusts can rapidly cool rock surfaces to freezing temperatures while some warmth is retained within the rock and endoliths can be at temperatures above freezing.

Conditions suitable for growth persist for only short periods during summer (Fig. 11.15). Even in the best positioned rock face, this totals only about 800 h each year. Growth rates are slow. A period of 10,000 years is estimated to be required for a community to replace itself through one cycle of death and re-growth.

In high altitude sandstones, different organisms occur where rocks are exposed to different light intensities and moisture availability. Also, over a scale of a few millimetres, different organisms occupy increasing depths below the rock surface. Most extensive are lichens that inhabit a zone up to 10 mm deep directly below the rock crust where light intensities are greatest. Below the lichen, in dimmer light, a layer is dominated by a single-celled green alga called *Hemichloris antarctica* which is known only from Antarctica. Cyanobacteria usually occur in the lower part of this layer where light is reduced to the minimum that sustains photosynthesis. Within rocks shaded by overhangs, lichens are absent and *Hemichloris antarctica* dominates. Additionally, there are communities of different cyanobacteria. Where snow melt is most frequent, *Gloeocapsa* dominates but is replaced by *Chroococcidiopsis* in particularly cold, dry rocks.

Cryptoendolithic lichens and algae can be identified using a light microscope and cultures grown in the laboratory. However, DNA analysis shows that there is considerably more complexity to cryptoendolithic communities (de la Torre et al. 2003). For instance, a community dominated by *Chroococcidiopsis* contained

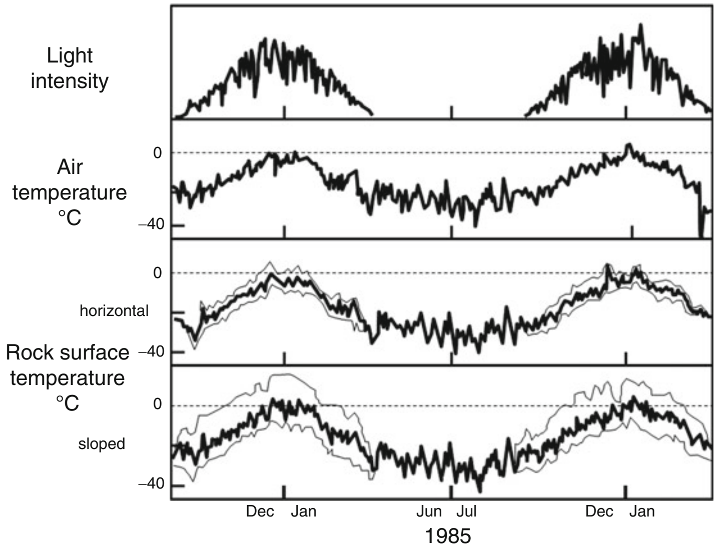



**Fig. 11.15** At Linnaeus Terrace, altitude 1,650 m, McMurdo Dry Valleys, temperatures adequate for growth of cryptoendolithic microbial communities occur for only short periods during summer. The winter period of constant night persists from mid-April to early September. The graphs show: light intensity at the rock surface, air temperature at about 70 cm above the rock and on rock surfaces that were horizontal and sloped 30° from the vertical towards the north-east. The latter receives more insolation than the horizontal surface. The *fine lines* in the *bottom* two graphs indicate the limits of maximum and minimum daily temperatures. *Thick lines* are daily averages. The total period over a year when temperatures and moisture availability allowed metabolic activity was estimated to be about 32 days for the horizontal rock surface. This was spread over about 135 days. Metabolic activity must start and stop many times during a year, being absent when the organisms are frozen or dry or both (Adapted from Nienow and Friedmann 1993)

26 distinct types of bacteria including some new to science. The functions of these are unknown.

Chasmoendolithic communities are found at lower altitudes in the McMurdo Dry Valleys and in coastal continental regions such as the Vestfold Hills. At 600 m altitude in the Taylor Valley, *Chroococcidiopsis* inhabits cracks in weathered granite (Büdel et al. 2008). At night, dew forms from atmospheric water vapour that condenses when rock surfaces become cooler than air. This water soaks into the rock and stimulates communities that are more active than those at higher altitude.

At Cape Geology, a coastal ice-free area just north of the McMurdo Dry Valleys, and at the Vestfold Hills, chasmoendolithic communities are often dominated by two green multicellular algae (Broady 2005). These relatively complex forms are not encountered at higher altitude sites. *Prasiococcus calcarius* thrives at high salinity where strong winds blowing off the open sea or across saline lakes deposit salt onto rock surfaces, while *Desmococcus* prefers less saline environments.

## 11.6 Microbes in Snow and Ice

Microbes occur in all the massive volume of Antarctic snow and ice. They are at low numbers and barely, if at all, metabolically active in the Antarctic ice sheet. In contrast, their high abundance in melting snow banks adds to the colour of the landscape in some coastal regions (Fig. 11.16).

### *11.6.1 Snow Algae*

Although each individual is microscopic, snow algae grow to such abundance that surface layers of snow turn pinkish-red, green, yellow or grey depending on the species present (Fig. 11.16a, b).

Snow algae are psychrophiles (cold loving) as they are adapted for growth at temperatures close to 0 °C in melt water occupying spaces between ice crystals. Cell numbers can exceed 200,000 per millilitre. For growth to occur, snow must be wet with melt water for a sufficient period of time during summer. Consequently,

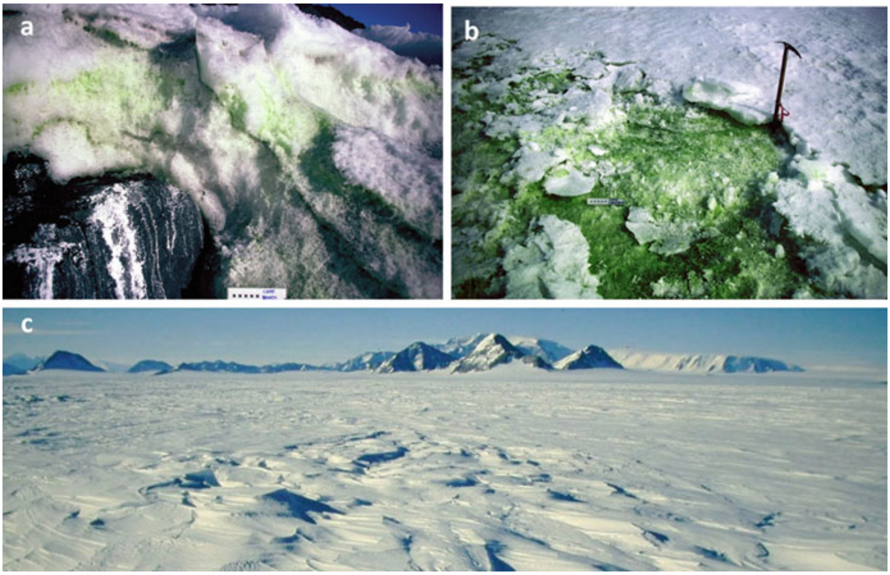



**Fig. 11.16** Microbes associated with snow and ice. Farthest south (77° 35′S) snow algae at (**a**) Cape Royds and (**b**) Cape Crozier, Ross Island. Single-cell green algae (chlorophytes) are present at sufficient abundance to colour the snow green. Growth is stimulated by melt water percolating through the snow for periods during summer and by fertilisation from guano deposited by Adelie penguins walking to and fro between nearby colonies and coastal waters. The scale is 10 cm. (**c**) Part of the Antarctic ice sheet in the vicinity of La Gorce Mountains. There is no melt of the snow and ice over the majority of the ice sheet but a low abundance of bacteria, archaea and fungal spores have been found from the surface down to more than 2 km depth (© Paul A. Broady)

snow algae are more frequently encountered in maritime (Corte 1970) than continental Antarctica (Ling 1996) and mostly in coastal regions.

Cells are exposed to potentially damaging light intensities and ultra-violet radiation. For protection they accumulate substances such as orange-red carotenoid pigments that act as sunscreens. Usually these algae are seen near penguin colonies where adjacent snow fields are fertilised by the birds. The furthest southern records (76°34′S) on Ross Island are close to Adélie penguin colonies. However, in some regions the most extensive snow algae are distant from fertilisation. At the Windmill Islands (66°20′S, 110°30′E) grey snow covers an area of about 50 km$^2$ and develops in snow with few nutrients. The species found here are different from those in fertilised snow.

### *11.6.2 The Continental Ice Sheet*

Although usually regarded as lifeless, the continental ice sheet is by no means devoid of microbes (Fig. 11.16c). Surface snow collected at an uncontaminated site near the Amundsen-Scott South Pole Station contained bacteria at concentrations of 200–5,000 cells per millilitre of snow melt (Carpenter et al. 2000). In the laboratory, these bacteria are able to make protein and DNA at temperatures as low as −17 °C. Analysis of DNA reveals several types of bacteria including those that grow best at low temperatures and one which is very resistant to desiccation and ionising radiation. Perhaps a similar abundance of bacteria can be found within the entire ice sheet. Although numbers of cells per millilitre are low, their total mass in the entire ice sheet could be considerable when its huge area is considered.

Slow accumulation of snow, at a rate of 2–10 cm per year, moves microorganisms that were initially at the surface progressively deeper into the ice. Bacteria, yeasts and filamentous fungi from deep within the Vostok ice core have all been grown in cultures (Abyzov 1993). The greatest diversity of microbes is in the upper 600 m, the deepest of which are in ice that is about 39,000 years old. Fewer are found with increasing depth but bacteria occur down to 2,400 m deep in ice about 200,000 years old. The search is on for 1 million year old ice. Perhaps microbes are also held within that.

## 11.7 Life in Subglacial Wetlands

Lakes are not the only water found below continental ice. Melting occurs under the entire extent of the ice sheet at the interface with rocks and sediments. Microorganisms trapped in ice and transported down from the surface over hundreds of thousands of years are thought to be released there. On the continental scale, melting averages about 2 mm per year and water probably soaks into underlying rocks and sediments, possibly to depths of hundreds of metres. It has been suggested that this could be Earth's largest wetland (Priscu et al. 2008) and that it might be an important habitat for microbial life. This has yet to be investigated.

## 11.8 Future Study of Terrestrial Ecosystems

Climate change is increasingly impacting the Antarctic terrestrial ecosystem. In maritime Antarctica, temperatures continue to rise and this is causing longer summers. Effects of this include changes to species distribution patterns and reductions in the duration of ice cover on lakes, with consequences for lake ecology. Warmer temperatures also increase the possibility of organisms invading from more temperate regions and establishing populations. Continued monitoring of these effects makes the terrestrial ecosystem a valuable and sensitive indicator of global change.

At a more pragmatic level, benefits could flow from discoveries made about the biochemical and genetic properties of indigenous Antarctic organisms (e.g. Heath et al. 2009). Many have evolved to cope in a highly stressful environment which can be on the margin of conditions that support life on Earth. Their genes undoubtedly encode metabolic pathways that produce biochemicals enabling their survival and growth. Bioprospecting is the search for these genes and their products and subsequent assessment of their potential for use in medicine, food technology, waste treatment and a variety of other industrial applications. The impact of bioprospecting on the natural environment is minimal as samples for laboratory study require a few grams of material at most. For instance, a teaspoonful of Antarctic soil is likely to contain many undescribed bacteria, some of which could produce novel proteins or antibiotics of great potential (Chap. 22).

Conservation of the terrestrial ecosystem in a condition unperturbed by scientific activity and tourism is essential if its natural values are to be maintained. With around 50,000 people visiting Antarctica each year, the possibilities of physical damage and the introduction of new organisms is higher than it has ever been. An extensive network of protected areas is needed which encompasses examples of the full diversity of habitats and their biota. Antarctic Specially Protected Areas require permits for entry and provide an additional level of protection over that provided for Antarctica in general. They have been increasing in number for about 40 years and some protect examples of this diversity. However, many unique habitats remain outside these areas. Before we can be confident that protection is adequate, we need to complete an inventory of species from all groups of organisms and map their distribution patterns at scales from local to regional. Additional protected areas can then be chosen on the basis of this knowledge.

Human curiosity is stimulated by the unusual. As we have seen, there is much that is outside our day-to-day experience in the organisms and their habitats in the Antarctic terrestrial ecosystem. In this there are potential educational benefits. The iconic animals of the Antarctic marine ecosystem have always inspired people's interest in the natural world. The more bizarre inhabitants of the terrestrial ecosystem have that potential too. We will need both expert biologists and well informed citizens in a rapidly changing world where solutions to many challenges will use biological knowledge.

## References

Abyzov SS (1993) Microorganisms in the Antarctic ice. In: Friedmann EI (ed) Antarctic microbiology. Wiley-Liss, New York, pp 265–295

Aislabie JM, Jordan S, Barker GM (2008) Relation between soil classification and bacterial diversity in soils of the Ross Sea region, Antarctica. Geoderma 144:9–20

Brabyn L, Green A, Beard C, Seppelt R (2005) GIS goes nano: vegetation studies in Victoria Land, Antarctica. N Z Geogr 61:139–147

Broady PA (1979) Feeding studies on the collembolan *Cryptopygus antarcticus* Willem at Signy Island, South Orkney Islands. Br Antarct Surv Bull 48:37–46

Broady PA (1986) Ecology and taxonomy of the terrestrial algae of the Vestfold Hills. In: Pickard J (ed) Antarctic Oasis. Academic, Sydney, pp 165–202

Broady PA (1993) Soils heated by volcanism. In: Friedmann EI (ed) Antarctic microbiology. Wiley-Liss, New York, pp 413–432

Broady PA (2005) The distribution of terrestrial and hydro-terrestrial algal associations at three contrasting locations in southern Victoria Land, Antarctica. Algol Stud 118:95–112

Broady PA, Weinstein R (1998) Algae, lichens and fungi in La Gorce Mountains, Antarctica. Antarct Sci 10:376–385

Büdel B, Bendix J, Bicker FR, Green TGA (2008) Dewfall as a water source frequently activates the endolithic cyanobacterial communities in the granites of Taylor Valley, Antarctica. J Phycol 44:1415–1424

Campbell IB (2000) Soil temperature, moisture and salinity patterns in Transantarctic Mountain cold desert ecosystems. In: Davison W, Howard-Williams C, Broady PA (eds) Antarctic ecosystems: models for wider understanding. New Zealand Natural Sciences, University of Canterbury, Christchurch, pp 233–240

Carpenter GH (1921) Insecta. Part I. Collembola. British Antarctic (“Terra Nova”) expedition, 1910. Nat Hist Rep Zool 3:259–267

Carpenter EJ, Lin S, Capone DG (2000) Bacterial activity in South Pole snow. Appl Environ Microbiol 66:4514–4517

Cary SC, McDonald IR, Barrett JE, Cowan DA (2010) On the rocks: the microbiology of Antarctic Dry Valley soils. Nat Rev 8:129–138

Chown SL (2007) Insects. In: Riffenburgh B (ed) Encyclopedia of the Antarctic, vol 1. Routledge, New York, pp 530–534

Connell L, Redman R, Craig S, Rodriguez R (2006) Distribution and abundance of fungi in the soils of Taylor Valley, Antarctica. Soil Biol Biochem 38:3083–3094

Corte A (1970) Bioecological aspects of the snow plant communities of Cape Spring, Argentine Antarctica. In: Ecology of the subantarctic regions, no 1. UNESCO, Paris, pp 101–104

Dartnall HJG, Hollowday ED (1985) Antarctic rotifers. Br Antarct Surv Sci Rep 100:46

Dastych H (1984) The Tardigrada from Antarctic with descriptions of several new species. Acta Zool Cracov 27:377–436

Davis RC (1981) Structure and function of two Antarctic terrestrial moss communities. Ecol Monogr 5:125–143

de la Torre JR, Goebel BM, Friedmann EI, Pace NR (2003) Microbial diversity of cryptoendolithic communities from the McMurdo Dry Valleys, Antarctica. Appl Environ Microbiol 69:3858–3867

Gerighausen U, Bräutigam K, Mustafa O, Peter H-U (2003) Expansion of vascular plants on an Antarctic island – a consequence of climate change? In: Huiskes AHL, Gieskes WWC, Rozema J, Schorno RML, van der Vies SM, Wolff WJ (eds) Antarctic biology in a global context. Backhuys Publishers, Leiden, pp 79–83

Gray NF, Smith RIL (1984) The distribution of nematophagous fungi in the Maritime Antarctic. Mycopathologia 85:81–92

Heath C, Hu X-P, Cary C, Cowan D (2009) Identification of a novel alkaliphilic esterase active at low temperatures by screening a metagenomic library from Antarctic desert soil. Appl Environ Microbiol 75:4657–4659

Hooker TN (1980) Factors affecting the growth of Antarctic crustose lichens. Br Antarct Surv Bull 50:1–19

Hopkins DW, Sparrow AD, Novis PM, Gregoricj EG, Elberling B, Greenfield LG (2006) Controls on the distribution of productivity and organic resources in Antarctic Dry Valley soils. Proc R Soc B 273:2687–2695

Hughes KA, Convey P (2010) The protection of terrestrial Antarctic ecosystems from inter- and intra-continental transfer of non-indigenous species by human activities: a review of current systems and practices. Glob Environ Chang 20:96–112

Kahn N, Tuffin M, Stafford W, Cary C, Lacap D, Pointing SB, Cowan D (2011) Hypolithic microbial communities of quartz rocks from Miers Valley, McMurdo Dry Valleys, Antarctica. Polar Biol 34:1657–1668

Kappen L, Schroeter B (2002) Plants and lichens in the Antarctic, their way of life and their relevance to soil formation. In: Beyer L, Bölter M (eds) Geoecology of Antarctic ice-free coastal landscapes. Springer, Berlin, pp 327–373

Kennedy AD (1993) Water as a limiting factor in the Antarctic terrestrial environment: a biogeographical synthesis. Arct Alp Res 25:308–315

Lewis-Smith RI (2007a) Mosses. In: Riffenburgh B (ed) Encyclopedia of the Antarctic, vol 2. Routledge, New York, pp 652–656

Lewis-Smith RI (2007b) Liverworts. In: Riffenburgh B (ed) Encyclopedia of the Antarctic, vol 2. Routledge, New York, pp 596–597

Lewis-Smith RI (2007c) Lichens. In: Riffenburgh B (ed) Encyclopedia of the Antarctic, vol 2. Routledge, New York, pp 591–595

Ling HU (1996) Snow algae of the Windmill Islands region, Antarctica. Hydrobiologia 336:99–106

Maslen NR (1979) Six new nematode species from the maritime Antarctic. Nematologica 25:288–308

Nienow JA, Friedmann EI (1993) Terrestrial lithophytic (rock) communities. In: Friedmann EI (ed) Antarctic microbiology. Wiley-Liss, New York, pp 343–412

Priscu J, Tulaczyk S et al (2008) Antarctic subglacial water: origin, evolution, and ecology. In: Vincent WF, Laybourn-Parry J (eds) Polar lakes and rivers. Limnology of Arctic and Antarctic aquatic ecosystems. Oxford University Press, Oxford, pp 119–135

Ryan PG, Watkins BP, Smith RIL, Dastych H, Eicker A, Foissner W, Heatwole H, Miller WR, Thompson G (1989) Biological survey of Robertskollen, western Dronning Maud Land: area description and preliminary species list. S Afr J Antarct Res 19:10–20

Schroeter B, Green TGA, Kappen L, Seppelt RD (1993) The history of Granite House and the western geological party of Scott's Terra Nova expedition. Polar Rec 29:219–224

Schroeter B, Kappen L, Green TGA, Seppelt RD (1997) Lichens and the Antarctic environment: effects of temperature and water availability on photosynthesis. In: Lyons WB, Howard-Williams C, Hawes I (eds) Ecosystem processes in Antarctic ice-free landscapes. A.A. Balkema, Rotterdam, pp 103–117

Schwarz AMJ, Green TGA, Seppelt RD (1992) Terrestrial vegetation at Canada Glacier, southern Victoria Land, Antarctica. Polar Biol 12:397–404

Selkirk PM, Skotnicki ML (2007) Measurement of moss growth in continental Antarctica. Polar Biol 30:407–413

Skotnicki ML, Selkirk PM, Broady PA, Adam KD, Ninham JA (2001) Dispersal of the moss *Campylopus pyriformis* on geothermal ground near the summits of Mount Erebus and Mount Melbourne, Victoria Land, Antarctica. Antarct Sci 13:280–285
Smith HG (1978) The distribution and ecology of terrestrial protozoa of sub-antarctic and maritime Antarctic islands. Br Antarct Surv Sci Rep 95:104
Smith RIL (1990) Signy Island as a paradigm of biological and environmental change in Antarctic terrestrial ecosystems. In: Kerry KR, Hempel G (eds) Antarctic ecosystems, ecological change and conservation. Springer, Berlin, pp 32–50
Smith RIL (1997) Impact of an increasing fur seal population on Antarctic plant communities: resilience and recovery. In: Battaglia B, Valencia J, Walton DWH (eds) Antarctic communities: species, structure, and survival. Cambridge University Press, Cambridge, pp 432–436
Smith RIL (2003) The enigma of *Colobanthus quitensis* and *Deschampsia antarctica* in Antarctica. In: Huiskes AHL, Gieskes WWC, Rozema J, Schorno RML, van der Vies SM, Wolff WJ (eds) Antarctic biology in a global context. Backhuys Publishers, Leiden, pp 234–239
Soo RM, Wood SA, Grzymski JJ, McDonald IR, Cary SG (2009) Microbial diversity of thermophilic communities in hot mineral soils of Tramway Ridge, Mount Erebus, Antarctica. Environ Microbiol 11:715–728
Strandtmann RW (1967) Terrestrial prostigmata (trombidiform mites). In: Gressitt JL (ed) Entomology of Antarctica, vol 10, Antarctic research series. American Geophysical Union, Washington, DC, pp 51–80
Wirth WW, Gressitt JL (1967) Diptera: chironomidae (Midges). In: Gressitt JL (ed) Entomology of Antarctica, vol 10, Antarctic research series. American Geophysical Union, Washington, DC, pp 197–203
Womersley H, Strandtmann RW (1963) On some free-living prostigmatic mites of Antarctica. Pac Insects 5:451–472

## General Books and Articles

Bergstrom DM, Convey P, Huiskes AHL (eds) (2006) Trends in Antarctic terrestrial and limnetic ecosystems. Springer, Dordrecht, xiv + 369 pp
Broady PA, Vincent WF (1990) Life in land, ice and inland water habitats. In: Hatherton T (ed) Antarctica: the Ross Sea region. DSIR Publishing, Wellington, pp 176–194
Cowan DA (ed) (2014) Antarctic terrestrial microbiology: physical and biological properties of Antarctic soils. Springer, Heidelberg, vi + 324 pp
Friedmann EI (ed) (1993) Antarctic microbiology. Wiley-Liss, New York, x + 634 pp
Green TGA (2001) Terrestrial biota. In: Waterhouse EJ (ed) Ross Sea region 2001: a state of the environment report for the Ross Sea region of Antarctica. New Zealand Antarctic Institute, Christchurch, pp 4.36–4.57
Green TGA, Scroeter B, Sancho L (1999) Plant life in Antarctica. In: Pugnaire F, Valladares F (eds) Handbook of functional plant ecology. Marcel Dekker, New York, pp 496–543
Smith RIL (1996) Terrestrial and freshwater biotic components of the western Antarctic Peninsula. In: Ross RM, Hofmann EE, Quetin LB (eds) Foundations for ecological research west of the Antarctic Peninsula, vol 70, Antarctic research series. American Geophysical Union, Washington, DC, pp 15–59
Vincent WF (1988) Microbial ecosystems of Antarctica. Cambridge University Press, Cambridge, xiii + 304 pp

# Chapter 12
# Life Beyond the Ice

## Marine Ecosystems in the Southern Ocean

**José C. Xavier and Lloyd S. Peck**

**Abstract** The Antarctic Circumpolar Current isolates Antarctic waters and their living organisms from warmer waters to the north. Over the last 25–35 million years, this isolation has led to specific environmental conditions, including a sharp drop in water temperatures south of the Polar Frontal Zone and the formation of sea ice during winter. Three key factors control productivity in the Southern Ocean today. Firstly, the Southern Ocean contains about 1.8 times as much oxygen as tropical seawater because more oxygen can dissolve in water at lower temperatures. Secondly, upwelling currents bring nutrients from the seabed to feed microscopic algae at the surface, and, lastly, the seasonal formation of sea ice has a profound impact on marine life. In addition, there is a long period of low or no light in winter, extreme physical disturbance from icebergs and a very high level of coastal productivity. All these factors have been important in the evolution of the characteristic Southern Ocean species and have resulted in a high degree of endemism, particularly in certain groupings of Antarctic organisms such as crustaceans and fish. The Southern Ocean represents 9.6 % of the world's oceans and is a key part of Earth's system. As the climate changes and sea level rises, the behavior of deep-ocean currents associated with the global thermohaline conveyor belt is altered and marine organisms respond. Our knowledge of the Southern Ocean has increased considerably in the last 20 years, but our understanding of adaptations, biological cycles and responses to change is still poor and more research is needed.

**Keywords** Zooplankton • Antarctic krill • Fish • Benthic food web • Pelagic food web

J.C. Xavier (✉)
Marine and Environmental Research Centre (MARE), Department of Life Sciences, University of Coimbra, Coimbra, Portugal
e-mail: jccx@cantab.net

L.S. Peck
British Antarctic Survey, Cambridge, UK



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_12

## 12.1 Primary Production

During the summer, between October and March, the 24-h daylight and availability of nutrients result in periods when conditions are favourable for primary production, which in turn leads to phytoplankton blooms (Fig. 12.1, Clarke et al. 2008). This marked seasonal variability propagates through the food web, so organisms that feed on these blooms, the pelagic consumers, must be able to make full use of the short summer periods to breed and build up energy to survive the low-production periods of winter. In contrast, various benthic species spawn in early or mid-winter and have their developmental periods during winter, suggesting that benthic species are not solely dependent on the main phytoplankton bloom and that they are able to survive long periods with low concentrations of food.

The primary production consists of the synthesis and storage of organic matter during the growth and reproduction of photosynthetic organisms. Almost all life on Earth is directly or indirectly reliant on primary production. In marine ecosystems, the main organisms responsible for primary production are algae. Within algal cells, chlorophyll is an extremely important biomolecule, critical in photosynthesis, which allows plants to obtain energy from light. Chlorophyll has been widely used as an index of phytoplankton biomass for primary production estimates.

The oceanic part of the Southern Ocean is an example of a high-nutrient, low-chlorophyll region, although in specific areas chlorophyll can be very high

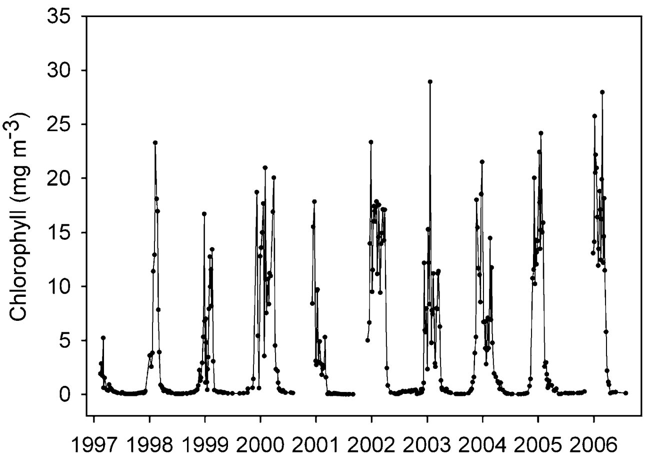



**Fig. 12.1** Total chlorophyll a (a specific form of chlorophyll used in oxygenic photosynthesis) at the Rothera Oceanographic and Biological Time-Series (RaTS) station, Ryder Bay (Antarctica) at 15 m depth, between 1997/1998 until 2005/2006 (Clarke et al. 2008). It shows strong intra- and inter-annual variability of chlorophyll a. In 1997/1998 there was a single bloom with a well-defined January peak, whereas in the 2000/2001 season the bloom was extended in time over the entire summer from late November to late March with at least three separate peaks in total chlorophyll. In the 2003/2004 season the bloom showed a steady deepening from late January to late March (Reprinted from Clarke et al. 2008, with kind permission from Elsevier)

(Holm-Hansen et al. 2004; Peck et al. 2010a). Some of the most intense phytoplankton blooms on Earth build up close to the outlets of glaciers from the Antarctic continent. These glaciers supply key nutrients such as iron, which is required for the synthesis of chlorophyll. In Marguerite Bay, on the Antarctic Peninsula, near-shore productivity within 3–4 km of the coast is amongst the highest on Earth, with chlorophyll levels over 20 mg $m^{-3}$ reported regularly (Clarke et al. 2008).

A lack of micronutrients, especially iron, is the major factor limiting phytoplankton growth and community composition during the summer. Experiments involving the addition of iron to the Southern Ocean resulted in dramatic increases in phytoplankton activity (Kaiser et al. 2005). The phytoplankton blooms at the beginning of summer are often dominated by large diatoms, as well as other species including dinoflagellates, bacteria and tintinnids. Silico-flagellates are also important. Over 100 diatom and 60 or so dinoflagellate species have been found in Antarctic waters (Knox 2007). Only one species of silicoflagellates, *Dictyota speculum*, is common in Antarctic waters and sometimes individuals outnumber those of any of the diatom species.

With the loss of ice shelves and a retreat of coastal glaciers around the Antarctic Peninsula in the last 50 years (Chaps. 5 and 25), new open water has been exposed, allowing phytoplankton blooms in areas where they did not previously occur (Peck et al. 2010b, Fig. 12.2).

Few observations have been made of phytoplankton biomass and primary production in the Southern Ocean and values vary widely, with evident geographical variability (Clarke et al. 2008; Peck et al. 2009a). The overall estimate of Southern Ocean phytoplankton production is 740–1,000 Tg C $y^{-1}$ (Teragram of Carbon per year; 1 Tg C = 1 million metric tons Carbon) (Knox 2007), which is

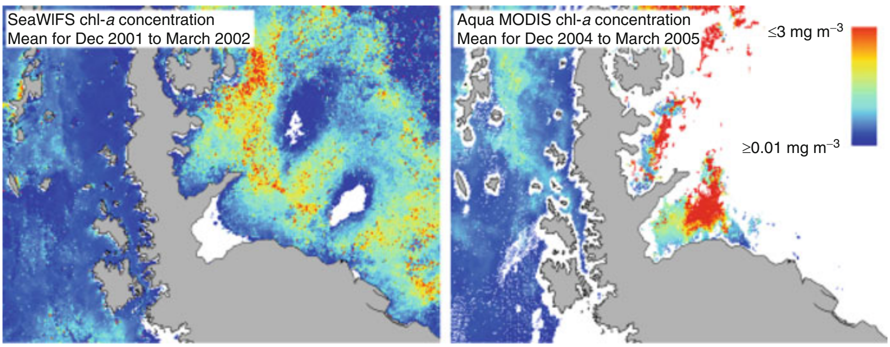



**Fig. 12.2** These satellite images of the Larsen B ice shelf show the ice-covered area in 2000 (*left panel*), before its collapse, and chlorophyll a from the dense phytoplankton bloom that was present there from December to March 2004/2005 (*right panel*) (Peck et al. 2010a). This is an example of how an opening of new coastal areas can enhance biological productivity. Following the collapse of the Larsen B ice shelf, a large amount of new production has built up in the area that was previously covered by ice. The area of the ocean previously covered by the Larson B ice shelf and now open is about 9,700 $km^2$, and a bloom covers a significant portion of this area (Reprinted from Peck et al. 2010a, b, with kind permission from Wiley)

similar to the average values in temperate zones but higher than tropical ones per square kilometre.

The annual growth and decay of 10–15 million km$^2$ of sea ice each year is the most prominent physical process in Antarctica and has a profound impact on marine life (Brierley and Thomas 2002). Only a very small percentage of sea ice lasts for more than one season. Rates of primary production in the underlying water column are often low because of shading by sea ice, but the sea ice itself forms a layer that provides habitat for great quantities of bacteria, algae and grazers that, at times, can be significantly higher than those in ice-free areas. Decay of sea ice in summer plays a major role in biogeochemical cycling by releasing organic particles and dissolved organic matter to the water column, which may lead to phytoplankton blooms (Brierley and Thomas 2002).

The most conspicuous organisms in the sea ice are unicellular photosynthetic microalgae called pennate diatoms. A biomass of diatoms up to 1,000 μg chlorophyll $l^{-1}$ has been recorded in sea ice, which is high compared with the 0–5 μg chlorophyll $l^{-1}$ in surface waters in the Southern Ocean (Legendre et al. 1992; Lizotte 2001). The primary production in Antarctic sea ice accounts for 63–70 Tg C $y^{-1}$, which corresponds to 5 % of the total annual primary production in the sea-ice influenced zone of the Southern Ocean (Kaiser et al. 2005). There are high levels of primary production at the ice edge. This is partly due to the adaption of Southern Ocean algae, which can photosynthesis at low levels of luminosity, between 0.1 and 0.01 % (Berkman 1992).

## 12.2 Zooplankton and the Key Role of Antarctic Krill

Within the zooplankton, Antarctic krill, *Euphausia superba*, (hereafter referred to as krill) are usually the major link between primary production and vertebrate predators in the Southern Ocean food webs (Box 12.1) (Everson 2000).

**Box 12.1: Top Predators and Antarctic Krill**

Within the top predators, whales, seals, penguins and albatrosses are amongst those that consume high quantities of krill. For example, crabeater seals, *Lobodon carcinophaga*, and minke whales, *Balaenoptera acutorostrata*, living closer to the Antarctic continent, feed almost exclusively (>95 % by mass) on krill (Armstrong and Siegfried 1991; Adam 2005). At Bird Island, South Georgia, the mean percentage of krill consumed by mass by Macaroni penguins *Eudyptes chrysolophus* between 1977 and 1995 was 89.8 %, with years higher than 90 % (Croxall et al. 1999). The diet of black-browed albatrosses *Thalassarche chrysostoma*, breeding on the same site, may contain more than 60 % of krill by mass (Xavier et al. 2003). In the diet of

(continued)

**Box 12.1** (continued)

Antarctic fur seals *Arctocephalus gazella* from the Antarctic Peninsula, South Shetland Islands, South Georgia and South Orkney Islands, krill has also been the most frequent and numerous prey in various years (>50 %).

Krill have a 5- to 7-year life cycle and are most common near the continent, between 75°S and 65°S approximately (Box 12.2). However, in the Scotia Sea krill distribution extends further north than in any other region of the Southern Ocean, with high densities occurring north of 53°S (Murphy et al. 2007). Krill are omnivorous, and their prey includes phytoplankton and copepod crustaceans (Everson 2000). Krill stocks in the Southern Ocean are estimated to exceed 1.5 billion tones. At early stages in their life cycle, krill may be eaten by carnivorous zooplankton, such as chaetognaths and amphipod crustaceans, and older individuals form the primary food for numerous species of predators (see Everson 2000). Juvenile krill require a constant supply of food, but adult krill can survive extended periods of starvation, even shrinking over winter periods. The distribution patterns of krill are closely linked to sea-ice conditions.

Sea ice is an important nursery habitat for krill because they graze sea-ice algae, protected from surface predators by the overlying ice (Brierley and Thomas 2002). In years following prolonged sea-ice cover, krill numbers are significantly higher, and in some regions krill abundance can be predicted on the basis of cyclical variations in sea-ice extent (Atkinson et al. 2004). When krill numbers are lower, due to reduced sea ice, salps, *Salpa thompsoni*, are able to exploit the spring phytoplankton bloom and undergo massive population growth, resulting in a negative relationship between salp numbers and sea-ice extent (Atkinson et al. 2004). As salps are far less nutritious to predators, it is likely that populations of species that depend on krill, such as Antarctic fur seals, may be affected when the extent of sea ice is low and salp numbers are high.

**Box 12.2: Antarctic Krill Stages (Fig. 12.3)**

The eggs hatch as a nauplius larva which then moults into a metanauplius. The next two larval stages, termed second nauplius and metanauplius, still do not eat but are nourished by the remaining yolk. Growing larger, additional larval stages follow (i.e. second and third calyptopis, first to sixth furcilia). They are characterised by increasing development of the additional legs, the compound eyes and the setae (bristles). As juvenile krill, they resemble the adults. Krill reach maturity after 2–3 years. Like all crustaceans, krill must moult in order to grow.

(continued)

**Box 12.2** (continued)

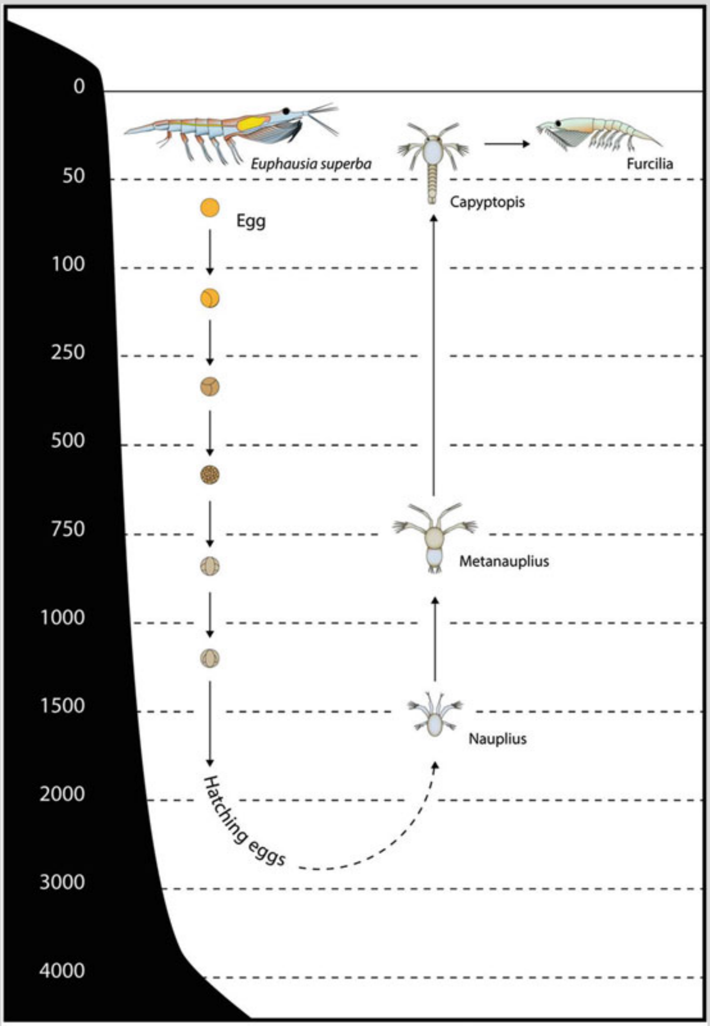



**Fig. 12.3** The Antarctic krill life stages, from egg to adult krill (With kind permission from Bruno Boto/MARE)

## 12.3 Cephalopods

Cephalopods play an important role in Southern Ocean ecology. They feed on fish and crustaceans and themselves are eaten by higher predators such as seabirds, seals and whales (Xavier and Cherel 2009; Xavier et al. 2011). There are approximately 70 species of Southern Ocean cephalopod and many are endemic. Loliginid squid,

**Fig. 12.4** The Antarctic squid, *Galiteuthis glacialis* (José Xavier, MARE/BAS). From the *left*, close to the fins, it is possible to see the caecum/gonads (*yellow*), stomach (*darker*, close to the caecum/gonads) and digestive gland/liver/ink sac (*dark and fusiform*) in the middle of the body. The Antarctic squid is a moderately large cranchiid squid, with a circumpolar Antarctic distribution and is considered one of the most abundant squid species in Antarctic waters. It is consumed by a wide range of predators, including wandering, black-browed and grey-headed albatrosses, Antarctic fur seals, Patagonian toothfish, sleeper sharks, sperm whales, gentoo, emperor and king penguins (Reprinted from Xavier and Cherel 2009, with kind permission from José C. Xavier, MARE/BAS)

sepiids and sepiolids, that are important for fisheries elsewhere in the world, are absent from the Southern Ocean, and all the squid are oceanic pelagic species (Fig. 12.4), including the colossal squid, *Mesonychoteuthis hamiltoni* (Box 12.3). The octopodids species are very diverse and dominate the coastal cephalopod fauna.

**Box 12.3: The Colossal Squid *Mesonychoteuthis hamiltoni***

This Antarctic squid species is the largest squid on Earth and is estimated to be bigger than 14 m in length, overtaking the giant squid *Architeuthis* sp. Moreover, *M. hamiltoni* is also thought to have the largest animal eye in our planet, at more than 28 cm long (from a specimen 8 m long and 450 kg). This squid species is thought to descend at least to 2,000 m depth and is known to occur in the diets of a wide range of Antarctic predators, including sperm whales *Physeter macrocephalus*, wandering albatrosses *Diomedea exulans*, Patagonian toothfish *Dissostichus eleginoides*, sleeper sharks *Somniosus* spp. and Southern elephant seals *Mirounga leonina*. For example, *M. hamiltoni* can make up to 77 % by mass of the prey ingested by sperm whales in Antarctic waters and 52 % in the diet of sleeper sharks. Both of these predators ingested adult specimens. Other predators, such as wandering albatrosses (<1 % by mass), Patagonian toothfish (<1 %) and Southern elephant seals (<1 %), feed mostly on sub-adults and juveniles.

Southern Ocean cephalopods appear to be semelparous, but growth rates are probably lower and longevity greater than in their temperate counterparts (Collins and Rodhouse 2006). Reproduction may be seasonal in the squid but not for octopodids, which have big eggs. The extended development times at low temperatures, particularly in species with large eggs, make it difficult to coordinate the timing of spawning with the brief summer season and many species of octopod appear to have extended spawning seasons or even spawn throughout the year. Antarctic squid feed mostly on pelagic prey (e.g. lanternfish, krill and other crustaceans) while octopods feed on benthic prey. The estimated consumption of cephalopods annually by predators is more than 30 million tons. To date Southern Ocean cephalopods have not been commercially exploited, but there is potential for the harvesting of muscular species of the family Ommastrephidae such as the seven-star flying squid *Martialia hyadesi* (Xavier et al. 2007).

## 12.4 Fish

Fish in the Southern Ocean play an important role in the transfer of energy from primary producers to higher predators (Kock 1992), although the diversity of fish species is low (Clarke and Johnston 2003). After krill, fish are the most important food for higher predators. The energy-rich pelagic lanternfish found in open waters and the Antarctic silver fish, *Pleuragramma antarcticum*, found in the high Antarctic zone are most significant.

Of approximately 200 fish species in the Southern Ocean, those living above the continental shelf show a high degree of endemism (more than 85 % are endemic). Antarctic fish families are absent in waters less than 200 m deep (Rodhouse and White 1995). Fish families that occur deeper than 200 m are descended from species that live in water deeper than 1,000 m, and from species that live on or close to the bottom. They are mostly members of the families Nototheniidae, Channichthyidae and Myctophidae. These species have become secondarily adapted to permanent or temporary mid-water life (Eastman 1993; Rodhouse and White 1995).

Most deep-water adult fish, including the Patagonian toothfish, *Dissostichus eleginoides*, live on the bottom and lack swim bladders, but some species have also evolved to occupy mid-waters, especially for feeding (Eastman 1993). For example, some deep-water mesopelagic fish, such as the Antarctic silver fish, *Pleuragramma antarcticum*, and the lanternfish, *Electrona antarctica*, may migrate to shallow depths beneath sea ice to feed on the high concentrations of shallow zooplankton there (Brierley and Thomas 2002).

The Antarctic silver fish occupies a critical role in the food web close to the continent. This species comprises more than 90 % of the biomass of mid-water fish and is one of several species that produce antifreeze proteins as an adaptation against the extreme cold of Antarctic waters (Chap. 14). In times and locations where ice krill, *Euphausia crystallorophias*, are absent, or in greatly reduced numbers, *P. antarcticum* may provide the major link between primary production and vertebrate predators. In areas of reduced sea ice, other fish species are important. For example, in the northern Scotia Sea, energy-rich lanternfish (15 species in 5 genera) that live in the water column dominate the fish fauna, with species such as the Antarctic deep sea smelt, *Bathylagus antarcticus*, and Antarctic snaggletooth, *Borostomias antarcticus*, abundant in deeper waters (Collins et al. 2008).

Antarctic fish in general can feed on a wide range of prey, including copepods, krill, other crustaceans, cephalopods and fish (e.g. Shreeve et al. 2009). Squid and fish interact, probably consuming each other at various stages of their lives, and both are major components of the diets of marine mammals and other top predators.

## 12.5 Top Predators

The enhanced production of the Southern Ocean supports some of the largest and most diverse concentrations of seabirds and marine mammals anywhere on Earth (Everson 1977). The top predators of the Antarctic ecosystem include penguins, seals, whales and albatrosses, and certain species of fish and squid (Fig. 12.5). Typical top marine predators that mostly live close to, or on the continent, include the emperor penguins, *Aptenodytes forsteri*, Adélie penguins, *Pygoscelis adeliae*, Antarctic petrels, *Thalassoica antarctica* and Weddell seals, *Leptonychotes weddellii*, (e.g. Ducklow et al. 2007). These predators feed typically on a range of endemic cephalopods (e.g. *Psychroteuthis glacialis*, *Galiteuthis glacialis*), crustaceans (e.g. krill) and Antarctic fish (e.g. *P. antarcticum*, *Electrona antarctica*) that forage close to the sea ice (e.g. Cherel 2008; Plötz et al. 2008). Leopard seals, *Hydrurga leptonyx*, are considered a top predator, feeding on penguins, fur and elephant seals. Killer whales, *Orcinus orca*, are also top predators in this region, feeding on minke whales, *Balaenoptera bonaerensis*, penguins, fish, squid and seals, including leopard seals (Visser et al. 2008).

In relatively open, ice-free waters of the northern Southern Ocean, other top predators are common, including albatrosses (e.g. wandering albatrosses, *Diomedea exulans*), king, *Aptenodytes patagonicus*, and macaroni, *Eudyptes chrysolophus*, penguins and Antarctic fur seals, *Arctocephalus gazella*. Their diets comprise typical Antarctic prey, such as krill and fish (e.g. lanternfish *Gymnoscopelus* spp., *Protomyctophum* spp., mackerel icefish *Champsocephalus gunnari*) but they also contain subantarctic and subtropical prey (e.g. ommastrephid squid *Martialia hyadesi*, histioteuthid squid *Histioteuthis eltaninae* and the pelagic octopodid *Haliphron atlanticus*) depending on the foraging range of each predator (e.g. Williams 1995; Xavier et al. 2004; Staniland and Robinson 2008).

Whales occur in both ice-covered and ice-free areas of the Southern Ocean and none is exclusive to the region. Among baleen whales the most frequently recorded are blue, *Balaenoptera musculus intermedia*, fin, *Balaenoptera physalus*, sei, *Balaenoptera borealis*, minke, *Balaenoptera bonaerensis*, humpack, *Megaptera*


**Fig. 12.5** Examples of marine predators in the Southern Ocean: (**a**) macaroni penguins, which are the most numerous penguins in the world (~18 million individuals, population trend declining, conservation status vulnerable); (**b**) black-browed albatrosses (~1.2 million individuals, population trend declining, conservation status endangered); (**c**) leopard seal (~250,000 individuals, population trend stable, conservation status least concern); and (**d**) southern elephant seal (~740,000 individuals, population trend stable, conservation status less concern) (With kind permission from José C. Xavier, MARE/BAS)

*novaeangliae* and southern right, *Eubalaena australis*, whales (Shirihai 2008). Baleen whales breed in tropical and subtropical areas, but generally migrate to Antarctic waters in the summer to take advantage of the abundant krill, and to establish sufficient food reserves to sustain them for the rest of the year. Some species such as fin, blue and humpback whales feed mostly, and more intensively, in the Southern Ocean for about one-third of the year, during the summer, and at a reduced rate, and sometimes taking no food for extended periods, for the rest of the year (Knox 2007).

Each whale species tends to arrive at different times of the year. Within toothed whales, southern bottlenose whales, *Hyperoodon planifrons*, and killer whales, *Orcinus orca*, are most abundant in the southernmost ice-edge waters, whereas sperm whales, *Physeter macrocephalus*, occur mostly south of 60°S (Kasamatsu and Joyce 1995), but their populations are still poorly known. Sperm whales eat squid and fish (Table 12.1).

**Table 12.1** Distribution of some of the most well-known species of the Antarctic marine ecosystem

| | Common name | Species name | Distribution | Bathymetric range (m) |
|---|---|---|---|---|
| Crustacea | Antarctic krill | *Euphausia superba* | Circumpolar | 0–3500 |
| Crustacea | Giant isopod | *Glyptonotus antarcticus* | Pacific and Atlantic sectors | 0–585 |
| Cephalopoda | Antarctic cranchiid squid | *Galiteuthis glacialis* | Circumpolar | 0–5188 |
| Cephalopoda | Antarctic hooked squid | *Kondakovia longimana* | Circumpolar | 0–890 |
| Fish | Antarctic toothfish | *Dissostichus mawsoni* | Circumpolar | 88≥2000 |
| Fish | Antarctic silverfish | *Pleurogramma antarcticum* | Circumpolar | 0–700 |
| Penguin | Emperor penguin | *Aptenodytes forsteri* | Circumpolar | 0≥500 |
| Penguin | Macaroni penguin | *Eudyptes chrysolophus* | Atlantic (includes Antarctic peninsula) and Indian sectors | 0–163 |
| Albatross | Grey-headed albatross | *Thalassarche chrysostoma* | Circumpolar | 0–6.5 |
| Seal | Antarctic fur seal | *Arctocephalus gazella* | Between 60° W and 155° E (mostly in Atlantic and Indian sectors) | 0–354 |
| Whale | Killer whale | *Orcinus orca* | Circumpolar | 0≥240 |

## 12.6 Benthic Food Web

The benthic zone is usually regarded as rich and diverse in contrast to the pelagic system which appears relatively simple but productive (Clarke and Johnston 2003; Barnes and Griffiths 2008; Knox 2007). Over 4,100 benthic species live in the Southern Ocean and the benthic fauna is characterised by gigantism, slow metabolism, longevity and a reduced number of offspring combined with late maturation (Brandt 2005).

Although the Antarctic Polar Front limits the distribution of many pelagic species, this surface-ocean feature is no barrier to the Antarctic benthic fauna. Indeed, the northward movement of deep water formed in the Weddell Sea (Chap. 7) makes close faunal connections between the Southern Ocean and other ocean basins more likely (Brandt et al. 2007). The Antarctic marine environment has more than 8 % of the world's species in many major groups, including sea spiders (pycnogonids), marine worms (polychaetes), moss animals (bryozoans), sea

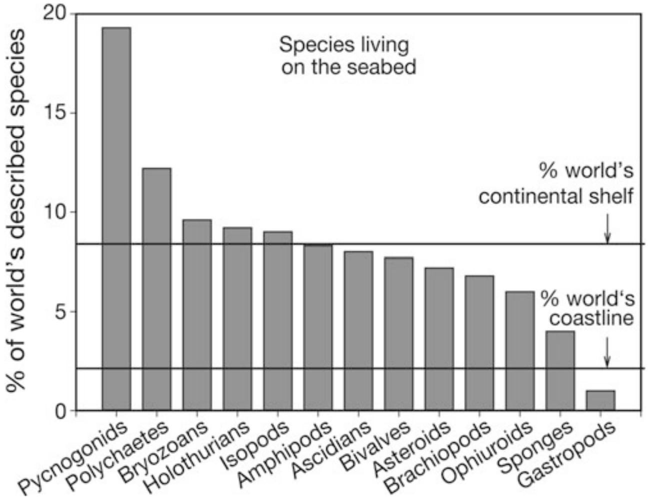



**Fig. 12.6** Proportion of total number of global species present in the Southern Ocean for several major animal groups. Pycnogonids have the highest percentage of their members living in the Southern Ocean, the gastropods have the least. Antarctica has around 2.6 % of the world's coastline (although >50 % of this is ice bound) and about 8 % of the world's continental shelf. Surprisingly, Antarctica has less than 8 % of the world's species in many major groups, such as pycnogonids and polychaetes. Horizontal lines: proportions of global coastline and shelf area for the Southern Ocean in relation to the world's continental shelf and world's coastline, e.g. the Antarctic continental shelf area only represents approximately 8 % of the world's continental shelf area (Reprinted from Barnes and Peck 2008, with kind permission from Inter-Research Science Center)

cucumbers (holothurians) and isopod crustaceans, with marine worms and amphipod crustaceans containing the most species (Clarke and Johnston 2003; Brandt 2005). Locally, the variety of species is very high compared to the Arctic and to most temperate and even tropical localities apart from coral reefs (Fig. 12.6, Barnes and Peck 2008). For example, 90 % of Antarctic sea spiders and 80 % of amphipod crustacean species are endemic (Arntz et al. 1997).

On the other hand, the low diversity of sea snails (gastropods), bivalves (e.g. clams, oysters, scallops and mussels) and decapod crustaceans in the Southern Ocean is striking in comparison with the richness of both groups in some tropical regions (Clarke and Johnston 2003). In tropical reef systems, sea snail and bivalve diversity is very high, and many of their species live in very shallow or intertidal habitats, whereas in Antarctica the ice that covers the vast majority of the coastlines prevents the presence of such species. Some decapod crustacean groups (lobsters and crabs, except spider crabs but not shrimps and prawns) are absent from Antarctica. These groups have high levels of magnesium in their blood. Magnesium is a narcotic which has a more powerful effect as temperature decreases. It is believed that this is the factor precluding these groups colonising the coldest of Earth's environments.

Antarctic benthos shows significant differences compared with benthos elsewhere. For example, growth and development are an order of magnitude slower compared to that in temperate and tropical areas (Peck et al. 2007). This may be partly due to very slow protein synthesis and relatively fast protein degradation seen in Antarctic marine species. There has been a debate over the last four to five decades about whether slow growth is the result of the low temperature per se, or due to seasonal restriction of resources. There is good evidence that temperature plays a major role in slowing development of marine species (Hoegh-Guldberg and Pearse 1995; Peck et al. 2007) but the relative importance of both factors in limiting growth of juveniles and adults remains a topic of debate. As well as growing slowly, Antarctic benthos can reach a great age compared to similar species elsewhere. Some sponges and starfish may grow for 100 years or more, bivalves and sea urchins may live half a century (Peck and Bullough 1993, Table 12.2). This great age may be a result of the generally lowered metabolic rates of cold-blooded species living at low temperatures, and a concomitant reduction in the build-up of deleterious products and cellular damage (Abele and Puntarulo 2004).

**Table 12.2** Growth and reproduction of Antarctic taxa

| | Common name | Species | Growth | Maximum known age |
|---|---|---|---|---|
| Brachiopoda | Antarctic articulate brachiopod | *Liothyrella uva* | 0.96–2.3 mm $year^{-1}$ | >50 years |
| Bryozoa | Antarctic bryozoan | *Cellaria incula* | 8 mm branch length $year^{-1}$ | >14 years |
| Crustacea | Antarctic krill | *Euphausia superba* | 1–8.5 mm total length at age 0 | 6–7 years |
| Asteroidea | Antarctic red starfish | *Odontaster validus* | 30 g in 9 years | >9 years |
| Cephalopoda | Antarctic octopodid | *Pareledone charcoti* | ~0.1 % body weight $day^{-1}$ | |
| Cephalopoda | Seven star flying squid | *Martialia hyadesi* | 1.10–1.46 mm mantle length $day^{-1}$ | 1–2 years |
| Cephalopoda | Great hooked squid | *Moroteuthis ingens* | 1.13–2.11 mm mantle length $day^{-1}$ | ~1 year |
| Cephalopoda | Glacial squid | *Psychroteuthis glacialis* | | 2–3 years |
| Fish | Antarctic toothfish | *Dissostichus mawsoni* | 1 m total length at 8 years | >48 years |
| Fish | Antarctic silverfish | *Pleurogramma antarcticum* | | ~20 years |

**Fig. 12.7** Typical benthic species endemic of the Antarctic ecosystem: On the *right*, the valviferan isopod *Antarcturus* spp. standing proud on a strand of Desmarestia at a depth of 4 m (Simon Brockington, BAS); on the *left*, giant sea spider in shallow water off Rothera Research Station (Western Antarctic Peninsula). Antarctic sea spiders can grow up to 500 mm across and have up to 12 legs (Terry Souster, BAS, with kind permission from BAS)

## 12.6.1 The Continental Shelf

The continental shelf around Antarctica includes some of the least known regions of our planet (Barnes and Peck 2008). The average depth of water is over 450 m, which is much greater than the 100–220 m depth typical of continental shelves elsewhere in the world (Clarke and Johnston 2003). The Antarctic continental shelf also provides some of the most stable temperatures and oceanographically stable environments because there is minimal disruption by warm northern currents. However, the shelf also has seasonally intense conditions for benthic life due particularly to the formation of sea ice (Fig. 12.7a, b; Barnes and Peck 2008). At depths shallower than 250 m the seafloor is frequently gouged and destroyed by the bases of large icebergs as they move across the ocean, affecting the benthic biodiversity in these areas (Arntz et al. 1997).

Despite these conditions, the Antarctic continental shelf has abundant and rich benthic life, with high biodiversity of sea worms, molluscs and echinoderms, such as starfish and sea urchins (Clarke and Johnston 2003; Brandt 2005).

The cold and vertically well-mixed water on the Antarctic shelf has very high levels of oxygen, allowing some marine organisms, notably some amphipod crustaceans, isopod crustaceans and sea spiders, to become relative giants (Chapelle and Peck 1999). The macro- and megafauna is dominated by sessile suspension feeders (Arntz et al. 1997), and even some of the predators, such as sea spiders, sea urchins (echinoderms), or sea slugs (nudibranch molluscs), have been observed as moving little more than a meter in a week (Barnes and Peck 2008).

Availability of food is seasonal and is more easily available during the summer. Phytoplankton, ice algae and benthic microalgae that produce energy from sunlight are most productive then. Food provided by small marine items such as algae, detritus, fecal pellets and plankton is consumed by suspension feeders (e.g. sponges, jellyfish, marine worms and sea cucumbers, holothurians). Much of this material is also consumed by deposit feeders (e.g. sea urchins, sea cucumbers,

**Table 12.3** Diet of some species of zooplankton, squid, fish and top predators in the Antarctic marine ecosystem

| | Common name | Predator species | Main components |
|---|---|---|---|
| Crustacea | Antarctic krill | *Euphausia superba* | Diatoms and copepods |
| Crustacea | Giant isopod | *Glyptonotus antarcticus* | Ophiuroids |
| Squid | Great hooked squid | *Moroteuthis ingens* | Fish (mostly myctophids) |
| Fish | Patagonian toothfish | *Dissostichus eleginoides* | Fish and crustaceans |
| Penguin | Emperor penguin | *Aptenodytes forsteri* | Fish (mostly nototheniid *Pleuragramma antarcticum*) |
| Albatross | Wandering albatross | *Diomedea exulans* | Squid and fish |
| Seal | Crabeater seal | *Lobodon carcinophagus* | Krill |
| Whale | Killer whale | *Orcinus orca* | Minke whales, seals (mainly Weddell and crabeater seals), penguins, fish (particularly Antarctic toothfish) |

starfish and sea worms). Numerous benthic invertebrates are herbivorous (e.g. some amphipod crustaceans and sea snails species), or scavengers (e.g. starfishes, sea urchins and sea worms; examples in Table 12.3). Others are omnivorous (e.g. some sea snails) and opportunistic (e.g. the isopod crustacean *Glyptonotus antarctica*). Compared to any other shelf environment, there are very few crushing predators around Antarctica (Aronson et al. 2007).

### *12.6.2 The Deep Sea*

The composition, biodiversity and zoogeography of the Southern Ocean deep-sea animals is poorly known in comparison with shelf areas (Brandt 2005). Despite latitudinal gradients in species diversity being hotly debated in the literature (e.g. Gray 2001), the basis for these data is still quite weak, as vast areas of the deep sea, especially of the Southern Hemisphere, remain unexplored.

Based on available data, there is a rich variety of benthic species in the Antarctic deep sea (e.g. foramifera, roundworms (nematodes), seed shrimps (ostracod crustaceans), sea worms), with most diversity occurring at about 3,000 m depth. In general the number of individuals decreases with depth, but the number of species increases (Brandt 2005; Gutzmann et al. 2004). Bathymetric and biogeographic trends vary between groups of organisms, such as sea worms (polychaetes) and isopod crustaceans. Deep-sea fauna with good dispersal capabilities, such as foraminifera, tend to have strong links to other oceans (Brandt et al. 2007).

There is significant variation in the diversity of large marine invertebrate and fish species on the Lord Howe Rise and Norfolk Ridge, and in the Southern Ocean to the south of the Tasman and Southern Coral Seas (Williams et al. 2011). This was thought to result from hydrography, topography and the type of seabed. Most deep-sea studies lack the resolution to identify spatial patterns, but this is becoming an important topic as more studies find differences in biodiversity patterns between sites.

## 12.7 Pelagic Food Web

In contrast to the tremendous diversity of benthic organisms, only a limited range of fish inhabits the water column, producing a relatively simple but productive pelagic system. Microscopic algae, particularly large diatoms, are involved in nitrate-based production (Box 12.4). This provides food for krill, the key Southern Ocean species, which in turn are eaten by fish, squid, whales, seals and birds (Fig. 12.8).

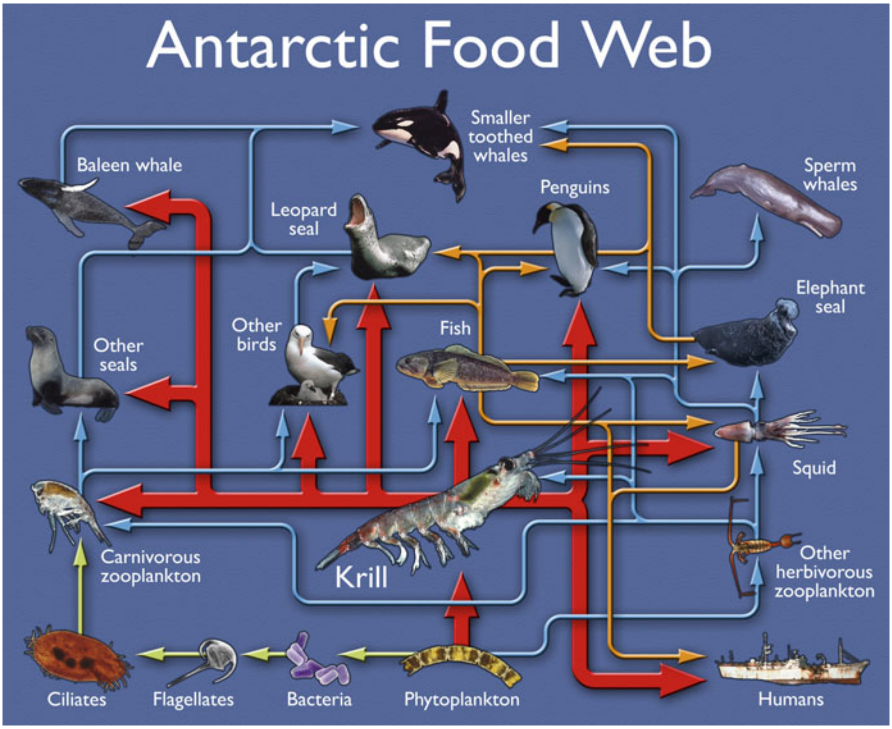



**Fig. 12.8** The Antarctic marine food web. It emphasises the key role of Antarctic krill, *Euphausia superba*, which is the major link between primary production and vertebrate predators in the Southern Ocean food web. The copepod *Calanus propinquus* is one of the dominant copepod species in the zooplankton of the Southern Ocean. Amphipods are common and abundant members of the benthic scavenging community and a very biodiverse group in the Southern Ocean (With kind permission from BAS)

**Box 12.4: Nitrate-Based Production**

Phytoplankton photosynthesis and growth take place in the euphotic zone when nutrients from deeper waters are used. This primary production, based upon external inputs, is termed new production. An example is the use of nitrate by algae from the deep reservoir (huge pool of nitrogen whose availability to primary producers in the euphotic zone is controlled largely by physical processes like water mixing), in the euphotic zone.

However, in many regions across the Southern Ocean there are alternative pathways as other key species such as ice krill, *Euphausia crystallorophias*, and copepods dominate the food web at different times (Murphy et al. 2007; Ducklow et al. 2007). For example, in certain years the food web (phytoplankton, lantern fish, king penguins and seals) may occur when krill is low in abundance (Murphy et al. 2007, Fig. 12.9).

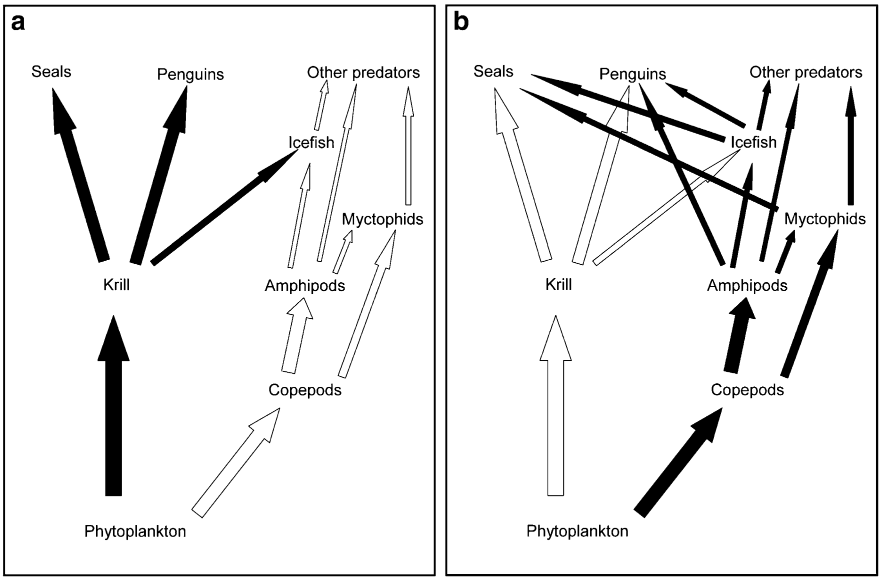



**Fig. 12.9** Schematic illustration of alternative pathways in part of the Scotia Sea food web, showing shifts between: (**a**) years when krill are abundant across the Scotia Sea, krill consumes the majority of the phytoplankton available and is predated by a wide range of predators such as seals and penguins and (**b**) years when krill are scarce, phytoplankton is mainly consumed by copepods that are predated by amphipods and myctophid (also known as lanternfish) that compose the diet of the top predators. Major pathways shown as *black arrows* (Reprinted from Murphy et al. 2007, with kind permission from the Royal Society)

## 12.8 Effects on Antarctic Marine Ecosystems

### *12.8.1 Climate Change*

The Southern Ocean is of special significance to climate change because of the variety of water masses produced there and the effect these water masses have on the global ocean and global heat balance (Chap. 7). If climate change is sustained, it is likely to produce long-term and perhaps irreversible changes in the large-scale physical environment of the Southern Ocean (Anisimov et al. 2007). These changes will also alter the nature and amount of life in the ocean and on surrounding islands, shores and ice (Barnes and Peck 2008).

During the last 50 years, air temperatures have risen by 2–3 °C, sea ice has declined and ocean temperatures have increased by 1 °C to the west of the Antarctic Peninsula and in the Scotia Sea (Meredith and King 2005). In near-shore waters this has lead to a dramatic increase in the area of open ocean available for productivity due to the loss of coastal glaciers and ice sheets. Antarctic marine species are generally amongst the least capable of responding to environmental change. There are three main reasons (Peck 2005):

- the range over which they can live or disperse is restricted;
- they have evolved to live in a very specific environment and are unable to cope with a wide range of environmental constraints; and
- they have long life histories and consequently slow rates of adaptation.

### *12.8.2 Benthic Species*

Benthic species have been shown to be particularly sensitive to warming (Peck et al. 2009a, b; Fig. 12.10). Scallops are unable to perform essential activities, such as swimming, with less than a 2 °C warming above current average summer maximum temperatures, and the most sensitive species, the brittle star *Ophionotus victoriae*, is incapable of surviving 1 month at a temperature less than 0.5 °C above experienced summer maxima (Peck et al. 2009b). The ability of species to survive warming environments is probably set by their aerobic scopes, their abilities to supply tissues with oxygen (Pörtner et al. 2007).

Experimental evidence suggests the shallow mega- and macrobenthos are also very sensitive to temperature change (stenothermal). Being warmed to about 5 °C kills most species tested to date over periods greater than 1 month, but even smaller experimental rises (just 2 or 3 °C above normal) drastically hinder their ability to perform critical functions, such as avoid predators (Barnes and Peck 2008). For example, the critical physiological limit for the large bivalve mollusc *Laternula elliptica* is around 5–6 °C, when no individuals of this species are able to rebury after removal from sediment, and 50 % of the population fail at temperatures of

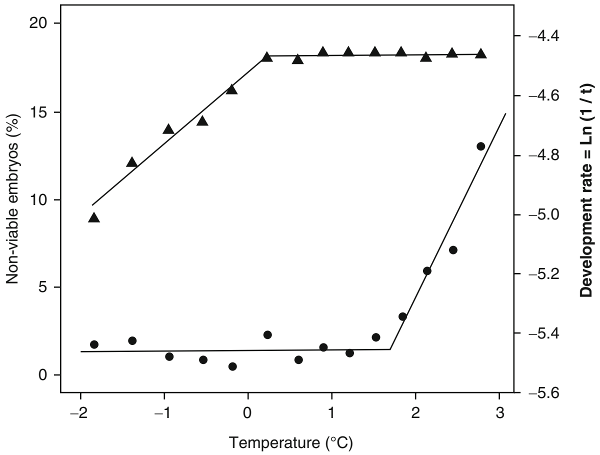



**Fig. 12.10** Development rate (*triangles*) and embryo viability (*circles*) for sea urchin *Sterechinus neumayeri*, from a population from Signy Island (Antarctic Peninsula), over a range of temperatures from −2 to 2.5 °C (with development rate shown as the natural logarithm of the inverse of the time between fertilisation and hatching of 50 % of the embryos). This figure shows an optimum window between 0.2 and 1.7 °C where development rate is maximum and embryo viability optimum, with temperatures higher than 1.7 °C causing a significant increase of the number of non-viable embryos (Reprinted from Peck 2002, with kind permission from Springer)

2–3 °C (Peck 2005). Another example is the scallop *Adamussium colbecki* which lose their capacity to swim between 1 and 2 °C and die at 5–6 °C (Barnes and Peck 2008).

### *12.8.3 Pelagic Species*

Changes to key pelagic species have also been notable, with over 50 % of the krill stock lost in the Scotia Sea region (Atkinson et al. 2004). This appears to be associated with changes in sea ice in the southern Scotia Sea and around the Antarctic Peninsula. Future reductions in sea ice in this region are likely to lead to further changes in distribution and abundance of krill across the whole area. This will impact food webs, where krill are currently key prey items for many predator species and where the additional pressure of krill fishing occurs (Chap. 20, Reid and Croxall 2001). For example, reductions in krill abundance may have negative effects on species of fish, as the fish then become a greater target for predators (Anisimov et al. 2007).

For species other than krill the uncertainty in climate predictions leads to uncertainty in determining the impacts of climate change, but increases in temperatures and reductions in winter sea ice would undoubtedly affect the reproduction, growth and development of numerous species, leading to further reductions in population sizes and changes in distributions. For example, species inhabiting the

Southern Ocean seabed have less scope to migrate away from poor conditions (e.g. increased temperatures) than faunas elsewhere. However, the potential for species to adapt is mixed, some cold-blooded (poikilothermic) organisms may die if water temperatures rise to between 5 and 10 °C, while the bald rock cod, *Pagothenia borchgrevinki*, which uses antifreeze proteins in its blood to live at sub-zero temperatures (Chap. 14), can acclimatise so that its swimming performance at 10 °C is similar to that at −1 °C (Seebacher et al. 2005).

Changes at the ecosystem level are inevitable as climate changes in the coming decades. To maintain the societal benefits of the Antarctic marine ecosystem, including harvestable marine resources, it is essential that we rapidly obtain knowledge that will enhance our ability to predict ecosystem changes as global climate changes.

### *12.8.4 Cyclical Phenomena*

The extent and duration of sea ice in the Southern Ocean fluctuates periodically under the influence of global climatic phenomena including the El Niño Southern Oscillation and the Southern Annular Mode (Chaps. 6 and 25) (Forcada and Trathan 2009). The impacts of these and climate change may differ between regions, species and populations. For certain penguin species, the most likely mechanism of response is dispersal when adaptation mechanisms fail to maintain performance (Forcada et al. 2006; Forcada and Trathan 2009). Penguin species or populations with low adaptability or low dispersal ability are likely to be most affected (Box 12.5).

The best long-term data for high-latitude Antarctic seabirds (Adélie and emperor penguins and snow petrels) indicate that winter sea ice has a profound influence on their population dynamics (Croxall et al. 2002). However, some effects are inconsistent between species and areas, some have effects in opposite directions at different stages of breeding and life cycles, and others remain paradoxical (Croxall et al. 2002; Forcada et al. 2006). Changes to the ecosystem resulting from fishing, krill harvesting and climate change may produce rapid shifts rather than gradual changes. For example, information for a 55-year period shows that the entire community of Antarctic seabirds in East Antarctica now arrive at their colonies 9.1 days later, on average, and lay eggs an average of 2.1 days later than in the early 1950s (Barbraud and Weimerskirch 2006). These delays are linked to a decrease in sea-ice extent that has occurred in eastern Antarctica from the twentieth century up to 1980 (Curran et al. 2003). These changes in sea ice may be just one of several physical changes resulting from climate change (others include temperature and food resources at sea) and may explain why certain Antarctic seabirds tend to arrive and reproduce later (Barbraud and Weimerskirch 2006).

**Box 12.5: Penguins Affected by Ice Extent**

The only long-term data set for the populations of emperor penguins, *Aptenodytes forsteri*, is from Adélie Land. These data show that populations were essentially stable from the 1950s to the mid-1970s, followed by a rapid decline until about 1982. Since then, populations have fluctuated around a level about half of that in the 1960s. This decline is apparently caused by a significant reduction (about 10 % per annum, corresponding to halving life expectancy) in adult survival from 1973 and 1979 (Croxall et al. 2002).

## 12.9 Conclusions

Overall, marine ecosystems across the world are complex. In Antarctica, pelagic ecosystems are less complex than elsewhere, and they are the habitat for some of the most iconic animals known to science. Species on the seabed are amongst the most sensitive to warming globally. The environment around the Antarctic Peninsula is one that is warming as fast, or faster than anywhere else. There is great need to identify how life on Earth is responding to, and will continue to respond to change. Antarctica offers unparalleled opportunities to understand responses to change from organism to ecosystem, and there is now an imperative to focus efforts on this unique environment and biota.

## References

Adam PJ (2005) Lobodon carcinophaga. Mamm Species 772:1–14

Armstrong AJ, Siegfried WR (1991) Consumption of Antarctic krill by minke whales. Antarct Sci 3:13–18

Barnes DKA, Peck LS (2008) Vulnerability of Antarctic shelf biodiversity to predicted regional warming. Climate Res 37:149–163

Cherel Y (2008) Isotopic niches of emperor and Adélie penguins in Adélie Land, Antarctica. Mar Biol 154:813–821

Clarke A, Meredith MP, Wallace MI, Brandon MA, Thomas DN (2008) Seasonal and interannual variability in temperature, chlorophyll and macronutrients in northern Marguerite Bay, Antarctica. Deep Sea Res II (Palmer LTER Special Issue) 55:1988–2006

Croxall JP, Reid K, Prince PA (1999) Diet, provisioning and productivity responses of marine predators to differences in availability of Antarctic krill. Mar Ecol Prog Ser 177:115–131

Kasamatsu F, Joyce GG (1995) Current status of odontocetes in the Antarctic. Antarct Sci 7:365–379

Murphy EJ, Watkins JL, Trathan PN, Reid K, Meredith MP, Thorpe SE, Johnston NM, Clarke A, Tarling GA, Collins MA, Forcada J, Shreeve RS, Atkinson A, Korb R, Whitehouse MJ, Ward P, Rodhouse PG, Enderlein P, Hirst AG, Martin AG, Hill SL, Staniland IJ, Pond DW, Briggs DR, Cunningham NJ, Fleming AH (2007) Spatial and temporal operation of the Scotia Sea ecosystem: a review of large-scale links in a krill centred food web. Philos Trans R Soc B 362:113–148

Peck LS (2002) Ecophysiology of Antarctic marine ectotherms: limits to life. Polar Biol 25:31–40

Peck LS, Barnes DKA, Cook AJ, Fleming AH, Clarke A (2010a) Negative feedback in the cold: ice retreat produces new carbon sinks in Antarctica. Glob Chang Biol 16:2614–2623
Plötz J, Ekau W, Reijnders PJH (2008) Diet of Weddell seals *Leptonychotes weddellii* at Vestkapp, Eastern Weddell Sea (Antarctica), in relation to local food supply. Mar Mamm Sci 7:136–144
Shirihai H (2008) A complete guide to Antarctic wildlife: the birds and marine mammals of the Antarctic continent and the Southern Ocean. A & C Black Publications, London, p 544
Staniland IJ, Robinson SL (2008) Segregation between the sexes: Antarctic fur seals, Arctocephalus gazella, foraging at South Georgia. Anim Behav 75:1581–1590
Visser IN, Smith TG, Bullock ID, Green GD, Carlsson OGL, Imberti S (2008) Antarctic peninsula killer whales (*Orcinus orca*) hunt seals and a penguin on floating ice. Mar Mamm Sci 24:225–234
Williams TD (1995) The penguins. Oxford University Press, Oxford
Xavier JC, Cherel Y (2009) Cephalopod beak guide for the Southern Ocean. British Antarctic Survey, Cambridge, p 129
Xavier JC, Croxall JP, Reid K (2003) Inter-annual variation in the diets of two albatross species breeding at South Georgia: implications of breeding performance. Ibis 145:593–610
Xavier JC, Trathan PN, Croxall JP, Wood AG, Podesta G, Rodhouse PG (2004) Foraging ecology and interactions with fisheries of wandering albatrosses at South Georgia. Fish Oceanogr 13 (5):324–344
Xavier JC, Rodhouse PG, Croxall JP, Wood AG (2007) Inter-annual variations in cephalopod consumption by albatrosses at South Georgia: implications for future commercial exploitation of cephalopods. Mar Freshw Res 58:1136–1143

## *Further Reading on Antarctic Benthic Ecosystem*

Abele D, Puntarulo S (2004) Formation of reactive species and induction of antioxidant defence systems in polar and temperate marine invertebrates and fish. Comp Biochem Physiol A Mol Integr Physiol 183:405–415
Arntz WE, Gutt J, Klages M (1997) Antarctic marine biodiversity: an overview. In: Battaglia B (ed) Antarctic communities: species, structure and survival. Cambridge University Press, Cambridge, pp 3–14
Barnes DKA, Griffiths HG (2008) Biodiversity and biogeography of southern temperate and polar bryozoans. Glob Ecol Biogeogr 17:84–99
Brandt A (2005) Evolution of Antarctic biodiversity in the context of the past: the importance of the Southern Ocean deep sea. Antarct Sci 17:509–521
Brandt A, Gooday AJ, Brandão SN, Brix S, Brökeland W, Cedhagen T, Choudhury M, Cornelius N, Danis D, De Mesel I, Diaz RJ, Gillan DC, Ebbe B, Howe JA, Janussen D, Kaiser S, Linse K, Malyutina M, Pawlowski J, Raupach M, Vanreusel A (2007) First insights into the biodiversity and biogeography of the Southern Ocean deep sea. Nature 444:307–311
Chapelle G, Peck LS (1999) Polar gigantism dictated by oxygen availability. Nature 399:114–115
Clarke A, Johnston NM (2003) Antarctic marine benthic diversity. Oceanogr Mar Biol Annu Rev 41:47–114
Gray JH (2001) Antarctic marine benthic biodiversity in a worldwide latitudinal context. Polar Biol 24:633–641
Gutzmann E, Martínez Arbizu P, Rose A, Veit-Köhler G (2004) Meiofauna communities along an abyssal depth gradient in the Drake Passage. Deep Sea Res II 51:1617–1628
Hoegh-Guldberg O, Pearse JS (1995) Temperature, food availability and the development of marine invertebrate larvae. Am Zool 35:415–425
Peck LS (2002) Ecophysiology of Antarctic marine ectotherms: limits to life. Polar Biol 25:31–40

Peck LS, Bullough LW (1993) Growth and population structure in the infaunal bivalve Yoldia eightsi in relation to iceberg activity at Signy Island, Antarctica. Mar Biol 117:235–241

Peck LS, Powell DK, Tyler PA (2007) Very slow development in two Antarctic bivalve molluscs, the infaunal clam *Laternula elliptica* and the scallop *Adamussium colbecki*. Mar Biol 150:1191–1197

Peck LS, Clark MS, Morley SA, Massey A, Rossetti H (2009a) Animal temperature limits and ecological relevance: effects of size, activity and rates of change. Funct Ecol 23:248–253

Peck LS, Massey A, Thorne M, Clark MS (2009b) Lack of acclimation in *Ophionotus victoriae*: brittle stars are not fish. Polar Biol 32:399–402

Pörtner HO, Somero GA, Peck LS (2007) Thermal limits and adaptation in marine Antarctic ectotherms: an integrative view. In: Rogers A, Murphy E (eds) Antarctic ecology, from genes to ecosystems. Special Volume Philosophical, Transactions of the Royal Society of London doi:10.1098/rstb.2006.1947

Smith WO, Ainley DG, Cattaneo-Vietti R (2007) Trophic interactions within the Ross Sea continental shelf ecosystem. Philos Trans R Soc B 362:95–111

Williams A, Althaus F, Clark MR, Gowlett-Holmes K (2011) Composition and distribution of deep-sea benthic invertebrate megafauna on the Lord Howe Rise and Norfolk Ridge, southwest Pacific Ocean. Deep Sea Res II – Top Stud Oceanogr 58:948–958

## *Further Reading on Antarctic Pelagic Ecosystem*

Atkinson A, Siegel V, Pakhomov E, Rothery P (2004) Long-term decline in krill stock and increase in salps within the Southern Ocean. Nature 432:100–103

Berkman PA (1992) The Antarctic marine ecosystem and humankind. Rev Aquat Sci 6:295–333

Collins MA, Rodhouse PG (2006) Southern Ocean cephalopods. Adv Mar Biol 50:191–265

Collins M, Xavier JC, Johnston N, North AW, Enderlein P, Tarling GA, Waluda C, Hawker E, Cunningham N (2008) Patterns in the distribution of myctophid fish in the northern Scotia Sea ecosystem. Polar Biol 31:837–851

Ducklow HW, Baker K, Martinson DG, Langdon LB, Ross MR, Smith RC, Stammerjohn SE, Vernet M, Fraser W (2007) Marine pelagic ecosystems: the West Antarctic Peninsula. Philos Trans R Soc Lond B 362:67–94

Eastman JT (1993) Antarctic fish biology: evolution in a unique environment. Academic, London

Everson I (1977) The living resources of the Southern Ocean. FAO, Rome, p 160

Everson I (2000) Krill: biology, ecology and fisheries. Blackwell Science, Oxford, p 372

Holm-Hansen O, Naganobu M, Kawaguchi S, Kameda T, Krasovski I, Tchernyshkov P, Priddle J, Korb R, Brandon M, Demer D, Hewitt RP, Kahru M, Hewes CD (2004) Factors influencing the distribution, biomass, and productivity of phytoplankton in the Scotia Sea and adjoining waters. Deep Sea Res II 51:1333–1350

Knox GA (2007) The biology of the Southern Ocean. Cambridge University Press, Cambridge, p 444

Kock K-H (1992) Antarctic fish and fisheries. University Press, Cambridge, p 359

Legendre L, Ackley SF, Dieckmann GS, Gulliksen V, Horner R, Hoshiai T, Melnikov IA, Reeburgh WS, Spindler M, Sullivan CW (1992) Ecology of sea ice biota. Polar Biol 12:429–444

Lizotte MP (2001) The contributions of sea ice algae to Antarctic marine primary production. Integr Comp Biol 41:57–73

Rodhouse PG, White MG (1995) Cephalopods occupy the ecological niche of epipelagic fish in the Antarctic Polar Frontal Zone. Biol Bull 189:77–80

Shreeve RS, Collins MA, Tarling GA, Main CE, Ward P, Johnston NM (2009) Feeding ecology of myctophid fish in the northern Scotia Sea. Mar Ecol Prog Ser 336:226–236

Wohrmann AP (1995) Antifreeze glycopeptides in the high-Antarctic silverfish *Pleurogramma antarcticum* (Notothenioidei). Comp Biochem Physiol C Toxicol Endocrinol 111(1):121–129

Xavier JC, Phillips RA, Cherel Y (2011) Cephalopods in marine predator diet assessments: why identifying upper and lower beaks is important? ICES J Mar Sci 68(9):1857–1864

## *Further Reading on Responses to Climate Change*

Anisimov OA, Vaughan DG, Callaghan TV, Furgal C, Marchant H, Prowse TD, Vilhjálmsson H, Walsh JE (2007) Polar regions (Arctic and Antarctic). Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Cambridge University Press, Cambridge, pp 653–685

Aronson RB, Thatje S, Clarke A, Peck LS, Blake DB, Wilga CD, Seibel BA (2007) Climate change and invisibility of the Antarctic benthos. Annu Rev Ecol Evol Syst 38:129–154

Barbraud C, Weimerskirch H (2006) Antarctic birds breed later in response to climate change. Proc Natl Acad Sci 103:6248–6251

Brierley AS, Thomas DN (2002) Ecology of Southern Ocean pack ice. Adv Mar Biol 43:171–276

Croxall JP, Trathan PN, Murphy EJ (2002) Environmental change and Antarctic seabird populations. Science 297:1510–1514

Curran MAJ, van Ommen TD, Morgan VI, Phillips KL, Palmer AS (2003) Science 302:1203–1206

Forcada J, Trathan PN (2009) Penguin responses to climate change in the Southern Ocean. Glob Chang Biol 15:1618–1630

Forcada J, Trathan PN, Reid K, Murphy EJ, Croxall JP (2006) Contrasting population changes in sympatric penguin species in association with climate warming. Glob Chang Biol 12:411–423

Kaiser MJ, Attrill MJ, Jennings S, Thomas DN, Barnes DKA, Brierley AS, Polunin NV, Raffaelli DG, Williams PJB (2005) Marine ecology. Processes, systems, and impacts. Oxford University Press, Oxford, p 557

Meredith MP, King JC (2005) Climate change in the ocean to the west of the Antarctic Peninsula during the second half of the 20th century. Geophys Res Lett 32:L19604

Peck LS (2005) Prospects for surviving climate change in Antarctic aquatic species. Front Zool 2:2–9

Peck LS, Morley SA, Clark MS (2010b) Poor acclimation capacities in Antarctic marine ectotherms. Mar Biol 157:2051–2059

Reid K, Croxall JP (2001) Environmental response of upper trophic-level predators reveals a system change in an Antarctic marine ecosystem. Philos Trans R Soc Lond 268:377–384

Seebacher F, Davison W, Lowe CJ, Franklin CE (2005) The falsification of the thermal specialization paradigm: compensation for elevated temperatures in Antarctic fishes. Biol Lett 1:151–154

# Chapter 13
# Antarctic Megafauna

## The Birds and Mammals of Antarctica

**Regina Eisert**

**Abstract** The megafauna (Greek μεγα: great; Latin fauna: animal life) of Antarctica is defined by absence. Two classes of vertebrates, reptiles and amphibians, are missing from the continent and its surrounding waters, and Antarctica has lacked true land vertebrates since dinosaurs last roamed the continent in the late Cretaceous. The ocean is the foundation of all vertebrate life in Antarctica, and none of its native birds and mammals can survive permanently in the continent's frigid, white interior. Antarctic vertebrates are all classified as marine and ultimately derive their food from the sea. Unlike in much of the Arctic, the harsher climate of Antarctica does not allow for significant plant growth, and no vertebrate herbivores exist. Antarctica's long isolation from other landmasses has resulted in the absence of surface predators such as the polar fox *Alopex lagopus* or polar bear *Ursus maritimus*, an important distinction between Antarctic and Arctic habitats. Antarctica and the Southern Ocean present some of the most challenging environmental conditions on Earth, including extreme cold, wind, dryness, radical seasonal changes in photoperiod, and extensive ice cover. But Antarctica also offers tremendous opportunity because it is a continent free of terrestrial mammalian predators, and the Southern Ocean surrounding the Antarctic continent includes some of the most productive marine habitats in the world.

**Keywords** Megafauna • Birds • Seals • Whales • Adaptation • Thermoregulation • Insulation

## 13.1 Introduction

Antarctic animals possess numerous distinct morphological, physiological and behavioural adaptations that enable them to live and thrive in this unique environment. The Antarctic megafauna covered in this chapter comprises seabirds and

R. Eisert (✉)
Gateway Antarctica, University of Canterbury, Christchurch, New Zealand

Smithsonian Environmental Research Center, Mayo, MD, USA
e-mail: regina.eisert@canterbury.ac.nz

 
D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_13

mammals, including seals and whales (Table 13.1). While whales are fully aquatic, seals and birds require ice or land as a substrate to care for their young, as well as for moulting, resting and to escape from predators. In the Arctic, sea ice allows surface predators to access their prey – for example, polar bears depend on sea ice to access seal pupping colonies. By contrast, all Antarctic vertebrate predators are either small seabirds and thus independent of ice cover (e.g. south polar skua), or marine (e.g. leopard seals, killer whales), and are excluded from areas of continuous ice cover because they need access to the surface to breathe. The only exception to this rule is the Weddell seal, which is able to find and maintain breathing holes and lives deep inside the Antarctic fast ice (Box 13.1).

Many Antarctic mammals and birds exhibit strong philopatry, i.e. they return to the same breeding areas every year. In terms of habitat, one can distinguish breeding and moulting areas, summer feeding grounds and overwintering areas. Breeding habitats are present along the coastline of the Antarctic continent, on the Antarctic Peninsula, and on Antarctic and subantarctic islands. For animals that use ice rather than land (most seals and the emperor penguin), different habitats include fast ice, and heavy and loose pack ice that is present at varying distances from the Antarctic coast depending on the time of year (Chap. 5). Outside the breeding period, Antarctic animals feed in the Southern Ocean, and many species spend most of their life at sea. Some species migrate great distances north during the Antarctic winter, and return to summer feeding grounds. Many seabirds, seals and whales undertake long, directed foraging trips to oceanographic (fronts, polynyas, edge of pack ice) and bathymetric (ridges, shelf slopes, seamounts) features that are associated with high primary productivity (Bornemann et al. 2000; Bost et al. 2004, 2009; Erdmann et al. 2011; Ribic et al. 2011) (Fig. 13.1).

Although the Southern Ocean forms a continuous body of water surrounding the continent of Antarctica, different regions are dominated by different food webs, and there may be considerable heterogeneity in diet and foraging patterns of circumpolar predators depending on local conditions (Trathan et al. 2007). The climate of the Antarctic Peninsula is milder and wetter than in the Antarctic heartland, and supports a much greater diversity of wildlife than the rest of the continent (Shirihai 2008).

Antarctic megafauna is protected by the Antarctic Treaty (Chap. 16) and by the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) (Chaps. 20 and 21), which prohibits the kind of exploitation that brought several Antarctic species close to extinction during the nineteenth and twentieth centuries. However, CCAMLR permits scientific research and ‘rational use’ of marine resources such as regulated fishing. The latter has the potential to impact Antarctic megafauna both directly (e.g. mortality of seabirds in longline fisheries) and indirectly (through removal of important prey species such as krill or fish). In addition, under the premise of scientific whaling, killing of whales in Antarctic waters is ongoing (Baker et al. 2010).

**Table 13.1** Antarctic Megafauna

| Class | | Species name | Common name | Adult body mass [kg] | Breeding distribution |
|---|---|---|---|---|---|
| AVES | | | | | |
| Order Ciconiiformes | | | | | |
| | Family | | | | |
| | Chionididae (sheathbills) | *Chionis alba* | Snowy sheathbill | 0.46–0.78 | 54°–65°S |
| | Hydrobatidae (storm petrels) | *Oceanites oceanicus* | Wilson's storm petrel | 0.028–0.050 | 46°–72°S |
| | | *Fregetta tropica* | Black-bellied storm petrel | 0.043–0.063 | 46°–62°S |
| | Laridae (auks, gulls, puffins and terns) | *Larus dominicanus* | Kelp gull | 0.9–1.34 | 38°–63°S |
| | | *Sterna vittata* | Antarctic tern | 0.11–0.21 | 37°–63°S |
| | Phalacrocoracidae (cormorants and shags) | *Phalacrocorax georgianus* | South Georgia shag | 2.5–2.9 | 53°–60°S |
| | | *Phalacrocorax bransfieldensis* | Antarctic shag | 2.5–3.0 | 62°–67°S |
| | Procellariidae (fulmars, petrels, shearwaters) | *Pachyptila desolata* | Antarctic prion | 0.095–0.224 | 46°–67°S |
| | | *Pagodroma nivea nivea* | Lesser snow petrel | 0.2–0.4 | 54°–78°S |
| | | *Pagodroma nivea confusa* | Greater snow petrel | 0.3–0.6 | 54°–78°S |
| | | *Daption capense* | Cape petrel | ~0.44 | 46°–68°S |
| | | *Thalassoica Antarctica* | Antarctic petrel | ~0.68 | 63°–70°S |
| | | *Fulmarus glacialoides* | Southern fulmar | 0.7–1.0 | 54°–70°S |
| | | *Macronectes giganteus* | Southern giant petrel | 3.8–5.0 | 40°–70°S |

(continued)

**Table 13.1** (continued)

| Class | | Species name | Common name | Adult body mass [kg] | Breeding distribution |
|---|---|---|---|---|---|
| | Stercorariidae (skuas and jaegers) | *Stercorarius maccormicki* | South polar skua | 0.6–1.7 | 62°–77°S |
| | | *Stercorarius antarctica* | Subantarctic skua | 1.25–2.54 | 44°–65°S |
| | Spheniscidae (penguins) | *Aptenodytes forsteri* | Emperor penguin | 22–37 | 66°–77°S |
| | | *Aptenodytes patagonicus* | King penguin | 9.3–17.3 | 46°–60°S |
| | | *Eudyptes chrysolophus* | Macaroni penguin | 3.1–6.6 | 46°–63°S |
| | | *Pygoscelis adeliae* | Adélie penguin | 3.8–8.2 | 54°–77°S |
| | | *Pygoscelis antarcticus* | Chinstrap penguin | 3.2–5.3 | 54°–65°S |
| | | *Pygoscelis papua* | Gentoo penguin | 4.5–8.5 | 46°–65°S |
| MAMMALIA | | | | | |
| Order Carnivora | | | | | |
| | Family Phocidae (true seals) | *Ommatophoca rossii* | Ross seal | 170–225 | 67°–77°S |
| | | *Lobodon carcinophaga* | Crabeater seal | 180–410 | 60°–76°S |
| | | *Leptonychotes weddellii* | Weddell seal | 300–580 | 54°–78°S |
| | | *Hydrurga leptonyx* | Leopard seal | 400–600 | 60°–75°S |
| | | *Mirounga leonine* | Southern elephant seal | ♀ 350–800<br>♂ 3,000–5,000 | 38°–62°S |
| | Otariidae (fur seals and sea lions) | *Arctophoca gazelle* | Antarctic fur seal | ♀ ~45, ♂ ~190 | 46°–62°S |
| Order Cetacea | | | | | |
| Suborder Mysticeti (baleen whales) | | | | | |
| | Family Balaenidae (bowhead and right whales) | *Eubalaena australis* | Southern right whale | 20,000–30,000 | |
| | Balaenopteridae (rorquals) | *Balaenoptera bonaerensis* | Antarctic minke whale | 5,800–9,100 | |

| | | | | | |
|---|---|---|---|---|---|
| | | *Balaenoptera musculus intermedia* | Southern blue whale | 80,000–150,000 | |
| | | *Balaenoptera musculus brevicauda* | Pygmy blue whale | ~70,000 | |
| | | *Balaenoptera borealis schlegelii* | Southern sei whale | 15,200–30,400 | |
| | | *Balaenoptera physalus quoyi* | Southern fin whale | 30,400–81,200 | |
| | | *Megaptera novaeangliae* | Humpback whale | 25,400–35,500 | |
| Cetacea suborder Odontoceti (toothed whales) | | | | | |
| | Family | | | | |
| | Delphinidae (dolphins, killer and pilot whales) | *Globicephala melas edwardii* | Longfinned pilot whale | 2,000–3,000 | |
| | | *Lagenorhynchus cruciger* | Hourglass dolphin | 73.5–94 | |
| | | *Orcinus orca* | Orca, killer whale | 3,000–8,000 | |
| | Hyperoodontidae (beaked whales) | *Hyperoodon planifrons* | Southern bottlenose whale | 6,900–8,100 | |
| | | *Berardius arnuxii* | Arnoux's beaked whale | ~8,000 | |
| | Physeteridae (sperm whales) | *Physeter macrocephalus* | Sperm whale | ♀13,500–20,000<br>♂43,500–55,800 | |

Note on selection criteria: For birds and seals, the breeding distribution of the species must extend to at least 60°S; for cetaceans, species that have a reasonable sighting probability in the Southern Ocean at or below 60°S

Note on taxonomy: Species names and classification follows ITIS (www.itis.gov); note that the taxonomy of some species or taxa is under debate and may be reported differently elsewhere (e.g. skuas)

**Fig. 13.1** Gentoo penguins breed on the Antarctic Peninsula (With kind permission from Jon Brack/NSF)

**Box 13.1: Masters of the Fast Ice (Fig. 13.2)**

The Weddell seal is the only Antarctic mammal that can live inside the fast ice, because Weddell seals can find cracks that result from wind and tidal action, and they maintain breathing holes by abrading the ice with their teeth.

**Fig. 13.2** A Weddell seal sports a video data recorder scientists use to create three-dimensional maps of its movement in the water (With kind permission from Randall Davis/NSF)

(continued)

**Box 13.1** (continued)
As long as the ice does not break out, Weddell seals are virtually immune from predation (since there are no sharks in Antarctica, and killer whales and leopard seals do not enter closed ice), and there is little competition for fish and other prey. But the seals' upper canines and second incisors become progressively worn with age, and jaw infections and the inability to keep ice holes open are major causes of mortality in Weddell seals. By contrast, crabeater seals live in heavy pack ice, where pups face severe predation pressure from killer whales and leopard seals, but those that survive to adulthood may live almost twice as long as Weddell seals.

## 13.2 Overview of Antarctic Megafauna

### *13.2.1 Birds (Aves)*

The native birds of Antarctica belong to two major groups, the flightless penguins (family Spheniscidae) and the volant (flying) seabirds including storm petrels, gulls, terns, cormorants, petrels, fulmars, shearwaters, sheathbills and skuas (families Chionididae, Hydrobatidae, Laridae, Phalacrocoracidae, Procellariidae, Stercorariidae; Table 13.1). With the sole exception of the emperor penguin, which raises its offspring on fast ice, all Antarctic birds return to land to incubate and raise their young. Many more seabirds than listed in Table 13.1 breed elsewhere and visit the Antarctic during summer to take advantage of the high productivity of the Southern Ocean (Chap. 7), such as the albatrosses (Diomedeidae) and diving petrels (Pelecanoididae). A famous example of long-distance migration is the Arctic tern, *Sterna paradisaea*, which nests in the Arctic and migrates to Antarctica during the boreal winter. Similar long migrations are made by Wilson's petrel and the south polar skua, which breed on the Antarctic continent during summer and migrate as far as Alaska and Greenland in the austral winter, boreal summer (Shirihai 2008).

The volant seabirds of Antarctica range in size from 40 g to 3.5 kg and include Antarctica's smallest endotherms (Shirihai 2008; Obst et al. 1987), or warm-blooded animals. Unlike some of the larger penguin species, all volant seabirds complete breeding (mating, incubation and rearing of chicks to fledging) during the Antarctic summer season. The three most southerly breeding species, the snow petrel, Antarctic petrel and south polar skua, regularly face temperatures of 0 °C, and sometimes as low as −25 °C, during the breeding season (Weathers et al. 2000; Hodum and Weathers 2003). Antarctic seabirds rarely build anything that resembles a conventional nest; larger species such as the cape petrel, giant petrel, southern fulmars and the skua incubate their eggs in shallow scrapes, whereas smaller species such as Wilson's storm petrel, snow petrel, and the Antarctic prion tend to nest in burrows or crevices that protect nestlings and adults from harsh weather and predators. Antarctic petrels nest on steep cliffs and nunataks, sometimes far from the sea, to escape predation by skuas and giant petrels (Brooke et al. 1999; van Franeker et al. 2001). Only the more northerly-breeding shags and the kelp gull construct nests out of seaweed or plant material (Shirihai 2008).

Both parents generally share the duties of incubation and provisioning of chicks. Antarctic seabirds often show philopatry, returning to the same nesting site or their natal site year after year, and many colony sites may be very old. For example, a colony of snow petrels in Dronning Maud Land has existed in the same place for at least 37,000 years (Thor and Low 2011).

Antarctic volant seabirds forage on a wide variety of marine prey including krill (*Euphausia* spp.), copepods, amphipods, fish and fish larvae, cephalopods (mostly squid) and molluscs that they catch either at the surface or by shallow diving (Shirihai 2008; Croxall and Prince 1996). An exception are the shags (family Phalacrocoracidae) which dive the deepest (~40–90 m maximum depth) and longest (1–3 min) among all flying birds in Antarctica (Casaux and Barrera-Oro 2006). Storm petrels feed by skimming zooplankton off the surface but practically never settle on the water to rest, instead spending the entire time at sea on the wing (Obst et al. 1987). Like the kiwi, *Apteryx spp*., many seabirds have a well-developed sense of smell (Zelenitsky et al. 2011; Wright et al. 2011), which is important in locating food sources such as krill patches or carrion (Lequette et al. 1989).

Several prominent Antarctic birds such as the south polar and subantarctic skuas, southern giant petrel and the snowy sheathbill are facultative scavengers, i.e. they consume dead animals and waste such as faeces, eggs, or afterbirth. Scavengers congregate near breeding colonies of birds and seals, and also attend kills made by marine predators such as killer whales or leopard seals that dismember their prey at or near the surface (Pitman and Durban 2010). The willingness of many scavengers such as skuas and snowy sheathbills to eat almost anything frequently proved fatal during the early days of human occupation of Antarctica, because birds would be attracted to open incinerators or ingest toxic materials at rubbish dumps (dumping and open burning of refuse are now prohibited under Annex III of the Protocol on Environmental Protection to the Antarctic Treaty; Chap. 16). Depending on the season and available resources, scavengers also actively hunt marine fish and invertebrates (Hahn et al. 2008), as well as preying on other Antarctic birds. Skuas and sheathbills will attack and kill penguin chicks (Shirihai 2008), and skuas and giant petrels prey on chicks and adults of smaller seabird species such as Antarctic fulmars, Antarctic petrels, cape petrels and Wilson's storm petrels (Weidinger 1998; Baker and Barbraud 2001).

Predation by skuas and giant petrels on breeding birds may be severe and a major determinant of breeding success (Weidinger 1998). Skuas at the American McMurdo Station (77°55′ S, 166°39′ E) will attack humans who carry food by flying at their faces, and frequently succeed in getting people to spill food on the ground (Eisert pers. obs.). This behaviour is possibly a modified form of kleptoparasitism, a type of parasitism by stealing of food, which is common among the Laridae (sea gulls) and Stercorariidae (skuas and jaegers).

In contrast to volant seabirds, penguins are mostly limited to the Southern Hemisphere. But despite their reputation as the quintessential Antarctic birds, only 2 of 17 extant species of penguin (emperor and Adélie) breed on the Antarctic mainland, with an additional four species breeding on the Antarctic Peninsula and in the maritime Antarctic (gentoo, king, macaroni, and chinstrap penguins). For comparison, six distinct species of penguin breed in New Zealand and its subantarctic islands (Shirihai 2008).

Antarctic penguins are large birds, ranging in size from 3 to 40 kg (Table 13.1). All penguins are flightless. Their wings have evolved into flippers and their hind limbs are short and placed far back on the body, resulting in the typical upright posture on land. While penguins may move somewhat awkwardly out of the water, their streamlined shape, a result of ample fat reserves and special modified plumage (Taylor 1986), allows them to move with speed and ease through the sea propelled by their front flippers (Fig. 13.3).

Like seals, penguins are active marine hunters with superb diving abilities, and catch their prey by pursuing it underwater. As an example of parallel evolution, penguins and marine mammals have developed similar adaptations to diving, including increased tissue oxygen storage (Burns and Kooyman 2001) (Box 13.2). Depending on species and area, penguins eat small crustaceans including krill, small fish such as *Pleuragramma antarcticum*, and squid (Croxall and Prince 1996; Ainley et al. 2003). Penguins, in turn, are preyed on by Antarctic fur seals, leopard seals, and killer whales, and penguin chicks are vulnerable to attacks by skuas and giant petrels (Janes 1997; Charbonnier et al. 2010).

**Fig. 13.3** Adélie penguins look after their chicks at Cape Royds, their southernmost breeding colony (With kind permission from Peter Rejcek/NSF)

**Box 13.2: Dive Physiology**

For air-breathing vertebrates, diving to depth means coping with oxygen deprivation (hypoxia) and high pressure, and avoiding decompression sickness (DCS) (Kooyman and Ponganis 1998). Adaptations that prolong dive duration are increased body oxygen stores and decreased use of oxygen (Burns and Kooyman 2001) e.g. by regional heterothermy (Blix et al. 2010). Seals, whales and penguins have increased oxygen stores in the form of high haematocrit values (red cells per ml of blood; Fig. 13.6 at left) and high concentrations of oxygen-binding molecules in red blood cells (haemoglobin) and in muscle (myoglobin). Blood flow during diving is restricted to prioritise essential organs (e.g. heart, brain), whereas muscle is supported by tissue oxygen stores. When oxygen stores run low, by-products of anaerobic metabolism such as lactate start accumulating in the blood, and this signals the aerobic dive limit (ADL). Larger divers have typically longer ADLs because they have greater capacity to store oxygen in their tissues and a lower mass-specific metabolic rate. ADL values for king penguins, emperor penguins, adult Weddell seals and sperm whales are 4.2 min (Culik et al. 1996), 5.6 min (Meir and Ponganis 2009), 20–23 min (Kooyman and Ponganis 1998), and 54 min (Watwood et al. 2006), respectively.

DCS (also known as the 'bends') is caused by absorption of nitrogen from the lungs under pressure during deep or prolonged dives. During rapid ascent, the decrease in pressure releases dissolved nitrogen ($N_2$) from body fluids as gas bubbles, potentially causing tissue damage and death. Shallow divers (small penguins, cormorants) have a low risk of DCS. Human divers, who breathe air under pressure and can absorb excess nitrogen, use decompression stops during the ascent to allow $N_2$ to gas off slowly and to avoid bubble formation. It has been proposed that whales may use similar behavioural mechanisms to avoid DCS (Jepson et al. 2003; Piantadosi and Thalmann 2004). In seals, the thorax and respiratory tract is modified so it collapses under pressure reversibly and without injury. Because little air remains in the lungs, only small quantities of nitrogen are absorbed and seals are immune to DCS (Falke et al. 1985). It is not clear how sperm whales and emperor penguins avoid DCS (Beatty and Rothschild 2008; Moore and Early 2004).

Penguins nest in large, traditional colonies on ice (emperor penguin) or land (all other species). Penguin eggs have an organic coating or cuticle that reduces water loss, something that may be of adaptive value in the extremely dry climate of Antarctica (Handrich 1989; Thompson and Goldie 1990; Tyler 1965). Most land-breeding penguins construct shallow nests of stones or other debris (Fig. 13.5), whereas in emperor and king penguins (Fig. 13.4), the egg is incubated by being placed on the adult's feet and enclosed in a specialised structure called a brood pouch. Inside the brood pouch, the egg is in contact with an area of bare skin, the brood patch, that is both moist and highly vascularised (i.e. contains many blood

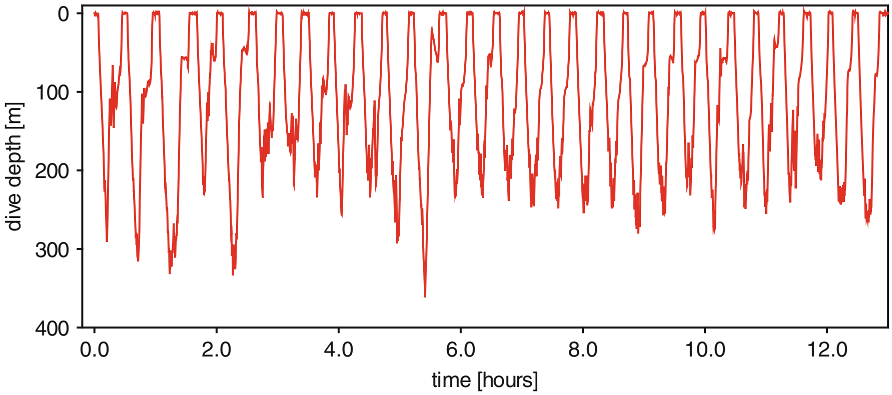



**Fig. 13.4** Dive bout of a lactating Weddell seal. Mean dive duration is ca. 22 min and within the aerobic dive limit for Weddell seals. Because dives do not exceed the ADL, surface intervals can be brief (4–6 min). Total bout length was 13 h (Adapted from Eisert and Oftedal, unpublished data)

vessels to effectively transfer body heat), and thus creates a favourable microclimate for egg incubation (Handrich 1989; Oftedal 2002).

The length of the breeding cycle in penguins varies with species size. The smaller species (Adélie, chinstrap, gentoo, and macaroni) complete the entire breeding cycle during the summer season, whereas the emperor penguin incubates its eggs during the winter (no doubt this is only possible because the species has a brood pouch), and chicks fledge by the following spring (Stonehouse 1953). The king penguin, which is smaller than the emperor penguin and has a much more northerly distribution (Table 13.1), breeds on average twice during each 3-year period, with chicks overwintering before fledging (Stonehouse 1956; Olsson and Brodin 1997). While incubating and rearing chicks, both parents take turns to tend to the offspring and go on foraging trips. After the chick has reached a certain degree of maturity, both parents may leave to forage (Janes 1997). In the two winter-breeding species, parents (emperor, king) and chicks (king) must undergo prolonged periods of starvation while one parent or both are at sea to feed. Penguin chicks waiting for the return of their parents congregate in tight groups called crèches that may include several hundred individuals (Shirihai 2008). This behaviour is thought to reduce the risk of predation, confer a thermo-regulatory advantage, and to minimise the impact of intraspecific aggression of brooding adults against unrelated chicks (Le Bohec et al. 2005).

Of all birds, penguins are the ones most completely adapted to the marine environment (Cherel et al. 1993). It is now clear that penguins represent a highly specialised taxon, but it was once thought that because penguins were flightless, they represented a primitive stage in the evolution of birds; an erroneous view that motivated one of the most famous of all Antarctic journeys (Cherry-Garrard 2010) (Box 13.3).

**Box 13.3: The Worst Journey in the World Was Made for Science**

> Polar exploration is at once the cleanest and most isolated way of having a bad time which has been devised. (Cherry-Garrard 2010)

When Apsley Cherry-Gerrard accompanied Robert Falcon Scott to Antarctica in 1910, the scientific wisdom of the day was that the embryonic development of individual animals represented a time-lapse sequence of the species' evolution from more primitive ancestral forms. This principle was summarised as "ontogeny (individual development) recapitulates phylogeny (evolution of species)" by the German scientist Ernst Haeckel in 1874. Because penguins were then considered the most primitive living birds, the biologist on Scott's expedition, Edward Wilson, believed that the study of penguin embryos might reveal much about the evolution of birds (Wilson 1907). This is why Wilson, Cherry-Gerrard and Bowers set out in the middle of the Antarctic winter to cross Ross Island on foot to bring back emperor penguin eggs. After barely surviving incredible hardship, the men managed to bring back three intact eggs. We know now that penguins are not at all primitive, and Haeckel's theory has been revised in the light of modern molecular evidence (Sander 2002). But Cherry-Garrard immortalised the quest for the emperor's eggs in a book, *The Worst Journey in the World*, which is widely regarded as one of the finest books on Antarctic exploration ever written.

### *13.2.2 Seals (Carnivora: Pinnipedia)*

Seals or pinnipeds are aquatic animals in the mammalian order Carnivora and have evolved from arctoid carnivore (bear or weasel-like) ancestors (Berta et al. 2006). Seals occur in all oceans of the world as well as some freshwater lakes, and include apex predators in both the Arctic and Antarctica. Pinnipeds are classified into three families, the fur seals and sea lions (Otariidae; 16 species), the true seals (Phocidae; 18 species) and the walrus (Odobenidae; 1 species). Six species of seal breed in Antarctica (Table 13.1): Ross, leopard, crabeater, southern elephant and Weddell seals (all Phocidae) and the Antarctic fur seal (Otariidae) (Siniff 1991). Two Antarctic species were extensively exploited during the eighteenth and nineteenth centuries; Antarctic fur seals for fur and southern elephant seals for oil (Chap. 15). Antarctic fur seals were considered extinct in Antarctica in the early 1900s (Rudmose Brown 1915). Five Antarctic fur seals were discovered on South Georgia in 1919, and the species has since made a spectacular comeback (Payne 1977; Kooyman and Kooyman 2009). There was little persecution of the more southerly Antarctic seals due to their inaccessibility.

Unlike the fully aquatic cetaceans, seals require a solid substrate on which to breed, moult and rest. All Antarctic seals give birth to single offspring (very rarely, twins are born but never survive; Gelatt et al. 2001), and breeding is tightly synchronised. In the spring, seals congregate in breeding colonies on land or fast ice (Antarctic fur, southern elephant, Weddell seal) or enter the pack ice (Ross, crabeater, leopard seal) to give birth, nurse their young and mate. In the two sexually dimorphic species, southern elephant and Antarctic fur seals, dominant males guard groups of females called harems, whereas Weddell seal males defend underwater territories (maritories), and the pack ice seals are presumed to form transient mated pairs. Females come into oestrus and mate around the time their pups are weaned (Siniff 1991). The Weddell seal breeds in colonies near tidal cracks deep into the closed fast ice that forms above the continental shelf zones of Antarctica (Box 13.1). A colony of Weddell seals at White Island (78°10′S, 167°20′E), near Scott Base, has the distinction of being the most southerly breeding population of mammals in the world (Gelatt et al. 2010; Littlepage and Pearse 1962). Because Weddell seal colonies are frequently located in the vicinity of research stations and easily accessible via sea ice (e.g. Scott Base and McMurdo Station), scientists have investigated, among other things, the diving physiology, population dynamics, foraging behaviour and lactation energetics of Weddell seals (Stirling 1969; Testa 1994; Dearborn 1965; Eisert and Oftedal 2009; Ainley and Siniff 2009), making them probably the most intensively studied marine mammal in the world. By contrast, conducting research in pack ice is very difficult, and comparatively little is known about reproduction and general biology in the pack ice seals (Southwell et al. 2003).

Seals cannot feed while hauled out (moving out of the water onto a solid substrate, i.e. tidal rocks, land or ice). This problem is particularly acute during the lactation period, since the mother has a greatly increased demand for energy and substrates to support milk production. Phocid and otariid seals have evolved different solutions to this problem (Oftedal et al. 1987a, b; Boness and Bowen 1996). Phocid seals meet the energy demand of lactation primarily by catabolising (breaking down) body stores, and at least half of 18 extant phocid species fast completely during lactation (Schulz and Bowen 2005). Lactation in the phocid seals is greatly abbreviated relative to terrestrial mammals of similar size, milk is high in energy (Box 13.4) and transferred to the pup at tremendous rates, and pup growth is rapid (Oftedal 1993). An Arctic phocid, the hooded seal *Cystophora cristata*, weans its pup after nursing it for only 4 days, during which the pup at least doubles its birth mass (Oftedal et al. 1993). In Antarctic phocids, lactation lasts from 2 to 4 weeks (Ross, leopard, crabeater, southern elephant seal) to 6–7 weeks (Weddell seal) (Stirling 1969; Southwell et al. 2003; Thomas and DeMaster 1983; Laws et al. 2003). Lactating seals typically invest a large proportion of their body stores into milk production (Oftedal 2000). For example, elephant seals lactate for 23 days and lose 35 % of their initial body mass, whereas Weddell seals lose 40 % or more of their initial body mass during a 6-week lactation, despite the fact that Weddell seals forage during lactation while elephant seals fast (Carlini et al. 2004; Eisert et al 2005; Sato et al. 2002). In contrast to the abbreviated lactation in phocid seals, otariid seals such as the Antarctic fur seal nurse their offspring for relatively long periods (120 days in the Antarctic fur seal), and leave their young intermittently to forage. Lactation in the Antarctic fur seal consists of a brief initial fast of ca. 1 week followed by a nursing-foraging cycle (4–6 days at sea, 2 days nursing pups ashore) (Costa and Trillmich 1988; Arnould et al. 2001).

Provisioning of offspring in fur seals thus resembles in some respects the pattern found in seabirds (Boyd 1999). Otariid pups grow more slowly than phocid pups, because they fast during maternal foraging trips, and the average rate of milk transfer is much lower than in phocid seals (Oftedal et al. 1987a, b; Luque et al. 2007). Foraging Antarctic fur seal mothers may travel more than 300 km away from the breeding colony (Staniland et al. 2010) and may leave their pup for as long as 13 days (Boyd 1999). In mammals including phocid seals, cessation of suckling typically abolishes lactation, but all otariids have the unique ability to maintain the mammary gland in an active state despite very long inter-suckling intervals (23+ days in some species) while the mother forages (Reich and Arnould 2007).

Seals are active predators and have exceptional diving abilities (Box 13.2). Recorded maximum depth of Ross, Weddell, and southern elephant seals are 792 m (Blix and Nordøy 2007), 904 m (Andrews-Goff et al. 2010), and 1,500 m (Bennett et al. 2001), and seals may stay submerged for as long as 95 min (Weddell seal) to 2 h (elephant seal) (Kooyman and Ponganis 1998). Phocid seals swim primarily with their hindflippers, whereas otariids propel themselves with their long front flippers. All Antarctic seals take krill, fish and cephalopods (squid and octopods), but the relative contribution of different diet items varies with region, season and species (Boyd 2008). Weddell seals are generalists and consume a wide variety of prey (Casaux et al. 2009; Plötz 1986), whereas Ross and southern elephant seals prefer squid (Blix and Nordøy 2007), and the crabeater seal is a krill specialist (Siniff 1991). Antarctic fur and leopard seals both consume krill and fish but also prey on other Antarctic megafauna including penguins (Antarctic fur and leopard seal) and seal pups (leopard seal) (Casaux et al. 2003, 2009; Hall-Aspland and Rogers 2004). Weddell seals have been observed preying on penguins, but it is not clear whether this behaviour is representative for the species (Cobley and Bell 1998; Todd 1988).

**Box 13.4: Feeding Baby**

The milks of marine mammals are high in fat, protein and energy, and support rapid fattening of nursing young (Oftedal et al. 1988; Oftedal 2011). Fast growth and acquisition of an insulating fat layer is vital for the offspring of polar birds and mammals (Blix and Steen 1979), and energy is required to meet thermo-regulatory costs. From the lining of their oesophagus, male emperor penguins secrete a milk analogue, crop milk, which contains 28 % fat and 59 % protein in dry mass (Prévost and Vilter 1962). Crop milk has evolved independently in emperor penguins (Schmidt-Nielsen 1997), pigeons and doves (Davies 1939), and the flamingo (Ward et al. 2001). Albatrosses

(continued)

**Box 13.4** (continued)
and petrels (families Diomedeidae, Hydrobatidae, Procellariidae) produce stomach oil, a high-energy mixture of wax esters, triglycerides and other lipids extracted from prey and stored in the proventriculus (a forestomach chamber located between the crop and the muscular stomach or gizzard in birds) (Warham 1977). Parents add stomach oil when regurgitating feed for hatchlings, and this increases the energy content of a feed to ~16 $kJg^{-1}$, or by a factor of 1.3 (Antarctic prions) (Roby et al. 1997) to 3 (Wilson's petrel) relative to an unsupplemented feed (Obst and Nagy 1993). Unlike milk, stomach oil is also a serious weapon. Petrel chicks and adults, in particular giant petrels and southern fulmars, spit stomach oil in self-defence. If a bird is hit, its feathers are matted by the oil, and this may result in death from starvation and/or hypothermia (Warham 1977) (Fig. 13.5).

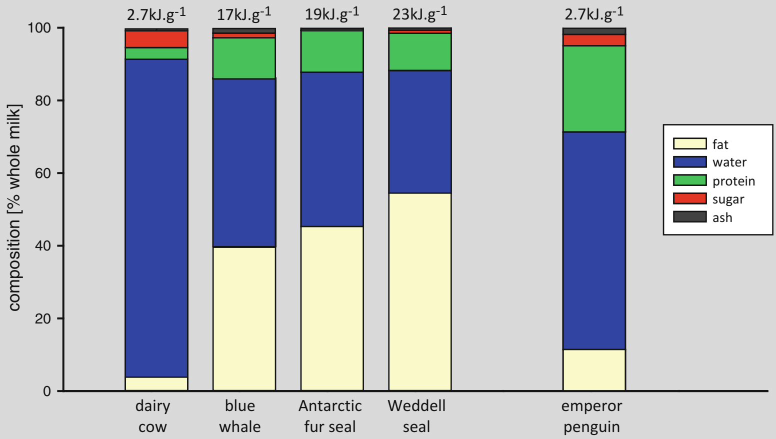



**Fig. 13.5** Composition and energy content of the milks of Antarctic megafauna relative to cow's milk

### *13.2.3 Whales (Cetacea)*

Whales are the largest representatives of the Antarctic megafauna and include the largest animal that has ever lived on Earth, the blue whale (≤160 t) (Berta et al. 2006). Whales are a fully aquatic animals that evolved from proto-ungulate terrestrial ancestors (the group that also gave rise to modern hoofed mammals), and are grouped together with the even-toed ungulates (formerly order Artiodactyla) into the superorder Cetartiodactyla (Agnarsson and May-Collado 2008). Like pinnipeds, whales give birth to single offspring. There are two suborders of whales, Odontoceti (toothed whales; 72 species) and Mysticeti (baleen whales; 14 species), and representatives of both groups occur in Antarctic waters (Table 13.1). Differences between odontocetes and mysticetes include dentition (teeth vs. baleen) and the use of echolocation (Box 13.5), which is thought to only occur in odontocetes (Thomas et al. 2004). Mysticete whales are generally larger than odontocetes, with the exception of the sperm whale, which equals the great baleen whales. Unlike birds and seals, many whales are thought to breed north of the Antarctic Convergence, and migrate south during the austral summer to feed. Whales generally avoid solid sea ice, but both Antarctic minke whales and killer whales penetrate into heavy pack ice, and killer whales may follow narrow leads into the fast ice (Gill and Thiele 1997; Thiele and Gill 1999; Ainley et al. 2007) (Fig. 13.6).

The polar regions are a central component of the life cycle of the large mysticetes. In both hemispheres, populations of fin, sei, blue, humpback and right whales commute annually between high-latitude feeding areas and low-latitude breeding grounds where calves are born. It is assumed that whales fast or feed very little in tropical and warm temperate waters, which means they may fast for 5–6 months every year (Oftedal 1997). Possible reasons for why whales move from the productive polar oceans to lower latitudes where they cannot feed include that newborn calves cannot tolerate cold water (Berta et al. 2006), and to avoid predation by killer whales (Corkeron and Connor 1999). However, no generally accepted explanation for the phenomenon of whale migrations has been proposed to date. Female mysticetes are thought to follow a fasting lactation strategy similar to that found in the phocid seals, i.e. offspring growth is rapid (the estimated growth rate of a nursing blue whale calf is ~80 kg per day), and the energy and substrate demand of lactation is met primarily through the catabolism of body stores. This

**Fig. 13.6** A humpback whale near Palmer Station on the Antarctic Peninsula (With kind permission from Peter Rejcek/NSF)

strategy is possible because the enormous abundance of krill in the Southern Ocean allows whales to amass extensive fat reserves during the summer season (Laws 1977). The relatively small Antarctic minke whale probably does not fast during its migrations, and some individuals appear to remain in the Antarctic pack-ice zone year-round (Berta et al. 2006; Thiele and Gill 1999).

Mysticetes, or baleen whales, are named for their unique feeding apparatus. Baleen consists of closely packed plates, made of a keratinaceous material, that are arranged along the upper jaw to form a highly effective tool for filtering zooplankton (small marine invertebrates including krill) out of the sea. The size and arrangement of baleen differs between species, and correlates with different feeding techniques. The southern right whale (family Balaenidae) has very long baleen ($\leq$2.4 m) in a strongly curved jaw that admits water and prey through a gap in the front (Fig. 13.7). Right whales feed predominantly by skimming relatively dispersed prey out of the water.

The so-called rorquals (whales in the family Balaenopteridae) have shorter, wider baleen and feed by gulping or lunging at clustered prey, often from below. In both cases, water taken into the oral cavity during feeding is expelled through the fringe of baleen, which retains the prey (Bannister 2008). Mysticetes generally feed in the upper 100 m of the water column. Their digestive tract is complex, resembling that of the closely related ruminants, and may permit efficient digestion of wax esters present in krill (Nordøy 1995).

Baleen whales (grey and right whales) were heavily exploited during the classical period of unregulated whaling (eighteenth to nineteenth centuries) as well as in the twentieth century, for oil and for their baleen (whalebone), a unique and desirable raw material before the invention of plastics. In 1904, Antarctic whaling started in earnest with the establishment of the Grytviken station on South Georgia, and the pace further accelerated with the introduction of ship-board processing in 1925 (Francis 1990).

Although protection measures were instituted in the 1930s, whaling continued in Antarctic waters. In the period from 1951 to 1971, Soviet whalers alone took at least 3,335 southern right whales, in addition to smaller numbers of southern blue and humpback whales, despite a total ban on the commercial exploitation of all three

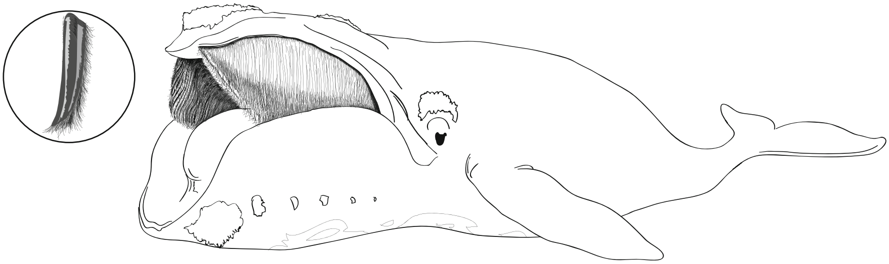


**Fig. 13.7** Southern right whale showing baleen. The side of the baleen plate facing the inside of the mouth has a feathery fringe that helps retain krill (Drawing © Regina Eisert)

species (Tormosov et al. 1998). In the period from 1900 to 2000, an estimated total of two million whales were killed in the Southern Hemisphere (Clapham and Baker 2008); Antarctic blue whales may have been reduced to less than 1 % of their original abundance (Branch et al. 2007). Large cetaceans are a central component of Southern Ocean food webs, and the severe reduction in their numbers and total biomass is likely to have a significant impact on the Antarctic ecosystem (Ainley et al. 2010). It has been suggested that the removal of great whales has created a krill surplus, resulting in increased populations of seals and penguins, but the long-term consequences for the Antarctic ecosystem are likely to be complex and resistant to simple extrapolation (Laws 1977; Ainley et al. 2010) (Fig. 13.8).

Six species of odontocetes occur regularly in the Southern Ocean south of 60°S. The largest of these is the sperm whale, which is often grouped with the large mysticetes into the great whales, and suffered similar exploitation. The sperm whale was hunted for blubber oil and the oil extracted from its spermaceti organ (a specialised structure believed to be involved in echolocation), and commercial sperm whaling only ceased following an International Whaling Commission (IWC) moratorium in 1988 (Whitehead 2008). The sperm whale is the only odontocete that undertakes migrations comparable in distance to mysticete migrations. Only male sperm whales migrate to the Antarctic to feed (Hooker 2008; Kasamatsu and Joyce 1995). Sperm whales hold the mammalian world record for dive duration (138 min) (Watwood et al. 2006; Box 13.2). Among Antarctic odontocetes, sperm whales are the least numerous, followed by, in ascending order of abundance, killer whales, hourglass dolphins, pilot whales and beaked whales. As their name suggests, odontocetes have teeth rather than baleen, and do not filter-feed but capture discrete

**Fig. 13.8** Antarctic minke whale (With kind permission from Steven Profaizer/NSF)

prey including cephalopods, fish, and marine mammals and birds. Many odontocetes have a homodont dentition consisting of a large number of uniformly shaped, often conical, teeth (Fig. 13.9). Sperm whales only have teeth in their lower jaw. The medium-sized beaked whales (family Ziphiidae) have few or no functional teeth and feed primarily on squid that they ingest by suction (Heyning and Mead 1996).

Little is known about the breeding grounds of Antarctic odontocetes. It is possible that killer whales remain, and perhaps give birth, at high latitudes in winter (Gill and Thiele 1997), but conclusive data are lacking. In contrast to the short, intensive lactation in mysticetes, odontocetes have prolonged lactation periods

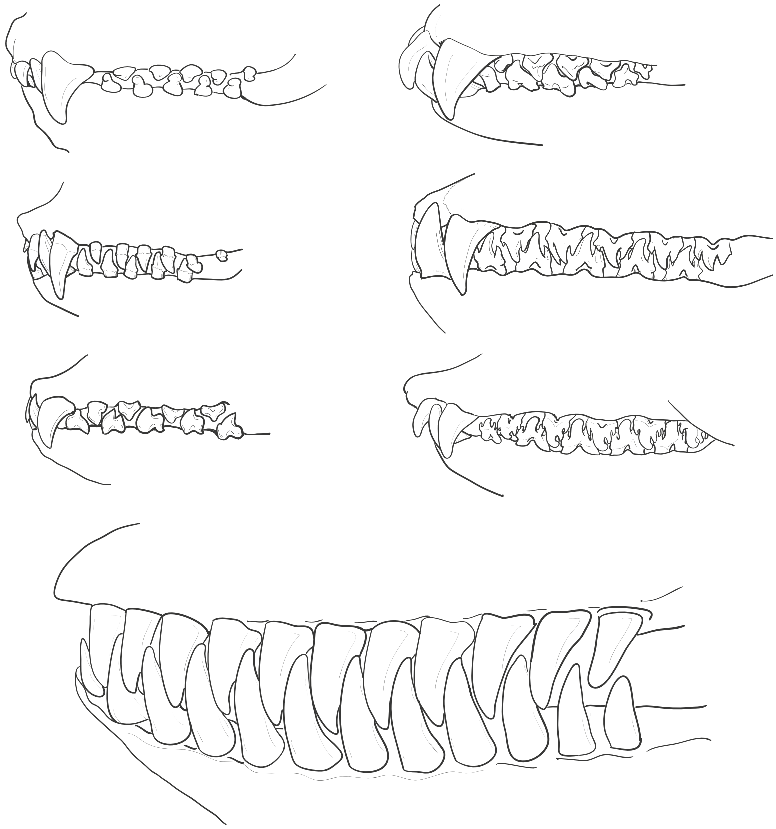


**Fig. 13.9** Dentition in Antarctic megafauna: Dentition of Antarctic seals (*top* three rows) in order of increasing complexity. The killer whale (*bottom*) has a homodont (uniform) dentition typical of the delphinids. (*top left*) southern elephant seal, (*top right*) Antarctic fur seal, (*middle left*) Ross seal, (*middle right*) Weddell seal, (*bottom left*) leopard seal and (*bottom right*) crabeater seal. Squid feeders (*top row*) and generalist feeders (*middle row*) have relatively simple cheek teeth, whereas krill feeding (*bottom row*) is associated with complex postcanines that are used to strain prey out of the water (Drawing © Regina Eisert)

lasting between 32 and 100 weeks, and mothers are thought to feed throughout the lactation period. Even after calves start taking solid food, they may remain dependent for several years. In some species (e.g. killer whales and pilot whales), grown calves remain in family groups for their entire lives (Berta et al. 2006; Oftedal 1997; Hooker 2008; West et al. 2007).

By far the best-studied toothed whale in Antarctica is the orca or killer whale (Fig. 13.13). Killer whales in Antarctica occur as three different ecotypes (A, B, C), i.e. as sympatric (occurring in the same place) populations that do not interbreed, prefer different prey and differ in morphological and behavioural traits (Shirihai 2008). It has been suggested that these ecotypes represent in fact different species (LeDuc et al. 2008). Killer whales of type A are thought to specialise in preying on Antarctic minke whales, type B preys mainly on seals and penguins, and type C, the Ross Sea killer whale, prefers fish (Ainley et al. 2009; Pitman and Ensor 2003).

While mysticetes do not have particularly large brains in relation to body mass (Thewissen et al. 2011; Marino 2007; Marino et al. 2006; Knudsen et al. 2002), odontocetes are highly encephalised, i.e. they possess complex, highly evolved brains that are large relative to body mass. The family Delphinidae, which includes the killer whale, are more highly encephalised than non-human primates (Marino 1998). Killer whales form matrilineal social groups (pods) of five to ten individuals led by a dominant female, and practice complex cooperative hunting tactics for capturing seals or penguins resting on ice floes (Visser et al. 2008; Pitman and Durban 2012) (Fig. 13.10).

**Fig. 13.10** A C-type killer whale spyhopping (With kind permission from Jaime Ramos/NSF)

**Box 13.5: Acoustic Ecology**

Sound travels faster in water than in air, and all marine mammals have a more or less complex vocal repertoire. Proposed functions of vocalisations include communication, courtship displays, territorial defence, stunning of prey through sound and echolocation. Echolocation has evolved independently in several mammalian lineages, most notably in bats and odontocetes, and is defined as the detection and identification of objects using sound generated by an animal (Berta et al. 2006). Because resolution improves with increasing frequency, measured in Hertz (Hz), sounds used in echolocation are in the ultrasonic range, i.e. above the human auditory range. Killer whales can detect sounds to at least 120 kHz (Au 2008), whereas the upper limit for humans is 15–20 kHz.

Pinnipeds and mysticete whales do not possess the specialised morphological features associated with echolocation. At breeding colonies, mother-pup pairs recognise each other by their calls. This is particularly important in the Antarctic fur seal, which needs to find her pup on returning from extended foraging trips. The underwater vocalisations of Antarctic pinnipeds are sufficiently distinct so that presence and distribution of species can be monitored using hydrophone arrays (Van Opzeeland et al. 2010). One proposed function of underwater calls is sexual advertising by adult males. While Ross, crabeater and leopard seals do not form breeding aggregations, Weddell seal males defend maritories (underwater territories, from Latin mare: sea) beneath fast-ice breeding colonies and frequently vocalise while patrolling underneath the ice. With 14 distinct call types, Weddell seals have the most complex vocal repertoire of any Antarctic pinniped. The otherworldly quality of their calls has inspired recording artists and filmmakers, such as Werner Herzog (Encounters at the End of the World 2008), and even an underwater opera (Anon. 2011).

## 13.3 Adaptation: How to Survive at the End of the World

Adaptations are morphological, physiological or behavioural features or mechanisms that species acquire through evolution and that enable them to thrive in a particular environment. Antarctica represents one of the most challenging environments on Earth. The birds and mammals of Antarctica need to cope with extreme cold, extreme seasonality and dependence on the marine environment for food. Thus specific adaptations in Antarctic megafauna primarily relate to thermoregulation, i.e. the ability to maintain body temperature, and seasonality, or the ability to synchronise life history with radical seasonal changes.

### *13.3.1 Thermoregulation*

Birds and mammals are endotherms, i.e. they maintain and defend a set core body temperature against environmental fluctuations. Successful maintenance of body temperature depends on four factors: the physical environment, generation of body heat (thermogenesis), insulation and behavioural mechanisms. Unlike fish (Chap. 14) and some invertebrates such as the New Zealand alpine weta, *Hemideina maori* (Wharton 2011), birds and mammals do not possess antifreeze compounds. In a cold environment, animals lose heat by conduction (heat flux through direct contact), convection (heat transmission by a fluid, gas or liquid), radiation (emission of long-wave infrared radiation) and evaporation (heat consumed by the phase transition of water from liquid to vapour). Total heat loss depends on the interplay between environmental factors and the animal's adaptive response (Fig. 13.11).

#### 13.3.1.1 Physical Environment

Antarctica is not just the coldest, it is also the windiest place on Earth, and the majority of Antarctic megafauna feed while immersed in the icy waters of the Southern Ocean. Both air flow and immersion greatly increase the rate of heat loss. In still air, a boundary layer forms next to the body surface and this layer retards the loss of heat, since air has low thermal conductivity. Heat loss in still air is primarily through conduction and radiation (Willmer et al. 2005). Movement of air disrupts the boundary layer and changes the mode of heat loss from conduction to the more

**Fig. 13.11** Penguin feet on ice are an example of conductive heat loss (With kind permission from Patrick Rowe/NSF)

rapid convective heat loss, thus creating wind chill. For penguins or seals immersed in icy water, heat loss is accelerated for two reasons: water is a much better conductor of heat than air, and movement through the medium (water) increases convective heat loss.

**Box 13.6: Controlling Heat Loss**

Thermoregulatory adaptations of the vascular system include countercurrent heat exchangers (CCHE) and selective perfusion. CCHE (Fig. 13.15) consist of arteries surrounded by veins, often in form of a rete (net), and occur in flippers and fins of whales (Scholander and Schevill 1955), seals (Kvadsheim and Folkow 1997) and penguins (Thomas and Fordyce 2008), in the legs of seabirds (Irving and Krog 1955) and the tongue of baleen whales (Heyning and Mead 1997). Hot arterial blood flowing from the core to the periphery transfers heat to cold venous blood returning to the core (Fig. 13.16), with the net effect of retaining body heat. Heat loss can be adjusted by selective perfusion of the periphery and CCHE (Kvadsheim and Folkow 1997). By decreasing peripheral perfusion (vasoconstriction) and increasing flow through CCHE, heat is conserved, the temperature of body layers decreases from core to periphery and is coldest in appendages. This regional heterothermy reduces the temperature difference between the skin and the environment and thereby minimises heat loss, which is proportional to the temperature gradient (Irving and Krog 1955). Loss of excess heat is achieved by increasing peripheral blood flow (vasodilation) and the proportion of venous return that bypasses CCHE. In contrast to fur and feathers, which are external to the vascular system, insulation provided by blubber can be controlled by changes in perfusion and a concomitant increase in the proportion of heat loss by convection (i.e. blood flow). Species that rely primarily on fur or feathers for insulation have areas of bare skin, so-called heat windows, that can be perfused to prevent overheating (Schmidt-Nielsen 1997) (Fig. 13.12).

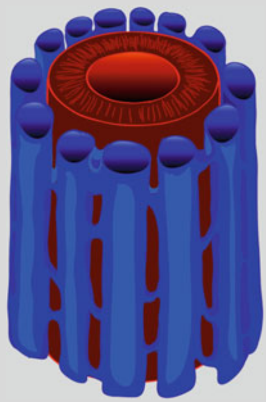


**Fig. 13.12** Countercurrent heat exchanger (*CCHE*) consisting of a central artery (*red*) surrounded by a rete, or net, of thin-walled veins (*blue*)


**Fig. 13.13** Principle of countercurrent heat exchangers (CCHE). Heat flows from arteries (A) to adjacent veins (V), thus reducing convective heat loss to the body periphery

Sunlight intensity greatly affects the net balance of radiative heat flux in polar animals. When exposed to sunlight, animals experience a net gain of radiation as they are absorbing more heat than they are radiating. Evaporative heat loss in Antarctic megafauna occurs primarily from the respiratory surfaces. Most of Antarctica is a polar desert, i.e. a low-humidity environment, and this accelerates water loss and evaporative cooling.

Mammals and birds possess respiratory turbinates, convoluted structures in the nose (Fig. 13.13) or beak that slow down air flow and promote countercurrent exchange of heat and water (Hillenius 1994). Water vapour in exhaled air condenses inside the turbinates, whereas inspired air is warmed and enriched with moisture before entering the lungs, thus conserving both heat and water (Van Valkenburgh et al. 2004).

#### 13.3.1.2 Thermogenesis

To maintain body temperature, heat production (thermogenesis) has to equal heat loss. Metabolic activity such as cellular respiration, digestion and muscular exertion (exercise) always results in heat production, because the chemical reactions that constitute metabolism proceed with less than 100 % efficiency. The higher an animal's metabolic rate, the higher is the rate of heat production.

On a seasonal time scale, animals can increase their metabolic rate and insulation to improve cold tolerance (Chaffee and Roberts 1971). To acutely increase heat production, an animal can engage in shivering, i.e. rapid reflexive muscular contractions that produce little net movement, and non-shivering thermogenesis (NST) (Willmer et al. 2005). NST takes place in specialised adipose tissue that is highly vascularised to allow transport of heat generated there to the rest of the body, and contains a high density of mitochondria, the sites of cellular energy production (Blix et al. 1975). In NST, oxidation of fat (an exergonic metabolic reaction that results in a net release of energy) is decoupled from its usual metabolic goal of ATP production, so that most of the energy produced by the oxidation reaction is released as heat. Both shivering and NST require substrates (fatty acids, glucose), and therefore increase food requirements. Newborn seals use both shivering and NST (Blix et al. 1979). Birds appear to be capable of NST, but it occurs in muscle rather than adipose tissue (body fat), and the exact mechanism remains to be clarified (Teulier et al. 2010).

#### 13.3.1.3 Insulation

The primary means of thermal insulation in many mammals and birds is a layer of subcutaneous adipose tissue, which may be complemented to a varying degree by hair, fur or feathers. Adipose tissue consists of adipose cells containing large quantities of triglycerides (fat) that are embedded in a matrix of connective tissue; in marine mammals, the subcutaneous fat layer is called blubber. Fat is a very good insulator. The fluidity of fat at low temperatures depends on its constituent fatty acids and increases with the degree of unsaturation and increasing length of the fatty acid carbon chain. Consider, for example, the behaviour of butter (mostly saturated) versus plant oils (mostly unsaturated) in the fridge. Marine animals and birds manipulate the composition of subcutaneous fat to maintain adequate fluidity of cellular membranes and flexibility of outer body layers (Willmer et al. 2005; Chaffee and Roberts 1971). In addition, body fat also serves as an important energy store to buffer seasonal fluctuations in food supply and energy demand, for example during reproduction. The high fat content of whales, seals and penguins motivated their exploitation for oil rendered from subcutaneous adipose stores.

While cetaceans rely on blubber alone to keep warm, seals and birds possess additional insulation in the form of hair, fur or feathers. Penguins and other Antarctic birds have down covered by outer contour feathers. Down consists of specialised feathers that trap a large amount of air, which provides the actual insulation. Penguin chicks and other nestling birds are kept warm by a thick layer of down (Taylor 1986). While down is an efficient insulator, it is delicate and only works while dry, and rain can cause hypothermia and significant mortality among penguin chicks (Boersma 2008). In adult birds, down is protected from wetting and abrasion by stiff outer feathers, which the birds waterproof by applying oily secretions from the uropygial gland (preening).

Seals possess both hair and blubber as insulation but the relative importance of the two components varies with species. Otariid seals have a thinner layer of blubber than phocid seals but very dense fur that consists of a soft undercoat protected by outer guard hairs, analogous to down and contour feathers in penguins. Phocid seals have a relatively sparse, hairy coat devoid of an undercoat, and rely mostly on a thick layer of blubber for insulation. The only otariid breeding in Antarctica, the Antarctic fur seal, is limited to a more northern range than the phocid seals, suggesting that its insulation may be less effective than that of the phocid seals. In addition to the insulation provided by the skin and associated structures (blubber, feathers, fur), Antarctic megafauna have vascular adaptations that regulate the flow of heat from the core to the periphery (Box 13.6). Seal pups are born with very little body fat, 3–7 % of body mass compared to 20–40 % in adults (Oftedal et al. 1996). Pups must accumulate blubber as quickly as possible (Box 13.4) to reduce heat loss, particularly in severe weather, and in preparation for swimming and diving. The same applies to penguin chicks (Raccurt et al. 2008). Newborn seals have a special woolly neonatal coat called lanugo (Fig. 13.14) that has a similar function to the down of penguin chicks, and is effective only when dry (Blix et al. 1979).

**Fig. 13.14** Anteroposterior view of a seal skull showing the maxilloturbinal bones (© Regina Eisert)

Seal pups and chicks moult their neonatal lanugo and down, respectively, and acquire an adult coat prior to weaning/fledging. Adult seals and birds moult annually to replace worn fur or feathers and to maintain their insulating properties. During moult, the animal's insulation is compromised due to loss of fur or feathers, and because the skin is heavily perfused with blood to support the growth of new feathers or hair. Thus moulting animals generally remain on land or ice and fast (Boily 1995).

#### 13.3.1.4 Behavioural Mechanisms

Examples for behavioural adaptations to cold include use of shelter, migration and huddling with conspecifics (Ancel et al. 1997). Antarctic petrels nest in burrows or crevices that provide protection against the cold as well as predation during the summer breeding season. During the winter, most Antarctic birds and mammals do not remain in the deep south, but move further north to varying degrees. Migration may be motivated by additional factors, such as ice cover or lack of food. Two notable exceptions to the annual exodus north are the Weddell seal and the emperor penguin. Emperor penguins form large colonies on sea ice where eggs are incubated by male penguins during the Antarctic winter (Cherry-Garrard 2010; Pinshow et al. 1976). The male emperor penguin fasts from the arrival at the colony in March to April for about 115 days until hatching and the return of the female. To reduce heat loss, incubating males huddle in dynamic groups of thousands of penguins that slowly circulate to regulate intra-huddle temperature and balance the exposure of each individual (Ancel et al. 1997; Le Maho et al. 1976; Gilbert et al. 2006). This strategy greatly decreases the thermoregulatory costs of huddling penguins relative to isolated penguins (Gilbert et al. 2008). Because emperor penguins must fast while incubating, the reduction in energetic costs achieved by huddling is an essential adaptation that allows males to survive the entire incubation period while living off their body stores.

Penguin chicks also use huddling as a thermoregulatory strategy. Penguins and small seabirds keep their offspring warm by physical contact (brooding). In snow petrels, the resting metabolic rate of hatchlings doubles after brooding ceases at 5 days of age due to an increase in the amount of energy devoted to thermoregulation (Weathers et al. 2000).

### *13.3.2 Extreme Seasonality*

Radical seasonal changes in climate, photoperiod and biological productivity are characteristic of the polar regions. The Antarctic summer presents a brief window of opportunity for Antarctic animals to complete activities that depend on transient resources (e.g. fattening on krill) and/or require relatively mild climatic conditions (e.g. moulting, raising offspring). The timing of birth or hatching is constrained by incompletely developed thermoregulation of neonates (Blix and Steen 1979), as severe weather (blizzards, rain) may cause high mortality among young animals. Another constraint is the need for offspring to acquire sufficient skills and body reserves before the onset of the next polar winter. Reproduction in Antarctic megafauna is tightly synchronised to take advantage of favourable conditions, and timing of reproduction may vary with latitude in parallel to climatic gradients. For example, Weddell seals in McMurdo Sound (77°S 168°E) pup 6–8 weeks later than Weddell seals on Signy Island at 60°S (Croxall and Hiby 1983).

Breeding cycles of Antarctic megafauna generally fit into either a summer breeding cycle (volant seabirds and penguins except the genus Aptenodytes), or an annual cycle (seals, whales, emperor penguin). The only exception is the mostly subantarctic king penguin, which breeds asynchronously and completes two breeding cycles per 3-year period (Gauthier-Clerc et al. 2002). In phocid seals, the synchronisation of parturition (pupping) is achieved by delayed implantation. Female seals mate around the time they wean their pup (3–7 weeks after giving birth), i.e. 10–11 months prior to the next pupping period. Because this is longer than the time required for embryonic development, the implantation of the blastocyst (very early embryo) is delayed for a variable period so that pups are born around the same time every year (Sandell 1990; Smith 1966). Weddell seal pups that are born either early or late in the pupping season have reduced chances of survival (Thomas and DeMaster 1983).

The young of Antarctic seals and birds are relatively precocial (Bucher et al. 1986), meaning that they are born in an advanced state of maturity, which gives them a head start. Despite this advantage, rapid growth and fattening of newborn young is essential both for their immediate survival in extreme cold and to ensure their survival once parental care ceases (fledging/weaning) (Raccurt et al. 2008). Antarctic fulmarine petrels complete their entire breeding cycle from mating to fledging in 90–99 days and chick growth rates are up to twice as fast as predicted (Hodum and Weathers 2003). Seal pups triple to quadruple their birth mass during the lactation period. A large proportion of weight gain is fat that provides insulation as well as an energy reserve for the immediate post-weaning period while pups acquire the necessary skills to become effective marine hunters.

Extreme cold reduces the efficiency of growth, as dietary energy and substrates that could be used for growth are instead used to maintain body temperature (Kgwatalala and Nielsen 2004; Lopez et al. 1991). Rapid postnatal growth and fattening of Antarctic offspring is made possible by parental provisioning of high-energy, readily digestible food in the form of concentrated milks (seals, whales) or partially digested prey (birds) that in petrels is supplemented with stomach oil. Male emperor penguins produce a milk-like secretion from their crops that they feed to newly hatched chicks. A general difference in parental provisioning between birds and mammals is that the amount of food birds can deliver to chicks is limited by the stomach and crop capacity of the parent and associated transport costs, whereas milk is synthesised from already digested and assimilated substrates and is not subject to the same constraints (Boyd 1999). Antarctic petrels produce stomach oil that is fed to chicks. Stomach oil (Box 13.4) is functionally analogous to milk insofar as it represents a processed concentrate (stomach oil contains 5–35 times the energy of the original prey) and provides an easily digestible, high-energy substrate to the young. In Wilson's storm petrel, the smallest endotherm breeding in Antarctica, a typical feed of regurgitated prey given to chicks contains 42 % stomach oil by mass. Energy budgets calculated for chicks and adults indicate that Wilson's storm petrel could not breed successfully in the Antarctic without the ability to produce stomach oil (Obst and Nagy 1993).

Another important aspect of the life cycle of Antarctic megafauna is seasonal starvation. Three examples of seasonal starvation in Antarctic megafauna are the emperor penguin already mentioned, king penguin chicks, and lactating phocid seals. During incubation, emperor penguins lose 35–40 % of their initial body mass (Ancel et al. 1997; Pinshow et al. 1976). King penguin chicks overwinter in their natal colony and are rarely or never fed for 5 months before completing their growth and fledging the following summer (Olsson and Brodin 1997). During their 23-day lactation, southern elephant seals catabolise on average 35 % of their initial body mass, consisting of 60 % of their body fat and 22 % of their body protein (Carlini et al. 2004).

In contrast to involuntary starvation caused by random catastrophic events, seasonal starvation is adaptive in the context of life-history patterns of Antarctic mammals and birds and has evolved in response to predictable seasonal food shortages, or to accommodate essential activities that conflict with foraging (breeding, lactation, brooding, moult). Among mammals and birds, the ability to tolerate starvation is positively correlated with body fat content (Cuendet et al. 1975; Elia et al. 1999; Goodman et al. 1984) and species size. With increasing body mass, the capacity to accumulate body stores increases faster (proportional to body mass to the power of 1.0) than the animal's energy expenditure (proportional to body mass to the power of 0.75). Thus larger species have larger reserves, both absolutely and relative to energy demand, and can tolerate longer periods without food (Oftedal 1993, 2000).

Seasonality also imposes limitations on scientific research. Antarctic megafauna are typically accessible only for a fraction of their life cycle (breeding, moult), and this enforced selectivity may severely distort our understanding of the life history of species. For example, the Ross seal was long considered to be a rare pack-ice seal, but satellite-linked instrumentation revealed that Ross seals only move into pack ice to breed and moult. The rest of the year, Ross seals forage in the open ocean, where they cannot be observed directly (Blix and Nordøy 2007).

## 13.4 Science and Antarctic Megafauna

Owing to its singular status as a continent dedicated to science, Antarctica has been called a natural laboratory. Antarctic megafauna has been the focus of scientific research from the earliest days of human exploration of Antarctica (Wilson 1907). Research on Antarctic megafauna continues to generate fascinating insights relevant not only to the polar regions, but of global significance.

### *13.4.1 Unique Solutions to Difficult Problems*

Antarctic megafauna is predominantly endemic (i.e. consists of species that occur nowhere else in the world) and represents a unique and fascinating species assemblage adapted to the cold, dry, icy and radically seasonal environment of Antarctica. Species that evolve in challenging environments frequently develop adaptations that represent an extreme end of the spectrum of physiological mechanisms found in all birds and/or mammals. Such extreme adaptations can advance scientific understanding, not only through demonstrating what is possible, but also by highlighting the limits of a given physiological process, such as hypoxia tolerance, thermoregulation, or the ability to rapidly mobilise body tissues during starvation.

### *13.4.2 Indicators of Change*

As a result of its geographical and ecological isolation, Antarctica remains comparatively unaffected by anthropogenic changes that have significantly modified most other terrestrial and marine ecosystems. High-latitude regions of the Southern Ocean present an opportunity to study the last relatively intact marine ecosystems on Earth (Halpern et al. 2008), although the impacts of whaling on Southern Ocean food webs are largely unknown. The absence of pervasive human modification in Antarctica also allows the quantification of ecological effects of naturally occurring oscillations in physical parameters, such as the El Niño-Southern Ocean (ENSO) cycle. This in turn permits the assessment and prediction of the effects of future climate change on the Antarctic ecosystem (Trathan et al. 2007). Because Antarctic megafaunal species occupy key positions in the food web as predators (seals, whales, penguins) and megaconsumers (baleen whales), they are central to this endeavour. Megafauna populations integrate the complex interactions of multiple ecosystem drivers and effectively act as ecosystem sentinels (Boersma 2008). Climate warming leading to a loss of ice and a greater incidence of liquid precipitation (rain, sleet) is a significant threat to immature seals and penguins, whose thermal insulation (down, lanugo) is only effective when dry.

### 13.4.3 Antarctic Megafauna Needs Science

Antarctic megafauna is protected by international agreements and through the establishment of protected areas. At the same time, there is considerable concern regarding the potential impact of fisheries for krill and Antarctic toothfish on Antarctic megafauna (Ainley and Siniff 2009; Ainley et al. 2009; Schiermeier 2010). While it was previously believed that removal of large whales produced a krill surplus, there is now considerable uncertainty regarding the magnitude of krill stocks and the sustainability of large-scale harvesting (Schiermeier 2010). Harvesting of Antarctic toothfish, *Dissostichus mawsoni*, is of concern because there are insufficient data regarding the dependence of Weddell seals (Fig. 13.15) and C-type killer whales on toothfish (Pinkerton et al. 2010). Clearly, effective protection and rational management of Antarctic megafauna can only occur on the basis of solid scientific knowledge, and understanding the ecological vulnerabilities and requirements is essential for identifying and mitigating potential threats. For example, during the breeding season, Antarctic megafauna may depend on a

**Fig. 13.15** Newborn Weddell seal with lanugo, next to its very fat mother (© Regina Eisert)

**Fig. 13.16** A Weddell seal with a large adult Antarctic toothfish it has brought to a hole in the sea ice near Scott Base (77.85° S, 166.75° E). Weddell seals hold the head of captured toothfish out of the water and then tear the fish apart by shaking it vigorously (often at the surface), possibly because the seal's dentition is relatively unsuited for handling large prey. Toothfish captured by seals are estimated to measure 1–1.5 m in length and weigh 20–50 kg (With kind permission from Sal Genovese)

relatively narrow range of prey (Trathan et al. 2007). Because reproduction in Antarctic megafauna is characterised by high parental investment and tight seasonal synchronisation to use brief windows of opportunity, changes that delay offspring development or increase the cost of parental provisioning, such as decreased availability or quality of prey, may disproportionately decrease offspring survival and recruitment (Raccurt et al. 2008) (Fig. 13.16).

## References


Agnarsson I, May-Collado LJ (2008) The phylogeny of Cetartiodactyla: the importance of dense taxon sampling, missing data, and the remarkable promise of cytochrome b to provide reliable species-level phylogenies. Mol Phylogenet Evol 48:964–985

Ainley DG, Siniff DB (2009) The importance of Antarctic toothfish as prey of Weddell seals in the Ross Sea. Antarct Sci 21:317–327

Ainley DG et al (2003) Spatial and temporal variation of diet within a presumed metapopulation of Adelie Penguins. Condor 105:95–106

Ainley DG, Dugger KM, Toniolo V, Gaffney I (2007) Cetacean occurrence patterns in the Amundsen and southern Bellingshausen sea sector, Southern Ocean. Mar Mamm Sci 23:287–305

Ainley DG, Ballard G, Olmastroni S (2009) An apparent decrease in the prevalence of "Ross Sea killer whales" in the Southern Ross Sea. Aquat Mamm 35:335–347

Ainley D et al (2010) Impacts of cetaceans on the structure of Southern Ocean food webs. Mar Mamm Sci 26:482–498

Ancel A, Visser H, Handrich Y, Masman D, Le Maho Y (1997) Energy saving in huddling penguins. Nature 385:304–305

Andrews-Goff V, Hindell M, Patterson T, Charrassin J (2010) In 4th SCAR Open Science conference CD-ROM Abstract number 28, Buenos Aires, Argentina

Anon. (2011) Songs from the sea. Science 332:1134
Arnould JPY, Boyd IL, Rawlins DR, Hindell MA (2001) Variation in maternal provisioning by lactating Antarctic fur seals (*Arctocephalus gazella*): response to experimental manipulation in pup demand. Behav Ecol Sociobiol 50:461–466
Au WWL (2008) Echolocation. In: Perrin WF, Würsig BG, Thewissen JGM (eds) Encyclopedia of marine mammals. Academic, San Diego, pp 348–357
Baker SC, Barbraud C (2001) Food of the south polar skua *Catharacta maccormicki* at Ardery Island, Windmill Islands, Antarctica. Polar Biol 24:59–61
Baker CS et al (2010) Genetic evidence of illegal trade in protected whales links Japan with the US and South Korea. Biol Lett 6:647–650
Bannister JL (2008) Baleen whales (mysticetes). In: Perrin WF, Würsig BG, Thewissen JGM (eds) Encyclopedia of marine mammals. Academic, San Diego, pp 80–89
Beatty BL, Rothschild BM (2008) Decompression syndrome and the evolution of deep diving physiology in the Cetacea. Naturwissenschaften 95:793–801
Bennett KA, McConnell BJ, Fedak MA (2001) Diurnal and seasonal variations in the duration and depth of the longest dives in southern elephant seals (*Mirounga leonina*): possible physiological and behavioural constraints. J Exp Biol 204:649–662
Berta A, Sumich J, Kovacs KM (2006) Marine mammals: evolutionary biology, 2nd edn. Academic, San Diego
Blix AS, Nordøy ES (2007) Ross seal (*Ommatophoca rossii*) annual distribution, diving behaviour, breeding and moulting, off Queen Maud Land, Antarctica. Polar Biol 30:1449–1458
Blix AS, Steen JB (1979) Temperature regulation in newborn polar homeotherms. Physiol Rev 59:285–304
Blix AS, Grav HJ, Ronald K (1975) Brown adipose tissue and the significance of the venous plexuses in pinnipeds. Acta Physiol Scand 94:133–135
Blix AS, Grav HJ, Ronald K (1979) Some aspects of temperature regulation in newborn harp seal pups. Am J Physiol 236:R188–R197
Blix AS, Walloe L, Messelt EB, Folkow LP (2010) Selective brain cooling and its vascular basis in diving seals. J Exp Biol 213(15):2610–2616
Boersma PD (2008) Penguins as marine sentinels. Bioscience 58:597–607
Boily P (1995) Theoretical heat flux in water and habitat selection of phocid seals and beluga whales during the annual molt. J Theor Biol 172:235–244
Boness DJ, Bowen WD (1996) The evolution of maternal care in Pinnipeds. Bioscience 46:645–654
Bornemann H et al (2000) Southern elephant seal movements and Antarctic sea ice. Antarct Sci 12:3–15
Bost CA, Charrassin JB, Clerquin Y, Ropert-Coudert Y, Le Maho Y (2004) Exploitation of distant marginal ice zones by king penguins during winter. Mar Ecol Prog Ser 283:293–297
Bost CA et al (2009) The importance of oceanographic fronts to marine birds and mammals of the southern oceans. J Mar Syst 78:363–376
Boyd IL (1999) Foraging and provisioning in Antarctic fur seals. Behav Ecol 10:198–208
Boyd IL (2008) Antarctic marine mammals. In: Perrin WF, Würsig BG, Thewissen JGM (eds) Encyclopedia of marine mammals. Academic, San Diego, pp 42–46
Branch TA et al (2007) Past and present distribution, densities and movements of blue whales *Balaenoptera musculus* in the Southern Hemisphere and northern Indian Ocean. Mammal Rev 37:116–175
Brooke MD, Keith D, Rov N (1999) Exploitation of inland-breeding Antarctic petrels by south polar skuas. Oecologia 121:25–31
Bucher TL, Bartholomew GA, Trivelpiece WZ, Volkman NJ (1986) Metabolism, growth, and activity in Adélie and emperor penguin embryos. Auk 103:485–493
Burns JM, Kooyman GL (2001) Habitat use by Weddell seals and emperor penguins foraging in the Ross Sea, Antarctica. Am Zool 41:90–98

Carlini AR et al (2004) Lactation costs in southern elephant seals at King George Island, South Shetland Islands. Polar Biol 27:266–276

Casaux R, Barrera-Oro E (2006) Shags in Antarctica: their feeding behaviour and ecological role in the marine food web. Antarct Sci 18:3–14

Casaux R, Baroni A, Arrighetti F, Ramón A, Carlini A (2003) Geographical variation in the diet of the Antarctic fur seal *Arctocephalus gazella*. Polar Biol 26:753–758

Casaux R et al (2009a) Diet of the Leopard seal *Hydrurga leptonyx* at the Danco Coast, Antarctic Peninsula. Polar Biol 32:307–310

Casaux R, Carlini A, Corbalán A, Bertolin L, DiPrinzio CY (2009b) The diet of the Weddell seal *Leptonychotes weddellii* at Laurie Island, South Orkney Islands. Polar Biol 32:833–838

Chaffee RRJ, Roberts JC (1971) Temperature acclimation in birds and mammals. Annu Rev Physiol 33:155–202

Charbonnier Y, Delord K, Thiebot JB (2010) King-size fast food for Antarctic fur seals. Polar Biol 33:721–724

Cherel Y, Charrassin J-B, Handrich Y (1993) Comparison of body reserve buildup in prefasting chicks and adults of king penguins (*Aptenodytes patagonicus*). Physiol Zool 66:750–770

Cherry-Garrard A (2010) The worst journey in the world. Vintage Books, London

Clapham PJ, Baker SC (2008) Modern whaling. In: Perrin WF, Würsig BG, Thewissen JGM (eds) Encyclopedia of marine mammals. Academic, San Diego, pp 1239–1243

Cobley ND, Bell G (1998) Weddell seal (*Leptonychotes weddellii*) feeding on gentoo penguins (*Pygoscelis papua*). Mar Mamm Sci 14:881–883

Corkeron PJ, Connor RC (1999) Why do baleen whales migrate? Mar Mamm Sci 15:1228–1245

Costa DP, Trillmich F (1988) Mass changes and metabolism during the perinatal fast: a comparison between Antarctic (*Arctocephalus gazella*) and Galápagos fur seals (*Arctocephalus galapagoensis*). Physiol Zool 61:160–169

Croxall J, Hiby L (1983) Fecundity, survival and site fidelity in Weddell seals, *Leptonychotes weddelli*. J Appl Ecol 20:19–32

Croxall JP, Prince PA (1996) Cephalopods as prey. 1. Seabirds. Philos Trans R Soc Lond Ser B 351:1023–1043

Cuendet GS, Loten EG, Cameron DP, Renold AE, Marliss EB (1975) Hormone-substrate responses to total fasting in lean and obese mice. Am J Physiol 228:276–283

Culik BM et al (1996) Diving energetics in king penguins (Aptenodytes patagonicus). J Exp Biol 199:973–983

Davies WL (1939) The composition of the crop milk of pigeons. Biochem J 33:898–901

Dearborn JH (1965) Food of Weddell seals at McMurdo Sound, Antarctica. J Mammal 46:37–43

Eisert R, Oftedal OT (2009) Capital expenditure and income (foraging) during pinniped lactation: the example of the Weddell seal (*Leptonychotes weddellii*). In: Krupnik I, Lang MA, Miller SE (eds) Smithsonian at the poles: contributions to international polar year science – a Smithsonian contribution to knowledge. Smithsonian Institution Scholarly Press, pp 335–346

Eisert R et al (2005) Detection of food intake in a marine mammal using marine osmolytes and their analogues as dietary biomarkers. Mar Ecol Prog Ser 300:213–228

Elia M, Stubbs RJ, Henry CJK (1999) Differences in fat, carbohydrate, and protein metabolism between lean and obese subjects undergoing total starvation. Obes Res 7:597–604

Encounters at the End of the World. Directed by Herzog, W. Discovery Films, 2008

Erdmann ES, Ribic CA, Patterson-Fraser DL, Fraser WR (2011) Characterization of winter foraging locations of Adélie penguins along the Western Antarctic Peninsula, 2001–2002. Deep-Sea Res Part II-Top Stud Oceanogr 58:1710–1718

Falke K et al (1985) Seal lungs collapse during free diving: evidence from arterial nitrogen tensions. Science 229:556–558

Francis D (1990) A history of world whaling. Penguin, New York

Gauthier-Clerc M, Maho YL, Clerquin Y, Bost C-A, Handrich Y (2002) Seabird reproduction in an unpredictable environment: how King penguins provide their young chicks with food. Mar Ecol Prog Ser 237:291–300

Gelatt TS, Davis CS, Siniff DB, Strobeck C (2001) Molecular evidence for twinning in Weddell seal (*Leptonychotes weddellii*). J Mammal 82:491–499

Gelatt TS et al (2010) History and fate of a small isolated population of Weddell seals at White Island, Antarctica. Conserv Genet 11:721–735

Gilbert C, Robertson G, Le Maho Y, Naito Y, Ancel A (2006) Huddling behavior in emperor penguins: dynamics of huddling. Physiol Behav 88:479–488

Gilbert C, Blanc S, Le Maho Y, Ancel A (2008) Energy saving processes in huddling emperor penguins: from experiments to theory. J Exp Biol 211:1–8

Gill PC, Thiele D (1997) A winter sighting of killer whales (*Orcinus orca*) in Antarctic sea ice. Polar Biol 17:401–404

Goodman MN, Lowell B, Belur E, Ruderman NB (1984) Sites of protein conservation and loss during starvation: influence of adiposity. Am J Physiol 246:E383–E390

Hahn S, Ritz MS, Reinhardt K (2008) Marine foraging and annual fish consumption of a south polar skua population in the maritime Antarctic. Polar Biol 31:959–969

Hall-Aspland SA, Rogers TL (2004) Summer diet of leopard seals (*Hydrurga leptonyx*) in Prydz Bay, Eastern Antarctica. Polar Biol 27:729–734

Halpern BS et al (2008) A global map of human impact on marine ecosystems. Science 319:948–952

Handrich Y (1989a) Incubation water loss in king penguin egg. II. Does the brood patch interfere with eggshell conductance? Physiol Zool 62:119–132

Handrich Y (1989b) Incubation water loss in king penguin egg. I. Change in egg and brood pouch parameters. Physiol Zool 62:96–118

Heyning JE, Mead JG (1996) Suction feeding in beaked whales: morphological and observational evidence, vol 464 in Contributions in Science, Natural History Museum of Los Angeles County, pp 1–12

Heyning JE, Mead JG (1997) Thermoregulation in the mouths of feeding gray whales. Science 278:1138–1140

Hillenius WJ (1994) Turbinates in therapsids: evidence for Late Permian origins of mammalian endothermy. Evolution 48:207–229

Hodum PJ, Weathers WW (2003) Energetics of nestling growth and parental effort in Antarctic fulmarine petrels. J Exp Biol 206:2125–2133

Hooker SK (2008) Toothed whales, overview. In: Perrin WF, Würsig BG, Thewissen JGM (eds) Encyclopedia of marine mammals. Academic, San Diego, pp 1173–1179

Integrated Taxonomic Information System on-line database. http://www.itis.gov

Irving L, Krog J (1955) Temperature of skin in the Arctic as a regulator of heat. J Appl Physiol 7:355–364

Janes DN (1997) Energetics, growth, and body composition of Adélie penguin chicks, *Pygoscelis adeliae*. Physiol Zool 70:237–243

Jepson PD et al (2003) Gas-bubble lesions in stranded cetaceans. Nature 425:575–576

Kasamatsu F, Joyce GG (1995) Current status of odontocetes in the Antarctic. Antarct Sci 7:365–379

Kgwatalala PM, Nielsen MK (2004) Performance of mouse lines divergently selected for heat loss when exposed to different environmental temperatures. II. Feed intake, growth, fatness, and body organs 1. J Anim Sci 82:2884–2891

Knudsen GM, Mørk S, Øen EO (2002) A novel method for in situ fixation of whale brains. J Neurosci Methods 120:35–44

Kooyman MM, Kooyman GL (2009) The history of pinniped studies in Antarctica. Aquat Mamm 35:523–556

Kooyman GL, Ponganis PJ (1998) The physiological basis of diving to depth: birds and mammals. Annu Rev Physiol 60:19–32

Kvadsheim PH, Folkow LP (1997) Blubber and flipper heat transfer in harp seals. Acta Physiol Scand 161:385–395

Laws RM (1977) Seals and whales of the Southern Ocean. Philos Trans R Soc Lond B Biol Sci 279:81–96
Laws RM, Baird A, Bryden MM (2003) Breeding season and embryonic diapause in crabeater seals (*Lobodon carcinophaga*). Reproduction 126:365–370
Le Bohec C, Gauthier-Clerc M, Le Maho Y (2005) The adaptive significance of crèches in the king penguin. Anim Behav 70:527–538
Le Maho Y, Delclitte P, Chatonnet J (1976) Thermoregulation in fasting emperor penguins under natural conditions. Am J Physiol 231:913–922
LeDuc RG, Robertson KM, Pitman RL (2008) Mitochondrial sequence divergence among Antarctic killer whale ecotypes is consistent with multiple species. Biol Lett 4:426–429
Lequette B, Verheyden C, Jouventin P (1989) Olfaction in subantarctic seabirds: its phylogenetic and ecological significance. Condor 91:732–735
Littlepage JL, Pearse JS (1962) Biological and oceanographic observations under an Antarctic ice shelf. Science 137:679–681
Lopez J, Jesse GW, Becker BA, Ellersieck MR (1991) Effects of temperature on the performance of finishing swine: II. Effects of a cold, diurnal temperature on average daily gain, feed intake, and feed efficiency. J Anim Sci 69:1850–1855
Luque SP, Miller EH, Arnould JPY, Chambellant M, Guinet C (2007) Ontogeny of body size and shape of Antarctic and subantarctic fur seals. Can J Zool 85:1275–1285
Marino L (1998) A comparison of encephalization between odontocete cetaceans and anthropoid primates. Brain Behav Evol 51:230–238
Marino L (2007) Cetacean brains: how aquatic are they? Anat Rec 290:694–700
Marino L, Sol D, Toren K, Lefèvre L (2006) Does diving limit brain size in cetaceans? Mar Mamm Sci 22:413–425
Meir JU, Ponganis PJ (2009) High-affinity hemoglobin and blood oxygen saturation in diving emperor penguins. J Exp Biol 212:3330–3338
Moore MJ, Early GA (2004) Cumulative sperm whale bone damage and the bends. Science 306:2215
Nordøy ES (1995) Do minke whales (*Balaenoptera acutorostrata*) digest wax esters? Br J Nutr 74:717–722
Obst BS, Nagy KA (1993) Stomach oil and the energy budget of Wilson's storm-petrel nestlings. Condor 95:792–805
Obst BS, Nagy KA, Ricklefs RE (1987) Energy utilization by Wilson's storm petrel (*Oceanites oceanicus*). Physiol Zool 60:200–210
Oftedal OT (1993) The adaptation of milk secretion to the constraints of fasting in bears, seals and baleen whales. J Dairy Sci 76:3234–3246
Oftedal OT (1997) Lactation in whales and dolphins: evidence of divergence between baleen- and toothed-species. J Mammary Gland Biol Neoplasia 2:205–230
Oftedal OT (2000) Use of maternal reserves as a lactation strategy in large mammals. Proc Nutr Soc 59:99–106
Oftedal OT (2002) The origin of lactation as a water source for parchment-shelled eggs. J Mammary Gland Biol Neoplasia 7:253–266
Oftedal OT (2011) Milk of marine mammals. In: Fuquay JW, Fox PF, McSweeney PLH (eds) Encyclopedia of dairy sciences, vol 3. Academic, San Diego, pp 563–580
Oftedal OT, Boness DJ, Tedman RA (1987a) The behavior, physiology, and anatomy of lactation in the Pinnipedia. In: Genoways H (ed) Current mammalogy, vol 1. Plenum Press, New York, pp 175–245
Oftedal OT, Iverson SJ, Boness DJ (1987b) Milk and energy intakes of suckling California sea lion *Zalophus californianus* pups in relation to sex, growth, and predicted maintenance requirements. Physiol Zool 60:560–575
Oftedal OT, Boness DJ, Bowen DW (1988) The composition of hooded seal (*Cystophora cristata*) milk: an adaptation for postnatal fattening. Can J Zool 66:318–322

Oftedal OT, Bowen DW, Boness DJ (1993) Energy transfer by lactating hooded seals and nutrient deposition in their pups during the 4 days from birth to weaning. Physiol Zool 66:412–436
Oftedal OT, Bowen WD, Boness DJ (1996) Lactation performance and nutrient deposition in pups of the harp seal, *Phoca groenlandica*, on ice floes off Southeast Labrador. Physiol Zool 69:635–657
Olsson O, Brodin A (1997) Changes in king penguin breeding cycle in response to food availability. Condor 99:994–997
Payne MR (1977) Growth of a fur seal population. Philos Trans Roy Soc Lond Ser B 279:67–79
Piantadosi CA, Thalmann ED (2004) Pathology: whales, sonar and decompression sickness. Nature 428. doi:10.1038/nature02527a
Pinkerton MH, Bradford-Grieve JM, Hanchet SM (2010) A balanced model of the food web of the Ross Sea, Antarctica. CCAMLR Sci 17:1–31
Pinshow B, Fedak M, Battles D, Schmidt-Nielsen K (1976) Energy expenditure for thermoregulation and locomotion in emperor penguins. Am J Physiol 231:903–912
Pitman RL, Durban JW (2010) Killer whale predation on penguins in Antarctica. Polar Biol 33:1589–1594
Pitman RL, Durban JW (2012) Cooperative hunting behavior, prey selectivity and prey handling by pack ice killer whales (*Orcinus orca*), type B, in Antarctic Peninsula waters. Marine Mammal Sci 28:16–36
Pitman RL, Ensor P (2003) Three forms of killer whales (*Orcinus orca*) in Antarctic waters. J Cetac Res Manag 5:131–139
Plötz J (1986) Summer diet of Weddell seals (*Leptonychotes weddellii*) in the Eastern and Southern Weddell Sea, Antarctica. Polar Biol 6:97–102
Prévost J, Vilter V (1962) Histologie de la sécretion oesophagienne du Manchot Empereur. In: Proceedings of the 13th International Ornithologic Congress, vol 2, American Ornithologists' Union, pp 1085–1094
Quin D (1998) Antarctica. Audio CD, Miramar
Raccurt M et al (2008) Growing in Antarctica, a challenge for white adipose tissue development in Adélie penguin chicks (*Pygoscelis adeliae*). Am J Physiol Regul Integr Comp Physiol 295: R1671–R1679
Reich CM, Arnould JPY (2007) Evolution of Pinnipedia lactation strategies: a potential role for α-lactalbumin? Biol Lett 3:546–549
Ribic CA et al (2011) Water masses, ocean fronts, and the structure of Antarctic seabird communities: putting the eastern Bellingshausen Sea in perspective. Deep-Sea Res Part I-Top Stud Oceanogr 58:1695–1709
Roby DD, Taylor JRE, Place AR (1997) Significance of stomach oil for reproduction in seabirds: an interspecies cross-fostering experiment. Auk 114:725–736
Rudmose Brown RN (1915) Part XIII. The seals of the Weddell Sea: notes on their habits and distribution. In: Bruce WS (ed) Report on the scientific results of the voyage of the SY "Scotia". The Scottish Oceanographical Laboratory, Edinburgh
Sandell M (1990) The evolution of seasonal delayed implantation. Q Rev Biol 65:23–42
Sander K (2002) Ernst Haeckel's ontogenetic recapitulation: irritation and incentive from 1866 to our time. Ann Anat Anat Anz 184:523–533
Sato K et al (2002) Deep foraging dives in relation to the energy depletion of Weddell seal (*Leptonychotes weddelli*) mothers during lactation. Polar Biol 25:696–702
Schiermeier Q (2010) Ecologists fear Antarctic krill crisis. Nature 467:15
Schmidt-Nielsen K (1997) Animal physiology. Adaptation and environment, 5th edn. Cambridge University Press, Cambridge
Scholander PF, Schevill WE (1955) Counter-current vascular heat exchange in the fins of whales. J Appl Physiol 8:279–282
Schulz TM, Bowen DW (2005) The evolution of lactation strategies in pinnipeds: a phylogenetic analysis. Ecol Monogr 75:159–177

Shirihai H (2008) The complete guide to Antarctic wildlife. Birds and marine mammals of the Antarctic continent and the Southern Ocean, 2nd edn. Princeton University Press, Princeton
Siniff DB (1991) An overview of the ecology of Antarctic seals. Am Zool 31:143–149
Smith M (1966) Studies on the Weddell seal (*Leptonychotes weddellii* Lesson) in McMurdo Sound, Antarctica. Ph.D. thesis, University of Canterbury
Southwell C, Kerry K, Ensor P, Woehler E, Rogers T (2003) The timing of pupping by pack-ice seals in East Antarctica. Polar Biol 26:648–652
Staniland IJ et al (2010) Geographical variation in the behaviour of a central place forager: Antarctic fur seals foraging in contrasting environments. Mar Biol 157:2383–2396
Stirling I (1969) Ecology of the Weddell seal in McMurdo Sound, Antarctica. Ecology 50:573–586
Stonehouse B (1953) The emperor penguin *Aptenodytes forsteri* Gray. I. Breeding behaviour and development. Falkland Islands Depend Surv Sci Rep 6:1–33
Stonehouse B (1956) The king penguin of South Georgia. Nature 178:1424–1426
Taylor JRE (1986) Thermal insulation of the down and feathers of pygoscelid penguin chicks and the unique properties of penguin feathers. Auk 103:160–168
Testa J (1994) Over-winter movements and diving behavior of female Weddell seals (*Leptonychotes weddellii*) in the southwestern Ross Sea, Antarctica. Can J Zool 72:1700–1710
Teulier L, Rouanet J-L, Letexier D, Romestaing C, Belouze M, Rey B, Duchamp C, Roussel D (2010) Cold-acclimation-induced non-shivering thermogenesis in birds is associated with upregulation of avian UCP but not with innate uncoupling or altered ATP efficiency. J Exp Biol 213:2476–2482
Thewissen JGM, George J, Rosa C, Kishida T (2011) Olfaction and brain size in the bowhead whale (*Balaena mysticetus*). Mar Mamm Sci 27:282–294
Thiele D, Gill PC (1999) Cetacean observations during a winter voyage into Antarctic sea ice south of Australia. Antarct Sci 11:48–53
Thomas J, DeMaster D (1983) Parameters affecting survival of Weddell seal pups (*Leptonychotes weddelli*) to weaning. Can J Zool 61:2078–2083
Thomas DB, Fordyce RE (2008) The heterothermic loophole exploited by penguins. Aust J Zool 55:317–321
Thomas J, Moss CF, Vater M (2004) Echolocation in bats and dolphins. The University of Chicago Press, Chicago
Thompson MB, Goldie KN (1990) Conductance and structure of eggs of Adélie penguins, *Pygoscelis adeliae*, and its implications for incubation. Condor 92:304–312
Thor G, Low M (2011) The persistence of the snow petrel (*Pagodroma nivea*) in Dronning Maud Land (Antarctica) for over 37,000 years. Polar Biol 34:609–613
Todd F (1988) Weddell seal preys on chinstrap penguin. Condor 90:249–250
Tormosov DD et al (1998) Soviet catches of southern right whales Eubalaena australis, 1951–1971. Biological data and conservation implications. Biol Conserv 86:185–197
Trathan PN, Forcada J, Murphy EJ (2007) Environmental forcing and Southern Ocean marine predator populations: effects of climate change and variability. Philos Trans R Soc B 362:2351–2365
Tyler C (1965) A study of the egg shells of the Sphenisciformes. Proc Zool Soc London 147:1–19
van Franeker JA, Creuwels JCS, van der Veer W, Cleland S, Robertson G (2001) Unexpected effects of climate change on the predation of Antarctic petrels. Antarct Sci 13:430–439
Van Opzeeland I et al (2010) Acoustic ecology of Antarctic pinnipeds. Mar Ecol Prog Ser 414:267–291
Van Valkenburgh B, Theodor J, Friscia A, Pollack A, Rowe T (2004) Respiratory turbinates of canids and felids: a quantitative comparison. J Zool 264:281–293
Visser IN et al (2008) Antarctic peninsula killer whales (*Orcinus orca*) hunt seals and a penguin on floating ice. Mar Mamm Sci 24:225–234

Ward AM, Hunt A, Maslanka M, Brown C (2001) Nutrient composition of American flamingo crop milk. In: Edwards MS, Lisi KJ, Schlegel ML, Bray RE (eds) Proceedings of the AZA Nutrition Advisory Group 4th Conference on Zoo and Wildlife Nutrition, pp 187–193

Warham J (1977) The incidence, functions and ecological significance of petrel stomach oils. Proc N Z Ecol Soc 24:84–93

Watwood SL, Miller PJO, Johnson M, Madsen PT, Tyack PL (2006) Deep-diving foraging behaviour of sperm whales (*Physeter macrocephalus*). J Anim Ecol 75:814–825

Weathers WW, Gerhart KL, Hodum PJ (2000) Thermoregulation in Antarctic fulmarine petrels. J Comp Physiol B 170:561–572

Weidinger K (1998) Effect of predation by skuas on breeding success of the Cape petrel *Daption capense* at Nelson Island, Antarctica. Polar Biol 20:170–177

West KL et al (2007) Effect of lactation stage and concurrent pregnancy on milk composition in the bottlenose dolphin (*Tursiops truncatus*). J Zool 273:148–160

Wharton DA (2011) Cold tolerance of New Zealand alpine insects. J Insect Physiol 57:1090–1095

Whitehead H (2008) Sperm whale *Physeter macrocephalus*. In: Perrin WF, Würsig BG, Thewissen JGM (eds) Encyclopedia of marine mammals. Academic, San Diego, pp 1091–1097

Willmer P, Stone G, Johnston I (2005) Environmental physiology of animals, 2nd edn. Blackwell Publishing, Oxford

Wilson EA (1907) II. Aves. National Antarctic Expedition, 1901–4, vol II, Zoology, Vertebrata

Wright KLB, Pichegru L, Ryan PG (2011) Penguins are attracted to dimethyl sulphide at sea. J Exp Biol 214:2509–2511

Zelenitsky DK, Therrien F, Ridgely RC, McGee AR, Witmer LM (2011) Evolution of olfaction in non-avian theropod dinosaurs and birds. Proceedings of the Royal Society B

# Chapter 14
# Surviving in the Cold

## Invertebrates and Fish in Antarctica

**Crystal Lenky and Bill Davison**

**Abstract** To survive in Antarctica, animals must be tolerant of a wide range of environmental conditions. These include extremely strong winds, the state of water (whether it is liquid or solid) and extreme seasonality, which affects food supply and results in prolonged periods of light or darkness. The Antarctic continent and its surrounding oceans are cold, and animals that are successful must be adapted to survive at extreme temperatures. Terrestrial animals must withstand great daily and seasonal temperature changes, and any adaptations are influenced by the animal's immediate environment. Daytime summer temperatures on north-facing rock surfaces can reach over 20 °C, while these same rocks in winter can fall to below −40 °C. On a daily basis, terrestrial temperatures in summer can fluctuate by more than 30 °C. By contrast, animals living in the sea have a very constant temperature regime, with temperatures in the Ross Sea at minus 1.9 °C year round (Hunt et al., Antarc Sci 15(3):333–338, 2003). This chapter focuses on ectotherms, animals whose body temperatures match environmental temperature. Endotherms such as penguins and seals, which can regulate their body temperature, also require adaptations for life in Antarctica (Chap. 10), but these are mainly related to staying at a constant, warm body temperature and involve blubber, fur and feathers; similar to what is required by their more northerly cousins.

**Keywords** Freeze avoidance • Freeze tolerance • Anhydrobiosis • Antifreeze glycoproteins (AFGPs) • Osmolytes • Ectotherm

C. Lenky
Gateway Antarctica, University of Canterbury, Christchurch, New Zealand
e-mail: crystal.lenky@gmail.com

B. Davison (✉)
School of Biological Sciences, University of Canterbury, Christchurch, New Zealand
e-mail: bill.davison@canterbury.ac.nz

 
D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_14

## 14.1 Surviving on Land

Antarctica's terrestrial fauna is species poor and dominated by invertebrates (animals that lack a backbone). The most common invertebrates are arthropods (flies, spiders and beetles), micro-arthropods (mites and springtails) and micro-invertebrates (nematode worms and tardigrades) (Fig. 14.1).

Terrestrial environments are divided into three broad ecological zones: the subantarctic, maritime and continental Antarctica (Fig. 14.2). Moving south from

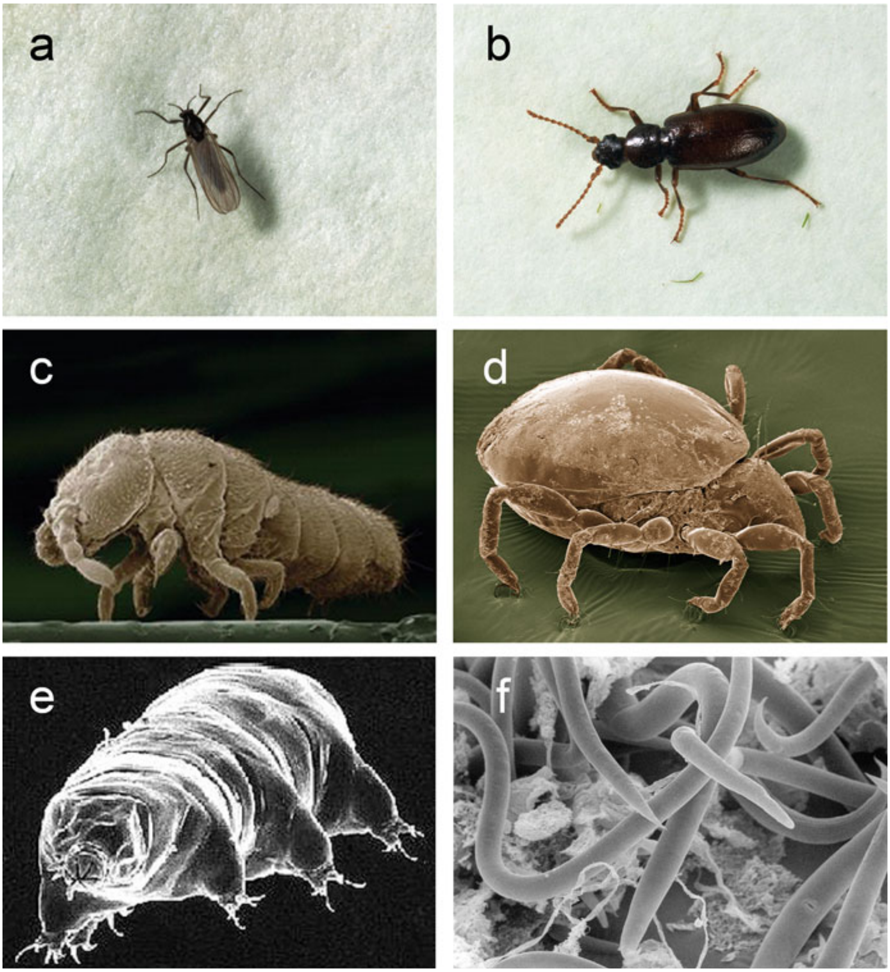



**Fig. 14.1** From *left* to *right*, *top* to *bottom*: A fly (unidentified species), beetle (*Hydromedion sparsutum*), springtail (*Cryptopygus antarcticus*), mite (*Alaskozetes antarcticus*), tardigrade and nematode (*Panagrolaimus davidi*) (With kind permission from BAS, University of Waikato, David Wharton)

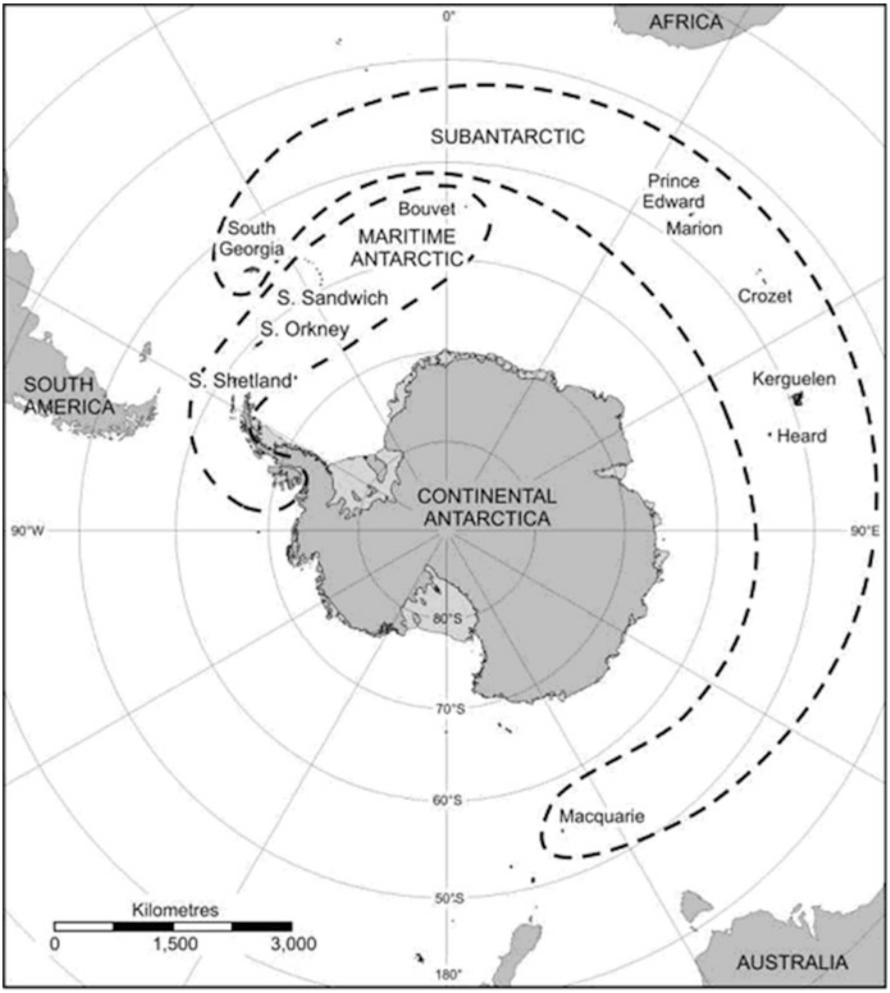



**Fig. 14.2** Terrestrial biogeographic regions within Antarctica (With kind permission from SCAR 2009)

one zone to the next, the diversity and abundance of the invertebrate fauna decrease as the animals are required to cope with increasingly extreme environmental stresses. Those species that have adopted strategies for life in maritime and continental Antarctica are considered here. The maritime region is relatively warm and moist and is strongly influenced by the surrounding ocean. Mean summer air temperatures are above 0 °C and rarely fall below −15 °C in winter (Block 1994). These conditions support the growth of lichens, moss and even two species of flowering plants (Chap. 11). The food web here is more complex than in continental Antarctica, with some higher insects colonising the area, and mites (Acari) and springtails (Collembola) being the dominant arthropods. By contrast, continental Antarctica is colder and drier and invertebrate animals are restricted to ice-free ground and rock faces. Mites and springtails are present but are less abundant than soil nematodes and tardigrades (also known as water bears).

Survival in Antarctic terrestrial environments is related to water and its state (Kennedy 1993). On land, water can change to ice very quickly and in summer this can happen several times per day. An active animal is typically about 70 % water. Within the cells of most animals this water must be in a liquid state because ice crystals destroy cell membranes, killing the cells. For much of the year, air temperature in Antarctica is below the freezing point of water and Antarctic animals must find ways of coping with the constant threat of ice. In ice-free areas of Antarctica, terrestrial organisms must also cope with the additional stress of dehydration.

Three main strategies are used by arthropods and other invertebrates to avoid the risk of tissue freezing: freeze avoidance or supercooling, freeze tolerance and anhydrobiosis.

### 14.1.1 Freeze Avoidance: Supercooling of Animals

Freeze-intolerant species are unable to survive if ice forms within their tissues. Species that are exposed to sub-zero temperatures with little or no contact with water can avoid freezing by maintaining their body fluids in a liquid state below their normal freezing point. This is known as supercooling and is a common survival strategy for many terrestrial arthropods. The supercooling point is usually equivalent to the lower lethal temperature (the temperature below which the animal will freeze and not survive). The temperature of an insect is measured using a thermocouple, a device consisting of wires of two different metal alloys that are fused together at both ends, and which produce a voltage that is proportional to the difference in temperatures between the two ends. The supercooling point is measured by cooling at a constant rate of 1 °C per minute (Salt 1961). Supercooling points are usually lower in the winter and higher in summer. Springtails and mites both use the freeze-avoidance strategy (Box 14.1).

Freezing occurs through nucleation, the process of water molecules coming together around ice nucleators to form an ice crystal. Ice nucleators can be classified into two categories: external origin, such as food particles and dust, and internal origin, such as extracellular proteins and lipoproteins. By removing sources of ice nucleation, arthropods can supercool to as low as −30 °C before freezing occurs. They do this by emptying food material from the gut at the onset of winter, removing lipoprotein ice nucleators from the haemolymph (fluid compartment in arthropods) or by having a cuticle that repels water, thus avoiding ice nucleation from external sources (Cannon and Block 1988).

In order to survive at even lower temperatures, freeze-avoiding insects employ two mechanisms to enhance supercooling. The first is the production of low molecular weight molecules such as polyols (alcohols) and sugars that act as cryoprotective compounds. These compounds reduce the supercooling point through their colligative (water-binding) properties by taking up space in a solution (Block 1990). Species differ in the types of compounds they use. For example, the continental Antarctic springtail, *Cryptopygus sverdrupi*, accumulates mainly glycerol (Somme 1986) while the maritime Antarctic springtail, *C. antarcticus*, uses glycerol, mannitol and trehalose (Somme and Block 1982). The widely distributed maritime Antarctic mite, *Alaskozetes antarcticus*, accumulates glycerol and ribitol (Young and Block 1980). In spring, when conditions are suitable for foraging, the insects must remove most of the molecules which potentially makes them susceptible to a sudden cold spell.

The second is the production of high molecular mass compounds called thermal hysteresis proteins which act as antifreezes in a non-colligative manner. Thermal hysteresis proteins attach to ice crystals which prevent other water molecules from attaching to them, thus preventing their growth (Block 1990). Thermal hysteresis proteins also occur in freeze-tolerant species, and help to stabilise the body fluids of supercooled insects. These proteins are similar to the antifreeze proteins and glycoproteins that are found in the blood of Antarctic fish, discussed below.

**Box 14.1: Freezing-Intolerant Arthropods**

Freezing is not an option for these insects because at sub-zero temperatures they would be completely frozen, including their intracellular water. For these insects, the survival strategy is freeze avoidance. The freezing point of body fluids is determined by the number of molecules dissolved in it, so the freezing point can be lowered by increasing the number of molecules.

Primitive herbivorous insects called collembolans, or springtails, derive their common name from the long fork-like ‘spring’ or furcula found on the underside of their abdomens. All are very small, about 1 mm long. *Gomphiocephalus hodgonsi* is endemic to Southern Victoria Land, and is the dominant springtail found in the McMurdo region. It is present in the McMurdo Dry Valleys, an area where winter temperatures can get down to −50 °C or lower. *Gomphiocephalus hodgonsi* survives here by loading its body fluids with glycerol (a polyol) as well as the sugars glucose and trehalose. In order to stay fluid, concentrations of these molecules must be high to depress its supercooling point which has been shown to range from −28.3 to 35.4 °C (Sinclair and Sjursen 2001).

*Alaskozetes antarcticus* is an oribatid mite (a mite that lives in the soil) which is widely distributed throughout maritime Antarctica. It is about 1 mm long and weighs only 200–300 μg. In order to survive winter temperatures down to −30 °C, *Alaskozetes antarcticus* accumulates glycerol and ribitol (Young and Block 1980). It is often encased in ice but survives by secreting a waxy cuticle.

### *14.1.2 Freeze Tolerance: Forming Ice in the Body*

Freeze-tolerant species are those that can survive varying degrees of ice formation inside their bodies, and include some species of arthropods and nematodes. Most freeze at fairly high sub-zero temperatures. This prevents supercooling and allows the cells to adjust to ice formation within the body over periods of hours to days (Storey and Storey 1988).

Like their freeze-avoiding counterparts, freeze-tolerant insects produce sugars and polyols which increase the solute concentration of cells, prevent ice formation and reduce dehydration by increasing the proportion of unfreezable water (Cannon and Block 1988). In contrast to freeze-avoiding insects that try to rid their body of ice-nucleating agents, insects that can freeze produce proteins or lipoproteins in their haemolymph that promote ice crystal formation. Ice nucleators work at relatively high temperatures, just below the freezing point of water, by mimicking growing ice crystals, which encourages true ice to form around them. By restricting these nucleators to the extracellular fluid, the insect ensures that the ice builds up only outside its cells.

There are limitations to freezing as a survival strategy. The insects must freeze at a high sub-zero temperature and will undergo numerous freeze-thaw cycles throughout a winter. The amount of ice present in the insect is related to the temperature, so as temperature falls, the amount of ice increases to a maximum at which point cell damage occurs and the animal will die. The amount of the animal's body water that can freeze ranges from 40 to 60 %.

The flightless midge, *Belgica antarctica*, inhabits penguin colonies on the northern parts of the Antarctic Peninsula where temperatures do not get particularly cold. Growing up to 6 mm long, it is the largest terrestrial animal on the continent, and it is flightless probably because if it could fly it would get blown away. The larvae live in wet, guano-laden low-lying regions of penguin colonies and live for at least 2 years, surviving a full winter. The adults are relatively short lived. Their job is to reproduce as quickly as possible and lay the next generation of eggs in the guano. The adults are found only during the summer and are not especially tolerant of cold conditions, dying if temperatures get below −5 °C (Lee et al. 2006). In contrast, the larvae can survive down to almost −20 °C, a feat achieved by allowing extracellular (outside the cells) ice to form in their blood and in the fluids surrounding their cells. If ice forms within the cells, the larvae will die. The survival of a freezing event requires ice to form slowly and at a relatively high temperature. If the insect's body becomes too cold too quickly there is the danger of the animal snap freezing, which then causes cells to freeze.

The freezing ability of the midge larvae changes with the seasons, so midges frozen in summer will die when the temperature decreases to −10 °C. During autumn, the insects undergo a process called cold hardening and during winter they can survive down to −20 °C (Lee et al. 2006) (Box 14.2).

**Box 14.2: A Remarkable Worm**

As a general rule, animals cannot simply freeze. However, there is a single animal worldwide that is able to do this. The small nematode worm, *Panagrolaimus davidi*, is endemic to continental Antarctica, and freezing solid is simply one of several strategies it uses to survive freezing conditions. Eighty-two per cent of its water can freeze, which is higher than the 65 % of most freeze-tolerant animals (Storey and Storey 1988), and freezing occurs within 0.21 s. It is the only animal able to survive intracellular freezing (freezing of the cells themselves) (Wharton and Ferns 1995). *Panagrolaimus davidi* can survive temperatures as low as −80 °C (Wharton and Brown 1991). At the moment we do not know how it does this, although there is a great deal of interest in discovering how it survives because of the potential for cryogenic work (Wharton 2003).

### *14.1.3 Anhydrobiosis: Surviving the Cold and Dry*

Anhydrobiosis is a survival strategy used by nematodes and tardigrades in order to survive a combination of desiccation (extreme water stress) and extremely low temperatures. Anhydrobiosis involves the animal entering a dormant (inactive) state and losing up to 95 % of its body water. In this dehydrated state, the animal can survive for several years, becoming active again only when it is immersed in liquid water (Somme 1996).

The McMurdo Dry Valleys are one of the most extreme environments on Earth, often referred to as a cold desert, and comprise one of the largest ice-free areas (~4,000 km$^2$) in Antarctica. Organisms living in this environment must cope with freezing temperatures as well as desiccation. The average annual air temperature is −20 °C, while the summer average is near 0 °C. In winter, temperatures can drop to −50 °C. Annual precipitation is less than 100 mm (as snow) and being ice-free, water is limited to areas of snow and glacial melt streams during the short summer (Fountain et al. 1999). Despite this extreme environment, soil invertebrates, including nematodes and tardigrades, are able to survive by employing an anhydriobiotic survival strategy.

#### 14.1.3.1 Nematodes

Three species of nematodes live in water in the spaces between soil particles in the McMurdo Dry Valleys: *Scottnema lindsayae*, *Eudorylaimus antarcticus* and *Plectus murrayi* (Fig. 14.3).

A nematode is determined to be in anhydrobiosis when it is coiled, while an uncoiled nematode is considered to be active or dead at the time of sampling. The

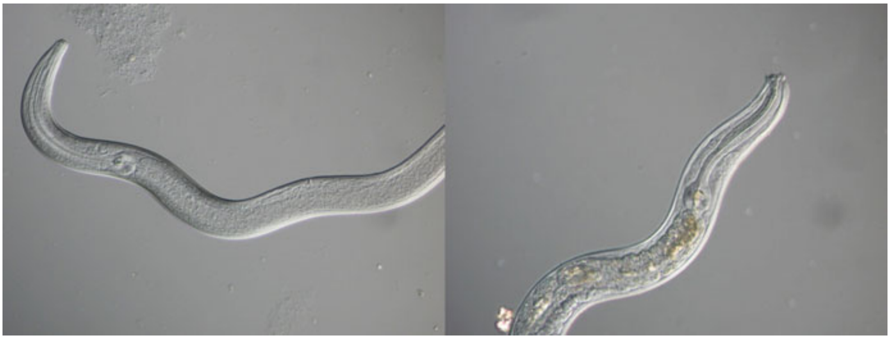


**Fig. 14.3** *Plectus murrayi* (*left*) and *Scottnema lindsayae* (*right*) (With kind permission from David Wharton)

percentage of nematodes in the coiled state increases with decreasing soil moisture (Treonis et al. 2000).

#### 14.1.3.2 Tardigrades

Tardigrades are distributed throughout maritime and continental Antarctica. During dehydration, tardigrades withdraw their legs into their bodies, forming a tun (barrel) configuration. By withdrawing their legs, tardigrades lessen the rate of evaporative loss by reducing the surface area available to the surrounding air, and protect their internal organs (Somme 1996). A waxy substance is also secreted which may help reduce water loss due to transpiration.

Little is known about the tardigrades' ability to survive low temperatures, but three species facing extremely harsh conditions on nunataks in Dronning Maud Land survived exposure for ca. 600 days at −22 °C (Somme and Meier 1995). It has also been shown that dehydrated tardigrades are better adapted to extremely cold temperatures, being able to survive at −180 °C (Somme and Meier 1995).

## 14.2 Surviving in the Sea

The freezing point of a fluid is related to the number of molecules dissolved in it. Seawater contains 1,000 milliosmoles (mOsm) of dissolved material (mainly sodium and chloride molecules) and has a freezing point of −1.9 °C. The body fluids of marine invertebrates are also about 1,000 mOsm, therefore they are iso-osmotic (same solute concentration) with seawater. Both seawater and invertebrates are at the edge of freezing, thus as long as the sea water is liquid, so are the animals. As winter approaches, sea ice forming on the surface of the water floats and acts as an insulator, keeping the water below it liquid and the animals alive. Ice tends to form on the seafloor (called anchor ice) in very shallow waters, and this kills any invertebrates living there. As a consequence, water shallower than about 15 m has very little life, and most Antarctic marine invertebrate fauna live in relatively deep water. Antarctic invertebrates do not have any special adaptations for surviving changes to temperature, but do have biochemical adaptations that allow their enzymes to function in these extreme conditions.

### 14.2.1 Fish

Fish are different from marine invertebrates in that they have evolved adaptation mechanisms. When the waters around Antarctica first cooled millions of years ago, most of the resident fish died out, leaving only fish adapted for living in deep water, plus a special group known as the notothenioids (Perciformes, Notothenioidei). Today the notothenioids make up almost all of the shallow-water fish, around a third of all fish known from Antarctic waters, and form about 90 % of the biomass (Eastman 2005).

The blood of Antarctic fish contains very high levels of salts (600 mOsm, mainly as sodium chloride) compared with a temperate water fish (350 mOsm). This is still only two thirds the salinity of seawater, and fish blood will freeze at −1 °C, which is not a stable situation for an animal living in water at −1.9 °C. Fish will frequently come into contact with ice and some (e.g. the crypopelagic fish *Pagothenia borchgrevinki*) use under-ice habitats such as the platelet ice layer to forage for food and escape predators. Sodium chloride is not able to solely depress the freezing point of body fluids, so Antarctic fish produce antifreeze molecules (Fig. 14.4).

**Fig. 14.4** The cryopelagic fish *Pagothenia borchgrevinki* is termed cryopelagic because it lives in shallow water immediately below sea ice. Because of this it is constantly surrounded by ice crystals and requires high levels of antifreeze proteins in its blood to keep it from freezing (With kind permission from Victoria Metcalf)

#### 14.2.1.1 Antifreeze Glycoproteins (AFGPs)

Antifreeze molecules are not simple chemicals but are glycopeptides, small protein molecules with extra sugar molecules attached, known as antifreeze glycoproteins (AFGPs). They are made of repeating triplets of amino acids (alanine – alanine – threonine) with a dissacharide (sugar) linked to threonine (Fig. 14.5). There are eight differently sized glycoproteins (AFGPs 1–8) depending on the number of repeats of the tripeptide backbone, thus allowing different antifreeze properties. The antifreeze proteins do not prevent the start of the freezing process, but instead act on developing ice crystals to stop them from growing. They act by adsorbing (adhering) onto the surface of a growing ice crystal in the blood of the fish, altering its surface chemistry (making it look less like a crystal) and inhibiting its growth (DeVries 1983). Ice must already be present for this process to work. Endogenous (internal) ice is found in the gastrointestinal tract as a result of fish ingesting ice-laden seawater and food. What is not currently known is what happens to these arrested ice crystals in the fish blood as they cannot simply be allowed to accumulate. One current idea is that the spleen (part of the fish's immune system) detects the crystals as foreign and removes them from the circulation (Evans et al. 2011).

The antifreezes appear to be a modified form of the gene that codes for a digestive enzyme. They are produced by the pancreas, secreted into the gut, absorbed across the intestinal wall into the blood stream and distributed throughout the body (Cheng et al. 2006). These antifreeze proteins have a remarkable ability to reduce the freezing point of fish tissues, working at very low concentrations, but act to reduce the freezing point only by around 1.5 °C. This is exactly what is required, as this lowers the freezing point to −2.5 °C, and by that point the seawater surrounding it will have frozen.

Constant production of antifreeze proteins is metabolically expensive and so Antarctic fish alter their antifreeze concentrations depending on where they live.

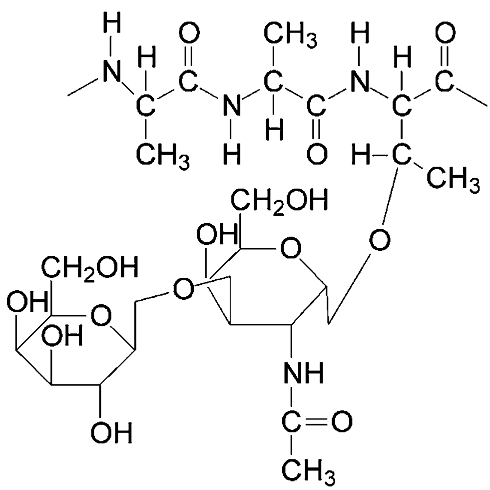


**Fig. 14.5** Hydorgen (*H*), nitrogen (*N*), oxygen (*O*) and carbon (*C*) forming a repeating structural unit of alanine – alanine – threonine with attached dissacharide, as found in the antifreeze glycopeptides isolated from Antarctic notothenioid fish

Animals such as *P. borchgrevinki* that live in shallow water and are likely to encounter ice crystals have the highest levels of antifreeze glycoproteins in their blood, while deeper-water fish such as *Trematomus loennbergii* have low levels. Increasing the water temperature reduces antifreeze concentrations (Jin and DeVries 2006).

#### 14.2.1.2 Organic Molecules

Some fish contain the organic compound trimethylamine N-oxide (TMAO). TMAO levels in cold-water fishes are greater than those from temperate regions, suggesting TMAO may play a role in protecting against freezing (Raymond 1998, Raymond and DeVries 1998). Marine fishes are unable to synthesise TMAO and therefore acquire it through their diet. TMAO assists in maintaining the cells in osmotic equilibrium with the blood, and helps to reduce the freezing point of body fluids, although this may not be its only role. Most data on TMAO come from northern polar fishes and little is known about the function of TMAO in Antarctic fishes. Among Antarctic species, the toothfish *Dissostichus mawsoni* has the highest concentrations of muscle (153.9 mmol $kg^{-1}$) and serum (93.7 mmol $l^{-1}$) TMAO (Raymond and DeVries 1998).

## 14.3 Climate Change

As a result of global climate change, the environment of the Antarctic Peninsula is one of the fastest changing systems in the world. Will rising temperatures alter the distribution of animals around Antarctica? In the short term, a temperature increase will not affect the distribution of terrestrial animals because they are already exposed to fluctuating temperatures, but it will affect how they live. For example, there is evidence that the life cycle of the flightless midge on the Antarctic Peninsula is changing and that rather than having a larva that needs to spend two years growing into an adult, it is now completing its life cycle in a single year.

A major factor in this change is an increase in winter minimum temperatures because this allows the insect to be active longer, and face less extreme temperatures. A looming threat to Antarctic terrestrial animals comes from invasions by other species. Increased temperatures could allow invasions by animals currently excluded because they cannot survive in the extreme cold.

Changes to the marine environment pose more immediate risks. Antarctic marine animals are regarded as extreme stenotherms; they are adapted for life at an extreme, but stable temperature and are unable to tolerate even small changes. Water temperatures around the Peninsula have already increased by 1 °C and may be having effects on some marine life, such as the Antarctic scallop, *Adamussium colbecki*, which is unable to function at temperatures above 2 °C (Peck et al. 2006) (Chap. 12).

## References


Block W (1990) Cold tolerance of insects and other arthropods. Philos Trans R Soc B-Biol Sci 326 (1237):613. doi:10.1098/rstb.1990.0035

Block W (1994) Terrestrial ecosystems – Antarctica. Polar Biol 14(5):293–300

Cannon RJC, Block W (1988) Cold tolerance of microarthropods. Biol Rev Camb Philos Soc 63 (1):23–77. doi:10.1111/j.1469-185X.1988.tb00468.x

Cheng CHC, Cziko PA, Evans CW (2006) Nonhepatic origin of notothenioid antifreeze reveals pancreatic synthesis as common mechanism in polar fish freezing avoidance. Proc Natl Acad Sci U S A 103(27):10491–10496. doi:10.1073/pnas.0603796103

DeVries AL (1983) Antifreeze peptides and glycopeptides in cold-water fishes. Ann Rev Physiol 45:245–260

Eastman JT (2005) The nature of the diversity of Antarctic fishes. Polar Biol 28(2):93–107. doi:10.1007/s00300-004-0667-4

Evans CW, Gubala V, Nooney R, Williams DE, Brimble MA, Devries AL (2011) How do Antarctic notothenioid fishes cope with internal ice? A novel function for antifreeze glycoproteins. Antarct Sci 23(1):57–64. doi:10.1017/s0954102010000635

Fountain AG, Lyons WB, Burkins MB, Dana GL, Doran PT, Lewis KJ, McKnight DM, Moorhead DL, Parsons AN, Priscu JC, Wall DH, Wharton RA, Virginia RA (1999) Physical controls on the Taylor Valley ecosystem, Antarctica. Bioscience 49(12):961–971. doi:10.2307/1313730

Hunt BM, Hoefling K, Cheng CHC (2003) Annual warming episodes in seawater temperatures in McMurdo Sound in relationship to endogenous ice in notothenioid fish. Antarct Sci 15 (3):333–338. doi:10.1017/s0954102003001342

Jin YM, DeVries AL (2006) Antifreeze glycoprotein levels in Antarctic notothenioid fishes inhabiting different thermal enviroments and the effect of warm acclimation. Comp Biochem Physiol B Biochem Mol Biol 144(3):290–300. doi:10.1016/j.cbpb.2006.03.006

Kennedy AD (1993) Water as a limiting factor in the Antarctic terrestrial environment – a biogeographical synthesis. Arct Alp Res 25(4):308–315. doi:10.2307/1551914

Lee RE, Elnitsky MA, Rinehart JP, Hayward SAL, Sandro LH, Denlinger DL (2006) Rapid cold-hardening increases the freezing tolerance of the Antarctic midge Belgica antarctica. J Exp Biol 209(3):399–406. doi:10.1242/jeb.02001

Peck LS, Convey P, Barnes DKA (2006) Environmental constraints on life histories in Antarctic ecosystems: tempos, timings and predictability. Biol Rev 81(1):75–109. doi:10.1017/s1464793105006871

Raymond JA (1998) Trimethylamine oxide and urea synthesis in rainbow smelt and some other northern fishes. Physiol Zool 71(5):515–523

Raymond JA, DeVries AL (1998) Elevated concentrations and synthetic pathways of trimethylamine oxide and urea in some teleost fishes of McMurdo Sound, Antarctica. Fish Physiol Biochem 18:387–398

Salt RW (1961) Principles of insect cold-hardiness. Annu Rev Entomol 6:55. doi:10.1146/annurev.en.06.010161.000415

Sinclair BJ, Sjursen H (2001) Cold tolerance of the Antarctic springtail Gomphiocephalus hodgsoni (Collembola, Hypogastruridae). Antarct Sci 13(3):271–279

Somme L (1986) Ecology of *Cryptopygus sverdrupi* (Insecta, Collembola) from Dronning Maud Land, Antarctica. Polar Biol 6(3):179–184. doi:10.1007/bf00274881

Somme L (1996) Anhydrobiosis and cold tolerance in tardigrades. Eur J Entomol 93(3):349–357

Somme L, Block W (1982) Cold hardiness of Collembola at Signy Island, maritime Antarctic. Oikos 38(2):168–176. doi:10.2307/3544016

Somme L, Meier T (1995) Cold tolerance in Tardigrada from Dronning Maud Land, Antarctica. Polar Biol 15(3):221–224

Storey KB, Storey JM (1988) Freeze tolerance in animals. Physiol Rev 68(1):27–84

Treonis AM, Wall DH, Virginia RA (2000) The use of anhydrobiosis by soil nematodes in the Antarctic Dry Valleys. Funct Ecol 14(4):460–467. doi:10.1046/j.1365-2435.2000.00442.x

Turner J, Bindschadler R, Convey P, di Prisco G, Fahrbach E, Gutt J, Hodgson D, Mayewski P, Summerhayes C (eds) (2009) Antarctic climate change and the environment (ACCE): a contribution to the international polar year 2007–2008. Scientific Committee on Antarctic Research, Cambridge

Wharton DA (2003) The environmental physiology of Antarctic terrestrial nematodes: a review. J Comp Physiol B Biochem Syst Environ Physiol 173(8):621–628. doi:10.1007/s00360-003-0378-0

Wharton DA, Brown IM (1991) Cold-tolerance mechanisms of the Antarctic nematode *Panagrolaimus davidi*. J Exp Biol 155:629–641

Wharton DA, Ferns DJ (1995) Survival of intracellular freezing by the Antarctic nematode *Panagrolaimus davidi*. J Exp Biol 198(6):1381–1387

Young SR, Block W (1980) Some factors affecting metabolic rate in an Antarctic mite. Oikos 34 (2):178–185. doi:10.2307/3544180

# Part III
# Social Sciences and Humanities

# Chapter 15
# Polar Expeditions

## Historical and Social Aspects of Antarctic Exploration

**Ursula Rack**

**Abstract** The word Antarctica invokes many responses. In some people it brings to mind protection and conservation, some people are inspired to write plays, novels and symphonies, to paint or take pictures, and many think of the early scientists and adventurers who risked their lives exploring new territory. Antarctic exploration has a very complex history with many components: political, social, economic, scientific and relating to tourism. The following pages cover some of the less widely known historical aspects of expeditions to the frozen land.

**Keywords** Sealing and whaling • Heroic era • Polar expeditions • Hut life • Social history

## 15.1 The Beginnings

In order to balance Earth, Greek philosophers proposed a Southern Hemisphere continent as a counterpart to landmasses in the north. The Greeks thought this southern land would be plentiful, with special creatures and treasures, and the discovery of this fabulous place became an obsession.

Antarctica was first approached by European explorers in 1520 when Ferdinand Magellan (1480–1521) circumnavigated the world. He sailed through the South American Straits of Magellan and discovered Tierra del Fuego. Fifty-eight years later, Francis Drake (1540–1596) discovered the Drake Passage, a relatively narrow stretch of water between the South Shetland Islands and Cape Horn. Sometime later, in 1739, Jean-Baptiste Charles Bouvet de Lozier (1705–1786) discovered Bouvet Island, southwest of Cape Town, and was inspired to describe the penguins he saw as ducks with flippers. In the years 1768–1771, James Cook (1728–1779) explored Tierra del Fuego and searched for the Terra Australis Incognita; Yves-Joseph de Kerguélen-Trémarec (1734–1797) discovered Îles Kerguélen (south-east of Africa) in 1771–1772; and finally, in 1773, Cook reached 71°10′S, the closest

U. Rack (✉)
Gateway Antarctica, University of Canterbury, Christchurch, New Zealand
e-mail: ursula.rack@canterbury.ac.nz



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_15

point to Antarctica to that date, and also claimed South Georgia for Britain Headland (2009).

Terra Australis Incognita as such seemed not to exist, but Cook went so far south as to cross the Antarctic Circle and told of the richness of seals and whales in the southern regions. William Smith (1790–1847), a British merchant sea captain discovered the South Shetland Islands in 1819 and charted them for England. British and American sealers and whalers began arriving, but their discoveries were not well documented for commercial reasons, and it is difficult to say who saw certain islands or coastlines first (Landis 2001; Gurney 1996; Martin 1996; Rosove 2002).

Nationalism became of vital importance in the nineteenth century when the idea of nation states took place (Fig. 15.2). Commercial and national interests meant that many expeditions endeavoured to be the first to reach new territory and claim it for their country. Russia initially had no interest in the southern regions, instead concentrating on exploring the Arctic. However, Russia was interested in science and decided to organise an expedition to Antarctica under the leadership of Fabian Gottlieb von Bellinghausen (1778–1852) Raymond (2006) and Riffenburgh (2007). This expedition penetrated the Antarctic Circle several times in 1820, the first since Cook's crossing 47 years earlier. However, it is until the 1830s that the race for Antarctica really began as countries moved to claim sealing and whaling grounds in addition to land.

France sent Jules-Sebastian Cesar Dumont d'Urville (1740–1842) (Fig. 15.1), Britain sent James Clark Ross (1800–1862) and the Americans sent Charles Wilkes (1798–1877) to Antarctica to find the South Magnetic Pole. D'Urville and Wilkes sighted each other in Antarctica, but could not communicate as Wilkes disappeared into the fog leaving unresolved the question of who sighted the Antarctic continent first McGonical and Woodworth (2001).

## 15.2 Sealing and Whaling

Seal furs had special value for European trade with China, and Bellinghausen, Smith and many others were tasked with finding good sealing grounds. The seals were killed, their fur stripped, cleaned and put in barrels, and in some regions this harvesting brought their numbers almost to extinction (Chap. 20). Four years after the discovery of Deception Island in 1819, the population of seals was almost exterminated and not worth any further visits by sealers.

Dealing with seal furs was easy compared to processing whales. Whaling in Antarctic waters became important in the middle of the nineteenth century as northern waters were depleted (Krause and Rack 2006). In the Southern Ocean, whales were hunted in such high numbers that they too almost became extinct. The slow and readily identifiable baleen whales were easy to hunt, but tooth whales and pot or sperm whales were also targeted. Whale oil (also called blubber oil, fish oil or train oil) and the long baleen (whalebone) were essential to economies of the era.

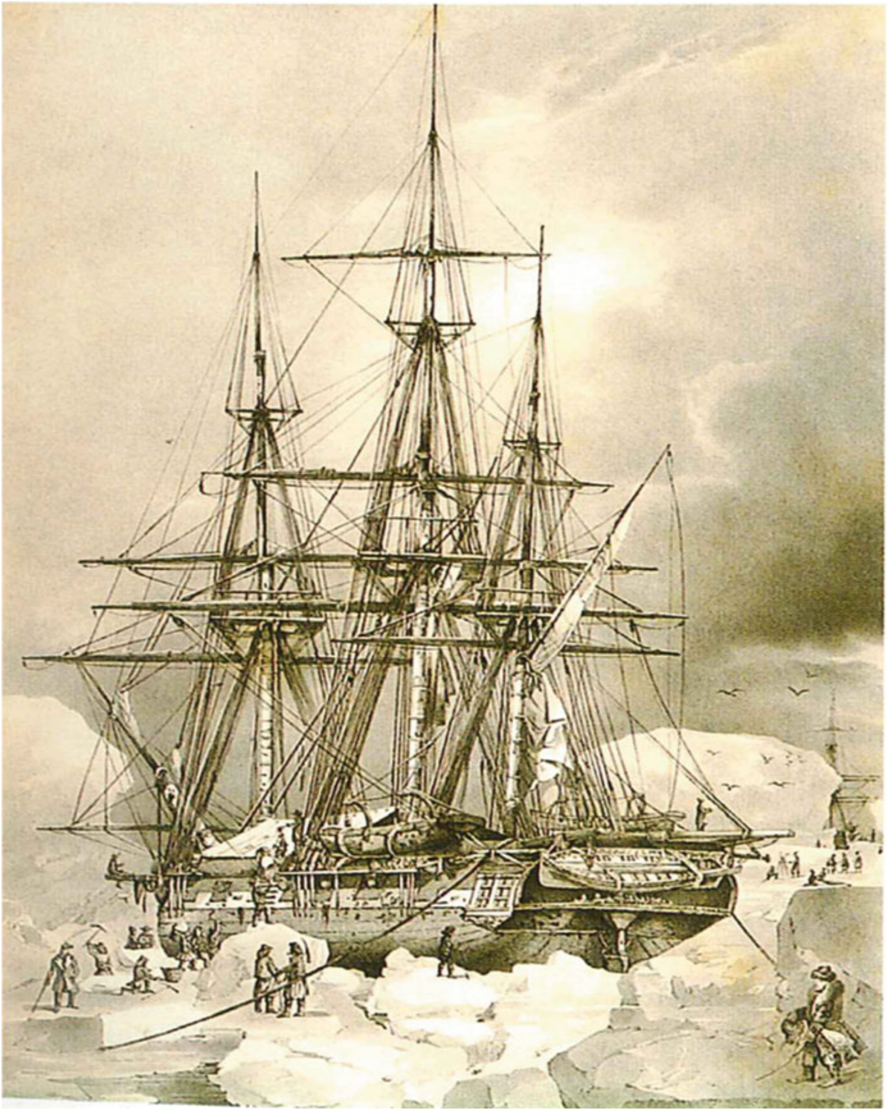


**Fig. 15.1** D'Urville's ship, the *Astrolabe*, trapped in ice. The scientists do their observations in the background and the crew is chopping ice to provide drinking water. The people in the picture do not wear the typical polar clothing we know today; their purpose was not to research the inner land and when they were not trapped in the ice, they were on shore only for a few hours to make their observations (Reprinted from Martin 1996)

Whalebone was used for corsets and umbrellas, and the whale blubber was taken ashore and cooked to extract the oil which was used mainly for lighting, for example in street lamps. In the 1870s, most vessels whaling around the Antarctic Peninsula were American, but they were soon joined by Germans and Norwegians and many islands around the Antarctic Peninsula were ‘re-discovered’ by different whalers. The Norwegians reformed whaling techniques by replacing small boats and hand harpoons with harpoon-cannons on faster and larger vessels that also allowed oil processing on board.

The oil became increasingly important for use in factory machines, and a German chemist found a way of producing edible margarine by hardening the whale oil and removing the fishy taste. Wilhelm Normann (1870–1939) described the procedure as it existed in 1901/1902, but with the beginning of the First World War margarine was able to be produced in larger amounts. Production of whale oil margarine became increasingly important before and during the Second World War, especially for the Germans.

Around the year 1900, the British took it upon themselves to organise the Antarctic whaling industry. They sold whaling licences, mostly to the Norwegians, and in 1904 they established a whaling station at Grytviken on South Georgia, led by Anton Carl Larsen (1860–1924).

Larsen was a Norwegian captain and was part of the Swedish Antarctic expedition of Otto Nordenskjöld in 1901–1903. He later became a British citizen. Larsen was well known for his experience and was a source of information for explorers when they stopped at the station on their way to Antarctica. The station in Grytviken was very successful and closed only recently in the 1960s.

In almost three decades of whaling, from 1900, 2.7 million whales were killed (Headland 1996, p. 44). In 1931, governments of whaling nations decided to reorganise whaling practices to guard against overharvesting, but it took until 1945 to establish the International Whaling Commission (IWC). In Māori culture the concept of whale meant plenty and richness; in recent history it has become a symbol for the extinction of endangered species and the destruction of a fragile ecosystem. The history of whaling is as complex and controversial as the ongoing discussion of present-day whaling.

## 15.3 Heroic Era (1893–1922)

The era of Antarctic heroes, symbolised by men such as Robert Falcon Scott (1868–1912) and Ernest Shackleton (1874–1922) (Reader’s Digest 1985, p. 292–299) is perhaps best known to the wider public. These men came to prominence early during the twentieth century, a time of profound national and international change. The development of industry and mass produced goods prompted the need for more commodities, and efficient transport of both goods and people became increasingly important. This required better and faster vessels, powered by steam rather than sail. The routes these boats travelled were taking them further south than ever before and needed to be trustworthy. Such issues motivated explorers and provided an economic incentive to obtain detailed knowledge of ocean conditions.

New rapidly evolving technologies and products, such as cars, planes, photographic equipment and new surveying techniques, required testing. Many

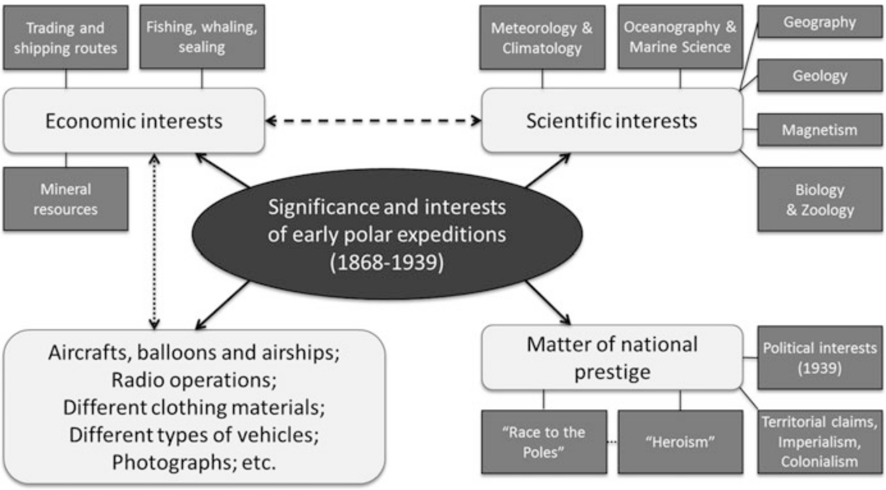



**Fig. 15.2** This graphic summarises interests in the polar regions and the factors driving Antarctic and Arctic exploration. The various drivers are often closely related (see the *dotted lines*) with scientific interests being strongly linked with the economy. Winning the race to key locations was important for national pride and identity (© Ursula Rack)

companies were interested in the quality of their products and wanted to know how they would perform in extreme conditions, including very low temperatures. This particularly applied to food, fibres and other materials, which were often supplied free for expeditions to use and test in the Antarctic environment.

With the rapid development of technologies came a change in social conditions. Increasingly people had the opportunity of good education and science was no longer a pastime of the aristocracy, privileged and wealthy. This resulted in a large community of natural scientists who asked testing questions that the traditional disciplines of theology and philosophy could not answer, and which provided the impetus for scientific exploration (Fig. 15.2).

International cooperation in the polar regions began in 1882/1883 with the first International Polar Year. The aim of the IPY was to survey temperature, airflow and wind to increase knowledge of the world's climate, weather and ocean conditions for shipping and other commercial interests. To successfully gather the data, cooperation between many nations was required. At that time the focus was on Arctic regions and only a few observations were made in Antarctica. However, 12 years later at the International Geographic Congress in London (1895) the idea of cooperation became important. Key supporters of this notion were Georg von Neumayer (1826–1909) from Germany and Sir Clements Markham (1830–1916) from the United Kingdom (Table 15.1).

It is notable that at a time of political tensions, especially between Germany and Britain, the scientists were keen to work together, with some recognising the possibility of peace between their countries. Nonetheless, nationalism was a delicate issue and became important for winning the 'race' to the poles. German

**Table 15.1** International expeditions from 1899 to 1905

| Time | Expedition leader | Ship | Nation |
|---|---|---|---|
| 1899–1900 | Adrian Victor Gerlach (1866–1934) | Belgica | Belgium |
| 1898–1900 | Carsten Egeberg Borchgrevink (1864–1934) | Southern Cross | Great Britain |
| 1901–1903 | Robert Falcon Scott (1868–1912) | Discovery and morning; from 1903: Terra Nova | Great Britain |
| 1901–1903 | Erich von Drygalski (1865–1949) | Gauss | Germany |
| 1901–1903 | Nils Otto Nordenskjöld (1869–1928) | Antarctic | Sweden |
| 1902–1905 | William Spiers Bruce (1867–1921) | Scotia | Scotland |
| 1903–1905 | Jean-Baptiste Charcot (1867–1936) | Pourquoi-pas? | France |

**Table 15.2** International expeditions from 1907 to 1917

| Time | Expedition leader | Ship | Nation |
|---|---|---|---|
| 1907–1909 | Ernest Shackleton (1874–1922) | Nimrod | Great Britain |
| 1910–1913 | Robert Falcon Scott (1868–1912) | Terra Nova | Great Britain |
| 1910–1912 | Roald Amundsen (1872–1928) | Fram | Norway |
| 1911–1912 | Wilhelm Filchner (1877–1957) | Deutschland | Germany |
| 1911–1914 | Douglas Mawson (1882–1958) | Aurora | Australia |
| 1911–1912 | Nobu Shirase (1861–1946) | Kainan-maru | Japan |
| 1914–1917 | Ernest Shackleton | Endurance | Great Britain |

nationalism was growing and the new German Empire perceived a great danger in British domination in the North Sea, which was an important fishing ground for both countries. Each nation raced to produce large fleets of sophisticated vessels and much propaganda was involved. By 1907, the spirit of international cooperation had faded and concerted efforts were being made by some to be first to reach the South Pole (Table 15.2, Fig. 15.3).

The conflicts between Britain and Norway, which had only become an independent state in 1905, were constantly apparent in the whaling business. Norwegian Roald Amundsen's (1872–1928) expedition to reach the South Pole was purely for sport and national pride (Borman-Larsen 2006). That he was first in 1911, beating Britain's Scott, was a huge disappointment for the British. Not only did Scott and his companions lose their lives on their return from the pole, it was also a humiliation for Britain as a nation, which, as a result of the discoveries of Drake, Cook and other explorers had claimed Antarctica as her territory (Jones 2003; Crane 2006; Fiennes 2004; Cherry-Garrard 2010; Gurney 2000).

Shackleton's goal in 1914–1917 was a traverse of Antarctica. This privately financed expedition would potentially recover the national pride of Britain and also justify her claim to the continent (Huntford 2007; Tyler-Lewis 2006). However, Shackleton failed in his attempt and his epic return home is well known (Shackleton 1999, 2008; Worsley 1999). The traverse from the Weddell Sea to the Ross Sea was

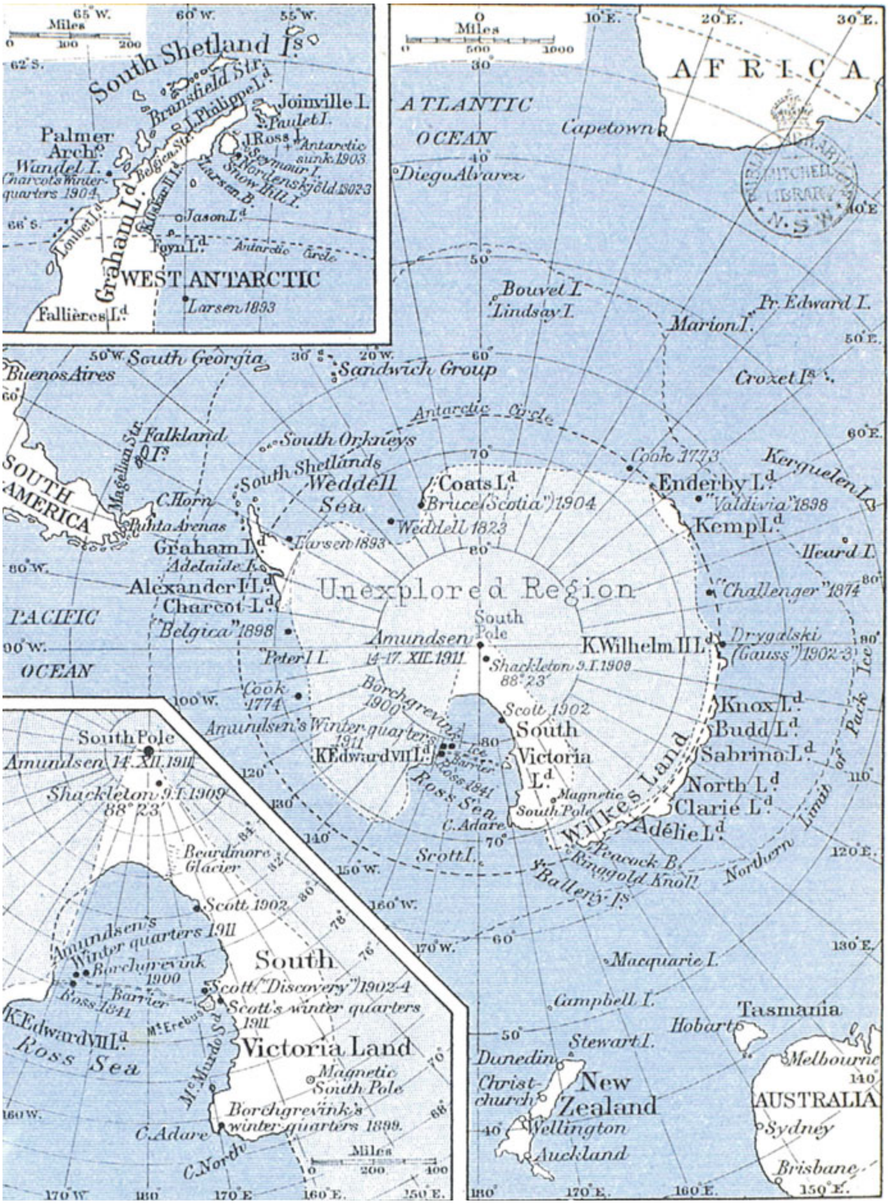



**Fig. 15.3** A map of the areas of the Southern Ocean that were well known by 1911 (Reprinted from Martin 1996)

eventually completed during the British organised Commonwealth Trans-Antarctic Expedition in 1957 by Vivian Fuchs (1908–1999), supported by Edmund Hillary (1919–2008). This expedition took place simultaneously with the fourth

International Geophysical Year in 1957/1958, which brought 12 nations together in an effort to study both polar regions.

The Heroic Era is filled with dramatic events, but also with great scientific outcomes, such as Mawson's observations of wind direction, the earth-magnetic observations made by Bidlingmaier as part of the Drygalski expedition, and deep ocean measurements from Brennecke on the Filchner expedition (Filchner 1994). However, after the First World War scientists were absent from Antarctica until the late 1920s.

## 15.4 The Years Before the Second World War

After the First World War, the use of aeroplanes led to a new kind of race: the conquest of Antarctica by air. These aerial expeditions were more personal than the big expeditions of old as aviators tested their skills in the remote and challenging environments. However, national goals continued to be important. In 1928 and 1929, Hubert Wilkins (1888–1958), an American explorer and adventurer, made the first attempts to use aircraft and aerial photography to survey the continent. Initially these efforts were disappointing, but as this was the new way of Antarctic exploration, there was much willingness to make it a success.

The first flight to the South Pole was completed by Richard Byrd (1888–1957) in 1929, following Amundsen's path from the Ross Sea. There was also a group of geologists with Byrd who were there to make their own scientific observations. From the base camp, Little America, Byrd flew to the Queen Maud Mountains where he installed a fuel depot because he could not make a nonstop return flight between the camp and the pole. This flight was also important to test the aeroplane in the Antarctic conditions. The pilots flew by sight and required visual points of orientation for navigation. Flying was therefore only possible during summer when weather and temperatures were suitable. Byrd and his crew were successful. In 15 h and 51 min they completed a journey that had taken Amundsen and his men 3 months. Byrd claimed to be the first to fly over both the North and South Pole but his claim to the North Pole has since been shown to be false (Rawlins 2000).

Byrd's second expedition in 1933–1935 initiated the United States government interests in Antarctica. He went on to lead three more expeditions to Antarctica (1939–1941; Operation Highjump in 1946/1947; Operation Deepfreeze in 1955/1956) (Fig. 15.4).

Germany also became increasingly interested in Antarctica and in 1939 sent the sea and air supported Schwabenland expedition, led by Alfred Ritscher (1879–1963), to the continent. As with British, American, Norwegian and Australian expeditions, the goal was to claim parts of Antarctica for whaling grounds and possible mineral resources. Nations tried to ensure their land claims by having their nationals dropped on the ice when overflying a territory, but these claims were not accepted as legitimate.

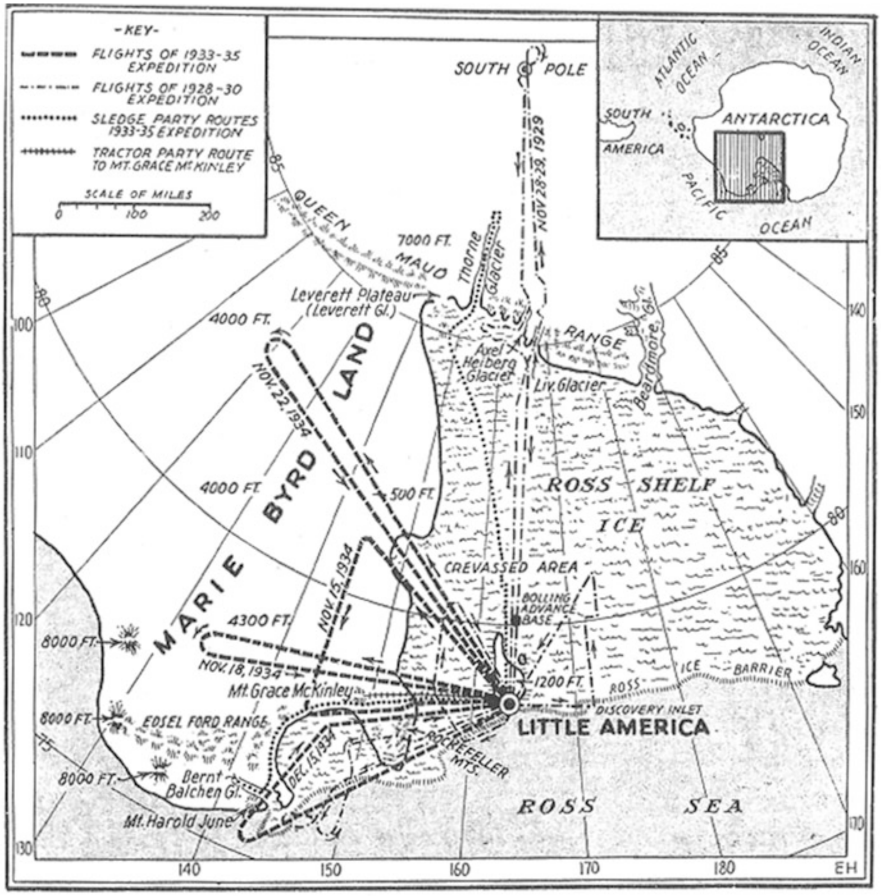



**Fig. 15.4** A map of flights made on Byrd's second expedition (Reprinted from Martin 1996)

The outbreak of the Second World War temporarily interrupted further activities in Antarctica, and after the war the question of claims to Antarctic territory needed a solution. The Antarctic Treaty was created in 1957 (Chap. 16), allowing peaceful research in Antarctica. However, it is not free of controversy.

## 15.5 After the Second World War

The end of the Second World War saw fundamental changes in the methods of exploration and research. In 1946, the United States Navy launched Operation Highjump, which was one of the biggest single expedition events in Antarctica, including 13 ships, 23 aircraft and over 4,700 men. This was a clear sign America was showing an interest in establishing a presence on and deepening her knowledge of the continent.

The Commonwealth Trans-Antarctic Expedition from 1955 to 1958 was the last event that was run in the spirit of the Heroic Era, albeit with the help of motorised vehicles. Vivian Fuchs and his crew started to cross Antarctica from the Weddell Sea. The Ross Sea Party, led by Edmund Hillary, prepared the way for Fuchs and his team to travel from the South Pole to the Ross Sea. The crossing was eventually completed and Shackleton's idea of reaching the South Pole by traversing the continent was realised almost 30 years later.

A new era of Antarctic research started in the 1950s. Instead of sending single expeditions to the ice, nations such as New Zealand built their own research stations (Scott Base was built in 1957). Stations provided a safe environment for scientists and technical staff to do their work and the whole concept of scientific research became more organised and coordinated. The peaceful scientific cooperation between nations, endorsed by the Antarctic Treaty, is still practised today with the focus on the global concerns of climate change.

However, some adventurers still try to conquer Antarctica with sporting activities and feats of endurance, and tourism brings more people than ever to the region (Chap. 18). Tourists are not only interested in the landscape, but also in the history and heritage of the region. The Antarctic Heritage Trust cares for four historic sites in the Ross Sea Region, from the British Antarctic Expedition (Southern Cross 1898–1900), the National Antarctic Expedition (Discovery 1901–1904), the British Antarctic Expedition (Nimrod 1907–1909) and the British Antarctic Expedition (Terra Nova 1910–1913). The responsibility of the AHT is the restoration and preservation of the remaining huts, not only for tourists but also for scientific research.

## 15.6 Social Conditions of Polar Expeditions

The living conditions at the first polar stations often resulted from improvements made to the procedures and standards of the earliest polar expeditions and covered a wide range of aspects.

### *15.6.1 Onboard Ship*

The lives of early explorers were characterised by hardship and everyday life largely confined to the ship. Life for the crew was not much different to other journeys by ship except the duration of their employment contracts was longer than usual, and when the ship was frozen into the sea ice the crew had specific duties, such as assisting the scientists (particularly on German expeditions). The ship not only served as transport for the expedition, it was a self-contained research station and home for many months.

Cabins were allocated according to rank. The men's quarters were basic, perhaps a row of lockers outside the bedrooms, communal washing facilities and communal general living. There was no room for privacy. On most expeditions the officers and scientists considered privacy important for their work and recuperation, and consequently each had his own cabin, although the lower ranks amongst them had to share a cabin between two. This structure also aimed to avoid conflict between officers and men but was only partially successful.

Captain Scott followed standard practice in the British Navy by segregating his crew between officers and scientists in terms of room and food. Shackleton, a merchant navy officer, had a different philosophy. He realised the importance of each helping hand in the demanding Antarctic conditions and included the crew in the activities of the scientists and higher ranking staff. Drygalski, in his 1901–1903 expedition, operated in a similar manner, with the lower ranks being involved in a wide range of activities when the situation demanded. So, although living conditions may have been similar across all those early expeditions, the hierarchies, task and duties could vary widely, leading to very different experiences on each expedition.

Room temperature was usually between 0 and 15 °C. During winter, doors and windows were protected from snow, cold and wind by timber, making conditions dark inside. The only light came from petroleum lamps, but this was an expensive method of lighting and lamps that could burn seal blubber were developed. These blubber lamps were very smoky and emitted a lot of grease that covered everything in the room, which meant the men had to clean up after winter.

To reach Antarctica, ships had to travel through different climate zones, particularly when leaving from the Northern Hemisphere. When traversing the warmer zones, the cabins could become unbearably hot and fans were used for cooling. The opposite problem arose once in Antarctica, but the crew eventually acclimatised to the lower temperatures.

Initially, cabin floors were carpeted, which could lead to dampness and the growth of mould. However, removing carpets also removed their insulating effect. On some expeditions, cabin walls were insulated with natural rubber wall paper but this increased condensation.

### *15.6.2 Hut Life*

The conditions in a hut were very similar to those onboard the ship. The main difference was that the ship was always in danger of being crushed by sea ice while the huts were built on secure ground. Temperatures and condensation continued to be issues, and even when huts were insulated, the problems were obvious. It was smoky inside when the blubber lamps were used for heating and when the heating stopped, ice formed on the walls and the humidity was too high Crawford (1998).

**Fig. 15.5** The interior of the Commonwealth Bay hut, built during Mawson's 1911–1914 expedition to Antarctica. There is not much room for privacy, but the place seems comfortable, given the circumstances (Reprinted from Martin 1996)

Everything was greasy and black from the smoke and the general environment was very unhealthy. Wall insulation comprised double boarding inside and outside the frame with layers of quilted seaweed between each pair of boards. Sometimes the roof also incorporated layers of seaweed. During their time on the ice, the men improvised with the materials they had around their base and each expedition learned from those that had gone before (Fig. 15.5).

If hut building was planned in advance, then usually a modular hut was taken to Antarctica and assembled on site. However, if use of a hut was not anticipated and one was built for survival purposes, construction was much more problematic. The Nordenskjöld expedition of 1902–1904 had to construct an emergency shelter from stones after they lost their ship (it sank on 12 February 1902, 45 km from Paulet Island) and their living conditions were extremely basic because most of their equipment was lost with the ship Elzinga (2004) (Fig. 15.6).

### *15.6.3 Sledge Travel*

Sledge parties had to be self-sufficient and carry a tent for accommodation. Life in a tent was difficult, especially in strong winds and snowfall. Inside it was cramped, uncomfortable and impossible to sit properly, so the men stayed in their sleeping bags reading, writing, chatting or sleeping Drygalski (1989). Condensation

**Fig. 15.6** Erecting the hut at Commonwealth Bay. The huts were often pre-fabricated like a modular home (Reprinted from Martin 1996)

accumulated from breathing and cooking and froze inside the tent, only to melt and drip on the men when temperatures rose.

Another issue for sledge parties was their sleeping bags. These were mostly made of reindeer fur or wolf skin, but the reindeer bags tended to lose their insulating hair and were very stiff. Two men used a double bag in order to make use of each other's body heat to stay warm. Sleeping in their bulky clothing was not always easy and prompted many complaints.

Usually, sledging trips were planned for only a few days or weeks and rations of food, water and general material were calculated accordingly. However, during unplanned travel such as the retreat of Shackleton and his men, which lasted 10 months until the team was rescued from Elephant Island, the men had to rely on food resources they found along the way, including seals, penguins and, sometimes, sledge dogs.

The danger of dehydration was always present due to low temperatures, dry and windy conditions and the exhausting physical work with dogs or hauling sledges. Obtaining enough drinking water was a persistent problem. It was time and fuel consuming to melt ice for water but, for this, the Nansen cooker was a revolution. It consists of a central container for cooking food, surrounded by a second, double walled container which could hold ice for melting. When this is placed on a heat source, food is cooked and water is produced simultaneously.

Dog handling could be frustrating work. Some dogs were difficult to control, the men were not well trained in handling them and it was a struggle to keep the sledges on track while the dogs were running. The dogs would eat anything, even their leather harnesses, so the men had to secure all items after long and exhausting journeys.

### 15.6.4 Food and Alcohol

Food is always an important component of expeditions. Many expeditions were well prepared and stocked such good food that some expedition members ate better than they would have back at home. Expedition doctors were usually responsible for the calculation of rations and the balance of nutrients. Some doctors even conducted experiments on themselves to test the nutritional value of food. Most food was either tinned, dried or otherwise preserved, and included vegetables, fruits and basic ingredients such as flour, sugar and powdered milk. However, the preserved foods were often without essential nutrients, leading to vitamin and mineral deficiencies and ultimately scurvy and beriberi. These ailments could become dangerous in such demanding conditions, sometimes even fatal. Some expeditions brought animals such as goats, pigs and chickens and kept them alive on board to provide a source of fresh ingredients. The most common drinks were tea, coffee and hot chocolate. If vessels became trapped in ice, seals and penguins, as well as penguin eggs, became favoured additions to the menu.

During some expeditions, alcohol was carefully rationed and there was no excessive drinking, but on others the consumption of alcohol was a problem (Murphy 2002). On the Filchner expedition (1911/1912) some members drank excessively and the resulting falls, fights and beatings lead to significant injuries. The use and benefit of alcohol was discussed by many of the expedition leaders and physicians but no general consensus on whether it should be made available was reached.

### 15.6.5 Everyday Life

Routine was essential to guard against boredom and monotony during the dark, long winter. Scientific work was carried out daily and mealtimes provided a regular event onboard ship or in the huts. However, the men had a lot of spare time and to occupy themselves, they started to edit newspapers or write books (Fig. 15.7).

Various clubs were established, music was played and reading was very popular. Rifle shooting competitions were held and sports activities undertaken. Some men found their routine in special duties, such as looking after dogs or any of the other animals onboard, or hunting. Caring for animals was very popular as it provided an opportunity for the men to deal with feelings of anger, frustration or fear, which were rarely shared with other expedition members. Many men also wrote diaries to help them deal with their emotions. Fun activities such as fancy dress parties provided important diversions. Scientists and officers presented lectures on their


**Fig. 15.7** The frontispiece for the first book written, printed and published in Antarctica in 1908, during Shackleton's Nimrod expedition (Reprinted from Martin 1996)

work and taught the basics of first aid, knowledge of the ship and the science of navigation. Birthdays and other anniversaries were celebrated, including those of family members, emperors and kings, battles and similar events.

Another practical method to deal with spare time was the vital job of cleaning and repairing clothing and footwear with whatever material became available. During the long months of winter some crew members experienced psychological problems (Chap. 17), including one case during the Drygalski expedition (1901–1903) when a man hallucinated that god would give him a sign to convert other expedition members. However, most nervous breakdowns or strange behaviours disappeared when sun light returned.

### *15.6.6 Hygiene, Health and Death*

Much of the time, hygiene during expeditions was better than back home, but on sledging trips and during winter, environmental conditions meant hygiene could deteriorate significantly. It was a big effort to provide water and many men suffered boils due to a lack of washing facilities, although their diaries describe frequent cleaning of clothes. If the expedition had to deal with unexpected survival issues, hygiene and medical conditions could change significantly. Members of Shackleton's expedition (1914–1917) had good conditions during their time on ship, but during their epic journey home, conditions were horrifying. Filcher shared his advice gained by hard experience when he wrote that instead of washing the face with water, blubber should be used to protect the face and hands from freezing temperatures (Filchner 1994).

Fortunately most expeditions were medically well equipped. Besides common injuries and some minor surgeries there were serious illnesses such as tuberculosis, venereal diseases and severe vitamin deficiency such as scurvy and beriberi. Once expeditions were based on land, there were also many cases of frostbite. Sometimes frostbite resulted not only from low temperatures and exposed skin, but also from poorly fitting clothing. Frequently the men's footwear was too small, leading to frostbitten toes. Interestingly, frostbite was often not covered by insurance companies (Box 15.1, also see insurance policy, Schwartze and Lübbers 1901).

**Box 15.1: Insurance on Polar Expeditions, Early Twentieth Century**
Members of the Drygalski expedition (1901–1903) were insured, as summarised in a very detailed account outlining the compensation offered for particular injuries. The payout was related to the common income of merchant navy personnel. The figures below show the percentage of the claimant's annuity that could be expected if he was injured in the following manner:

100 % if the person has injured both eyes, both arms, both hands, both legs, both feet or whenever one arm or one hand are injured together with one leg etc.
60 % if the right arm or the right hand is injured
50 % if the left arm or left hand is injured or one leg or one arm
23 % if one eye is injured
25 % if the thumb of the right hand is injured
18 % if the thumb of the left hand is injured
16 % if the forefinger of the right hand is injured
12 % if the forefinger of the left hand is injured
10 % if the middle finger or ring finger of the right hand is injured
7 % if the middle finger or ring finger of the left hand is injured

(continued)

**Box 15.1** (continued)

If some part of the body was damaged during the expedition and that body part was not listed, a complicated calculation identified the grade of disability. This calculation included the occupation and age of the claimant. No coverage was available if a part of the body was injured before the expedition started. This was one of the reasons a physical examination was required for most expedition members. Frostbite cover was available only if the premium was increased from 27,450 to 73,200 Mark, but this was beyond the budget of Drygalski's expedition. For comparison, at the end of the expedition the value of the ship was 400,000 Mark.

In order to be paid compensation a detailed report on the injury and its cause had to be submitted by the ship's doctor. If alcohol was involved the policy was invalid. Likewise, there was no coverage if the man was hurt in a fight or harmed himself deliberately.

Heart and stomach problems were infrequent among the crew but more prevalent in officers and scientists. Shackleton is the best known leader with a heart condition, and this was responsible for his death in 1922. The different view of disease and the treatments applied during earlier times makes it difficult to reconstruct the effects of the illness itself. For example, it was long thought that wine helped prevent scurvy and was beneficial against the common cold, which led to alcohol being seen as a medicine. However, its use probably did more harm than good as we now know that it exacerbates the effects of hypothermia and other illnesses. The doctors were generally thorough with their various observations and reported their results to help improve conditions on subsequent expeditions.

Extreme emotional stress was inevitably caused by the death of an expedition member, particularly if the expedition leader died. Each expedition had to deal with death caused by accidents of various kinds, diseases such as tuberculosis and scurvy, and cases of starvation, hypothermia and exhaustion. Tuberculosis and scurvy were not always fatal, but they both affected the physical condition of patients. Venereal disease and syphilis also caused deaths but these diseases were generally not mentioned by name because of the shame associated with them. There were also cases of suicide, but these were not discussed and often disguised as accidents. General health examinations were carried out before an expedition following navy regulations, but some diseases were not discovered beforehand or appeared only once the expedition was underway.

### *15.6.7 Clothing*

Different conditions required different clothing. When living onboard ship, everyday materials similar to those from home were used, or familiar garments were made from improved cloth obtained from the navy. However, life in a hut or on a sledging trip required different designs and materials. Initially, the choice of clothing was strongly influenced by the navy, but in the cold conditions of Antarctica, clothing was adapted by trial and error. Materials used included wool, leather, fur, natural rubber, cotton and silk. The Jägerwool brand was very popular for underwear and was used by nearly every expedition in the Heroic Era. Footwear was always a big problem as ill-fitting shoes could lead to frostbitten toes. Some explorers used the very warm practical clothing of the Arctic native Inuit or Greenlanders. Amundsen chose fur clothing for sledging, while Scott's Burberry (waxed cotton or linen) for man hauling was also well chosen. Inevitably, in survival situations the men had to improvise with the existing cloth and whatever other material was available.

Eye protection was also important and many experiments were undertaken to find the optimal eye wear. On some expeditions the men used darkened glass set into leather headbands; others had wooden or metal goggles with leather strips around the wearer's head. These protected against snow blindness but also diminished visibility.

## 15.7 Social History

The social history of Antarctica is multifaceted and direct comparisons between different expeditions are difficult. National and personal preferences underlie much of what was written in reports and diaries, and rarely do two people have the same perspective on an issue. National culture also led to differences in everyday life during expeditions, but the experiences of these early, pioneering journeys led to improvements in equipment, clothing and social activity and ultimately to the working environment we have in Antarctica today.

Very early Antarctic exploration aimed to find and claim land. Even if it was not obvious how land could be used, waterways and extended territories were important for trade, business and to demonstrate power. By the middle of the nineteenth century, a demand for scientific knowledge emerged and soon became a driving factor in Antarctic exploration. Economics, science and politics were strongly linked. Even now, as peaceful use of Antarctica is promoted under the Antarctic Treaty, economic factors and politics are working in the background to exert influence on decisions and outcomes. Antarctica is considered by some as a symbol of wilderness, purity and inviolacy, but it also stands for danger and sensitivity as the general population becomes aware of issues such as climate change. History has shown that Antarctica was always a special place; from the mystique of a fabulous continent to a place of plentiful hunting grounds to a unique location for science and a place in need of protection.

## References

Antarctic Heritage Trusts, United Kingdom and New Zealand, www.heritage-antarctica.org
Borman-Larsen T (2006) Roald Amundsen: a full biography. Sutton Publishing Ltd, Storud
Cherry-Garrard A (2010) The worst journey in the world: Antarctic 1910–13. Qontro Classical Books, London
Crane D (2006) Scott of the Antarctic. Harper Perennial, London
Crawford J (1998) That first Antarctic winter. The story of the southern cross expedition of 1898–1900 as told in the diaries of Louis Charles Bernacchi. South Latitude Research Ltd, Christchurch
Elzinga A (ed) (2004) Antarctic challenges. Historical and current perspectives on Otto Nordenskjöld's Antarctic expedition 1901–1903. Royal Society of Arts and Sciences, Göteborg
Fiennes R (2004) Captain Scott. Coronet Books, London
Filchner W (1994) To the sixth continent: the second German south polar expedition. Cambridge University Press, Cambridge
Gurney A (1996) Below the convergence: voyages toward Antarctica 1699–1839. Norton, New York
Gurney A (2000) The race to the white continent. Voyages to Antarctica 1966–1839. W.W. Norton & Company, New York
Headland R (1996) Chronological list of Antarctic expeditions and related historical events. Cambridge University Press, Cambridge, p 44
Headland R (2009) A chronology of Antarctic exploration. A synopsis of events and activities from the earliest times until the International Polar years, 2007–2009. Quaritch, London
Huntford R (2007) Shackleton, 7th edn. Brown Book Group, London
Jones M (2003) The last great quest: captain Scott's Antarctic sacrifice. Oxford University Press, Oxford
Krause R, Rack U (2006) Logbook of the German steam barge Groenland, written during a sealing and whaling campaign in Antarctica in 1873–1874 under the command of captain Dallmann. In: Berichte zur Polarforschung, Bremerhaven, 530, pp LVI–LXIII
Landis MJ (2001) Antarctica, exploring the extreme, 400 years of adventure. Chicago University Press, Chicago, pp 3–109
Martin S (1996) A history of Antarctica. State Library of New South Wales Press, Sydney, pp 16–104
McGonical D, Woodworth L (2001) Antarctic and the Arctic: the complete encyclopaedia. Firefly Books, Ontario
Murphy DT (2002) German exploration of the polar world: a history, 1870–1940. University of Nebraska Press, Lincoln
Rawlins D (2000) Byrd's heroic 1926 flight and its faked last leg. Int J Sci Hist 10:9–107
Raymond J (2006) Encyclopaedia of exploration 1850 to 1940: the oceans, islands and polar regions. Howgego, Sydney
Reader's Digest (1985) Antarctica: great stories from the frozen continent. Reader's Digest Services, Sydney, pp 292–299
Riffenburgh B (ed) (2007) Encyclopaedia of the Antarctic: 2 volumes. Routledge, New York
Rosove MH (2002) Let heroes speak: Antarctic explorers 1772–1922. Berkley Books, New York
Schwartze, Lübbers & Co Hamburg (15th April 1901) Drygalski estate. Institute of Länderkunde, Leipzig, Box 61/4
Shackleton E (2008) South: the story of Shackleton's last expedition 1914–1917. Morris Book, London
Tyler-Lewis K (2006) The lost men: the harrowing story of Shackleton's Ross sea party. Bloomsbury Publishing, London
von Drygalski E (1989) The Southern Ice-continent: the German South Polar expedition aboard the gauss, 1901–1903. Bluntisham Books & Erskine Press, Harleston
Worsley F (1999) Endurance: an epic of polar adventure. Norton, New York

# Chapter 16
# A Continent for Peace and Science

## Governance in Antarctica

**Neil Gilbert**

**Abstract** There are few places on Earth where international cooperation, scientific endeavour and environmental protection are steadfastly held up as the primary principles for interactions between governments, but that is precisely the situation in Antarctica, where a unique international governance regime exists. In 1959, at the height of the Cold War, and with much dispute over ownership of the Antarctic continent, 12 countries managed to agree a short international treaty to establish a means of governing the region. The resulting Antarctic Treaty has been one of the most successful international agreements ever made. For its time it was highly innovative. It did not attempt to find a solution to the political disputes of the time. Instead the treaty set out to establish a regime to manage the issues and to promote ongoing cooperation between countries. The original 12 Treaty Parties have been joined by an additional 36 countries, 28 of whom have active scientific research programmes in Antarctica. All decisions among the parties at their annual meetings are taken by consensus, ensuring all countries are fully aligned on how to manage the region. However, the Antarctic Treaty did not put in place all necessary measures for comprehensive management and governance of the region. Over time the Treaty Parties have negotiated several additional free-standing international agreements. These agreements deal with commercial sealing and fishing, mineral resource activities and comprehensive environmental protection. Collectively, this suite of international law that applies to the Antarctic continent and the surrounding Southern Ocean is known as the Antarctic Treaty System.

**Keywords** Antarctic Treaty System • Sovereignty • CCAMLR • Mining • Environmental impact assessment

N. Gilbert (✉)
Constantia Consulting, Christchurch, New Zealand
e-mail: neil@constantiaconsulting.net



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_16

## 16.1 Ownership of Antarctica

At the turn of the nineteenth century, reports of seals and whales in the Southern Ocean indicated potential economic gain which, along with broader imperial ambitions, lay behind the first territorial claim to be made to Antarctica by the United Kingdom in 1908. The UK initially claimed the Antarctic Peninsula and Weddell Sea region of Antarctica but elaborated this claim in 1917, at the height of the First World War, to include the Falkland Islands Dependencies. Following the First World War, further claims were made by France (1924), the UK on behalf of New Zealand (1923) and Australia (1933), and by Norway (1939). During the Second World War, two additional claims were made to Antarctica by Chile (1940) and Argentina (1943). These latter claims were notable in that they significantly overlapped with the earlier claim to the Antarctica Peninsula made by the UK, as well as each other (Fig. 16.1). Six of the claims converge at the South

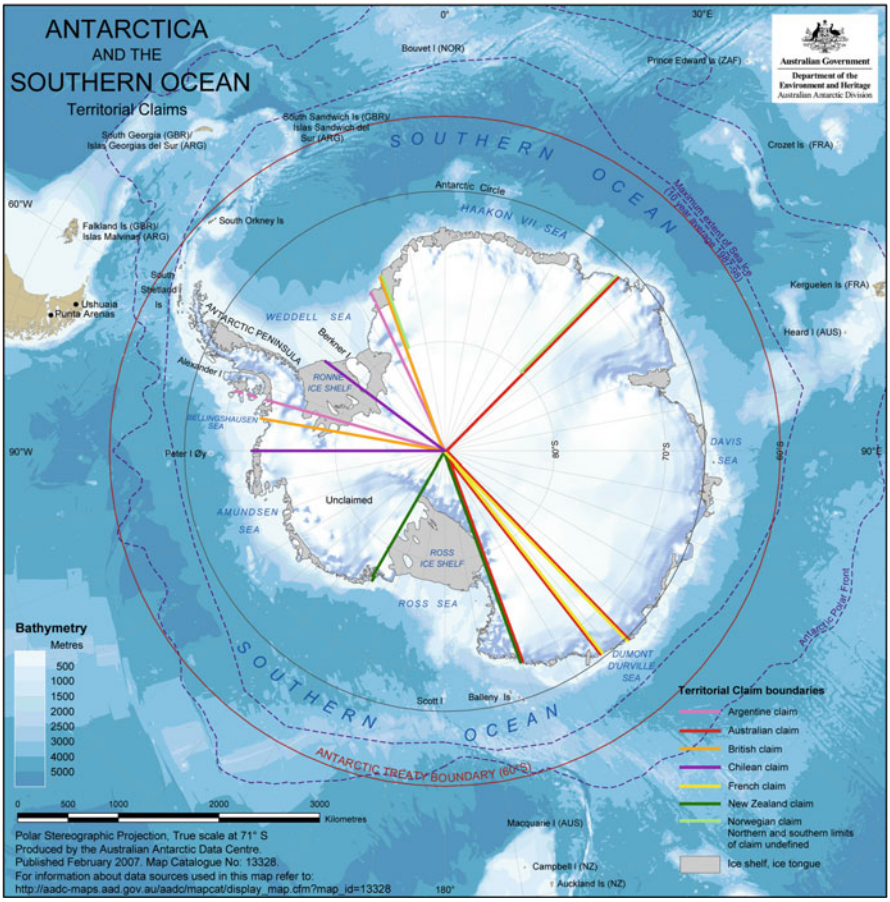



**Fig. 16.1** Territorial claims to Antarctica (With kind permission from the Australian Antarctic Division, © Commonwealth of Australia 2013)

Geographic Pole but the northern and southern boundaries of the Norwegian claim are undefined.

However, these claims were not formally recognised by non-claimant nations, nor were they necessarily recognised by the other claimant nations. Moreover, both the USA, and the former Soviet Union, reserved their right to make a claim to Antarctica in the future should they so wish. At the height of the Cold War (1940s and 1950s), the international tension that surrounded these disputed claims was exacerbated by international concern over the possible use of Antarctica for military and nuclear activities. A number of attempts were made to resolve these rising apprehensions, including suggestions to involve the United Nations (Box 16.1). However, the UN option received significant opposition, not least from the claimant states themselves which were concerned about the potential for the UN to overturn their claims (Sollie 1984).

**Box 16.1: The United Nations and the Question of Antarctica**

The Antarctic Treaty regime has not been without its detractors. Over time its legitimacy has been called into question by a number of non-treaty countries, not least by Malaysia. In a speech to the United Nations General Assembly in 1982 (21 years after the Antarctic Treaty entered into force) the then Malaysian prime minister Dr Mahathir bin Mohamad proposed that the United Nations should take over administration of the Antarctic Treaty area and openly criticised the Antarctic Treaty as an agreement among a few privileged states that did not represent the true aspirations of the United Nations membership. Mahathir proposed that a new international treaty be negotiated to replace the Antarctic Treaty (UNGA Official Records 1982).

In 1983, Malaysia called for the 'question of Antarctica' to be placed on the agenda of the General Assembly, a debate which ran in the First Committee of the General Assembly for the next 20 years. During the 1980s, there emerged a number of themes around which Malaysia and its supporters built their case. These themes included the Antarctic environment itself, and recognition that it had a profound influence on environmental and climate conditions worldwide; the issue of exclusivity and concern over the 'secretive' character of Antarctic Treaty meetings; and not least the issue of mineral resources. It was during the 1980s that the Antarctic Treaty Parties negotiated the Antarctic Minerals Regime (CRAMRA). During this time, developing countries grew increasingly wary over the potential for a limited number of states to have access to Antarctica's perceived wealth of mineral and hydrocarbon resources.

In 1989, a shift in the UN debate came about, which was likely heavily influenced by Australia's and France's decision not to sign the Antarctic Minerals Convention. The focus of the debate in the United Nations moved more towards the issue of environmental protection and conservation, with

(continued)

**Box 16.1** (continued)
Malaysia calling for the establishment of Antarctica as a nature reserve or world park (UN Resolution 44/124 Part B). This issue was in large part met by the Treaty Parties with the demise of the minerals regime in 1989 and the adoption of the Environmental Protocol in 1991. The protocol designates Antarctica as a “natural reserve devoted to peace and science”, and introduces an indefinite prohibition on mineral resource activities. As such the concerns of the UN and Malaysia were largely addressed.

Nevertheless, the question of Antarctica remained on the agenda of the First Committee of the UN General Assembly and was discussed every 2 years until 2003. At that time Mahathir stood down as the Malaysian Prime Minister. This eased the pressure on the need to continue the debate within the UN and the matter was removed from its agenda. In return (and with a degree of inventiveness), the Antarctic Treaty Parties invited Malaysia to ‘observe its meetings’, which Malaysia did for the first time at the 26th ATCM in Madrid in June 2003.

Since then Malaysia has been invited to observe subsequent Antarctic Treaty Consultative Meetings (ATCMs), though the understanding has been clear that the expectation of the Treaty Parties was that Malaysia would take the necessary steps to accede to the Antarctic Treaty and its Protocol, which it eventually did on October 31, 2011.

(United Nations General Assembly Official Records, 37th Session, U.N. Doc. A/37/PV.10 (1982), 17–20 Statement of Mahathir bin Mohamad)

## 16.2 A Political Solution

During the late 1940s and early 1950s, international discussions were taking place to plan an international scientific programme to coincide with a solar maximum event in 1957/1958. Coordinated by the International Council of Scientific Unions (ICSU), the International Geophysical Year (IGY) included a significant Antarctic research component owing to the region’s influence on global weather, atmosphere and oceans.

From 1956 to 1958, 12 nations (the 7 claimant nations and Belgium, Japan, South Africa, USA, and USSR) cooperated in a major Antarctic research effort. Numerous bases were established around the continent, including the US Amundsen-Scott station at the geographic South Pole and the USSR bases at the Pole of Inaccessibility and the South Geomagnetic Pole. The research and the level of cooperation were so successful that a proposal was made to renew discussions to address the political tensions surrounding Antarctica. On May 2, 1958, the United States issued an invitation to the other 11 IGY countries to negotiate a treaty to give the basic principles of IGY a legal and lasting effect (Sollie 1984).

Following a series of preparatory meetings among the 12 IGY nations, a conference was convened in Washington D.C. on October 15, 1959, the outcome of which was the signing of the Antarctic Treaty on December 1, 1959.

## 16.3 The Antarctic Treaty

The Antarctic Treaty is a remarkable document. Negotiated at the height of the Cold War and including the two superpowers of the time, it has stood the test of time for more than 50 years and is one of the more successful international agreements. The treaty itself is short and succinct: just 14 articles, but written in carefully crafted language; the most notable being that of its Article IV (Box 16.2). The objectives of the treaty are to promote peaceful cooperation and freedom of scientific investigation in the region south of 60° South. To achieve these outcomes, the treaty puts in place a number of provisions:

- Activities of a military nature are prohibited, unless in support of scientific or other peaceful purposes (Article I).
- The exchange of scientific personnel, scientific data, research and logistics plans is required in order to promote international scientific cooperation (Article III).
- Nuclear explosions and the disposal of radioactive waste in Antarctica are prohibited (Article V).
- The treaty applies to all land and ice shelves below 60°S, but within the high seas of the treaty area additional agreements exist for the regulation of maritime activities such as sealing and fishing (Article VI).
- Any Treaty Party is allowed to inspect the facilities and installations, aircraft and vessels of any other party, and parties are required to share advance notification of expeditions and activities in the treaty area (Article VII).
- Regular meetings are required among the Treaty Parties to exchange information, consult on matters of common interest, and to develop recommendations for their governments (Article IX).

The Antarctic Treaty was agreed in four languages (English, French, Russian and Spanish) and entered into force on 23 June 1961. While the treaty has no end date, Article XII of the treaty allows for a review after 30 years (1991) should any party request a review. To date no such review has been requested.

**Box 16.2: Article IV: The Issue of Disputes over Sovereignty**

Article IV of the treaty addresses the contentious matter of territorial sovereignty and the difference of views between claimant and non-claimant nations. It is this carefully worded article that contributes significantly to the success of the treaty. Article IV states that nothing in the treaty will affect the existing claims to sovereignty and also that non-claimant states will not be

(continued)

**Box 16.2** (continued)
disadvantaged, regardless of whether or not they recognise the claims of others. While the treaty remains in force, Article IV also ensures that no activities undertaken in the treaty area shall constitute a basis for asserting, supporting or denying a claim, and that existing claims cannot be enlarged, nor new claims made.

Article IV has been referred to as a 'gentleman's agreement' or an 'agreement to disagree' on the issue of territorial claims. The success of Article IV lies in its intent to manage rather than resolve any territorial disputes (Watts 1992).

Article IV preserves, and makes equal, the status of all parties to the treaty irrespective of their claimant status or their recognition or not of existing claims. This equality is manifested in the consensus decision making approach taken at meetings within the Antarctic Treaty System (see below).

### *16.3.1 Antarctic Treaty Parties*

A further measure of the success of the Antarctic Treaty has been its growth in membership. The original 12 signatory nations have been joined by a further 38 nations, making a total of 50 Antarctic Treaty Parties. These 50 parties to the treaty are either Consultative Parties or Non-Consultative Parties (Tables 16.1 and 16.2). Consultative Parties participate in Antarctic Treaty meetings (known as Consultative Meetings or ATCM) and take decisions or votes under Article IX of the treaty. Consultative Party status is gained by demonstrating interest in Antarctica through conducting substantial research, building a base in Antarctica, or organising scientific expeditions (Article IX (2) of the treaty). Non-Consultative Parties, or countries that are simply signatories to the treaty, are allowed to participate in meetings, but cannot take formal decisions or vote.

Following a modest increase in membership of the Antarctic Treaty between 1959 and 1979 (eight additional nations), significant growth was observed between 1979 and 1991, when membership doubled from 20 nations to 40 (Fig. 16.2). Over the same period, the number of Consultative Parties also doubled from 13 to 26. Currently there are 29 Consultative Parties to the Antarctic Treaty (Table 16.1) and 21 Non-Consultative Parties (Table 16.2).

This growth in membership was influenced by two significant factors relating to commercial activity in Antarctica during the 1980s: the convention to regulate commercial fishing in the Southern Ocean (CCAMLR, Chap. 20) entered into force, and the Treaty Parties negotiated a convention to regulate mineral resource activities (CRAMRA, see below).

The actual or potential commercial use of the region, particularly for minerals and oil, generated significant Antarctic interest globally, with several countries joining the treaty, developing national programmes and establishing bases so as to

**Table 16.1** List of consultative parties to the Antarctic Treaty showing the date at which the treaty entered into force for each party, and the date at which consultative party status was gained

| Country | Entry into force | Consultative status |
|---|---|---|
| Argentina | 23 Jun 1961 | 23 Jun 1961[a] |
| Australia | 23 Jun 1961 | 23 Jun 1961[a] |
| Belgium | 23 Jun 1961 | 23 Jun 1961[a] |
| Brazil | 16 May 1975 | 27 Sep 1983 |
| Bulgaria | 11 Sep 1978 | 05 Jun 1998 |
| Czech Republic | 01 Jan 1993 | 29 May 2013 |
| Chile | 23 Jun 1961 | 23 Jun 1961[a] |
| China | 08 Jun 1983 | 07 Oct 1985 |
| Ecuador | 15 Sep 1987 | 19 Nov 1990 |
| Finland | 15 May 1984 | 20 Oct 1989 |
| France | 23 Jun 1961 | 23 Jun 1961[a] |
| Germany | 05 Feb 1979 | 03 Mar 1981 |
| India | 19 Aug 1983 | 12 Sep 1983 |
| Italy | 18 Mar 1981 | 05 Oct 1987 |
| Japan | 23 Jun 1961 | 23 Jun 1961[a] |
| Korea (ROK) | 28 Nov 1986 | 09 Oct 1989 |
| Netherlands | 30 Mar 1967 | 19 Nov 1990 |
| New Zealand | 23 Jun 1961 | 23 Jun 1961[a] |
| Norway | 23 Jun 1961 | 23 Jun 1961[a] |
| Peru | 10 Apr 1981 | 09 Oct 1989 |
| Poland | 23 Jun 1961 | 29 Jul 1977 |

(continued)

**Table 16.1** (continued)

| Country | Entry into force | Consultative status |
|---|---|---|
|  Russian Federation | 23 Jun 1961 | 23 Jun 1961[a] |
|  South Africa | 23 Jun 1961 | 23 Jun 1961[a] |
|  Spain | 31 Mar 1982 | 21 Sep 1988 |
|  Sweden | 24 Apr 1984 | 21 Sep 1988 |
|  Ukraine | 28 Oct 1992 | 04 Jun 2004 |
|  United Kingdom | 23 Jun 1961 | 23 Jun 1961[a] |
|  United States | 23 Jun 1961 | 23 Jun 1961[a] |
|  Uruguay | 11 Jan 1980 | 07 Oct 1985 |

[a]Denotes the 12 original signatory nations

ensure a seat at the treaty table as well as a role in deciding future management and governance of the region.

The situation changed in the early 1990s when the Environmental Protocol to the Antarctic Treaty was adopted, with its prohibition on mineral resources activities in the treaty area. Since 1991, the number of parties has continued to increase with, on average, one new country joining the treaty every 2 years, but the rate of voting membership growth has slowed with the number of Consultative Parties rising by only 3, from 26 to 29 over the same period.

### *16.3.2 Antarctic Treaty Consultative Meetings (ATCM)*

Between 1961 and 2013 there have been 36 Antarctic Treaty Consultative Meetings (ATCMs). Until the early 1990s, ATCMs were held usually every 2 years but since the adoption of the Protocol in 1991 they have been held annually. Meeting locations are generally rotated among the Consultative Parties in (English) alphabetical order (Fig. 16.3).

**Table 16.2** List of non-consultative parties to the Antarctic Treaty showing the date at which the treaty entered into force for each party

| Country | Entry into force |
|---|---|
| Austria | 25 Aug 1987 |
| Belarus | 27 Dec 2006 |
| Canada | 04 May 1988 |
| Colombia | 31 Jan 1989 |
| Cuba | 16 Aug 1984 |
| Denmark | 20 May 1965 |
| Estonia | 17 May 2001 |
| Greece | 08 Jan 1987 |
| Guatemala | 31 Jul 1991 |
| Hungary | 27 Jan 1984 |
| Korea (DPRK) | 21 Jan 1987 |
| Malaysia | 31 Oct 2011 |
| Monaco | 30 May 2008 |
| Pakistan | 01 Mar 2012 |
| Papua New Guinea | 16 Mar 1981 |
| Portugal | 29 Jan 2010 |
| Romania | 15 Sep 1971 |
| Slovak Republic | 01 Jan 1993 |
| Switzerland | 15 Nov 1990 |
| Turkey | 24 Jan 1996 |
| Venezuela | 24 Mar 1999 |

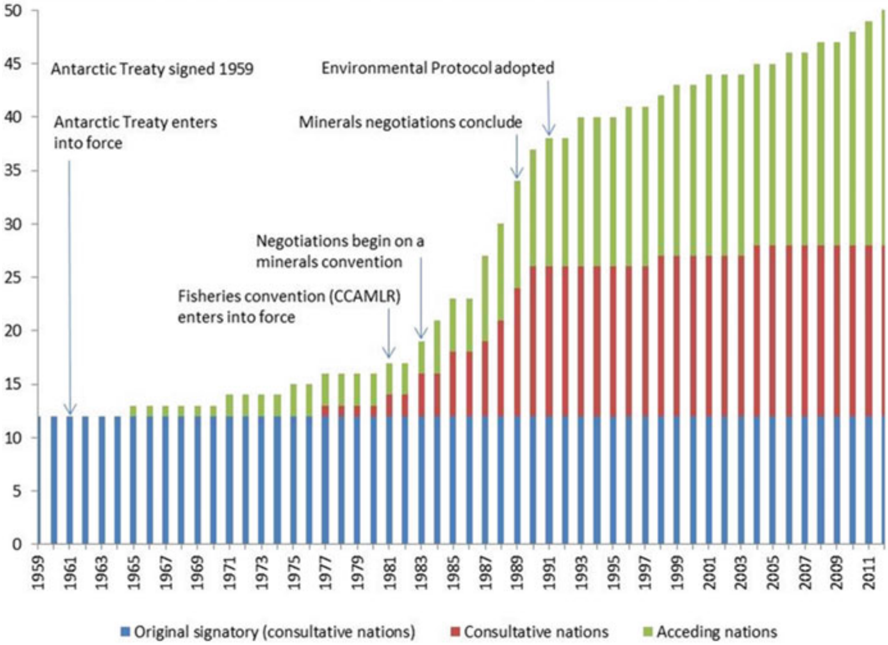



**Fig. 16.2** The number of Antarctic Treaty Parties over time divided into original signatory nations, consultative nations and acceding nations (With kind permission from Antarctica New Zealand)

**Fig. 16.3** The Antarctic Treaty Consultative Meeting XXXIV in Buenos Aires (With kind permission from Jose Luis Agraz, Antarctic Treaty Secretariat)

### 16.3.3 Decision Making

There are three separate categories for decision making by the ATCM: measures, decisions and resolutions.

Measures are intended to be legally binding once they have been approved by all Antarctic Treaty Consultative Parties. Decisions deal with internal organisational matters (such as rules of procedure) and become operative when adopted. Resolutions cover general agreements that are not intended to be legally binding (guidelines, for example).

Measures are adopted at ATCMs in the form of recommendations to governments, but they do not enter into force until the parties have taken the necessary legal action to implement the provisions of the measures in their own domestic legal and administrative systems, and have communicated to the Depositary Government of the Antarctic Treaty (US) that they have done so (a process known as ratification). For any particular measure, it can take considerable time (years) before all parties have completed the process (Box 16.3).

**Box 16.3: Consensus Decision Making**

All decisions taken at ATCMs and all other treaty instruments, including CCAMLR, are taken by consensus. Consensus is not defined in the treaty, but is taken as being the absence of any formal objection (rarely does formal voting take place). As such, any party has the right of veto over any decision.

The importance of consensus decision making was recognised when the treaty was established. Consensus guards against potential inequality between Treaty Parties, i.e. the original signatory claimant nations, original signatory non-claimant nations and (non-claimant) acceding states. Regardless of their status, all Treaty Parties have the right of veto.

A consensus approach brings with it certain challenges, not least the slowness of decision making and the risk of one or more parties holding veto for political motives. However, the advantages of all parties moving forward at the same pace, and being equally bound by all treaty provisions, are regarded as fundamentally important in an Antarctic context.

### 16.3.4 Antarctic Treaty Secretariat

Initially Antarctic Treaty Consultative Meetings were supported administratively solely by the country hosting the meeting at the time. This contrasts with CCAMLR, which has the support of a permanent secretariat. The need for a permanent secretariat to support ATCMs was something on which Treaty Parties disagreed for a number of years. It was not until the 12th ATCM (Australia, 1983) that the concept began to gain more widespread appeal. And it was not until the 18th ATCM (Italy, 1992), just after the adoption of the Environmental Protocol, and with the additional administrative complexities that came with it, that consensus on the need for a secretariat emerged.

Even so, the Secretariat of the Antarctic Treaty was not established until September 2004. As of 2013, the secretariat includes an executive secretary, an assistant executive officer and seven other staff, and is based in Buenos Aires (Box 16.4).

**Box 16.4: Establishing the Secretariat**

While discussions on the structure, functions and the legal requirements for the establishment of a secretariat were somewhat glacial in their pace, it was the matter of the secretariat's location that proved to be the real sticking point. During the 1990s, support for Buenos Aires as the location grew quickly, but consensus proved elusive, largely due to British concerns over the potential political capital that Argentina (a counter-claimant nation to the UK in Antarctica) would seek to gain from hosting a permanent Treaty Secretariat (Scoti 2003). As such, and as an example of the consensus decision making process in action, Britain withheld its support for Buenos Aires for several years.

After numerous bilateral negotiations with Argentina, Britain finally agreed to join a consensus of parties and, in 2001, with only one location formally on the table, ATCM XXIV (held that year in St Petersburg, Russia) decided that "the Antarctic Treaty Secretariat shall be established in Buenos Aires following the development of the necessary modalities and agreements, which the Parties shall urgently pursue" (ATCM Decision 1, 2001).

## 16.4 Evolution of the Antarctic Treaty System

The Antarctic Treaty has stood the test of time despite significant criticism from non-party nations and external challenges to its legitimacy, not least through a Malaysian-led attempt throughout the 1980s and 1990s to dissolve the Antarctic Treaty and bring governance of Antarctica under the purview of the UN (Beck 1986, 1989). The Treaty has provided a solution to the political tensions that surrounded Antarctica in the first half of the twentieth century because the alternative, i.e. disintegration of the system and potential conflict, remains too difficult to contemplate (Beck 1991a, b).

However, there are certain matters related to the management and governance of Antarctica that the treaty itself does not address, such as resource use and environmental management, largely because these issues were not of importance at the time the treaty was negotiated. To deal with such issues, a series of separate, free-standing agreements have been negotiated over time. These are:

- The Agreed Measures on the Conservation of Antarctic Fauna and Flora (concluded in 1964, entered into force in 1982);

- The Convention on the Conservation of Antarctic Seals (CCAS; concluded in 1972, entered into force in 1978);
- The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR; concluded in 1980, entered into force in 1982);
- The Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA; concluded in 1988, but has not entered into force);
- The Protocol on Environmental Protection to the Antarctic Treaty (concluded in 1991, entered into force in 1998).

### *16.4.1 Agreed Measures*

Even though the issue of managing the natural environment of Antarctica is not explicitly considered in the treaty itself, the matter was discussed at the very first Antarctic Treaty meeting in July 1961. Just two meetings later, in 1964, the parties adopted the Agreed Measures for the Conservation of Antarctic Fauna and Flora (Agreed Measures).

The Agreed Measures recognised the scientific importance and unique nature of the region's fauna and flora, and:

- Required permits to be issued for killing, wounding, capturing or molesting any native mammals or birds (including for scientific purposes);
- Provided for the designation of 'specially protected species';
- Allowed for the introduction of 'specially protected areas' for areas of outstanding scientific interest;
- Introduced controls on the importation of non-native species into Antarctica.

The Agreed Measures provided the foundation for managing the Antarctic environment for almost 30 years. Under the provisions of the Agreed Measures, 29 specially protected areas were established in Antarctica. It was not until 1991 that the Agreed Measures were superseded by the more comprehensive Protocol on Environmental Protection to the Antarctic Treaty (see below); though it is worth noting that Annex II to the Environmental Protocol is based significantly on the provisions of the Agreed Measures.

### *16.4.2 Convention on the Conservation of Antarctic Seals (CCAS)*

Commercial sealing in Antarctic waters was discussed at the fourth ATCM in 1966 due to concerns over the potential resumption of the activity, and the Interim Guidelines for the Voluntary Regulation of Pelagic Sealing (Recommendation

IV-21) were adopted. Further elaboration of these guidelines took place over the next few years, and at a conference in 1972, the Seals Convention was adopted.

The Convention on the Conservation of Antarctic Seals (CCAS) aims to promote protection, scientific study and rational use of Antarctic seals, by:

- Establishing catch limits for specified seal species;
- Prohibiting the commercial take of Ross seals and Antarctic fur seals (which were designated as specially protected species under the Agreed Measures);
- Setting open and closed sealing seasons and establishing a number of sealing zones and three seal reserves around the Southern Ocean (Box 16.5).

**Box 16.5: Sealing in Antarctica**

Antarctic seals had been commercially and uncontrollably exploited since the late 1700s. In particular, Antarctic fur seals were almost totally removed from South Georgia by 1786 and from the South Shetland Islands by the early 1820s (Heap 1994). Commercial sealing fell away in the late 1800s, although commercial harvests of elephant seals at South Georgia continued until the 1960s.

In 1964, a sealing expedition took place to Antarctica to determine if crabeater seals (known to exist in huge numbers) might be economically exploited (Heap 1994). Although the industry never materialised, the expedition provided a warning to the Treaty Parties.

At a meeting of parties to CCAS in 1988 it was agreed that commercial sealing had not re-emerged and looked unlikely to do so. Nevertheless, the convention remains in force and countries can still sign and ratify the convention if they so wish. A list of parties to the Seals Convention is provided in Table 16.3.

### *16.4.3 The Convention on the Conservation of Antarctic Marine Living Resources*

At the ninth Antarctic Treaty meeting in 1977, the parties called for a Special Consultative Meeting to address governance and conservation of Antarctic marine living resources. Negotiations lasted over 2 years (1978–1980) until the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) was adopted. It entered into force on 7 April 1982. The list of parties to CCAMLR is provided in Tables 16.4 and 16.5.

The Convention broke new ground by taking an ecosystem-wide approach to fisheries management, aiming to take account of the effects of fishing on target species as well as on dependent and associated species. It also aims to ensure the maintenance of marine ecological relationships. Given the central role of krill as a prey species in the Southern Ocean food web (Chap. 12) such an approach was

**Table 16.3** Consultative parties and non-consultative parties to the Antarctic Treaty that are also parties to the Antarctic Seals Convention (CCAS), with the date of deposit of instrument of ratification

| Country | Entry into force |
|---|---|
| Consultative parties | |
| Argentina | 7 Mar 1978 |
| Australia | 1 Jul 1987 |
| Belgium | 9 Feb 1978 |
| Brazil | 11 Feb 1991 |
| Chile | 7 Feb 1980 |
| France | 19 Feb 1975 |
| Germany | 30 Sep 1987 |
| Italy | 2 Apr 1992 |
| Japan | 28 Aug 1980 |
| Norway | 10 Dec 1973 |
| Poland | 15 Aug 1980 |
| Russian Federation | 8 Feb 1978 |
| South Africa | 15 Aug 1972 |
| United Kingdom | 10 Sep 1974 |
| United States | 19 Jan 1977 |
| Non-consultative parties | |
| Canada | 4 Oct 1990 |
| Pakistan | 25 Mar 2013 |

essential. To have adopted a single species approach, as many regional fisheries management agreements have done, would have been to ignore the consequences of krill harvesting on many other Southern Ocean species.

CCAMLR extends beyond the Antarctic Treaty area by attempting to follow the natural oceanographic features of the polar frontal zone, or Antarctic Convergence,

**Table 16.4** List of contracting parties to the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR convention), that are also members of the commission

| Country | Entry into force | Date of becoming a member |
|---|---|---|
| Argentina | 27 Jun 1982 | 27 Jun 1982 |
| Australia | 7 Apr 1982 | 7 Apr 1982 |
| Belgium | 23 Mar 1984 | 23 Mar 1984 |
| Brazil | 27 Feb 1986 | 8 Jul 1986 |
| Chile | 7 Apr 1982 | 7 Apr 1982 |
| China | 19 Oct 2006 | 2 Oct 2007 |
| European Community | 21 May 1982 | 21 May 1982 |
| France | 16 Oct 1982 | 16 Oct 1982 |
| Germany | 23 May 1982 | 23 May 1982 |
| India | 17 Jul 1985 | 29 Jun 1986 |
| Italy | 28 Apr 1989 | 30 Jun 1990 |
| Japan | 7 Apr 1982 | 7 Apr 1982 |
| Korea (ROK) | 28 Apr 1989 | 19 Nov 1985 |
| Namibia | 29 Jul 2000 | 5 Feb 2001 |
| New Zealand | 7 Apr 1982 | 7 Apr 1982 |
| Norway | 5 Jan 1984 | 5 Jan 1984 |
| Poland | 27 Apr 1984 | 27 Apr 1984 |
| Russian Federation | 7 Apr 1982 | 7 Apr 1982 |
| South Africa | 7 Apr 1982 | 7 Apr 1982 |

(continued)

**Table 16.4** (continued)

| Country | Entry into force | Date of becoming a member |
|---|---|---|
| Spain | 9 May 1984 | 21 Oct 1987 |
| Sweden | 6 Jul 1984 | 30 Dec 1989 |
| Ukraine | 22 May 1994 | 14 Dec 1994 |
| United Kingdom | 7 Apr 1982 | 7 Apr 1982 |
| United States | 7 Apr 1982 | 7 Apr 1982 |
| Uruguay | 21 Apr 1985 | 21 Apr 1985 |

**Table 16.5** List of contracting parties to the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR convention), that are not members of the commission

| Country | Entry into force |
|---|---|
| Bulgaria | 1 Oct 1992 |
| Canada | 31 Jul 1988 |
| Cook Islands | 19 Nov 2005 |
| Finland | 6 Oct 1989 |
| Greece | 14 Mar 1987 |
| Mauritius | 1 Nov 2004 |
| Netherlands | 25 Mar 1990 |
| Pakistan | 22 Feb 2012 |
| Panama | 19 Apr 2013 |
| Peru | 23 Jul 1989 |
| Vanuatu | 19 Aug 2001 |

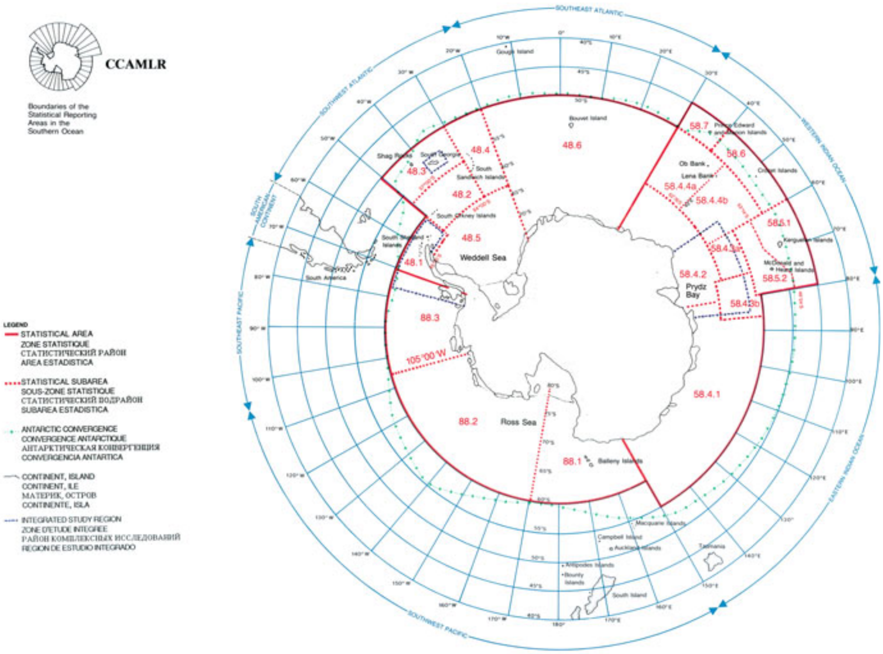



**Fig. 16.4** The area of application of CCAMLR and its statistical sub-units (With kind permission from CCAMLR)

thus encompassing the natural range of Antarctic krill and other harvested Antarctic marine species (Fig. 16.4). As a result, the convention area is considerably larger than the area covered by the Antarctic Treaty itself (Box 16.6).

**Box 16.6: Extraction of Marine Resources**

The concept of Antarctica as a pristine untouched wilderness does not apply to the Southern Ocean. Marine resources of the Southern Ocean have been exploited since the late 1700s (Chap. 20). Certain seal species were exploited to near extinction in the early 1800s. This was followed by commercial harvesting of whales in the Southern Ocean in the late 1800s and early 1900s. Having resolved the issue of regulation of commercial sealing in 1972, the Treaty Parties turned their attention to other matters related to marine resource exploitation. The need to do so stemmed in particular from the emergence of experimental fishing for Antarctic krill in the 1960s as well as a significant increase in Antarctic fin-fish fishing in 1969. These activities coupled with the emergence and expansion in the number of distant-water freezer trawlers gave a sense of urgency to the Treaty Parties in their attempts to manage marine resource activities (Heap 1994).

The convention also applies to species other than krill. Marine living resources are defined as including "the populations of fin fish, molluscs, crustaceans and all other species of living organisms, including birds, found south of the Antarctic Convergence" (Article I(2)).

The convention's objective is the conservation of Antarctic marine living resources, although Article II of the convention makes clear that the term conservation includes "rational use" (Box 16.7).

**Box 16.7: Conservation Principles of CCAMLR**

Article II of CCAMLR sets out the principles of conservation of the convention, which are to:

(a) Prevent harvested populations from falling to levels which mean that they cannot sustain themselves;
(b) Maintain ecological relationships between harvested, dependent and related populations of Antarctic marine species, as well as to restore already depleted populations, and
(c) Minimise the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades, taking into account several factors including: the state of available knowledge of the direct and indirect impacts of fishing; the effect of the introduction of species not native to the Southern Ocean; the effects of associated activities on the marine ecosystem, and of the effects of environmental change.

The convention established an institution which is the Commission for the Conservation of Antarctic Mineral Living Resources. The Commission is supported by a scientific committee, which provides scientific assessments and recommendations to the commission, and by a secretariat, headquartered in Hobart, Tasmania.

Like the ATCM, the commission takes decisions by consensus, in the form of Conservation Measures. Among other things, they set catch limits for harvested species, establish limits for by catch species, specify areas that are either open or closed to fishing, and determine fishing methods. Once adopted, the commission notifies a Conservation Measure to all its members. However, a key element of Article IX of the convention is its tacit approval mechanism, a point of difference to the decision making process of the ATCM. Article IX(6)(b) states that "conservation measures shall become binding upon all Members of the Commission 180 days after ... [notification] ...". Members of the commission are still required to incorporate the Conservation Measure within their own domestic law, but the Conservation Measure nevertheless becomes binding after the 180-day period.

There are currently (2013) 36 parties to CCAMLR, of whom 25 are full (voting) members and 11 are acceding states. Membership of the commission is open to those countries that are engaged in research or harvesting activities to which the convention applies (Tables 16.4 and 16.5). Unlike the Antarctic Treaty, which is open only to individual countries, CCAMLR provides for regional economic organisations, such as the European Union to become a member, during such time as its member countries are so entitled. In this way, the European Union (EU) can be a member of the CCAMLR Commission, but cannot become a party to the Antarctic Treaty.

Since CCAMLR entered into force in 1982, there has been steady progress in developing a scientific basis for assessing the status of and trends in the population of key species and in implementing conservation measures, particularly those aimed at restoring fish stocks depleted during the 1970s, and in elaborating a system of observation and inspection (Box 16.8).

**Box 16.8: Illegal Fishing**

During the late 1990s and early 2000s, CCAMLR was faced with combating high levels of illegal, unregulated and unreported (IUU) fishing in its waters. The high incidence of IUU fishing has had a detrimental effect on some toothfish stocks (the most lucrative Antarctic fish), particularly in the Indian Ocean part of the CCAMLR area, and has impacted heavily on seabird populations. Whereas legal fishing vessels are required to report regularly on the amount of fish they are catching and from where, the lack of information from IUU fisheries undermines CCAMLR's Conservation Measures and severely complicates efforts to determine future trends of harvested species with any level of certainty.

The introduction of a catch documentation scheme (CDS) by CCAMLR in 2000 to monitor landings of and global trade in toothfish was an unprecedented initiative, aimed at eliminating IUU fishing in the convention area. Other such measures include strict vessel licensing requirements, at-sea and port vessel inspections and the requirement for the continuous monitoring of vessel positions in the convention area, using automated satellite-linked monitoring systems.

CCAMLR annually reviews information on IUU fishing activities in the convention area and, in accordance with relevant Conservation Measures, has established a list of IUU vessels of contracting and non-contracting parties that are undermining the effectiveness of CCAMLR. Collectively, these initiatives have contributed to a significant overall decline in IUU fishing since 2003 (CCAMLR 2010).

### *16.4.4 Convention for the Regulation of Antarctic Mineral Resource Activities*

The convention is a complex document comprising 67 articles. It applies to the continent of Antarctica and all Antarctic islands, including all ice shelves, south of 60° South, as well as the seabed and subsoil of adjacent offshore areas up to the deep seabed, an area beyond the continental shelf break.

Article 4 states that adequate information should be obtained so that informed judgments can be made about the potential impacts of activities, particularly on the Antarctic environment. Article 4 also states the importance of safe technology and procedures, of monitoring environmental impacts and of the ability to respond to environmental emergencies. These principles provide a sense of the strong environmental protection provisions, which are at the heart of the convention.

In order to regulate activity relating to Antarctic mineral resources, CRAMRA envisages the establishment of:

- The Antarctic Mineral Resources Commission as the ultimate decision making authority;
- The Scientific, Technical and Environmental Advisory Committee;
- Special meetings of parties;
- Regulatory committees for geographical areas of mineral resource interest, and
- A secretariat to serve the commission and its supporting committees and meetings.

Any operator wishing to undertake mineral resource activities would need to apply for three distinct stages: prospecting, exploration and development, with the latter two phases requiring a management scheme by the relevant regulatory committee.

All in all, CRAMRA established a detailed regulatory regime for Antarctic mineral resource activities with strict provisions in place to protect the Antarctic environment (Box 16.9).

**Box 16.9: Mining in Antarctica**

The Antarctic Treaty is largely silent on the issue of resource use in Antarctica. During negotiations of the Antarctic Treaty consideration had been given to the question of mineral exploration and exploitation, but it was agreed that it would be premature to include any provisions relating to the issue in the treaty itself. However, if there had been any hope among some states that the issue of mining in Antarctic might simply go away, it became clear fairly quickly that it would not. Within less than a decade of the treaty entering into force, a number of treaty states had received enquiries from marine geophysical prospecting companies about the potential to undertake exploratory activities in Antarctic waters (Heap 1994). While the matter received some attention, it was not until the 11th ATCM in 1981, after CCAMLR negotiations had finished, that the parties agreed to convene a special consultative meeting to discuss mineral resource activities. The negotiations themselves were lengthy and involved. The meeting held 12 sessions from 1982, and in 1988, the Convention for the Regulation of Antarctic Mineral Resource Activities (CRAMRA) was adopted by consensus of the Consultative Parties.

However, despite the significant effort that went into negotiating the convention, CRAMRA is unlikely to enter into force. During the 6 years the convention was being negotiated, concerns were expressed by non-governmental organisations (NGOs) and political commentators that limitations on liability and provisions for environmental protection were not sufficiently strict (Hansom and Gordon 1998). Perhaps more significantly, the very principle of mining in Antarctica was thought to be incompatible with environmental protection, a view that was reinforced by the sinking of the Argentine vessel *Bahia Paraiso* near Anvers Island in January 1989 as well as the *Exxon Valdez* oil spill in Alaska, just a few months later. NGOs ran a vociferous campaign during the 1980s calling on Antarctica to be declared a world park. Some claimant countries also (more quietly) retained a concern that permits to undertake mining could be granted within their claimed territory without their approval.

As a result of these tensions, and within just a few months of CRAMRA being agreed, both Australia and France stated that they would not sign the convention. Both countries stated their preference for a more comprehensive environmental protection regime that included a prohibition on mining (Beck 1991b). This action by Australia and France was quickly followed by New Zealand, which in 1990 announced that it too would neither sign nor ratify the convention. Given that the convention required ratification by 16 states, including all claimant nations (which Australia, France and New Zealand are), the positions taken by these 3 governments effectively sealed CRAMRA's fate.

The demise of CRAMRA created a significant gap in the Antarctic Treaty System and left it open to potential criticism from outside, not least from the United Nations, which for several years, under a Malaysian-led initiative had been debating whether to subsume the governance of Antarctica under the UN (Kammerer 1992). As a result, several Antarctic Treaty countries saw the need to develop a comprehensive environmental protection regime.

### *16.4.5 The Protocol on Environmental Protection to the Antarctic Treaty*

Following CRAMRA's demise, there was political urgency to develop a new environmental regime. Many of the potential component parts of such a regime were already in place either as recommendations adopted by earlier ATCM's or as part of CRAMRA. The Protocol on Environmental Protection to the Antarctic Treaty (the protocol) builds on these early provisions and fills in any gaps. The protocol was agreed in Madrid in 1991, just 2 years after the demise of CRAMRA, and entered into force in 1998.

The protocol aims to protect the Antarctic environment and ecosystems. It designates Antarctica as "a natural reserve, devoted to peace and science", and sets forth legally binding environmental protection provisions, which must be applied to all Antarctic activities.

On the issue of mineral resource activities (mining and hydrocarbon extraction), the protocol introduces a prohibition on all such activities except for those related to scientific research. This represents a fascinating turnaround in the collective thinking of the Treaty Parties. Having spent much of the 1980s negotiating a regime to regulate such activities, 2 years later they were able to agree on an outright ban (Box 16.10).

**Box 16.10: A 50-year Mining Ban: True or False?**
There is a common misconception that the prohibition on mining runs out after a 50-year period. That is incorrect. The prohibition on mineral resource activities is an indefinite prohibition. However, the protocol does contain provisions that allow changes to be made to any part of it at any time, provided that such changes are agreed by consensus. However, 50 years after the protocol entered into force (i.e. after 14 January 2048), any party can request a conference to review the protocol, and any changes that are made at such a conference need only be agreed by a simple majority of the parties, provided that majority includes three-quarters of the parties that were consultative parties at the time the protocol was adopted. Regardless of any such reviews of the protocol (before or after 2048), the protocol states that the ban on mineral resource activities must remain unless there is put in place a binding legal regime to regulate such activities (i.e. something akin to CRAMRA).

The protocol also establishes a new body: the Committee for Environment Protection. All parties to the protocol are entitled to be a member of the committee. The list of parties to the Environmental Protocol is shown in Table 16.6.

The committee is an expert advisory body (not a decision-making body) providing advice and formulating recommendations to the Antarctic Treaty Consultative Meetings. It also advises on the:

- Means for minimising or mitigating environmental impacts;
- Procedures for situations requiring urgent action;
- State of the Antarctic environment, and
- The need for scientific research in support of the protocol's objectives.

The first meeting of the committee took place in 1998 and meetings occur annually and normally in conjunction with ATCMs. Detailed mandatory rules for environmental protection are incorporated in a series of annexes to the protocol. These are:

- Annex I on environmental impact assessment (adopted 1991; entered into force 1998);
- Annex II on conservation of Antarctic fauna and flora (adopted 1991; entered into force 1998; revised 2009)

**Table 16.6** Parties to the Protocol on Environmental Protection to the Antarctic Treaty, showing the date of entry into force

| Country | Environmental Protocol |
|---|---|
| Consultative parties | |
|  Argentina | 14 Jan 1998 |
|  Australia | 14 Jan 1998 |
|  Belgium | 14 Jan 1998 |
|  Brazil | 14 Jan 1998 |
|  Bulgaria | 21 May 1998 |
|  Chile | 14 Jan 1998 |
|  China | 14 Jan 1998 |
|  Czech Republic | 24 Sep 2004 |
|  Ecuador | 14 Jan 1998 |
|  Finland | 14 Jan 1998 |
|  France | 14 Jan 1998 |
|  Germany | 14 Jan 1998 |
|  India | 14 Jan 1998 |
|  Italy | 14 Jan 1998 |
|  Japan | 14 Jan 1998 |
|  Korea (ROK) | 14 Jan 1998 |
|  Netherlands | 14 Jan 1998 |
|  New Zealand | 14 Jan 1998 |
|  Norway | 14 Jan 1998 |

(continued)

**Table 16.6** (continued)

| Country | Environmental Protocol |
|---|---|
|  Peru | 14 Jan 1998 |
|  Poland | 14 Jan 1998 |
|  Russian Federation | 14 Jan 1998 |
|  South Africa | 14 Jan 1998 |
|  Spain | 14 Jan 1998 |
|  Sweden | 14 Jan 1998 |
|  Ukraine | 24 Jun 2001 |
|  United Kingdom | 14 Jan 1998 |
|  United States | 14 Jan 1998 |
|  Uruguay | 14 Jan 1998 |
| Non-consultative parties | |
|  Belarus | 15 Aug 2008 |
|  Canada | 13 Dec 2003 |
|  Greece | 14 Jan 1998 |
|  Monaco | 31 Jul 2009 |
|  Pakistan | 31 Mar 2012 |
|  Portugal | 10 Oct 2014 |
|  Romania | 05 Mar 2003 |
|  Venezuela | 31 Aug 2014 |

The table is divided into consultative parties to the treaty and non-consultative parties to the treaty

- Annex III on waste disposal and waste management (adopted 1991; entered into force 1998)
- Annex IV on the prevention of marine pollution (adopted 1991; entered into force 1998)

- Annex V on area protection and management (adopted 1991; entered into force 2002)
- Annex VI on liability for environmental damage (adopted 2005; not yet entered into force).

This modular approach to the protocol was deliberate. Each annex can be modified at any time and additional annexes can be added as agreed by the parties.

Annex I to the protocol requires an environmental impact assessment to be undertaken prior to any activity occurring in Antarctica. This requirement applies to any activity within the Antarctic Treaty area whether conducted by government programmes, non-governmental organisations or commercial companies. The annex sets out three levels of environmental impact assessment: a preliminary assessment, an initial environmental evaluation (IEE) and a comprehensive environmental evaluation (CEE). The level of impact assessment to be applied depends upon the nature and potential environmental consequences of the activity in question.

Activities assessed at preliminary and IEE levels are normally handled within the domestic legal and administrative systems of the various Treaty Parties. Such procedures are normally managed by a relevant government department or agency. However, if an activity is assessed at the level of a CEE, then the draft document must be made publicly available for comment, circulated to all parties to the protocol and forwarded to the Committee for Environmental Protection. Annex I states that the activity in question cannot proceed unless there has been the opportunity for consideration of the draft CEE by the CEP and the ATCM (Box 16.11).

**Box 16.11: Environmental Impact Assessments**

The protocol is not explicit about what level of environmental impact assessment to apply to various activities. Instead it says that the nature of the assessment required depends upon whether the activity in question is identified as having “less than”, “no more than” or “more than” a minor or transitory impact upon the Antarctic environment. However, the terms minor and transitory are not defined.

If an activity is deemed likely to have less than a minor or transitory impact, then it can simply proceed. Such activities might include a small, short-term scientific field camp for example. Activities considered likely to have no more than a minor or transitory impact require an initial environmental evaluation (IEE) and might include adding a new building to an existing station, or conducting a slightly longer-term scientific study. Larger-scale activities, which have the potential for impacts of a more than minor or transitory nature, such as constructing a new runway or a new Antarctic base, require a far more detailed comprehensive environmental evaluation (CEE).

Annex II puts in place a number of provisions to protect Antarctic wildlife, including:

- A prohibition on taking or harmful interference, except with a permit;

- A prohibition on introducing non-native species, except with a permit; and
- The ability to designate native mammals, birds and plants as Specially Protected Species (Box 16.12).

**Box 16.12: Non-native Species in Antarctica**

It is easy to think of Antarctica as a remote, cold and desolate place, somewhat self-protecting from invasion from non-native species. But parts of Antarctica are warming quickly, and the numbers of people going to Antarctica are increasing. As a result the risks of new species migrating to Antarctica and becoming established are also increasing (Chap. 27). Indeed non-native species have been found in parts of Antarctica (Frenot et al. 2005; CEP 2010). One example is the discovery of *Poa annua* (a grass species) on King George Island, northern Antarctic Peninsula. The grass has not only become established, but has also survived several seasons and has expanded its coverage (Olech and Chwedorzewska 2011; Fig. 16.5).

The Committee for Environmental Protection has placed the management of non-native species as the highest priority on its agenda, and has endorsed a range of guidance materials aimed at minimising the risk of inadvertent introduction of non-native species to the region (ATCM 2011). However, it will require all countries operating in Antarctica to implement such measures if they are to have any effect.

**Fig. 16.5** *Poa annua*, a non-native species to Antarctica, photographed at the Henryk Arctowski Polish Station on King George Island, Antarctic Peninsula (With kind permission from Katarzyna Chwedorzewska)

**Fig. 16.6** Cape Hallett station, in the Ross Sea region of Antarctica, was a joint US/New Zealand station that was constructed in the late 1950s and abandoned in the early 1970s. Over three field seasons between 2004 and 2007, the US and New Zealand cooperated in a joint clean-up and removal of the station (With kind permission from Antarctica New Zealand Pictorial Collection, Photo: Rebecca Roper-Gee K500-04/05)

Annex III has had a significant impact on national Antarctic programmes and operators, given its requirements to remove all wastes from Antarctica. The annex also establishes general rules for storage and disposal of waste and prohibits disposal of any waste, including human waste, on ice-free ground or into freshwater systems, although human waste can be disposed of on ice shelves, or in to the sea.

Old waste dumps and abandoned work sites are required to be cleaned up, provided that this does not cause greater environmental harm (Fig. 16.6).

Discharge of oil, noxious liquids and garbage in the sea within the Antarctic Treaty area is prohibited under the provisions of Annex IV, which also requires parties to develop emergency response plans and to cooperate in responding to marine pollution emergencies (Box 16.13).

**Box 16.13: Managing Marine Pollution**

The Treaty Parties have expanded upon the provisions of Annex IV in a number of ways. Concerns were raised by a number of Treaty Parties over the use of heavy (less environmentally friendly) fuel oil by some ships operating in

(continued)

**Box 16.13** (continued)
Antarctic waters. The 28th ATCM requested the International Maritime Organization (IMO) to examine the use of heavy fuel oil in Antarctic waters, due to the potential for fuel spills in the treaty area arising from risks such as icebergs, sea ice and uncharted waters, and the high potential for environmental impacts should a spill of such fuel occur. Further, in 2006, the 29th ATCM adopted the Practical Guidelines for Ballast Water Exchange in Antarctic Waters (Resolution 3, 2006), which were subsequently adopted by the IMO.

Annex V of the protocol designates two types of special site: Antarctica Specially Protected Areas (ASPAs) and Antarctic Specially Managed Areas (ASMAs). Any area, including any marine area, may be designated as an Antarctic Specially Protected Area "to protect outstanding environmental, scientific, historic, aesthetic or wilderness values, any combination of those values, or ongoing or planned scientific research". Both require the preparation of a management plan. Entry into an ASPA is prohibited except in accordance with a permit and management of ASMAs is carefully coordinated although no entry restrictions apply. A review of all management plans must be initiated at least every 5 years.

As of 2013 there are 73 ASPAs and seven ASMAs that have been designated across the continent (Fig. 16.7).

Annex V also provides for sites of recognised historic value to be listed as a historic site or monument. Such sites can also be designated as an ASPA or ASMA. The list of historic sites and monuments is held under Decision 3 (2003).

Article 16 of the protocol requires the parties to elaborate rules and procedures relating to liability for damage resulting from activities in the Antarctic Treaty area. Although it took some time to achieve (largely due to significant differences between countries on how comprehensive the regime should be), the 28th ATCM (Sweden, 2005) adopted Annex VI to the protocol, which deals with environmental emergencies related to scientific research programmes, tourism and all other governmental and non-governmental activities in the Antarctic Treaty area. The operators of such activities should undertake preventative measures and establish contingency plans for responses to incidents with adverse impact on the Antarctic environment. In case of environmental emergencies, operators must respond promptly and effectively or, if they fail to do so they could be held liable for any costs, including any costs incurred by another party responding to the incident.

Annex VI will enter into force after its approval by all consultative parties that participated in the Sweden ATCM.

Without doubt the Environmental Protocol has been a significant milestone in the evolution of the Antarctic Treaty System. It synthesises a raft of earlier treaty measures and establishes a comprehensive regime for the protection of the Antarctic environment. Nevertheless, as is the case with much Antarctic law, the true effectiveness of the protocol relies on the commitment of the parties to implement and enforce its provisions consistently, as well as to support and enforce the recommendations and advice stemming from the CEP.


Fig. 16.7 An overview map of ASMA number 2, the McMurdo Dry Valleys. The McMurdo Dry Valleys are characterised as the largest, relatively ice-free region in Antarctica with approximately 30 % of the ground surface free of snow and ice. The region encompasses a cold desert ecosystem, whose climate is not only cold and extremely arid, but also windy. The landscape of the area contains glaciers, mountain ranges, ice-covered lakes, meltwater streams, arid patterned soils and permafrost, sand dunes, and interconnected watershed systems. The McMurdo Dry Valleys was first designated as ASMA number 2 in 2004. The management plan for the ASMA was revised in 2011 (With kind permission from Antarctica New Zealand)

## 16.5 The Antarctic Treaty System

The Antarctic Treaty, the various additional agreements made under the auspices of the treaty, together with the regular meetings and agreements made at those meetings, are collectively known as the Antarctic Treaty System. The system is summarised in the model shown in Fig. 16.8, which has been updated and adapted from Harris and Meadows (1992).

The model demonstrates the central and overarching status of the Antarctic Treaty itself. From this agreement the system has grown to include:

- Additional agreements relevant to the Antarctic and the Southern Ocean (the Agreed Measures, CCAS, CCAMLR and CRAMRA);
- The regular meetings of the bodies established by these various agreements (i.e. annual meetings of CCAMLR, the ATCM and the CEP);
- Two permanent secretariats for CCAMLR and the ATCM, and
- Relationships that the treaty parties have established with external bodies such as SCAR and COMNAP, as well as technical expert bodies such as IAATO, IMO and ASOC.

This overview helps to illustrate how the regime has grown since 1959 when just 12 countries agreed the (relatively short) Antarctic Treaty. It also helps to show the

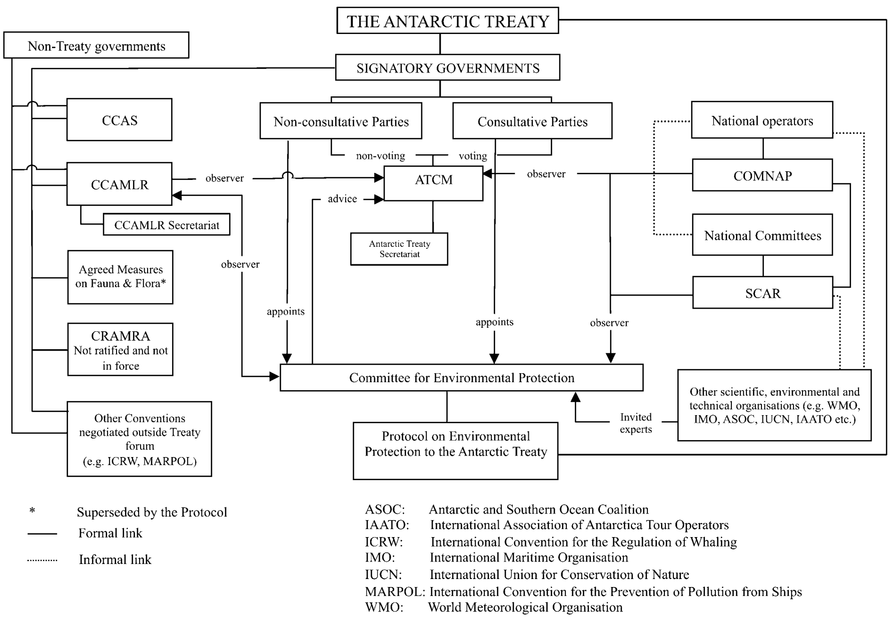



**Fig. 16.8** Summary model of the Antarctic Treaty System showing the primary interactions and relationships (Adapted and updated from Harris and Meadows 1992)

significant international effort that has been and continues to be put in to the governance and management of Antarctica and the Southern Ocean.

## 16.6 The Antarctic Treaty System and Future Challenges

The Antarctic Treaty is one of the most successful international agreements. It has stood the test of time, and for more than 50 years has provided the foundation for peaceful cooperation in the region. Its membership has grown from the original 12 signatory nations to almost 4 times that number. Over time, the Treaty Parties have negotiated additional agreements, which provide robust regulation of human activities in Antarctica. The Antarctic Treaty System has also withstood external pressure and scrutiny, not least from the UN throughout the 'Question of Antarctica' debates of the 1980s and 1990s.

However, there are significant challenges ahead. Human activity in the region is increasing, new bases are being established, tourist numbers and the number and size of vessels cruising Antarctic waters have steadily increased, and commercial interest and technology continue to place pressure on marine resources. Such increasing human pressure on the environment is compounded by a significantly changing Antarctic and Southern Ocean climate, demanding ever closer attention if the intrinsic, environmental and scientific values of the region are to be maintained.

To be effective in managing increasing human activity within a rapidly changing climate, it is becoming increasingly apparent that the parties need to ensure a close and effective relationship with the Antarctic science community (not least through the Scientific Committee on Antarctic Research, SCAR), to ensure that policy debates are well informed and that management decisions are scientifically supported.

Further still, the Antarctic Treaty System will need to continue to demonstrate its ability to govern effectively what amounts to 10 % of the planet's surface area, while at the same time maintaining adequate links with other interested international agreements and organisations.

To achieve these outcomes, the Treaty Parties will need to remain alert, be prepared to adapt, remain proactive and to the extent possible anticipate future challenges, to ensure that for at least the next 50 years Antarctica is maintained for peaceful and scientific purposes.

## References

ATCM (2011) Non-native species manual, adopted by means of ATCM Resolution 6

Beck P (1986) Antarctica at the United Nations, 1985: the end of consensus? Polar Rec 23:159–166

Beck P (1989) Antarctica at the UN 1988: seeking a bridge of understanding. Polar Rec 25:329–334

Beck P (1991a) The Antarctic resource conventions implemented: consequences for the sovereignty issue. In: Jorgensen-Dahl A, Ostreng W (eds) The Antarctic treaty system in world politics. Macmillan, Basingstoke, pp 229–276

Beck P (1991b) The 1991 UN session: the environmental protocol fails to satisfy the Antarctic Treaty System's critics. Polar Rec 28:307–314

CCAMLR (2010) http://www.ccamlr.org/pu/E/sc/fish-monit/iuu-intro.htm

CEP (2010) Colonisation status of known non-native species in the Antarctic terrestrial environment. Information Paper 42 submitted to the 13th meeting of the Committee for Environmental Protection by the United Kingdom

Frenot Y, Chown SL, Whinam J, Selkirk PM, Convey P, Skotniki M, Bergstrom DM (2005) Biological invasions in the Antarctic: extent, impacts and implications. Biol Rev 80:45–72

Hansom JD, Gordon JE (1998) Antarctic environments and resources: a geographical perspective. Addison Wesley Longman Ltd, London

Harris C, Meadows J (1992) Environmental management in Antarctica. Instruments and institutions. Mar Pollut Bull 25:239–249

Heap J (1994) Handbook of the Antarctic Treaty System, 8th edn. US Department of State, Washington, DC

Kammerer J-A (1992) The protocol on environmental protection to the Antarctic Treaty. Law State 45:68–80

Olech M, Chwedorzewska KJ (2011) The first appearance and establishment of an alien vascular plant in natural habitats on the forefield of a retreating glacier in Antarctica. Antarct Sci 23:153–154

Scoti K (2003) Institutional developments within the Antarctic Treaty System. Int Comp Law Q 52 (2):473–487

Sollie F (1984) The development of the Antarctic Treaty System. In: Wolfrum R (ed) Antarctic challenge. Conflicting interests, cooperation, environmental protection, economic development. In: Proceedings of an interdisciplinary symposium, June 22–24. Dunker and Humbolt, Berlin

UNGA Official Records (1982) United Nations general assembly official records, 37th Session, U. N. Doc. A/37/PV.10 (1982), 17–20 Statement of Mahathir bin Mohamad

Watts A (1992) International law and the Antarctic Treaty System. Grotius Publications Limited, Cambridge

# Chapter 17
# Extreme and Unusual

## Psychology in Antarctica

**G. Daniel Steel**

**Abstract** The title for this chapter is taken from Suedfeld's (1987) influential chapter in the *Handbook of Environmental Psychology*. Suedfeld used two dimensions to classify environments. The first dimension, extremeness, is most often associated with Antarctica and can be defined by assessing how much technology is needed to keep one alive. The second dimension is unusualness. This describes the degree to which an environment is different from the one a person normally experiences. This aspect of the polar environment does not capture as much attention as extremeness but it can have a great influence on polar sojourners' thoughts, emotions and behaviours. Taken together, these simple two dimensions have had a long-standing impact on the manner in which psychological research is conducted in the polar regions. The principal focus of this chapter is the psychology of polar personnel. We begin with some historical examples of polar psychology, then move on to examine the results of more current scientific studies of human psychological adaptation in the southern continent. Next, we consider the question of who goes to Antarctica. This takes us into a description of one of the more robust findings of polar psychology, the 'three abilities', which is followed by an overview of what is known about the connection between personality and work performance on the Ice. The pathogenic aspect of Antarctic work includes a discussion of two other areas of research: the third-quarter phenomenon and winter-over (or T3) syndrome. The chapter concludes on a more positive note as we move into a discussion of the salutogenic effects (Antonovsky A, Unraveling the mystery of health: how people manage stress and stay well. Jossey-Bass, San Francisco, 1987) of a polar deployment.

**Keywords** Polar personality • Third-quarter phenomenon • Winter-over syndrome • Insomnia

G.D. Steel (✉)
Faculty of Environment, Society and Design, Lincoln University, Lincoln, New Zealand
e-mail: Gary.Steel@lincoln.ac.nz



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_17

## 17.1 Lessons from History

Because polar psychology is such a young field of study, it is easy to forget that the phenomena it deals with have been around for as long as people have been journeying to Antarctica. Most polar students will be well familiar with the stories of Scott and Shackleton, and the challenges they faced. Much has already been written about these expeditions, so we will turn, instead, to a lesser-known but very instructive episode in polar exploration; the Belgica expedition.

The *Belgica* sailed for Antarctica in late August of 1897, under the command of Adrien de Gerlache, and with a crew of 19 onboard. This number included one Dr Frederick Cook, who was listed as surgeon, anthropologist and photographer (Cook 1900). Such a combination of roles was not unusual for early expeditions. Small ships and limited resources meant that a person, especially if well educated, needed to take on several occupations.

The Belgica expedition is most famous among polar scholars because it was the first expedition to spend an entire winter in Antarctica. This occurred when the ship and crew found themselves trapped by the pack ice in the Bellingshausen Sea. Whether or not this had been planned by the captain of the ship is debated even today. It seems unlikely. More probable is that it was simply a matter of bad luck. This was the first time that European explorers had endured the rigours of 24-h darkness in the depth of an Antarctic winter, and the observations of Cook during the winter period provide a fascinating insight into their difficulties.

On May 31, 1898, Frederick Cook wrote in his diary:

> . . .we had placed before us the outline for industrious occupation; but we did little of it. As the darkness increased our energy waned. We became indifferent, and found it difficult to concentrate our minds or fix our efforts to any one plan of action . . . The men were incapable of concentration, and unable to continue prolonged thought.

The next day, he added:

> During the early part of the night it is next to impossible to go to sleep, and if we did drink coffee we do not sleep at all. When we do sink into a slumber, it is so deep that we are not easily awakened.

These are the first recorded descriptions of the so-called winter-over syndrome, which is still noted in modern Antarctic bases. Frederick Cook had few medicines to offer the officers and sailors, and those he did have he found to be ineffective. Reasoning that what was needed was the opposite of the winter environment, Cook prescribed a change in diet, exercise and temperature. He had the men eat nothing but milk, cranberry juice and fresh meat (there were, of course, no fresh fruit or vegetables by that time), insured that their bedding was well aired so that they were as dry as possible, and he curtailed any work duties that he felt would be overly taxing. He also had the men sit in a small room with a hot stove, whose door was kept open so that his patients were exposed to warmth and very bright light. Eventually, the sailors came to refer to this as ‘the baking treatment’.

The mid-winter signs and symptoms he describes in his journal bear a strong resemblance to what is currently diagnosed as Seasonal Affective Disorder (SAD). This is a condition in which the person feels moderately to severely depressed, is excessively sleepy, becomes less sociable, and has an increased desire for carbohydrate-laden foods. It is most prevalent in the winter months and in populations who live at high latitudes. Amongst the more common treatments for SAD is exposure to very bright light for extended periods. Cook would not have been surprised. It is somewhat bemusing, however, to note that this treatment was not rediscovered by the wider medical community until the early 1980s (Rosenthal et al. 1984).

There are several such incidents throughout the history of polar exploration. Many of the problems we see in modern camps were faced by early explorers. It is beyond the scope of this chapter to review all of these episodes but the author recommends that any serious student of polar psychology look not only forward to what might be found, but back to what has already been discovered.

One enduring concern for leaders and managers of expeditions, from the days of the first ships reaching the ice to current times, is the selection of personnel. For several years, psychological fitness has been a formal requirement for working in Antarctica. The proper combination of assessment techniques has been an elusive goal for many polar psychologists; one that has occupied them for many decades. This search has not been a steady one, though, and it has been driven by the need to populate research camps and stations. Thus, there was a pronounced surge in research following the International Geophysical Year, but this effort tailed off at the beginning of the 1970s and very few selection studies have been carried out since then. Throughout this time, there has been much less research into the selection of team members for exploratory or adventure expeditions (Box 17.1).

In choosing amongst applicants, psychologists engage in two procedures: selecting out and selecting in (Suedfeld and Steel 2000). Selecting out involves screening for undesirable traits or conditions that would significantly reduce the chance of a successful polar deployment. These include such problems as substance abuse, mental disorders or antisocial tendencies. The assessment is normally done using published psychological instruments and an interview with a psychologist. However, this procedure is not carried out by all national programmes, and even then is mainly aimed at wintering personnel. It is rarely undertaken for private expeditions, short-term science groups and distinguished visitors.

Selecting in focuses on desirable traits. In recent years, there has been an increasing emphasis on this part of the process, perhaps because wintering in the Antarctic turned out not to be the uniformly distressing experience that it was first feared to be. Moreover, the working environment has changed significantly in the last half-century. Many of the perceived stressors, such as long-term confinement and extreme isolation, have been moderated substantially.

**Box 17.1: Who Makes a Good Tentmate?**

There are those who choose the much more adventurous experience of private expeditions in Antarctica. It is this group, and ones venturing in the northern polar regions, that psychologist Gloria Leon has chosen to study. The physical and social challenges that these expeditioners face are daunting. They may trek great distances across an ice sheet, living in small tents with one or two others, experiencing life-threatening weather conditions, and carrying most if not all that they need to survive during their expedition. Leon has found that successful polar adventurers are extraverted, psychologically resilient in the face of large stressors, and showed a very strong disposition to achieving goals (Leon 1991; Leon et al. 2002, 2011). Interestingly, poorer coping was associated with *seeking* social support. Similar characteristics were found in a study of an all-women Antarctic expedition team (Khan and Leon 1994), except that this team showed greater concern over interpersonal issues, and worked at overcoming these using problem-solving and sharing of positive emotions. Such positive emotions may arise through feelings of camaraderie and a sense of wonder and awe about the natural environment through which traverse teams pass (Atlis et al. 2004). Because of the comparable nature of the tasks and environments, these positive characteristics and experiences appear to be associated with adventuring in either polar regions.

## 17.2 The Three Abilities

The most robust set of findings to emerge over the past five decades of selection research has been the existence of the ‘three abilities’ (Taylor 1969, 1987). In the early 1960s, E. K. E. Gunderson first identified these characteristics in a study undertaken in a large US station (Gunderson 1963, 1973; see also Gunderson and Nelson 1965, 1966). Those who were rated highly by their managers and their peers generally scored well on three qualities: task ability, sociability and emotional stability.

Task ability is simply how well one performs the duties associated with their job. National programmes who field a winter-over group normally cannot afford to have more than one or two people in any of the necessary occupations. Thus, for example, if the person who handles the water supply is not very good at his or her job, then the people on base may find themselves unexpectedly taking cold showers or drinking poor-quality water. Poor task ability has obvious repercussions on the popularity of that person and on the functioning of the crew.

Sociability is the ability to interact smoothly with other people. This includes accurate social perception – quickly summarising the situation or the person’s mood – and a wide repertoire of social skills that enables a person to act appropriately. Sociability is important in small groups that are confined to one location for great lengths of time. In such situations, group members interact with one another more frequently than they would in their off-ice environments. It is only with

**Fig. 17.1** Increased isolation brings with it a greater need for good social skills

difficulty that a station crew member can avoid another member. Because of this, any tension that arises amongst members can be exacerbated very quickly. It can also spread rapidly in the group (Fig. 17.1).

Emotional stability also makes its biggest impact in social situations. Polar workers who are emotionally stable show infrequent and small mood swings, and such mood changes have easily justifiable causes. This gives predictability. One knows, with a reasonable degree of certainty, how to interact with an emotionally stable person. Interestingly, this suggests that it is quite possible to be a relatively successful polar person even if one is grumpy, just as long as one is consistently so. While this is not the most desirable trait, others will know what to expect from that person and, one hopes, how to deal with her or him.

## 17.3 Personality and Performance

From the early 1960s onwards, interest in a possible 'polar personality' grew in the research community. This was, in part, connected to a desire to see if any improvement in selection criteria could be gained. However, the impact of this research on selection has been mixed. Some researchers have found only low-to-modest correlations between the three abilities and a measure assessing personality, while others have had more success. It is perhaps not surprising that there has been reasonably consistent support for a relationship between good performance and low scores on personality traits reflecting such things as vulnerability to stress and depression.

One study examined the effectiveness of a battery of psychological measures in predicting managerial ratings of the adaptation of members of the British Antarctic Survey to the polar environment (Grant et al. 2007). The study found that those personnel rated as well adapted were more likely to show a greater disposition towards focusing on one's emotions when under stress, and to being open to many different types of new experiences. Poorly adapted individuals, on the other hand, showed a greater tendency to react in a defensive, hostile manner.

The relationship between personality and performance is complex, and has been shown to interact with other factors. In fact, it is quite possible that the features of the Antarctic environment may nearly overwhelm any effect of personality. Summarising the research literature on personality and selection, Palinkas (2003, p 357) has suggested that:

> baseline measures of personality. . .are weak prospective predictors of behavior and performance during the winter because such performance is influenced more by the conditions of isolation and confinement than by stable traits of individuals.

### 17.3.1 The Polar Personality

Despite the lack of clear trait indicators of successful adaptation and performance in Antarctica, there are still reasons to study personality in the polar regions. People are not only chosen to go, they also choose to do so. This means that there are a group of readily identifiable people who decide to pursue something quite out of the ordinary. This pursuit takes time and effort, and often has costs associated with their families, income and career progression. It is natural to wonder whether or not there is something in the personalities of these individuals that makes them different from those that do not go south.

In one of the largest polar psychology studies to date, the Polar Psychology Project analysed the personality scores of 156 polar sojourners from eight nations during the time they were deployed. Interestingly, the overall analysis showed that the polar contingent did not differ significantly from a non-polar sample based in the US. One may infer from this that the modern amenities and requirements in Antarctica no longer demand a particular type of personality. Rather, the changes being made to living and working conditions have led to it being suitable for a wider variety of personality types.

### *17.3.2 Stability of Personality in Antarctica*

Other researchers have investigated the potential impacts on personality of a year's stay in Antarctica. Early research suggested that wintering was associated with an increase in personality traits that reflected feeling sad and lethargic, being taciturn, denial of hostile feelings and a lack of interest in seeking stimulation (Blackburn et al. 1973). However, later research has shown little effect of wintering on personality (Butcher and Ryan 1974; Paterson 1978). Taylor (1978, p. 33) concluded that 'results indicated that the basic personality structure of the men was unchanged after their Antarctic service'.

Other than the multinational Polar Psychology Project (Suedfeld et al. 1989; see also Steel et al. 1997), most of the research on personality to this time has used populations of predominantly Anglo-European descent (e.g., from the US, Australia and New Zealand). The cultural mosaic of Antarctica is much broader than this, however, and there have been some welcome additions to the research literature from new national programmes. Two studies of Japanese winter-over personnel have found that personality was stable and showed good levels of resilience and coping (Ikegawa et al. 1998; Weiss et al. 2000). Similar stability of personality has been found in a Chinese sample (Xue and Xue 1994).

The preponderance of evidence indicates that Antarctica makes little impact on the personality of polar sojourners. There is good reason to expect this. The main tenet of personality theory is that behavioural dispositions are generally stable across situations. It would seem that even the extreme physical nature of Antarctica, and the experiences that such an environment can bring about, are simply not enough to shift traits in any significant, long-term manner.

### *17.3.3 Other Considerations*

Several other personal characteristics have been found to be related to successful adaptation. Those who are older than 30 years of age, show a high tolerance for boredom, and are able to cope well with an inability to achieve goals all tend to do well. When contemplating such lists of characteristics, though, we need to consider the rapidly changing composition and, especially, the culture of polar stations (Sarris 2006, 2007, 2008). Aspects such as the increased proportion of women on base and wintering, the increased multicultural nature of the science and support personnel, the larger proportion of civilian (versus military) personnel, the increased ease with which most people travel to and from Antarctica in the summer months, and the far greater number of communication links available to polar personnel are all forcing psychological researchers to have another look at formerly robust predictors of Antarctic adaptation.

The changes listed above represent, in Suedfeld's (1987) terms, a reduction in the unusualness of the polar working environment. Although it is still not the same as home (for most polar workers), this moderation of the social and physical nature of the human experience in the southern continent has meant that the task of selecting personnel has become somewhat easier. In several national programmes, selection standards have been relaxed in recent years. Thus, the option of visiting and working in Antarctica is opening up to a more diverse population.

## 17.4 Antarctica as a Pathogenic Environment

The emphasis on possible connections between personality and Antarctic adaptation is based, in part, on the long-standing perception that living on the continent could only be regarded as distressful; something that must be endured and overcome. This is a pathogenic orientation – one that regards the Antarctic environment as almost inevitably leading to psychological problems (Suedfeld and Steel 2000). In times past, this stance was quite understandable, particularly given the often harrowing tales and public accounts that were published in the wake of the Heroic Age of Antarctic exploration. Polar psychology's infancy was largely taken up with identifying the potentially harmful effects of living in an isolated and physically demanding place.

As we shall see later in this chapter, there is a growing realisation that the experience of polar sojourning is not the inexorably detrimental environment first thought. In fact, experience in the polar region may lead to some substantial benefits to the polar sojourner. We begin this section, though, with a look at the darker side of living in Antarctica.

### *17.4.1 Sleep*

One of the most striking aspects of living in high latitudes is the unusual light cycle. For large parts of the year, and in most locations, there is 24-h sunlight or darkness. It is only in the brief transition seasons of spring and autumn that anything resembling a normal day/night pattern occurs. Because the daily (circadian) rhythms in most mammals – including human beings – show a synchrony with day/night cycles, Antarctica quite naturally drew the attention of chrono-psychologists interested in daylight's effect on human arousal responses. The majority of research into this area has focused on sleep.

Insomnia is recognised as one of the most common problems for polar sojourners. Two forms of this sleep disturbance – difficulty in falling asleep and difficulty staying asleep – are the two most prevalent forms of insomnia in the polar population. Insomnia can occur at any time during the year, but its highest incidence is during the middle periods of summer and winter; i.e. in 24-h light and 24-h darkness (Fig. 17.2).

It is believed that two environmental mechanisms work in combination to produce polar insomnia. First, 24-h daylight increases our psychological and physiological levels of arousal, possibly through the action of light on the hypothalamic–pituitary–thyroid system (Palinkas et al. 2007a). It has long been

**Fig. 17.2** Antarctic winters provide a diverse set of psychological challenges, but repay the effort with spectacular experiences not found in many other environments (© G.Daniel Steel)

known that exposure to light, especially bright light, has a direct impact on areas in the brain having to do with maintaining circadian rhythms. A second and less direct mechanism could have to do with the lack of naturally occurring external cues for sleeping (Czeisler et al. 1986; Dijk and Lockely 2002). Where there is no discernible evening or morning, Antarcticans may simply not notice the time of day, and thus fail to stay with a regular sleep/wake cycle.

Why is this important? As anyone who has experienced insomnia knows, there is a discernible loss in mental functioning that is the result of a lack of sleep (Coren 1996). This fuzziness is measurable as a loss in one's intelligence, one's memory and one's ability to make good decisions. In a physical environment as unforgiving as Antarctica, such a loss in mental capacity increases the risk of harm to oneself and one's fellow station members.

Besides a reduction in the amount of sleep, there is also evidence that life in Antarctica has a negative effect on the quality of sleep one obtains. Human beings normally experience four distinct stages of sleep, from light to deep, that are measurable using electroencephalogram (EEG) recordings. Research has shown that there can be an acute and complete loss of the deepest, slow-wave sleep (SWS) associated with Stage 4 sleep in new arrivals to the South Pole (Natani et al. 1970; Natani and Shurley 1974; Brooks et al. 1974). Recovery from this initial drop does normally occur, but it can be followed by a gradual, marked reduction in SWS through the course of the winter. This is of concern because research into sleep has shown that Stage 4 sleep has particular ties to memory consolidation (Diekelmann and Born 2010).

**Box 17.2: Antarctica: A Different State of Consciousness**

One of the features felt to be a stressor in Antarctica was the supposed monotony of the social and physical environment. Such monotony had been shown in laboratory studies to have some occasionally startling effects (Zubek 1973). Thus, a belief arose that the polar environment would bring about similarly odd problems in the human psyche.

Two effects were almost immediately identified: ‘long eye’ (Rohrer 1961) and ‘drifting’ (Popkin et al. 1974). Both these phenomena occurred in the mid- to late-winter period. Long eye was the name given to a condition in which a man would appear listless, often stare into space, and have a reduced awareness of his surroundings. It was colourfully described by one of Rohrer’s study participants as a ‘twelve-foot stare in a ten-foot room’. This altered state of consciousness could be easily interrupted or even set aside by the individual. Drifting resembles long eye in its mental blanking (Popkin et al. 1974, p 651) but lasts longer and is less able to be interrupted. In trying to explain both of these effects, Popkin and his colleagues drew on findings that increased staring and extended blank looks were associated with severe thiamine deficiency. A study of Amundsen-Scott South Pole station members showed that neither of these explanatory mechanisms was evident in the study group.

An alternative explanation may be that lower stimulation levels require less mental processing. This lack of engagement can be so strong that it may lead to a fugue-like state, in which a person wanders about with minimal or no conscious awareness (Mullin 1960). This is not, of course, a condition that is unique to Antarctica. Many automobile drivers in more mundane environments will have had the experience of driving from one point to another on a well-known route, only to arrive with very little awareness of the trip there.

Monotony may make it possible for particularly interesting or persuasive stimuli to more fully capture the polar sojourner’s consciousness. Barabasz (1991) confirmed support for these hypotheses, stating that exposure to the Antarctic environment can enhance hypnotisability (Barabasz 1978, 1980) and the ability to engage in deep, imaginative involvement (Barabasz et al. 1983).

## 17.5 Patterns Across a Season

### *17.5.1 The Third-Quarter Phenomenon*

In a modest but influential conference presentation in 1987, Robert Bechtel discussed anecdotes he had heard while conducting research into cold-weather phenomena. These stories suggested that the hardest part of winter for people came in the second half of the season. A further review of the research literature dealing with isolated environments led him to the hypothesis that the lowest point for a variety of psychological functions, but primarily mood and morale, comes around two-thirds of the way through a deployment. This point was approximately mid-way through the third quarter. Therefore, he labelled the collective effects associated with this period the ‘third-quarter phenomenon’ (Bechtel and Berning 1991).

An intriguing aspect of this phenomenon was that it was based on proportional time; not an absolute number of days, weeks, or months, or tied to a specific season. The hypothetical nadir would appear during the third quarter of the stay, whatever the length of that stay and whenever it began, as long as it had an expected end date. If this observation held, then polar psychologists (and others) could expect to see such things as mood and morale reach their lowest point 6 days into a 9-day visit, 16 weeks into a 6-month deployment, and approximately 8 months into a year-long deployment.

This was theoretically intriguing to researchers, and had the potential to be a highly useful tool for programme managers and Antarctic personnel. It began to generate research almost immediately. Taken across all measures examined to date, there is only moderate support for a third-quarter dip in levels. However, those that have dealt specifically with the trend of mood across time have shown a reasonably clear pattern. In these studies, mood appears to show a distinct drop at the expected time. There is also an unexpected, sharp increase in negative mood just before the end of deployment (Décamps and Rosnet 2005; Palinkas and Houseal 2000; Steel 2001).

What causes these swings and dips in mood? For the moment, we shall set aside speculation about the third-quarter phenomenon, reserving it for a later discussion in connection with ‘winter-over syndrome’. As for the curious spike in stress and negative mood during the last month, it is possible that station personnel come under increasing pressure as they attempt to complete their list of tasks and, at the same time, prepare for a major transition in their lives; namely, the return home. Such distress would be reflected in the types of data collected in these studies.

The changes in mood described immediately above do not, in general, meet the diagnostic criteria for any clinical disorder. However, certain disorders have a recognisable level just below the threshold at which they become a major impediment in one’s life. One of these is ‘sub-syndromal Seasonal Affective Disorder (s-SAD), in which the person may experience symptoms such as mild depression, a tendency to oversleep, and unusual weight gain during the winter. In a study conducted by Palinkas and his colleagues, levels of s-SAD during winter were found to be well above the level found in a US population in the mid-latitudes (Box 17.3).

**Box 17.3: Clinical Disorders in Antarctica**

The reader may have noticed that there has been a lack of discussion about psychological disorders in Antarctica. There is a very good reason for this. To quote Lawrence Palinkas and his colleagues (1995), “cases of psychoses and

(continued)

**Box 17.3** (continued)
other severe psychiatric disorders have been rare". While there certainly are records of events that clearly demonstrate the behaviour of an unbalanced mind, these events have been remarkably few, and well below the expected incidence in a randomly selected, non-polar population. Palinkas and Suedfeld (2007) have suggested that this may be due to the fact that most wintering personnel have been passed through a multi-level psychological screening prior to deployment. However, as any winter-over person will wryly tell you, such screening may reduce the odds of psychological disorders but not the level of eccentricity. Polar sojourners, as a group, are among the most colourful people one is likely to meet.

Although there is a lower prevalence of psychological disorders when compared to normative populations, the Antarctic population is not entirely free of such afflictions. Palinkas et al. (2004) found that 12.4 % of those going through a winter debriefing met criteria that would result in the diagnosis of a clinical disorder. The largest category was mood disorders, which accounted for approximately one-third of the total. The rest were related to adjustment disorders, sleep disturbance, personality issues and substance abuse, in descending order of prevalence.

### *17.5.2 Winter-Over and Polar T3 Syndromes*

Several researchers have noted that the depth of winter brings with it a decrease in morale, cognitive performance and physical activity levels, an increase in negative interpersonal reactions, and, as noted above, an increase in negative moods and sleep disturbance (see, e.g., Palmai 1963; Carrère et al. 1991; Oliver 1991; Palinkas and Cravalho 1995). Collectively, these came to be known as 'the winter-over syndrome' (Strange and Youngman 1971).

With respect to cognitive performance, research has examined performance in learning, memory and complex mental tasks (Strange and Klein 1974). The findings are complex and not completely clear. Most current research has found decrements in the accuracy, efficiency and response times of both simple and complex tasks (Palinkas and Suedfeld 2007; Palinkas et al. 2007a, b; Terelak et al. 1985). On the other hand, a few studies have shown that winter brings with it better cognitive performance (Paul et al. 2010). Thus, while the majority of evidence indicates that mental functioning in the winter is not as good as in the summer, it is still an area that requires further research to clarify the findings.

Early theory suggested that changes to mental functioning would be due to the isolated and confined nature of the social environment (Terelak 1986) or to changes in sleep (Natani and Shurley 1973). More recently, physiological explanations have come to the forefront. The effects associated with wintering bear a resemblance to low thyroid functioning, and there is a clearly defined trend in thyroid response over the course of an Antarctic deployment (Palinkas et al. 1997; Palinkas et al. 2007a, b; Reed et al. 1990, 2001). Because one of the hormones that marks the changes in thyroid functioning is triiodothyronine (T3), use of the term winter-over syndrome is slowly being replaced in many academic references, and colloquially, by the phrase ‘polar T3 syndrome’. Research has indicated that intervention using thyroid-stimulating substances may help moderate some of the psychological effects of winter. Thus, this is a promising area for future research.

## 17.6 Antarctica as a Salutogenic Environment

As noted earlier, Antarctica may not be as psychologically threatening an environment as early researchers believed. In fact, there have been several positive outcomes associated with Antarctic experience. In one of the earliest examples of this, Palinkas (1985) showed that deployment to Antarctica was positively correlated with lower rates of post-deployment hospitalisations. Several reviews of polar psychology research have noted positive incentives and pay-offs related to spending an extended time in Antarctica (Suedfeld 2001; Wood et al. 2000). These include the enjoyment of overcoming challenges (personal achievement), the growth of good social relationships, an increase in one’s sense of being an individual, and the ability to reflect and contemplate over an extended period away from normal daily hassles.

It is not surprising then, that experience in the polar environment can lead to a strong and positive relationship with it. While newcomers to the regions may feel more passionate about it, the degree to which one cares and feels committed to the polar regions does not appear to change substantially over several seasons (Steel 2000). Falling in love with Antarctica can lead to a deep and enduring attachment.

## 17.7 Summary

This chapter has provided a brief overview of polar psychological research over the last 50 years. This research has shown that the ideal polar worker is an emotionally stable and sociable individual who is well-trained and conscientious about her or his job. These people face several unusual circumstances, including isolation, continual cold, and 24-h daylight or night for several months of the year.

The reactions to these conditions can be highly idiosyncratic. However, there is evidence that insomnia is not an uncommon occurrence. It also appears that mood and certain types of cognitive performance drop in mid-winter, and that there may be a biological basis for some, if not all, of this winter-over syndrome. In spite of this, there is a growing list of positive psychological outcomes of Antarctic deployment.

## References[1]

Antonovsky A (1987) Unraveling the mystery of health: how people manage stress and stay well. Jossey-Bass, San Francisco

Atlis MM, Leon GR, Sandal GM, Infante M (2004) Decision processes and interactions during a two-woman traverse of Antarctica. Environ Behav 36:402–423

Barabasz AF (1978) Electroencephalography, isolation, and hypnotic capability at Scott Base. N Z Antarct Rec 1:35–42

Barabasz AF (1980) EEG alpha, skin conductance and hypnotizability in Antarctica. Int J Clin Exp Hypn 28:63–74

Barabasz AF (1991) Effects of isolation on states of consciousness. In: Harrison AA, Clearwater YA, McKay CP (eds) From Antarctica to outer space: life in isolation and confinement. Springer, New York, pp 201–208

Barabasz M, Barabasz AF, Mullins CS (1983) Effects of brief Antarctic isolation on absorption and hypnotic susceptibility. Int J Clin Exp Hypn 31:235–238

Bechtel RB, Berning A (1991) The third-quarter phenomenon: do people experience discomfort after the stress has passed? In: Harrison AA, Clearwater YA, McKay CP (eds) From Antarctica to outer space: life in isolation and confinement. Springer, New York

Blackburn AB, Shurley JT, Natani K (1973) Psychological adjustment at a small Antarctic station: an MMPI study. In: Edholm OG, Gunderson EKE (eds) Polar human biology: proceeding of the SCAR/IUPS/IUBS symposium on human biology and medicine in the Antarctic. William Heinemann, Chicago, pp 369–383

Brooks RE, Natani K, Shurley JT, Pierce CM, Joern A (1974) An Antarctic sleep and dream laboratory. In: Edholm OG, Gunderson EKE (eds) Polar human biology: proceeding of the SCAR/IUPS/IUBS symposium on human biology and medicine in the Antarctic. William Heinemann, Chicago, pp 322–340

Butcher JN, Ryan M (1974) Personality stability and adjustment to an extreme environment. J Appl Psychol 59:107–109

Carrère S, Evans GW, Stokol D (1991) Winter-over stress: physiological and psychological adaptation to an Antarctic isolated and confined environment. In: Harrison AA, Clearwater YA, McKay CP (eds) From Antarctica to outer space: life in isolation and confinement. Springer, New York, pp 229–238

Cook FA (1900) Through the first Antarctic night, 1898–1899: a narrative of the voyage of the Belgica among newly discovered lands and over an unknown sea about the South Pole. William Heinemann, London

Coren S (1996) Sleep thieves. The Free Press, New York

Czeisler CA, Allan JS, Strogatz SH, Ronda JM, Sanchez R, Rios CD, Freitag WO, Richardson GS, Kronauer RE (1986) Bright light resets the human circadian pacemaker independent of the timing of the sleep-wake cycle. Science 233:667–671

Décamps G, Rosnet EA (2005) A longitudinal assessment of psychological adaptation during a winter-over in Antarctica. Environ Behav 37:418–435

Diekelmann S, Born J (2010) The memory function of sleep. Nat Rev Neurosci 11:114–127

[1] The following is a list of suggested sources of information for those who may wish to pursue this topic in greater depth. Key summaries of various aspects of polar psychology can be found in:

Harrison, Clearwater, McKay (1991)
Stuster (1996)
Suedfeld and Steel (2000)
Taylor (1987)
Palinkas and Suedfeld (2007)

Dijk D-J, Lockely SW (2002) Invited review: integration of human sleep-wake regulation and circadian rhythmicity. J Appl Physiol 92:852–862

Grant I, Eriksen HR, Marquis P, Orre IJ, Palinkas LA, Suedfeld P, Svensen E, Ursin H (2007) Psychological selection of Antarctic personnel: the "SOAP" instrument. Aviat Space Environ Med 78:793–800

Gunderson EKE (1963) Emotional symptoms in extremely isolated groups. Arch Gen Psychiatry 9:362–368

Gunderson EKE (1973) Individuals in confined or isolated groups. In: Rasmussen JE (ed) Man in isolation and confinement. Aldine Publishing Company, Chicago, pp 145–164

Gunderson EKE, Nelson PD (1965) Measurement of group effectiveness in natural isolated groups. J Soc Psych 66:241–249

Gunderson EKE, Nelson PD (1966) Criterion measures for extremely isolated groups. Pers Psychol 19:67–80

Ikegawa M, Kimura M, Makita K, Itokawa Y (1998) Psychological studies of a Japanese winter-over group at Asuka station, Antarctica. Aviat Space Environ Med 69:452–460

Kahn PM, Leon GR (1994) Group climate and individual functioning in a all women's Antarctic expedition team. Environ Behav 26:669–691

Leon GR (1991) Individual and group process characteristics of polar expedition teams. Environ Behav 23:723–748

Leon GR, Atlis M, Ones D, Magor G (2002) A one-year three-couple expedition as a crew analog for a Mars mission. Environ Behav 34:672–700

Leon GR, Sandal GM, Fink BA, Ciofani P (2011) Positive experiences and personal growth in a two-man North Pole expedition team. Environ Behav 43:672–700

Mullin CS (1960) Some psychological aspects of isolated Antarctic living. Am J Psychiatry 117:323–326

Natani K, Shurley JT (1973) Disturbed sleep and effect in an extreme environment. In: Koella WP, Levin P (eds) Sleep: physiology biochemistry, psychology, pharmacology, clinical implications. Karger, Basel, pp 426–430

Natani K, Shurley JT (1974) Sociopsychological aspect of a winter vigil at South Pole Station. In: Gunderson EKE (ed) Human adaptability to Antarctic condition, vol 22, Antarctic research series. American Geophysical Union, Washington, DC, pp 89–114

Natani K, Shurley JT, Pierce CM, Brooks RE (1970) Long-term changes in sleep patterns in men on the South Polar plateau. Arch Intern Med 125:655–659

Oliver DC (1991) Psychological effects of isolation and confinement of a winter-over group at McMurdo Station, Antarctica. In: Harrison AA, Clearwater YA, McKay CP (eds) From Antarctica to outer space: life in isolation and confinement. Springer, New York, pp 217–228

Palinkas LA (1985) Long-term effects of environment on health and performance of Antarctic winter-over personnel. U.S. Naval Health Report No.85–48, ADA-165 982. U.S. Naval Health Research Center

Palinkas LA (2003) The psychology of isolated and confined environments: understanding human behavior in Antarctica. Am Psychol 58:353–363

Palinkas LA, Cravalho M (1995) Seasonal variation of depressive symptoms in Antarctica. Acta Psychiatr Scand 91:423–429

Palinkas LA, Houseal M (2000) Stages of change in mood and behavior during a winter in Antarctica. Environ Behav 32:28–141

Palinkas LA, Suedfeld P (2007) Psychological effects of polar expeditions. Lancet. doi:10.1016/S0140-6736(07)61056-3, published online

Palinkas LA, Houseal M, Rosenthal NE (1995) Subsyndromal seasonal affective disorder in Antarctica. J Nerv Mental Disord 184:30–534

Palinkas LA, Reed HL, Do NV (1997) Association between the polar T3 syndrome and the winter-over syndrome in Antarctica. Antarct J 32:12–114

Palinkas LA, Glogower F, Dembert M, Hansen K, Smullen R (2004) Incidence of psychiatric disorders after extended residence in Antarctica. Int J Circumpolar Health 63:57–168

Palinkas LA, Reedy K, Shepanek M, Smith M, Anghel M, Steel GD, Reeves D, Case HS, Do NV, Reed HL (2007a) Environmental influences on hypothalamic-thyroid function and behavior in Antarctica. Physiol Behav 92:90–799

Palinkas LA, Reedy K, Smith M, Anghel M, Steel GD, Reeves D, Shurtleff D, Case HS, Do NV, Reed HL (2007b) Psychoneuroendocrine effects of combined thyroxine and triiodothyronine versus tyrosine during prolonged Antarctic residence. Int J Circumpolar Health 66:01–417

Palmai G (1963) Psychological observations on an isolated group in Antarctica. Br J Psychiatry 109:64–370

Paterson RAH (1978) Personality profiles in a group of Antarctic men. Int Rev Appl Psychol 27:3–37

Paul FUJ, Mandal MK, Ramachandran K, Panwar MR (2010) Cognitive performance during long-term residence in a polar environment. J Environ Psychol 30:129–132

Popkin MK, Stillner V, Osborn LW, Pierce CM, Shurley JT (1974) Novel behaviors in an extreme environment. Am J Psychiatry 131:51–654

Reed HL, Silverman ED, Shakir KM, Dons R, Burman KD, O'Brian JT (1990) Changes in serum triiodothyronine (T3) kinetics after prolonged Antarctic residence: the polar T3 syndrome. J Clin Endocrinol Metabol 70:65–974

Reed HL, Reedy KR, Palinkas LA, Do NV, Finney NS, Case HS, LeMar HJ, Wright J, Thomas J (2001) Impairment in cognitive and exercise performance during prolonged Antarctic residence: effect of thyroxine supplementation in the polar triiodothyronine syndrome. J Clin Endocrinol Metabol 86:10–116

Rohrer JM (1961) Interpersonal relationships in isolated groups. In: Flaherty EF (ed) Psychological aspects of space flight. Columbia University Press, New York, pp 263–270

Rosenthal NE, Sack DA, Gillin JC, Lewy AJ, Goodwin FK, Davenport Y, Mueller PS, Newsome DA, Wehr TA (1984) A description of the syndrome and preliminary findings with light therapy. Arch Gen Psychiatry 41:72–80

Sarris A (2006) Personality, culture fit, and job outcomes on Australian Antarctic stations. Environ Behav 38:356–372

Sarris A (2007) Antarctic culture: 50 years of Antarctic expeditions. Aviat Space Environ Med 78:886–892

Sarris A (2008) Applying organisational theory to isolated, confined and extreme settings. Aust N Z J Organ Psychol 1:1–6

Steel GD (2000) Polar bonds: the environmental relationship in polar regions. Environ Behav 32:796–816

Steel GD (2001) Polar moods: the third-quarter phenomena in Antarctica. Environ Behav 33:126–133

Steel GD, Suedfeld P, Peri A, Palinkas LA (1997) People in high latitudes: the big five personality characteristics of the circumpolar sojourner. Environ Behav 29:324–347

Strange RE, Klein WJ (1974) Emotional and social adjustment of recent US winter-over parties in isolated Antarctic stations. In: Edholm OG, Gunderson EKE (eds) Polar human biology: proceeding of the SCAR/IUPS/IUBS symposium on human biology and medicine in the Antarctic. William Heinemann, Chicago, pp 410–416

Strange RE, Youngman SA (1971) Emotional aspects of wintering over. Antarct J 6:255–257

Suedfeld P (1987) Extreme and unusual environments. In: Stokols D, Altman I (eds) Handbook of environmental psychology. Wiley, New York, pp 863–886

Suedfeld P (2001) Applying positive psychology in the study of extreme environments. J Hum Perform Extrem Environ 6:21–25

Suedfeld P, Steel GD (2000) The psychology of capsule environments. Annu Rev Psychol 51:227–253

Suedfeld P, Bernaldes JP, Stossel DL (1989) The Polar Psychology Project (PPP): a cross-national investigation of polar adaptation. Arctic Med Res 48:91–94

Taylor AJW (1969) Ability, stability, and social adjustment among Scott Base personnel, Antarctica. Occup Psychol 43:81–93

Taylor AJW (1978) Antarctica psychometrika. N Z Antarct Rec 1:33–40
Taylor AJW (1987) Antarctic psychology. New Zealand Department of Scientific and Industrial Research, Wellington
Terelak J (1986) Gruppovaia dinamika i éffektivnost‘ deiatel'nosti v ékstremal'nykh usloviiakh [Group dynamics and work efficiency under extreme conditions][Abstract]. Kosmičeskaâ biologija i aviakosmičeskaâ medicina 20:82–83
Terelak J, Turlejski J, Szczechura J, Rozynski J (1985) Dynamics of simple arithmetic task performance under Antarctic isolation [Abstract]. Pol Psychol Bull 16:123–128
Weiss K, Suedfeld P, Steel GD, Tanaka M (2000) Psychological adjustment during three Japanese Antarctic research expeditions. Environ Behav 32:142–156
Wood J, Hysong SL, Lugg DJ, Harm DL (2000) Is it really so bad? A comparison of positive and negative experiences in Antarctic winter stations. Environ Behav 32:84–110
Xue Z, Xue Q (1994) Psychological changes of fifteen Chinese Antarctic Research Expedition members. Antarct Res 5:27–33
Zubek JP (1973) Behavioral and physiological effects of prolonged sensory and perceptual deprivation: a review. In: Rasmussen JE (ed) Man in isolation and confinement. Aldine Publishing Company, Chicago, pp 9–85

## *Further Reading*

Doll RE, Gunderson EKE, Ryman DH (1969) Relative predictability of occupational groups and performance criteria in an extreme environment. J Clin Psychol 25:399–402
Harrison AA, Clearwater YA, McKay CP (1991) From Antarctica to outer space: life in isolation and confinement. Springer, New York
McCrae RR, Sutin AR (2009) Openness to experience. In: Leary MR, Hoyle RH (eds) Handbook of individual differences in social behaviour. Guilford Press, New York, pp 257–273
Owens AG (1975) The performance and selection of men in small Antarctic groups. Psychological Research Unit Report 4/47. Australian Military Forces
Rosenthal NE, Sack D, Gillin JC, Lewy AJ, Goodwin FK, Davenport Y, Mueller PS, Newsome DA, Wehr TA (1984) Seasonal affective disorder: a description of the syndrome and preliminary findings with light therapy. Arch Gen Psychiatry 41:72–80
Russell JA (1980) A circumplex model of affect. J Pers Soc Psychol 39:1161–1178
Sarris A, Kirby N (2005) Antarctica: a study of person-culture fit. Aust J Psychol 57:161–169
Schultz W (1958) FIRO: a three-dimensional theory of interpersonal behavior. Hold, Rinehart, and Winston, New York
Seymour GE, Gunderson EKE (1971) Attitudes as predictors of adjustment in extremely isolated groups. J Clin Psychol 27:333–338
Stuster J (1996) Bold endeavours: lessons from polar and space exploration. Naval Institute Press, Annapolis
Taylor AJW, Shurley JT (1971) Some Antarctic troglodytes. Int Rev Appl Psychol 20:143–148
Weybrew BB, Molish HB, Youniss RP (1961) Prediction of adjustment to the Antarctic. U.S. Naval Medical Research Laboratory Report No. 350, Bureau of Medicine and Surgery, U.S. Navy Department

# Chapter 18
# Destination Icy Wilderness

## Tourism in Antarctica

**Daniela Liggett**

**Abstract** Tourism is a late starter in Antarctica. However, visitor numbers have increased dramatically since the 1990s to more than 30,000 per summer season, raising concerns about the potential impacts on the continent and the surrounding ocean. Unsurprisingly, the rapid increase in the numbers of people visiting Antarctica has had significant consequences for the regulation and management of Antarctic tourism. Since the creation of the International Association of Antarctica Tour Operators (IAATO) in 1991, much of the in situ management of Antarctic tourism has been undertaken by the industry itself, which resulted in some complacency by Antarctic Treaty Consultative Parties (ATCPs) with regard to tourism regulation. This chapter introduces the main characteristics of Antarctic tourism, its brief history and explores some of the concerns and impacts that can arise from tourism activities in and around Antarctica. This chapter also sheds light on the current regulation, management and regulatory challenges of Antarctic tourism.

**Keywords** Lars-Eric Lindblad • Ship-based tourism • Airborne tourism • Environmental impacts • Social impacts • Economic impacts • Regulation

## 18.1 Pioneering Antarctic Travel

Lars-Eric Lindblad had mapped out his Antarctic itinerary as a child. Born in 1927 in Sweden, he read voraciously and was mesmerised by the adventures of some of the greatest explorers: Marco Polo, Livingstone, Scott, Shackleton, Amundsen, and his compatriots Sven Hedin and Nils Otto Nordenskjöld.

---

Sections of this chapter are reprinted with permission. The original text by the same author appeared as "Case Study 4: Policy challenges of tourism as a commercial activity in Antarctica" (pp. 107–117), In: Edgell Sr., DL, Swanson JR (2012) Tourism Policy and Planning: Yesterday, today, and tomorrow, 2nd ed, Routledge, London and New York.

D. Liggett (✉)
Gateway Antarctica, University of Canterbury, Christchurch, New Zealand
e-mail: daniela.liggett@canterbury.ac.nz

 
D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_18

In his autobiography he recalls his first taste of travel in the back seat of a Packard convertible in which his father drove the family around Scandinavia and Estonia before the Second World War. Post-war, Lindblad took a summer job with Thomas Cook, left Sweden for the United States and soon started his own expedition travel company in New York in 1958 (Lindblad and Fuller 1983).

At a time when commercial tourism operators in the US were focusing on safe and mostly European destinations, Lindblad Travel began offering trips to the Middle East, the wilds of Africa and, eventually, the icy wonders of Antarctica. In 1966, Lindblad was the first to take a group of tourists to the Antarctic Peninsula aboard chartered Argentinean and Chilean naval vessels (Headland 1994). Two years later, he ventured into the Ross Sea region with an ice-working ship chartered from Denmark (Stonehouse and Snyder 2010) and in 1969 he commissioned his own ship, a 92-berth ice-strengthened vessel, to be built specifically for cruising Antarctic waters (Headland 1994; Tracey 2001). The MS *Lindblad Explorer*, later known merely as the MS *Explorer* and nicknamed the 'little red ship', was the first vessel to be purpose-built for Antarctic tourism. However, the ship also holds another record. In November 2007, en route to Antarctica, she struck submerged ice and became the first tourist vessel to sink in Antarctic waters.

Antarctic tourism is a late starter. The main currency in Antarctica is science, but there are other activities on the continent and the surrounding ocean with a much more profit-driven focus. Commercial fishing operations (Chap. 21) have been closely linked to the history of Antarctic exploration (Chap. 15), while the interest in bioprospecting (Chap. 22) has arisen partly from the study and genetic screening of organisms that thrive in Antarctica's extreme environment.

As a regular activity with purely commercial purposes, Antarctic tourism gained a foothold only during the mid-1960s through Lindblad's first voyages and then developed quietly for two decades in conjunction with, but mostly outside, the governmental framework of the Antarctic Treaty System. It was not until the late 1980s that tourism in Antarctica received increasing political and media attention, owing to its unprecedented exponential growth and diversification in the 1990s and the early twenty first century. This rapid increase has had significant consequences for the regulation and management of Antarctic tourism. Increasingly, the laissez-faire attitude that dominated tourism regulation through the Antarctic Treaty System for most of the second half of the twentieth century is being replaced by a range of regulatory mechanisms that focus on Antarctic tourism operations. However, questions remain about the effectiveness of such measures. The Antarctic Treaty Consultative Parties have been criticised for taking an inconsistent and non-strategic approach to regulating tourism operations in the Antarctic Treaty area.

## 18.2 Definition of Antarctic Tourism

For practical reasons, the definition of tourism in Antarctica falls within the same geopolitical boundary of 60°S latitude as the Antarctic Treaty System uses to define the extent of Antarctic governance (Chap. 16). In the early years of Antarctic tourism research in the 1990s, Antarctic tourism was defined loosely as "all existing human activities other than those directly involved in scientific research and the normal operation of government bases" (Hall 1992, p. 4). However, complications arise regarding recreational activities of base personnel, such as skiing or hiking, in comparison with similar activities undertaken by visitors who are not stationed in Antarctica. In addition, the commercial aspect inherent in most Antarctic tourism ventures needs to be reflected in any definition, be it from the perspective of those who supply the product and make money from it, or those who constitute demand and pay for participating. For regulatory purposes, a narrower definition of more conventional Antarctic tourism is necessary and, with this in mind, it can be defined as "all human activities either mainly pursuing recreational and/or educational activities in the Antarctic Treaty areas south of 60°S Lat." (Liggett 2009, p. 41).

## 18.3 Characteristics of Antarctic Tourism

Antarctic tourism differs from tourism to most other places in the world. It happens in an area beyond the sovereign jurisdiction of any one country, and it is confined to a relatively narrow window of opportunity during the southern summer. Antarctic tourism typically takes place between November and March, when the extent of sea ice around Antarctica is at its minimum, temperatures are milder and many wildlife species are breeding. Recent years have seen an extension of the tourist season, with some operators offering visits in October and April. This has been attributed to increased demand but also to the effects of climate change, which result in diminished sea ice cover, especially around the Antarctic Peninsula, and consequently enlarge the window of opportunity for tourism operators to organise commercial expeditions to the continent (Lamers et al. 2008).

One of the distinguishing characteristics of Antarctic tourism is its strong reliance on ships as the main mode of transport. The majority of tourists arrive in Antarctica by sea, while a few travel by air from South America or South Africa. From a regulatory and management perspective, the latter are no less important, but nonetheless, most attention is paid to ship-based tourism, partly because this is the sector that has experienced an unparalleled exponential growth since the 1990s (Fig. 18.1). Antarctic tourism experienced a slight decline in popularity in the latter part of the first decade of the twenty first century. The decrease in the number of tourists embarking on Antarctic expeditions at that time is commonly seen as a result of the global economic downturn and the related financial uncertainty. However, since the 2012/13 season, the numbers of tourists visiting Antarctica

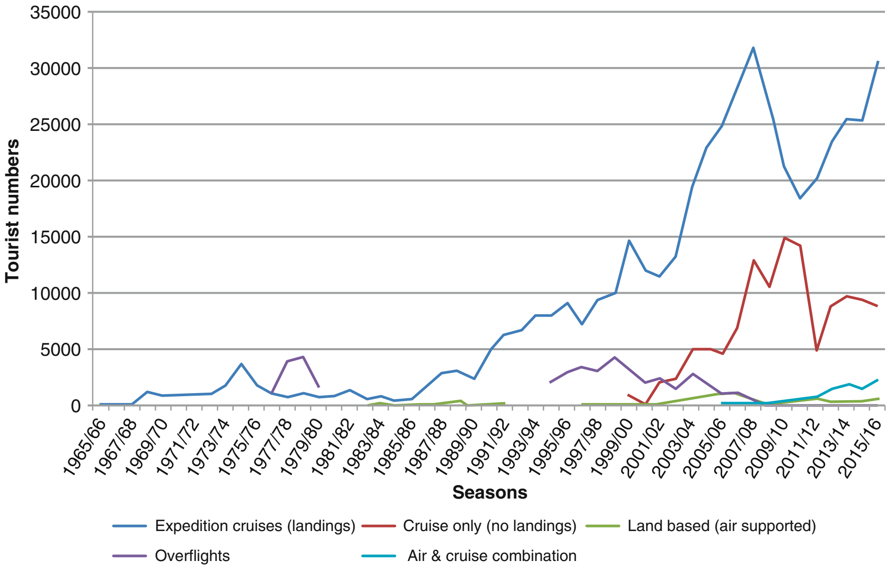



**Fig. 18.1** Estimated numbers of Antarctic tourists from 1965 to 2009 (Based on historical records published by Enzenbacher (1993), Headland (2005) and Reich (1980) as well as annual reports by the International Association of Antarctica Tour Operators (IAATO)). This illustrates the development of Antarctic tourism over the last half century. Apart from the growth in the expedition cruise sector, cruise-only tourism was firmly established as part of the Antarctic tourism spectrum in the 1990s. Land-based and airborne tourism operations do not report significant increases in numbers. In fact, the opposite seems to be the case. This figure also illustrates the sudden collapse of the overflight market in the late 1970s, the reasons for which will be explored in greater detail in the section on airborne tourism. [The 2015/16 data included in this graph represented predicted rather than actual numbers]

began rising steadily again. This trend is expected to continue at least over the next couple of seasons according to recent IAATO statistics and predictions.

## 18.4 History of Ship-Based Tourism

Sea voyages represent the oldest segment of Antarctic cruise tourism. The earliest records indicating that tourists were granted passage date back to the late nineteenth and early twentieth centuries when, for instance, paying passengers were taken on New Zealand government expeditions to its subantarctic islands, and on the Falkland Islands Dependencies Government mail service voyages to the Falkland Islands, South Georgia and the South Shetland Islands (Headland 1994). In 1910, Thomas Cook and Sons proposed a cruise to the Ross Sea region leaving from

New Zealand, but despite some interest, this journey never came to fruition (Stonehouse and Snyder 2010). Similarly, other ambitious journeys proposed in the 1920s and 1930s, including a trip to the Bay of Whales on board a luxurious 6000-tonne motor yacht offered by Holland America Line, never eventuated (Headland 1994; Stonehouse and Snyder 2010).

The 1950s saw the first tourist-only cruises to Antarctica. The Argentinean naval vessel *Les Eclaireurs* visited the Antarctic Peninsula with a total of 194 passengers on two voyages in 1958 and Chilean naval vessels followed suit with two trips to the same area (Stonehouse and Snyder 2010). However, modern Antarctic cruise tourism did not commence effectively until the late 1960s when Lars-Eric Lindblad began organising annual voyages, first on chartered naval vessels and later with his own ice-strengthened vessel, the MS *Lindblad Explorer*.

For a typical Antarctic tourist, the cruise begins in one of the five gateway ports (Ushuaia, Argentina; Punta Arenas, Chile; Hobart, Australia; Christchurch/Lyttelton, New Zealand; Cape Town, South Africa). From there, tourists venture across the Southern Ocean to explore subantarctic islands and coastal areas of the Antarctic continent. Roughly 90 % of Antarctic ship-borne tourists pass through South American gateway ports and travel to the Antarctic Peninsula (Liggett 2009; Mason and Legg 2000), a much sought-after destination because of its proximity to South America and its diverse and attractive landscapes, fauna and flora. Gentoo, chinstrap and Adélie penguin rookeries, elephant and fur seals on rocky beaches, several seabird colonies, and jagged ice-covered mountains looming in the background represent important drawing cards for tourism operators. Additional attractions on the peninsula are the numerous historic monuments and huts as well as the presence of more than half of all Antarctic stations (Cessford 1997; Mason and Legg 2000). Many Antarctic stations welcome visits by tourists and expeditioners because they can generate additional funds through the sale of souvenirs, even though visits by tourists can also entail a potential distraction from research activities or base management.

Most ships visiting Antarctica are small (up to 200 passengers) or medium-sized (up to 500 passengers), and these voyages involve landings on offshore islands or the Antarctic continent itself. This type of tourism, conventionally classified as expedition cruise tourism, usually follows a model developed and pioneered by Lindblad (Box 18.1). From 2009 onwards, about one in ten of all known commercial vessels operating in Antarctica was capable of carrying more than 500 passengers and, collectively, these large ships were carrying approximately one third of all Antarctic cruise tourists between 2009 and 2011. Indeed, during the first decade of the twenty first century, cruise-only tourism, using vessels with a capacity of more than 500 passengers, has significantly grown and constitutes a considerable share of the Antarctic tourism market (Fig. 18.1). Cruise-only tourism ventures have caused some concern because of the difficulties of search and rescue operations involving a large number of passengers and crew in a remote location, and the potential of environmental damage. One of the potential risk factors for the Antarctic marine environment is the release of oil into the ocean following a grounding of a vessel or a collision with an iceberg, for example. In recognition of this risk factor, the

International Maritime Organization has recently signed off on an amendment to its MARPOL Convention (i.e. the International Convention for the Prevention of Pollution from Ships). A new chapter on fuel oils in Antarctica, which bans heavy fuel oil from being used or carried as cargo in the area south of 60°S latitude, has been added to the Convention's Annex I and came into effect on 1 August 2011. This amendment to MARPOL is largely considered responsible for a decrease in the number of cruise-only voyages in 2010/2011 as the ban of heavy oil in Antarctica has made it more expensive to operate larger vessels, which traditionally used to run on heavy oil.

**Box 18.1: The Lindblad Pattern**

Lindblad's destinations broke new ground, and so did his ideas on how group travel should be organised. He was passionate about travel and believed it should offer a combination of adventure, fun and learning. Lindblad's cruises and tours were always accompanied by specialist lecturers, and his approach to running expedition cruises in Antarctica became known as the Lindblad model, or Lindblad pattern.

The model refers to a particular in situ preparation and management of tourists during their cruise. Originally tailored to small-cruise operations catering for up to 140 passengers, it is now applied by almost all commercial cruise vessels that include landings in their itineraries.

Passengers undergo detailed compulsory briefings before any landing on general landing procedures, safety aspects, the flora and fauna they can expect to see, and how they should behave on shore. The need to prevent any disturbance of plants and animals and to avoid interfering with scientific research is stressed, and passengers receive instructions on how far away they should keep from wildlife. In addition to these compulsory briefings, passengers are given the option to participate in a number of lectures on topics such as Antarctic geology, the history of exploration, Antarctic ecosystems, marine mammals, Antarctic birds or the governance of the continent.

Small, agile rubber boats, commonly referred to by their brand name Zodiac, are used to land 10–14 passengers on easily accessible, and often rocky, beaches. No more than 100 passengers are allowed to be on shore at any one time. Once on land, passengers are usually free to wander, although some tour operators demarcate the area visitors are permitted to access with traffic cones and ropes laid out on the ground. During the landing, passengers, who are issued brightly coloured jackets, are closely monitored by tour guides and are usually required to stay in sight of the landing area (Mason and Legg 2000; Stonehouse 1994; Stonehouse and Crosbie 1995; Stonehouse and Snyder 2010).

## 18.5 History of Airborne Tourism

Tourist flights to Antarctica first appeared in the 1960s, when the Richard E. Byrd Polar Center in Boston, USA, negotiated access to the US airstrip near McMurdo Station to organise a non-commercial sightseeing flight for 75 passengers (Stonehouse and Snyder 2010). In the early 1970s, six further flights brought small numbers of passengers to Antarctica (Reich 1980), but by the late 1970s, overflights gained popularity and a series of flights carrying about 10,000 passengers was organised by Qantas and Air New Zealand (Bauer 2007). These flights explored the Ross Sea region, Adélie coast and Victoria Land (Stonehouse and Snyder 2010).

The steep increase in the number of overflights in the late 1970s (Fig. 18.1) ended abruptly when on 28 November 1979 an Air New Zealand DC-10 crashed into Mount Erebus, resulting in the death of all 237 passengers and 20 crew (Bauer 2007). Air New Zealand and Qantas discontinued Antarctic overflights, and it took more than a decade before Qantas resumed them in 1994. Despite the serious implications of the Air New Zealand crash, the Chilean airline LADECO has been conducting very occasional overflights from South America since 1980 (Swithinbank 1993). Air New Zealand has not re-established Antarctic overflights and is unlikely to do so.

Between 1968 and 1987, fixed-wing aircraft were used to cover short distances along Antarctica's coastline, but a few commercial flights ventured further south and landed at the American McMurdo Station on Ross Island or the Argentinean Marambio Station in the Antarctic Peninsula region (Swithinbank 1993). The first known air-cruise operation, which took tourists across the Drake Passage on a plane to allow them to board a cruise ship on King George Island, was organised by Fuerza Aérea de Chile (FACH, the Chilean Air Force) in January 1982 (Swithinbank 1993). Soon, fixed-wing aircraft started opening up Antarctica to land-based adventure tourists. More recently, air-cruise operations have become increasingly popular. For instance, in the 2012/2013 season 1,587 passengers explored parts of the Antarctic Peninsula region in 24 air-cruise trips. These passengers would embark on either a one-way or return flight between South America and King George Island and would then join an expedition cruise in King George Island.

From 1987 onwards, airborne tourism supported land-based adventure tourism, primarily facilitated through Adventure Network International (ANI) and its parent company Antarctic Logistics and Expeditions (ALE). The pioneering effort of landing wheeled aircraft, rather than the less economic and less fuel-efficient ski-equipped planes, on blue-ice runways by ANI pilots in 1987 reduced the cost of aircraft-supported tourism and pushed further into Antarctica's interior (Swithinbank 1993).

## 18.6 Land-Based Tourism

Even though expedition cruise tourism includes a range of land-based experiences, from short strolls along the beach to overnight camping, its primary mode of transport and accommodation is ship-based and most of the tourists' time is spent onboard a vessel. By contrast, Antarctic land-based tourism concentrates on experiences and activities on land and uses air or ship support only to transport tourists, expedition staff and equipment across the Southern Ocean. Often, Antarctic land-based tourism involves adventure activities, i.e. undertakings that entail a degree of risk and uncertainty (Lamers and Amelung 2007).

In 1983, the Chilean Teniente Rodolfo Marsh Station on King George Island opened its airways to commercial and private aircraft (Swithinbank 1993) and encouraged land-based tourism at the station, where accommodation for paying visitors was provided in the government-operated Hotel Estrella Polar (the Polar Star Hotel). In 1987, a semi-permanent camp was established by ANI in the Patriot Hills to facilitate a wide range of adventure tourism operations in Antarctica. ANI, the largest provider in the Antarctic adventure tourism market, offers activities from 'safe' private flights, photo safaris and skiing expeditions to more challenging mountaineering and climbing expeditions (Murray and Jabour 2004). Marathon running in Antarctica is another land-based tourism activity (Mortimer and Prior 2009) which is currently offered not only in the Antarctic Peninsula region but also further inland at the foot of the Ellsworth Mountains at 80°S latitude (Donovan 2011).

## 18.7 Impacts of Antarctic Tourism

Antarctica is a remote and potentially dangerous destination, characterised by slow growth rates of native flora and lengthy breakdown rates of waste or sewage. As a result, it is important to assess any potential impacts human activities may have on the environment and to eliminate or minimise these impacts as much as possible. Although regulation tends to focus on potential environmental impacts, Antarctic tourism can also affect cultural and social values (Mason and Legg 1999) as well as the political (Enzenbacher 2007) and economic environment (Snyder 2007) (Box 18.2).

**Box 18.2: Potential Impacts of Antarctic Tourism (Liggett 2009)**
Environmental impacts can include:

– disturbance of wildlife resulting in modifications of behaviour or diminishing numbers of breeding birds in colonies;
– littering or waste disposal (accidental or intentional);
– trampling of flora and fauna;

(continued)

**Box 18.2** (continued)
- development of footpaths, soil erosion and compaction;
- introduction of diseases or non-native species (e.g. through ballast water of ships or through seeds or spores unintentionally carried in backpacks or clothing of visitors);
- marine pollution (e.g. fuel or oil spills);
- air pollution through aircraft, ship and small-boat operations; and
- noise pollution (generally a temporary impact).

Social impacts can include:

- disruption of research activities, including the social costs incurred by base personnel when having to provide support to expeditioners in distress;
- potential harm to unmarked sites of scientific interest;
- negative effects of crowding at a limited number of landing sites on visitors' perception of the Antarctic environment; and
- broadly speaking, any interference with the activities of other stakeholders.

Cultural impacts can include:

- detrimental effects of changes in the internal atmosphere of buildings due to visitors;
- damage to or appropriation of historical artefacts;
- transportation of material on boots (snow/ice/rocks) into historic huts; and
- adverse effects of human activity on Antarctic wilderness values.

Economic impacts can include the costs incurred by national Antarctic programmes if they have to participate in search and rescue operations for members of private expeditions or commercial tourism operations.

Political impacts relate to the discordance of positions among Antarctic Treaty Consultative Parties (the ultimate political decision-makers for Antarctica) with regard to Antarctic tourism regulation. As a result, Antarctic tourism could trigger international disputes that might pose a threat to the stability of the Antarctic Treaty System and might re-animate questions of sovereignty and territorial claims (Enzenbacher 2007).

## 18.8 Linking Impacts to Maritime Accidents

Land-based activities (skiing, hiking, climbing or mountaineering) that venture deeper into the Antarctic hinterland are often considered more harmful to the Antarctic environment than ship-based operations (Kriwoken and Rootes 2000). However, most land-based activities occur further away from the more sensitive coastal areas, which are breeding sites for marine wildlife (Chap. 13). Marine accidents involving Antarctic tourism vessels, such as groundings or collisions with whales or icebergs, could result in serious environmental disasters. One such example is the significant oil spill that followed the grounding and sinking of the *Bahia Paraiso* in 1989 (Table 18.1). The *Bahia Paraiso* was a supply vessel en route to Argentinean stations on the Antarctic Peninsula when she ran aground. Technically, the *Bahia Paraiso* was not a tourist vessel, but she carried a number of paying passengers on her final trip. Another vessel involved in tourism operations that sank in Antarctic waters was the MS *Explorer* (originally owned by Lindblad), which struck submerged ice and sank in the Bransfield Strait in 2007. In this case, the weather and sea were calm and all passengers and crew could be evacuated. No lives were lost, but this incident nevertheless serves as a sombre reminder of the risks of Antarctic tourism.

Table 18.1 not only highlights the risks of operating in the Southern Ocean and Antarctica but also shows how frequently accidents occur. It is worth noting that the list is probably incomplete as record-keeping and reporting systems were not well established in the early years of Antarctic tourism and minor incidents are likely to have gone unmentioned.

## 18.9 A Critical Look at Impacts and Their Assessment

Although potential impacts of tourism on the wider Antarctic environment have been discussed (Box 18.2), relatively few studies have focused on quantifying and validating the environmental effects of Antarctic tourism. The main reasons for this deficiency are the cost and long-term commitment required to measure cumulative human impacts, defined by Bastmeijer & Roura as "impact[s] of combined past, present and reasonably foreseeable future activities" (2004, p. 766). Yet, any impact, however small, could leave a long-lasting effect on an ecosystem with extremely slow regeneration rates, which makes the consideration of cumulative impacts even more important.

In the same vein, it is important to critically assess potential and actual impacts of the entire range of human activities in Antarctica rather than focusing on tourism alone. The latter has received increasing scrutiny by political decision makers. Antarctic tourism operations are viewed as falling within the purview of the Antarctic Treaty System but, at the same time, are beyond reach of effective and consensual decision-making because of the diverging interests of Antarctic Treaty Consultative Parties and the special non-governmental character of tourism operations. As Antarctic tourism is not officially endorsed, nor explicitly prohibited, by the 1959 Antarctic Treaty, which devotes the Antarctic continent to science and peace, Antarctic policy makers can easily justify taking a critical, and in many cases unfavourable, approach to tourism regulation. It must not be forgotten that any form of human activity can have a significant impact on the Antarctic environment, and the impacts of science and logistic support activities will have to be scrutinised in the same way as Antarctic tourism operations. Although tourists by far outnumber scientists and their support staff in the summer months, the overall person days spent by tourists on the Antarctic continent are estimated to be only about 5 % of the person days spent there by science staff (Jabour 2009). National Antarctic

**Table 18.1** A selection of ship-based incidents in Antarctica

| Date | Vessel/ aircraft | Tour operator | Occurrence |
|---|---|---|---|
| 14-Feb-67 | *Lapataia* | Lindblad Travel | 26 tourists stranded on Half Moon Island |
| 1-Jan-68 | *Navarino* | Lindblad Travel | Steering engine failure |
| 22-Jan-68 | *Magga Dan* | Lindblad Travel | Ship ran aground off Hut Point, McMurdo Sound |
| 22-Jan-69 | *Aquiles* | Lindblad Travel | Approximately 70 tourists stranded at Palmer station |
| 24-Dec-71 | *Lindblad Explorer* | Lindblad Travel | Ship grounded in Gerlache Strait, tourists rescued by Chilean Navy |
| 11-Feb-72 | *Lindblad Explorer* | Lindblad Travel | Ship grounded on rocks in Admiralty Bay, King George Island |
| 29-Nov-72 | *Ice Bird* | David Lewis | Second capsize of yacht, later reconstructed at Palmer station in 1973 |
| 1973 | *Libertad* | DNT/ELMA | Damage to ship |
| 24-Dec-79 | *Lindblad Explorer* | Lindblad Travel | Ship grounded on rocks off Wiencke Island |
| 10-Jan-86 | *Southern Quest* | "In the Footsteps of Scott" expedition | Ship crushed by pack ice, 21 crew members rescued by US helicopters from McMurdo, ship sank 4 miles east of Beaufort Island |
| 28-Jan-89 | *Bahia Paraiso* | Argentine Government supply/ tourist ship | Ship ran aground off Anvers Island then sank leaving 600,000 litres of fuel |
| 1-Feb-91 | *Pomaire* | Marinsular | Ship grounded in Jones Sound |
| 21-Jan-91 | *World Discoverer* | Society Expeditions | While approaching Cape Evans/ Ross Island the vessel grounded on a uncharted rock |
| 24-Jan-96 | *Professor Multanovskiy* | Marine Expeditions Inc | Vessel was grounded on rocks WNW from Penguin Island |
| 4-Jan-97 | *Professor Khromov* | Quark Expedition/Supernova Expeditions | Vessel grounded on shoal, uncharted rock in Neumayer Channel |
| 18-Jan-97 | *Akademik Sergei Vavilov* | Marine Expeditions (operator); Supernova/Quark Expeditions (charterer) | Oil Spill: Oil was observed leaking from the vessel in the Pleneau/Hovgaard area |
| 3-Feb-99 | *Hanseatic* | Hapag Lloyd | Transport Incident – starboard propeller sustained damage in Paradise Bay |
| 31-Dec-99 | *Clipper Adventurer* | New World Ship Management Co LLC/Clipper Cruise Line (operator); Zegrahm Expeditions (charterer) | While at anchor the vessel was contacted by ice damaging 2 of the 5 blades on the port propeller near Seymor Island |
| 1-Feb-00 | *Clipper Adventurer* | New World Ship Management Co LLC/Clipper Cruise Line | Vessel was beset in pack ice while navigating in Martha Strait |

(continued)

**Table 18.1** (continued)

| Date | Vessel/ aircraft | Tour operator | Occurrence |
|---|---|---|---|
| 1-Feb-00 | *Akademik Sergei Vavilov* | Quark/Supernova Expeditions | Collision with humpback whale, whale injured, when approaching Dallmann Bay |
| 28-Dec-01 | *Vista Mar* | Gauss mbH | Oil Spill: Port propeller damaged during manoeuvring in Hope Bay; Gland oil (<1 l) leaking into the sea |
| 18-Jan-02 | *Professor Molchanov* | Oceanwide Expeditions (operator); Quark Expeditions (subcharterer) | Vessel nudged an iceberg, which damaged the bow bulwark |
| 17-Nov-02 | *Explorer* | Abercrombie and Kent Explorer Shipping | Generator/alternator failure causing several electrical problems |
| 22-Nov-02 | *Clipper Adventurer* | Clipper/New World Shipping | A strong wind blew the vessel onto the sandbar in Whalers Bay, Deception Island |
| 13-Feb-03 | *Marco Polo* | Orient Lines | Grounding of vessel due to weather and mechanical conditions at Half Moon Island |
| 30-Jan-07 | *Nordkapp* | Hurtigruten | Grounding at Neptune's Bellows, Deception Island, as a result of human error; parts of the hull and tank damaged |
| 23-Nov-07 | *Explorer* | G.A.P. Adventures | Sank in Bransfield Strait, near the South Shetland Islands after striking submerged ice that damaged the hull |
| 28-Dec-07 | *Fram* | Hurtigruten | Vessel drifts onto a glacier after an electricity outage and damages one lifeboat at Brown Bluff |
| 4-Dec-08 | *Ushuaia* | Antarpply Expeditions | Grounding at the entrance of Wilhelmina Bay near Cape Anna; passengers transferred to Chilean naval vessel *Aquiles*; minor damage to the hull and to two diesel tanks carrying MGO; some leakage of oil |
| 17-Feb-09 | *Ocean Nova* | Quark Expeditions | Grounding in Marguerite Bay, West of Debenham Island; passengers transferred to *Clipper Adventurer* for transport to Ushuaia; no leakage of oil reported |

(continued)

**Table 18.1** (continued)

| Date | Vessel/ aircraft | Tour operator | Occurrence |
|---|---|---|---|
| 4-Jan-10 | *Clelia II* | Travel Dynamics International | While landing passengers at Peterman Island, Penola Strait, a southerly current pushed the vessel onto rocks; damage to the starboard engine with some minor leakage of lubricating oil of the drive shaft and a power outage occurred |
| Feb-11 | *Berserk* | Yacht | Lost in the Ross Sea region (presumed sunk) and loss of crew of three |
| 9-Dec-11 | *Sea Spirit* | Quark Expeditions | Grounding of the yacht in Whalers Bay, Deception Island; yacht freed itself when the tide came in |
| 1-Apr-12 | *Endless Sea* | Yacht | Beset in ice in the vicinity of King George Island, South Shetland Islands and sank (reported to be carrying 8,000 l of fuel) |
| 7-Apr-12 | *Mar Sern Firn (yacht)* | Independent expedition | Loss of the yacht in Maxwell Bay, South Shetland Islands; all four passengers/crew were rescued unharmed by the Chilean Navy |
| 25-Dec-13 | *Akademik Shokalskiy* | Australiasian Antarctic Expedition "The Spirit of Mawson" | Vessel got trapped in pack ice off East Antarctica but eventually broke free on 8 January 2014; four other vessels provided assistance (L'Astrolabe/France; Xue Long/China; Aurora Australis/Australia; USCGC Polar Star/USA) |
| 20-Feb-13 | *Orion* | Orion Expedition Cruises/ Lindblad Expeditions | Vessel had a technical issue with its engine cooling system; auxiliary systems were used until the issue was rectified within a few hours; no threat to life or the environment. |
| 2014/15 | *Various non-IAATO yachts* | Unknown | Several incidents involving non-IAATO yachts include a grounding in the South Shetlands that resulted in an IAATO operator repatriating seven Polish nationals |

programmes operate more than 50 stations in Antarctica, whereas there are no permanent tourism facilities on the continent. Scientific activities may well leave a more significant footprint than tourism. This aspect and other considerations are elegantly summarised by Jabour (2009, p. 228):

> All humans have an impact, of this there is no doubt, and being a scientist with a 'legitimate' reason for being there does not legitim[ise] the impact. But, neither does being a tourist visiting by the good grace of some Antarctic Treaty Parties make the impact worse. If anything, national operators could take a leaf from the book they have written for the tourism industry and adopt for their stations site-specific guidelines with environmental codes of conduct, long-term monitoring programs, agreed terminology, fine-scale maps and the input of organizations like SCAR to help with calibrations on the sensitivity of the receiving environment.

## 18.10 Benefits of Antarctic Tourism

Any discussion of potential impacts has to take into account the positive effects of Antarctic tourism. The most tangible benefits include the financial gains tourism brings to gateway cities, which host visitors and crew every summer. Research stations in Antarctica can also benefit financially from the sale of souvenirs (Snyder 2007) or from receiving logistics support from Antarctic tourism operators, who occasionally provide free passage to scientists, assist in emergency situations or supply some Antarctic stations with much-needed fresh water. Less concrete benefits include the contested notion of turning tourists into ambassadors for the continent (Powell et al. 2008), the donations tourists and operators make towards environmental and heritage conservation (Snyder 2007) and the sometimes questionable political benefits that some Antarctic Treaty states gain from supporting tourism (Enzenbacher 2007).

## 18.11 Regulation and Management of Antarctic Tourism

Antarctic tourism regulation and management is primarily undertaken by two different groups: the International Association of Antarctica Tour Operators (IAATO) and the Antarctic Treaty Consultative Parties (ATCPs). There is some overlap between the self-regulatory system the tour operators have developed and governmental regulation through the ATCPs, but significant synergies exist as well (Scully 2008). Whereas the ATCPs are primarily concerned with high-level regulation of all human activities in Antarctica, IAATO focuses on tourism operations in particular and assumes considerable management functions in the field (Box 18.3). Finally, indirect regulation of Antarctic tourism is achieved through shipping codes imposed by the International Maritime Organization[1] or other

[1] In November 2014, the International Maritime Organization adopted a mandatory International Code for Ships Operating in Polar Waters (Polar Code), which is expected to enter into force in January 2017.

guidelines such as the World Tourism Organization's global code of ethics for tourism. The following paragraphs will focus on Antarctic tourism regulation and management by IAATO and the ATCPs.

**Box 18.3: Regulation, Self-Regulation and Management**

**Regulation** comprises mandatory and authoritative sets of rules and procedures that are to be abided by – commonly known as the law. Violations of such rules can be sanctioned. As such, regulations are usually the responsibility of states or governments. In the Antarctic context, regulation is represented by measures adopted by the Antarctic Treaty Consultative Parties (ATCPs).

The establishment and adoption of common standards and rules and procedures within one sector or industry are referred to as **self-regulation**. Here, members of a group within a sector or industry agree on the rules and enforce them. All members of this group have to abide by these rules and can be sanctioned for violating them. IAATO, for instance, has adopted bylaws and other operational procedures that form the backbone of the Antarctic tourism industry's self-regulation.

**Management** applies to administrative processes or acts with the goal of controlling behaviour or the use of certain things. Consequently, management is often concerned with how activities in the field are planned and carried out. These activities have to be in accordance with regulations that are in place, and management has to ensure that this is the case. Antarctic tourism management occurs mostly in the field, carried out by the operators themselves, but also extends beyond the field to include pre-visit planning and post-visit reporting. Adapted from Scully (2008) and Liggett (2009)

## 18.12 Industry Approach to Tourism Regulation

To a large extent, Antarctic tourism regulation draws on the self-organisation and motivation of operators. In 1991, seven Antarctic tourism operators formed the International Association of Antarctica Tour Operators (IAATO), which has developed a range of guidelines for responsible tourism in Antarctica. Since the 1990s, IAATO has grown from a small organisation of owner-operators to a diverse international group with more than 100 members ranging from ship-based ventures, land-based operators, companies offering overflights, travel agents and non-governmental organisations concerned about Antarctic heritage and conservation. IAATO subscribes to what has been referred to as 'environmental stewardship' with the intention of "advocate[ing], promot[ing] and practice[ing] safe and environmentally responsible private-sector travel to the Antarctic" (IAATO 2011). As such, IAATO embraces a proactive approach to managing its members' activities, which is aided by its commitment to develop and adopt best-practice operational guidelines. IAATO also represents its member organisations' interests within the framework of Antarctic governance (Chap. 16). The host of guidelines developed and adopted by IAATO includes procedures on "numbers ashore, wildlife

**Fig. 18.2** Boot washing before leaving Jougla Point, Antarctic Peninsula

watching, small boat and helicopter operations, activity reporting, passenger, crew and staff briefings; contingency and emergency medical evacuation plans; and communication procedures to coordinate site visits" (Mortimer and Prior 2009, p. 235). The latter is facilitated through a web-based ship scheduling system, which allows individual operators to log their itineraries with IAATO and to 'book' landing sites at certain times, when no other operator will be able to land there. In the 1990s, IAATO also developed a document called the Guidance for Visitors to the Antarctic, which has been translated into eight languages and made widely available online and in hardcopy. These guidelines include five basic messages to Antarctic visitors: protect Antarctic wildlife, respect protected areas, respect scientific research, be safe, and keep Antarctica pristine. In 1994, this document was adopted as a recommendation by the Antarctic Treaty Consultative Parties.

Aside from these generic visitor guidelines, IAATO members adhere to strict decontamination protocols. Among other responsibilities, these protocols require tour operators to ensure that visitors do not carry any diseases or alien species onto land in Antarctica. As illustrated in Fig. 18.2 (Box 18.1), the boots of anyone leaving the ship to go to shore in Antarctica are being washing and disinfected, usually before and after any landings.

In general, any form of self-regulation is limited to those who belong to a certain group or professional body. IAATO membership is not compulsory and comes with certain costs (e.g. membership fees) and obligations (e.g. compliance with bylaws and other rules and guidelines; participation in Annual General Meetings and decision-making). The benefits include having a forum for representation, rights to participate in decision-making, positive advertising and a boost to the image of the company. Currently, the majority of commercial Antarctica tour operators are IAATO members, but the mere fact of voluntary membership and incomprehensive coverage of the Antarctic tourism sector weakens the regulatory power and influence of IAATO's self-regulation.

The strength of self-regulation through IAATO rests within the organisation's capacity to react swiftly, creatively and knowledgably to changing conditions by drawing on the combined experience and expertise of its members. In addition, low levels of hierarchy and majority decision-making processes in IAATO also facilitate quick responses to emerging issues, incidents or changing requirements. Finally, it is in the operators' interest to maintain the relatively pristine character of the Antarctic environment they sell to the tourists.

## 18.13 Tourism Regulation Through the Antarctic Treaty System

Within the framework of the Antarctic Treaty System, tourism regulation occurs at two main levels: the Protocol of Environmental Protection to the Antarctic Treaty (Chap. 16), which regulates all human activities in Antarctica, and a range of recommendations, resolutions, decisions and measures adopted during annual Antarctic Treaty Consultative Meetings (ATCMs). Between 1966 and 2012, 38 regulatory mechanisms directly focused on tourism have been adopted by the ATCPs, eight of which were adopted prior to 1991, and 13 before the turn of the century. Such a steep increase in the number of tourism mechanisms indicates the growing concern and urgency ATCPs sense with regard to tourism. Most of the mechanisms adopted by the ATCPs are recommendations or resolutions, both of which have a largely hortatory character and are best described as guidelines. Only two binding mechanisms have been adopted by 2012: Measure 4 (2004) on insurance and contingency planning, and Measure 15 (2009) on landing operations (Box 18.4). Neither of these two binding measures is effective yet.

**Box 18.4: Binding Regulatory Mechanisms**

Measure 15 builds on IAATO practice and provides a framework for landing operations in Antarctica, stipulating that:

– only one vessel can land at any one site at any one time
– no more than 100 passengers can land at one time
– the guide-to-passenger ratio on land has to be 1:20 (or less)
– vessels carrying more than 500 passengers are not permitted to land.

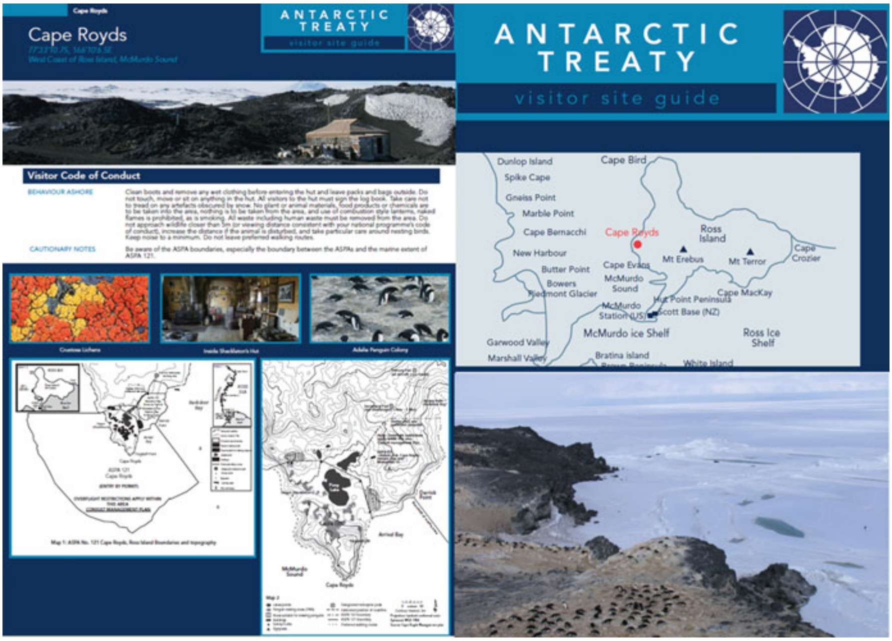



**Fig. 18.3** Site guidelines for Cape Royds (77°33′10.7 S, 166°10′6.5 E), which is one of the 35 frequently visited sites, require visitors to clean their boots and remove any wet clothing before entering the hut and to leave packs and bags outside. A guide must accompany any visitors entering the hut. They are not allowed to touch, move or sit on anything in the hut, and all visitors to the hut must sign the log book. They are asked to take care not to tread on any artefacts obscured by snow. No plant or animal materials, food products or chemicals are to be taken into the area, nothing is to be taken from the area, and use of combustion style lanterns, naked flames is prohibited, as is smoking. All waste, including human waste, must be removed from the area. Finally, visitors must not approach wildlife closer than 5 m, should increase the distance if the animal is disturbed, take particular care around nesting birds, keep noise to a minimum and stay on preferred walking routes

With IAATO's support, the ATCPs also developed site-specific guidelines, which are now available for 35 frequently visited sites (Fig. 18.3) primarily in the Antarctic Peninsula region. These site guidelines provide a site map, outline the key characteristics of a site, detail specific landing requirements and make operators and tourists aware of closed areas, potential impacts and precautions that have to be taken. All of these site guidelines contain visitor codes of conduct.

The ATCPs are recognised as the ultimate decision makers and authority with regard to Antarctic governance. Consequently, their measures can have regulatory teeth and can be strengthened through national legislative acts. However, tourism regulation by ATCPs is hampered by their consensus decision-making system. It takes a long time for the parties to react to tourism developments, agree on and adopt regulatory mechanisms and ratify them. Furthermore, the extent to which tourism operations are monitored and regulation is enforced varies among ATCPs and is generally impeded by a lack of resources and Antarctic tourism experience.

## 18.14 Concluding Critical Questions

As highlighted in this chapter, Antarctic tourism has grown rapidly and diversified considerably since the 1990s. Its future development will depend on the global economic situation, but market shifts, including a further opening up of the Asian market, are to be anticipated. The role of national Antarctic programmes in supporting tourism development by opening their runways to tourism operators or by providing tourism services themselves will affect how Antarctic tourism is perceived by policy makers and the wider public. An increasing blurring of the boundaries between science and tourism can have significant geopolitical repercussions and might widen the gap between ATCPs regarding their position on Antarctic tourism matters.

Private and independent expeditions and tourism operations originating from states that have not signed the Antarctic Treaty might test the limits of tourism regulation through ATCPs and IAATO. With regard to private expeditions, matters of operational safety and risk management are of primary concern. Are national Antarctic programmes obliged to come to the rescue of private expeditioners in distress, especially if they have not heeded any advice or warning? How can the behaviour and impact of operators that fall through the cracks of existing tourism regulations put in place by the ATCPs or IAATO be controlled?

These and many other questions inform an ongoing and intense Antarctic tourism debate. Last but not least, the consumer plays a significant role. What experience do visitors expect, what do they want to see, and how far are they going to go to encounter what is often heralded as one of the world's last wildernesses?

## References

Bastmeijer K, Roura R (2004) Regulating Antarctic tourism and the precautionary principle. Am J Int Law 98(4):763–781

Bauer T (2007) Antarctic scenic overflights. In: Snyder J, Stonehouse B (eds) Prospects for polar tourism. CABI, Wallingford, pp 188–197

Cessford G (1997) Antarctic tourism: a frontier for wilderness management. Int J Wilderness 3 (3):7–11

Donovan R (2011) Antarctic ice marathon. Retrieved 31 Oct 2011, from http://www.icemarathon.com/

Enzenbacher DJ (1993) Tourists in Antarctica: numbers and trends. Tour Manag 14(2):143–146

Enzenbacher DJ (2007) Antarctic tourism policy-making: current challenges and future prospects. In: Triggs G, Riddell A (eds) Antarctica: legal and environmental challenges for the future. The British Institute of International and Comparative Law, London, pp 155–189

Hall CM (1992) Tourism in Antarctica: activities, impacts, and management. J Travel Res 30:2–9

Headland RK (1994) Historical development of Antarctic tourism. Ann Tour Res 21(2):269–280

Headland RK (2005) Chronological list of Antarctic expeditions and related historical events. Cambridge University Press, Cambridge

IAATO (2011) Home – International Association of Antarctica Tour Operators. Retrieved 27 Oct 2011, from http://iaato.org/home

Jabour J (2009) National Antarctic programs and their impact on the environment. In: Kerry KR, Riddle MJ (eds) Health of Antarctic wildlife: a challenge for science and policy. Springer, Dordrecht, pp 211–229
Kriwoken LK, Rootes D (2000) Tourism on ice: environmental impact assessment of Antarctic tourism. Impact Assess Proj Apprais 18(2):138–150
Lamers M, Amelung B (2007) Adventure tourism and private expeditions in Antarctica: framing the issue and conceptualising the risk. In: Snyder J, Stonehouse B (eds) Prospects for polar tourism. CABI, London, pp 170–187
Lamers M, Haase D, Amelung B (2008) Facing the elements: analysing trends in Antarctic tourism. Tour Rev 63(1):15–27
Liggett DH (2009) Tourism in the Antarctic: modi operandi and regulatory effectiveness. VDM Verlag Dr. Müller, Saarbrücken
Liggett D (2011) From frozen continent to tourism hotspot? Five decades of Antarctic tourism development and management, and a glimpse into the future. Tour Manag 32:357–366
Lindblad L, Fuller JG (1983) Passport to anywhere. The story of Lars-eric Lindblad. Times Publishing, New York
Mason PA, Legg SJ (1999) Antarctic tourism: activities, impacts, management issues, and a proposed research agenda. Pac Tour Rev 3:71–84
Mason PA, Legg SJ (2000) The growth of tourism in Antarctica. Geography 85(4):358–362
Mortimer G, Prior E (2009) Antarctic tourism: an operator's perspective. In: Kerry KR, Riddle MJ (eds) Health of Antarctic wildlife: a challenge for science and policy. Springer, Dordrecht, pp 231–240
Murray C, Jabour J (2004) Independent expeditions and Antarctic tourism policy. Polar Rec 40 (215):309–317
Powell RB, Kellert SR, Ham SH (2008) Antarctic tourists: ambassadors or consumers? Polar Rec 44(230):233–241
Reich RJ (1980) The development of Antarctic tourism. Polar Rec 20(126):203–214
Scully T (2008) Chairman's report from the Miami Meeting (17–19 Mar 2008) on Antarctic Tourism. Information paper (IP) 19, XXXI Antarctic Treaty Consultative Meeting (ATCM), Kiev
Snyder J (2007) Tourism in the polar regions: the sustainability challenge. UNEP, Paris
Stonehouse B (1994) Ecotourism in Antarctica. In: Cater EL, Lowman G (eds) Ecotourism: a sustainable option? Wiley, Chichester, pp 196–212
Stonehouse B, Crosbie K (1995) Tourist impacts and management in the Antarctic Peninsula area. In: Hall CM, Johnston ME (eds) Polar tourism: tourism in the Arctic and Antarctic regions. Wiley, Chichester, pp 217–233
Stonehouse B, Snyder J (2010) Polar tourism: an environmental perspective. Channel View Publications, Bristol
Swithinbank C (1993) Airborne tourism in the Antarctic. Polar Rec 29(169):103–110
Tracey PJ (2001) Managing Antarctic tourism. Unpublished PhD thesis, The University of Tasmania, Hobart

# Chapter 19
# Creativity at the Frozen Frontier

## The Arts in Antarctica

**Patrick Shepherd**

**Abstract** For nearly 200 years Antarctica has been a focus for scientific endeavour and strategic political and economic aspirations. During that time, artists of many disciplines have made a steady and significant contribution to our understanding of life on the ice, adding further dimensions to the Antarctic experience by sharing unique insights and helping raise public awareness of the scientific issues. Many of these artists have been amateurs, heading south in other capacities, but in later years many have been professional artists travelling specifically to produce artistic works. This chapter presents some of their thoughts on their experience and how it affected their work as well as the rather unique challenges faced by creating their works in one of the most hostile environments on Earth. But just as it is brutal, Antarctica is also supremely beautiful, a "symphony of splendour" in the words of the photographer Emil Schulthess, and "at times anxious and at times peacefully resolute", according to photographer Craig Potton.

**Keywords** Art • Imagination • Science and art • Photography • Writers • National artists' programmes

### 19.1 Making Art on Ice

The study of Antarctic arts can be approached in several different ways. A distinction can be drawn between works created in the imagination, those from the direct experience of amateur artists and, most recently, those produced by the professional artists. There is also an interesting subcategory emerging, that of making art from Antarctica, as in the compositions by Cheryl Leonard (USA) that use recorded sound and naturally sourced instruments such as stones, shells and penguin bones.

Many aspects of Antarctic art can be explored, but presented here is the historical context of Antarctic arts; from the mysterious, mythical continent existing beyond the known physical world that excited the imagination of writers

P. Shepherd (✉)
College of Education, University of Canterbury, Christchurch, New Zealand
e-mail: patrick.shepherd@canterbury.ac.nz

 
D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_19

and painters, through the photographs and paintings charting the heroic quests for sovereignty and scientific knowledge, and finally to the work of artists keen to absorb "these exotic and intoxicating lands of Antarctica" into their work (Manhire, Antarctica NZ Archives). Apsley Cherry-Garrard's (Scott's Terra Nova Expedition) statement that "everyone who has been through such an extraordinary experience has much to say, and ought to say it if he has any faculty that way" (Cherry-Garrard 1922) has almost become the mantra for Antarctic artists when talking about their Antarctic experience. In addition to comparing the products of the dream with the reality, and the imagined with the experienced, there are also offerings from the amateur artists on early expeditions and the growing body of works by the many artists that have benefited from the artist programmes since.

## 19.2 Dream and Reality

One can divide the artists who have represented Antarctica into two categories – those for whom it has existed purely as an imaginary destination and those who have actually been there and experienced it first-hand.

### *19.2.1 Antarctica in the Imagination*

Edgar Allan Poe's "the perfect whiteness of the snow" (Poe 1838) and "the blackness of eternal night [great] ramparts of ice ... like walls of the universe" (Poe 1833, 1845) are as true as any first-hand account. James Fenimore Cooper (1849) and Jules Verne (1897) both incorporated tales from polar travellers into their work, and any writer's imagination would surely have been fired by the closely documented southern voyages of Captain James Cook, accompanied by the evocative paintings of William Hodges on Cook's second expedition (1772–1775). In 1788, Andrew Kippis wrote that Cook's voyages "have opened up new scenes for a poetical fancy to range in" (Kippis 1788). J. M. W. Turner painted two whaling scenes based on the narrative of James Clark Ross and in Samuel Coleridge Taylor's *Rime of the Ancient Mariner* (1878) the mariner's journey briefly takes him to Antarctica, as the ice "cracked and growled, and roared and howled", echoed brilliantly in Gustave Doré's bleak illustrations to the text (Manhire 2004). H. P. Lovecraft's novella *At the Mountain of Madness* (1939) and Don L. Stuart's (aka John Wood Campbell) *Who Goes There?* (1938) were both inspired by Richard Byrd's exploits (Byrd 1938), Stuart's short story transferring to the movie screen as *The Thing*. T. S. Eliot incorporated elements of Shackleton's narrative from *The Heart of The Antarctic* in *The Waste Land* and parallels with polar exploration are often drawn with Joseph Conrad's *Heart of Darkness*, in its "brooding damnation of European imperialism and intellectual self-complacency" (Pyne 1986).

In a different sphere altogether, Ralph Vaughan Williams' Symphony no. 7 *Sinfonia Antartica* [sic] used music from the composer's film score for *Scott of the Antarctic* (1948), starring John Mills. Vaughan Williams' score is evocative and eerie, aided by his use of a female chorus that wails in the distance like sirens luring sailors to their doom.

Incidentally, composer Sir Peter Maxwell Davies did travel to Antarctica in 1997 with the British Antarctic Survey and wrote his Antarctic Symphony (Symphony no. 8) to mark the 50th anniversary of the film *Scott of the Antarctic*.

### *19.2.2 Experiencing Antarctica First-Hand*

One can further subcategorise the artists who have been to Antarctica; those who went in another capacity, e.g. Edward Wilson who went as Scott's chief scientist, and those who have gone purely as artists. This is not intended to draw any conclusions regarding an amateur or professional status, nor the technical capabilities of either, merely the focus under which their respective trips were taken.

## 19.3 Science and the Artist

Wilson was an excellent artist with a keen eye for detail; his paintings of birds done in England are near-photographic likenesses. Wilson overcame the practical problem of painting with watercolours in Antarctica (i.e. water and paints freezing) by sketching the outlines then creating a painting-by-numbers schema so he could complete them later, either back in the expedition hut or in England. Wilson edited *The Polar Times*, which featured cartoon drawings, poems, songs and articles, both serious and humorous, allowing the amateur artists a chance to express themselves. Under Wilson's tutelage, Cherry-Garrard improved his skills considerably (Fig. 19.1).

The works of amateur artists such as Herbert Swire (Challenger Expedition 1872–1876), George Marston (Shackleton's Nimrod expedition of 1907), Charles Royds (Scott's Discovery expedition 1901–1904) and John Hamilton (aboard HMS Endurance for two winters during the 1990s) are just some of the many examples that provide a surprisingly large body of work.

This relationship between science and art in Antarctica has continued, with scientists such as Richard Laws, Gordon (Tony) Fogg, Sir Alister Hardy, Rolfe Gunther, Sandra Chapman (all from the UK), and Kim Westerskov (NZ) expressing themselves through art as well as science. Douglas Quin (USA), Andrea Juan (Argentina) and Andrea Polli (USA) use scientific research as the foundation for their Antarctic music and sonic art.


**Fig. 19.1** *Mount Erebus*, by Edward Wilson (With kind permission from the Scott Polar Research Institute, University of Cambridge)

## 19.4 Antarctica Through the Lens

Of course, the medium through which Antarctica is most widely recognised is photography. It is principally through the work of Herbert Ponting (Scott's Terra Nova Expedition), described by Captain Scott as "an artist in love with his work" (Scott 1923) and Frank Hurley (Shackleton's Imperial Trans-Antarctic Expedition) that we truly capture the spirit of the Heroic Age. In some respects, the fact that these images are starkly portrayed in black and white adds further pathos and depth to the subjects being portrayed, the underlying human drama unfolding in monotone through an impassive and almost fatalistic lens. Poet Chris Orsman highlights this perfectly in the lines "This early footage is played hard/with a graceful optimism./ Men smile, stamp, breathe/into their permanent images," (Orsman 1996). As well as heightening the moment-in-time aspect, the black and white images provide a clarity and crispness that in an instant brings back to anybody who has lived in a cold climate – but particularly Antarctica – that brutal sense of cold (Fig. 19.2).

**Fig. 19.2** *Meares and Oates at the blubber stove*, by Herbert Ponting (With kind permission from the Scott Polar Institute, University of Cambridge)

## 19.5 New Zealand Artists Programme

Several countries run programmes for visitors to Antarctica, some of which specifically include artists. In addition to New Zealand some of the more significant ones include Great Britain, the USA, Australia, Argentina and Chile, supporting artist visits. Consequently a significant body of Antarctic-related art has been established, enabling artists to enrich the story of Antarctica with their personal insights and responses. A typical description of the aims of these programmes appeared in a 2005 press release from Elizabeth Kerr, Creative New Zealand's chief executive, describing New Zealand's programme as "an admirable example of how arts, science and the environment can come together".

New Zealand has supported sending artists to Antarctica for nearly 50 years, a relationship that began in 1957 with the first invited artist, painter Peter McIntyre, continuing in 1970 with Maurice Conly, an official artist with the RNZAF. Others followed but it was not until 1997, following Resolution 2, adopted at the 1996 Antarctic Treaty Consultative Meeting (ATCM), that an official programme was put in place, recommending the "promotion of understanding and appreciation of the values of Antarctica, in particular its scientific, aesthetic and wilderness values, through... the contribution of writers, artists and musicians" (Antarctica New Zealand) (Fig. 19.3).


**Fig. 19.3** *Cape Royds*, by Nigel Brown (With kind permission from Nigel Brown)

**Box 19.1: Artists in Antarctica**

"In Antarctica I felt the curve of the earth, our fragile reliance on the sun, on temperature, on supplies, as never before."

Nigel Brown, painter

"I had not counted on the presence of the Sublime there and what it means to come to terms with this challenging concept, part aesthetic, part philosophical, part spatial."

Chris Orsman, poet

"Visiting the Antarctic is the closest I will ever get to being on another planet. It is not a natural place for humans to be."

Margaret Mahy, author

Later that year, the board of Antarctica New Zealand approved the strategy, affirming the artists' role by supporting the aims of the Antarctic Treaty with the Artists to Antarctica Programme. Antarctica New Zealand provided administrative and logistical support and Creative New Zealand financial support. The programme encouraged New Zealand artists in all disciplines to explore Antarctica through their work, thus increasing New Zealanders' understanding of Antarctica's value and global importance. Each year two to three artists headed south, ranging from visual artists of various media (painters, ceramicists, photographers, sculptors, choreographers, jewellers, designers) through to writers and composers, with each artist awarded the title of Antarctic Arts Fellow. The first recipients were the painter

Nigel Brown and poet Chris Orsman who travelled with Invited Artist poet and writer Bill Manhire, during the 1997/1998 season. During their time in Antarctica, this creative trio produced their own equivalent to *The Polar Times*, entitled *Homelight*. The Artists to Antarctica Programme ran for 10 years and is currently in abeyance, replaced by an invited artist scheme. Incidentally, at the time of writing both the British and American schemes are also in abeyance.

Currently, each year Antarctica New Zealand invites one or two artists and writers to travel to Antarctica for specific projects. The artists become honorary Antarctic Arts Fellows and travel to Antarctica under the Invited Artists Programme. The aim of the programme is "to increase New Zealanders' understanding of Antarctica's value and its international importance through the work of our top artists" (Antarctic 2008).

## 19.6 Unique Challenges

For many of the artists, the experience has been a life-changing one. Pyne refers to Antarctica as "nature as modernist", alluding to the problems all Antarctic artists face, that Antarctica is already "abstracted, minimalist, conceptual. Here is not another case of information overload but of underload", driving all human conventions to their absolute extremes, an "esthetic sink, not an inspiration . . . its fantastic isolation seemingly defied any but self-referential attempts to assimilate it". Antarctica's laying attraction in its "alienness and inaccessibility" (Pyne 1986). This effect on the senses is also acknowledged by author Laurence Fearnley when explaining the initial impressions after the plane has touched down, describing "a kind of sensory overload; for as far as the eye can see, everything is white. It's as if the pilot has somehow managed to touch down on a cloud." (Fearnley 2006).

Perhaps paradoxical then, seeing as the intrinsic value of artist programmes and the work of a number of artists is under discussion here, that Manhire should articulate that, "Antarctica is – exhilaratingly – what reality must have looked like before the frames of the human imagination did their work" (Manhire, Antarctica NZ Archives).

In his poem *Erebus Voices*, Manhire also encapsulated the sorrow of a nation, the "tears you will weep tomorrow" (Manhire 2005), commemorating the crash of Air New Zealand flight TE901 into Mount Erebus in 1979, another link inextricably binding New Zealand to Antarctica.

For textile artist Clare Plug the solution to assimilating Antarctica into her work was to consider "the possibilities that the origins, role and function of textiles in Antarctica offered" (Hammond et al. 2009), from flag motifs to emblems and symbols, such as the cross in the work below, ASPA 156 – Erebus Voices (Fig. 19.4).

Dancer Bronwyn Judge described Antarctica as having "no wind, no bird song, no water dripping, no smells, no life . . . absolute stillness", while painter Margaret Elliot has alluded to "the strangeness of the place". Painter Dick Frizzell referred to "the intense mood and atmosphere" of Scott's Discovery Hut which changed his

**Fig. 19.4** Banner Detail, 2008, Clare Plug, Look South! (With kind permission from Clare Plug; image courtesy of MTG Hawke's Bay)

plan for his artistic response, while composer Chris Cree Brown aimed "to create abstract sounds that would reflect some of the magnificence of the continent . . . an expressive link between a real, unaltered and recognisable sound source and more abstract textures". Fellow composer Phil Dadson was "awestruck" and Antarctica made him realise what "an absolute miniscule remote and insignificant dot" we are on our planet (all Antarctica NZ Archives) (Fig. 19.5).

The effect the trip south has had on the artists and their work is as diverse as the artists themselves. For some it became almost spiritual, for others it meant a connection, or reconnection, with their own beliefs and modus operandi. For painter Grahame Sydney it meant he "could get far more out of far less subject matter", while for Plug it added "greater authenticity and impact . . . creating works that go beyond the trite and tried, the stereotypic views" (both quoted in Taylor 2009). Sculptor Virginia King felt that she had "set out to try and trap magic", while both printmaker Denise Copland and jeweller Kirsten Haydon found new ways of working. Copland was taken out of her "comfort zone and into the unknown, resulting in new ways of working, thinking and responding to elements of chance and change", while for Haydon the Antarctic Fellowship "altered the way that I see, and the experience of Antarctica's grand landscape has influenced the way I create work" (Antarctica NZ Archives).

For composer Gareth Farr it was "the epiphany moment – when I realised that it was the people who have been to Antarctica in the last hundred years" (Shepherd 2006) that he could reflect in his music. Writer Owen Marshall also indentified the importance of the human element saying, "people are the most fascinating thing of

**Fig. 19.5** *Echoes 10*, by Margaret Elliot (With kind permission from Margaret Elliott)

all" (Marshall 2010a) and, in his poem *Sleepwalking in Antarctica*, referring to the "close familiarity of strangers" (Marshall 2010b). Several artists found themselves looking at the details. I found inspiration in the minutae and the human interest aspects, Antarctica taught furniture maker and designer David Trubridge "to focus on tiny little details and the importance of them". Fashion designer Fieke Neuman summed it up by saying, "it might seem strange to concentrate on the small and colourful in a place like Antarctica, which is so huge and colourless and relentlessly terrifying". The adventurous aspect struck poet Bernadette Hall, who "felt like a survivor . . . I had walked right outside my usual self, back to something like the heroine all girls are at about age nine" (all Antarctica NZ Archives) (Fig. 19.6).

## 19.7 Artists' Contributions to Life on Ice

The value to the artists is inestimable in terms of the impact on their work, but the logistics are also important and the cost of sending artists to Antarctica is significant. The purpose and value of such programmes undergoes continual scrutiny. Sydney has suggested that artists "reach an audience that otherwise would not be particularly interested in, or bothered with, Antarctic awareness" and that Antarctic-related art is "part of the humanising of Antarctica". Author Margaret Mahy agreed, stating that art "expresses the Antarctic in a way that makes aspects of it absorbable in human terms – makes it part of the human imagery of the world". Laura Taylor, in her treatise on the arts programmes, believes that not only do the

**Fig. 19.6** Biodiversity Dress, by Fieke Neuman (With kind permission from Fieke Neuman)

arts "give texture and substance to the public perception of Antarctica" but also that artists "are able to communicate ideas and feelings, emotions, quite complex and multifaceted things in often quite different ways than scientists do. [artists are] able to reach out to a different audience. . .. [and] can increase awareness to a very wide audience, to capture their imaginations, move them emotionally even!" (Taylor 2009).

## 19.8 Conclusions

The final words are best left to the artists themselves. Marshall summed up the feelings of most, if not all, of the artists who have headed south as part of an artist programme, saying: "How fortunate I am to have been given the opportunity to make the trip. In time, the things of significance will become clear as the present swirl of impressions settles" (Marshall 2010a). Sydney has acknowledged that each artist responds differently "so it adds up to a colourful tapestry of responses in the end" (Taylor 2009) and painter Kathryn Madill has commented that "Antarctica is what you make it, that you take your ideas and expectations down with you, and make of it what you will. I found that gigantic indifference thrilling – it was as if everything in my head was swept clean – scoured like the stones in the Dry Valleys". Manhire says quite simply, "You can't copyright Antarctica".

## References

Antarctic (2008) Antarctica New Zealand announces invited artists. Antarctic 26(2):21–42
Antarctica New Zealand. www.antarcticanz.govt.nz
Byrd RE (1938) Alone. G. P. Putnam's Sons, New York
Cherry-Garrard A (1922) The worst journey in the world. Picador, London
Cooper JF (1849) The sea lions (1965 reprint). University of Nebraska Press, Nebraska
Fearnley L (2006) Degrees of separation. Penguin, Auckland
Hammond L, Lloyd D, Ryan U (2009) Clare Plug: look south! Hawke's Bay Museum and Gallery, Napier
Kippis A (1788) The life of Captain James Cook. George Newnes, London
Manhire B (ed) (2004) The wide white page. Victoria University Press, Wellington
Manhire B (2005) Lifted. Victoria University Press, Wellington
Marshall O (2010a, 14/2/2010) Life on the ice. Sunday Star Times
Marshall O (2010b) Sleepwalking in Antarctica and other poems. Canterbury University Press, Christchurch
Orsman C (1996) South: an Antarctic journey. Victoria University Press, Wellington
Poe EA (1833, 1845) Manuscript found in a bottle. Oxford University Press, Oxford
Poe EA (1838) The narrative of Arthur Gordon Pym. http://books.eserver.org/fiction/poe/narr_of_arthur_gordon_pym.html
Pyne SJ (1986) The ice. Phoenix, London
Scott RF (1923; this ed 2003) Scott's last expedition: the Journals of Captain RF Scott. Pan Books, London
Shepherd P (2006) Antarctica – a cold, quiet place. Canzona Yearb Compos Assoc N Z 26 (47):102–105
Taylor L (2009) Communicating gateway identity. University of Canterbury, Christchurch
Verne JG (1897) An Antarctic mystery (the Sphinx of the ice fields). Pierre-Jules Hetzel, Paris

## *Further Reading*

Andrews L (2008) Antarctic eye: the visual journey. Studio One, Tasmania
Bellamy J (2006) Art in the freezer [DVD]. Canaan Lane Productions, New Zealand
Braunarts/BAS (2002) Antarctic waves 1.0: making music from science: Braunarts/British Antarctic Survey
Brown CC (2001) A composer in Antarctica. Paper presented at the Australasian Computer Music Association, University of Western Sydney
Couture P (2004) Ice. Beauty. Danger. History. McArthur & Company, Toronto
Dadson P (producer) Polar projects. http://www.sonicsfromscratch.co.nz

DJSpooky (producer) Sinfonia Antarctica. http://www.djspooky.com/art/terra_nova.php
Farr G (composer/entertainer). http://www.garethfarr.com
Guin UL (1982) Sur. Harper and Row, New York
Harrowfield DL (2007) Call of the ice: fifty years of New Zealand in Antarctica. David Bateman, Auckland
Hoflehner J, Hoflehner K (2003) Frozen history: the legacy of Scott and Shackleton. Josef Hoflehner, Wels
Irish G (Summer 2005/2006) Southbound: artists to Antarctica. Art New Zealand 117
Joshi ST (ed) (2001) The thing on the doorstep and other weird stories. Penguin Classics, London
Judge B (artist) (2002) Kathleen's Antarctica. Multimedia presentation including dance, drama, video and live music: video held in archives at Antarctica NZ
Kenneally T (1977) Victim of the Aurora. Harcourt, San Diego
Kolbert E, Spufford F (eds) (2007) The ends of the Earth. Granta Publications, London
Leonard CE (composer, performer, instrument builder). http://www.allwaysnorth.com/contact.html
Lovecraft HP (1939) At the mountains of madness. Reprint 1964, Ballantine Books
Mastro J (2002) Antarctica: a year at the bottom of the world. Bulfinch Press, Portland
Morris S (1997) Terra incognita: travels in Antarctica. Vintage, London
Moss S (2006) Scott's last biscuit. Signal Books Limited, Oxford
Potton C (2003) Improbable Eden: the dry valleys of Antarctica. Craig Potton Publishing, Nelson
Quin D (1997–98) Antarctica: Austral soundscapes. Musicworks: exploration in sound 69
Rex T (2001) South with endurance: Shackleton's Antarctic expedition 1914–1917. BCL Press, London
Riffenburgh B, Cruwys E, Arnold HJP (2004) With Scott to the pole: the Terra Nova expedition 1910–1913. BCL Press, London
Rosove MH (ed) (2000) Let heroes speak: Antarctic explorers 1772–1922. Berkley/Penguin Putnam, New York
Schulthess E (1960) Antarctica. Simon & Schuster, New York
Shepherd P (2008) Shades of blankness in a pale palette. Research in New Zealand Performing Arts: Nga Mahi a Rehia no Aotearoa (eJournal)
Shepherd P (2009a) From ice to music: the challenges of translating the sights and sounds of Antarctica into music. Sound Scr 2:79–88
Shepherd P (2009b) Sounds of Antarctica: how composers process the natural environment in their music and the impact these conclusions might have for the broader aspect of learning through they art of composition. In: Proceedings of the joint conference of XXXIst ANZARME annual conference and the 1st conference of the Music Educators Research Centre (MERC), pp 261–271
Simpson-Housley P (1992) Antarctica: exploration, perception, and metaphor. Routledge, London
Sonic Antarctica. http://www.andreapolli.com/
Spufford F (1996) I may be some time: ice and the English imagination. Faber & Faber, London
Stephenson RB (producer) Antarctic art. http://www.antarctic-circle.org/
Stewart D (artist) (1964) The fire on the snow. Radio play
Ussher J, Watson N (2010) Still life. Murdoch Books, Sydney
Walton DWH, Pearson B (eds) (2006) White horizons – British art from Antarctica 1775–2006. British Antarctic Survey, Ipswich
Weiss R (1984) Antarctica and concepts of order: two installments. Leonardo 17(2):95–99

# Part IV
# Current Issues

# Chapter 20
# Commercial Harvest in Antarctica

## Exploitation of Antarctic Marine Living Resources

**Alan D. Hemmings**

**Abstract** James Cook's discovery that the ocean around Antarctica teemed with life inspired a massive hunt for seals and later whales, which in part drove subsequent Antarctic exploration. While formal commercial whaling in Antarctic waters ended with the 1986/1987 season, following the adoption of a moratorium by the International Whaling Commission (IWC), the practice has continued under the guise of so-called scientific whaling. Antarctic fishing began in the early 1960s, with exploratory activities conducted by the Soviet Union, and has since developed into a substantial industry focusing mainly on Antarctic krill and finfish. The 1980 Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) was set up to manage commercial harvests of marine organisms in the ocean around Antarctica and has succeeded in regulating fisheries, but it grapples with issues such as accidental bycatch of non-target species and substantial illegal or unreported catches. From Cook's bold statements about the abundance of life in Antarctic waters to over half a billion dollars of commercial revenue from harvests each year, this chapter provides a basic outline of the nature of, and issues posed by, the exploitation of Antarctic marine living resources in the early twenty first century.

**Keywords** Antarctic • Sealing • Whaling • International Whaling Commission • Fishing • CCAMLR

## 20.1 Abundant Life

James Cook, one of the greatest European navigators, effectively delimited the Antarctic continent within very high latitudes during his second expedition of 1772–1775 with HMS *Resolution* and *Adventure* (Fig. 20.1). Although he never actually saw the Antarctic continent, Cook made the first documented voyage south

A.D. Hemmings (✉)
Gateway Antarctica, University of Canterbury, Christchurch, New Zealand
e-mail: ahe30184@bigpond.net.au



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_20

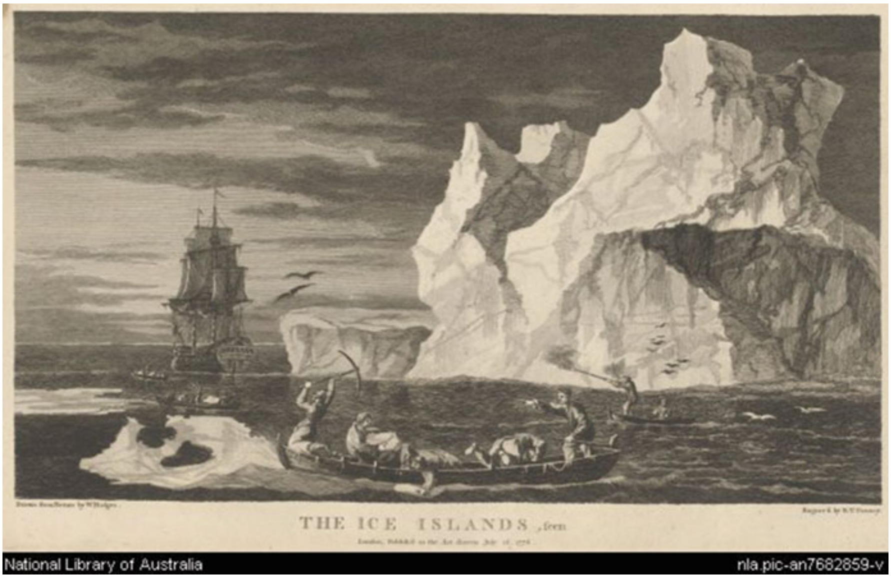



**Fig. 20.1** This image depicts a scene from Cook's second expedition in the Antarctic. Titled *The ice islands seen on the 9th of Jany* (sic) *1773*, it was drawn from Nature by William Hodges and engraved by Benjamin Thomas Pouncy (With kind permission from the National Library of Australia, http://nla.gov.au/nla.pic-an7682859)

of the Antarctic Circle in the course of this expedition, crossing it in both the south Indian and south Pacific sectors and penetrating as far as 71° South in what we now call the Amundsen Sea in January 1774. Cook also charted subantarctic South Georgia and the southern group of the South Sandwich Islands, both of which bear names he assigned them.

The discovery that the waters of the Antarctic region teemed with life, and most notably the commercially valuable fur seals and whales, led directly to the massive, and to modern sensibilities ecologically unsustainable and brutal, hunting of seals and later whales in Antarctic waters. This in part drove subsequent Antarctic exploration. Cook was, for all the brilliance of his navigational skills and contribution to knowledge of our world, the harbinger of a rapacious approach to Antarctic marine living resources, whose ecological consequences are with us still.

Ironically, given the 150 plus years of Antarctic marine mammal exploitation that this voyage ushered in (with so-called scientific whaling continuing to this day), Cook had a less than sanguine view of the benefits of the "lands doomed by Nature to perpetual frigidness; never to feel the warmth of the sun's rays; whose horrible and savage aspect I have not words to describe", suggesting that "if any one should have resolution and perseverance . . . proceeding farther than I have done, I shall not envy him the honour of the discovery; but I will be bold to say, that the world will not be benefited by it" (Cook 1777).

Around the entire Antarctic and subantarctic, contemporary annual returns from fisheries are now substantial. Within the area managed by the 1980 Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) we are now talking about a commercial value of approximately $US640 million a year, based upon a doubling of the wholesale price per tonne calculated for the commercial catch in 2009/2010 (Denzil Miller, pers. comm.). The economic returns to Australia alone from its subantarctic fisheries are presently estimated at $A30 million per annum. Whilst the rump of whaling is likely a financial loss-maker, a well-established tourism industry (Chap. 18) and emerging biological prospecting interests in Antarctic waters (as well as on the continent in both cases), combined with fishing, means the benefits, in a financial sense, are now very considerable.

## 20.2 The Antarctic Marine Environment

For our purposes, the Antarctic marine environment is best seen as the ocean area south of the Antarctic Convergence or Polar Front (we shall use the latter term), where the very cold Antarctic waters abut the less cold subantarctic waters. The Polar Front varies in its position, being at its most southerly in the Pacific sector, where it is at around 60°S; around 50°S in the Atlantic sector, and reaching to 45°South in the Indian Ocean sector. All of the Antarctic continent and about half the subantarctic islands are south of the Polar Front (although in some definitions, subantarctic islands are only those islands south of the Polar Front). The Antarctic marine environment south of the Polar Front covers approximately 32 million square kilometres (Croxall and Nicol 2004), constituting just under 10 % of the global marine area.

The Antarctic marine environment may also be defined as the area south of the Antarctic Circumpolar Current (Aronson et al. 2011), or within what is termed the Southern Ocean, although the latter is variously used to refer to the entire oceanic area south of the southern continents (i.e. the ocean south of Stewart Island or off Adelaide), the oceanic area south of the Polar Front, or as the oceanic area south of 60°S only.

Since one of the principal multilateral environmental agreements regulating marine harvesting, CCAMLR, defines its northern boundary by an approximation to the position of the Polar Front, this makes a convenient and precise boundary for consideration of the exploitation of living resources in the Antarctic marine environment. The major physical features, within the CCAMLR boundary, are shown in Fig. 20.2.

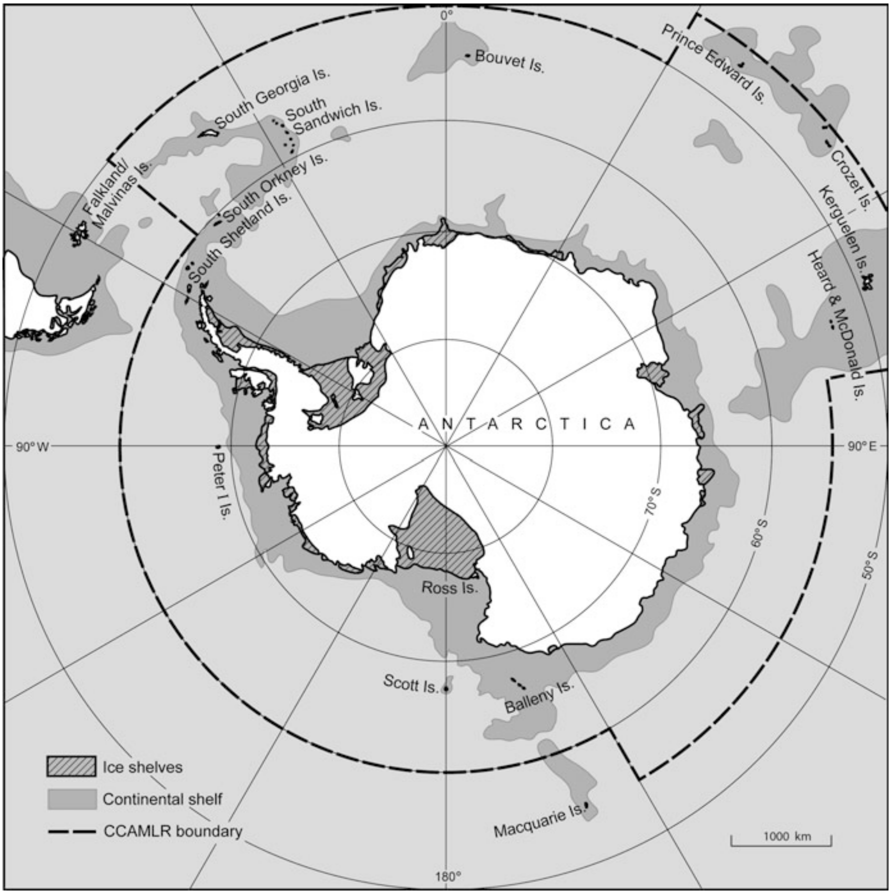



**Fig. 20.2** The Antarctic marine environment delimited by the CCAMLR boundary (Compiled by Philip Stickler for Alan D. Hemmings and Tim Stephens)

## 20.3 Historical Development of Exploitation

### *20.3.1 Sealing*

The Antarctic fur seal, *Arctocephalus gazella* (Fig. 20.3) and subantarctic fur seal, *A. tropicalis*, were hunted at South Georgia for their pelts within a decade of the publication of Cook's *A Voyage Towards the South Pole and Round the World*. Hunting spread thereafter to the South Shetland Islands and Antarctic Peninsula, and around the subantarctic. In many locations fur seals were effectively extirpated within a few years, millions of them were killed, and by 1830 the industry was no longer economically viable across much of the region (Kock 2007). This catastrophic boom and bust approach to fur seals ranks alongside the better known

**Fig. 20.3** Antarctic fur seal (© Alan D. Hemmings)

slaughter of North American bison as one of the greatest human-caused ecological disasters of the nineteenth century. Whilst the twentieth century saw a recovery of fur seal numbers (possibly to levels today which are higher than those of the late eighteenth century as a result of other ecological changes in the region), they were still sufficiently at risk in the early 1960s that the first substantive proto-conservation initiative in Antarctica, the 1964 Agreed Measures for the Conservation of Antarctic Fauna and Flora, established its highest level protection category (Specially Protected Species) in order to safeguard fur and Ross seals. Fur seals were only removed from the Specially Protected Species list in 2006, 220 years after we first started butchering them.

From the early nineteenth century, elephant seals, *Mirounga leonine*, were hunted for blubber oil, and within the century massively reduced in numbers across their subantarctic breeding range (there are also populations in the Antarctic Peninsula and East Antarctica). Whilst the ending of elephant sealing allowed South Georgia, where possibly above a million were killed, and Scotia Arc populations to recover, elephant seal populations in the Indian Ocean subantarctic seem not to have, and some other ecological effects may have kicked in.

Other Antarctic seals, principally the crabeater, *Lobodon carcinophagus*, and Weddell, *Leptonychotes weddellii*, were killed for human and dog food throughout the twentieth century until the adoption of the 1991 Protocol on Environmental Protection to the Antarctic Treaty, which, amongst other things, required the removal of dogs from Antarctica. The possibility that a new commercial sealing industry would start in Antarctica led to the adoption of the 1972 Convention for the Conservation of Antarctic Seals, but the industry has not eventuated and thus this regulatory structure (which is now rather old and unlikely to meet present sensibilities) whilst in legal force has not needed to operate.

### *20.3.2 Whaling*

Cook's observation of large numbers of whales in Antarctic waters was reinforced by James Clark Ross' reports of whales in the open waters of the Ross Sea, first penetrated in his expedition of 1839–1843 (Ross 1847). It was not until the early 1890s that the first whalers visited Antarctic waters, and 1904 before it really took off there. Whaling occurred earlier in the nineteenth century in lower latitudes of the Southern Ocean, and into the subantarctic (Darby 2007). Until the early 1930s, Antarctic whaling (initially from shore stations, but thereafter increasingly pelagic with factory ships processing whales at sea) was, despite coming under scientific enquiry, subject to only patchy regulation (Burnett 2012). Up to the Second World War, several regulatory developments occurred, but the activity was essentially ended by that war and only recommenced in 1946 (Tønnessen and Johnsen 1982). That year also saw the adoption of the International Convention for the Regulation of Whaling (ICRW), which established the International Whaling Commission (IWC), which continues to be the formal institution responsible for managing whaling, including in Antarctica, to this day.

Antarctic whaling has variously focused on blue (*Balaenoptera musculus*), fin (*B. physalus*), humpback (*Megaptera novaeangliae*), sei (*B. borealis*), sperm (*Physeter macrocephalus*) and minke (*B. bonaerensis*) whales, tending to focus on smaller species such as the minke as the larger blue and fin whales were exterminated. The total whale catch in Antarctica between 1904 and 1978 has been calculated at 1,393,254 (Tønnessen and Johnsen 1982), a catch level that was entirely unsustainable ecologically, or for most of us morally.

Formal commercial whaling in Antarctic waters ended with the 1986/1987 season, following the adoption by the IWC of a moratorium on commercial whaling, although as we shall see below, de facto commercial whaling has continued since under the guise of Special Permit or so-called scientific whaling.

### 20.3.3 Fishing

Antarctic fishing began in the early 1960s with exploratory activities conducted by the Soviet Union (Kock 1992). Throughout the 1970s, Nototheniid fish, particularly marbled rock cod, *Notothenia rossii*, and the mackerel icefish, *Champsochephalus gunnari*, were overfished around some subantarctic islands, particularly South Georgia and Kerguelen. These fisheries commenced before there was any international regulatory structure in place in relation to marine harvesting in Antarctic waters.

In the early 1970s, harvesting of Antarctic krill, *Euphausia superba*, began, initially again led by the Soviet Union. Antarctic krill constitutes not only an enormous potential biomass, but it is an important (often dominant) ingredient in the diets of many other Antarctic organisms. It soon became imperative that a regulatory structure was put in place. The resulting Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), adopted in 1980, established an ecosystem-based mechanism for the science-based (and science-seeking) setting of catches and conditions for finfish, krill and other marine organisms (CCAMLR 2013). Notwithstanding its progressive nature, particularly in relation to other regional fisheries management organisations (RFMOs) (Fabra and Gascón 2008), and whilst seemingly successful in relation to managing the first-generation krill fishery which peaked at some 400,000 tonnes per annum in the mid 1980s before the collapse of the Soviet system also collapsed this fishery (Fig. 20.4), CCAMLR failed to prevent the effective collapse of the first-generation finfish fishery of *Notothenia spp*. The second-generation fishery for toothfish, *Dissostichus spp.*, has posed similar challenges, which CCAMLR appears to have been more successful in managing.

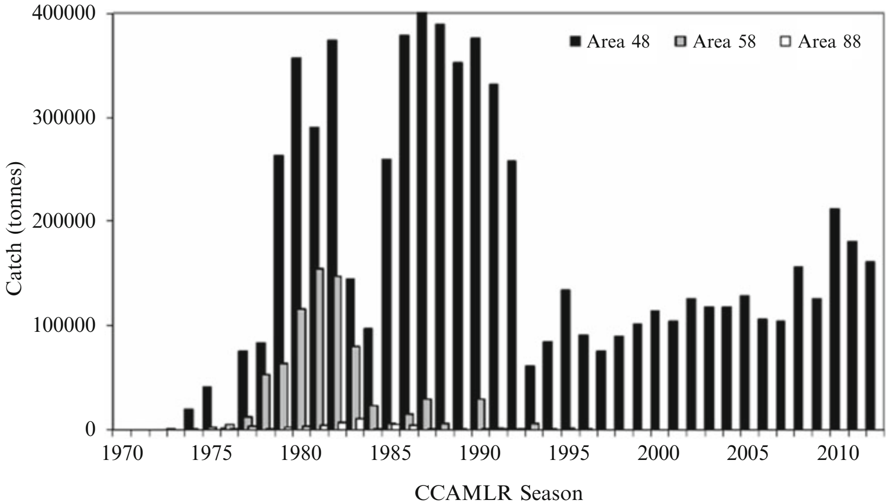



**Fig. 20.4** Antarctic krill, *Euphausia superba*, catch history within the CCAMLR area from 1970 to 2011 (With kind permission from CCAMLR, http://www.ccamlr.org/en/fisheries/krill-fisheries)

## 20.4 Contemporary Whaling

The only whaling now conducted in the Antarctic marine environment is that carried out by Japan under Article VII(1) of the ICRW which allows parties to "grant to any of its nationals a special permit authorising that national to kill, take and treat whales *for the purposes of scientific research*" (emphasis added) (Canberra Panel 2009). Japan has claimed that its research throws useful light on the functioning of the Antarctic marine environment. However, the purposes, manner of killing, and the numbers of whales killed (Table 20.1) are opposed by scientific communities, many states, and western public opinion. In the past 11 years, Japan has killed 103–866 whales a year in the Antarctic marine environment, a figure that would likely be substantially higher were it not for the anti-whaling activities by Greenpeace and the Sea Shepherd Conservation Society (Fig. 20.5). Australia initiated legal action against Japan in the International Court of Justice in 2010, with the case having been considered by the bench in June and July of 2013. The Court delivered its judgement on 31 March 2014, substantially finding against Japan and directing, inter alia, that it should revoke the permits it had granted, and refrain from granting any further permits, in relation to its whale research programme (International Court of Justice 2014).

**Table 20.1** Japan's special permit whale catches in the Southern Ocean, 2002/2003 to 2012/2013

| | Whale | | | | | |
|---|---|---|---|---|---|---|
| Reporting year | Fin | Sperm | Sei | Brydes | Minke | Total |
| 2002/2003 | 0 | 0 | 0 | 0 | 441 | 441 |
| 2003/2004 | 0 | 0 | 0 | 0 | 443 | 443 |
| 2004/2005 | 0 | 0 | 0 | 0 | 441 | 441 |
| 2005/2006 | 10 | 0 | 0 | 0 | 856 | 866 |
| 2006/2007 | 3 | 0 | 0 | 0 | 508 | 511 |
| 2007/2008 | 0 | 0 | 0 | 0 | 551 | 551 |
| 2008/2009 | 1 | 0 | 0 | 0 | 680 | 681 |
| 2009/2010 | 1 | 0 | 0 | 0 | 507 | 508 |
| 2010/2011 | 2 | 0 | 0 | 0 | 171 | 173 |
| 2011/2012 | 1 | 0 | 0 | 0 | 266 | 267 |
| 2012/2013 | 0 | 0 | 0 | 0 | 103 | 103 |
| Total | 18 | 0 | 0 | 0 | 4,967 | 4,985 |

From International Whaling Commission, Special Permit Catches since 1985; http://iwc.int/table_permit.htm


**Fig. 20.5** Greenpeace protesting against Japanese whaling in Antarctica (With kind permission from Greenpeace/Jeremy Sutton-Hibbert)

## 20.5 Contemporary Fishing

Whilst a variety of marine living resources, including squid and even crabs, have attracted interest, the major fisheries today remain those for krill and finfish, presently dominated by interest in toothfish, *Dissostichus spp*. The krill fishery is now directed to a wider market than existed during the first-generation fishery, with biological products and fishmeal being perhaps more important than direct human consumption. In the 2010/2011 season, 180,992 tonnes of krill were taken (all from the Scotia Arc, Antarctic Peninsula region) (CCAMLR Commission 2012). Clearly the present annual catches of krill are well below those at the peak of the fishery in the 1980s, although trending upwards for the past decade (Fig. 20.4).

Toothfish is largely harvested with longlines (although some are caught with trawls) from increasingly sophisticated vessels (Fig. 20.6).

For the dominant target toothfish, Antarctic toothfish, *D. eleginoides*, there has been a steady upward trend in the annual catch since the mid-1980s (Fig. 20.7). The toothfish catch (both *D. eleginoides* and *D. mawsonii*) for the 2010/2011 season was 14,669 tonnes (CCAMLR Commission 2012).

Combining krill, finfish and other taxa, 196,315 tonnes of marine life were caught in the 2010/2011 season by the 20 states engaged in marine harvesting in the Antarctic marine environment (Fig. 20.8). About half of this figure is due to

**Fig. 20.6** The New Zealand Longliner San Aspiring in Antarctica (With kind permission from Sandford Limited)

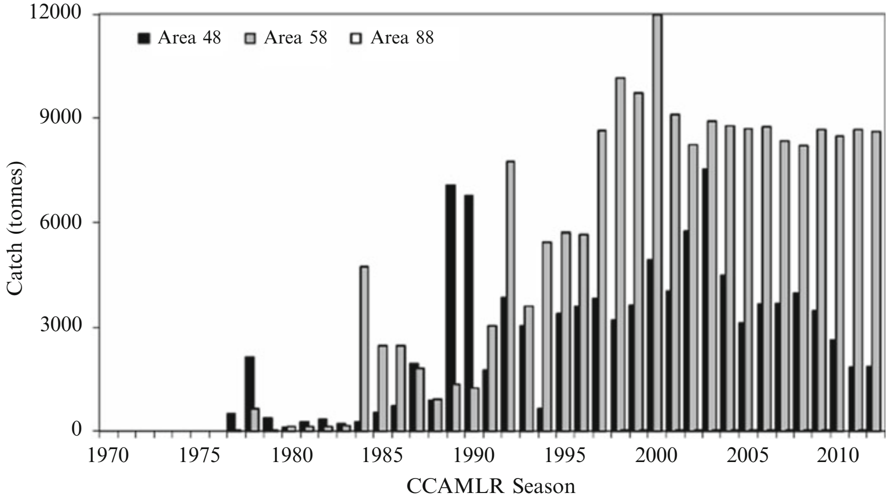



**Fig. 20.7** Patagonian Toothfish, *Dissostichus elegenoides*, catch history within the CCAMLR area from 1970 to 2011 (With kind permission from CCAMLR, http://www.ccamlr.org/en/fisheries/toothfish-fisheries)

| | 2001/02 | 2002/03 | 2003/04 | 2004/05 | 2005/06 | 2006/07 | 2007/08 | 2008/09 | 2009/10 | 2010/11 |
|---|---|---|---|---|---|---|---|---|---|---|
| ARG | – | – | 254 | 284 | 263 | 260 | 0 | – | 42 | – |
| AUS | 3628 | 5396 | 3116 | 4798 | 3274 | 2502 | 2672 | 2780 | 3092 | 2818 |
| CHL | 1545 | 3715 | 2520 | 987 | 1705 | 1850 | 897 | 517 | 356 | 2714 |
| CHN | – | – | – | – | – | – | – | – | 1956 | 16014 |
| DEU | – | – | – | – | – | 15 | – | – | – | – |
| ESP | 832 | 882 | 787 | 894 | 1026 | 704 | 959 | 1222 | 1035 | 511 |
| FRA | 6545 | 7496 | 7036 | 6782 | 6989 | 6607 | 7178 | 7872 | 7463 | 7433 |
| GBR | 2151 | 2157 | 2208 | 2139 | 2427 | 3867 | 4226 | 3675 | 1555 | 1598 |
| JPN | 51192 | 59944 | 33590 | 22848 | 32886 | 24529 | 39028 | 21234 | 30288 | 26647 |
| KOR | 15258 | 22079 | 25998 | 29364 | 44202 | 35368 | 39157 | 44585 | 47096 | 30695 |
| NAM | – | – | – | – | – | 117 | 225 | – | – | – |
| NOR | – | – | 182 | 293 | 9613 | 40122 | 63293 | 44175 | 119401 | 102460 |
| NZL | 1559 | 1603 | 1318 | 2057 | 1925 | 1722 | 1697 | 1415 | 1818 | 1714 |
| POL | 16720 | 8905 | 8967 | 4335 | 6413 | 7414 | 8035 | 8149 | 6995 | 3044 |
| RUS | 1686 | 1329 | 1040 | 675 | 716 | 608 | 510 | 9654 | 8127 | 467 |
| UKR | 32015 | 17715 | 12429 | 22441 | 15252 | – | 8133 | – | – | – |
| URY | 693 | 347 | 578 | 464 | 745 | 693 | 377 | 391 | 147 | 39 |
| USA | 12175 | 10150 | 8785 | 2159 | 2 | – | – | – | – | – |
| VUT | – | – | 29491 | 48389 | – | – | – | – | – | – |
| ZAF | 514 | 836 | 589 | 586 | 471 | 598 | 591 | 348 | 334 | 161 |
| | 146512 | 142555 | 138889 | 149492 | 127912 | 126976 | 176979 | 146018 | 229705 | 196315 |

**Fig. 20.8** Catch (tonnes) of all species, by state from 2001/2002 to 2010/2011 (With kind permission from CCAMLR, Statistical Bulletin 24, 2012, p 29)

krill. This is a considerable fishery, and clearly were the krill fishery alone to again approach the levels seen in the 1980s, we might be looking at a total annual catch of around half a million tonnes, which is a very big fishery.

Two sorts of problem, often coupled, have dominated CCAMLR's management agenda for the past decade. First the unintentional catching of other species in the course of fishing activities, particularly using longlines, as what is termed bycatch, and secondly the issue of Illegal, Unreported and Unregulated (IUU) fishing in the CCAMLR area.

The bycatch problem attained particular notoriety as a result of the large number of albatross and other seabirds (particularly petrels) snared as they grabbed the baits on longlines as these were deployed from the stern of fishing vessels. The level of mortality resulting, including the fact that even those birds that escaped were often killing their chicks by feeding them hooks and other fishing debris, was such that it posed a massive threat to a number of albatross and petrel species. Whilst particularly acute in the Antarctic marine environment, the problem is global, with 21 of 24 albatross species known to be killed on longline hooks (Gales 1998). Responses by CCAMLR have included obligations to deploy various bird-avoiding or mortality-mitigating measures, and substantive inspection and reporting requirements. Bycatch of seabirds has been addressed within the authorised fishery managed by CCAMLR. Marine mammal mortality involving longlines and trawls is an ongoing challenge. Bycatch of other finfish species (particularly rays) seems to continue, albeit with some reductions within CCAMLR authorised fisheries.

The term IUU fishing (see FAO 2001, for definitions and further details) embraces a number of situations where the operator is not actually regulated, because they are either in breach of duties owed to the state to whom they are responsible, or fishing without authorisation in particular waters, or not under the effective control of a state that is obliged to meet the particular international obligations, or their activities are simply not reported. Clearly IUU fishing poses particular problems for a regulatory body such as CCAMLR whose capacity to manage fishing depends on receiving accurate reports of what is caught, when and where. CCAMLR effectively licenses those who may fish and depends upon its member states and their operators (including vessels at sea, fishing) to acquire the scientific data that underpins its management.

At various stages the estimated IUU catch has been larger than the CCAMLR authorised catch, and the existence of a substantial IUU fishery plainly undermines the authorised fishery, in that the IUU operators don't have to meet any of the standards imposed upon the authorised operators (such as bycatch mitigation). It has posed challenges of corruption and laundering of catches. Responding to this has been difficult, time consuming and very expensive, particularly for states such as New Zealand and Australia which have sought to conduct surveillance and interdiction of IUU activity in the Southern Ocean. Both the targeted catch and bycatch takes in the IUU fishery are almost certainly ecologically unsustainable and economically damaging.

## 20.6 Biological Prospecting

The final form of current exploitation of Antarctic marine living resources to be surveyed here is biological prospecting (or bioprospecting), the search for biologically (including genetically) interesting and useful properties which may offer commercial benefits across a range of industries (Chap. 22). Biological prospecting seems to have been underway in Antarctica for some decades, although it first became a subject for discussion in the Antarctic scientific and political fora in only 2001 (Hemmings and Rogan-Finnemore 2005). Although the majority of the known biological prospecting activity has taken place ashore in Antarctica (and no doubt on subantarctic islands subject to solely national jurisdiction), some has also taken place in the Antarctic marine environment, both in coastal areas and in the open ocean, and potentially on the deep seabed. Although the quantities of materials harvested in most biological prospecting projects are small, and substantially smaller than conventional marine harvesting, some sorts of biological prospecting may still require reasonably large initial harvests (in the case of some sponges, for example). Whether the quantities are tiny or more considerable, harvesting for biological prospecting purposes poses some of the same issues as for other marine harvesting, including questions around the sustainability of the target species, the need for definitions of acceptable takes, and the risks of incidental damage to other species or ecosystems.

For biological prospecting, whilst these are no doubt tractable issues, the existing legal and policy framework for managing this activity is far less developed than for the other contemporary areas of marine exploitation in the Antarctic marine environment, even in the vexed areas such as whaling and IUU fishing. At least in those areas some in-principle options are available.

It would be unreasonable to suggest that biological prospecting is currently a key concern in the Antarctic marine environment, but it seems likely to become a more important issue in the years ahead.

## 20.7 Conclusions

Exploitation of Antarctic marine living resources is the foundational industry in the Antarctic region. From Cook on, it has been the dollar to be earned from harvesting Antarctica's animals, as much as intellectual curiosity around geography and national honour, that have pulled people into the region. The teeming seals and whales reported by Cook and others stimulated the sealers and later whalers. As technology allowed it, so more and more marine living resources were pursued further and further into the Antarctic. The wealth of many places in New Zealand, Australia, southern South America and further afield in New England and old England and Scotland's Dundee was built on this. As international discussion began in the 1970s around what would be adopted in 1982 as the United Nations

Convention on the Law of the Sea, with its codification of 200 nautical mile Exclusive Economic Zones (EEZs) and coastal state rights, so states with distant water fishing fleets looked for fishing grounds that would remain beyond national jurisdiction, and so sustain these industries. Antarctica was one of the places they went to, and that massively stimulated a new global fishery for krill and finfish there.

Technology has been the great enabler in Antarctica, and the historic protections afforded the marine environment there (never beyond breach, as the fate that befell fur seals and later whales indicates) have been progressively eroded. In parallel, our increasing scientific knowledge of the biota and ecosystem functioning in the Antarctic marine environment, achieved as part of the wider international scientific project in the region over the past half century, has provided a steady stream of useful data on the location, numbers and behaviour of things, and about the climatic and oceanographic conditions that we will face there.

This poses some significant challenges during the twenty first century. Everywhere, and not just in the polar regions, there are questions about the sustainability and ethics of many of our activities in the marine environment. The evidence for substantial depletion of once abundant stocks of fish worldwide seems to grow almost daily, and long-term trends of fishing further and further down the food web have been argued for a decade and a half (Pauly et al. 1998). Recently, concerns have emerged about the risks of exploitation of the Antarctic marine environment, surely one of the less abused parts of the planet. A corollary of this concern is a building case for improved protection for places such as the Ross Sea continental shelf which may be "the least affected of any on the globe" (Ainley 2010). More states, more operators, more fishing vessels and more technology deployed to track down the target stocks all add stresses to an already long-modified marine environment which now faces the newer and profound effects of climate change as well. Because of the unresolved situation around territorial sovereignty ashore in Antarctica, the legal and jurisdiction framework within which we have to manage human activity is even slighter than in other environments (Dodds and Hemmings 2015).

The Antarctic marine environment already displays the effects of global climate change. Salinity, temperature, sea ice, circulation and frontal systems all seem to have been affected, with significant instabilities predicted over the next 100 years (Turner et al. 2009, 2013). For a rationally grounded, science-based management of the Antarctic marine environment this has profound implications for international management (Trathan and Agnew 2010). Not the least of the challenges is integrating the scientific data on the changing environment with the powerful applied fisheries science, which seems so often to be directed to legitimising ever more resource exploitation, in the complex international legal context of Antarctica. Only international agreement and collaboration can achieve results in a situation where conflicting national positions are delicately balanced and international law and norms meet national law and practice (Hemmings 2011).

Across the range of issues, the choices we make about the exploitation of marine living resources in Antarctica will be significant not only for the Antarctic marine environment, but potentially at the global level, too.

## References


Ainley D (2010) A history of the exploitation of the Ross Sea, Antarctica. Polar Rec 46:233–243

Aronson RB, Thatje S, McClintock JB, Hughes KA (2011) Anthropogenic impacts on marine ecosystems in Antarctica. Ann N Y Acad Sci 1223:82–107

Burnett DG (2012) The sounding of the whale: science and cetaceans in the twentieth century. University of Chicago Press, Chicago

Canberra Panel (2009) Japan's 'scientific' whaling program and the Antarctic treaty system: independent panel of legal and policy experts. Report of the Canberra Panel, 12 Jan 2009. http://cbialdia.mardecetaceos.net/archivos/download/ReporteCanberrazc1527.pdf. Accessed 18 July 13

CCAMLR (2012) Statistical bulletin. 24, CCAMLR, Hobart

CCAMLR (2013) About CCAMLR http://www.ccamlr.org/en/organisation/about-ccamlr. Accessed 18 July 13

Cook J (1777) A voyage towards the south pole and round the world. Strahan and Cadell, London

Croxall JP, Nicol S (2004) Management of Southern Ocean fisheries: global forces and future sustainability. Antarct Sci 16:569–584

Darby A (2007) Harpoon: into the heart of whaling. Allen & Unwin, Crows Nest

Dodds K, Hemmings AD (2015) Polar oceans: sovereignty and the contestation of territorial and resource rights. In: Smith HD, Suarez de Vivero JL, Agardy TS (eds) Handbook of ocean resources and management. Routledge, Abingdon

Fabra A, Gascón V (2008) The convention on the conservation of Antarctic marine living resources (CCAMLR) and the ecosystem approach. Int J Mar Coast Law 23:567–598

FAO (2001) International plan of action to prevent, deter and eliminate illegal, unreported and unregulated fishing. FAO, Rome ftp://ftp.fao.org/docrep/fao/012/y1224e/y1224e00.pdf. Accessed 18 July 13

Gales R (1998) Albatross populations: status and threats. In: Robertson G, Gales R (eds) Albatross biology and conservation. Surrey Beatty, Chipping Norton, pp 2–45

Hemmings AD (2011) Environmental law – Antarctica. In: Bosselmann K, Fogel D, Ruhl JB (eds) The encylcopedia of sustainability, vol 3, The law and politics of sustainability. Berkshire Publishing, Great Barrington, pp 188–194

Hemmings AD, Rogan-Finnemore M (eds) (2005) Antarctic bioprospecting. Gateway Antarctica, Christchurch

International Court of Justice (2014) Whaling in the Antarctic (Australia v. Japan: New Zealand Intervening). All documents available at: http://www.icj-cij.org/docket/index.php?p1=3&p2=3&k=64&case=148&code=aj. Accessed 10 Apr 14

Kock K-H (1992) Antarctic fish and fisheries. Cambridge University Press, Cambridge

Kock K-H (2007) Antarctic marine living resources – exploitation and its management in the Southern Ocean. Antarct Sci 19:231–238

Pauly D, Christensen V, Dalsgaard J, Froese R, Torres F (1998) Fishing down marine food webs. Science 279:860–863

Report of the Thirty-First Meeting of the CCAMLR Commission (2012) Commission for the conservation of Antarctic marine living resources, CCAMLR, Hobart

Ross JC (1847) A voyage of discovery and research in the southern and Antarctic regions during the years 1839-43. John Murray, London

Tønnessen JN, Johnsen AO (1982) The history of modern whaling. Hurst, London

Trathan PN, Agnew D (2010) Climate change and the Antarctic marine ecosystem: an essay on management implications. Antarct Sci 22:387–398

Turner J, Bindschadler R, Convet P, di Prisco G, Fahrbach E, Gutt J, Hodgson D, Mayewski P, Summerhayes C (eds) (2009) Antarctic climate change and the environment. Scientific Committee for Antarctic Research, Cambridge

Turner J, Barrand NE, Bracegirdle TJ, Convey P, Hodgson DA, Jarvis M, Jenkins A, Marshall G, Meredith MP, Roscoe H, Shanklin J, French J, Goosse H, Guglielmin M, Gutt J, Jacobs S, Kennicutt MC II, Masson-Delmotte V, Mayewski P, Navarro F, Robinson S, Scambos T, Sparrow M, Summerhayes C, Speer K, Klepikov A (2013) Antarctic climate change and the environment: an update. Polar Rec. doi:10.1017/S0032247413000296, Accessed 18 July 2013

# Chapter 21
# Southern Ocean Fisheries

## Managing Harvests of Marine Life

**Denzil G.M. Miller**

**Abstract** Despite its inhospitality and relative remoteness, the Southern Ocean has not escaped the immediate, unrestrained and unregulated exploitation accompanying newly discovered biological resources. Historically, opportunistic harvesting of seabirds, eggs, seals and fish occurred to supplement the food of ship-based expeditions. However, from the late 1800s onwards four major phases of harvesting progressively targeted seals, whales, finfish and krill (*Euphausia superba*). This culminated in severe depletion of Antarctic fur seals and some whale species, and in the case of blue whales and finfish, subsequent regulation did not compensate for their near extinction, or for the decimation that resulted in further exploitation being uneconomic. While some seal populations have recovered (e.g. fur seals at South Georgia) and some whale populations (e.g. southern minke whale) may have benefited from exploitation of larger species, there is still widespread concern about the ecological consequences of unsustainable and heavy exploitation of marine life in the Southern Ocean. Many Southern Ocean species are slow-growing and long-lived. They are also slow to repopulate when numbers are depleted. For most species, very little is known about their detailed biology and life histories. These qualities and other considerable uncertainties affect management efforts aimed at ensuring the sustainable exploitation of Southern Ocean marine living resources in general, and the potentially large krill resource in particular.

**Keywords** CAMLR Convention • Fishing grounds • Catch limits • Krill • Exploratory fishery • IUU fishing

---

D.G.M. Miller (✉)
Australian National Center for Ocean Resources and Strategy, University of Wollongong, Wollongong, Australia
e-mail: denzilgmiller@gmail.com



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_21

## 21.1 Managing Living Resources

Although the current management system for the Southern Ocean toothfish fishery, which includes the Patagonian Toothfish, *Dissostichus eleginoides*, and the Antarctic Toothfish, *D. mawsoni*, appears to have had some success, exploitation of many marine species at a global level has entailed fishing "down the food chain". This practice means that profitable higher-order predators are fished first, followed by lesser-value species that directly or indirectly feed animals at higher trophic levels. In the Southern Ocean's case, this has raised considerable concern over the past four decades as exploitation moves towards Antarctic krill, *Euphausia superba*, a low-level food species. With its huge exploitation potential and its ecological significance, concern for krill sustainability was behind the adoption of the 1980 Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention) (CCAMLR 2011a).

From the above, it is clear that exploitation of marine living resources in the Southern Ocean should be managed carefully, particularly if ecosystem function is to be preserved and fisheries are to be sustainable. Climate change and environmental impacts from pollution, tourism, science and support activities all compound the complexities of the management paradigm. Clarke and Harris (2003) indicate that unsustainable exploitation is the most likely impact to negatively affect the Southern Ocean marine ecosystem over the next 20–25 years. They see the impacts of unregulated fisheries surpassing those of climate change. Therefore, the future sustainability of Southern Ocean marine stocks depends on how effectively relevant regulatory authorities, particularly international arrangements, develop, manage and implement sustainable exploitation regimes.

## 21.2 Southern Ocean Fisheries

The Southern Ocean extends north from the Antarctic landmass to the Antarctic Polar Front (APF), located between about 45°S and 55°S. The waters south of the APF fall under the CAMLR Convention, and constitute about 10 % of the global ocean surface (Fig. 21.1). Over half of this area is covered by seasonal ice during winter, which largely becomes open water during summer.

The surface, intermediate and bottom waters of the Southern Ocean mix to varying extents, and this greatly influences biological productivity. In particular, oceanic fronts such as the APF have characteristic signatures (Fig. 21.2) that reflect prevailing surface temperature, nutrient gradients and chlorophyll levels. Such fronts, and their associated eddies, combine with upwelling nutrients to create a perception that the Southern Ocean is the most biologically productive marine area on Earth. However, low micronutrient availability, particularly of iron, generally limits the ocean's productivity, except close to the islands located in the Antarctic Circumpolar Current (ACC). Raised near-shore productivity and the presence of

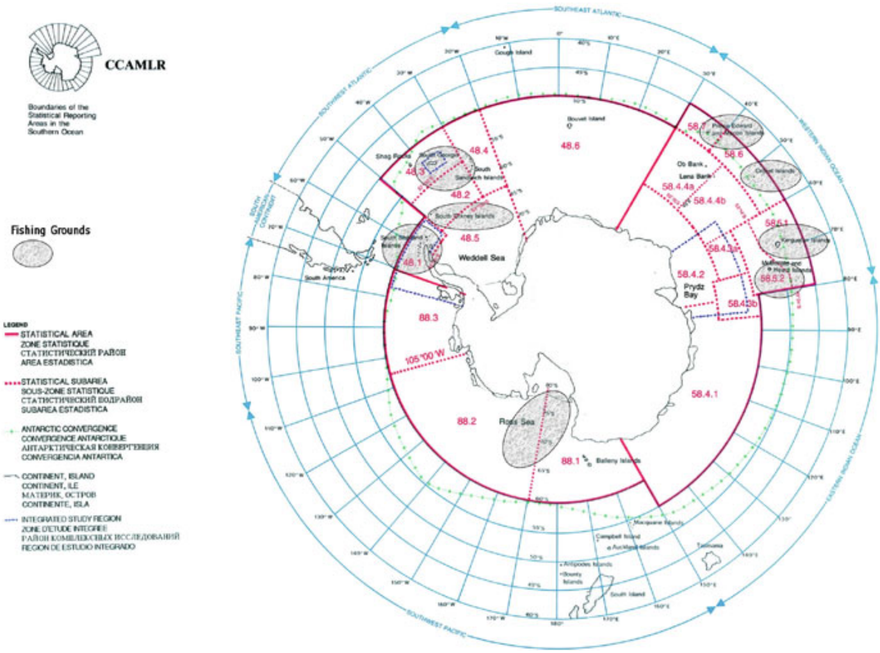



Fig. 21.1 This shows the CAMLR Convention area, indicating the location of various fishing grounds. CCAMLR Statistical Subareas and Divisions are used for reporting fisheries data. The CAMLR Convention boundary, the position of the Antarctic Convergence (Antarctic Polar Front) and location of various fishing grounds are also shown (CCAMLR 2011a)

fishable waters have meant that fisheries, particularly for finfish, have historically tended to concentrate around these islands.

## 21.3 A Brief History of Fishing in the Southern Ocean

During the mid- to late 1970s, finfish fisheries in the Southern Ocean were not regulated. They expanded rapidly and by the end of the decade species such as the Antarctic (marbled) rock cod, *Notothenia rossii*, were severely depleted by over-exploitation. This increased the concerns already highlighted that unregulated harvesting of key food species, such as krill, could place the entire Antarctic marine ecosystem in jeopardy. The 1975 Eighth Antarctic Treaty Consultative Party Meeting (ATCM-VIII) thus attempted to address such concerns. Subsequent negotiations resulted in the CAMLR convention being signed in Canberra on 20 May 1980, and entering into force on 7 April 1982.

The development, course and fate of finfish fisheries in the CCAMLR area have been comprehensively described. In this respect, the acronym for the Commission, CCAMLR, should not be confused with that for the CAMLR Convention.

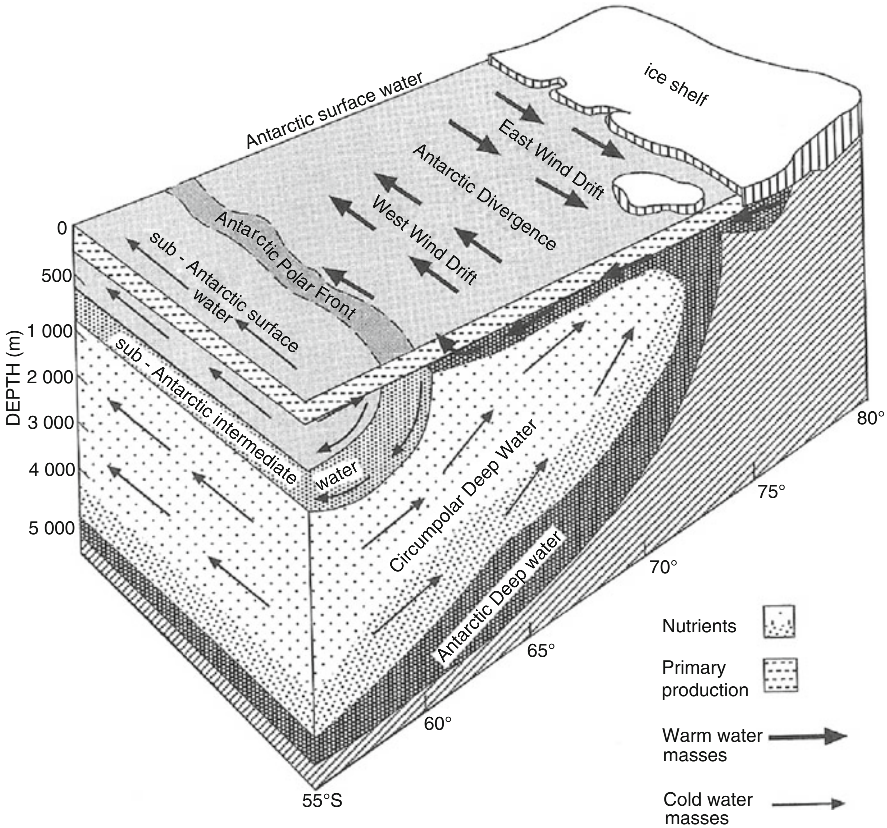



**Fig. 21.2** Three-dimensional cross-section of Southern Ocean water masses. Nutrients advect to the surface at the Antarctic Divergence due to the passage of Circumpolar Deep Water over cold, dense Antarctic Deep (Bottom) Water

Between 1969/1970 and 2010/2011, a total of approximately 4.9 million tonnes of finfish was taken in the CCAMLR area (CCAMLR 2012a). Of this total, about three million tonnes were taken in the West Atlantic (CCAMLR Statistical Area 48), with 2.26 million tonnes (75 %) being caught around South Georgia (CCAMLR Subarea 48.3). Of the 1.8 million tonnes caught between 1969/1970 and 2009/2010 in the Indian Ocean, 1.1 million tonnes are attributable to the Kerguelen Islands environs (CCAMLR Division 58.5.1), with the balance coming from the Heard and McDonald Islands area and Ob/Lena Banks. A little over 33,000 tonnes (predominantly Antarctic toothfish) were taken in the Ross Sea (CCAMLR Subareas 88.1 and 88.2). Much of the overall finfish catch taken prior to the entry into force of the CAMLR Convention in 1982 was made up of some 500,000 tonnes of the Antarctic rock cod, *N. rossii*, around South Georgia (CCAMLR Subarea 48.3) from 1970 to 1971, and 272,000 tonnes of the same species in CCAMLR Area

58 close to the Kerguelen Islands from 1971 to 1978. The stocks concerned have never recovered to commercially viable levels since this initial exploitation.

Many of the historic finfish fisheries in the Southern Ocean remain commercially non-viable. Furthermore, there is a need to overcome the economic challenges associated with rising fuel costs and the relative remoteness of Southern Ocean fishing grounds.

Based on its status as a food source for a number of predators, the sevenstar flying squid, *Martialia hyadesi*, appears to have some fisheries potential. There have been four attempts (in 1996, 1997 (twice) and 2001) to develop an exploratory fishery for this squid on the South Georgia/Shag Rocks shelf (CCAMLR Subarea 48.3), and in the vicinity of the APF to the north of South Georgia. Between 1995/1996 and 2005/2006, CCAMLR had measures in place to limit the *M. hyadesi* catch to 2500 tonnes and govern how the fishery should operate as an exploratory enterprise. There is currently little interest in the fishery given its variable and unpredictable nature. The easier accessibility of the Argentine shortfin squid, *Illex argentines*, in waters farther north, as well as its lower market price, has also meant that the *M. hyadesi* fishery is economically uncompetitive.

Commercial efforts to exploit stone crabs, Lithodidae spp., took about 800 tonnes between 1992 and 2004 around South Georgia. Despite high abundances in some places, interest in the fishery remains low, due to processing difficulties in extracting the meat and CCAMLR regulations to limit the catch of larger male animals to less than 7 % of the total catch.

Sporadic catches of the myctophid, *Electrona carlsbergi*, have been reported from the southern edge of the APF to the north of South Georgia. Between 1989/1990 and 1991/1992, 154,000 tonnes were taken by the former Soviet fleet. Further catches of 5 and 68 tonnes were taken by Russia in 1998/1999 and 1999/2000 respectively.

Japan and the Soviet Union began exploratory fisheries for krill in the early 1960s, and a fully-fledged experimental commercial fishery commenced in the summer of 1973/1974 (Fig. 21.3). Between 1973 and 1994, krill catches rose steadily from 19,785 tonnes in 1973/1974 to a peak of 535,253 tonnes in 1981/1982. Post-1982 catches declined sharply in 1983/1984 to a level (130,875 tonnes) similar to that accompanying the fishery's early expansion in 1977/1978. They then increased to a second peak (446,673 tonnes) in 1985/1986 and subsequently plateaued at about 300,000–400,000 tonnes until the dissolution of the Soviet Union in 1991. Thereafter, krill catch levels declined markedly to the 1993/1994 level of about 80,000 tonnes, rising slightly to 118,715 tonnes in 1993/1994 due to an increased catch of about 42,000 tonnes in that split year by Ukraine. Catches then varied between 80,000 and 120,000 tonnes, until growing expansion of the fishery peaked at 129,000 tonnes in 2004/2005, 156,000 tonnes in 2007/2008, 126,000 tonnes in 2008/2009, 212,000 tonnes in 2009/2010, and about 180,000 tonnes in 2010/2011 (CCAMLR 2012a). The total krill catch in the CCAMLR area since the fishery began is about 7.43 million tonnes. The approximate value of this catch is about US$7 billion dollars.

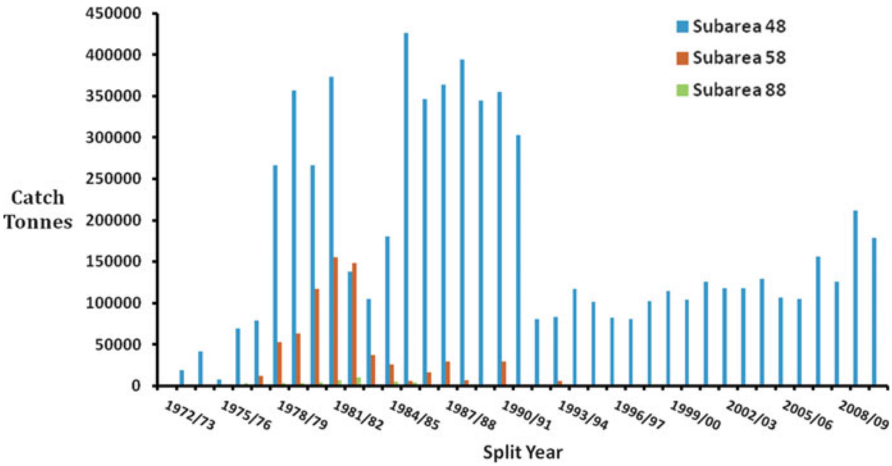



**Fig. 21.3** Annual krill catches by CCAMLR Statistical Area between 1972/1973 and 2010/2011. Catches are grouped by split year (i.e. from 1 July one year to 30 June the next)

It is worth noting that the krill fishery in CCAMLR Subarea 48.1 (South Shetlands) was closed in 2009/2010, when the catch reached 99.8 % of the trigger level (155,000 tonnes) for that subarea under CCAMLR Conservation Measures (CMs) 51-01 and 51-07 (paragraph 4.7 in CCAMLR 2010). This was the first closure of any krill fishery subarea under the apportioned trigger levels requirements introduced in 2009 (CM 51-07). CCAMLR CMs are adopted in accordance with the provisions of Article IX.(6) of the CAMLR Convention (see discussion below). A schedule of CMs in force is published annually and made publicly available by the CCAMLR Secretariat (CCAMLR 2012b).

The above trigger level is currently being used to divide the overall areal krill catch limit into smaller management units until a procedure is agreed for such a division (CCAMLR CM 51-01). Currently, it is only applied in CCAMLR Statistical Area 48 (Subareas 48.1–48.4) and is ultimately aimed at distributing the krill catch to avoid predator populations, particularly land-based predators, being disproportionately affected by fishing activity (see Sect. 21.5.1.3).

## 21.4 Convention on the Conservation of Antarctic Marine Living Resources

The CAMLR Convention defines Antarctic marine living resources as “the populations of finfish, molluscs, crustaceans and all other species of living organisms, including birds, found south of the Antarctic Convergence” (i.e. the APF). The Convention also indicates that the Antarctic marine ecosystem is “the complex of relationships of Antarctic marine living resources with each other and with their physical environment". Despite the Convention's implicit recognition of seals and whales as important components of the Antarctic marine ecosystem, whales and seals fall outside the CAMLR Convention's remit. They are, however, specifically addressed by the 1946 International Convention for the Regulation of Whaling and the 1972 Convention for the Conservation of Antarctic Seals (CCAS) respectively.

Article II of the CAMLR Convention specifically aims to provide for the conservation and management of marine living resources in the Convention area. Recognising that conservation includes 'rational' (i.e. sustainable) use, Article II elaborates how CCAMLR should go about implementing the Convention's key principles in terms of applying an ecosystem-based and precautionary management approach. Key features of such an approach include:

- setting target levels for sustainable fishing;
- accounting for ecological related species as well as those being fished;
- restoring depleted populations;
- minimising the risks of irreversible ecosystem changes, and
- accounting for various natural, environmental or human-induced effects other than fishing.

The Convention conservation approach had no precedents and stands as a unique example of sustainable and precautionary-based resource management (Miller 2012; Miller and Slicer 2013). The approach notably distinguishes the Convention from more traditional fisheries management instruments, which tend to follow maximum sustainable yield (MSY) principles.

In identifying the Convention area of application south of the APF, Article I recognises the biogeographic integrity of the marine living resources in the Convention area. Along with various other articles (III, IV and V), it effectively extends the influence of the 1959 Antarctic Treaty north of 60°S to the APF. While this extension is confined to the management of marine living resources, it recognises "the importance of safeguarding the environment and protecting the integrity of the ecosystem of the seas surrounding Antarctica".

### *21.4.1 The CCAMLR Legal Framework*

From a legal perspective, the CCAMLR area is mostly classed as the high seas, consistent with Part VII, Section 2 of the 1982 United Nations Convention on the Law of the Sea (UNCLOS). Under UNCLOS Article 116, the right to fish the high seas is moderated by a requirement that states co-operate in taking and supporting measures necessary for the conservation of high seas living resources. While these conditions are generally applicable in the Southern Ocean, there are notable exceptions.

A number of Southern Ocean islands are subject to undisputed territorial sovereignty. This means that the States concerned are 'coastal States' which enjoy all the rights and obligations attached to their adjacent 'territorial seas' (UNCLOS Article

2 and 3). These rights are extended to the attached Exclusive Economic Zones (EEZs), 200 nautical miles offshore, under UNCLOS Part V (Articles 56, 58 and 61–62 in particular). Consequently, coastal States possess the right to determine allowable catches (Article 61), to promote the optimum use of living resources (Article 62) in their EEZs and to determine what other states may fish in their EEZs.

To ensure harmony between CCAMLR-adopted CMs and those being applied by coastal states to their waters within the Convention area, the CCAMLR Chairman's Statement (CCAMLR 2011b) provides a legal framework for how this should be done. Nonetheless, this has not precluded some states (e.g. France and South Africa) from reserving their positions on the application of CCAMLR CMs in their Southern Ocean EEZs north of the Antarctic Treaty area, as is their right under the relevant UNCLOS provisions (Articles 61 and 62). Given the prevailing sovereign dispute between Argentina and the United Kingdom, questions have thus been raised concerning application of the Chairman's Statement around some South-West Atlantic islands.

The area south of 60°S (including all ice shelves) falls under the Antarctic Treaty, where Article IV effectively freezes all claims to territorial sovereignty in the Treaty area. This implies that there are no coastal Antarctic claimant states to exercise national sovereignty in waters adjacent to their territories south of 60°S. Despite this situation, Treaty Article VI clearly indicates that nothing in the treaty "shall prejudice or in any way affect the rights, or the exercise of the rights, of any State under international law with regards to the high seas in the area". Together, both sets of provision imply that CCAMLR measures apply throughout the treaty area on the high seas and elsewhere. In particular, CAMLR Convention Articles III to V outline the delicate relationship between the Convention and the Treaty concerning sovereign claims in the Treaty area. This means that the provisions of Treaty Article VI apply in the Treaty area to CCAMLR Contracting Parties, whether they are parties to the Treaty or not.

Various other international agreements falling outside the Antarctic Treaty System (ATS) apply to the Southern Ocean. These address environmental protection, environmental management, mutual security, scientific research, scientific information exchange and regional governance. Such instruments all strive to promote 'responsible' and sustainable, exploitation of marine living resources in general. Furthermore, preservation of the marine environment and protection of its biodiversity are specifically mandated by the 1991 Madrid Protocol to the Antarctic Treaty on Environmental Protection (Madrid Protocol) and the 1992 Convention on Biological Diversity (CBD).

### *21.4.2 CCAMLR Membership and Decision-Making*

The CAMLR Convention legally binds its Contracting Parties to the decisions and measures agreed by CCAMLR. All substantive Commission decisions are taken by consensus (Article XII). While not defined, consensus in the CCAMLR setting is

**Table 21.1** CAMLR Convention Contracting Parties, as of 20 August 2013

| Commission Members | | | Non-Commission Members ('Acceding States') | |
|---|---|---|---|---|
| Argentina | India | Russian Federation | Bulgaria | Panama |
| Australia | Italy | South Africa | Canada | Peru |
| Belgium | Japan | Spain | Cook Islands | Vanuatu |
| Brazil | Korea (Republic of) | Sweden | Finland | |
| China (People's Republic of) | Namibia | Ukraine | Greece | |
| European Economic Community | New Zealand | United Kingdom | Mauritius | |
| France | Norway | USA | Netherlands | |
| Germany | Poland | Uruguay | Pakistan | |

usually viewed as the absence of any substantive objection to a decision, rule or measure.

All Convention signatories are deemed to be Contracting Parties (Table 21.1). There are essentially two types of Contracting Party: individual states and one regional economic integration organisation (REIO), the European Economic Community (EC). Commission Members may participate in decision-making (Article XII), contribute to the budget, which provides for CCAMLRS's day-to-day activities supported by a full-time secretariat, and are provided access to CCAMLR-sanctioned fisheries. Acceding States, which are interested in research on, or harvesting activities of, CCAMLR marine living resources, are eligible to become Commission Members, but only if they are engaged in research on, or harvesting of the marine living resources to which the Convention applies.

### *21.4.3 CCAMLR in Action*

Convention Article IX outlines various CCAMLR functions to be pursued in giving effect to Article II objectives and principles. Broadly, these functions entail facilitating relevant research, compiling essential data, ensuring collection of relevant fisheries statistics, exchanging necessary information, identifying conservation needs and formulating appropriate conservation measures (i.e. CMs). Once in place, CMs are legally binding on the Convention Contracting Parties. CCAMLR also adopts resolutions, which although legally non-binding are salutatory in effect and serve as agreed codes of practice.

CMs include catch limits, effort controls, closed areas and seasons, compliance and trade-related processes. The schedule of CMs in force (CCAMLR 2012b) is usually reviewed annually. CCAMLR also takes account of any relevant measures or regulations adopted by other Antarctic Treaty instruments or other relevant fisheries arrangements. In developing CMs, a key requirement is that the measures are formulated, adopted and revised on the basis of the best scientific evidence available. CCAMLR thus relies on the advice, research and data analyses (SC-CAMLR 1982–2012) provided by the Scientific Committee (SC-CAMLR) established under Articles XIV and XV of the Convention. The CCAMLR Ecosystem Monitoring Program (CEMP) was consequently established in 1985 to improve scientific insight into potential interactions between fishery, harvested species and the environment.

SC-CAMLR now undertakes regular (usually annual) analyses of both historical and contemporary fishery data. Standardised, analytical assessment techniques (e.g. the Krill Yield Model (KYM), General Yield Model (GYM) and Integrated Model (IM)) have been developed. Data collections methods have also been improved, most notably through the institution of the CCAMLR Scheme of International Scientific Observation in 1992 (CCAMLR 2011c). Additional research has been initiated to improve understanding of Antarctic marine ecosystem dynamics, biological productivity and functioning.

From a practical point of view, CCAMLR is required to pursue four areas of action in addressing key conservation principles identified by Article II of the Convention. These comprise:

- Determining the management status for relevant (target and non-target) species, and/or ecosystem qualities;
- Assessing ecosystem status in terms of perceived health, to provide adequate safeguards for harvested species so that harvesting does not prejudice the long-term future of dependent, or related, species;
- Implementing harvest controls to account for differences between the assessed status of exploited stocks and agreed conservation objectives, and
- Striving to attain scientific consensus on key advice being offered to the Commission for use in the formulation of CMs.

To address the Convention's conservation principles, these action areas are operationalised by:

- Meeting Article II objectives in a timely manner, particularly by minimising any risk of ecosystem changes that are not reversible in two to three decades;
- Monitoring harvest controls to ensure sustainable exploitation, and to minimise potential effects (direct and indirect) on dependent and related species (such as predators, or ecologically-connected species, which may occupy the same geographical space at critical times), and
- Refining assessments to account for new information and to account for uncertainties in available information, particularly concerning harvested stock status, as well as the potential responses of non-harvested species and ecosystem function.

The management paradigm associated with these actions is neither trivial nor uncomplicated, and CCAMLR does not rely on a single management approach alone. Rather, its decisions are scientifically-driven, iterative, responsive and

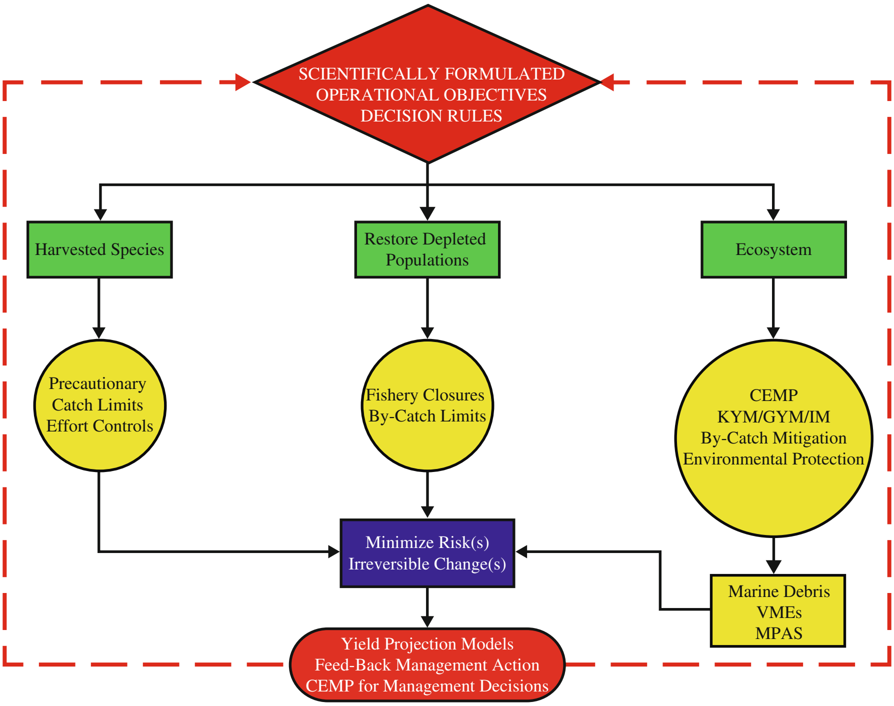



**Fig. 21.4** CCAMLR's management approach to address Convention Article II objectives. (CEMP CCAMLR Ecosystem Monitoring Programme, *KYM* Krill Yield Model, *GYM* General Yield Model, *VMEs* Vulnerable Marine Ecosystems, *MPA* Marine Protected Areas)

ongoing. This has promoted the recognised innovation and flexibility for which CCAMLR is renowned in terms of its efforts to address the key conservation challenges being faced (Miller 2012). These efforts have evolved into a procedure (Fig. 21.4), which integrates scientific antecedents and management decisions to:

- apply correct/timely decisions consistent with CCAMLR conservation principles;
- undertake monitoring of sufficient power for harvest controls not to affect dependent predators;
- allow sufficient time to detect/rectify harvest induced ecosystem changes within two or three decades, and
- refine precautionary assessments of the harvested stock yield to revise estimates of key demographic parameters.

The procedure entails an annual cycle of work (Fig. 21.5) involving the Commission, CCAMLR Members, SC-CAMLR, the Secretariat and various scientific working groups (e.g. the Working Groups on Fish Stock Assessment (WG-FSA),

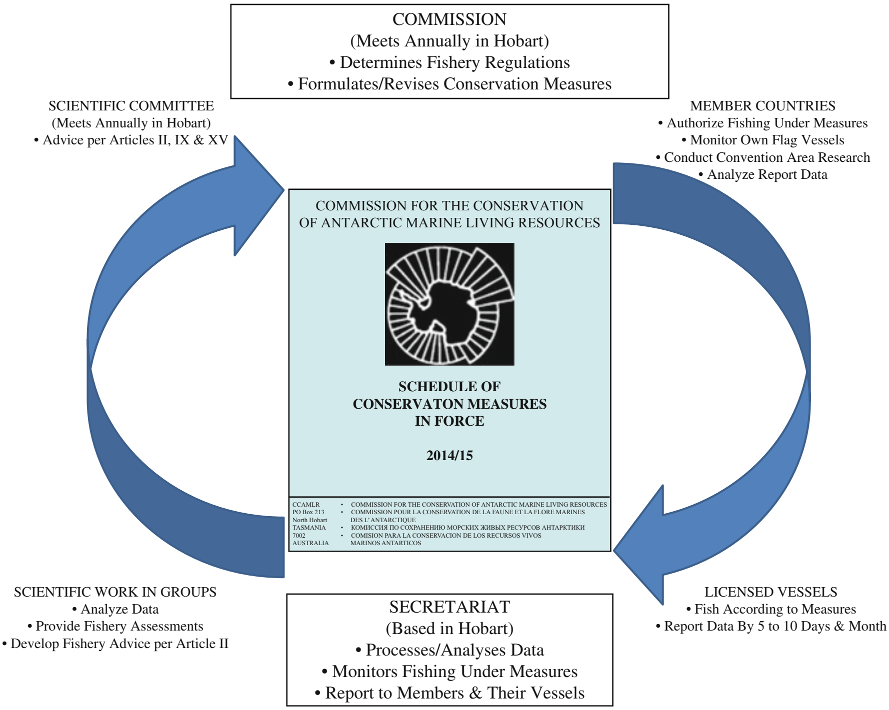



**Fig. 21.5** Annual cycle of CCAMLR management and associated actions

Statistics, Assessment and Modelling (WG-SAM), and Ecosystem Monitoring and Management (WG-EMM)).

## 21.5 CCAMLR Outcomes

In terms of CCAMLR's outcomes, the three key Article II objectives are translatable into harvested species management, restoring depleted populations and ecosystem management. Work relevant to these three categories is summarised as follows.

### *21.5.1 Harvested Species Management*

#### 21.5.1.1 Fishing Grounds

Various fishing grounds within the CCAMLR area are shown in Fig. 21.1. The most noticeable of these are: Subareas 48.1 (South Shetlands), 48.2 (South Orkneys) and 48.3 (South Georgia) for krill and finfish. Icefish, *Champsocephalus gunnari*, and toothfish, *Dissostichus* spp., fisheries around the Australian Heard and Macdonald

**Table 21.2** Examples of catch limit and other conservation measures (CMs)

| Area | Fishery | Measure | Comments |
|---|---|---|---|
| All | All | Marking of fishing vessels and gear (CM 10-01) | |
| All | All | Licensing and inspection obligations (CM 10-02) | |
| All | Toothfish | Port inspection of toothfish-carrying vessels (CM 10-03) | |
| All | Finfish | Vessel monitoring systems (VMS) | |
| | Various | Catch reporting requirements (CMs 23-01 to 23-05) | |
| All | Exploratory toothfish fisheries | General measure (CM 41-01) | Includes SSRU designation, bycatch provisions and data reporting obligations |
| Various<br>(Subareas 48.3 and 48.4, others) | Toothfish (*Dissostichus sp.*) | Catch limits for developed (CMs 41-02 and 48-03) and exploratory fisheries(CMs 41-04 to 41-11) | |
| Various<br>(Subarea 48.3 and division 58.5.2) | Icefish (*Champsocephalus gunnari*) | Catch limits (CMs 42-01 and 42-03) | |
| Various<br>(Subareas 48.1, 48.2, 48.3 and divisions 58.4.1 and 58.4.2) | Krill | Precautionary catch limits (CMs 51-01 to 51-03) | |

Adopted by CCAMLR (2012a)

Islands (Division 58.5.2). Patagonian toothfish, *D. eleginoides*, fisheries are located in the French EEZs around the Crozet (Subarea 58.6) and Kerguelen islands (Division 58.5.1), as well as in the South African EEZ at the Prince Edward Islands (Subareas 58.6 and 58.7). Exploratory toothfish fisheries are located in Subarea 48.6, Division 58.4.2, Division 58.4.3a (Elan Bank) and 58.4.3b (BANZARE Bank) (outside areas of national jurisdiction), as well as in Subareas 88.1 and 88.2.

#### 21.5.1.2 Catch Limits

All current CCAMLR fisheries are governed by catch limits determined on the basis of scientific advice provided by SC-CAMLR. Fully developed fisheries include those for krill, Patagonian toothfish and icefish. In addition, directed fishing on various species (e.g. *N. rossii*, *Lepidonotothen squamifrons* and *Chaenocephalus aceratus*) is prohibited, while limits have been placed on non-target bycatch

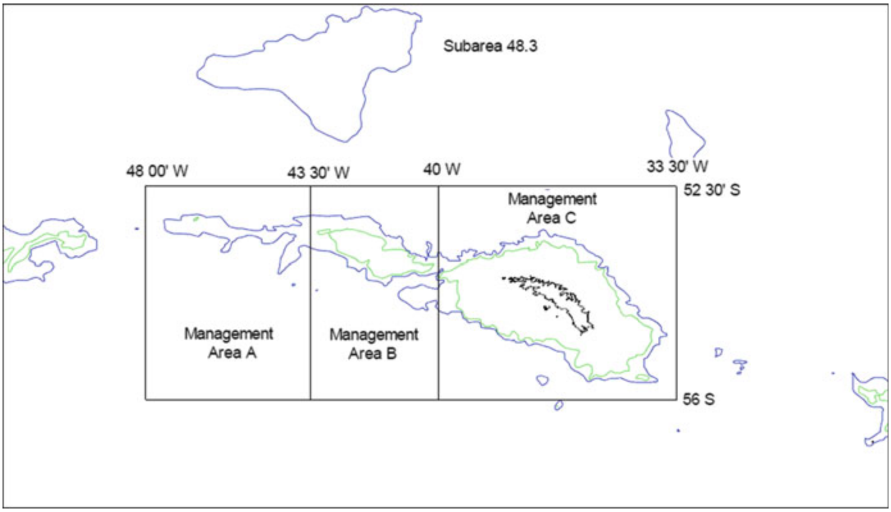



**Fig. 21.6** Management Areas around South Georgia (CCAMLR Subarea 48.3) for the subdivision of toothfish catch limits (From Annex 41-02A of CM 41-02)

species. Table 21.2 summarises CCAMLR fishery catch limit regulations and other associated management provisions.

CCAMLR catch limits are not usually subject to any form of quota allocation and are provided on a first-come first-served basis unless otherwise stipulated. Some areal catch limits (e.g. toothfish in Subarea 48.3) may be subdivided into smaller pre-identified Management Areas (MAs) (Fig. 21.6), not to be confused with Small-Scale Management Units (SSMUs) which were selected by SC-CAMLR in 2002 to better identify areas for apportioning krill sub-areal limits to account for potential interactions between krill, their predators, and the fishery (see below). All CCAMLR-sanctioned finfish fisheries mandate the deployment of at least one scientific observer per vessel in accordance with the CCAMLR Scheme of International Scientific Observation. Stringent data and catch reporting requirements are also stipulated, while finfish vessels are required to carry vessel monitoring systems (VMS) to verify their location.

### 21.5.1.3 Precautionary Catch Limits

The krill fishery is globally unique as its catch limits have been formally ascribed precautionary status, and have been based on direct surveys of the stock's status in 1981 and 2000–2003. They have also been tuned to account for krill's key ecosystem status as a predator food source and the species' variable life (notably recruitment) history. Uncertainties attached to the determination methodologies used are also considered. The application of krill precautionary catch limit determination approaches has subsequently been advanced to finfish assessments.

On-going work focuses on objectively dividing krill precautionary yields into SSMUs to improve predictive power and spread any risk of irreversible ecosystem changes arising from fishing. Additionally, this entails developing operational objectives for non-harvested species to account for uncertainties associated with ecosystem function and dynamic relationships amongst predators, particularly between krill availability and predator food demands.

#### 21.5.1.4 Fishery Notifications

A requirement to provide pre-notification of intentions to participate in the krill fishery (CM 21-03), as well as in new (CM 21-01) and exploratory fisheries (CM 21-02) (see below), has introduced an added element of precaution into CCAMLR's management protocols and responses. It also identifies procedures for the collection of essential data from operators involved in a particular fishery for the first time and/or in an undeveloped (i.e. exploratory) fishery.

#### 21.5.1.5 New and Exploratory Fisheries

In the early 1990s, CCAMLR came to recognise that fisheries under development frequently commence operations without the essential data being available to ensure that their management is sufficiently precautionary to meet the conservation principles set out in Article II of the Convention. In 1989, CCAMLR initiated a process that aimed to manage developing, 'exploratory', fisheries. This process expressly recognises that fishery development "should be directly linked with elaborating scientific advice and management measures".

CCAMLR adopted a CM (now CM 21–01) in 1991 to deal with any new fishery, defining it as a fishery on a species using a particular fishing method in a CCAMLR Statistical Subarea for which data on the distribution, abundance, demography, potential yield and stock identity have not yet been submitted to CCAMLR.

CM- 21-01 thus sets out conditions for a new fishery's impending implementation, recognising that fisheries are to be managed from the time of their initial commencement. A key condition of the measure is that pre-notification is essential for sustainable management, particularly when fishing is targeting species, and/or a fishing ground, that have not previously been fished. Similar considerations apply if it is intended that the fishery use a new fishing technique. The measure aims to collect essential information on target, as well as dependent and related, species, to facilitate development of regulatory controls for a new fishery as it develops further. It also strives to limit catch, and/or fishing effort, while still allowing for fishing to occur so that the necessary data are accrued to manage the fishery's sustainability.

In 1993, CCAMLR outlined the conditions for a new fishery to become an exploratory fishery, along with the regulatory provisions to be applied (CM 21-02). For exploratory fisheries, a fishery previously defined as new for one year, becomes an exploratory fishery thereafter, based on the premise that it stills lacks critical management information (e.g. as outlined in Box 21.1), or that such information remains incomplete.

**Box 21.1: Key Requirements for a CCAMLR Exploratory Fishery (CM 21-02)**

(a) An evaluation of the distribution, abundance and demography of the target species, leading to an estimate of the fishery's potential yield;
(b) A review of the fishery's potential impacts on dependent and related species, and
(c) Formulation and provision of advice to the Commission by SC-CAMLR to identify appropriate harvest catch levels, fishery effort levels and fishing gear, where appropriate.

As noted, both new and exploratory fisheries are subject to rigid notification and review procedures before CCAMLR authorises full-scale fishing. All other fisheries are seen either as closed (i.e. not specifically open to fishing as new or exploratory fisheries, or as closed by specific CCAMLR CMs). CCAMLR fisheries are no longer classed as exploratory, once the necessary management and catch/effort information are available for them to be fully assessed.

To minimise any risk of an exploratory fishery concentrating fishing effort in a particular, or restricted, area, CCAMLR has developed a system of small-scale research units (SSRUs) (Fig. 21.7) to spread the fishery's geographic cover. This aims to improve target stock(s) distributional information, and has been used (e.g. in the South West Atlantic crab fishery) to implement an experimental approach to gather key knowledge about the fishery's dynamics. The gathering of knowledge from exploratory fisheries is augmented by the deployment of scientific observers appointed under the CCAMLR Scheme of International Scientific Observation (see below). The most notable exploratory fisheries to date include those for toothfish in parts of the Indian Ocean, as well as in the Ross Sea. All other (i.e. developed) fisheries have been subject to full assessments, or have not yet been opened as new fisheries, or have been specifically prohibited. Although the krill fishery is considered a developed fishery, it remains subject to a participatory notification requirement (CM 21-03), largely as a result of the species' recognised importance in the ecosystem.

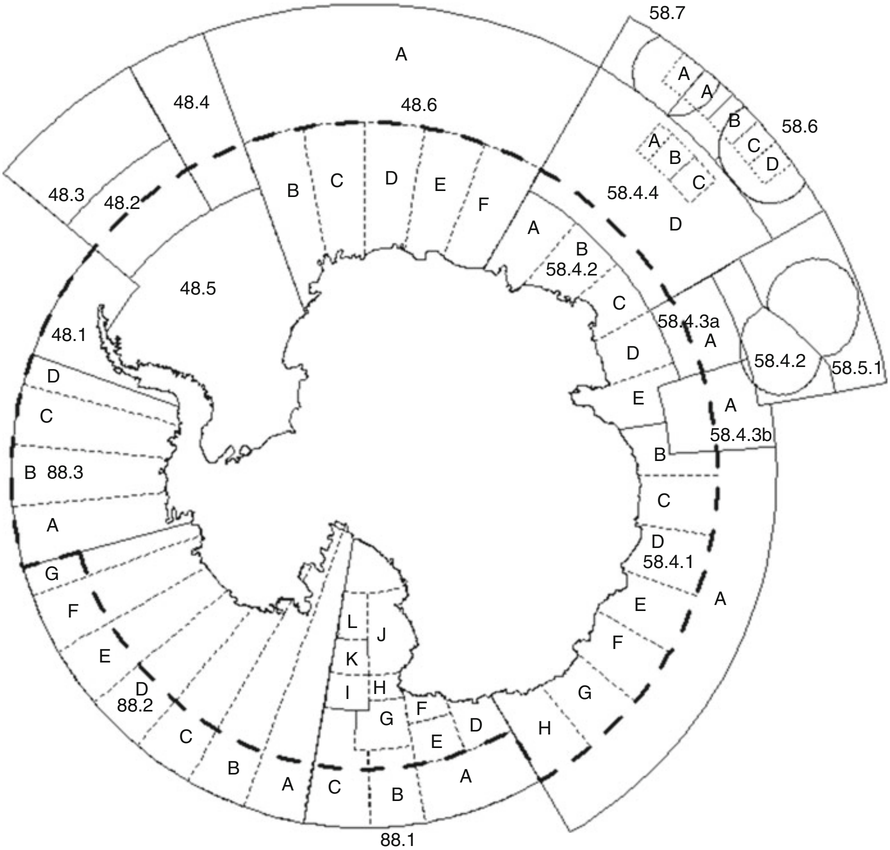



**Fig. 21.7** Small-scale research units (*SSRUs*) in the CCAMLR Area. The Australian, French and South African EEZ boundaries are shown in order to address new and exploratory fishery notifications in waters adjacent to these zones. The *dashed line* is the approximate boundary between the distribution of *Dissostichus eleginoides* and *Dissostichus mawsoni* (From CCAMLR CM 41-01)

#### 21.5.1.6 Scientific Observation

The CCAMLR Scheme of International Scientific Observation (CCAMLR 2011c) provides for deployment of independent scientific observers to observe and report on fishing operations, and attached activities, with the "Convention's objectives and principles in mind".

CCAMLR scientific observers have no regulatory function, and their defined tasks (e.g. recording vessel operations, sampling fisheries catches and recording incidental mortality of non-target species) are undertaken using observation formats approved by SC-CAMLR. Their independence is assured by the requirement that they not be nationals of the flag State of the vessel on which they serve. Finally, CCAMLR scientific observer safety, living conditions and status are subject to bilateral agreements (i.e. legal contracts) between the CCAMLR Members of which they are nationals (i.e. designating Member) and the vessel flag state (i.e. receiving Member).

The Scheme has provided significant amounts of objective information, as well as considerable insights into how CCAMLR's new and exploratory fisheries have evolved. It has also provided considerable data on the prosecution of developed (especially finfish) fisheries where observers are deployed. Furthermore, the presence of CCAMLR scientific observers appears to have a noticeable, and positive, effect on the behaviour of the fishing vessels on which they serve. This has been particularly true with respect to CCAMLR efforts to eliminate incidental seabird bycatch during toothfish longline fishing (Miller 2012).

#### 21.5.1.7 Fishery Reporting Requirements

Fisheries reporting requirements are attached to many CCAMLR CMs in force. These provide directive guidance on the frequency of reporting, formats for reporting catch-effort information, periodicity of reporting (ranging from daily to annual) and other reporting requirements. Examples include a monthly catch and effort reporting system (CM 23-04), data reporting system for the krill fishery (CM 23-06) and reporting requirements for exploratory fisheries (CM 23-07). Under Article XX of the CAMLR Convention, CCAMLR member vessels licensed to fish in the Convention area are legally obligated to provide such information as the commission and SC-CAMLR require in their execution of their functions and at intervals prescribed by CCAMLR. Again, CCAMLR scientific observers play an essential role in ensuring that the desired data are provided.

#### 21.5.1.8 Fishery Regulatory Measures

The CMs in force in the CCAMLR area can be grouped into three categories: compliance, general fishery matters, and fishery regulation. Collectively, they are usually termed monitoring, control and surveillance (MCS) measures.

**Compliance** measures include vessel licensing requirements, inspection (including port inspections) provisions, vessel monitoring system (VMS) obligations, schemes to promote compliance by Convention Contracting as well as Non-Contracting Parties, toothfish catch documentation scheme (CDS) details and transhipment notification procedures.

**General fishery** measures comprise fishery notification procedures, fishing gear regulations, date reporting requirements and conditions attached to research/experimental fishing. They also outline provisions attached to mitigation of incidental (non-target species) mortality during fishing and general protection of the environment.

**Fishery regulation** (see also Table 21.2) measures regulate fishing by area, fishing season (including definition of specific types of seasons), fished species and/or other prescribed situations (such as limiting finfish bycatch). General measures in this category also outline procedures for the closure of fisheries and refer specifically to the management of fisheries around South Georgia (CCAMLR Subarea 48.3).

### *21.5.2 Illegal, Unreported and Unregulated (IUU) Fishing*

It is probably true to say that IUU fishing (Box 21.2) has constituted the single-most profound challenge to CCAMLR's regulatory regime. Up until the mid-1990s, CCAMLR's regulatory measures were largely based on conventional approaches common to many fisheries enforcement agencies. Inter alia, these measures aimed to prohibit unauthorised fishing in the CCAMLR area, monitor fishing locations using vessel monitoring systems (VMS) and require notification of vessel movements. They were expanded to include at-sea and in-port inspections as well as comprehensive fisheries data reporting.

The expansion of toothfish longline fisheries in the early to mid-1990s led CCAMLR to realise that its traditional approaches were likely to be less effective in facing up to a persistent and expanding IUU fishery that was emerging at the time. Furthermore, it was recognised that the problem is compounded by the size of the CCAMLR area, as well as by the mix of jurisdictional conditions therein.

The above situation meant that CCAMLR was forced to face the challenge posed by IUU fishing as a matter of priority, recognising the significant potential of large-scale IUU fishing to undermine CCAMLR's efforts to manage the Patagonian toothfish, *D. eleginoides*, fishery in the Indian Ocean in particular. The Commission's primary motive was to preserve the toothfish fishery's sustainability and economic benefits. This entailed the implementation of management action consistent with the Convention's objectives so that the rights of CCAMLR members were not prejudiced. CCAMLR Parties with EEZs in the CCAMLR area had most to lose in terms of a CCAMLR failure to manage target toothfish stocks effectively.

A further key limitation in CCAMLR's efforts has been the continued uncertainty attached to the accurate monitoring and assessment of the IUU fishery's impact and extent. Prior to 1996, CCAMLR largely used sightings of unlicensed fishing vessels to determine IUU activities and catch levels. To counter the increase in unregulated fishing for toothfish in the late 1990s, along with a geographic expansion of the IUU fleet, CCAMLR developed a number of ways to assess IUU catches. These were based on the catch rate from the geographically closest legitimate fishery, with the total annual IUU catch being summed for all IUU vessels observed and/or being reported. The consequent information was accordingly weighted with actual observation of IUU activities being afforded the highest weighting.

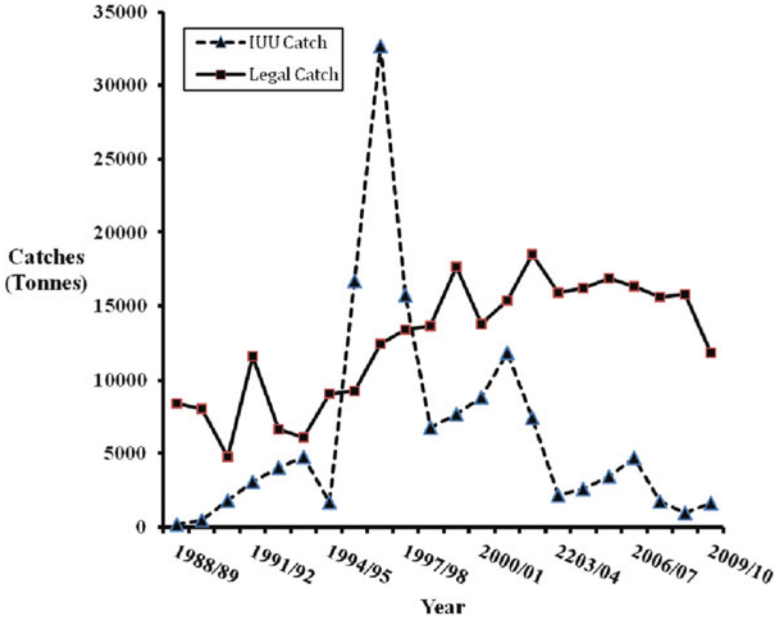



**Fig. 21.8** Annual estimates of IUU toothfish catches in the CCAMLR area compared to legitimately reported catches. Data are in tonnes and have been compiled from annual CCAMLR estimates. Annual point estimates for IUU catches were discontinued in 2011

However, it was not until the introduction of the CCAMLR Catch Documentation Scheme (CDS) for toothfish in 2000 (CCAMLR 2012b), that IUU catches derived from trade information could be used to improve the ground truthing of actual toothfish removals. From about 2002 onwards, assessment of toothfish IUU fishing came to rely on an amalgamation of anecdotal information, the exchange of intelligence (e.g. on vessel location or port visits) information, visuals sightings of IUU vessels in the CCAMLR area and information acquired during enforcement action (e.g. vessel logbooks).

Nonetheless, CCAMLR estimates of the IUU toothfish catch should be treated with caution and as approximations only. Subject to the recognised, and inherent, uncertainty attached to the estimates, noticeable peaks in IUU catches between 1994/1995 and 1998/1999 (Fig. 21.8) are probably attributable to a large number of IUU operations migrating from the Atlantic to Indian Ocean. It is also likely that CCAMLR's efforts to eliminate IUU fishing in one area were compromised as the fishery was able to relocate. Relocation often included a change of flag, vessel name and/or ownership (Baird 2006).

The IUU fishery's migration continued as stocks of toothfish were progressively depleted around the Prince Edward Islands, on Ob and Lena Banks, and around the French Crozet and Kerguelen islands (Fig. 21.1). Since 2007, IUU vessels have been entering the Ross Sea to a limited extent. The total IUU toothfish catch has exceeded the legitimate regulated catch by more than two and half times on occasion (i.e. in 1995/1996) and has been slightly less than 50 % of the regulated catch on average since 1988/1989 (Fig. 21.8).

**Box 21.2: IUU Fishing**

The term "IUU fishing" was initially coined by CCAMLR in 1996 as reflected in paragraphs 8.7-8.13 of the Commission's 1997 report (CCAMLR-1982–2012). Since then, it has been elaborated by the FAO in the IPOA-IUU. Put simply, the term defines IUU fishing as fishing in areas under national jurisdiction without the authorisation of the coastal States, fishing in contravention of conservation and management measures, failure to effectively exercise required jurisdiction or control over vessels and/or national persons, and failure to fully comply with the fishery and fishing vessel data reporting requirements.

The conventional regulatory approach followed by CCAMLR, and alluded to in the text, largely relies on the effective application of flag state control and the fulfilment of port State responsibilities. Under UNCLOS provisions, a flag State legally grants nationality to a vessel that flies its flag. Thus the State concerned is responsible for fixing the conditions under which it grants such nationality. Similarly, port States possess certain rights allowing them to inspect, investigate, or otherwise take action against, vessels which voluntarily enter their ports. In fisheries terms, specific elements of UNCLOS Part VII (Sections 1 and 2) require all States to cooperate in the conservation of living resources on the high seas in particular. Therefore, a real link between a flag State and its fishing vessels is necessary to ensure that such cooperation is universally ascribed. Equally, port States are essential to providing support, as well as a monitoring capability, to determine to what extent marine living resource conservation provisions are being applied in accordance with prevailing fishery regulatory measures. This framework for responsible fishing is at the centre of modern international fisheries agreements such as the CAMLR Convention, and the more recent 2002 Convention on the Fishery Resources of the South East Atlantic Ocean. It has also been interpreted further in the FAO Compliance Agreement (Article III) and 1995 UNFSA (1995 United Nations Fish Stock Agreement) (Article 18), which clearly outline flag State responsibilities. UNFSA Article 21 goes on to specifically outline conditions for regional and subregional cooperation in the enforcement of conservation provisions, irrespective of whether a State is party to a particular fisheries arrangement or not. IUU fishing thus aims to circumvent, or even violate these requirements and obligations so as to gain an economic advantage by harvesting a particular fishery stock, or species, unhindered by conservation regulations.

IUU fishing usually benefits from fishing vessels being able to acquire the flag of a State that is unwilling or unable to enforce relevant fishery

(continued)

**Box 21.2** (continued)
conservation measures and/or requirements. These are often termed Flags of Convenience Vessels or vessels flying flags of Non-Compliance. A comprehensive study of the toothfish IUU fishery is available in Baird (2006).

A noticeable decrease in the estimated IUU toothfish catch was evident between 2006/2007 and 2009/2010. One interpretation for this observation is that CCAMLR's improved ability to identify fishing locations and monitor toothfish trade, along with increasingly effective enforcement actions, such as those flowing from 'long arm enforcement' under United States' Lacey Act type legislation (Anon. 2013). The latter include improved flag State control and enhanced cooperation between CCAMLR Members on deterring IUU activities (Miller et al. 2010). Such successes raise the probability of IUU activities being detected, and hence prosecuted (Baird 2006).

A simple economic incentive may also be at play. Toothfish traded in compliance with the CCAMLR CDS tend to fetch a higher price in the most lucrative (USA and Japan) markets, which makes the under-price potential of the IUU-caught product less economically attractive. A contrary assumption is that IUU fishing (particularly in parts of the Indian Ocean) has become self-regulating with toothfish stocks being fished below realistic economic yields, or expectations.

Apart from implications for toothfish stock sustainability in the CCAMLR area, the IUU fishery is likely to have done little to avoid bycatch and incidental mortality during fishing. Therefore, the anticipated effects of IUU fishing on other species are probably substantial, although they remain largely undetermined. Some estimates have suggested that IUU fishing impacts on seabirds may be as much as seven times greater than peak impacts of CCAMLR-regulated fisheries.

Overall, the combined effects of CCAMLR and individual state measures/actions have been positive, particularly in the subantarctic Indian Ocean. IUU fishing has probably been deterred by the increased risk of being apprehended and prosecuted, and the increasingly effective enforcement action and/or improved intelligence on IUU operations. Improved intelligence has also allowed CCAMLR, to focus on the most persistent IUU vessels, their flags and their beneficial owners.

As already noted, IUU fishing has severely depleted toothfish stocks in the southern Indian Ocean in general, and around the Prince Edward Islands in particular. This has seriously impacted the future of these stocks (Miller 2012). Furthermore, the recovery of depleted stocks, especially around the Prince Edward and Kerguelen Islands, is likely to be slow. In contrast, the longline fishery for toothfish in CCAMLR Subarea 48.3 (South Georgia) has remained predictably productive. This particular fishery was recently awarded Marine Stewardship Council (MSC) accreditation as a sustainable and well managed fishery. A similar certification, although more controversial, was granted in 2010 to the CCAMLR exploratory fishery for Antarctic toothfish in the Ross Sea. In 2012, MSC certification was granted to the Toothfish fisheries around Macquarie, as well as Heard and Macdonald, Islands. Disturbingly, CCAMLR has indicated that IUU vessels may be operating in the Ross Sea. Nevertheless, it must be stressed that toothfish fisheries around South Georgia, Heard and McDonald and Macquarie islands are only likely to remain sustainable if good management practices continue to be rigorously enforced.

### 21.5.3 Ecosystem Management

#### 21.5.3.1 Krill Fishery

With krill as the central link between the primary food supply (phytoplankton) and major predators, the fishery is potentially an acute management challenge in terms of meeting the Convention's Article II ecosystem objectives. This largely comprises the need to take account of essentially depredatory impacts associated with krill predators such as whales, seals, birds, fish, squid, and of course the fishery. Although, understanding of krill's biology, population ecology and life cycle remains incomplete, it is worth reiterating that as a key food item the species is central to a number of Antarctic marine-dependent food webs at various spatial scales. Therefore, over-concentration of krill fisheries in areas where krill predators, especially land-based predators, feed may cause short-to-medium term negative impacts on these predators.

Although variable in the past, the krill catch has been gradually increasing again in recent times. Nineteen countries have fished for krill since the fishery commenced, and by 2008/2009, the former Soviet Union states (Russia and Ukraine post-1992) and Japan had taken the bulk (88 %) of the total krill catch (7.2 million tonnes) since 1972/1973. In descending order, Norway, Vanuatu, USA, Chile, Korea and Poland have accounted for a further 11.9 %. Other sporadic participants in the fishery have included Argentina, Bulgaria, Germany, India, Panama and the United Kingdom. Six CCAMLR Members (Japan, Korea, Norway, People's Republic of China, Poland, Russia) are currently active in the krill fishery, and the bulk of the catches (about 6.2 million tonnes, or 86 % of the total catch taken) has come from Statistical Area 48.

Until the early 2000s, krill fishery products were limited by cost, processing methods and demand for saleable products (livestock feed, human supplements and aquaculture feed) (Nicol et al. 2011). These shortcomings were attributable to prevailing inefficiencies associated with trawling as the primary fishing method. During trawling, krill may be extruded through the net mesh, and often do not survive. Extrusion makes accurate catch estimation more difficult as lost krill are effectively subject to fishery-induced mortality. Such mortality compounds uncertainty attached to assessing long-term stock productivity. Furthermore, krill are often crushed in the net when trawl catches are large. This affects the quality of the catch being landed.

In 2005, the Norwegian company Aker BioMarine patented a krill fishing method similar to purse-seining, where live animals are surrounded by a large net and pumped aboard the processing vessel. The technique is often referred to as ‘eco-friendly’ trawling due to its high selectivity and reduced catch wastage. Consequently, this trawling (‘krill pumping’) method, and the attached Norwegian krill fishery, have been afforded Marine Stewardship (MSC) certification as a sustainable fishery. However, the certification was not without controversy. A number of environmental organisations have indicated that “progress against the certification criteria will be monitored via annual surveillance audits, and stakeholder organisations will have further opportunities to review the resulting data and how they relate to the fishery’s performance”.

There are also ecosystem consequences arising from krill fishing directly. These include the fishery taking large quantities from time to time in certain areas, as well as the incidental mortality of fur seals entangled in krill trawls. The introduction of net escapement panels by CCAMLR in 2003 appears to have reduced such mortality significantly (Nicol et al. 2011).

#### 21.5.3.2 Management Limitations

The precautionary approach adopted by CCAMLR for managing the krill fishery leaves some scope for the fishery’s expansion within the context of management efforts to minimise its potential impacts on the ecosystem in general, and on krill-dependent species in particular. Therefore, and as noted, the main purpose of CCAMLR’s krill precautionary catch limit is to ensure sustainability without compromising the species’ important role in the ecosystem. As a management strategy, this requires that the krill precautionary limit(s) be spread between designated SSMUs to avoid concentrating the fishery in small areas, where damage to localised ecosystems may occur. The persistent failure of CCAMLR to agree on how krill precautionary catch limits are to be apportioned in terms of SSMU, or other, criteria can thus be perceived as a failure in the operational implementation of CCAMLR’s precautionary management of the fishery. This also implies a failure to minimise the risk of irreversible changes in the krill-based ecosystem, a consideration which may be contrary to Convention Article II objectives.

#### 21.5.3.3 Future Krill Harvest Trends

At present, krill catches are relatively low compared to estimates of the species’ potential yield, as well as prevailing CCAMLR precautionary catch limits. Increasing interest in the fishery, the recent and rapid diversification of krill products, and a growing number of krill fishing countries all point towards the fishery expanding significantly in the short to medium term. These developments are largely the

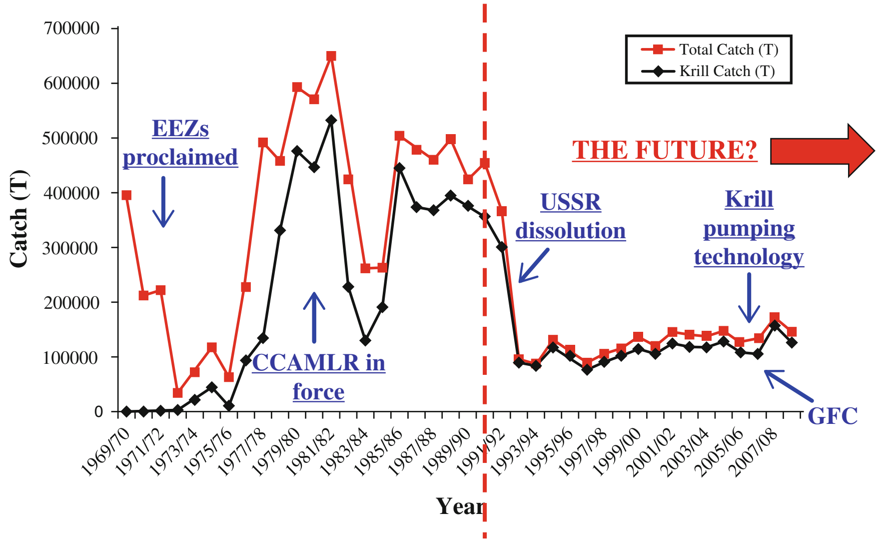



**Fig. 21.9** Total krill and finfish catches reported to CCAMLR between 1973 and 2010. Various events likely to have impacted the krill fishery are marked (***EEZs*** Exclusive Economic Zones, ***GFC*** Global Financial Crisis). All catches are in tonnes (CCAMLR 2012a)

consequence of the pioneering Norwegian fishing and processing techniques outlined above. In particular, the processing technology has allowed for considerable diversification in high-end products due to improved product quality. Finally, the recent MSC certification undoubtedly underscores the fishery's attraction to the environmentally-conscious investor. In this context, recent studies have focused on improving our understanding of the krill fishery's general environmental implications should it reach significant levels (Wayne et al. 2012). Such implications include the potential interactions between the distance from port and the location where fishing takes place. The linkages between fuel emissions, attached environmental impacts and economic costs are one manifestation of such considerations.

Nonetheless, recent trends do seem to favour a marked expansion of krill catches in the foreseeable future. The recent development of krill-focused bioprospecting for new products further raises expectations of near-future increases in catches. The increasing number of patents for krill-related products now stands in excess of 800, more than double the number lodged in 1999. Together, these considerations highlight the role that extraneous influences, in this case new fishing technology, may play in terms of impacting fishery development in the Southern Ocean. Figure 21.9 illustrates a number of associations between various extraneous (to the fishery) events relative to both finfish and krill catch levels. In the case of finfish such events include the global trend in the early 1970s of coastal states declaring EEZs to augment their jurisdictional rights and benefits from marine living resources located within 200 nautical miles of their territory. Equally, increased finfish and krill fishing preceded the CAMLR Convention's entry into force. This was followed by a decrease in both krill and finfish catches, which again

**Table 21.3** The projected krill catch (tonnes) from notifications on participation in the fishery reported annually to CCAMLR compared to the annual krill catch

| Year | Notified krill catch | Annual krill catch |
|---|---|---|
| 2002 | 113,000+ | 125,987 |
| 2003 | 115,000 | 117,728 |
| 2004 | 226,000 | 118,166 |
| 2005 | 226,000 | 129,026 |
| 2006 | 245,000 | 106,591 |
| 2007 | 368,400 | 104,586 |
| 2008 | 764,000 | 156,521 |
| 2009 | 629,000 | 125,826 |
| 2010 | 363,000 | 211,984 |
| 2011 | 410,000 | 180,986 |
| 2012 | 401,000 | 156,289 |

Data have been extracted from SC-CAMLR (SC-CAMLR 1982–2012), CCAMLR reports (CCAMLR 1982–2012), CCAMLR Statistical Bulletins (CCAMLR 2012b) and Nicol et al. (2011)
672,720 tonnes was notified for 2012/2013

began to rise once CCAMLR commenced development of fishery regulatory CMs. Further dips in catch levels accompanied the dissolution of the Soviet Union, while an increasing catch trend accompanied the 2008 Global Financial Crisis (GFC). In the latter case, increased krill catch immediately following development of the new Norwegian ‘pumping’ technology appear to have compensated for any potential GFC-attributable economic uncertainties.

While there is still considerable uncertainty surrounding the krill fishery’s potential future development, annual reports to CCAMLR indicate an increasing trend in notifications by CCAMLR members of their intended involvement in krill fishing annually over the past few years (Table 21.3). The attached ecosystem management implications are therefore self-evident if the krill fishery enters a rapid expansion phase, particularly in terms of increased uncertainty attached to the actual rate of such expansion.

Acoustic-based estimates of krill biomass in Subareas 48.1, 48.2 and 48.3 stand at 60.3 million tonnes. Using the CCAMLR-agreed approach to estimate krill precautionary catch limits, the overall limit amounts to 5.61 million tonnes for the three subareas. Consequently, the actual 2009/2010 catch of about 200,000 tonnes in the subareas is well below the calculated precautionary catch and biomass levels. Even if krill catches close to the estimated biomass are unlikely to be sustainable, this level of catch further indicates that there is considerable scope for current levels of krill fishing to expand. Nonetheless, the main purpose of the krill precautionary catch limit is to ensure the stock’s sustainability, along with that of its dependent predators. It follows that the limit should also be spread between designated SSMUs to avoid concentrating the fishery in small areas and producing localised damage to the ecosystem. The persistent failure of CCAMLR to agree on how krill precautionary catch limits are to be apportioned according to

SSMUs, or other criteria, is therefore a perceived failure in the operational implementation of CCAMLR's precautionary approach for the fishery.

It has been noted that the krill fishery is remote and relatively inaccessible. It is also sensitive to market and other economic and political forces (Nicol et al. 2011). While the fishery has remained at a relatively low level for a number of years, there is currently an upward catch trend and it is becoming more competitive when compared to other fisheries elsewhere. Any future developments of a bulk-driven (high catch level) krill fishery will enhance any such future upward catch trend. Together with a scarcity of underexploited stocks elsewhere, a future fishery five times the current level (i.e. of the order of one million tonnes $yr^{-1}$) seems realistic. This would place the krill catch amongst the top 10 globally for wild stocks. With the krill fishery improving its global market share and, by implication, its inherent value the possibility of IUU fishing developing cannot be ruled out. As for the toothfish IUU fishery, this development would seriously undermine CCAMLR's management efforts, particularly in light of krill's ecological importance.

#### 21.5.3.4 Crab and Myctophid Fisheries

For both crabs, *Paralomis* spp., and myctophids (Lightfish), there is very little definitive information on their ecosystem status, although they are considered important in Subarea 48.3. Notably, the myctophid, *Electrona carlsbergi*, is considered an important food source for other fish species close to the APF. Although the *E. carlsbergi* catch trends already discussed suggest that the species might exhibit some commercial potential, there are no indications that a myctophid-targeted fishery will resume in the near future.

Most of the other historical finfish fisheries in the Southern Ocean are unlikely to be commercially viable, but such an assessment does not take into account any future impact of IUU fishing on stocks. Nevertheless, it would seem that market demand would have to be high for such fishing to occur, and/or to counteract economic uncertainties associated with fuel costs and the relative remoteness of Southern Ocean fishing grounds.

#### 21.5.3.5 Bycatch

Bycatch is a manifestation of direct interaction between a fishery and non-target species, or between a fishery and species that are found in association with fishing operations. CCAMLR has instituted three CMs specifically targeted at avoiding, monitoring or directly limiting bycatch. For example, CM 33-03 provides linkages to bycatch measures for select species, as well as move-on rules when such species are encountered, or particular catch levels are exceeded.

Other measures (CMs 32-02 to 32-08) limit directed fishing on certain species, including a number which are common as bycatch. CM 33-01 closes areas to fishing when stipulated bycatch limits arise and CM 32-04 closes Subarea 48.1 to directed fishing for *N. rossi*, and also to avoid bycatch. CCAMLR makes every effort to assess bycatch species productivity if possible, and requires reporting and retention of bycatch. In the latter regard, CCAMLR scientific observers play an important role in monitoring bycatch levels.

Most importantly, CCAMLR continues its efforts to counter incidental mortality caused by the catching of high-level species, such as seabirds and seals, during fishing operations.

Significant seabird bycatch by longline fisheries in the Southern Ocean, and elsewhere, were prevalent in the late 1980s. In the CCAMLR area, such bycatch was particularly significant during the 1990s, largely due to the expansion of both legitimate toothfish and IUU fisheries. Many threatened albatross and petrel species were affected.

CCAMLR mitigation measures introduced in the early 1990s have resulted in dramatic decreases of bird bycatch during longlining in the Convention area, except within the Crozet and Kerguelen island EEZs until relatively recently.

The icefish trawl fishery around South Georgia between 2004 and 2007 was also responsible for an annual mortality of 50–100 albatrosses and petrels. This particular problem appears to have been largely solved by CCAMLR introducing various operational procedures to minimise seabird and mammal entanglements during trawling.

Despite these successes, high levels of seabird mortality continue to occur in longline fisheries targeting tuna and similar species outside the CCAMLR area, as well as in national waters farther north. This continues to put seabirds breeding in the CCAMLR area at risk. Nonetheless, CCAMLR's efforts to counter seabird incidental mortality during longline fishing have come to be seen as a global benchmark for successful and cost-effective mitigating measures. "Fish the Sea, Not the Sky" has become the CCAMLR rallying cry (CCAMLR 2012c).

#### 21.5.3.6 Dependent/Related Species

Subject to the dependent and related species provisions of CAMLR Convention Article II.(3).(b), seals and whales are obvious such species. In this regard, direct interactions of fishing with seals and whales is an obvious concern, given their and 'dependent and related' status with respect to harvested stocks. For example, interactions between longline fisheries and marine mammals (predominantly killer whales, *Orcinus orca*) have been reported from the CCAMLR area. Since these interactions often result in loss of fishing gear, fishing masters will usually not retrieve lines when killer whales are present during line hauling. The consequences are that an undetermined amount of catch is lost, and in the case of IUU fisheries whales are actively deterred, sometimes with dynamite, from taking the lines. As already highlighted, other interactions include entanglements of non-target species with fishing gear.

Accepted, but internationally-controversial projections suggest that the southern minke whale, *Balaenoptera acutorostrata*, alone exhibits any potential for future exploitation, all other species having been decimated by whaling in the early to mid-twentieth century. Despite harvesting of minke whales in the Southern Ocean at commercially viable levels (about 300 to a little over 800 animals annually) since 1980 under the guise of scientific whaling, international opinion predominantly does not appear to favour resumption of whaling there. Prohibition by the International Whaling Commission (IWC) of commercial harvesting of all Southern Ocean whales since 1980 and the Ocean's status as a whale sanctuary since 1994 underscore this opinion. Nonetheless, scientific whaling by Japan of minke whales continues. Therefore, it remains to be seen how decisions arising from Australian efforts in seeking a ruling from the International Court of Justice on scientific whaling's legality play out to influence future Southern Ocean whale exploitation.

Apart from minke whales, three other mammal species might be potentially exploitable in the Southern Ocean. Annual catches of 175,000 crabeater, *Lobodon carcinophagus*, 12,000 Weddell, *Leptonychtes weddellii*, and 5,000 leopard, *Hydrurga leptonyx*, seals are permitted under CCAS. However, humanitarian concerns and low market demand suggest that Southern Ocean sealing will not be readily condoned in the foreseeable future, if ever.

#### 21.5.3.7 General Environmental Protection

Aside from SSMUs, CCAMLR is considering, or has initiated, various spatially-bound measures to address the precautionary and ecosystem-directed elements of Convention Article II. One such measure (CM 26-01) applies to the entire CCAMLR area and is aimed at minimising risks of alien-species contamination and marine pollution from fishing vessels. The measure specifically establishes controls on dumping, or discharge, and the translocation of poultry into the CCAMLR area south of 60°S, where the effects of such events are likely to be most acutely felt.

Further measures (e.g., CM 91-01) protect CEMP sites, while others set ice-strengthening requirements for fishing vessels at high latitude (Resolution 20/XXII), general vessel safety standards (Resolution 23/XXIII), and ballast-water exchange restrictions (Resolution 28/XXVII). Most recently, Resolution 29/XXVIII urges CCAMLR Members to ratify the 1989 International Convention on Salvage, or any other measures deemed appropriate to facilitate the recovery of reasonable expenses incurred by vessel operators assisting other vessels, or other property in danger, in the CCAMLR area. All such measures have drawn on SC-CAMLR advice to mitigate any potential dangers to the Antarctic marine environment.

As already noted, CCAMLR has developed SSRUs to spread the risk of spatially concentrated fishing when scientific knowledge of the stocks concerned is limited. Initially applied to experimental crab fisheries, the approach was subsequently expanded to various exploratory toothfish fisheries. SSRUs not only impose a degree of precaution by spreading fishing effort, they also promote the collection of essential operational data from the fishery, a responsibility assumed by

CCAMLR scientific observers aboard the vessels involved. The application of SSRUs provides an inexpensive alternative to research vessel surveys through the collection of data over wide time and space scales. For CCAMLR, scientific observers provide the necessary objectivity to render such data worthwhile.

Over the past decade, CCAMLR has considered implementing spatial management measures to facilitate biodiversity conservation consistent with targets set by the 2002 World Summit on Sustainable Development (WSSD). CCAMLR and the Committee for Environmental Protection (CEP), established under Articles 11 and 12 of the 1991 Madrid Protocol, have afforded high priority to the designation of Southern Ocean marine areas for biodiversity conservation. In 2007, CCAMLR sponsored a workshop to develop benthic and pelagic bioregionalisations based on results of an expert workshop held the previous year. These bioregionalisations were put forward as a basis for designing a representative network of CCAMLR marine protected areas (MPAs) and this work continues. As matters currently stand, a scientific rationale for a CCAMLR MPA network is being consolidated as one of three SC-CAMLR priority tasks (Miller et al. 2013). A vigorous debate around CCAMLR MPAs in the Ross Seas and southern Indian Ocean has dominated much of the Commission's and SC-CAMLR's work over the past 3 years. The exact form that these MPAs might assume remains unresolved while detailed agreement remains elusive.

UNGA Resolution 61/105 calls upon Regional Fisheries Management Organizations (RFMOs) or arrangements (RFMO/As) to close areas to bottom fishing until appropriate measures are in place to prevent significant adverse impacts on vulnerable marine ecosystems (VMEs). Paragraph 83 of the Resolution (UNGA 2006) urged RFMO/As to implement relevant VME measures by 31 December 2008. Despite a recent increase in research, the data available for managing benthic fauna in the Southern Ocean remains sparse.

CCAMLR responded to the UNGA resolution by formulating CMs 22-06 and 22-07 in 2007. CM 22-06 froze the current bottom fishing footprint to areas approved for such fisheries in the 2006/2007 fishing season. CM 22-07 provides a format for identifying VMEs encountered during scientific research cruises, defining a VME encounter during fishing operations, and describes the resulting action to be taken by a vessel.

These CMs met the UNGA deadline and have formed the basis for CCAMLR's refinement of its approach to protecting VMEs. The approach effectively remains under development and care is being taken to ensure that the current CMs (CMs 22-06 and 22-07) are not viewed as having done the job. More work was scheduled on the issue for 2012 and 2013, while a review of CM 22-07 was scheduled for 2012, but has been deferred.

Finally, mention should be made of The Last Ocean Project, (Anon. 2012) which endorses the establishment of a comprehensive no-take MPA for the Ross Sea. The project also aims to raise public awareness of the Ross Sea's globally unique standing as a representative polar marine ecosystem largely unaffected by human impacts.

## 21.6 Conclusion

Enduring conservation successes, along with sustainable fishing's future, in the Southern Ocean are critically dependent on the effective implementation of, and compliance with, CCAMLR regulatory measures. However, the future well-being of the Southern Ocean marine ecosystem does not rest with CCAMLR alone. In common with other ocean areas, there is a global need to:

- Eliminate IUU fishing, particularly by outlawing flags of non-compliance;
- Develop and improve management and governance of the oceans, particularly the high seas, and their ecosystems;
- Enhance adaptability to a changing world through improved incorporation of ecosystem-based principles into management practices, and
- Improve knowledge and understanding of potential links between the physical environment and biological productivity to improve management decisions.

While there is little doubt that there is widespread global interest in Antarctica and the Southern Ocean, the seamless integration of the Antarctic Treaty System (ATS) with more global instruments, such as UNCLOS, remains unclear in some instances. For example, claims relating to the limits of the continental shelf in the Antarctic Treaty area have drawn at least three different responses from Antarctic claimant and non-claimant states.

Four areas where the understandings set out in various ATS instruments might be used to take account of more global considerations, such as IUU fishing, and other commercial activities in the Southern Ocean are:

- Preserving and globally broadening the Treaty's provisions as these apply to peaceful use, non-nuclear proliferation, scientific freedom, environmental conservation and the freezing of territorial claims, in order to clearly delineate the Treaty's powers and responsibilities in the marine realm;
- Expanding and broadening political representation resulting in wider participation by the global community in decision-making associated with the Southern Ocean's environmental well-being;
- Considering and promoting technical, cost-effective and cooperative ways to sustain Southern Ocean marine ecosystem health, and
- Searching for ways to strengthen links between ATS environmental conservation and protection provisions, and other relevant global instruments aimed at managing human activities in the marine environment. For example, recent ATS efforts to conserve biodiversity in the marine realm (e.g. MPAs) have provided impetus for global efforts to designate high seas MPAs in other areas (e.g. the north-east Atlantic).

In these terms, there is a clear need to ensure that Southern Ocean governance remains responsive to the requirements and interests of all humankind. The continued environmental well-being of the area is the most pervasive such need, particularly if the more global challenges of environmental uncertainty, food security and sustainable capture fisheries are to be addressed effectively there.

Finally, it is glaringly apparent that toothfish IUU fishing has posed a fundamental challenge to CCAMLR's conservation ethic and objectives. Such fishing has the potential to seriously compromise the conservation of both target, and to some extent related, stocks as per Convention Article II objectives. The critical import of this challenge has meant that IUU fishing remains a distraction that diverts CCAMLR's efforts away from managing other fisheries to the benefit of all the Convention's objectives and Contracting Parties. This obviously raises concerns about any future IUU fishery that CCAMLR may encounter. Most notably, and given krill's key place in the Antarctic marine ecosystem, the potential of an impending IUU krill fishery goes to the heart of whether CCAMLR and the Convention actually work as intended. In this regard, the possible failure of an acknowledged and successful multi-lateral agreement, such as CCAMLR, would hold little hope for humanity's future sustainable management of its natural endowments.

## References


Anon. (2012) The last ocean. http://www.lastocean.org/

Anon. (2013) United States district court: Southern district of New York. Case document – 1:03-cr-00308-LAK, Document 249, 14 June 2013, 15 pp. http://www.justice.gov/usao/nys/pressreleases/June13/BengisArnoldetalRestitutionPR/U.S.%20v.%20Arnold%20Bengis%20et%20al.%20Opinion.pdf

Baird RJ (2006) Aspects of illegal, unreported and unregulated fishing in the Southern Ocean. Springer, Dordrecht, 286 pp

CCAMLR (1982–2012) Reports of the commission for the conservation of Antarctic marine living resources. CCAMLR, Hobart. http://www.ccamlr.org/en/meetings/26

CCAMLR (2010) Report of the twenty-ninth meeting of the commission. CCAMLR, Hobart, Australia. 175 p. http://www.ccamlr.org/en/system/files/e-cc-xxix.pdf

CCAMLR (2011a) Basic Documents: Convention on the Conservatism of Antarctic Marine Living Resources. CCAMLR, Hobart, pp 1–20, http://www.ccamlr.org/en/document/publications/convention-conservation-antarctic-marine-living-resources

CCAMLR (2011b) Basic Documents: Statement by the Chairman of the Conference on the Conservation of Antarctic Marine Living Resources. CCAMLR, Hobart, p 22, http://www.ccamlr.org/en/document/publications/convention-conservation-antarctic-marine-living-resources

CCAMLR (2011c) Basic Documents: Scheme of International Scientific Observation. CCAMLR, Hobart, http://www.ccamlr.org/en/document/publications/ccamlr-scheme-international-scientific-observation

CCAMLR (2012a) Statistical Bulletin. CCAMLR, Hobart, http://www.ccamlr.org/en/data/statistical-bulletin

CCAMLR (2012b) Schedule of Conservation Measures in Force. CCAMLR, Hobart, http://www.ccamlr.org/en/conservation-and-management/conservation-measures

CCAMLR (2012c) Fish the Sea Not the Sky. CCAMLR, Hobart, http://www.ccamlr.org/en/publications/fishing-related-documents

Clarke AC, Harris CM (2003) Polar marine ecosystems: major threats and future change. Environ Conserv 30(1):1–25

Miller DGM (2012) Sustainable management in the Southern Ocean: CCAMLR science. In: Berkman PA, Lang MA, Walton DWH, Young OR (eds) Science diplomacy: Antarctica, science, and the governance of international spaces. Smithsonian Institution, Washington, DC, pp 103–121

Miller DGM, Slicer NM (2013) CCAMLR and Antarctic conservation: the leader to follow. In: Garcia SM, Rice J, Charles AT (eds) Governance for fisheries and marine conservation: interactions and co-evolution. Wiley-Blackwell, Chichester. [In Press]

Miller DGM, Slicer NM, Sabourenkov E (2010) IUU fishing in Antarctic waters: CCAMLR actions and regulations. In: Vidas D (ed) Law, technology and science for oceans in globalization. Brill, Leiden, pp 175–196

Miller DGM, Slicer NM, Hanich Q (2013) Monitoring, control and surveillance of protected areas and specially managed areas in the marine domain. Mar Policy 39:64–71

Nicol S, Foster J, Kawaguchi S (2011) The fishery for Antarctic krill – recent developments. Fish Fish 13(1):30–40. doi:10.1111/j.1467-2979.2011.00406.x

SC-CAMLR (1982–2012) Reports of the Scientific Committee for the Conservation of Antarctic Marine Living Resources. CCAMLR, Hobart. http://www.ccamlr.org/en/meetings/27

UNGA (2006) United Nations General Assembly Resolution 61/105. United Nations, New York, http://www.un.org/depts/los/general_assembly/general_assembly_resolutions.htm

Wayne R, Parker R, Tydemars P (2012) Life cycle environmental impacts of products derived from Antarctic krill (*Euphasia superba*). Environ Sci Technol 46(9):4958–4965

# Chapter 22
# The Search for Extremophiles

## Antarctic Biological Prospecting

**Veronika Meduna**

**Abstract** Biological prospecting is taking place in the Antarctic Treaty area. It is an activity that involves searching for, extracting and testing components of Antarctic biodiversity for particular chemical properties that may then be developed for use in commercial products. So far, the activity appears to be relatively benign to the Antarctic environment, except that, any increase in human activity leads to an increase in cumulative impacts on the environment and increases the risk of introducing non-native species. Antarctic Treaty parties are very aware that biological prospecting is taking place in the Antarctic Treaty area, but some parties have been somewhat reluctant to discuss the legal implications of the activity at their annual Antarctic Treaty Consultative Meetings. Biological prospecting is not something that takes place only in the Antarctic region; it is an activity that countries carry out within their own national territories, and most countries have domestic legislation that governs the activity within their domestic territory. National perspectives on biological prospecting vary and this variation is often reflected in a country's view of Antarctic biological prospecting. Biological prospecting is a 'quasi-scientific' or a 'quasi-commercial' activity, meaning that the end goal for any good bioprospector is not just an academic exercise. The end goal is to develop a commercial product or process, which in some cases will earn the investors a significant amount of money. By its very nature, therefore, it is an activity that has raised concern from non-governmental organisations (NGOs) and non-signatory states, that is, those countries that have not signed up to the Antarctic Treaty.

**Keywords** Biological prospecting • Antarctic Treaty • Extremophiles • Biodiversity • Mining • Fishing

V. Meduna (✉)
Radio NZ House, Wellington, New Zealand
e-mail: vmeduna@clear.net.nz



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_22

## 22.1 Introduction

The extraction and use of any resources from the Antarctic Treaty area, be they non-living resources such as minerals or ice or a living resource such as the biodiversity sought by the bioprospectors, will always be a controversial topic for two main reasons: such extraction has the potential to impact the Antarctic environment, and the use of Antarctic resources always awakens the dormant argument on Antarctic sovereignty and sovereign rights. It re-ignites the territorial claims debate that was put to one side by Article IV of the Antarctic Treaty 1959 and remains to one side while that treaty remains in force. Therefore, Antarctic biological prospecting has the potential to awaken the sovereign sleeping giant in much the same way as the Antarctic minerals debate did in the 1980s. A focus on bioprospecting is warranted to assist understanding of this emerging activity and its legal implications.

Biological prospecting, more often referred to in its shortened form bioprospecting, is not a new activity. As far back as history records, humans have harvested and used biodiversity and components of biodiversity in the creation, development and commercialisation of new products or processes. Bioprospecting in the Antarctic Treaty area, however, is relatively new, and as a result, it is now often proposed as a topic for discussion at the annual Antarctic Treaty Consultative Meetings. There are only three ATCM resolutions in regards to Antarctic biological prospecting, Resolution 7 (2005), Resolution 9 (2009) and Resolution 6 (2013). As yet, however, there is no specific reference to bioprospecting in any of the major legal documents of the Antarctic Treaty System. The rules that currently govern Antarctic bioprospecting are the same generic rules that govern all human activity in the Antarctic Treaty area. These include the environmental protection rules found in the Environmental Protocol and the obligation found in Article III of the Antarctic Treaty for parties to exchange and make freely available scientific observations and results from Antarctica.

As long as certain rules are followed and legal conditions met, permits are given in order to extract biodiversity from Antarctica, including from the marine environment of the surrounding Southern Ocean. Since the first phase in any bioprospecting activity is to sample and extract biodiversity from a place, bioprospecting in the Antarctic Treaty area is not specifically banned and it is therefore allowed. Not only is the extraction allowed under certain permitted conditions, but currently, anyone can use Antarctic biodiversity or components of that biodiversity as part of a product or process that may lead to commercialisation.

So, is there a problem with this? After all, countries make money from Antarctic tourism via income to tour operators. Countries also make money from Antarctic fisheries via the fishing industry. Sometimes, over the long term, countries can even make money from the application of certain applied scientific research from Antarctica.

The problem involves ownership. Like the issues that were involved in the discussions surrounding rights to Antarctic mineral resources, the issues surrounding rights to the living biodiversity of the Antarctic Treaty area are similar. Generally, under existing international law principles, the sovereign or the country with ownership of a particular area of land has the right to use (or not use) that area's biodiversity as they wish, that is, the sovereign has the right to use its resources for its own benefit. There are some legal qualifications to this, but generally it is a given right over property, that is, resources found within a country's borders. This general right was reaffirmed in a legal document called the Convention on Biological Diversity 1992 (Box 22.1). For the Antarctic Treaty area, where ownership, territorial claims and sovereignty issues remain unresolved, the question regarding who has these property rights related to Antarctic biodiversity is difficult to discuss and even more difficult to answer. Many outside the Antarctic Treaty System argue that Antarctic biodiversity is the 'common concern of humankind', meaning that it belongs to everyone, and that such biodiversity should not be exploited for the commercial benefit of a few individuals or even the Antarctic Treaty parties alone.

**Box 22.1: The Convention on Biological Diversity (CBD) 1992**

Signed by 150 government leaders at the 1992 Rio Earth Summit, the CDB is a multi-lateral convention that came into force on 29 December 1993 and now has 193 parties to it.

The objective of the convention, found it its Article 1, is:

> . . . the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources. . .

The convention defines biological diversity as:

> . . . variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems.

Article 3 reaffirms the principle that:

> States have . . . the sovereign right to exploit their own resources . . .

and also notes in its Article 5 that, where appropriate, states should

> . . . cooperate . . . in respect of areas beyond national jurisdiction . . . for the conservation and sustainable use of biological diversity.

At a Conference of the Parties (COP) to the CBD in April 2002, the parties adopted the Bonn Guidelines on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising Out of Their Utilization (Decision VI/24). The guidelines are not themselves legally binding, but they were signed by 180 countries and are a document which identifies steps involved in the process regarding access to and benefit-sharing from the use of biological

(continued)

**Box 22.1** (continued)
diversity. At the tenth meeting of the COP, the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity was adopted. The Nagoya Protocol is a supplementary agreement to the Convention on Biological Diversity. It provides a legal framework for the effective implementation of one of the three objectives of the CBD: the fair and equitable sharing of benefits arising out of the use of genetic resources.

The Nagoya Protocol was adopted on 29 October 2010 in Nagoya, Japan, and entered into force on 12 October 2014. Find more information at www.cdb.int

The issue of Antarctic bioprospecting is currently being discussed within the Antarctic Treaty System. As yet, no conclusions have been reached on how to manage the activity and there are divergent views as to whether a specific Antarctic biological prospecting treaty or convention is presently needed. Antarctic scientists are collecting diverse species from Antarctica and are testing those species for activity or chemical markers that might be developed in the production of a commercial product or process. It is the commercial product or process that can then be patented or protected with some sort of intellectual property right.

In many cases, scientists undertake research in Antarctica for strictly academic purposes, that is, they are not targeting Antarctic biodiversity for a specific outcome. In some cases, however, potential outcomes have been identified and the researcher is focusing on finding a species with a particular chemical component or property. There is also the occasion where the researcher suddenly notices a valuable use for a discovery made or a sample collected for what started out as curiosity-driven investigations. In each of these examples, the goals of such research are admirable. Some research groups seek a cure for illnesses. Some are looking for ways to make ice cream smoother, others focus on ways to extract information from DNA faster. Whatever the outcome, it appears that biological prospecting in the Antarctic is going to continue for some time into the future.

Who decides whether such commercial development is an acceptable use of Antarctic biodiversity? Who should share in the benefits if a product or process is created? What are the risks to Antarctica of using its biodiversity in this way? Issues around these key questions are explored below.

## 22.2 In Search of a Legal Definition of Bioprospecting

While bioprospecting builds on traditional techniques employed by humans since civilisation began, advancements in technology, including discoveries of new species in what used to be remote and isolated regions of our planet, have raised the activity to a new level over a relatively short period of time. Putting a legal framework in place around an activity such as bioprospecting usually requires an understanding of the activity and often involves agreeing a legal definition of the activity. To date, this has been a problem for Antarctic bioprospecting since, internationally, there is no universally agreed legal definition of bioprospecting and at present there are no international legal agreements that specifically define the term (Rothwell 2005). The CBD and the Bonn Guidelines do not use the term despite being legal documents to protect biological diversity and regulate access to, and benefits derived from, living resources. The Nagoya Protocol refers to bioprospecting only once, in its Article 22 in regards to 'capacity' and cooperation in relation to capacity-building, however, it does not define the term. Arguably the lack of international agreement on a definition has done little to assist the Antarctic Treaty parties in composing a comprehensive definition of bioprospecting for themselves (Box 22.2).

**Box 22.2: Defining Bioprospecting**

Information Paper IP 123, produced by the Scientific Committee on Antarctic Research (SCAR), was the first paper to mention biological prospecting in the context of an Antarctic Treaty Consultative Meeting (IP 123 ATCM XXII, Lima, Peru 1999).

In that paper, under the heading of Life Sciences, SCAR said:

> At present there appear to be no provisions in the Antarctic Treaty to deal with exploitation of biological resources in the Antarctic, with the exception of fisheries. There have already been collections of micro-organisms for pharmaceutical purposes and a biological prospecting interest in the Antarctic is developing rapidly. The implications of biological prospecting, and the patenting of biological products, for biological research and conservation is of concern to the Working Group on Biology and the meeting agreed that these issues should be raised with SCAR and with CCAMLR.

IP 123 started a discussion that was followed up by the UK, which became the first Antarctic Treaty Consultative Party to bring bioprospecting up in a Working Paper (WP 43 ATCM XXV, Warsaw, Poland 2002).

It is noteworthy that it was a Working Paper and not an Information Paper and it was focused on the topic of biological prospecting, not just a mention of the activity within a report on broader issues. The paper made one recommendation to the Committee for Environmental Protection (CEP), which said:

> The UK therefore recommends that the CEP undertakes a thorough review of the issue of bioprospecting in Antarctica, with a view to advising the ATCM on potential implications.

After making that recommendation, the paper then includes a final section entitled Issues for Discussion, which says:

> In this regard the UK considers the following issues warrant particular attention: The potential conflict between the freedom of access to scientific information provided

(continued)

**Box 22.2** (continued)

for in Article III of the Antarctic Treaty, and the confidentiality that inevitably surrounds the commercial exploitation of bioactive material (i.e. patenting); Whether, and if so how regulation should be effected. ATCPs may wish to consider whether the provisions of existing international instruments might be drawn upon as a model for regulation in Antarctica (e.g. the 1992 Convention on Biological Diversity). The outcomes and implications of the 2002 World Summit on Sustainable Development may also have a bearing on the matter; What regulation my [sic] be required in respect of revenues derived from commercial exploitation of Antarctic species.

In the final report of the CEP it says:

The CEP concluded that the complexities and rapid developments in this field were strong reasons for the Antarctic community to be preemptive on this issue and that biological prospecting needed to be discussed during the next CEP meeting. The CEP, however, is not in a position to address all the problems. It was suggested that many issues require consideration by the ATCM. Members were encouraged to submit papers on biological prospecting for consideration at CEP VI.

Even without an internationally agreed legal definition, however, there is a general understanding of the steps involved in any bioprospecting activity and many countries have agreed a legal definition for use within their own national legislation (for example the USA, New Zealand and Australia). Jabour-Green and Nicol (2003) define four phases or steps in the process: sample collection; isolation, characterisation and culture; screening for pharmaceutical activity; and development of product, patenting, trials, sales and marketing.

The first phase of this, the sample collection, is the only phase currently being carried out in the Antarctic Treaty area. The rest of the process is undertaken in countries, usually at the home base of the scientist involved, so that the rest of the process is subject to the domestic laws of the particular country where the research is completed. Extracting a biological sample from Antarctica usually requires a permit. Such permitted activities are often brought to the attention of the Committee for Environmental Protection (CEP). However, once that permit is granted and a sample is collected and taken out of Antarctica, the scientist is free to do as he or she wishes with it, subject to the domestic laws related to the type of material in question.

Of particular interest to bioprospectors are organisms often referred to as 'extreme' biodiversity or extremophiles. These are living things which have adapted to Antarctic conditions, and so they are often good candidates for unique and useful biochemical activity that can be isolated in the lab and ultimately used in pharmaceutical, food, health or other products or processes. So, the initial target of a bioprospector is the biodiversity of a region, including plants, animals and microorganisms, in a range of environments. It is components of the diversity that are isolated, usually a chemical compound or enzyme. Bioprospectors are usually not interested in the organism as a whole since whole, living organisms cannot themselves be legally patented.

Chemists have found that the greater the number of species studied, the bigger the likelihood of a bioprospecting 'hit' (Munro 2003). Therefore bioprospecting efforts are often linked with scientific research efforts to understand the biodiversity of an area (Farrell and Duncan 2003). While Antarctica's known terrestrial biodiversity is relatively low, new organisms are constantly being identified. The Antarctic marine environment is a particularly rich area of Antarctic biodiversity. The recent project on the Census of Antarctic Marine Life (CAML) identified no less than 6000 different species living on the seafloor, with approximately half of these being unique to the Antarctic region (British Antarctic Survey 2010).

But it is not only the cold, dark areas of Antarctica where extremophiles can be found (Box 22.3). The hot spots around volcanic areas such as Mount Erebus are likely to be biodiverse regions. The scientific goal of penetrating into any of the Antarctic subglacial aquatic environments is often about learning about such pristine environments, but it is also about determining the form of life contained in isolated subglacial lakes, assuming extreme biodiversity is likely to be found there (Lake Ellsworth Consortium 2007). Such extremophiles, likely unique to the subglacial lakes, are of particular importance to bioprospectors. Such organisms thrive in what we would consider to be harsh or impossible living conditions because they have developed unique biological coping strategies (Sample 2004). Often it is these unique coping strategies that may be isolated and developed to address a specific target or purpose. The further we penetrate into Antarctic environments, the more likely it becomes that bioprospecting is going to be an issue for the Antarctic Treaty System.

**Box 22.3: An Extremophile . . . Who Me?**

Not all organisms experience the Antarctic environment as harsh. They thrive in the extreme environmental conditions of the area. Extreme environments are defined as those where physical (e.g. temperature, radiation, pressure) and chemical (e.g. salinity, acidity) conditions approach or exceed the tolerances for life. Some organisms can thrive under these conditions and do not survive outside them.

Examples on Earth include microbes living in scalding hot springs, hypersaline waters, the base of ice sheets, the deep Earth (to depths of greater than 1.6 km).

## 22.3 What Bioprospecting Is Not

What is clear is that bioprospecting is not the same as fishing, nor can it be likened to mining. This requires an explanation, since it has often been said that the current legal document which regulates Antarctic fishing and the legal document on

Antarctic mining, which was written but never put into force, could be used by Antarctic Treaty parties to govern Antarctic bioprospecting activities.

In the context of fishing, the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) has as its purpose conservation that includes 'rational use' (Chap. 21), but the fishing industry is looking for a significant quantity of a particular species in order to sell that amount of fish at a set price on global commercial markets. Here, the target of the fishing activity is known, usually permits are applied for and given for the extraction of a certain total weight of fish and the price of the harvest is known as the product goes to market. In this sense, fish from the Antarctic, including even those particular species of fish only found there, are the same as any other type of commercially marketed fish – they are a source of protein with a set market price that is known when the species is harvested.

In the context of mining, while mining does not involve extraction of a living resource, bioprospecting is often referred to in the same sort of way as mining, even though mining is more akin to fishing than to bioprospecting. Mining is the extraction of a specific mineral resource, often under permit, sometimes but not always up to a set amount of tonnage, which is sold on the commercial market at a known price. Like fishing, minerals that might be extracted from Antarctica (coal for example) are no different from the same type of mineral that might be extracted elsewhere in the world, except of course when we consider minerals that might be of a particularly high concentration or content. The fact that the coal comes from Antarctica does not make it any more valuable than coal from elsewhere in the world.

When biological prospectors collect Antarctic organisms or extract biodiversity from a water or soil sample they have collected, they often have no firm idea what their target is. They also have no idea whether what they have collected will yield no commercial result or if it will, eventually, make them a billionaire. Bioprospecting requires more than collection; there is a value-added component to the activity that is not found with fishing and mining.

From an environmental impact perspective, human activity related to biological prospecting can be treated the same as other human activity in Antarctica. Collection of a sample may often involve small quantities of biodiversity on the milligram to gram range – these are relatively tiny amounts that would appear to have no significant environmental consequence. In the later stages of biological prospecting, if a novel chemical or enzyme shows promise and is isolated from Antarctic biodiversity, chemists are usually able to synthesise the novel molecule, meaning further extraction of the organism is not required in order to take a product or process to market.

But beyond these generic environmental concerns, it has been argued that specific rules governing the use of Antarctic biodiversity are needed (Hemmings and Rogan-Finnemore 2005).

## 22.4 Is Antarctic Bioprospecting Legal?

For the past 50 years, Antarctic Treaty parties have been careful to consider the type of human activity that should be allowed to take place in Antarctica. The Antarctic Treaty promotes the area for peaceful purposes only and for international cooperation in scientific investigation. Therefore, scientific activity is not only allowed, but it is given primacy. Other peaceful activities are also allowed, specifically including tourism (recognised in the Environmental Protocol) and fishing (recognised in the CCAMLR).

Bioprospecting meets the criteria of being a peaceful use of Antarctica, and in most cases it supports the scientific cooperation objective found in Articles II and III of the Antarctic Treaty, since the activity is carried out principally by scientists working within and with support from national Antarctic programmes. We have noted already, that collection activities related to bioprospecting also do little damage to the Antarctic environment. So, since it is not specifically banned in any of the legal documents of the Antarctic Treaty System, it therefore must be an activity that is legally allowed under the current provisions of the Antarctic Treaty System.

## 22.5 Is Bioprospecting in Antarctica Ethical?

While arguments can be made and won indicating that bioprospecting in the Antarctic Treaty area is currently legal within the Antarctic Treaty System, some have argued that the activity raises important ethical considerations (Graham 2005). Two of these ethical considerations arise firstly around the free availability of information and results from Antarctica, an obligation found within the Antarctic Treaty System itself, and secondly around the idea that Antarctic biodiversity is the common concern of all humankind. This second obligation arises from outside the Antarctic Treaty System.

### *22.5.1 The Antarctic Treaty Article III(1)(c) Obligation*

Countries that have signed the Antarctic Treaty have agreed to a number of obligations that the treaty contains. One such obligation is in Antarctic Treaty Article III, paragraph 1, section c, that says:

> In order to promote international cooperation in scientific investigation in Antarctica, as provided for in Article II of the present Treaty, the Contracting Parties agree that, to the greatest extent feasible and practicable . . . scientific observations and results from Antarctica shall be exchanged and made freely available.

Until relatively recently, this obligation seemed fairly straightforward and was easily met. Scientists, as part of national Antarctic programmes, were eager to publish their observations and results, since publication was a recognition of good science and, especially recently, had become a requirement for further science funding from governmental sources. With the emergence of privately-funded (or at least partially privately-funded) research activity in Antarctica, however, there is not always a willingness to publish observations and results. This is especially true in cases where observations and results might include commercially sensitive information, the availability of which might impact the economic benefit for the private funding source.

Also, in the context of bioprospecting, there has been the view that trade secrets and intellectual property (IP) rights in the form of patents and copyright might lead to a situation where the obligation to freely exchange results is not being met. While intellectual property rights vary globally, patents are the primary means of granting exclusive use of a novel product or process to an inventor for a limited period of time. In a way, patents are a reward to the inventor which allows for the exclusive use of the invention for a period of time in order to capitalise on the invention, so as to recover costs related to the invention or to generate some sort of payback for the work. Some have argued that the establishment of a patent over a product or a process that was initially derived from Antarctic biodiversity limits the free availability of information and results, and therefore, is in breach of at least the spirit of the Article II.1.c. obligation (Connelly-Stone 2005).

Many patents related to Antarctic materials already exist. In fact, components of international law outside the Antarctic Treaty System, such as the Agreement on Trade-Related Aspects of Intellectual Property Rights, contain provisions that imply it would be illegal to prevent granting a patent simply because the invention is related to, or is originally sourced from the Antarctic. But a patent will only be granted when specific criteria are met, including that the novel product or the process must be described with adequate specification and disclosure and this description is made publically available. Connelly-Stone (2005) notes:

> The grant of a patent for an invention provides the owner with a right to exclude others from making, using or selling the patented invention during the term of the patent. In return for the grant of a patent, the owner must make public a complete description of the invention.

It may be that this requirement and the accompanying disclosure of the new product or process fulfills the obligation in Article III of the Antarctic Treaty. Consideration of this issue is continuing via many mechanisms. Within the Antarctic Treaty System, treaty parties have established and participated in informal intercessional contact groups and ad hoc working groups as one way to further discussion of the issues.

### 22.5.2 The Common Concern of Humankind and Benefit Sharing

The period after the Second World War saw international law addressing sovereignty, or rights of ownership, over natural resources. The United Nations General Assembly promoted the concept, which was advocated by developing countries that sought to secure benefits from their own natural resources. The Convention on Biological Diversity (CBD) and the more recent Nagoya Protocol both reaffirmed this sovereign right over resources. While environmental awareness has introduced a balance of duties along with sovereign rights, the general principle of a state's sovereignty over natural resources remains. Put another way, international law currently provides that it is the sovereign state that has the right to exploit its natural resources, subject to certain obligations relating to environmental protection, and it is the sovereign state which receives the benefit from the use of those resources.

For the Antarctic Treaty area, this presents a challenge, since the area is subject to multiple and conflicting territorial claims which have been put on hold by the Antarctic Treaty but have not been fully and finally resolved.

You will recall the discussion on Antarctic territorial claims in Chap. 16 and also the discussions regarding the operation of Article IV of the Antarctic Treaty. This leaves us with a situation, as long as the Antarctic Treaty is in force, where there is no internationally recognised sovereign or sovereigns over Antarctic territory, but at the same time, seven nations continue to maintain they have a legitimate claim to Antarctic territory or portions of that territory. Furthermore, two additional countries reserve the right to make claims should they choose to do so in the future.

In 1957, when the Antarctic Treaty was written, it was recognised that in order to ensure that the area would remain peaceful, the sovereignty issue had to be somehow addressed, and so provisions of the Antarctic Treaty represent substantial abatements of the normal attributes of sovereignty. These abatements include granting freedom of scientific investigation to anyone, anywhere in Antarctica, allowing the building of a scientific base or bases anywhere in Antarctica, the prohibition of military activity south of 60°S and inspection rights.

The Antarctic Treaty and the operation of the Antarctic Treaty System means that permanent sovereignty over Antarctic resources does not rest with the claimant states as individual sovereigns over any part of the Antarctic Treaty area. While the consultative states act as a group making decisions concerning the region, they do so within the confines of the Antarctic Treaty System. The Antarctic Treaty parties maintain that they have the right to regulate Antarctic resource use under Article IX of the Antarctic Treaty, and in the case of biological material reaffirmed in Resolution 7 (2005) and Resolution 6 (2013) that the Antarctic Treaty System is the appropriate framework for such management and consideration of its use. Therefore the model of permanent sovereignty over natural resources cannot strictly apply to the natural resources of the Antarctic region and, while the CBD supports international law and reaffirms a sovereign state's right to control its natural resources, there are emerging views regarding property rights associated with resources that oppose this model and which, some argue, may better suit the Antarctic situation. Importantly, for the purposes of any discussion on Antarctic bioprospecting, there is the idea of common property or common pool resources that are said to be located in resource domains known as commons or common areas (Joyner 1988).

The commons idea carries with it an implication that any resources found in the commons area are there to be used by anyone and should be shared with everyone, including even those countries which may not have the capacity to be involved in the extraction and value-added activity. The commons idea would also mean that any benefit acquired from the use of Antarctic biodiversity should be shared amongst all humankind, not for the benefit of the inventor or for the Antarctic Treaty party countries alone.

This represents a challenge to any Antarctic bioprospecting considerations and it is not an easy discussion to have within the confines of the Antarctic Treaty System. Even when discussion takes place, there are varying views on how this concept can be considered, and, in the Antarctic Treaty System, where consensus is essential to develop a solution, consensus on bioprospecting would be difficult to achieve. Still, the idea lives on and there are those who advocate for a publically viewable database which would contain information on all known Antarctic biodiversity, so that even those who do not have the capability to participate in the sample collection phase of Antarctic biodiversity would still have free and open access to organisms in the database that might be developed into a novel product or process (Table 22.1).

## 22.6 The Future of Antarctic Bioprospecting

To predict the future of Antarctic bioprospecting we have to look at the past. To date, there are many patents in relation to inventions that somehow involved Antarctic biodiversity. Increasingly, we see in annual reports to the Antarctic Treaty that countries are involving their scientists in Antarctic biological prospecting activities. As a result, there have been several recent bioprospecting success stories coming out of Antarctica.

It is likely that such success stories will be more and more common. Since product development takes many years, Antarctic samples collected in the 1980s and 1990s are likely to be reaching the end process of any development. New technologies mean new areas of Antarctica are opening up, where new biodiversity is likely to be discovered. Capacity is also increasing with more and more countries engaging in scientific activity in Antarctica.

So, bioprospecting in the Antarctic Treaty area is likely to continue. Unless a particularly influential Antarctic Treaty country opposes the activity, then, it will likely continue in the same manner in which it is happening now. There seems little chance that external pressure on the Antarctic Treaty System to ban activity related

**Table 22.1** History of discussions about bioprospecting in the Antarctic Treaty area

| |
|---|
| **Information Paper 47** (New Zealand) and **Information Paper 75** (UK and Norway) were both presented to the CEP VI and are noteworthy in that both stress that the papers are not necessarily the views of the countries which submitted them. |
| At the ATCM XXVII (Cape Town, South Africa 2004) **Information Paper 106** (UNEP) was introduced under its own agenda item, ATCM Agenda Item 17 Biological Prospecting in Antarctica. |
| At the ATCM XXVIII (Stockholm, Sweden 2005) **Information Paper 8** (Spain) focused on providing information principally on marine bioprospecting, while **Information Paper 93** (UNEP) highlighted developments in five international fora; and **Working Paper 13** (New Zealand and Sweden) proposed a draft resolution, which was adopted as Resolution 7 (2005). |
| At the ATCM XXIX (Edinburgh, Scotland 2006) **Information Paper 13** (France) **Information Paper 112** (Argentina) and **Information Paper 116** (UNEP) were submitted. |
| At the ATCM XXX (New Delhi, India 2007) **Information Paper 67** (UNEP) and **Working Paper 36** (Netherlands) were presented. After a lengthy discussion on how to proceed and terms of reference, the meeting agreed to establish an informal open-ended web-based Intersessional Contact Group (ICG) to be chaired by the Netherlands. |
| At the ATCM XXXI (Kyev, Ukraine 2008) **Working Paper 4** (Netherlands) and **Working Paper 11** (Belgium) were presented. The final report notes that the ATCM should continue to monitor the issue. |
| At the ATCM XXXII (Baltimore, USA 2009) **Working Paper 1** (Belgium, Brazil, Bulgaria, Finland, France, German, Netherlands and Sweden) and **Working Paper 18** (Australia and New Zealand) proposed a draft resolution, which was adopted as Resolution 9 (2009). |
| The same meeting discussed **Working Paper 26** (Netherlands, Belgium, Bulgaria, Finland, France, Germany, Spain and Sweden), **Working Paper 49** (rev.2, Chile), **Information Paper 65** (SCAR), **Information Paper 70** (Sweden, Belgium, Finland, France, Netherlands and Spain), **Information Paper 84** (Argentina), **Information Paper 91** (UNEP) and **Information Paper 115** (Brazil). Given the importance and complexity of the issues associated with biological prospecting, the meeting agreed to convene an Intersessional Contact Group to consider the following issues: definitions, scope, status, access, environmental impact, commercialisation, benefit-sharing, giving advance notice of and reporting on biological prospecting activities, freedom of scientific investigation, free exchange of scientific information, applicable intellectual property regimes, merits of further regulation, and any other issues identified by the ICG. |
| At the ATXM XXXIII (Punta del Este, Uruguay 2010) **Working Paper 2** (SCAR), **Working Paper 13** (Netherlands), **Working Paper 24** (Netherlands), **Information Paper 96 (**Belgium and UNEP), **Information paper 125** (Ecuador) were presented. While some parties considered the concepts in WP 24 might provide a basis for future discussion, others thought they were neither sufficiently defined nor was there consensus on the concepts to allow for an agreement based on these points. |
| At the ATCM XXXIV (Buenos Aires, Argentina, 2011) **Information Paper 16** (Argentina) and **Information Paper 62** (Netherlands) were presented. |
| At the ATCM XXXV (Hobart, Australia, 2012) **Information Paper 22** (Belgium), **Information Paper 63** (Netherlands, Belgium, Finland, Sweden, UNEP) and **Information Paper 84** (Romania) were presented. |
| At the ATCM XXXVI (Brussels, Belgium, 2013) **Working Paper 48** (Belgium, Netherlands, Sweden), **Information Paper 18** (Argentina), **Information Paper 22** (Belgium, Netherlands) and **Information Paper 64** (ASOC) were presented. |

to biological prospecting and to share any benefits with those countries not involved in Antarctic biological prospecting activity would have an effect. This may change if environmental damage from the activity occurs, since environmental concerns were what stopped the progression of allowing mining in the Antarctic Treaty area. The management implications of a changing Antarctica, the increase in tourism activity and diversity of that activity, the impact on Antarctic biodiversity from fishing and the risk of introduction of non-native species are the more pressing issues within the Antarctic Treaty System right now. With such lofty issues to challenge the system, it seems that Antarctic biological prospecting will not take a high place on the Antarctic Treaty meeting agenda but will continue to be discussed and will continue to interest scientists for the near future.

## References

British Antarctic Survey (2010) Understanding global climate change through new breakthroughs in polar research. ScienceDaily, retrieved 22 Sept 2010 from http://www.sciencedaily.com/releases/2010/02/100218110933.htm

Connelly-Stone K (2005) Patents, property rights and benefit sharing. In: Hemmings A, Rogan-Finnemore M (eds) Antarctic bioprospecting. Gateway Antarctica Special Publication, Christchurch, pp 60–97

Farrell R, Duncan S (2003) Uniqueness of Antarctica and potential for commercial success. Paper presented at the bioprospecting in Antarctica Workshop, Christchurch, 7–8 Apr 2003

Graham A (2005) Environmental, ethical and equity issues. In: Hemmings A, Rogan-Finnemore M (eds) Antarctic bioprospecting, vol 0501, Gateway Antarctica Special Publication series. University of Canterbury, Christchurch, pp 41–68

Hemmings A, Rogan-Finnemore M (2005) Antarctic bioprospecting, vol 0501, Gateway Antarctica Special Publication series. Gateway Antarctica, Christchurch

Jabour-Green J, Nicol D (2003) Bioprospecting in areas outside national jurisdiction: Antarctica and the Southern Ocean. Melbourne J Int Law 4(2):76–78

Joyner CC (1988) Governing the frozen commons: the Antarctic regime and environmental protection. University of South Carolina Press, Columbia

Lake Ellsworth Consortium (2007) Biological analysis. In: Exploration of Ellsworth Subglacial Lake: a concept paper on the development, organisation and execution of an experiment to explore, measure and sample the environment of a West Antarctic subglacial lake. Rev Environ Sci Biotechnol 6:161–179. doi:10.1007/s11157-006-9109-9

Munro M (2003) Biodiversity and bioprospecting in Antarctica. Presentation delivered at the Graduate Certificate in Antarctic Studies Programme, University of Canterbury, Christchurch, 9 Dec 2003

Rothwell D (2005) Bioprospecting in Antarctica under the Antarctic Treaty System. In: Hemmings A, Rogan-Finnemore M (eds) Antarctic bioprospecting, Gateway Antarctica Special Publication series number 0501. University of Canterbury, Christchurch http://www.anta.canterbury.ac.nz/documents/

Sample I (2004) Cold rush threatens pristine Antarctic. The Guardian (UK), 2 Feb 2004, The Week

# Chapter 23
# The Question of Mining

## Geological Resources in Antarctica

**Yvonne Cook and Bryan Storey**

**Abstract** Long before the discovery of Antarctica, a landmass was assumed to exist at the bottom of the world, and it was widely expected that this land would contain a wealth of resources in the broadest sense. After penetration of the Southern Ocean and discovery of the continent, a succession of explorers and scientists returned from Antarctica with increasing knowledge of its geology, and proposing oil, coal and metals as potential resources. Since the 1950s, debates concerning the feasibility and desirability of resource extraction have come and gone and have reflected the economic, political and social concerns of the day. Yet despite research improving geological knowledge of the continent, and advances in remote sensing and other field technology, few data are available for use to support or refute the various positions.

**Keywords** Mineral resources • Hydrocarbons • Mining • CRAMRA • Prospecting

## 23.1 Antarctica's Potential Mineral Wealth

The 1980s saw considerable speculation about the potential for mineral and hydrocarbon extraction at the same time as the Antarctic Treaty parties were negotiating an agreement permitting controlled mineral resource activity (CRAMRA, Chap. 16). This agreement was never ratified and was soon superseded by an indefinite ban on mineral-resource activities, resulting in a lull in the debate on Antarctic mining. Despite this ban, high commodity prices and improved extraction technologies have again put Antarctic resources in the spotlight. As quotes from the 1980s and the 2000s indicate (Boxes 23.1 and 23.2), there are conflicting views on whether mineral and

Y. Cook
School of Earth and Environmental Science, James Cook University, Townsville, QLD, Australia
e-mail: yvonne.cook@jcu.edu.au

B. Storey (✉)
Gateway Antarctica, University of Canterbury, Christchurch, New Zealand
e-mail: bryan.storey@canterbury.ac.nz



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_23

hydrocarbon exploration and extraction could or should proceed. The reasons for and against are political, environmental and philosophical as well as economic, and have not changed substantially over the last 30 or more years.

**Box 23.1: Quotes from the 1980s**

Probably no one will go down to Antarctica for economic reasons; however, they may go down for political reasons. Garrett, in Alexander and Hansen, 1984, p. 217

Someone eventually may take oil out of Antarctica, but I doubt that such petroleum operations will be cost effective. (1983)

As remote as it may seem now, Antarctica may fool us all and yield some real whopper oil fields. You never know until you look. (1983)

"Anywhere else in the world, oil companies would be swarming all over this deposit." Stephen Eittreim, US Geological Survey in Anderson, 1985. Eittreim was referring to seismic data collected in the Ross Sea region during the US Geological Survey's Operation Deep Sweep in 1983.

The big hurdle for commercial interests in Antarctic minerals will lie between exploration and exploitation .... Prospecting and even exploration could be expected to proceed .... Oil prices are cyclical and volatile and money spent today might prove to be a very small investment for knowledge that might have a much higher value in years to come. Barry Fowke, New Zealand Ministry of Energy, in Dominion, September 29, 1987

A minerals regime will facilitate a minerals scramble rather than regulate it. . . . it is a framework that would enable them [the Antarctic Treaty nations] to retain the results of expensive exploration secure from the jealousies of other operators and/or other nations. Cath Wallace, Convenor for the Antarctic and Southern Ocean Coalition; Dominion, October 6, 1987

"Ending six years of difficult negotiations, 33 nations have agreed to open all of Antarctica to regulated development of its oil and mineral resources." And an industry spokesman said "it could provide major resources for the global economy". Shabecoff in New York Times, June 1988, pp 1A, 5A

**Box 23.2: Quotes from the 2000s**

We can really realise that that's the game and play it in an environmentally sustainable way, the best way we can, or we can stick our head in the snow, so to speak, thinking the world's never going to change, and it'll all just change all around us. And then our purpose down there will look a bit peculiar. We'll have, you know, a scientific base and romantic voyages while other people are flying in and flying out miners.

What you have to ask is: do I turn my head and allow another country to exploit my resource, and do I just walk away from my territorial integrity of that claim, or do I position myself in such a way as they can't exploit it, or do I position myself in such a way as I'm going to exploit it myself before they get there? Barnaby Joyce, Australian Senator, Monday, 1 May, 2006

(continued)

**Box 23.2** (continued)

> Anyone that wanted to challenge there being a pristine environment in the Antarctic would find a very strong opponent in Australia. One of the great achievements for the Labor government was to be able to preserve the Antarctic for future generations. Tony Burke, member of Australian Parliament, Fri May 6, 2006

> Chinese-language polar-science discussions are dominated by debates about resources [in the broadest sense] and how China might gain its share. Anne-Marie Brady, in Asian Survey Vol. 50, No. 4, July/August 2010

> There is now only one frontier province left [for oil exploration] and that is Antarctica. I hope it will not happen because that would create enormous difficulties but when you have the enormous price increase that I can foresee . . . governments and companies will want to find oil anywhere. Dr Ali Samsam Bakhtiari, former senior adviser for the National Iranian Oil Company in Tehran, July 13, 2006

> The petroleum potential of Antarctica is lower than that of any other continent, by an order of magnitude. You would need a 10 billion barrel field . . . to actually justify putting in the resources. The point is really if anyone did it for political reasons but the economics just don't stack up at all. David McDonald, Feb 2011, lecture for the Bureau of Economic Geology, Texas

Much of the speculation about the potential of Antarctica to yield valuable resources appears provocative, designed to bring the matter to general attention and to test public and political opinion. However, there are currently no mineral or hydrocarbon resources or reserves in Antarctica (Box 23.3), and any suggestions to the contrary are conjecture. Nevertheless, lack of detailed knowledge tends not to dampen the optimism of mining proponents. The nature of exploration is such that an enthusiastic, upbeat and positive approach is prerequisite.

**Box 23.3: Definition of Terms, Summarised from Miskelly (2003)**

**Mineral Resource** An occurrence of material of intrinsic economic interest in or on the Earth's crust (a deposit) for which there are reasonable prospects for economic extraction. The assessment is based on geological extrapolation and statistical computations. Mineral resources are subdivided, in order of increasing geological confidence, into inferred, indicated and measured. Portions of a deposit that do not have reasonable prospects for eventual economic extraction are not included. Used generally on national or global scales, such as the world's oil resources, or Chinese coal resources.

**Mineral Reserve** The economically mineable part of a measured or indicated mineral resource. Appropriate assessments have been carried out and include consideration of mining, metallurgical, economic, marketing, legal, environmental, social and governmental factors. These assessments demonstrate at the time of reporting that extraction is reasonably justified. Mineral reserves are subdivided in order of increasing confidence into probable and proved mineral reserves.

The following is a basic summary of Antarctic geology as it relates to potential resources and issues associated with extraction. For details on legal issues see Chap. 24 and for a background on the Antarctic Treaty in relation to mining see Chap. 16.

## 23.2 Antarctic Treaty Considerations

Minerals activities are banned indefinitely in Antarctica (the treaty area) under the Protocol on Environmental Protection to the Antarctic Treaty. However, a consensus decision, or, from 2048, a majority decision, could see changes made to the protocol that may permit mining and hydrocarbon extraction in the future (Chap. 24). As of 2013, there are no known plans by any Antarctic Treaty nation to seek changes to the protocol.

The Antarctic Treaty System requires high standards of environmental practice for all operations in Antarctica. Mining and hydrocarbon extraction present risks over and above those of scientific research and tourism (Holdgate and Tinker 1979; Dugger 1978), and significant impacts on the Antarctic environment (Ohio State University 1977; Rutford 1986) could result, particularly if mishaps should occur (Weiss 1995). The Antarctic Treaty requires free sharing of scientific information. Much of the information gained during any future prospecting and exploration is likely to be commercially sensitive, and there may be reluctance to put this information in the public domain. National and legal issues would also need addressing (Chap. 24). It may be possible that, should mineral resource activities be permitted in the future, there would be a revival and modification of the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA), which specifically addresses these concerns (Chap. 16).

Opportunities for mineral extraction outside the constraints of the treaty are limited to nations that are not signatories of it, and to companies that are domiciled in non-signatory states. However, any nation or company acting in a manner contrary to the treaty should not expect to use infrastructure or resources of signatory states (whether in Antarctica or not) for such activities and will likely come under considerable international pressure from treaty parties.

## 23.3 Logistical Issues

The environment will provide some obstacles to mineral and hydrocarbon extraction (Dugger 1978). Operations in Antarctica would encounter poor visibility, mobile seasonal sea ice and complete darkness for some months of the year, along with poor coastal access, harbour and port facilities. The scale of many difficulties in Antarctica is significantly greater than those in the Arctic or other inhospitable regions. Most significant are the intense cold, moving ice streams and glaciers, immense thickness of ice on land, strong winds, rough seas, enormous drifting icebergs and deep water over the continental shelves. In addition, operations would be extremely remote from infrastructure and inhabited places and a very long distance from commercial markets. If extraction were to take place, there would be significant technical challenges and extremely high costs. Any deposits would have to be particularly rich to be economic.

## 23.4 General Geological Considerations

Antarctica has a long geological history involving a variety of tectonic processes (Chaps. 2 and 3), many of which have had the potential to result in a range of mineral deposits. Despite this, geological research to date has identified insignificant levels of mineralisation the introduction of minerals to the point of a potential ore deposit), and there have been no detailed searches for commercial deposits by resource geologists.

Elsewhere in the world, weathering and erosion of a deposit can concentrate minerals sufficiently to produce a reserve. Examples include bauxite (aluminium ore), some iron ores and some nickel bearing deposits. Such secondary processes are unlikely to be of significance in Antarctica because temperatures are too low for appropriate weathering, and because there is minimal surface water to enable leaching. Moreover, any secondary deposits are likely to be destroyed by glacial movement.

Heavy metals and minerals that are eroded, transported and deposited by streams and rivers can indicate the parent body and potential reserves upstream. Elsewhere, these deposits are important for prospecting, but in Antarctica surface rivers are few, small, seasonal and have very small catchments. The continent's largest rivers are under ice (Chap. 5), making access and sampling extremely difficult. Under these conditions, the parent body would need to be found without the benefit of sedimentary indicators.

## 23.5 From Exploration to Extraction

After regional geological exploration, several stages are required to reach the point of mineral extraction. Detailed observations are needed to identify mineral occurrences and local concentrations, and then these sites are examined in greater detail in the hope that deposits can be revealed or inferred. Finally, exploratory drilling is usually required to prove the deposit and assess its commercial viability.

### 23.5.1 Antarctic Geology in Relation to Potential Resources

East Antarctica, the Transantarctic Mountains, the Antarctic Peninsula and the offshore sectors of the continent are large-scale geological provinces of the Antarctic region that provide a basis for launching geological research and potential exploration. Due to extensive ice cover, proposals for sites of possible mineral deposits are based on examination of landmasses that were once contiguous. East Antarctica is inferred to have geological similarities with the other Gondwana continents (Runnells 1970) and regions of South America, Africa (particularly South Africa and Zambia), Australia and the Indian subcontinent that contain resources of iron, gold, uranium, copper, chromium, cobalt, lead, nickel, zinc, silver, platinum group minerals and diamonds. Iron and coal (see below) have been discovered in East Antarctica. However, direct correlations of mineral rich regions across the Gondwana continents should be made with caution. Mineral deposits are restricted in spatial extent, and although they form in specific tectonic environments, they may not be ubiquitous in those environments. Precambrian cratons generally have provided a significant quantity of the world's mineral resources, and comparison with cratons elsewhere on Earth may be equally informative as specific correlations with other Gondwana continents.

Mineralisation in subduction zones (Chap. 2) generally might inform the potential economic geology of the Peninsula. Along the South American Andes, rich copper ores were generated locally. On the basis of geological association, the Antarctic Peninsula has been put forward as a potential copper province. Some copper bearing minerals have been found on the Peninsula, but in only very small quantities. Other reported mineral occurrences include iron, lead, zinc, tin and silver.

Even though the Transantarctic Mountains contain some of the most-exposed sites in Antarctica, extensive mapping has failed to reveal anything of significant interest visible at the surface. The various igneous rocks that were emplaced during the Ross Orogeny have potential for mineralisation, but the Dufek Massif, in the Pensacola Mountains, is the most promising, and coal is present locally (see below).

The continental shelf around Antarctica formed during the breakup of Gondwana and is relatively deep and narrow compared to continental shelves elsewhere in the world. Its great depths would present some technical challenges for extracting seafloor deposits. The oldest sediments deposited on the seafloor go back to the time when the continent was warmer and vegetation flourished. At that time, any organic material would have been incorporated with the sediments to now be a potential source of hydrocarbons. The seafloor of the Southern Ocean has also given rise to concentrations of manganese and iron.

### 23.5.2 *Terrestrial Deposits*

Much of the world's iron is recovered from banded iron formations found in Precambrian sedimentary rocks. Banded iron formations comprise many thin layers of iron minerals (magnetite and hematite), alternating with bands of iron-poor shale and chert. The banding is assumed to have formed underwater due to cyclic variations in oxygen in a Precambrian environment very different from today's.

In East Antarctica, discontinuous banded iron layers, up to 70 m thick, have been discovered in the Price Charles Mountains. These can be traced for 180 km under the ice using remote sensing to map the layers on the basis of their magnetic properties. However, these rocks contain only about 35 % iron, far less than the 60 % or more mined elsewhere in the world. Boulders of banded iron are also widespread in glacial debris of East Antarctica and indicate the existence of more banded iron under the ice.

Coal is found in East Antarctica and the Transantarctic Mountains and has formed from vegetation growing in the Permian and Triassic periods (Isbell and Cúneo 1996; Holdgate et al. 2005). In the Transantarctic Mountains, Triassic coal beds are discontinuous, generally thin, although seams up to 7 m thick are found, and groups of up to 14 seams may be present. The coal is very low quality with high ash and moisture content (Rose and McElroy 1987).

In the Prince Charles Mountains coal seams are Permian in age. These seams are thicker, more continuous and contain bituminous coal of good quality.

The Dufek Massif is a Middle Jurassic (180 million years of age) igneous body several kilometres thick which formed by slow cooling and crystallisation, allowing other minerals to settle in layers to form gabbro. It is one of the largest layered intrusions of its kind in the world, and similar sized intrusions elsewhere contain reserves of at least one metal. As with many igneous bodies, the Dufek Massif has yielded very small concentrations of iron, nickel, chromium, copper, vanadium, platinum and similar minerals, palladium, rhodium, osmium and iridium, but nothing of any economic significance (de Wit 1985; Beike and Rozgonyi 1990). It is speculated that areas of mineralisation may be present in the massif beneath the ice.

### 23.5.3 *Ocean Floor Deposits*

Manganese and iron oxides, and more valuable elements such as copper, nickel and cobalt are concentrated to form pavements and nodules on the seafloor. Nodules and pavements are not widespread under the Ross Sea, but occur in greater quantities on the floor of the Southern Ocean and extend north into the south Pacific, Atlantic and Indian oceans (Watkins and Kennett 1977). In the more hospitable areas of the world, it has not yet proved to be economic to remove this material by seafloor mining or dredging, and the Southern Ocean is likely to be one of the last locations considered for such activity.

Not much is known about whether the sediments that fill basins on land could hold reservoirs of hydrocarbons, because they are covered by thick ice and have not been well delineated. These basins are unlikely to be targets for exploration because, in general, inland conditions are not favourable for the preservation of oil and gas.

Most oil and gas occurs in geologically young offshore marine rocks, (160 million years or younger), and while older deposits may exist, they are thought to be rare. Oil formed on the other Southern Hemisphere continents during the breakup of Gondwana is of lesser quality than that found in the Northern Hemisphere. The rift basins of the Ross and Weddell seas are extensive enough to host large accumulations of oil or gas, and one of the theoretically most promising areas includes the Weddell Sea sedimentary basins on the eastern side of the Peninsula (McDonald and Butterworth 1990). However, this is the site of persistent ice cover, is one of the more inhospitable regions in Antarctica, and the existence of oil and gas accumulations is unproven.

In the 1970s, scientific drilling was undertaken in the Ross Sea by the Ocean Drilling Program and Deep Sea Drilling Project, and traces of ethane and heavier hydrocarbons were found. Around the rest of Antarctica, more than 150,000 km of multichannel seismic reflection data have been collected since 1978, but the locations of data collection have been dictated by environmental and logistical constraints, and no comprehensive oil or gas exploration has been conducted. There has been no attempt at commercial drilling, and there are large areas of the seafloor for which almost nothing is known.

However, estimates of 19 billion barrels of crude oil and 106 trillion cubic feet of natural gas have been made for Antarctica (Kingston 1991; see Boxes 23.1 and 23.2), and the US Department of the Interior suggests that the Antarctic continental shelf could contain tens of billions of barrels with the most prospective areas being the Ross Sea, Weddell Sea, Bellingshausen Sea, Scotia Sea and under the Amery Ice Shelf. There is very high probability that oil and gas deposits exist offshore from Australia's Davis and Mawson bases (see Boxes 23.1 and 23.2).

## 23.6 The Bigger Picture

The exploitation of Antarctic resources depends on many geological and economic unknowns, and until these are adequately identified and quantified, any forecasts will remain speculative. In addition to logistical expenses, the economics of resource extraction depend on variables such as the costs of renewable power, of developing alternative products, and of recycling or extracting the product elsewhere. Decisions based on non-economic or political factors, such as war, the wish to secure emergency resources or to demonstrate extraction capability, may lead to the endorsement of mining operations in Antarctica, regardless of cost. However, there seems to be little appetite for such actions at present.

Far more geological data are needed before reserves and resources can begin to be defined, and the processes of mining and extraction will not happen until quite some time in the future, if they are to happen at all. Speculation is of no value in furthering the debate on whether extraction could or should be a goal in Antarctica; only with detailed knowledge of the geology can rational discussions on mineral and hydrocarbon extraction in Antarctica be held.

## References


The following list includes articles published as long ago as the 1970s. While technology has advanced and the economic situation has changed since, the issues themselves remain relevant.

Explanatory Notes For The Mineral-Resources Map Of The Circum-Pacific Region Antarctic Sheet 1:10,000,000, US Department of the Interior, US Geological Survey, To Accompany Map Cp-47 Cirum-Pacific Council Energy And Mineral Resources 1998, for a list of mineral occurrences.

Beike DK, Rozgonyi TG (1990) Mining the Dufek Intrusion Antarctica – engineering and economic factors. Int J Min Geol Eng 8:67–77

de Wit M (1985) Minerals and mining in Antarctica. Oxford University Press, Clarendon, UK, 127pp

Dugger JA (1978) Exploiting Antarctic mineral resources – technology, economics, and the environment. Univ Miami Law Rev 33(2):315

Holdgate MW, Tinker J (1979) Oil and other minerals in the Antarctic. The environmental implications of possible mineral exploration or exploitation in Antarctica. Report of a workshop sponsored by the Rockerfeller Foundation and held at the Foundation's Study and Conference Center, Bellagio, 5–8 March, 1979

Holdgate GR, Mcloughlin S, Drinnan AN, Finkelman RB, Willett JC, Chiehowsky LA (2005) Inorganic chemistry, petrography and palaeobotany of Permian coals in the Prince Charles Mountains, East Antarctica. Int J Coal Geol 63(1–2):156–177

Kingston J (1991) The undiscovered oil an d gas of Antarctica. Open file report, USGS 91–597, Department of the Interior, USGS, 71 pages

Isbell JL, Cúneo RN (1996) Depositional framework of Permian coal-bearing strata, southern Victoria Land, Antarctica. Palaeogeogr Palaeoclimatol Palaeoecol, AAPG 125(1–4):217–238

McDonald DIM, Butterworth P (1990) The stratigraphy, setting and hydrocarbon potential of the Mesozoic sedimentary basins of the Antarctic Peninsula. In: St. John B (ed) Antarctic as an exploration frontier, American Association of Petroleum Geologists, Studies in Geology, 31, pp 101–125

Miskelly N (2003) Progress on international standards for reporting of mineral resources and reserves. Combined Reserves International Reporting Standards Committee (CRIRSCO)

Ohio State University, Institute of Polar Studies (1977) A framework for assessing environmental impacts of possible Antarctic mineral development. Ohio State University, Columbus

Rose G, McElroy CT (1987) Coal potential of Antarctica. Australia Bureau of Mineral Resources, Geology and Geophysics

Runnells DD (1970) Continental drift and economic minerals in Antarctica. Earth Planet Sci Lett 8:400–402

Rutford RH (1986) Antarctic environmental implications of possible mineral exploration and exploitation. SCAR, Cambridge

Watkins ND, Kennett JP (1977) Erosion of deep-sea sediments in the Southern Ocean between longitudes 70°E and 190°E and contrasts in manganese nodule development. Mar Geol 23 (1–2):103–111

Weiss JD (1995) Balance of nature and human needs in Antarctica: the legality of mining. Temple Int Comp Law J 9(2):387–412

# Chapter 24
# Ice and Mineral Resources

## Regulatory Challenges of Commercial Exploitation

**Karen N. Scott**

**Abstract** The commercial exploitation of resources in Antarctica is not new. Sealing followed by whaling began in the nineteenth century and today, the Southern Ocean provides rich fishing grounds for fishers from many nations (Chap. 21). Even scientific research, which the 1959 Antarctic Treaty protects and prioritises above all other activities, may on occasion have commercial application. Antarctic biological prospecting, for example, is now an important activity in its own right within the region (Chap. 22). By contrast, comparatively little attention is paid today to the potential of Antarctic non-biological resources such as ice and minerals for commercial exploitation. This has not always been the case. During the 1970s, drought and global oil shortages led to significant international interest in Antarctic freshwater and petroleum resources. The fact that commercial exploitation of ice, oil and minerals has yet to occur does not mean that it will not do so in the future. Known oil reserves elsewhere in the world are rapidly depleting and a substantial increase in the price of oil may make exploitation in the Antarctic region economically viable. This chapter evaluates the current regulation of both ice and minerals exploitation against the background of the sovereignty dispute which dominates discussions on ownership of and rights to non-biological resources located within the Antarctic Treaty area.

**Keywords** Freshwater • Oil • Gas • Mineral deposits • Continental shelf • Antarctic treaty • UNCLOS

## 24.1 Antarctica's Potential Riches

It is estimated that three-quarters of the world's entire natural freshwater is locked up within ice sheets and glaciers, and 97 % of that is located in the Antarctic, Arctic and Greenland ice sheets. In contrast to biological resources, comparatively little attention today is paid to the value of these freshwater resources. This has not

K.N. Scott (✉)
School of Law, University of Canterbury, Christchurch, New Zealand
e-mail: karen.scott@canterbury.ac.nz


D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_24

always been the case. During the 1970s, drought led to significant interest in Antarctica's freshwater resources. In 1977, Prince Mohammed al Faisal of Saudi Arabia sponsored a conference on iceberg harvesting, and a number of studies from that era and beyond examined the economic and technological feasibility of towing icebergs from Antarctica to arid parts of the world such as California, the Middle East and Australia (Husseiny 1978).

The extent to which commercially exploitable oil, gas and other mineral deposits are located within the Antarctic is much more speculative and largely based on geographic comparisons between the coastlines of Antarctica, South America, Africa, Australia and India, which were once joined as part of the supercontinent Gondwana, rather than on actual finds of oil, gas and minerals (Rowley et al. 1991). Estimates of Antarctic oil reserves range from a conservative 15 million barrels of oil (US House of Representatives 1976) to 50 million barrels under the Ross and Weddell Seas alone, to a staggering 203 million barrels or four-times the amount of known reserves located in Alaska (Ward 1998). Nevertheless, the physical, technological and economic challenges of exploiting both ice and oil in the Antarctic have thus far proven too great to permit the exploitation of either resource.

However, as oil reserves elsewhere in the world are depleting (Owen et al. 2010), a substantial increase in the price of oil may make exploitation in the Antarctic economically viable. In addition, technological developments have made feasible the extraction of oil in the Arctic and in deep water locations. Moreover, increased aridity in parts of the world, particularly Australia, as a result of climate change (Hennessy et al. 2007) may well lead to renewed interest in the freshwater resources of Antarctica. It is therefore unsurprising that the commercial exploitation of both ice and minerals (including petroleum) have been considered and, to a greater or lesser extent, addressed by the parties to the Antarctic Treaty. However, the parties to the Antarctic Treaty have nevertheless taken very different approaches to how they regulate commercial exploitation of ice in contrast to commercial exploitation of mineral and petroleum resources.

The contested and unresolved sovereignty dispute over the continent of Antarctica impacts on all state and non-state activities taking place within the Antarctic Treaty area. However, the impact of this dispute is one of two important factors that make the regulation of ice and minerals exploitation particularly challenging. The second factor is that with respect to ice and offshore minerals exploitation, the 1959 Antarctic Treaty is not the only relevant regulatory instrument. In particular, the law of the sea as codified by the 1982 United Nations Convention on the Law of the Sea (UNCLOS), which entered into force 16 November 1994, provides an additional layer of international rights and obligations that apply to offshore activities within the Antarctic region. Furthermore, in connection with minerals exploitation on and under the seabed, UNCLOS establishes a separate regime based on quite different principles from those provided under the Antarctic Treaty System, and the relationship between the two regimes is not altogether clear, particularly from the perspective of the majority of states that are party to UNCLOS but not party to the 1959 Antarctic Treaty. This chapter will conclude with some observations on possible alternative regulatory mechanisms which might be designed to govern the commercial exploitation of ice and minerals in Antarctica.

## 24.2 Who Owns Antarctic Ice and Minerals?

As explained in Chap. 16, Antarctica is not subject to the sovereignty or control of any one state.

**Box 24.1: Sovereignty in the Antarctic**
Seven States (Argentina, Australia, Chile, France, New Zealand, Norway and the United Kingdom) maintain claims to the continent of Antarctica. These claims are not generally recognised by other states, a matter that has been elegantly addressed by Article IV of the 1959 Antarctic Treaty. In essence, Article IV preserves the seven claims made prior to 1959 without validating them. It facilitates the participation of non-claimant states in the management of Antarctica without permitting inferences to be drawn from that participation in connection with recognition (or otherwise) of the seven claims. Finally, Article IV(2) prohibits parties from making new claims or enlarging existing claims or from using activities taking place within Antarctica whilst the treaty is in force as a basis for asserting, supporting or denying a claim to territorial sovereignty.

The Antarctic Treaty does not provide for specific or even implicit provisions relating to the ownership of, or rights to, resources located within Antarctica. Although this might be regarded as a significant omission in the regulatory regime established by the treaty, any attempt to address rights over resources would have risked compromising the delicate solution to the sovereignty dispute developed in Article IV (Box 24.1). Nevertheless, the treaty leaves open the question as to whether the seven claimant states are entitled to exclusive or priority access to resources located within their sectors. Moreover, for any marine-based resources, such as ice and offshore oil, the question of resource entitlement is complicated further by developments in the law of the sea after 1959, which permit coastal states to exercise jurisdiction over marine resources located up to, and in some cases extending beyond, 200 nautical miles from the coast.

**Box 24.2: Maritime Zones Under UNCLOS**
The law of the sea has been codified by the 1982 United Nations Convention on the Law of the Sea (UNCLOS), which entered into force in 1994 and has been ratified by 166 States (as of 2013). UNCLOS permits states to claim a territorial sea of up to 12 nautical miles (Article 3, UNCLOS), a contiguous zone of up to 24 nautical miles (Article 33, UNCLOS), an Exclusive Economic Zone (EEZ) of up to 200 nautical miles (Article 57, UNCLOS) and a continental shelf of up to 350 nautical miles (Article 76, UNCLOS). These maritime zones are measured from a baseline, which is normally the low-water line on the coast.

### *24.2.1 Ownership of and Rights to Resources: Ice*

The status of ice has yet to be definitively determined under international law (Joyner 2001). Sea ice is most appropriately categorised as part of the sea and the ice sheets that cover the continental landmass of Antarctica can be regarded as part of the land. However, the status of ice shelves, which are attached to land but extend out over the seabed, is unclear. Article VI of the 1959 Antarctic Treaty defines the scope of the treaty as the area south of 60°S Latitude and explicitly includes all ice shelves within that area. Consequently, Article VI of the treaty might be interpreted as assimilating ice shelves with land and arguably supports the conclusion that a land-based regime rather than the law of the sea is better suited to ice shelves in light of their physical land-like characteristics. On this basis there would appear to be no legal impediment which would prevent a claimant state exercising exclusive control over the freshwater resources located within the ice shelf, provided of course that the state in question is able to prove its claim to Antarctica under international law. If no state is able to prove its claim to Antarctica, it may be argued that the Antarctic continent comprises terra nullius or land belonging to no one and its resources are potentially available for exploitation by any state subject to the provisions of the Antarctic Treaty and other relevant principles of international law.

In practice it is more likely that icebergs rather than the ice shelf itself will constitute the most viable freshwater resource. The extent to which a claimant state is entitled to exclusive control over icebergs will largely depend on where the iceberg is located at the point of exploitation. It is established under customary international law that coastal states are entitled to exercise exclusive rights over resources located within a maritime zone adjacent to their territory. Today, coastal states may claim a territorial sea of up to 12 nautical miles and an Exclusive Economic Zone (EEZ) of up to 200 nautical miles as measured from their coastal baselines (see Boxes 24.2 and 24.3).

**Box 24.3: Baselines**

A coastal state's maritime zones are measured from a point known as the baseline. The normal baseline is the low-water line along the coast (Article 5 of UNCLOS). Where a coastal state has a deeply indented coastline, a fringe of islands or an unstable coast it may use straight baselines, joining up appropriate points of its coast (Article 7 of UNCLOS). Other geographical features such as islands, rocks, low tide elevations, reefs, bays and harbour works may be relevant in designating a coastal baseline (Articles 9–14 of UNCLOS).

Within their EEZ coastal states have exclusive sovereign rights to explore and exploit living and non-living natural resources, whether in the water column or on or under the seabed (Rothwell 2001). Ice is not specifically referred to in Part V of

UNCLOS but it undoubtedly constitutes a non-living resource. Hence, it would be consistent to subject ice to the exclusive jurisdiction of coastal states where it is located within that state's EEZ for the purposes of UNCLOS. However, two important issues complicate this interpretation.

First, a coastal state's maritime zones are measured from baselines (Box 24.3) but ice is not referred to as a geographical feature under UNCLOS, and it is unclear whether the ice shelf itself can be used as the baseline from which the various maritime zones are measured.

Second, the EEZ is a modern maritime zone that was created by the 1982 UNCLOS and was not in existence in 1959 when the Antarctic Treaty was adopted. On the one hand, it may be argued that a claim to an EEZ off Antarctica is a new claim, which would violate Article IV (2) of the Antarctic Treaty. On the other hand, it might be argued that an EEZ claim off Antarctica is not a new claim for the purposes of the treaty but merely updates an existing claim in accordance with modern international law. To date only France and Australia have formally claimed an EEZ off their Antarctic territories, although Chile claims to exercise rights in the maritime zone adjacent to its claim on the basis of its controversial Presential Sea doctrine (Kaye and Rothwell 2002; Vigni 2001). Similarly, the extension of the territorial sea from 3 nautical miles – which was broadly although not universally accepted in 1959 – to 12 nautical miles post UNCLOS could be interpreted either as an enlarged claim contrary to Article IV (2) of the Antarctic Treaty, or as an updated claim in accordance with the law of the sea.

In the event that these maritime claims off Antarctica are not validated under international law, either because they are contrary to Article IV (2) or because claimant states fail to prove their claims to Antarctica under international law, the seas surrounding Antarctica shall be regarded as the high seas. All states are entitled to exercise so-called high seas freedoms, which include navigation, over-flight, fishing, scientific research, the right to lay submarine cables and pipelines and to construct artificial installations (1982 UNCLOS, Article 87). Iceberg harvesting is not listed as a high seas freedom but the prevailing view under customary international law is that any activity not prohibited by the law of the sea should be regarded as a high seas freedom (Churchill and Lowe 1999). In exercising high seas freedoms, including iceberg harvesting, states must have due regard to the rights of other states on the high seas (such as navigation and the freedom to lay pipelines and cables) as well as their environmental and other obligations under UNCLOS and other instruments to which they are party, such as the 1959 Antarctic Treaty. The high seas regime is naturally applicable to the harvesting of icebergs that have travelled to the high seas north of the established maritime boundaries surrounding Antarctica.

### 24.2.2 *Ownership of and Rights to Resources: Minerals*

Similar questions in connection with resource entitlement arise over minerals as with ice. Provided a claimant state can prove its claim to its Antarctic sector, that state is entitled to exercise exclusive sovereignty over onshore mineral resources subject to its obligations under the Antarctic Treaty. A claimant state's right to offshore resources depends on whether that state exercises sovereignty over the continental shelf associated with its claim.

**Box 24.4: The Continental Shelf**
The continental shelf is defined under Article 76(1) of UNCLOS as: "the seabed and subsoil of the submarine areas that extend beyond its territorial sea throughout the natural prolongation of its land territory to the outer edge of the continental margin, or to a distance of 200 nautical miles from the baselines from which the breadth of the territorial sea is measured where the outer edge of the continental margin does not extend up to that distance." All states are permitted to claim up to 200 nautical miles of continental shelf irrespective of whether the natural (geographical) shelf extends to that limit and this is sometimes referred to as the juridical continental shelf. Where a coastal state's natural continental shelf extends beyond 200 nautical miles their claim must not exceed 350 nautical miles as measured from the baseline or 100 nautical miles from the 2,500 m isobaths, which is a line connecting the depth of 2,500 m. (Articles 76(1)–76(6) UNCLOS). UNCLOS has established a process which must be followed by coastal states seeking to claim a continental shelf beyond the 200 nautical mile limit. The limits set out under UNCLOS are the maximum a coastal state can claim and in many cases these claims will be reduced owing to the presence of competing claims from opposite or adjacent states.

In contrast to the EEZ, the juridical continental shelf was a recognised concept in 1959 and need not be separately 'claimed' as such. Article 77(4) of UNCLOS, which codifies existing customary international law, asserts that "the rights of the coastal state do not depend on occupation, effective or notional, or on any express proclamation". Consequently, continental shelf claims cannot be regarded as new for the purposes of Article IV (2) of the Antarctic Treaty. In any case, it is worth noting that Chile and Australia asserted claims to areas of the continental shelf associated with their Antarctic territories before the adoption of the Antarctic Treaty, in 1947 and 1953 respectively.

However, the continental shelf in 1959 was defined as the "seabed and subsoil of the submarine areas adjacent to the coast but outside the area of the territorial sea, to a depth of 200 m or, beyond that limit, to where the depth of the superjacent waters admits of the exploitation of the natural resources of the said areas" (1958 Convention on the Continental Shelf, Article 1). Today, a coastal state is entitled to a

200 nautical mile continental shelf (maritime boundaries permitting) and in cases where the natural shelf extends beyond 200 nautical miles, the outer limits of the shelf may be extended to any point up to 350 nautical miles or 100 nautical miles from the 2,500 m isobaths, which is a line connecting the depth of 2,500 m (Box 24.4). Within an Antarctic context, the exercise of sovereign rights over an extended area of continental shelf might be legitimately regarded as an 'enlargement' of an existing claim and thus contrary to Article IV(2) of the Antarctic Treaty. Alternatively, it can be argued that extended continental shelf claims are compatible with Article IV(2) of the Antarctic Treaty because no claim is made for the purposes of Article IV(2) or that Article IV(2) was intended to apply to land rather than maritime claims or that the claims have simply been updated or finally delimited in accordance with modern international law, neither of which is inconsistent with the text or the spirit of Article IV(2) of the Antarctic Treaty (Elferink 2002; Kaye 2001; Scott 2009). The seven claimant states do not regard a continental shelf claim of 200 nautical miles and beyond as contrary to the Antarctic Treaty and, to a greater or less extent, have engaged in the continental shelf claims process established under UNCLOS (Box 24.5). Moreover, the non-claimant states that have responded to these submissions to the commission have not suggested that they view these potential claims as incompatible with Article IV(2) of the Antarctic Treaty, but rather, that as a consequence of their failure to recognise the broader claims to sovereignty over Antarctica, they similarly fail to recognise any claim to the continental shelf off Antarctica.

**Box 24.5: Continental Shelf Delimitation Process in Antarctica**

Under UNCLOS any state that intends to delimit its continental shelf beyond 200 nautical miles must submit technical information on the proposed limits to the Continental Shelf Commission (CSC) established under Annex II of UNCLOS. States that ratified UNCLOS before 1999 must have made their submissions to the commission by 2009 (see Decision SPLOS/72, 29 May 2001). Otherwise states must submit their data to the commission within 10 years of the entry into force of UNCLOS for that state (Article 76(8), UNCLOS). In 2008 it was decided that provided states submit preliminary data by 2009, they would be deemed to have met the deadline (See decision SPLOS/183, 18 June 2008).

In light of the sovereignty dispute over Antarctica, the seven claimant states agreed to adopt one of two submission strategies designed to acknowledge the presence of Antarctic claims, including a continental shelf component beyond 200 nautical miles, and to simultaneously recognise the disputed nature of those claims.

The first strategy – adopted by Australia (2004) and Norway (2009) – consists of making a full submission to the CSC and including data relating to the Antarctic continental shelf within that submission. Nevertheless, the state

(continued)

**Box 24.5** (continued)
making the full submission must include a request within the submission that the commission refrain from considering the Antarctic portion of the claim.

The second strategy – adopted by New Zealand (2006), the United Kingdom (2008) and France (2009) – consists of making a partial submission to the commission in respect of other parts of their territory and to include a clear reservation of the right to make a further submission to the commission at a later stage in connection with the continental shelf associated with their Antarctic claims.

Argentina has made a full submission to the commission (in 2009) but omitted to include a request that the commission refrain from considering the Antarctic portion of its claim notwithstanding the agreed two-pronged strategy. It is likely that this bolder approach to the submissions process resulted from Argentina's perception that, in contrast to other claimant states, it is in a competitive relationship with two other states – the UK and Chile – as to the status of its claim.

Chile has thus far submitted preliminary data to the commission pursuant to Decision SPLOS/183 (2008) and has yet to decide which strategy to adopt. Information on all submissions to the Commission including Australia's and Norway's submission as well as the Commission's recommendations in relation to these claims is available on the Commission's website at: http://www.un.org/depts/los/clcs_new/commission_submissions.htm.

Two further issues arise in connection with the disputed Antarctic continental shelf claims. First, at least three submissions to the Continental Shelf Commission include areas of continental shelf lying within the Antarctic Treaty area but which are associated with territory located north of 60°S Latitude. Nearly half of Australia's extended continental shelf lies off its subantarctic possessions – the Heard and McDonald Islands and, to a lesser extent, Macquarie Island – and is located within the Antarctic Treaty area. Similarly, part of the continental shelf off the disputed South Sandwich Islands is located south of 60°S Latitude and is included in both the United Kingdom's and Argentina's submission to the Continental Shelf Commission. The Antarctic Treaty is silent on the issue of how Article IV impacts on areas of the continental shelf associated with land north of 60°S Latitude but lying within the Antarctic Treaty area. Arguably, Article IV should have no application to such areas. As outlined in Chap. 16, the purpose of Article IV is to address the issue of disputed claims to the Antarctic continent and not to restrict the exercise of recognised sovereign rights associated with land located to the north of the Antarctic Treaty area. This position would appear to have been implicitly recognised by the commission itself when making general recommendations in connection with the outer limit of Australia's continental shelf within the Antarctic Treaty area. To date, no state appears to have objected to these recommendations. As a result of these recommendations, Australia has obtained sovereign rights over potential mineral resources in or underneath its continental shelf within the Antarctic Treaty area (Hemmings and Stephens 2008).

The second issue which arises in the context of offshore mineral resources relates to the legal status of the seabed south of 60°S Latitude which is not claimed (i.e. the continental shelf associated with the unclaimed sector of Antarctica) or which is not the subject of a successful claim by one or more claimant states. UNCLOS declares that the seabed, ocean floor and subsoil thereof are beyond the limits of national jurisdiction (designated "the Area") and its resources are the common heritage of mankind (1982 UNCLOS, Article 1.1(1) and 136). Part XI of UNCLOS as modified by the 1994 Agreement relating to the implementation of Part XI of UNCLOS, establishes a complex regime for the management and exploitation of the deep seabed based on far-reaching principles relating to benefit sharing. The question as to whether Part XI of UNCLOS should apply to the seabed surrounding Antarctica was assiduously avoided during the UNCLOS negotiations. However, it seems unlikely that, in the event that claims to sovereignty over Antarctica cannot be satisfactorily established under international law, states not party to the Antarctic Treaty would be prepared to allow the Antarctic Treaty parties to exploit the resources of the seabed, which would otherwise be regarded as the common heritage of mankind and owned by the international community as a whole (Joyner 1992).

### *24.2.3 Ownership of and Rights to Resources: Concluding Remarks*

The extent to which ownership of and sovereign rights to ice and minerals can be claimed in Antarctica depends on:

- whether any or all of the claimant states can successfully prove their sovereign claims to Antarctica, and
- whether the exercise of particular sovereign rights are precluded by the application of Article IV(2) of the 1959 Antarctic Treaty.

In practice, in deference to the sovereignty dispute, claimant states have largely refrained from claiming exclusive access to resources located within their sectors and have attempted to negotiate rules regulating Antarctic activities under the auspices of the Antarctic Treaty System. For example, no claimant state has attempted to impose catch limits or other restrictions on fish caught within their Antarctic maritime zones in contrast to zones associated with their metropolitan territories. Instead, as discussed in Chap. 21, catch limits and other conservation measures have been developed under the auspices of the 1980 Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). Similarly, the exploitation of both ice and, more particularly, minerals, is regulated under the Antarctic Treaty System. From the perspective of conservation and environmental protection in particular, such regulation is necessary. However, it is notable that so far no attempt has been made to decide who should benefit from the exploitation of Antarctic resources. Whilst the relative absence of commercial exploitation of Antarctic resources – with the exception of fishing, tourism and, increasingly, bioprospecting – has led to a corresponding relative lack of interest in the question of sharing the benefits of Antarctic resources, this will undoubtedly change in the event that the exploitation of ice or minerals becomes commercially feasible and desirable.

## 24.3 Exploitation of Antarctic Ice

Harvesting icebergs as a freshwater resource is not a new idea. In 1853 for example, San Francisco was supplied with water from the Baird Glacier in Alaska (Zuccaro 1979). During the early 1970s, Saudi Arabia commissioned a French firm to study the feasibility of towing icebergs from Antarctica to the Red Sea port of Jiddah (Pallone 1977–1978) and, during that decade, a number of serious studies were produced exploring the extent to which harvested icebergs could be used as a source of fresh water in arid regions such as California, Colorado and Australia (Hult and Ostrander 1973; Schwerdtfeger 1979; Weeks and Campbell 1973a, b; Smakhtin et al. 2001). Although these studies concluded that iceberg harvesting was feasible and that Antarctic tabular icebergs were relatively stable and could be towed, concerns were expressed over the high rate of melting losses whilst the iceberg was in transit and the processing costs once the iceberg reached its destination (Jacka and Barry-Giles 2007). The environmental risks associated with iceberg harvesting have not been fully evaluated but damage to the seabed through iceberg scour is predictable. Depending on the size and number of icebergs being transported, there is a theoretical possibility of damage to marine ecosystems through the input of large amounts of cold melt-water. Extensive harvesting activities could also potentially lead to environmental coastal damage around Antarctica. An alternative to towing large icebergs as a freshwater resource is the exploitation of icebergs for the high-value bottled water industry. However, although – at a price – it is now possible to purchase Arctic iceberg bottled water, the potential costs associated with iceberg exploitation in the Antarctic are likely to prove prohibitive, at least for the foreseeable future.

The Antarctic Treaty does not explicitly prohibit the exploitation of icebergs as a freshwater or even a premium bottled water resource. The parties to the Antarctic Treaty have on two occasions emphasised that the term “mineral resources” does not include ice and that any rules relating to minerals exploitation, including the current ban on commercial exploitation of minerals, do not apply to ice harvesting. The parties to the Antarctic Treaty have adopted only one instrument which directly relates to iceberg harvesting: Recommendation XV-21 (Paris 1989) on Exploitation of Icebergs. Recommendation XV-21 calls upon parties to exchange information on the feasibility and possible environmental impacts of the commercial exploitation of icebergs, and to continue research into ice-related topics. Nevertheless, the commercial exploitation of ice is far from unregulated. Iceberg harvesting activities are subject to the principles and rules established by the 1959 Antarctic Treaty, the 1991 Protocol on Environmental Protection to the Antarctic Treaty (Environmental Protocol) and the 1982 UNCLOS (Geon 1997–1998; Lundquist 1977; Trombetta-Pagigadi 1996).

### *24.3.1 The Application of the 1959 Antarctic Treaty and 1991 Environmental Protocol to Iceberg Harvesting Activities*

The Environmental Protocol requires that all activities taking place within the Antarctic Treaty area – including iceberg harvesting – are planned in order to protect the Antarctic environment, its dependent and associated ecosystems and its value as an area for scientific research. Activities must be planned so as to avoid adverse effects on climate, water quality, glacial environments and detrimental changes in the distribution, abundance or productivity of species of fauna and flora (1991 Environmental Protocol, Article 3(2)(a)–(c)).

Article 8 and Annex I of the Environmental Protocol require all activities subject to the advance notice requirements under Article VII(5) of the Antarctic Treaty, including logistical support activities, to be preceded by an environmental impact assessment. As explained in Chap. 16, unless an activity is determined to have a less than minor or transitory impact it must be assessed by means of an initial environmental evaluation (IEE). An IEE entails an assessment of any impacts the activity might have, including cumulative impacts (1991 Environmental Protocol, Annex I, Article 2). The state authorising the activity is responsible for ensuring an assessment is carried out. However, the results of that assessment do not have to be made public. It is likely that a major project to tow a large iceberg or to construct equipment for exploiting the freshwater resources of icebergs within Antarctica would have more than a minor or transitory impact and consequently, would be subject to a comprehensive environmental evaluation (CEE) (1991 Environmental Protocol, Annex I, Article 3). A CEE requires a much more detailed assessment of the proposed activity and the consideration of knowledge gaps. Further, alternative options, including the option of not proceeding with the activity, need to be considered in a CEE. A CEE is made publically available and circulated for comment at Antarctic Treaty Consultative Meetings (ATCM) (1991 Environmental Protocol, Annex I, Article 3(3)–(6)). Ultimately, the ATCM is only able to make recommendations and cannot prevent a state from proceeding with a proposed activity or impose mandatory conditions on that activity.

In carrying out ice harvesting activities operators must avoid taking or interfering with native flora and fauna without a permit (1991 Environmental Protocol, Annex II, Article 2). Taking or harmful interference includes the use of explosives, using vessels or vehicles in a manner that disturbs native birds and seals or any activity that results in the significant modification of habitats of any species or population of native mammal, bird, plant or invertebrate. Moreover, special care must be taken in connection with Antarctic Specially Protected Areas (ASPAs) and Antarctic Specially Managed Areas (ASMAs) (1991 Environmental Protocol, Annex V). Should ice harvesting become a commercial reality, it is likely that restrictions would be imposed upon taking ice from within protected areas and on towing icebergs through protected areas. Furthermore, all support activities associated with ice-harvesting must comply with the requirements of the protocol relating to waste management 1991 Environmental Protocol, Annex III), marine pollution (1991 Environmental Protocol Annex IV), contingency and emergency planning and liability in respect of environmental emergencies (1991 Environmental Protocol, Annex VI (not yet in force).

### *24.3.2 The Application of UNCLOS to Iceberg Harvesting Activities*

The requirements of the Environmental Protocol apply only to activities taking place within the Antarctic Treaty area, or where the effects of those activities impact upon dependent and associated ecosystems. The law of the sea as codified by UNCLOS applies to operators wherever they are located, from the point of harvesting to the port of destination. It is beyond the scope of this chapter to provide a comprehensive overview of the obligations that are relevant in this context. However, as noted above, high seas freedoms must be exercised with due regard for other users (1982 UNCLOS, Article 87(2)). In particular, vessels towing icebergs must respect and refrain from interfering with the navigational freedoms of other vessels, the freedom to fish, and, most importantly, the freedom to lay cables and pipelines (1982 UNCLOS, Articles 87(2) and 112). The latter activity is of particular risk from iceberg scour, and vessels responsible for damaging cables and pipelines would be liable for the damage caused (1982 UNCLOS, Article 113). Finally, UNCLOS establishes a number of obligations in connection with environmental protection (1982 UNCLOS, Part XII) and permits coastal states to take a range of measures to protect their maritime zones from environmental damage (1982 UNCLOS, Articles 21–23, 25, 42, 56 and Part XII).

## 24.4 Exploitation of Antarctic Minerals

In contrast to the self-evident freshwater resources located within Antarctica, the presence of mineral resources is much more speculative (Chap. 23). Notwithstanding the relatively poor prospects for minerals exploitation within the Antarctic, the development of a regulatory framework for the management of commercial minerals activities dominated the ATCM agenda during the 1970s and 1980s. The issue of commercial minerals exploitation was first raised informally at the VI ATCM in 1970 by New Zealand and was then included on the ATCM agenda in 1972. At the VIII ATCM in 1975 the parties to the Antarctic Treaty recommended that interested governments convene a preparatory meeting in order to deal with the question of minerals exploitation. In 1981, the ATCM adopted Recommendation XI-1, which called on the parties to convene a special consultative meeting to develop an Antarctic mineral resources regime. Recommendation XI-1 specified that the regime should be based on selected principles which included the maintenance of the Antarctic Treaty in its entirety, the safeguarding of Article IV of the Antarctic Treaty and the protection of the environment. Negotiations for the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA) took 6 years but by the time it was adopted in 1988, international opinion was turning against permitting any form of mining in Antarctica (Podehl and Rothwell 1992). Shortly after the adoption of CRAMRA, France and then Australia announced that they would not sign the convention, which had the practical effect of preventing CRAMRA from entering into force. Nevertheless, as the only comprehensive instrument to be adopted related to minerals exploitation in Antarctica it is worth providing a brief overview of CRAMRA before examining what replaced it in 1991.

### *24.4.1 1988 Convention on the Regulation of Antarctic Mineral Resources (CRAMRA)*

The 1988 CRAMRA (Scully and Kimball 1989; Cook Waller 1989) was a complex framework agreement, which set out principles and established institutions and processes designed to regulate both on- and offshore mining activities within the Antarctic Treaty area. Three bodies were to be established by CRAMRA. The Antarctic Minerals Resources Commission, comprising those states which were Antarctic Treaty Consultative Parties (ATCPs) on the date CRAMRA was opened for signature as well as other states engaged in substantial scientific, technical or environmental research of relevance to minerals themselves or that sponsored minerals exploitation (1988 CRAMRA, Article 18(2)). The commission was to be assisted by a Scientific, Technical and Environmental Advisory Committee. Membership of that committee was open to all parties (1988 CRAMRA, Article 23). Finally, CRAMRA provided for the creation of Antarctic Mineral Resources Regulatory Committees with responsibility for each area designated suitable for mining activities by the commission (1988 CRAMRA, Article 29). Each committee was to comprise ten members including the relevant claimant state, if the area in question lay within any claimed sector, those states which have reserved a right to make a claim (i.e. the United States and Russia) as well as non-claimant states (1988 CRAMRA, Article 29(2)).

Under CRAMRA operators were free to engage in prospecting activities provided they did so in compliance with the requirements of the convention (1988 CRAMRA, Article 37). Beyond prospecting, operators could have applied to the commission to have an area designated for possible exploration and development (1988 CRAMRA, Article 39). The commission was able to designate such an area on the advice of the advisory committee and a special meeting of the parties, taking into consideration physical, geological, environmental and other characteristics of the area (1988 CRAMRA, Article 41). In designating an area for exploration, the commission was able to prescribe conditions and guidelines relating to minerals activities, including maximum block sizes (1988 CRAMRA, Article 41(1)(e). Once an area was designated, any party on behalf of an operator had an opportunity to apply to the relevant regulatory committee for an exploration permit on submission of a detailed plan and payment of appropriate fees (1988 CRAMRA, Article 44). With the grant of a permit, the regulatory committee would be required to develop a detailed management scheme for each operator setting out the terms and conditions for exploration and, where appropriate, development of the mineral resources within the relevant block (1988 CRAMRA, Articles 45–47). The operator would have had an opportunity to apply for a development permit at any point during which the management plan and exploration permit were in force (1988 CRAMRA, Article 53).

Although subject to strident criticism from the anti-mining lobby, once adopted, CRAMRA established strict and wide-ranging measures designed to protect the Antarctic environment. The general principles provided for under Article 4 of CRAMRA were largely environmental in nature and environmental factors should have been considered at every stage of the prospecting and exploration permitting process. Moreover, the commission was also able to designate protected areas within which minerals resource activities would have been prohibited (1988 CRAMRA, Article 13). It is notable that many of these principles were subsequently incorporated into the 1991 Protocol on Environmental Protection to the Antarctic Treaty. CRAMRA also established relatively far-reaching response and liability requirements with regard to operators (1988 CRAMRA, Article 8) as well as complex dispute resolution provisions (1988 CRAMRA, Articles 55–59). Nevertheless, abruptly abandoned less than a year after it was adopted, it is now unlikely that CRAMRA will ever enter into force.

### *24.4.2 Article 7 of the 1991 Protocol on Environmental Protection to the Antarctic Treaty*

In the wake of the collapse of CRAMRA, the parties to the Antarctic Treaty embarked on fresh, and much more rapid, negotiations for an environmental instrument to replace it. In contrast to CRAMRA, the resulting 1991 Protocol on Environmental Protection to the Antarctic Treaty is designed to regulate all human activities taking place within the Antarctic Treaty area with a view to ensuring the continent benefits from high standards of environmental protection. Only one article in the Protocol, which is the shortest provision in the entire instrument, relates to minerals activities. Article 7 of the Protocol stipulates that "any activity relating to minerals resources, other than scientific research, shall be prohibited". Nevertheless, this so-called minerals ban is not inevitably permanent. Any party to the protocol may request a review conference after the expiration of 50 years from the date of entry into force of the protocol, i.e. in 2048 (1991 Environmental Protocol, Article 25(2)). The ban may be lifted or modified if the relevant amendment is adopted by a majority of the parties. Here, the majority of the parties needs to include three-quarters of the states that were ATCPs when the protocol was adopted in 1991 (1991 Environmental Protocol, Article 25(3)). However, in order to ensure that minerals activities are properly regulated, Article 25(5)(a) of the protocol specifies that the minerals ban may only be lifted if a binding minerals regime has been developed to regulate minerals activities in Antarctica. Nevertheless, at the insistence of the United States, a walk away clause was included in Article 25(5)(b). This clause allows any state to withdraw from the protocol in the event that a modification to or amendment of the minerals ban has not entered into force within 3 years of its adoption. A state that has withdrawn from the Environmental Protocol is obviously not bound by obligations under that protocol, including the prohibition on commercial minerals exploitation.

### *24.4.3 Application of the 1982 UNCLOS to Offshore Antarctic Minerals Activities*

The relationship between Part XI of UNCLOS, the Antarctic Treaty and, more particularly, the minerals ban under Article 7 of the Environmental Protocol is unclear. At least part of the seabed lying within the Antarctic Treaty area is clearly not subject to the sovereignty of any state and the various claims to the remainder of the seabed are vigorously contested by the international community. The Article 7 minerals ban applies only to states party to the Environmental Protocol, although it might be argued that all states party to the Antarctic Treaty have accepted the ban as no state has objected to it to date. However, unless the ban can be categorised as a principle of customary international law it is unlikely that it will bind states not party to the Antarctic Treaty. In these circumstances, it is possible that UNCLOS rather than the Antarctic Treaty will apply to minerals activities undertaken by states not party to the Antarctic Treaty. At the moment, the physical and economic challenges associated with minerals exploitation in the Southern Ocean render exploitation unlikely in practice. Consequently, direct conflict between the Antarctic Treaty and UNCLOS is avoided for at least the time being.

**Box 24.6: Customary International Law**
Customary international law is a source of international law. It consists of two components: state practice (i.e. what states actually do) and opinio juris (a belief that the action (or omission) is required by law). The presence of opinio juris (or belief) is crucial as it distinguishes between practice that is required by law and practice that is simply engaged in out of tradition or diplomatic comity. State practice must be consistent and virtually uniform. Customary international law generally applies to all states in contrast to treaties, which apply only to those states which have ratified them. It is open to debate whether the Antarctic Treaty has been incorporated into customary international law (Charney 1986).

## 24.5 Concluding Remarks

The physical, technical and economic challenges associated with iceberg and minerals exploitation within Antarctica has meant that the resources bonanza predicted in the 1970s has yet to come to pass. This lack of development is undoubtedly positive from both an environmental and a regulatory perspective. Should global circumstances change and the exploitation of ice or minerals become a realistic prospect, specific regulatory mechanisms building on the Antarctic Treaty, the Environmental Protocol and the defunct CRAMRA will need to be developed to protect the Antarctic environment and for the benefit of the international community.

The greatest challenge associated with ice and minerals exploitation lies in the issue of ownership and benefit sharing. To what extent should the economic and other benefits of Antarctic ice and minerals be confined to those states which maintain a historical claim to Antarctica? Does the fact that 50 states participate in the management and protection of Antarctica, justify confining the benefits derived from Antarctic resources to Antarctic Treaty parties alone? Or, should Antarctica and its resources be designated the common heritage of mankind and be used for the benefit of the international community more generally? As the collapse of CRAMRA illustrated, issues relating to resource rights, environmental protection and benefit sharing are not severable, and all three must be fully addressed if a stable, durable and ultimately fair regime for the exploitation of Antarctic non-renewable resources is to be created.

## References

Anderson JB (1991) The Antarctic continental shelf: results from marine geological and geophysical investigations. In: Tingey RJ (ed) The geology of Antarctica. Clarendon Press, Oxford, pp 285–334

Anderson JB (1999) Antarctic marine geology. Cambridge University Press, Cambridge

Beck PJ (2004) Twenty years on: the UN and the 'Question of Antarctica' 1983–2003. Polar Rec 40:205–212

Beck PJ (2006) The United Nations and Antarctica, 2005: the end of the "Question of Antarctica"? Polar Rec 24:217–227

Behrendt JC (1991) Scientific studies relevant to the question of Antarctica's petroleum resource potential. In: Tingey RJ (ed) The geology of Antarctica. Clarendon Press, Oxford, pp 588–616

Burmester C, Henry C (1989) Liability for damage from Antarctic mineral resource activities. Virginia J Int Law 29:621–657

Charney J (1986) The Antarctic system and customary international law. In: Rancioni F, Scovazzi T (eds) International law for Antarctica, 2nd edn. Kluwer Law, The Hague, pp 51–101

Churchill RR, Lowe AV (1999) The law of the sea, 3rd edn. Manchester University Press, Manchester

Cook Waller D (1989) Death of a treaty: the decline and fall of the Antarctic minerals convention. Vanderbilt J Transl Law 22:631–668

de Wit MJ (1985) Minerals and mining in Antarctica: science and technology, economics and politics. Clarendon Press, Oxford

Elferink AGO (2002) The continental shelf of Antarctica: implications of the requirement to make a submission to the CLCS under Article 76 of the LOS Convention 17 (2002). Int J Mar Coas Law 17:485–520

Geon BS (1997–1998) A right to ice? The application of international and national water laws to the acquisition of iceberg rights. Mich J Int Law 19:277–301

Hayashi M (1986) The Antarctica question in the United Nations. Cornell Int Law J 19:275–290

Hemmings A, Stephens T (2008) Reconciling global and regional dispensations: the implications of sub-Antarctic extended continental shelf penetration of the Antarctic Treaty Area. N Z Yearb Int Law 6:273–291

Hennessy KB et al (2007) In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Australia and New Zealand. Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 507–540

Hult JL, Ostrander NC (1973) Antarctic icebergs as a global fresh water resource. R-1255-NSF, October 1973, Rand, Santa Monica

Husseiny AA (ed) (1978) Iceberg utilization: proceedings of the first international conference and workshops on iceberg utilization for fresh water production, weather modification and other applications held at Iowa State University, Ames, Iowa, USA, October 2–6 1977. Pergamon Press, New York

Jacka TH, Barry-Giles A (2007) Antarctic iceberg distribution and dissolution from ship-based observations. J Glaciol 53:341–356

Joyner CC (1987) The Antarctic minerals negotiating process. Am J Int Law 81:888–905

Joyner CC (1992) Antarctica and the law of the sea. Kluwer Academic Publishers, The Hague

Joyner CC (2001) The status of ice in international law. In: Elferink AGO, Rothwell DR (eds) The law of the sea and polar maritime delimitation and jurisdiction. Martinus Nijhoff Publishers, The Hague, pp 23–48

Kaye S (2001) The outer continental shelf in the Antarctic. In: Elferink AGO, Rothwell DR (eds) The law of the sea and polar maritime delimitation and jurisdiction. Martinus Nijhoff Publishers, The Hague, pp 125–137

Kaye S, Rothwell DR (2002) Southern ocean boundaries and maritime claims: another Antarctic challenge for the law of the sea. Ocean Dev Int Law 33:359–389

Lundquist TR (1977) The iceberg cometh? International law relating to Antarctic iceberg exploitation. Natl Resour J 17:1–41
Owen NA, Inderwildi OR, King DA (2010) The status of conventional world oil reserves – hype of cause for concern? Energy Policy 38:4743–4749
Pallone F (1977–1978) Resource exploitation: the threat to the legal regime of Antarctica. Conn Law Rev 10:401–417
Peeters L (2004) Square peg, round hole: jurisdiction over minerals mining offshore Antarctica. Macquarie J Int Comp Environ Law 1:217–232
Podehl JG, Rothwell DR (1992) New Zealand and the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA): An unhappy divorce? Vict Univ Wellingt Law Rev 22:23–50
Rothwell DR (2001) Antarctic baselines: flexing the law for ice-covered coastlines. In: Elferink AGO, Rothwell DR (eds) The law of the sea and polar maritime delimitation and jurisdiction. Martinus Nijhoff Publishers, The Hague, pp 49–68
Rowley PD et al (1991) Metallic and non-metallic mineral resources of Antarctica. In: Tingey RJ (ed) The geology of Antarctica. Clarendon Press, Oxford, pp 617–651
Schwerdtfeger P (1979) Review on icebergs and their uses: a report to the Australian academy of science. Cold Reg Sci Technol 1:59–79
Scott KN (2009) Managing sovereignty and jurisdictional disputes in the Antarctic: the next 50 years. Yearb Int Environ Law 20:3–40
Scully RT, Kimball A (1989) Antarctica: is there life after minerals? The minerals treaty and beyond. Mar Policy 13:87–98
Smakhtin V et al (2001) Unconventional water supply options in South Africa. Water Int 26:314–334
Trombetta-Pagigadi F (1996) The exploitation of Antarctic icebergs in international law. In: Francioni F, Scovazzi T (eds) International law for Antarctica, 2nd edn. Kluwer Law International, The Hague, pp 225–257
UNESCO – WWAP (2006) Water: a shared responsibility. The United Nations world water development report. Berghahn Books, New York
US House of Representatives (1976) Polar energy resources potential: report of the committee on science and technology. US House of Representatives, 94th congress, second session
Vigni P (2001) Antarctic maritime claims: “Frozen Sovereignty” and the law of the sea. In: Elferink AGO, Rothwell DR (eds) The law of the sea and polar maritime delimitation and jurisdiction. Martinus Nijhoff Publishers, The Hague, pp 85–104
Ward JJ (1998) Black gold in a white wilderness – Antarctic oil: the past, present and potential of a region in need of sovereign environmental stewardship. J Land Use Environ Law 13:363–397
Weeks WF, Campbell WJ (1973a) Icebergs as a freshwater source: an appraisal. J Glaciol 12:207–233
Weeks WF, Campbell WJ (1973b) Antarctic icebergs as a fresh water resource. Polar Rec 16:661–665
Zuccaro EA (1979) Iceberg appropriation and the Antarctic’s Gordian knot. Calif West Int Law J 9:405–429

# Chapter 25
# Recent Climate Change

## Causes and Impacts of Climate Change in Antarctica

**Michael J. Bentley**

**Abstract** In recent decades, many changes have occurred in the atmosphere and the ocean around Antarctica as well as to the terrestrial environments of the continent itself. The causes of these changes are numerous and varied. All components of the Antarctic environment are linked – the hydrosphere, atmosphere, cryosphere and biosphere all respond to changes in any part of these systems, sometimes resulting in feedback mechanisms that amplify or accelerate changes that are underway. This complexity means that the causes and the consequences of climate change can be difficult to determine but some of the range of physical, biological and chemical impacts of climate change are starting to emerge or are already well established, and future effects can begin to be estimated. There is an extensive and wide-ranging literature on recent Antarctic climate change. In particular there is a comprehensive report by Turner et al. (Antarctic climate change and the environment. SCAR, Cambridge, pp 526, 2009), subject of an overview in Convey et al. (Antarct Sci 21:541–563, 2009).

**Keywords** Oceanography • Southern annular mode • Sea ice • Larsen B ice shelf • Satellite altimetry

## 25.1 Antarctic Climate Records

The Antarctic continent has a uniquely short climate record. Apart from a few scattered measurements by early explorers in the nineteenth and early twentieth centuries, the vast majority of Antarctic climate records began in the mid to late 1950s. This coincided with the building of many scientific stations in preparation for the International Geophysical Year (IGY) in 1957/1958. A small number of records predate the IGY, mainly in the Antarctic Peninsula where a precursor to the

M.J. Bentley (✉)
Department of Geography, University of Durham, Durham, UK
e-mail: m.j.bentley@durham.ac.uk



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_25

British Antarctic Survey had maintained stations since the 1940s, and on some subantarctic islands such as Orcadas (formerly Laurie Island) where a meteorological record was started by the Scottish National Antarctic Expedition in 1903/1904, and continued thereafter by Argentina.

A second characteristic of Antarctic climate records is that they are mostly concentrated around the coastline: only a small number of records exist from the interior of the continent. Notable exceptions are the US station at the South Pole and the Russian station at Vostok. Determining climate trends in the interior of Antarctica can be challenging and can require use of satellite records in addition to land-based weather stations.

## 25.2 Climate Changes in Antarctica

### *25.2.1 Warming of the Antarctic Peninsula*

Despite the short period of climate records and their limited distribution, there are some clear trends in the recent climate of Antarctica. The most marked of these is a significant warming along the Antarctic Peninsula. The peninsula is warming faster than anywhere else in the Southern Hemisphere and is amongst the three fastest warming parts of the planet: all of these are high-latitude regions with the other two being north-west North America and the Siberian sector of the Arctic. From 1951 to 2000, the warming trend was 0.56 °C per decade at Vernadsky station (65°S, 64°W, originally called Faraday station) (Fig. 25.1). Most of this warming has been concentrated in the winter months (1.09 °C per decade at Vernadsky) (Turner et al. 2005). Other stations on the Antarctic Peninsula also show this warming. For example, Rothera station, (67°S, 68°W) has warmed by approximately 1 °C per decade, in the period between 1978 and 2000 (Fig. 25.1), and Esperanza (63°S, 56°W) has warmed 0.41 °C per decade in the period between 1961 and 2000, with most of the warming in winter (Turner et al. 2005). For comparison the global average temperature rise in a comparable time interval is 0.13 °C per decade (IPCC 2007).

The warming is most pronounced along the west coast of the Antarctic Peninsula, with less warming on the east side. Total average warming of the peninsula since 1950 has been 2 °C in mean annual temperature, and 6 °C in winter (Stammerjohn et al. 2008).

### *25.2.2 Climate Trends Beyond the Antarctic Peninsula*

For several years, research suggested that although the Antarctic Peninsula was unequivocally warming, the trend of recent change in East Antarctica was one of

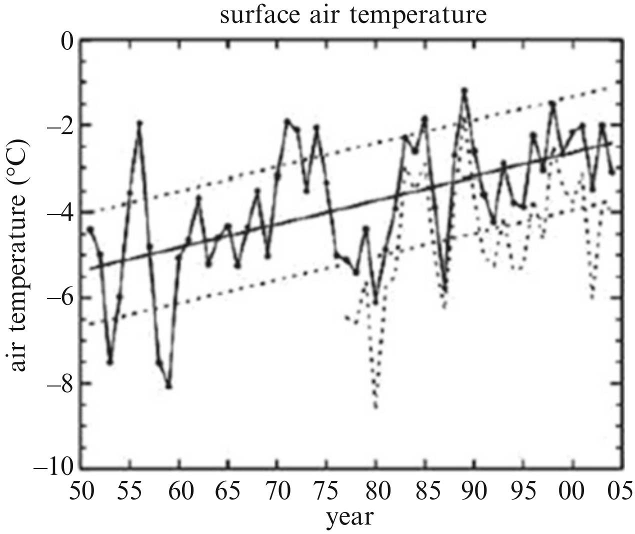



**Fig. 25.1** Mean annual temperatures from Faraday/Vernadsky 1951–2004 (*solid line*) and Rothera 1977–2004 (*dashed line*). The *solid trend line* is a linear regression fit with 1 standard deviation (*dashed straight lines*) (Reprinted from Ducklow et al. 2007, with kind permission from the Royal Society)

cooling (Turner et al. 2005). However, the pattern of interior cooling and peripheral warming seen in recent decades is not applicable to earlier intervals in the twentieth century. Satellite-derived climate data and measurements from automatic weather stations provide data over a wide area and show that since 1957 the whole continent has on average warmed up (Steig et al. 2009). This includes persistent warming for the entire period since 1957 of 0.17 °C per decade in West Antarctica (incorporating the peninsula), and a warming for East Antarctica that continued until some time in the 1970s, at which point a small cooling began. But the overall average rate of warming for East Antarctica since 1957 is positive at 0.1 °C per decade. In other words, the East Antarctic cooling detected in earlier studies applies only to the most recent parts of the records (Steig et al. 2009).

### 25.2.3 Oceanography

Measurements of oceanographic change in the Southern Ocean are sparse. Much information comes from limited ship-based measurements during science cruises, and from automated 'Argo' buoys that transmit water temperature and salinity data

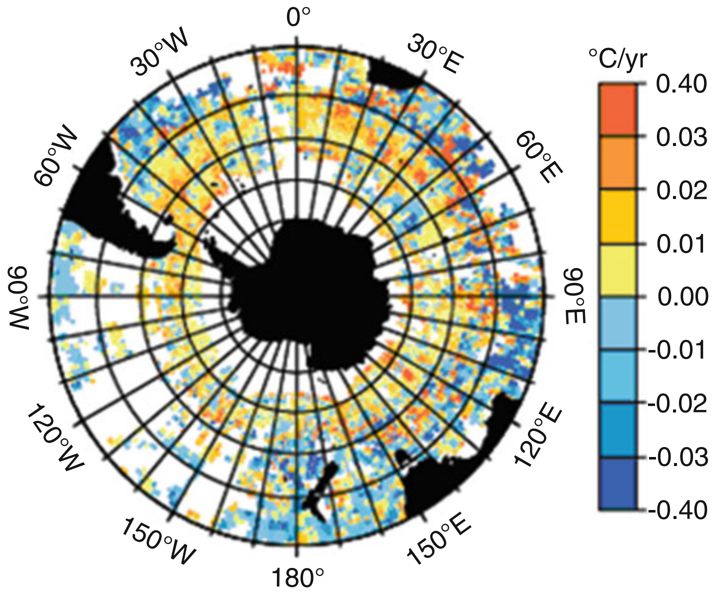



**Fig. 25.2** Temperature trends from shipborne measurements and automated float data since the 1950s for the Southern Ocean. Latitude and longitude grid lines are at 10° intervals. Most of the Southern Ocean warming is concentrated in the Antarctic Circumpolar Current (Reprinted from Gille 2002, with kind permission from AAAS)

via satellite (Chap. 7). The period of time for which we have measurements is small compared to other parts of the world's oceans but there are some clear trends in the data. The Southern Ocean shows a warming in recent decades, with many parts also getting fresher (i.e. lower salinity). The Southern Ocean has warmed by an average of $0.17 \pm 0.06$ °C since 1950 – nearly double the global ocean average amount – and much of this warming has been concentrated in the Antarctic Circumpolar Current, where mid-depth warming has been $0.008° \pm 0.002$ °C per year (Fig. 25.2) (Gille 2002). This puts it among the fastest warming parts of the global ocean.

Along the western margin of the Antarctic Peninsula there have been particularly marked changes. The surface waters have warmed by more than 1 °C since 1950 (Meredith and King 2005), and the upper 300 m by an average of 0.6 °C (Ducklow et al. 2007).

It is not just ocean temperature that has changed around Antarctica. There has been an increase in meltwater from the ice sheet, an increase in precipitation, and a reduction in sea-ice production locally, which have all led to a freshening of the oceans around parts of Antarctica. For example, repeat oceanographic measurements show that the Ross Sea freshened during the late twentieth century (Jacobs et al. 2002).

## 25.3 Causes of Climate Change

### *25.3.1 The Southern Annular Mode*

The pattern of peripheral warming and interior cooling has been used to suggest that changes in the Southern Annular Mode (SAM) are behind the climate changes in Antarctica. The SAM is the dominant factor in Southern Hemisphere climate, and is a measure of the relative strength of atmospheric pressure in the interior (or strength of the Antarctic vortex) and the peripheral pressure (or strength of the circumpolar trough) (Chap. 8). The SAM is described as being either positive or negative. In recent decades the SAM has shifted to a more positive mode (Turner et al. 2005), which means that the circumpolar trough around Antarctica has seen a more vigorous circulation (more storms, higher winds, and more mixing of warm air from lower latitudes). The end result has been a significant warming of regions such as the Antarctic Peninsula, which extend into the zone of influence of the circumpolar trough, while at the same time the interior of Antarctica has been cooling in recent decades (Steig et al. 2009).

Recent observations back this up with evidence of a shift of the westerly winds towards the South Pole during the last 40 years. Computer models suggest this is a response to anthropogenic warming (Shindell and Schmidt 2004). More recently, it has been suggested that the Recent Rapid Regional warming (Vaughan et al. 2003) in the northern Antarctic Peninsula is due to increased westerly wind strength, driven by increased greenhouse gas concentrations (Marshall et al. 2006). The shift to a more positive SAM may also be partly related to anthropogenic ozone depletion, which changes the thermal structure of the atmosphere (Chap. 8) (Thompson and Solomon 2002). So it seems that for the Antarctic Peninsula, anthropogenic-induced change in ozone and greenhouse gas concentrations may be driving the climate changes.

### *25.3.2 The Role of Sea Ice*

The marked winter warming of the Antarctic Peninsula is strongly linked to changes in sea ice immediately west (upwind) of the peninsula. During the same time span as the climate warming, winter sea ice to the west of the Antarctic Peninsula has been decreasing in extent by 10 % per decade, and has shortened in seasonal duration. There is a high correlation between the winter air temperatures at Vernadsky Station and the sea-ice concentration to the west of the peninsula: higher temperatures are strongly associated with lower sea-ice concentrations and vice versa (Fig. 25.3). This, along with the most marked warming occurring in winter has led to the suggestion that pronounced warming of the peninsula is at least partly due to reduced sea-ice concentration. Lower sea-ice concentrations can influence climate on the Antarctic Peninsula climate in at least three ways:

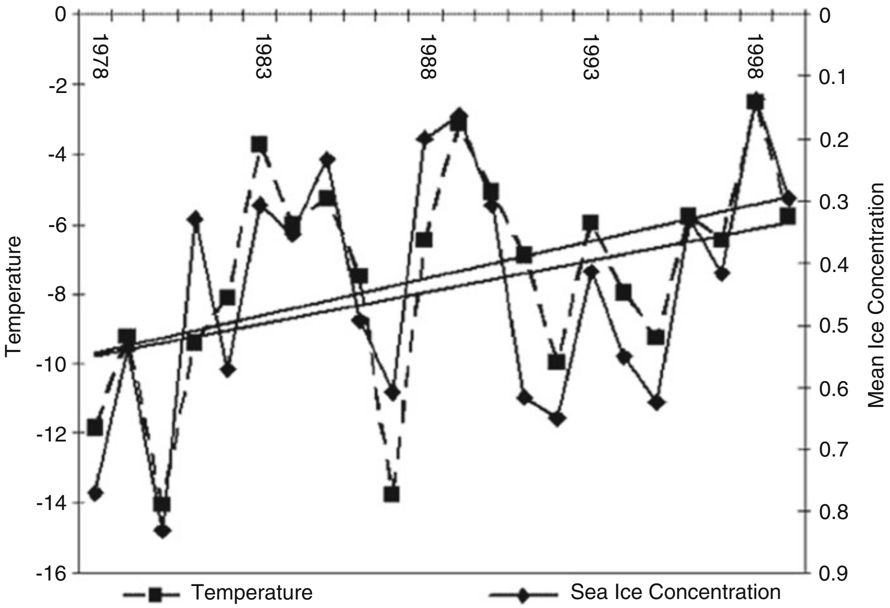



**Fig. 25.3** Winter season (June–August) mean sea-ice concentration at 70°W and Faraday/Vernadsky mean winter near-surface temperature. Trend lines produced by linear regression are shown for both time series. Note reversed scale for sea-ice concentration. Warmer temperatures correspond to smaller sea-ice concentrations (Reprinted from Turner et al. 2005, with kind permission from John Wiley & Sons)

- by allowing greater heat exchange from the relatively warm ocean to the atmosphere;
- by reducing the amount of solar radiation reflected back to the atmosphere (the albedo);
- by increasing maritime influence of the nearby land since the open ocean is closer and thus allows warm, moist air masses to penetrate more easily.

All of these factors promote warming and so it is thought that the sea-ice decline west of the peninsula may have contributed to the winter warming.

This relationship is unlikely to exist beyond the Antarctic Peninsula. Satellite data obtained since the late 1970s suggest that elsewhere around Antarctica there is either little change in sea-ice extent, or it may be increasing in extent (Turner et al. 2005; Bintanja et al. 2013). It is important to note that changes in sea-ice conditions result from processes occurring in the atmosphere or ocean and are therefore not the root cause of climate change on the peninsula. However, changes in sea ice have played a key role in amplifying climate change in the western peninsula.

### *25.3.3 Ocean Warming and Movement of Circumpolar Deep Water*

The warming of the ocean west of the Antarctic Peninsula is not fully understood. The warming of surface waters is a response to the warmer atmospheric temperatures (Meredith and King 2005) but the warming at depth may be due to increased movement of Circumpolar Deep Water onto the continental shelf of the peninsula (Chap. 7, Ducklow et al. 2007). The Circumpolar Deep Water is an important intermediate-depth water mass that is relatively warm, and floods onto the continental shelf at only a few sites around Antarctica. Where it does so, it delivers substantial additional heat. This can translate into surface warming when mixing of the top parts of the ocean occurs. The reason for the change in Circumpolar Deep Water is not well-understood but may be related to oceanic circulation changes – in turn influenced by atmospheric circulation patterns (Thoma et al. 2008). This variability can alter the topography of the ocean surface and thus the driving forces for water masses moving in the sub-surface.

## 25.4 The Physical Impacts of Climate Change

### *25.4.1 Ice Shelf Retreat and Collapse*

One of the most marked effects of climate warming in the Antarctic Peninsula is the abrupt retreat or collapse of ice shelves (Vaughan et al. 2003). In recent decades a number of ice shelves have shrunk to a tiny fraction of their former size, particularly on the east side of the Antarctic Peninsula where the Prince Gustav, Larsen A and Larsen B ice shelves have all collapsed. On the west side, the Wordie and Wilkins ice shelves have mostly disappeared whilst the George VI Ice Shelf has retreated significantly during the same period (Fig. 25.4). Some of these retreats have been spectacularly fast: for example the 3,250 $km^2$ Larsen B ice shelf collapsed in a matter of just a few weeks in the summer of 2001/2002. Some ice shelves have collapsed previously, during an interglacial period, but have then reformed, whereas for other ice shelves the recent collapse is unprecedented (Hodgson et al. 2006).

Ice shelf collapse in the Antarctic Peninsula is primarily attributed to atmospheric warming (Vaughan et al. 2003). There is a close association between ice shelves that have collapsed and locations where mean annual temperatures are between $-9$ °C and $-5$ °C (Morris and Vaughan 2003). Warming above the summer 0 °C isotherm (approximately coincident with the $-9$ °C mean annual temperature isotherm) leads to melting of the surface of the ice shelf. This melting results in lakes of water that fill crevasses and the pressure of this water can fracture the full depth of the shelf to break it into fragments and force collapse. Melting at the base of ice shelves by relatively warm marine water may also contribute to ice

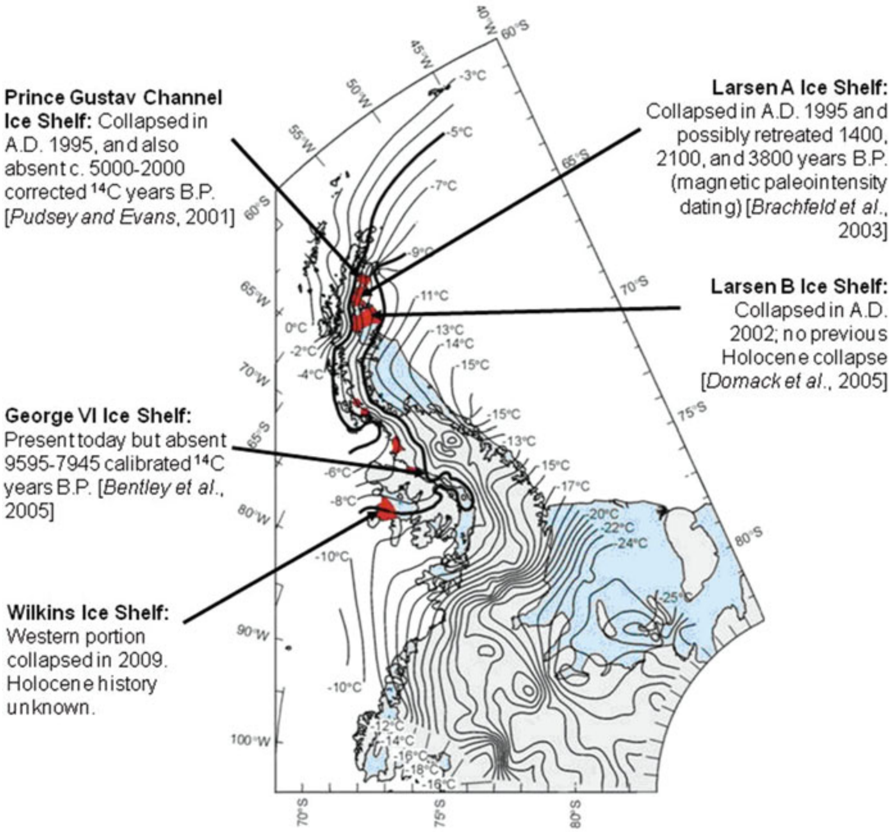



**Fig. 25.4** Recent retreat of Antarctic Peninsula ice shelves shown together with the mean annual isotherms. Retreated or collapsed ice shelves (*red*) coincide with the area between the −5 °C and −9 °C isotherms (*bold*). The −9 °C isotherm marks the southern limit of ice shelf stability, south of which there are still extant ice shelves (*blue*). No ice shelves exist north of the −5 °C isotherm. The stability of each ice shelf during the current interglacial (Holocene) is noted (Modified from Hodgson et al. 2006, with kind permission from John Wiley & Sons; original isotherm map courtesy of D. Vaughan, British Antarctic Survey)

shelf collapse, or at the very least make collapse easier by making the ice thinner (Shepherd et al. 2003).

An important effect of the collapse of fringing ice shelves along the Antarctic Peninsula is the acceleration of the glaciers feeding into the former ice shelves (Scambos et al. 2004). Collapse of the ice shelves themselves does not contribute significantly to sea-level rise because they are floating, but they hold back areas of grounded ice inland. As the ice shelves collapse and the buttressing effect is removed, the outlet glaciers thin and accelerate transporting their ice to the ocean and making a direct contribution to sea-level rise. For example, the collapse of the Larsen B ice shelf was followed by acceleration of Crane, Jorum, Hektoria and

Green glaciers that formerly fed into it. The nearby Flask and Leppard glaciers that continued to feed into a remnant portion of the same ice shelf showed little change over the same period (Scambos et al. 2004).

### 25.4.2 Glacier Retreat and Melting

Eighty-seven per cent of 244 marine-terminating glaciers in the Antarctic Peninsula have retreated since they were first surveyed, indicating marked glacial retreat in the peninsula (Fig. 25.5) (Cook et al. 2005). There is a clear boundary between those glaciers that show mean advance and those that show mean retreat, and this boundary has migrated southwards. The trend is consistent with the atmospheric warming, but this may not be the sole cause of glacier retreat (Cook et al. 2005).

The warming at Vernadsky Station has been accompanied by a 74 % rise in the number of days with temperatures above freezing, implying significant increases in surface melting on the Antarctic Peninsula (Vaughan 2006). However, much of the surface melt re-freezes in the ice sheet and it is not yet known what proportion of this extra melt reaches the ocean as run-off and contributes to sea level rise.

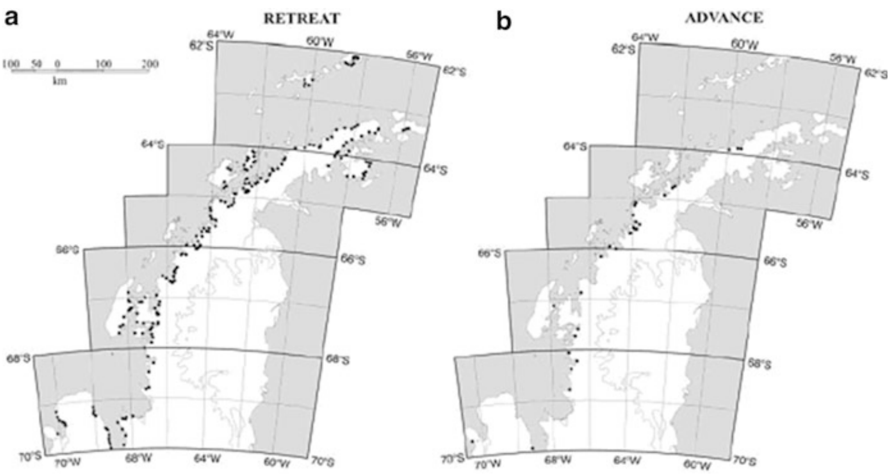



**Fig. 25.5** Change in Antarctic Peninsula glacier fronts since the earliest available records. Note that 87 % of the 244 glaciers measured have retreated since first surveyed. Dates of earliest records differ across the region (Reprinted from Cook et al. 2005, with kind permission from AAAS)

### 25.4.3 Glaciers in the Amundsen Sea Embayment

A major and ongoing change is occurring in the Amundsen Sea embayment. Here a series of major outlet glaciers are thinning, accelerating and retreating. The changes are most pronounced in the Pine Island Glacier but are also occurring in the Thwaites and Smith Glaciers (Fig. 25.6). Thinning of the Pine Island Glacier was first measured in detail in the 1990s but has accelerated markedly since then. In 1995, the lower reaches of the glacier were thinning at an average of 3 m per year

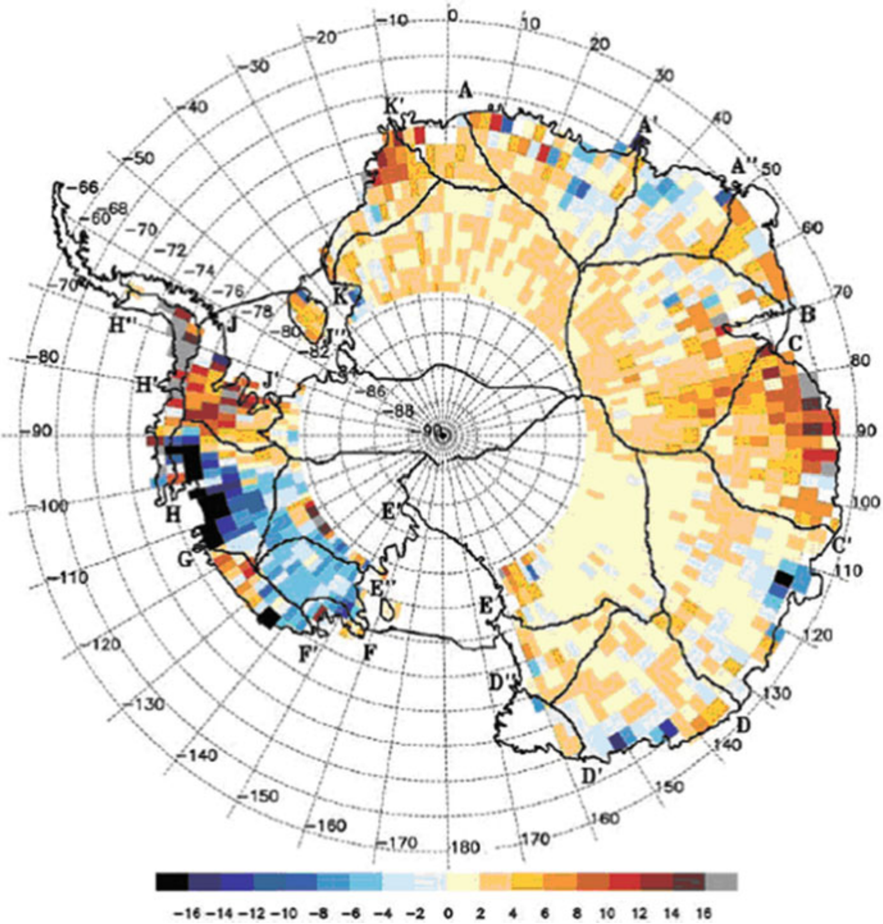



**Fig. 25.6** Satellite-altimetry measurements of the elevation change in the Antarctic Ice Sheet 1992–2003. The rapid thinning of glaciers in the Amundsen Sea embayment (−90 to −120 longitude) and the slow rates of thickening of the EAIS are clearly visible. Note that satellite coverage extends to 81.6°S and is considered unreliable in areas of steep topography, hence the lack of data along coastlines and the Antarctic Peninsula (Reprinted from Davis et al. 2005, with kind permission from AAAS)

but by 2006 this had increased to an average of 10 m per year (Wingham et al. 2009). The area affected by thinning has also expanded beyond the main trunk of the glacier and now extends over 100 km upstream and affects both the floating and grounded parts of the glacier. Thinning has also been accompanied by acceleration in velocity, and a retreat of the grounding line (Rignot et al. 2002; Park et al. 2013). The adjoining glaciers have also showed marked thinning and in some cases acceleration and/or retreat. The fastest-moving trunk of the Thwaites Glacier has also widened in recent years.

Such changes cannot be due to changes in precipitation because the thinning is too localised and it would not explain the acceleration and retreat of the glaciers. In addition, the similarity in behaviour of several major outlets over a large area suggests that there is a regional mechanism operating. The most likely mechanism is the intrusion of Circumpolar Deep Water onto the Amundsen Sea shelf (Payne et al. 2004). This warm water causes high rates of melting at the base of the ice, close to the grounding line, and the resultant thinning is transmitted rapidly upstream. This is particularly so in the Pine Island Glacier where the ice is thin and only lightly grounded in its lower reaches. The penetration of Circumpolar Deep Water may be related to changes in the seasonal wind circulation patterns around Antarctica. This is because changes in the winds can modify the transport of water onto the Antarctic continental shelf. The variability of these winds from year to year is consistent with greater delivery of Circumpolar Deep Water during intervals of enhanced thinning and acceleration of the Pine Island Glacier (Thoma et al. 2008).

The overall effect of glaciers in the Amundsen Sea is an ongoing positive (and probably accelerating) contribution to sea-level rise (King et al. 2012). Surveys of topography beneath the ice show that there are deep basins underlying the Pine Island Glacier. As the base of the ice melts and warm water reaches these basins, the ongoing retreat could become unstable and extend deep into the ice sheet. The potential vulnerability of this region was recognised by Hughes (1981) who dubbed the Pine Island Glacier “the weak underbelly of the West Antarctic Ice Sheet”.

### *25.4.4 Increased Snowfall Over East Antarctica*

Satellite measurements of the height of the East and West Antarctic ice sheets above sea level (satellite altimetry) have demonstrated that ice over large areas of the continent is thickening by 1–4 cm per year (Davis et al. 2005) (Fig. 25.6). This growth is particularly clear in the East Antarctic Ice Sheet (EAIS). Growth of the EAIS was predicted by the Intergovernmental Panel on Climate Change (Church et al. 2001) due to the likelihood of increased precipitation in a warming global climate, and it was suggested that the increased snowfall over Antarctica could offset some of the ice loss contributing to sea level. It has now been shown that although this effect exists, the snowfall-driven growth of the EAIS is not enough to offset the loss of ice from other parts of Antarctica such as the Amundsen Sea and the Antarctic Peninsula, and so the continent makes an overall positive contribution to sea-level rise (Velicogna 2009; King et al. 2012; Shepherd et al. 2012).

## 25.5 Biological Impacts of Climate Change

### *25.5.1 On Land*

On land, the warming climate of the Antarctic Peninsula has been accompanied by a southwards shift in some plant species, and more vigorous growth. There are also some concerns that as the peninsula warms, conditions will become increasingly similar to those on land to the north such as southernmost South America, and that this might mean that successful establishment of species from outside Antarctica becomes more likely (Chap. 27). Over 200 alien species of plants and animals have already been recorded in Antarctica, although most are on the subantarctic islands (Frenot et al. 2005) (Chap. 9). These include a wide range of taxa: microbes, invertebrates, plants and mammals. Not all of these introductions are due to climate change. Some introductions were deliberate and some may have been derived from propogules brought in inadvertently by scientists or tourists. However, it is clear that the potential for alien introductions has been increased by recent climate change. The island of South Georgia has been identified as particularly vulnerable because it is relatively far north, experiencing marked warming and with ongoing glacier retreat that opens up new, previously invader-free, areas, which might be colonised, and is also an increasingly popular tourist destination.

### *25.5.2 In the Oceans*

Warming has direct implications for a range of ocean organisms from penguins to invertebrates. Warming of the atmosphere and waters around the Antarctic Peninsula has been accompanied by local reductions in the ice-dependent Adélie penguin, and rises in the ice-intolerant gentoo and chinstrap penguins (Ducklow et al. 2007). This is thought to be related to the reduction in winter sea ice.

Experiments have shown that even modest warming of the ocean can affect the ability of invertebrates to carry out functions critical to their survival (Peck et al. 2004). For example, the Antarctic scallop (*Adamussium colbecki*) claps its valves together to 'swim' short distances and escape predators. When artificially warmed in aquaria, scallops show a marked loss of this ability; for every 1 °C of warming, about 50 % of the population lose their swimming ability (Fig. 25.7) and by the time waters reach plus 2 °C, none of the population can 'swim'. Similarly, as the surrounding water warms, the bivalve mollusc *Laternula elliptica* quickly loses the ability to rebury itself to escape from predators. These failures in activity are due to loss of aerobic function, and the experiments demonstrate that as little as 2 °C warming of the waters around Antarctica could cause population or species removal (Peck et al. 2004).

Some of the most sensitive species are killed by warming beyond 4 °C. Most Antarctic marine fauna are particularly poorly equipped physiologically to deal with such changes because they tend to be slow growing, long-lived, and relatively slow to reproduce. In addition, the shape of Antarctica and the small latitudinal

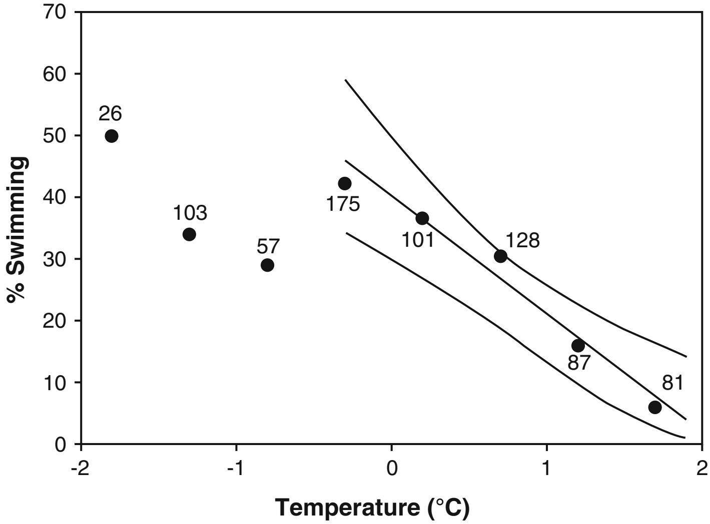



**Fig. 25.7** Temperature-related loss of critical functions in marine invertebrates. The plot shows the percentage of a population of *Adamussium colbecki* able to swim away from a freshwater stimulus, at a range of experimental temperatures. Numbers beside data points refer to the size of the experimental population. Above −0.3 °C there is a trend of decreased swimming ability shown by the central trend line (Reprinted from Peck et al. 2004, with kind permission from John Wiley & Sons)

range of the coastline means there is little opportunity to migrate away from such changes. Together these factors imply that Antarctic marine invertebrates may be one of the major animal groups threatened by climate change.

As with ecosystems on land, there are concerns that as the ocean warms the establishment of alien species from further north becomes more likely. However, much less is known about introductions to the marine environment, partly because it is less well surveyed in general than the terrestrial environment. So far only one marine invader has been confirmed: a species of spider crab from the North Atlantic that may have been introduced from ship's ballast water (Frenot et al. 2005).

## 25.6 Biogeochemical Cycles

The Southern Ocean is an important part of the global carbon cycle, one of several biogeochemical cycles on the planet. The ocean contains dissolved carbon dioxide ($CO_2$) and there is exchange of this carbon with the atmosphere (Chap. 8). The Southern Ocean can potentially act as a sink (or 'reservoir') for $CO_2$. Such sinks are crucial because they limit the increase in atmospheric $CO_2$ concentrations to only half the emitted amounts: in other words, sinks such as the Southern Ocean absorb half of what is emitted by human activities. The precise magnitude of the Southern Ocean sink is disputed but recent work suggests that the amount absorbed has gone down between 1981 and 2004 by 0.08 Pg carbon per year (1 Pg = 1 billion tonnes) (Le Quéré et al. 2007). The change is probably because of the observed increase in surface winds over the Southern Ocean, which can reduce $CO_2$ uptake by the ocean. The reduction happens because the stronger winds 'stir up' the ocean and cause it to release much of its dissolved $CO_2$. This trend is predicted to increase and atmospheric concentrations of $CO_2$ may reach higher concentrations than if the uptake had continued at its earlier rate.

More recent work has suggested that the retreat of ice shelves and glaciers along the Antarctic Peninsula has opened up new areas of open water and that there may be increased surface water plankton productivity in the region (Peck et al. 2009). If this is the case then carbon will be extracted from the atmosphere by plankton and then deposited on the seabed as they die, so these areas will act as new sinks for carbon. Peck et al. (2009) have shown that the new biomass created is several times greater than that lost by deforestation of a comparable area in the tropics, and that a significant fraction of the biomass will be deposited to the seabed. This recently discovered effect is important as it could potentially act as a negative feedback on greenhouse-gas induced climate change.

## 25.7 Summary

Recent climate change in Antarctica has occurred in both the atmosphere and oceans. Atmospheric warming has been most pronounced in the Antarctic Peninsula – one of the fastest warming regions on the planet – but is not restricted to this area. Similarly ocean warming has been marked in the waters west of the Antarctic Peninsula but most of the Southern Ocean is warming at a rate faster than the global average. The warming is at least partly due to anthropogenic effects of increased greenhouse gases and ozone depletion, but the effects in the Antarctic Peninsula are amplified by a significant loss of winter sea ice.

These changes have had a range of impacts, both physical and biological. These include the abrupt loss of ice shelves along the Antarctic Peninsula, accelerated movement of feeder glaciers and retreat of marine-terminating glaciers. In the Amundsen Sea embayment major outlet glaciers are thinning, accelerating and retreating. There is concern that these changes may result in an unstable retreat of a significant part of the West Antarctic Ice Sheet. The East Antarctic Ice Sheet is experiencing slow growth from increased precipitation associated with a warmer atmosphere but this is not sufficient to offset the ice mass loss in the Antarctic Peninsula and Amundsen Sea embayment, and overall Antarctica is making a net positive contribution to sea-level rise.

Biological impacts of climate change are diverse and include changes in species composition and range, and the increasing likelihood of alien species being introduced. In marine ecosystems, many invertebrates lose critical functions after even quite modest warming. Biogeochemical cycles are affected by changes in the ability of the Southern Ocean and Antarctic coastal waters to 'fix' carbon and act as a sink for some of the anthropogenic input to the atmosphere.

This chapter has highlighted recent advances in Antarctic climate research, and shown that major progress has been made in monitoring and understanding the Antarctic climate, both in the atmosphere and the oceans. However, robust predictions of what Antarctica and its climate will look like in the future are still hampered by a lack of understanding of some of the processes involved, and the complex connections between them.

## References

Bintanja R, van Oldenborgh GJ, Drijfhout SS, Wouters B, Katsman CA (2013) Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. Nat Geosci 6:376–379

Church JA et al (2001) In: climate change 2001: the scientific basis. Cambridge University Press, Cambridge, pp 639–694

Convey P, Bindschadler R, di Priscoa G, Fahrbach E, Gutt J, Hodgson DA, Mayewski PA, Summerhayes CP, Turner J, ACCE Consortium (2009) Antarctic climate change and the environment. Antarct Sci 21:541–563. doi:10.1017/S0954102009990642

Cook AJ, Fox AJ, Vaughan DG, Ferrigno JG (2005) Retreating glacier-fronts on the Antarctic Peninsula over the last 50 years. Science 308:541–544

Davis CH, Li Y, McConnell JR, Frey MM, Hanna E (2005) Snowfall-driven growth in east Antarctic ice sheet mitigates recent sea-level rise. Science 308:1898–1901

Ducklow HW, Baker K, Fraser WR, Martinson DG, Quetin LB, Ross RM, Smith RC, Stammerjohn S, Vernet M (2007) Marine pelagic ecosystems: the West Antarctic Peninsula. Philos Trans R Soc B 362:67–94. doi:10.1098/rstb.2006.1955

Frenot Y, Chown SL, Whinam J, Selkirk PM, Convey P, Skotnicki M, Bergstrom DM (2005) Biological invasions in the Antarctic: extent, impacts and implications. Biol Rev 80:45–72. doi:10.1017/S1464793104006542

Gille ST (2002) Warming of the southern ocean since the 1950s. Science 295:1275–1277

Hodgson DA, Bentley MJ, Roberts SJ, Smith JA, Sugden DE, Domack EW (2006) Examining Holocene stability of Antarctic Peninsula ice shelves. Eos Trans Am Geophys Union 87 (31):305–312

Hughes T (1981) The weak underbelly of the west Antarctic ice sheet. J Glaciol 27:518–525

IPCC (2007) Working group 1: summary for policymakers, fourth assessment report

Jacobs SS, Giulivi CF, Mele PA (2002) Freshening of the ross sea during the late 20th century. Science 297(5580):386–389

King MA, Bingham RJ, Moore P, Whitehouse PL, Bentley MJ, Milne GA (2012) Lower satellite-gravimetry estimates of Antarctic sea-level contribution. Nature 491:586–589. doi:10.1038/nature11621

Le Quéré C, Buitenhuis ET, Conway TJ, Langenfelds R, Gomez A, Labuschagne C, Ramonet M, Nakazawa T, Metzl N, Gillett N, Heimann M (2007) Saturation of the southern ocean $CO_2$ sink due to recent climate change. Science 316:1735. doi:10.1126/science.1136188

Marshall GJ, Orr A, van Lipzig NPM, King JC (2006) The impact of a changing Southern Hemisphere annular mode on Antarctic Peninsula summer temperatures. J Climate 19:5388–5404

Meredith MP, King JC (2005) Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. Geophys Res Lett 32:L19604. American Geophysical Union, Washington DC. doi:10.1029/2005GL024042

Morris EM, Vaughan DG (2003) Spatial and temporal variation of surface temperature on the Antarctic Peninsula and the limit of variability of ice shelves. In: Domack E, Burnett A,

Leventer A, Conley P, Kirby M, Bindschadler R (eds) Antarctic Peninsula climate variability: a historical and paleoenvironmental perspective. Antarctic Research Series, American Geophysical Union 79. American Geophysical Union, Washington DC, pp 61–68
Park JW, Gourmelen N, Shepherd A, Kim SW, Vaughan DG, Wingham DJ (2013) Sustained retreat of the Pine Island Glacier. Geophys Res Lett 40:1–6. doi:10.1002/grl.50379
Payne AJ, Vieli A, Shepherd AP, Wingham DJ, Rignot E (2004) Recent dramatic thinning of largest west Antarctic ice stream triggered by oceans. Geophys Res Lett 31:L23401. doi:10.1029/2004GL021284
Peck LS, Webb KE, Bailey DM (2004) Extreme sensitivity of biological function to temperature in Antarctic marine species. Funct Ecol 18(5):625–630
Peck L, Barnes D, Cook AJ, Fleming A, Clarke A (2009) Negative feedback in the cold: ice retreat produces new carbon sinks in Antarctica. Glob Chang Biol. doi:10.1111/j.1365-2486.2009.02071.x
Scambos T, Bohlander JA, Shuman CA, Skvarca P (2004) Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica. Geophys Res Lett 31:L18402. doi:10.1029/2004GL020670
Shepherd A, Wingham D, Payne A, Skvarca P (2003) Larsen ice shelf has progressively thinned. Science 302(5646):856–859
Shepherd A, Ivins ER, Geruo A, Barletta VB, Bentley MJ, Bettadpur S, Briggs KH, Bromwich DH, Forsberg R, Galin N, Horwath M, Jacobs S, Joughin I, King MA, Lenaerts JT, Li J, Ligtenberg SRM, Luckman A, Luthcke SB, McMillan M, Meister R, Milne G, Mouginot J, Muir A, Nicolas JP, Paden J, Payne AJ, Pritchard H, Rignot E, Rott H, Sørensen LS, Scambos TA, Scheuchl B, Schrama EJ, Smith B, Sundal AV, van Angelen JH, van de Berg W, van den Broeke MR, Vaughan DG, Velicogna I, Wahr J, Whitehouse PL, Wingham DJ, Yi D, Young D, Zwally HJ (2012) A reconciled estimate of ice sheet mass balance. Science 338:1183–1189. doi:10.1126/science.1228102
Shindell DT, Schmidt GA (2004) Southern Hemisphere climate response to ozone changes and greenhouse gas increases. Geophys Res Lett 31:L18209. doi:10.1029/2004 GL020724
Stammerjohn SE, Martinson DG, Smith RC, Iannuzzi RA (2008) Sea ice in the western Antarctic Peninsula region: spatio-temporal variability from ecological and climate change perspectives. Deep-Sea Res II 55:2041–2058
Steig et al (2009) Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. Nature 457:459–462
Thoma M, Jenkins A, Holland D, Jacobs S (2008) Modelling circumpolar deep water intrusions on the Amundsen Sea continental shelf, Antarctica. Geophys Res Lett 35:L18602. doi:10.1029/2008GL034939
Thompson DW, Solomon S (2002) Interpretation of recent Southern Hemisphere climate change. Science 296:895–899. doi:10.1126/science.1069270
Turner J, Colwell SR, Marshall GJ, Lachlan-Cope TA, Carleton AM, Jones PD, Lagun V, Reid PA, Iagovkina S (2005) Antarctic climate change during the last 50 years. Int J Climatol 25:279–294
Turner J, Bindschadler RA, Convey P, di Prisco G, Fahrbach E, Gutt J, Hodgson DA, Mayewski PA, Summerhayes CP (2009) Antarctic climate change and the environment. SCAR, Cambridge, p 526. ISBN 978 0 948277 22 1
Vaughan DG (2006) Recent trends in melting conditions on the Antarctic Peninsula and their implications for ice-sheet mass balance and sea level. Arct Antarct Alp Res 38(1):147–152. doi:10.1657/1523-0430(2006)038[0147:RTIMCO]2.0.CO;2
Vaughan DG, Marshall G, Connolley WM, Parkinson C, Mulvaney R, Hodgson DA, King JC, Pudsey CJ, Turner J, Wolff E (2003) Recent rapid regional climate warming on the Antarctic Peninsula. Clim Change 60(3):243–274
Velicogna I (2009) Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. Geophys Res Lett 36:L19503. doi:10.1029/2009GL040222
Wingham DJ, Wallis DW, Shepherd A (2009) The spatial and temporal evolution of Pine Island Glacier thinning, 1995–2006. Geophys Res Lett 36:LI7501. doi:10.1029/2009GL039126

# Chapter 26
# Reducing Fossil Fuel Consumption

## Renewable Energy in Antarctica

**Pat Bodger and Yvonne Cook**

**Abstract** Energy is needed for all human activity in Antarctica – generating electricity, heating buildings, supplying and heating water, treating and removing waste, and for transporting goods and people. Not only is the production of energy in Antarctica almost totally reliant on fossil fuels, so is the manufacture and supply of equipment for use once in Antarctica. Anything taken to the Antarctic continent, for any use, results from the consumption of fossil fuels somewhere on the planet. Using fossil fuels (petrol, diesel, oil and gas) has unwanted consequences. Carbon dioxide is released into the atmosphere and, if fuel spills occur in Antarctica, serious environmental damage can result. These are both good incentives for reducing the use of fossil fuels. Although we are a long way from using renewable energy for equipment manufacture and transport to Antarctica, the Antarctic community is increasingly meeting some day-to-day personnel and research needs while on the continent by using renewable energy.

**Keywords** Renewable energy • Solar systems • Wind systems • Hydrogen and fuel cells • Princess Elizabeth research station

## 26.1 Considerations for Renewable Energy

As a first step, opportunities exist to reduce energy consumption by improving the performance of lighting and heating systems, and only running appliances as needed. High-quality insulation to prevent heat loss, energy efficient light bulbs,

P. Bodger
Department of Electrical and Computer Engineering, University of Canterbury, Christchurch, New Zealand
e-mail: pat.bodger@canterbury.ac.nz

Y. Cook (✉)
School of Earth and Environmental Science, James Cook University, Townsville, QLD, Australia
e-mail: yvonne.cook@jcu.edu.au



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_26

motion sensors on lights to ensure they switch off when a room is empty, careful use of hot water and switching off appliances when not required can all save energy.

The conversion of the initial supply of energy, generated by the use of fossil fuels, into useable energy (e.g. electricity) can also be made more efficient. This requires up-to-date diesel electric generation technology and the use of exchangers on exhaust systems to recover heat from fossil-fuel combustion.

Renewable energy is derived from natural processes that are continually replenished and do not produce the high carbon dioxide emissions that result from burning fossil fuels. Included in the definition is energy (mainly electricity and heat) generated from the sun, wind, ocean, rivers, geothermal resources and bio fuels. Hydrogen, which is derived from renewable processes, is also included.

There are three main factors to consider when deciding to install renewable energy systems.

### *26.1.1 Availability*

Each geographical location where renewable energy is desired to be used will have different options in the amount of a particular energy form. For example, the amount of wind energy on a hill top or ridge line is likely to be significantly greater than in a cove or valley, thus affecting the location of wind turbines to convert the wind energy to electricity. Continued sunlight during the Antarctic summer can determine the orientation of solar panels for maximum energy capture.

### *26.1.2 Reliability*

Some renewable technologies provide intermittent energy. The wind doesn't always blow, or blow at a constant rate. In Antarctica, solar energy systems could only operate during the summer, and even then the sun may be obscured by cloud. Intermittency can lead to problems. For example, erratic supply means that generation from renewables and consumption of electricity are not in balance. Power might not be available for use when it is needed. The difference needs to be made up from somewhere. These potential problems can be overcome by either storing excess energy for use when energy production is low (Box 26.1) or combining two or more systems to produce a more constant energy supply.

**Box 26.1: Renewable Energy in Antarctica**

Solar panels and wind turbines do not generate power continuously. Unless connected alongside controlled generation, excess output must be stored, in batteries, for use when generation does not meet demand. One of the biggest challenges facing large-scale renewable energy systems is finding effective

(continued)

**Box 26.1** (continued)
storage of surplus energy. Battery banks holding 12–48-V lead-acid batteries are commonly used and should be able to withstand frequent deep discharging to meet high power demands. They are expensive due to their high initial cost and short battery life (they may need replacing every 4–10 years). The development of advanced materials for electrodes and techniques for managing current may allow batteries to absorb and release charge rapidly and with efficiencies and longevity well above conventional lead-acid batteries.

### *26.1.3 Cost*

When comparing renewable energy sources with each other and with conventional power sources, there are three main costs to consider: capital costs, operating and maintenance costs and fuel costs.

Renewable energy systems often require a lot of space or housing compared to fossil-fuel systems that produce the same amount of energy. This means that setup costs for alternative energy systems can be relatively expensive.

The extreme environment in Antarctica presents engineering and environmental challenges for installing renewable energy systems and well-trained technical staff are required to operate and maintain increasingly sophisticated systems.

Fossil and bio fuel costs are relatively high, and over the long term, fossil fuel costs have increased significantly. For other fuel, such as sun and wind, there may be no costs, or in the case of using waste products, the costs may be negative.

These three costs are brought together using 'discounted cash flow'. This means that all future cash flows are estimated and discounted to give their present day values. Renewable energy will become cheaper with time (it is on a decreasing cost curve), whereas non-renewable energy will become more expensive with time (it is on an increasing cost curve). In 2010, costs were comparable among wind, nuclear, coal and natural gas, but the costs for solar power were higher (Box 26.2).

**Box 26.2: Embodied Energy**
Embodied energy is the energy required to produce an item from raw materials, and deliver and install it on site for use. About 70–80 % of the embodied energy of material goods taken to Antarctica is in the transport of those goods, via shipping and aeroplanes.

## 26.2 Practical Renewable Energy Solutions

The windy Antarctic environment, along with 24-h daylight over the summer period, means that wind and sun are the most common means of providing renewable energy. Fortunately, these two forms of energy can complement each other. The wind is often blowing when the sun is obscured by clouds or is below the horizon during the Antarctic winter. The opportunity to use wind and sun together for maximum energy production occurs during the summer and coincides with high energy demand resulting from increased scientific activity. As the number of research and support staff grows over summer, water supply, waste treatment, transport and domestic energy requirements increase as well. However, heating requirements are largely independent of the number of people on base but instead are related to the outside temperature. Consequently, energy required for heating increases in winter as the outside temperature decreases. Some bases are not manned over winter and in these cases energy requirements for heating are very minimal. Other bases support a small population of research and support staff over winter and need to provide some heating and other domestic energy needs.

### *26.2.1 Solar Systems*

Solar energy systems work well in the extreme Antarctic environment. The key reasons for this are that Antarctica has clear and dry air, long summer daylight hours (when human activity at the station is most intense) and highly reflective, snow-covered ground. These all boost the solar energy available for use.

Solar technologies are either passive solar or active solar depending on the way they capture, convert and distribute energy. Passive solar techniques include orienting a building to the sun and using materials with high thermal mass (able to absorb, store and re-emit heat). Solar hot water systems are also passive and have been installed at some smaller bases. Active solar techniques include the use of solar (photovoltaic) panels and solar thermal collectors to gather energy (Box 26.3).

**Box 26.3: Energy Supply**

Power is the rate at which energy is converted and is directly related to current (ampere) and potential (volt) such that 1 W = 1 V × 1 amp. The higher the wattage, the more energy is produced during a given period of time. Active solar energy systems produce direct current (DC) which needs to be converted to alternating current (AC) via an inverter in order to use standard appliances. To find out how much energy is required, the total AC load needs to be calculated. This is done by adding together the power requirements of all the appliances that may be running at a time. This value is usually indicated on the appliance and is measured in watts (W). This total gives the power that the inverter needs to deal with and that the renewable energy system needs to supply. The number of hours per day this power is required is expresses as watt hours, or more commonly as kilowatt hours (kWh) which is the total watt hours divided by 1,000.

Any active solar system needs to withstand a wide range of temperatures without overheating. Also, it must be sited so it is protected from strong winds and is not covered by fresh or windblown snow, yet still able to receive maximum exposure to sunlight. The more solar cells in a solar panel and the higher the quality of the solar cells, the more total electrical output (watts) the solar panel can produce. However, solar panels capture only a small amount of the maximum potential energy from sun (some is lost due to cloud cover, etc.) and even when running at their most efficient, convert only a small percentage of the energy that strikes them into usable energy. The amount of power generated is given as a percentage of the maximum amount of power theoretically able to be generated and is called the capacity factor. This is typically under 25 for solar panels. The output of solar panels decreases with time and they are generally considered to have a maximum 25-year life span (Box 26.4).

**Box 26.4: How Solar Panels Work**
Each solar panel uses a grid of interconnected solar (photovoltaic) cells. Standard solar cells are made from silicon coated with metal conductors and covered in protective glass. The energy from light (photons) hitting the surface of the solar panel causes electrons to be knocked out of their orbits and released. Electric fields in the solar cells pull these free electrons in a directional current (DC), from which metal contacts in the solar cell can generate electricity.

### *26.2.2 Wind Systems*

The power from a wind turbine is proportional to the cube of the wind speed (the speed multiplied by itself twice) so as wind speed increases, power output increases dramatically. The power is also dependent on the wind mass (a function of air density and gravity) and the area swept by the blades of the turbine. While it is hard to predict the output power if a site is gusty, or where the wind speed varies considerably, the wind speed recorded at 10-min intervals can be used to estimate the likely power output. Areas where winds are stronger and more constant, such as offshore and high-altitude sites, are preferred locations for wind turbines, but usually several wind turbines are spread over a large area to increase the chance of harnessing wind continually. Larger modern wind turbines range from around 600 kW to 5 MW of rated power (maximum potential power output), although turbines with rated output of 1.5–3 MW have become the most common for commercial use. Capacity factors are typically 20–40 %, with values at the upper end of the range in good sites. Wind turbines usually require regular maintenance and typically last 20–25 years (Box 26.5).

**Box 26.5: How Wind Turbines Work**
The most common wind turbines are horizontal-axis turbines. They have the electrical generator at the top of a tower. The wind turns two or three blades attached to the rotor shaft. Since the tower produces turbulence behind it, the blades are usually pointed upwind of the tower. Small turbines are directed to the wind by a simple wind vane, while large turbines generally use a wind sensor linked to a small motor. The rotor contains either permanent or electro magnets such that when it spins inside the stator (coils or loops of copper wire wound around an iron core) it generates an alternating current (AC) electrical voltage in the stator coils. When connected to an electrical grid, the resulting current is fed into the grid for immediate use or fed into a battery for storage. Where a battery is used, a voltage regulator prevents overcharging. Most shafts have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator, but the turbines at Scott Base are gearless (see case study below).

### *26.2.3 Hydrogen and Fuel Cells*

Alternative energy systems using fuel cells and hydrogen are still in the technology development phase and are not yet commercially viable alternatives. Although hydrogen is relatively easy to store and is a high-energy, clean-burning fuel with only water as a by-product, it requires a lot of energy to produce and this energy is provided primarily either by fossil fuels or electricity. The Australian Antarctic Division is conducting a trial project to generate hydrogen using renewable energy supplied by wind turbines. The hydrogen could then be used for weather balloons, for heating and to power some vehicles.

## 26.3 Examples of Using Renewable Energy

### *26.3.1 Unmanned Field Stations*

Small-scale renewable energy systems using micro-scale solar arrays and small wind generators have been in use in remote locations in Antarctica for many years. These systems power scientific equipment and send the data back to a base either in Antarctica or elsewhere in the world.

Both solar and wind systems need to be able to withstand the ferocious katabatic winds that come from the Polar Plateau, especially during the winter. Mounting solar panels either vertically on a north-facing wall, or horizontally on the roof is usually sufficient. Both vertically and horizontally roof-mounted photovoltaic

**Fig. 26.1** The power-generation equipment at the Mount Newell field station consists of one diesel-fuelled generator, a solar array and a wind generator (© Pat Bodger)

panels and wind generators are shown at the New Zealand and American Mount Newell field station in Fig. 26.1.

A variety of different technologies are used to remotely monitor volcanic activity in the crater of Mount Erebus and to send this data back to base. The wind and solar-derived electricity is stored in a battery bank, as shown in Fig. 26.2. Diesel or petrol-driven electric generators can be used to top up or back up energy supply in the event of low battery storage or equipment failure.

Such a combined electrical system is summarised in the line diagram shown in Fig. 26.3, where a direct current conductor (DC bus) connects the wind turbines and solar panels with batteries, and an inverter converts the DC voltage to AC when AC power is required. Depending on the DC bus voltage, a DC-DC step down converter for DC loads may also be required.

## *26.3.2 Manned Field Camps*

Producing heat to keep people warm is one of the main energy requirements of manned field stations. In general, much more energy is required for heating than is needed to run scientific or communication equipment (for example heating needs


**Fig. 26.2** The battery bank at the Mount Newell field station with 36 sealed lead-calcium batteries (© Pat Bodger)

kilowatts of power but a computer needs only watts) so using renewable energy for heating would require a large amount of space and infrastructure. For this reason fossil fuels, particularly diesel, are commonly used for heating. However, buildings can be designed to incorporate passive solar heating and use double or triple-glazed windows, ceiling and floor insulation, as shown in the converted container used as a portable scientific laboratory in Fig. 26.4. Providing water, through melting snow, is also energy intensive, and while solar systems can be used, fossil fuels are generally found to be more convenient.

An electricity supply is also required for appliances, so a combination of fossil fuels for heating and renewable energies for electricity is appropriate. One example, shown in Fig. 26.5, is a building on Black Island, operated by the United States. Here diesel is used for heating the building but wind generators and horizontally mounted photovoltaic panels supply electricity for the operation of communications equipment. So, as for unmanned field stations, renewable energy for manned stations is mainly associated with providing electricity for scientific equipment and communication.

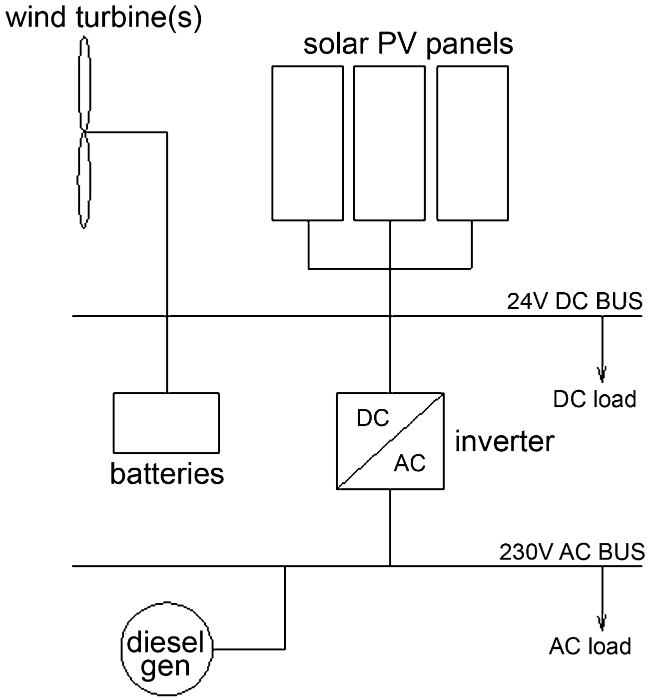



**Fig. 26.3** This *line* diagram shows a renewable electricity system (© Pat Bodger)

**Fig. 26.4** This shipping container has been converted into a portable scientific laboratory (© Pat Bodger)

**Fig. 26.5** These images show a portable wind generator which has been set up at to supply electricity for the operation of communications equipment (© Pat Bodger)

## 26.4 The World's First Zero-Emission Research Station

Wind and solar energy have been combined successfully in the state-of-the-art, purpose-built Belgian research station in Dronning Maud Land, East Antarctica. The Princess Elizabeth research station was commissioned by the Belgian government and officially opened in February 2009. This research station is home for up to 20 scientists during the summer and it supports them and their research entirely on renewable energy, without releasing any greenhouse gases.

The station uses eight small-scale wind turbines situated on a windy mountain ridge, and solar panels attached to the three-storey building, to provide all electricity. A solar heating system melts snow to provide water. The entire system is integrated and therefore extremely efficient. For example, by using the best waste management facilities (micro-organisms and decomposition allow reuse of shower and toilet water up to five times) energy consumption is reduced. The scheduling of the station's energy consumption can also be controlled. The energy system contains a 'programmable logic controller, the brain of the station, which continuously manages energy supply and demand, and prioritises energy needs to get the best energy efficiency. This means that the station can run on only one-tenth of the commonly accepted amount of energy. At the end of the 2009/2010 Antarctic summer, a satellite link was established to enable remote access to the programmable logic controller to monitor energy online, and to manage and adjust it remotely during winter when no people are on site.

## 26.5 Converting to Renewable Energy

The success of the Princess Elizabeth research station demonstrates that renewable energy is viable even in the harshest regions, where equipment has to withstand extreme cold, ferocious winds and winter darkness. However, it is one thing to construct a new, purpose-built facility, but quite another to retro-fit established research bases that might be more than 50 years old. Nevertheless, there are many opportunities to use renewables for a part of the overall energy supply.

### *26.5.1 New Zealand's Scott Base: Case Study*

Scott Base has been continually inhabited since 1957 and now accommodates up to 100 people during the summer as scientific research teams come and go. During winter, a small team of 10–15 people is present but the entire building is kept operational – no areas are completely shut down.

Until 2010, fossil fuels were used for almost all energy needs including heating and electricity generation for lighting, power, water desalination and other domestic services. Most fuel (about 80 %) is used for generating electricity using thermal heat recovery (as described below). A further 12 % of fuel is used to run diesel-fired boilers for additional heat and the remaining fuel (8 %) is used for transportation.

The heart of Scott Base's power system comprises three 225 kVA Caterpillar diesel generators, shown in Fig. 26.6. Only one unit is in operation at any one time, with one on standby, ready to go, and one as backup in case the other two fail. Heat is captured from the generators by marine manifolds in the engine and by exhaust heat exchangers. The heat recovered in this way is carried through Scott Base via a heating loop and is distributed to various rooms throughout the base. The generators are about 39 % efficient. Another 30 % of the waste heat is recovered for base heating to give an overall efficiency of the generators of about 69 %.

Additional heat is added to the heating loop by four diesel-fired boilers and two electric water heaters, as required. The boiler efficiency is about 80 %.

### *26.5.2 Energy Trends*

The yearly Scott Base energy requirement is influenced by two main factors: the level of activity at the base, which is highest in summer, and the level of heating and lighting required, which is highest in winter. The total amount of fuel used in the

**Fig. 26.6** One of three 225 kVA Caterpillar diesel generators at New Zealand's Scott Base (© Pat Bodger)

generators and boilers at Scott Base for 12 months from December 2001 through to the end of November 2002 is shown in Fig. 26.7.

As a comparison, the lower graph shows the recorded temperature. These graphs show that when the outside temperature is low during winter, the energy requirement is highest as a result of having to heat the base. This overrides other considerations such as the number of people on base.

The total energy production at Scott Base from December 2001 through to the end of November 2002 is shown in Fig. 26.8, with the estimated heating effects of the boilers and heat recovery from the diesel generator sets. As expected for a base run predominantly on diesel fuel, this correlates well with the total amount of fuel used. The extra energy for heating needed during winter is provided mainly through the use of the diesel-fired boilers, but both the electrical output and thermal energy recovered from the generators increase during winter. During summer, November through to March, the boilers are used only occasionally, with the thermal energy from the generator sets more than adequate to provide the base's heating requirements. The average electrical load is 155 kW with a maximum occurring during winter, near the generator's capacity of 225 kW.

### *26.5.3 Renewable Energy Potential*

Any system used to replace the generators will require, on average, 155 kW of power to provide a total reduction in fossil-fuel usage. The renewable energy

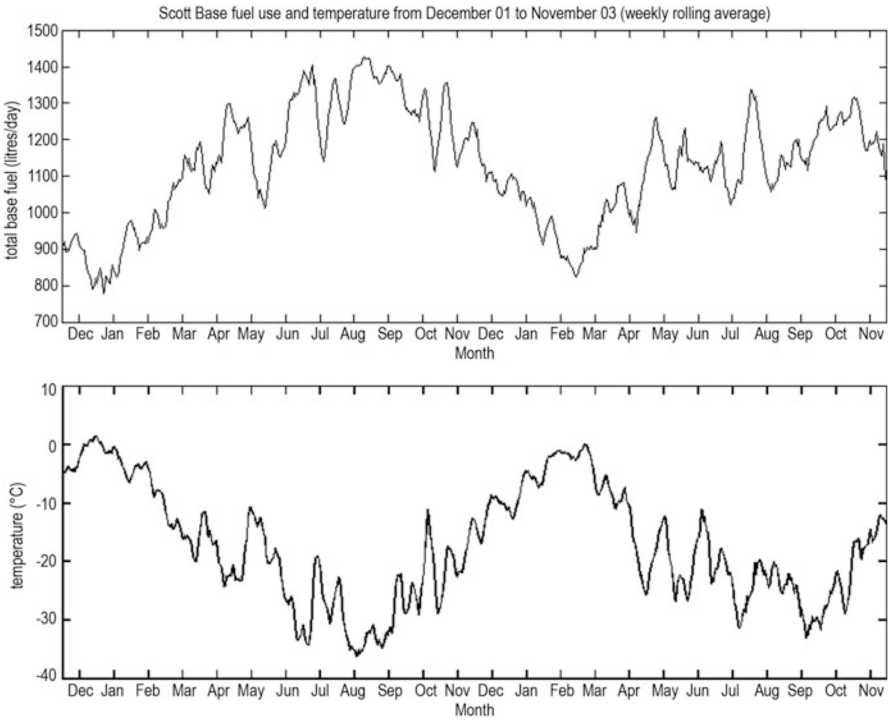



**Fig. 26.7** The *top panel* shows the total amount of fuel used at used at New Zealand's Scott Base, from December 2001 to November 2002. The *lower panel* shows the temperature in °Celsius (© Pat Bodger)

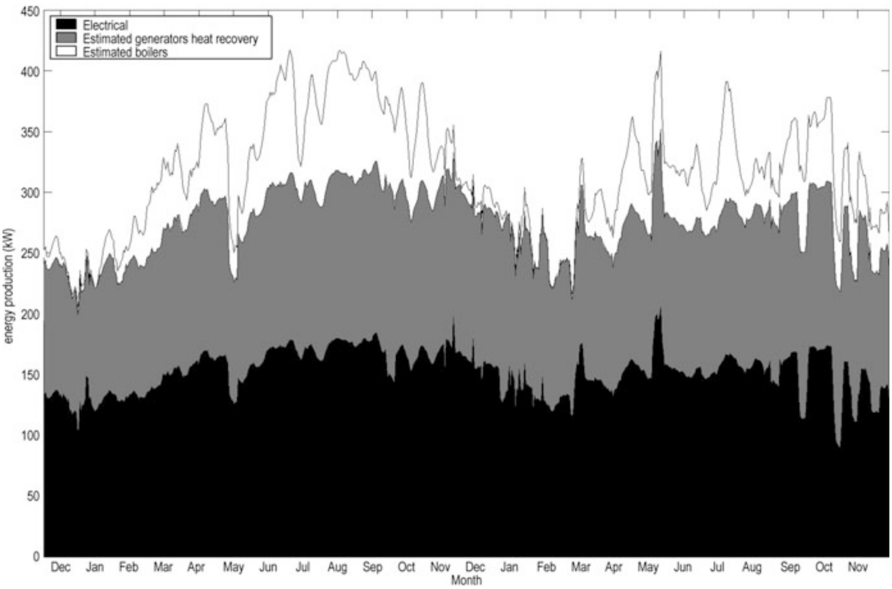



**Fig. 26.8** Total energy production, December 2001 to November 2002, at New Zealand's Scott Base (© Pat Bodger)

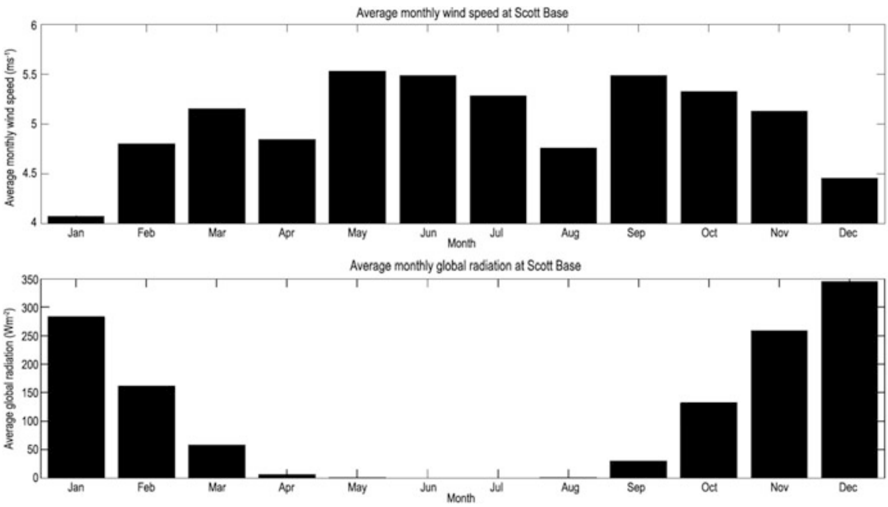



**Fig. 26.9** The average monthly wind speed (*top panel*) and solar radiation (*lower panel*) at New Zealand's Scott Base (© Pat Bodger)

potential for Scott Base can be assessed by looking at past metrological records of wind speed and sunlight exposure. Figure 26.9 shows the average monthly wind speed and global solar radiation at Scott Base from 1997 through to 2003. The plots show that, in a general way, in winter, when the sun is low or below the horizon, Scott Base experiences its windiest weather, so a combination of wind and solar energy are potentially suitable for year-round renewable energy supply.

The global solar radiation has high seasonal variation from zero watts per square metre (0 $W/m^2$) during winter to a peak of over 300 $W/m^2$ during December. If photovoltaic panels transform solar radiation into direct current with an efficiency of around 10 %, the maximum electrical power during December will be about 35 $W/m^2$, the average during summer from November to January will be 30 $W/m^2$ and the average for a typical year will be 11 $W/m^2$. The low transformation efficiency is the reason solar panels are generally limited to small summer field camps and field stations which have energy requirements no larger than several hundred watts and can be coupled with small wind turbines.

The average recorded wind speed at Scott Base is not high, with a yearly average of only 5 metres per second (5 $ms^{-1}$). Most turbines are rated at about 12–14 $ms^{-1}$. Since the power from the wind is proportional to the cube of the wind speed, if the wind is constant, a typical wind turbine of rated capacity at 12 $ms^{-1}$ would produce $(53/123) \times 100 = 7.2$ % of its rated output. However, Fig. 26.10 shows the typical 10-min wind speed and direction of data recorded at Scott Base during January 2003 and indicates that the wind speed is very variable with a maximum speed of about 17 $ms^{-1}$. A wind rose for Scott Base is shown in Fig. 26.11. The main wind directions are NE from the Ross Sea, NW from McMurdo Sound and the stronger SSW katabatic winds from the Polar Plateau.

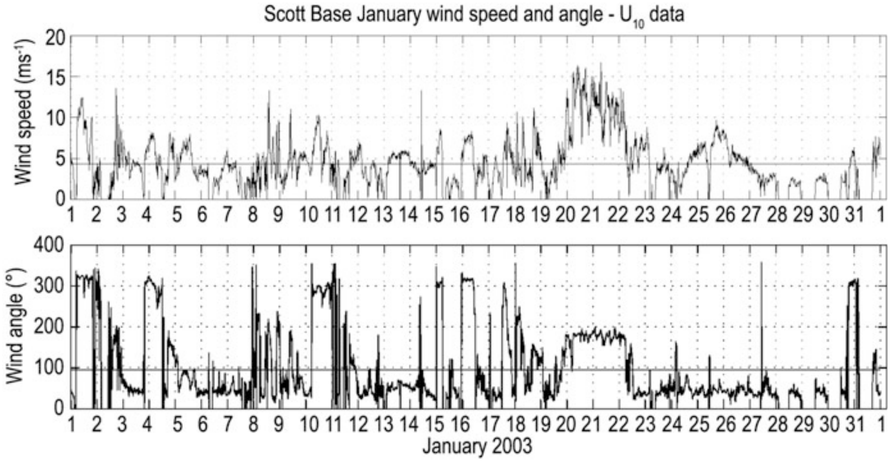



**Fig. 26.10** These panels show the typical 10-min wind speed and direction. Data recorded during January 2003 at New Zealand's Scott Base (© Pat Bodger)

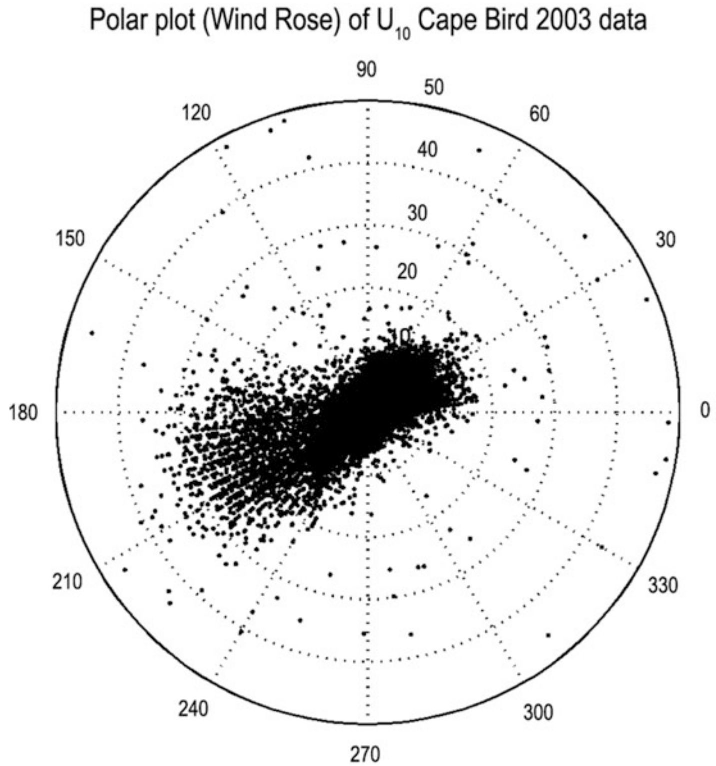



**Fig. 26.11** A wind rose for Scott Base shows the main wind directions and speed (© Pat Bodger)

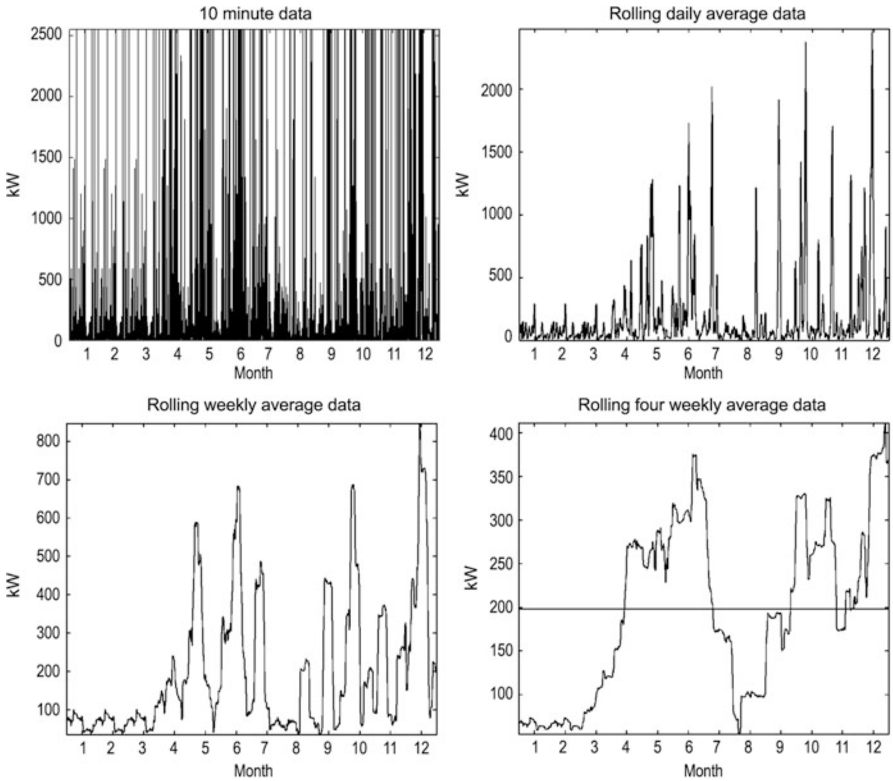



**Fig. 26.12** Power output of a Ropatec 3 kVA vertical axis wind turbine (© Pat Bodger)

If one makes the two assumptions that, firstly, a wind turbine will keep power to its rated output even at speeds above the rated wind speed and, secondly, a wind turbine will produce no power below the minimum rated wind speed, the data in Fig. 26.10 can be used to find the output power of a turbine. Figure 26.12 shows the output power of a 300 kW wind turbine rated for 12 $ms^{-1}$ during January 2003 at Scott Base. The average power produced during January is 37 kW or 13 % of rated capacity. Similarly, the average power output for May is 69 kW or 23 % of rated capacity. These power outputs are low, and a site with a higher average wind speed is required.

Arrival Heights is located 6 km from Scott Base on the west side of the American McMurdo station. It has an average wind speed of 7.5 $ms^{-1}$ with monthly averages. This is 1.5 times as windy as Scott Base.

Applying the same calculations and scaling for the Arrival Heights wind speed data gives an average power output of 82 kW or 27 % of rated capacity during January and 132.0 kW or 44 % of rated capacity during July.

Since the analysis for both Scott Base and Arrival Heights was undertaken, Antarctica NZ, in conjunction with Meridian Energy, a major New Zealand generation company, has installed and commissioned three wind turbines. The wind generators have been placed on Crater Hill, a site above Scott Base. While no wind data is presented for this site, it is expected to have a similar profile to that for Arrival Heights.

## 26.6 The Scott Base Wind Farm

**Box 26.6: Construction of the Scott Base Wind Farm**

The Scott Base wind farm cost about $7.4 million dollars. It was a large project that required careful planning. The opportunity to transport large, heavy items of equipment to Antarctica occurs only once a year, in February, by ship, and the practical working period is restricted to 12 weeks or so from November to January. During summer, the temperature was below minus 20 °C at times and good preparation and special techniques were required. The absence of equipment, infrastructure, aggregate and large quantities of fresh water makes it difficult to mix concrete onsite. Instead, prefabricated concrete foundations, as well as the structural steel foundations, the turbines themselves, a 65-tonne erection crane and other equipment were made in New Zealand and transported to Antarctica by ship. This made assembly easier and significantly reduced onsite risks. The equipment was stored over winter ready for summer installation. Also the steel foundations had to account for workers wearing bulky, extreme cold-weather clothing and thick gloves. Every metal edge had to be rounded off so they didn't cut through gloves during handling. Each foundation was built by using 8 of the 13-tonne pre-cast concrete blocks frozen into the permafrost. An eight-legged steel 'spider' was bolted to the concrete blocks and the turbine attached to this. Each of the eight foundation blocks was also fitted with two 12 m-long ground anchor bolts drilled and grouted in as a final safety measure to make sure the turbine can withstand wind gusts of up to 205 km/h. Major maintenance needs to be done once a year.

The Crater Hill site is approximately 190 m above sea level, and has an average annual wind speed of 7.9 m/s or 28.4 km/h at 39 m, the height of the turbine hubs. The new wind farm is comprised of three 333 kW, European-made Enercon E33 turbines that can generate up to 1 MW of electricity. Each structure is 41 m high and includes three blades with a diameter of 33.5 m, ideal for the conditions. Power electronics in the drive mechanism allow for the use of a variable-speed gearless turbine. No gearbox means no associated low-temperature oil issues. Ground-laid cables transmit power from the wind farm to Scott Base and McMurdo Station. These bases use different electrical frequencies (McMurdo 60 Hz, Scott Base 50 Hz) but a frequency converter at Scott Base converts the generated 60 Hz electricity to 50 Hz so it can be used. In addition, a flywheel system is also included which helps reduce the impact of fluctuating power on the area's small electric grid. The flywheel can absorb or supply 500 kW for 30 s to maintain the system frequency during sudden wind changes (Box 26.6).

## 26.7 Result

Renewable energy produced at the base reduces the need to ship down fossil fuels for use in the generators, saving hundreds of thousands of dollars, as well as reducing the carbon footprint. Diesel use at New Zealand's Scott Base and the American McMurdo Station has been cut by 463,000 l per year, roughly 11 %, and the carbon dioxide output has been reduced by 1,370 tonnes a year. The wind farm is a proof-of-concept development and if it continues to be successful, a more comprehensive system may be installed in the future.

## References

Arrillaga A, Bodger PS (2009) GREEN: Gathering Renewable Energy in Electrical Networks. EPECentre Series 1, University of Canterbury, Christchurch, New Zealand, ISBN 978-0-473-14428-9

Bodger PS (2204) Assessment of non-fossil fuel energy and waste minimisation research opportunities for Antarctica New Zealand. K233 Report, March 2004 and invited paper for keynote address, COMNAP (Council of Managers of National Antarctic Programs), X1 SCALOP (Symposium on Antarctic Logistics and Operations), Bremen, Germany, 25–30 August 2004

Hume D, Bodger PS (2004a) Renewable energy for Scott Base. A win-win situation. Electricity Engineers Association conference, Christchurch, 18–19 June 2004

Hume DJ, Bodger PS (2004b) An alternative energy proposal for Cape Bird Antarctic research station. International Conference on Power Systems (ICPS), Kathmandu, 3–5 November 2004

Hume DJ, Wood AR, Bodger PS (2005) Renewable energy in Antarctica. Poster presentations at annual Antarctic conference. University of Canterbury, Christchurch

Lo VL, Wood AR, Hume DJ, Bodger PS (2006) Modelling solar energy for Antarctic photovoltaic applications. COMNAP (Council of Managers of National Antarctic Programs), poster presentation at X1 SCALOP (Symposium on Antarctic Logistics and Operations), Hobart, Tasmania, Australia, 12–14 July 2006

# Chapter 27
# Alien Invasions

## The Impact of Non-native Species: Changing the Face of Life on Land in Antarctica?

**Peter Convey**

**Abstract** Unlike virtually any other area of land on the planet, the Antarctic continent is still largely un-impacted by the introduction of non-native species. Only a handful of non-native plants and animals (all invertebrates) are known, most from the northern Antarctic Peninsula and Scotia Arc. While several are persistent, and slowly increasing in local distribution, none have yet become truly invasive. The same is not the case in many of the subantarctic islands, where two centuries or more of human occupation and exploitation have led to many both deliberate and accidental introductions, and to sometimes drastic and probably irreversible changes in ecosystems. Recent years have seen an upsurge in primary research documenting the presence and impacts of non-native species in Antarctica, and in applying this information to the governance mechanisms within the Antarctic Treaty area and those of the various subantarctic islands. Organisms arriving through human activities, today primarily in the form of governmental (science and support) and tourism operations, numerically far outweigh natural colonisation events to this very isolated continent. Added to this, current and in some areas very strong regional climate change trends act in synergy to increase both the numbers of potential colonists and their establishment probability. Continued and increasing human contact with the Antarctic region is inevitable, and this can never be entirely separated from the risk of new introductions. Practicable control and mitigation measures, based on high levels of awareness and robust monitoring, survey and response protocols, are therefore the primary mechanisms available to slow and control rates of introduction and establishment.

**Keywords** Invasive species • Biosecurity • Governance • Subantarctic islands • Biogeography

---

P. Convey (✉)
British Antarctic Survey, Cambridge, UK
e-mail: pcon@bas.ac.uk



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_27

## 27.1 Introduction

Life on land in Antarctica receives less attention than that of the marine environment, not least because of the absence of charismatic terrestrial vertebrates amongst the fauna. Ice-free ground contributes only about 0.34 % of the total area of the continent, or around 44,000 km$^2$, with much of this experiencing the inhospitable conditions of inland areas, the high mountain ranges, and high latitudes, which prevent the survival of any but the most hardy species.

With the exception of the McMurdo Dry Valleys region of Victoria Land (itself 78–80° S), most ice-free ground on the continent consists of small islands or 'island-like' exposures of land surrounded by ice or sea (Bergstrom and Chown 1999; Convey et al. 2009a, b). The highest diversities of terrestrial life on the continent are found in lower altitude and less climatically extreme locations, generally close to the coast. Contrasting with the continent and Antarctic Peninsula, the subantarctic islands experience a much less strongly seasonal, although still chronically cool, climate and host more complex terrestrial biodiversity and communities. Nevertheless, overall the Antarctic terrestrial biota is species-poor and lacks many familiar higher taxonomic groups (Block et al. 2009; Convey 2013).

The native terrestrial fauna of the Antarctic continent consists entirely of invertebrates (Diptera – two species, only occurring in maritime Antarctica – Acari, Collembola, Nematoda, Rotifera, Tardigrada, Protista). Further higher insects and other arthropods are present on the subantarctic islands – particularly Diptera, Coleoptera, some Lepidoptera, and Aranaea, but terrestrial vertebrates remain limited to a single passerine bird on subantarctic South Georgia, two species of duck on South Georgia and Îles Kerguelen, and two species of seal- and penguin-associated sheathbill on South Georgia and Marion Island (one of which also occurs in maritime Antarctica). Likewise, continental plant communities largely comprise lower plants (mosses, liverworts) and lichens, with the two higher plants present limited to the maritime Antarctic. Ferns and a greater diversity of native flowering plants occur on the subantarctic islands, although overall diversity remains low. Biodiversity and the complexity of biological interactions within communities generally decrease with increasing latitude and environmental severity, although in detail this hides considerable complexity (Convey et al. 2014).

However, fine-scale baseline survey data are sparse and many gaps remain in our knowledge of the diversity and biogeography of much of Antarctica and/or specific groups of biota (Chown and Convey 2007; Convey 2011; Terauds et al. 2012). Ecosystem structure and trophic complexity are simplified and, at the extreme, the continent's terrestrial communities are amongst the simplest known (Freckman and Virginia 1997; Convey and McInnes 2005; Hodgson et al. 2010). Rigorous functional studies are rare (Hogg et al. 2006, but see Caruso et al. 2013), but most diversity and energy flows are thought to contribute to the decomposition cycle, with true herbivory or predation being insignificant.

Even accepting the weaknesses in the biodiversity data available for terrestrial plants and animals, that for most microbiota is minimal (Cowan et al. 2011; Chong et al. 2012, 2013). The importance of microbial autotrophs in polar terrestrial ecosystem processes is well-recognised (Vincent 1988; Wynn-Williams 1993, 1996a). However, it remains the case that understanding of their role in ecosystem function – a vital component in ecosystem responses to change – is poorly developed. The application of modern molecular biological techniques is now leading to a rapid, although spatially focused, increase in microbial diversity and functional data (Chong et al. 2012, 2013; Pearce et al. 2012; Chan et al. 2013).

Antarctic, and more generally polar, terrestrial ecosystems are predicted to be vulnerable to various consequences of environmental change and human activity, high amongst which is colonisation by non-native species (Kennedy 1995; Freckman and Virginia 1997; Walther et al. 2002; Frenot et al. 2005). The simplicity of Antarctic ecosystems is often assumed to indicate that they have little of the functional redundancy that typifies more diverse lower-latitude ecosystems. This opens up the possibility that new colonists may occupy currently non-utilised ecological niches (including unrepresented trophic functions and levels), potentially fundamentally changing the structure and function of these ecosystems (e.g. Convey et al. 2010). If so, the native biota may be further limited or disadvantaged by their adversity-selected life history strategies (Convey 1996), in which features relating to competitive ability are very poorly developed.

## 27.2 Antarctic Isolation

Antarctica as a whole is geographically isolated by simple distance, and is surrounded by oceanic and atmospheric barriers that act to reduce or minimise the probability of direct north-south transfers into the region. However, clearly such transfers do take place over both evolutionary and contemporary timescales (Marshall 1996; Clarke et al. 2005; Barnes et al. 2006).

As with colonisation events elsewhere, the most plausible routes of natural dispersal involve wind or water currents, and associations with migratory birds and mammals (zoochory) or debris (including human-sourced debris) (hydrochory) (reviewed by Hughes et al. 2006). Few studies have attempted to quantify the relative importance of natural compared with human-associated (anthropogenic) colonisation processes in Antarctica. The only data available, or from which inferences can be made, derive from studies on Gough Island (a cold-temperate oceanic island in the South Atlantic) and subantarctic Marion Island in the Indian Ocean (Gaston et al. 2003; Gremmen and Smith 2004). These studies indicate cases of anthropogenic colonisation have outweighed natural processes by at least a factor of 100 since the islands' respective discoveries, although how far this observation can be generalised to more extreme Antarctic Peninsula and continental locations is not clear.

## 27.3 Anthropogenic Assistance in Colonisation

The subantarctic islands were the first landmasses to be discovered in the Antarctic region, and were almost uniformly rapidly exploited. Therefore, most have experienced drastic alterations in their terrestrial ecosystems over the last two to three centuries (Frenot et al. 2005, 2008; Convey et al. 2006; Greenslade 2006; Chown and Froneman 2008; Convey and Lebouvier 2009).

Although the details and impacts vary between the different islands, most now host a wide range of non-native plants and animals. A number of islands have seen the deliberate establishment of grazing mammals including reindeer, sheep, mouflon, cattle and rabbits (Fig. 27.1; see Convey and Lebouvier 2009, for detailed summary), drastically altering the vegetation communities, which have themselves evolved in the complete absence of grazing herbivores (e.g. Bergstrom et al. 2009).

Cats were also introduced to several islands (Marion, Kerguelen, Macquarie, South Georgia) and feral populations became established on all these except South Georgia. In most cases this was in a vain attempt to control deliberately introduced rabbits or the rodents (rats and mice) that had inevitably been introduced accidentally from ships during early sealing operations or in shipwrecks. Similarly, the early and middle decades of the twentieth century saw examples of the deliberate

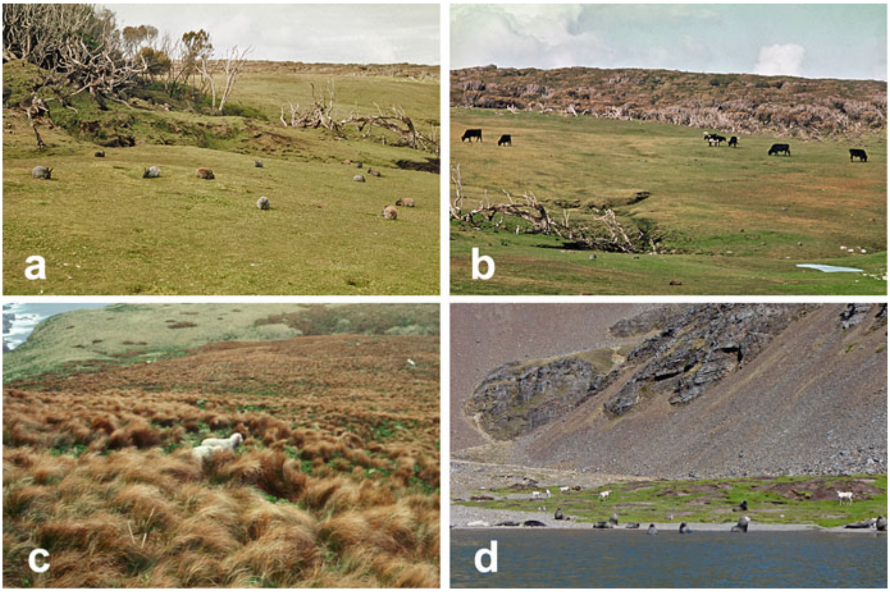



**Fig. 27.1** Grazing animals have been introduced deliberately on several subantarctic islands. This panels shows (**a**) rabbits and (**b**) cattle on Enderby Island, which is part of the Auckland Islands, (**c**) sheep on Campbell Island and (**d**) reindeer grazing amongst coastal vegetation and Antarctic fur seals (*Arctocephalus gazella*) in West Cumberland Bay, South Georgia (With kind permission from Pete McLelland (**a**–**c**) and Chester Sands/BAS (**d**))

**Fig. 27.2** This panel shows (**a**) the invasive carabid beetle *Trechisibus antarcticus* found on South Georgia, (**b**) a bank of dandelions (*Taraxacum officinale*) on South Georgia, (**c**) *Nassauvia magellanica*, a plant which is indigenous to Tierra del Fuego but was found growing on Deception Island in 2009, and (**d**) *Eretmoptera murphyi*, a subantarctic midge that has been introduced to Signy Island in the maritime Antarctic (With kind permission from BAS, Peter Convey/BAS)

import of various vertebrates to Antarctic expedition camps or the developing network of stations on the continent. However, in these cases the animals could only survive in close association with the human activity. While it is likely that rodents would have been taken ashore inadvertently at this time, they are not known from any location on the continent or Antarctic Peninsula at the present time.

Other than the deliberate introductions of larger vertebrates, the majority of instances of non-native species establishing on these islands have been inadvertent. Frenot et al. (2005) estimated that around 200 confirmed instances of establishment were known at that time, with >95 % of these applying to the subantarctic islands, and around half of the species being flowering plants and a third terrestrial arthropods (Fig. 27.2).

While on the face of it this number appears small, it should be placed in the context of the native biodiversity. For instance, several subantarctic islands now host more species of non-native flowering plant than are present in their natural flora. Furthermore, and as acknowledged at the time, the number given was a conservative estimate. Many locations, and many of the non-charismatic taxonomic groups requiring specialist expertise, have not been the subject of detailed survey or study. However, it is already clear that the subantarctic provides an urgent warning of the consequences that will ensue in the event of invasive non-native species establishing at more southern locations (Frenot et al. 2005; Convey et al. 2006).

Over the last decade, a range of new studies have identified further instances of species colonising both sub- and, increasingly, maritime Antarctic locations with anthropogenic assistance (e.g. Convey et al. 2010; Greenslade and Convey 2012; Smith and Richardson 2011; Greenslade et al. 2012; Molina-Montenegro et al. 2012; Volonterio et al. 2013), highlighting that the processes and associated risks are ongoing. There are also two very recent reports of exotic species of plant (a fern and a rush) germinating from propagules contained in sediments or soils obtained on or at the edge of glaciers (Cuba-Díaz et al. 2013; Smith 2014). These may indicate natural transfer of viable propagules into the region.

Wall et al. (2011) and Convey (2011), in the wider context of identifying the impacts of all aspects of environmental change in Antarctica including both direct and indirect human impacts, highlight the urgent requirement for, and chronic lack of, robust and wide-scale biological monitoring programmes. Without these, new instances of establishment and their subsequent impacts are likely to go unnoticed, at least beyond the period when effective mitigation or control might be practicable. Nevertheless, it is clear that many transfers of biota do occur, and the major vectors or risk factors have been identified, including cargo, vehicles, food, clothing and people themselves (e.g. Whinam et al. 2004; Frenot et al. 2005; Lewis et al. 2006; Hughes et al. 2006, 2010; Lee and Chown 2009a, b; Tsujimoto and Imura 2012; Chown et al. 2012).

Transfers are also facilitated by a change in the balance of different logistic means for reaching Antarctica. Historically, this generally involved extended periods at sea, which effectively acted as an (imperfect) 'colonisation filter' by requiring extended survival of any inadvertently transported propagules. In recent decades the use of air transport has increased rapidly, particularly in the more vulnerable Antarctic Peninsula region, and transport times are now only hours (Bölter and Stonehouse 2002; Frenot et al. 2005). Air transport has been routine to the USA's McMurdo Station in Victoria Land since its inception, but the high latitude and much more extreme environment have protected this region from known macrobiotic non-native colonisation.

## 27.4 Biosecurity and Governance Procedures

The Antarctic continent is exceptional in global terms through being governed by a major international treaty – the Antarctic Treaty (Chap. 16). This came into force in 1961 and applies to the area south of 60°S latitude. It recognises the existence of pre-existing national territorial claims, placing them in abeyance while the treaty is in operation. It promotes the peaceful use of the continent, in particular through international cooperation in scientific research, and defines measures for the "preservation and conservation of living resources in Antarctica".

The treaty currently has 52 signatory nations, representing about 65 % of the global population. These consist of 29 Consultative Parties which participate in consensus decision making, and 23 Non-Consultative Parties. All the parties meet annually at the Antarctic Treaty Consultative Meeting (ATCM). The Antarctic Treaty is an overall framework, but its agreements are implemented by parties through their own national laws (Kriwoken and Rootes 2000). This inevitably leads to both differences of interpretation and different methods of enforcement and levels of compliance between nations, as well as bureaucratic delays as the treaty's major conventions do not enter into force until they are approved by all Consultative Parties.

The Antarctic Treaty includes legal instruments specifically for the protection and management of the Antarctic environment and its biota. Most pre-existing instruments have largely been absorbed into the Protocol on Environmental Protection to the Antarctic Treaty (generally referred to as the Environmental Protocol or Madrid Protocol), which was approved by the ATCM in 1991 and entered into force in 1998. The Environmental Protocol effectively gives the entire Antarctic Treaty area protection and conservation (see Convey et al. 2012, for expanded discussion). Under the Environmental Protocol, the Committee for Environmental Protection (CEP) has been established as an expert body that meets annually, providing advice and recommendations to the ATCM. Three of the six annexes of the Environmental Protocol (dealing with environmental impact assessment, conservation of Antarctic fauna and flora, and area protection and management) are directly relevant in the context of non-native species.

Lying outside the Antarctic Treaty's area of control, the sub- and peri-Antarctic islands fall under national sovereignty and governance. In many cases, large parts or all of these islands are defined as some form of reserve, national park or conservation area within national legislation, with some islands also receiving World Heritage Site status in reflection of the importance of their natural environments.

Specific control measures and procedures are only as effective as the understanding, engagement and implementation of their users. Failures, often simple human error, can result in significant transfer events. For instance, the procedural failure to carry out simple visual inspections or cleaning of vehicles being transferred from subantarctic South Georgia to Adelaide Island towards the south of the maritime Antarctic resulted in over 132 kg of attached soil being transported, which was only discovered a week after arrival (Hughes et al. 2010). The soil contained living organisms and propagules of a range of biological groups, including plants, invertebrates and microbes, some already known to be capable of survival and establishment under the more extreme southern conditions.

Perhaps more seriously, it can already be argued that certain densely used locations – such as the Fildes Peninsula on King George Island (South Shetland Islands) – are already, in effect, little more than sacrificial areas, with compelling and visible evidence available that several nations amongst those operating there routinely pay little or no attention to the achievement and enforcement of existing environmental and biosecurity practices (Committee for Environmental Protection 2011; COMNAP and SCAR 2011) specified under the Environmental Protocol, even with respect to the defined Antarctic Specially Protected Areas within the location (ASPAs 151 Ardley Island and 125 Fildes Peninsula), or to the guidelines of organisations such as SCAR (Braun et al. 2012; Peter et al. 2013). Such instances generate serious damage to the credibility of the governance achieved under the Antarctic Treaty System.

## 27.5 Known Instances of Introduction and Establishment

The appreciation of the risks of non-native species introductions, and the biosecurity standards applied, have changed considerably over the years. In the 1950s, 1960s, and 1970s, for instance, there were several deliberate plant transplant experiments moving species from other locations (e.g. southern South America, Falkland Islands, South Georgia, the Arctic) to the maritime Antarctic South Orkney Islands and Antarctic Peninsula (Corte 1961; Edwards and Greene 1973; Edwards 1980; Smith 1996). While none of the transplanted species remain at these locations – either being unable to survive or removed at the end of the studies – procedures at the time did not properly address the risk of other species being transported with the plants or their associated soil. It later became clear that these experiments may have been the source of subsequently identified and now established non-native invertebrates (e.g. Block et al. 1984; Convey and Block 1996; Dozsa-Farkas and Convey 1997; Convey and Quintana 1997; Hughes and Worland 2010; Hughes et al. 2013a), as well as the completely unquantified possibility of microbial introductions.

Several of the subantarctic islands – particularly Îles Kerguelen – have seen more organised attempts at the establishment of plants as food crops, and of trees, and this is particularly the case with Îles Kerguelen and the peripheral or cool temperate island groups such as the New Zealand shelf islands, Amsterdam and St. Paul Islands, and the Tristan da Cunha archipelago. Within the Antarctic Treaty's area of governance, such transplants are no longer allowed, and a permitting system has been developed for controlling any import of non-native biota into Antarctica for scientific research and their subsequent removal or destruction.

While the number of non-native species established in the maritime and continental Antarctic biogeographic zones is clearly much lower than in the subantarctic, as noted above there have been several important new records of establishment in the maritime region in only the last few years. Frenot et al. (2005) considered that at that time there was no evidence suggesting that any of these species had become invasive in maritime or continental Antarctica.

However, recent evidence for the expansion of the distribution of the grass *Poa annua* both near to its introduction site on King George Island (South Shetland Islands) (Olech and Chwedorzewska 2011) and to new locations on the northern Antarctic Peninsula (Molina-Montenegro et al. 2012) suggests that this situation may be changing. Likewise, the most recent survey of the distribution of the introduced detritivorous midge *Eretmoptera murphyi* (Fig. 27.2) on Signy Island (South Orkney Islands) confirms a combination of expanding distribution and high larval population densities (Hughes and Worland 2010), and permits a reasonable calculation that this species, where it occurs, contributes to an up to five times greater magnitude of nutrient recycling than that achieved by the entire native invertebrate decomposer community (Hughes et al. 2013b).

Facilities at stations can provide a further reservoir of non-native species with the potential to become established in the Antarctic terrestrial environment. There are many examples of such species surviving synanthropically within occupied buildings for at least several years (e.g. Greenslade 2006; Hughes et al. 2005). Soil, equipment or clothing associated with a greenhouse facility at the Polish Arctowski Station are most likely to have been the source of seeds of *Poa annua*, which was originally noted near the entrance to one of the station buildings and has now spread widely around the station area and into local natural habitats (Olech 1996; Olech and Chwedorzewska 2011).

It should also be noted that this grass species, along with its congener *P. pratensis*, which is established near the Argentinian Pimavera Station on the north-west Antarctic Peninsula (probably inadvertently in association with the aforementioned transplant experiments; Corte 1961; Pertierra et al. 2013), are both invasive on several subantarctic islands, providing a warning of likely trajectories if the conditions of maritime Antarctica continue to warm as they have over recent decades. In this context, the approach of Greenslade (2002) and Greenslade and Convey (2012) to providing objective risk assessments ranking likely invading species in the subantarctic appears to be useful.

Even where the presence of non-native species has been recorded, few if any have been subject to any form of formal monitoring of populations or trends, or functional studies of impact. As an example, the cosmopolitan springtail *Hypogastrura viatica* has been recorded from the South Shetland Islands (a focus of human activity – both national operator and tourism industry – in the Antarctic Peninsula region) and in Marguerite Bay near Adelaide Island (Greenslade 1995; Greenslade et al. 2012). This species is a particular concern, as it has become an aggressively invasive species on some subantarctic islands, including South Georgia and Macquarie Island (Convey et al. 1999; Frenot et al. 2005; Greenslade 2006). Recently, Greenslade et al. (2012) have recorded three further non-native springtails to be established on Deception Island in this archipelago, it being noteworthy that these species feature highly in the precautionary risk assessment developed by Greenslade and Convey (2012) for identifying the greatest risk of invasions on subantarctic South Georgia.

Some of these examples highlight the challenge of assessing the natural or anthropogenic source of a newly discovered colonist (see Hughes and Convey 2012, for discussion). For instance, the springtails *Folsomia candida* and *Protaphorura* sp. have previously been reported from Deception Island (Greenslade and Wise 1984), but were not present in more recently made collections (Downie et al. 2000; Greenslade et al. 2012), and their association with human activity remains unproven. Deception Island is currently the centre of non-native arthropod diversity in the Antarctic Peninsula region, as well as being the site of several research stations over the last six decades and a major tourist visitation site. However, it is also geothermally active, a feature known to encourage the natural establishment of lower latitude plant and animal taxa otherwise unable to survive in the Antarctic terrestrial environment (Convey et al. 2000a, b; Smith 2005).

The recent discovery of the plant *Nassauvia magellanica* (Fig. 27.2), indigenous to Tierra del Fuego, growing on Deception Island led to its removal under the 'precautionary principle' (Smith and Richardson 2011; Hughes and Convey 2012). However, given the plant, on its discovery, had clearly been growing in situ for several years, there was no direct evidence of its source or route of entry, and likewise no objective means of assessing the relative probabilities of the various natural or assisted colonisation routes.

The requirement to make appropriate management decisions in such circumstances relating to non-charismatic groups of terrestrial organisms is likely to become the norm. This presents a serious practical challenge to the governing authorities at any given location – in this case the Antarctic Treaty Consultative Parties – who, in essence, are presented with the dichotomy between assessing a new discovery to be a natural colonist and hence requiring the highest level of protection available, or an anthropogenic import requiring immediate and careful removal (Hughes and Convey 2012; Convey et al. 2012).

## 27.6 Microbial Groups

The potential significance of microbial introductions to the Antarctic continent has only received attention recently, and few specific studies exist (Frenot et al. 2005; Convey 2008; Cowan et al. 2011). However, the risks of importation and subsequent dispersal within the continent have been recognised (Smith 1996; Wynn-Williams 1996b; Gavaghan 2002). There are also documented instances of microbial introductions (Cowan et al. 2011).

Comparison of microbial diversity at sites of human activity (e.g. near research stations, field camps) and in pristine areas, can provide circumstantial evidence of anthropogenic assistance (e.g. Hirsch et al. 1985; Kerry 1990; Azmi and Seppelt 1998). The cold and dry conditions across much of Antarctica may also promote long-term survival of microbial propagules at sites of historic human activity (Nedwell et al. 1994; Hughes and Nobbs 2004).

The lack of baseline and ongoing survey data compounds the real problem of assessing whether a new microbial record represents a native or introduced taxon or, if the latter, whether it has established successfully. Rapidly advancing molecular phylogenetic, phylogeographical and analytical technologies are now being applied in microbiological studies and are improving the description of the evolutionary history and isolation of elements of the microbial flora (Boenigk et al. 2006; de Wever et al. 2009; Vyverman et al. 2010; Chong et al. 2012, 2013).

While some elements of the microbial flora are clearly cosmopolitan and widespread, as would be expected under the 'global ubiquity hypothesis' (Finlay 2002), others show strong evidence of long-term isolation and evolutionary radiation on the continent. Molecular approaches can also be used to target specific microbial 'indicators' of human activity (Baker et al. 2003).

## 27.7 The Risk of Intra-continental Transfer

Inevitably there has been a focus on the risks of non-native species entering Antarctica in association with human activities. However, in terms of ecosystem structure and function there is possibly a greater risk associated with transfers of species native to one part of Antarctica to locations elsewhere on the continent where they are not part of the native biota. In many cases, such species are likely to possess appropriate ecological and physiological adaptations for life in the new location, unlike the majority of non-native species arriving in Antarctica from elsewhere.

In recent years there has been a paradigm shift in views of both the biogeographic structure and antiquity of Antarctica's terrestrial biota (Chown and Convey 2007; Convey and Stevens 2007; Convey et al. 2008; Vyverman et al. 2010; Fraser et al. 2012). It is now understood that Antarctica is not a single biogeographical unit. This has the consequence that there are clear threats to Antarctic biodiversity from transfers occurring between different distinct regions within the continent.

In the context of developing practical approaches to Antarctic conservation, this biogeographic structure has recently been incorporated into analyses aimed at identifying distinct regions within Antarctica and using this information to set conservation priorities within the Antarctic Treaty System (ATS) (Terauds et al. 2012). These analyses identified 15 distinct terrestrial regions (Antarctic Conservation Biogeographic Regions) within the area of control of the ATS, to which can be added the maritime Antarctic South Sandwich Islands archipelago (which lies completely outside the treaty area and therefore is under national, in this case United Kingdom, sovereignty) and the various subantarctic islands.

The biogeographic structure present in Antarctic terrestrial ecosystems, supported by the use of molecular biological approaches, highlights the importance of local evolutionary differentiation. The fragmented and island-like nature of these ecosystems provides the starting point for differentiation processes to occur. The genetic distinctness of such ecosystems is clearly vulnerable, with transfers leading to genetic homogenisation and, amongst other consequences, the weakening of local adaptations and the compromising of future areas of research in the region (Chown and Convey 2007; Convey 2008; Hughes et al. 2013a, c).

## 27.8 Conclusions

As yet, the Antarctic continent itself is largely unaffected by non-native species. This is, however, a somewhat deceptive statement, as the current level of knowledge is based on incomplete data, in part a consequence of most of the terrestrial biodiversity being drawn from small or microscopic and non-charismatic groups, and compounded by the lack of priority being given by national funding agencies to baseline survey and long-term monitoring activities. There are also very few studies specifically targeting the non-native species that are known to be established, to enable better understanding of their status or threats, or the development of appropriate control or mitigation strategies where possible.

However, the clear and often drastic impacts consequential on the introduction of vertebrates, invertebrates and plants to various of the subantarctic islands provide strong warning of the likely consequences and trajectories to be followed in the event of establishment of similar organisms in maritime or continental Antarctica (Frenot et al. 2005; Convey and Lebouvier 2009). It is also clear that anthropogenic influences already far outweigh natural dispersal and colonisation processes, negating the dispersal filter created through Antarctica's isolation.

Many organisms native to lower latitudes possess ecophysiological and life history features that are likely to assist them surviving in the more extreme conditions of Antarctica. Well documented contemporary regional climate change (Convey et al. 2009a, b; Turner et al. 2009, 2013), where it leads to amelioration of climate regimes, will result in a reduction of the barriers to be crossed for natural transfer and establishment to occur. Compounding this, continuing increases in human contact will inevitably result in more inadvertent assisted introduction events. The consequences of establishment will mirror those already well-documented worldwide, including loss of biodiversity through the blurring of biogeographic boundaries and loss of genetic identity (Chown and Convey 2007), in the process also compromising the value of the continent as a scientific research resource (see discussion in Cowan et al. 2011; Hughes et al. 2013c).

While the only way to reduce the risk of human-assisted transfer to zero would be to stop visiting or working on the continent, which is unrealistic, in an Antarctic context, in particular, there are practicable means to minimise this risk (e.g. Whinam et al. 2004; Frenot et al. 2005; Curry et al. 2005; De Poorter et al. 2006; Hughes and Convey 2010, 2012; Chown et al. 2012; Hughes et al. 2011, 2013a, d). This provides a challenge to the consensus governance system of the ATS, but there are a range of mechanisms through which appropriate biosecurity and environmental protection measures can be put in place (Convey et al. 2012; Hughes et al. 2013a, d).

In terms of non-native species colonisation and establishment, the Antarctic continent is still, arguably, unique. It is the continent least affected by non-native species to date and, given the limited number of logistic support routes and overall numbers of visitors, it is the most practicable on which to apply continent-wide control measures. The Antarctic Treaty places a high responsibility on its signatory nations to protect Antarctica's environments and ecosystems. Already, at least on paper, high standards are required of visitors through existing mechanisms within the ATS and the International Association of Antarctica Tour Operators. Therefore, Antarctica provides one of the last opportunities available to humankind to demonstrate our ability to develop and apply protection at a continental level. Failure to do so would be an indictment of the current generation of Antarctic researchers, visitors, logisticians and policy makers.

## References

Azmi OR, Seppelt RD (1998) The broad-scale distribution of microfungi in the Windmill Islands region, Antarctica. Polar Biol 19:92–100

Baker G, Tow LA, Cowan DA (2003) Detection of nonindigenous micro-organisms in 'pristine' environments. J Microbiol Methods 53:157–164

Barnes DKA, Hodgson DA, Convey P, Allen C, Clarke A (2006) Incursion and excursion of Antarctic biota: past, present and future. Glob Ecol Biogeogr 15:121–142

Bergstrom DM, Chown SL (1999) Life at the front: history, ecology and change on southern ocean islands. Trends Ecol Evol 14:472–476

Bergstrom DM, Lucieer A, Kiefer K, Wasley J, Belbin L, Pedersen TK, Chown SL (2009) Indirect effects of invasive species removal devastate World Heritage Island. J Appl Ecol 46:73–81

Block W, Burn AJ, Richard KJ (1984) An insect introduction to the maritime Antarctic. Biol J Linn Soc 23:33–39

Block W, Smith RIL, Kennedy AD (2009) Strategies of survival and resource exploitation in the Antarctic fellfield ecosystem. Biol Rev 84:449–484

Boenigk J, Pfandl K, Garstecki T, Harms H, Novarino G, Chatzinotas A (2006) Evidence for geographic isolation and signs of endemism within a protistan morphospecies. Appl Environ Microbiol 72:5159–5164

Bölter M, Stonehouse B (2002) Uses, preservation, and protection of Antarctic coastal regions. In: Beyer L, Bölter M (eds) Geoecology of Antarctic ice-free coastal landscapes. Ecological Studies 154. Springer, Berlin, pp 393–407

Braun C, Mustafa O, Nordt A, Pfeiffer S, Peter H-U (2012) Environmental monitoring and management proposals for the Fildes Region (King George Island, Antarctic). Polar Res 31:18206

Caruso T, Trokhymets V, Bargagli R, Convey P (2013) Biotic interactions as a structuring force in soil communities: evidence from the micro-arthropods of an Antarctic moss model system. Oecologia 172:495–503

Chan Y, Van Nostrand JD, Zhou J, Pointing SB, Farrell RL (2013) Functional ecology of an Antarctic Dry Valleys landscape. Proc Natl Acad Sci USA 110:8990–8995

Chong CW, Pearce DA, Convey P, Yew WC, Tan IKP (2012) Patterns in the distribution of soil bacterial 16S rRNA gene sequences from different regions of Antarctica. Geoderma 181:45–55

Chong CW, Goh YS, Convey P, Pearce DA, Tan IKP (2013) Bacterial biogeography: what can we learn from Antarctic bacterial isolates? Extremophiles 17:733–745

Chown SL, Convey P (2007) Spatial and temporal variability across life's hierarchies in the terrestrial Antarctic. Philos Trans R Soc Lond Ser B 362:2307–2331

Chown SL, Froneman PW (2008) The Prince Edward Islands. Land-sea interactions in a changing ecosystem. Sun Press, Stellenbosch

Chown SL, Huiskes AHL, Gremmen NJM, Lee JE, Terauds A, Crosbie K, Frenot Y, Hughes KA, Imura S, Kiefer K, Lebouvier M, Raymond B, Tsujimotoi M, Ware C, Van de Vijver B, Bergstrom DM (2012) Continent-wide risk assessment for the establishment of nonindigenous species in Antarctica. Proc Natl Acad Sci 109:4938–4943

Clarke A, Barnes DKA, Hodgson DA (2005) How isolated is Antarctica? Trends Ecol Evol 20:1–3

Committee for Environmental Protection (CEP) (2011). Non-native species manual – 1st Edition. Manual prepared by Intersessional Contact Group of the CEP and adopted by the Antarctic Treaty Consultative Meeting through Resolution 6 (2011). Buenos Aires, Secretariat of the Antarctic Treaty. Available at: http://www.ats.aq/documents/atcm34/ww/atcm34_ww004_e.pdf

Convey P (1996) The influence of environmental characteristics on the life history attributes of Antarctic terrestrial biota. Biol Rev 71:191–225

Convey P (2008) Non-native species in Antarctic terrestrial and freshwater environments: presence, sources, impacts and predictions. In: Rogan-Finnemore M (ed) Non-native species in the Antarctic. Proceedings, Gateway Antarctica, Christchurch, pp 97–130

Convey P (2011) Antarctic terrestrial biodiversity in a changing world. Polar Biol 34:1629–1641
Convey P (2013) Antarctic ecosystems. In: Levin SA (ed) Encyclopedia of biodiversity, vol 1, 2nd edn. Elsevier, San Diego, pp 179–188
Convey P, Block W (1996) Antarctic dipterans: ecology, physiology and distribution. Eur J Entomol 93:1–13
Convey P, Lebouvier M (2009) Environmental change and human impacts on terrestrial ecosystems of the sub-Antarctic islands between their discovery and the mid-twentieth century. Pap Proc R Soc Tasmania 143:33–44
Convey P, McInnes SJ (2005) Exceptional, tardigrade dominated, ecosystems from Ellsworth Land, Antarctica. Ecology 86:519–527
Convey P, Quintana RD (1997) The terrestrial arthropod fauna of Cierva Point SSSI, Danco Coast, northern Antarctic Peninsula. Eur J Soil Biol 33:19–29
Convey P, Greenslade P, Arnold RJ, Block W (1999) Collembola of Sub-Antarctic South Georgia. Polar Biol 22:1–6
Convey P, Greenslade P, Pugh PJA (2000a) Terrestrial fauna of the South Sandwich Island. J Nat Hist 34:597–609
Convey P, Smith RIL, Hodgson DA, Peat HJ (2000b) The flora of the South Sandwich Islands, with particular reference to the influence of geothermal heating. J Biogeogr 27:1279–1295
Convey P, Frenot F, Gremmen N, Bergstrom D (2006) Biological invasions. In: Bergstrom DM, Convey P, Huiskes AHL (eds) Trends in Antarctic terrestrial and limnetic ecosystems: Antarctica as a global indicator. Springer, Dordrecht
Convey P, Stevens MI (2007) Antarctic biodiversity. Science 317:1877–1878
Convey P, Gibson J, Hillenbrand C-D, Hodgson DA, Pugh PJA, Smellie JL, Stevens MI (2008) Antarctic terrestrial life – challenging the history of the frozen continent? Biol Rev 83:103–117
Convey P, Bindschadler RA, di Prisco G, Fahrbach E, Gutt J, Hodgson DA, Mayewski P, Summerhayes CP, Turner J (2009a) Antarctic climate change and the environment. Antarct Sci 21:541–563
Convey P, Stevens MI, Hodgson DA, Smellie JL, Hillenbrand C-D, Barnes DKA, Clarke A, Pugh PJA, Linse K, Cary SC (2009b) Exploring biological constraints on the glacial history of Antarctica. Quat Sci Rev 28:3035–3048
Convey P, Key RS, Key RJD (2010) The establishment of a new ecological guild of pollinating insects on sub-Antarctic South Georgia. Antarct Sci 22:508–512
Convey P, Hughes KA, Tin T (2012) Continental governance and environmental management mechanisms under the Antarctic Treaty System: sufficient for the biodiversity challenges of the next century? Biodiversity 13:234–248
Convey P, Chown SL, Clarke A, Barnes DKA, Cummings V, Ducklow H, Frati F, Green TGA, Gordon S, Griffiths H, Howard-Williams C, Huiskes AHL, Laybourn-Parry J, Lyons B, McMinn A, Peck LS, Quesada A, Schiaparelli S, Wall D (2014) The spatial structure of Antarctic biodiversity. Ecol Monogr 84:203–244
Corte A (1961) La primera fanerogama adventicia hallada en el continente Antartico. Contribucion del Instituto Antartico Argentino 62:1–14
Council of Managers of National Antarctic Programs (COMNAP), The Scientific Committee on Antarctic Research (SCAR) (2011). Checklists for supply chain managers of National Antarctic Programmes for the reduction in risk of transfer of non-native species. Available at: https://www.comnap.aq/Shared%20Documents/nnschecklists.pdf
Cowan DA, Chown SL, Convey P, Tuffin M, Hughes K, Pointing S, Vincent W (2011) Non-indigenous microorganisms in the Antarctic: assessing the risks. Trends Microbiol 19:540–548
Cuba-Diaz M, Troncosco JM, Cordero C, Finot VL, Rondanelli-Reyes M (2013) *Juncus bufonius*, a new non-native vascular plant in King George Island, South Shetland Islands. Antarct Sci 25:385–386
Curry CH, McCarthy JS, Darragh HM, Wake RA, Churchill SE, Robins AM, Lowen RJ (2005) Identification of an agent suitable for disinfecting boots of visitors to the Antarctic. Polar Rec 41(216):39–45

De Poorter M, Gilbert N, Storey B, Rogan-Finnemore M (2006) Non-native species in the Antarctic – a workshop. Gateway Antarctica, Christchurch
De Wever A, Leliaert F, Verleyen E, Vanormelingen P, Van der Gucht K, Hodgson DA, Sabbe K, Vyverman W (2009) Hidden levels of phylodiversity in Antarctic green algae: further evidence for the existence of glacial refugia. Proc R Soc Lond Ser B 276:3591–3600
Downie RH, Convey P, McInnes SJ, Pugh PJA (2000) The non-marine invertebrate fauna of Deception Island (Maritime Antarctic): a baseline for a comprehensive biodiversity database. Polar Rec 36(199):297–304
Dózsa-Farkas K, Convey P (1997) Christensenia, a new enchytraeid genus from Antarctica. Polar Biol 17:482–486 [this paper subsequently modified – see Erratum, Polar Biology 20:292 (1998)]
Edwards JA (1980) An experimental introduction of vascular plants from South Georgia to the maritime Antarctic. Brit Antarct Surv Bull 49:73–80
Edwards JA, Greene DM (1973) The survival of Falklands Islands transplants at South Georgia and Signy Island, South Orkney Islands. Brit Antarct Surv Bull 33 & 34:33–45
Finlay BJ (2002) Global dispersal of free-living microbial eukaryote species. Science 296:1061–1063
Fraser CI, Nikula R, Ruzzante DE, Waters JM (2012) Poleward bound: biological impacts of Southern Hemisphere glaciation. Trends Ecol Evol 27:462–471
Freckman DW, Virginia RA (1997) Low-diversity Antarctic soil nematode communities: distribution and response to disturbance. Ecology 78:363–369
Frenot Y, Chown SL, Whinam J, Selkirk P, Convey P, Skotnicki M, Bergstrom D (2005) Biological invasions in the Antarctic: extent, impacts and implications. Biol Rev 80:45–72
Frenot Y, Convey P, Lebouvier M, Chown SL, Whinam J, Selkirk PM, Skotnicki M, Bergstrom DM (2008) Antarctic biological invasions: sources, extents, impacts and implications. In: Rogan-Finnemore M (ed) Non-native species in the Antarctic. Proceedings, Gateway Antarctica, Christchurch, pp 53–96
Gaston KJ, Jones AG, Hänel C, Chown SL (2003) Rates of species introduction to a remote oceanic island. Proc R Soc Lond Ser B 270:1091–1098
Gavaghan H (2002) Life in the deep freeze. Nature 415:828–830
Greenslade P (1995) Collembola from the Scotia Arc and Antarctic Peninsula including descriptions of two new species and notes on biogeography. Pol Pismo Entomologiczne 64:305–319
Greenslade P (2002) Assessing the risk of exotic Collembola invading subantarctic islands, prioritising quarantine management. Pedobiologia 46:338–344
Greenslade P (2006) The invertebrates of Macquarie Island. Australian Antarctic Division, Kingston, xvi + 326
Greenslade P, Convey P (2012) Exotic Collembola on subantarctic islands: pathways, origins and biology. Biol Invasions 14:405–417
Greenslade P, Wise KAJ (1984) Additions to the collembolan fauna of the Antarctic. Trans R Soc S Aust 108:203–205
Greenslade P, Potapov M, Russel D, Convey P (2012) Lessons from history – global Collembola on Deception Island. J Insect Sci 12, Article 111
Gremmen N, Smith V (2004) The flora of Marion and Prince Edward Islands. Data Analyse Ecologie, Diever
Hirsch P, Gallikowski C, Friedmann E (1985) Microorganisms in soil samples from Linnaeus Terrace, southern Victoria Land: preliminary observations. Antarct J USA 20:183–186
Hodgson D, Convey P, Verleyen E, Vyverman W, McInnes S, Sands CS, Fernández-Carazo R, Wilmotte A (2010) Observations on the limnology and biology of the Dufek Massif, Transantarctic Mountains 82° South. Polar Sci 4:197–214
Hogg ID, Cary SC, Convey P, Newsham KK, O'Donnell T, Adams BJ, Aislabie J, Frati FF, Stevens MI, Wall DH (2006) Biotic interactions in Antarctic terrestrial ecosystems: are they a factor? Soil Biol Biochem 38:3035–3040

Hughes KA, Convey P (2010) The protection of Antarctic terrestrial ecosystems from inter and intra-continental transfer of non-indigenous species by human activities: a review of current systems and practices. Glob Environ Chang – Hum Policy Dimens 20:96–112
Hughes KA, Convey P (2012) Determining the native/non-native status of newly discovered terrestrial and freshwater species in Antarctica – current knowledge, methodology and management action. J Environ Manage 93:52–66
Hughes KA, Nobbs SJ (2004) Long-term survival of human faecal microorganisms on the Antarctic Peninsula. Antarct Sci 16:293–297
Hughes KA, Worland MR (2010) Spatial distribution, habitat preference and colonisation status of two alien terrestrial invertebrate species in Antarctica. Antarct Sci 22:221–231
Hughes KA, Walsh S, Convey P, Richards S, Bergstrom D (2005) Alien fly populations established at two Antarctic research stations. Polar Biol 28:568–570
Hughes K, Ott S, Bölter M, Convey P (2006) Colonisation processes. In: Bergstrom DM, Convey P, Huiskes AHL (eds) Trends in Antarctic terrestrial and limnetic ecosystems: Antarctica as a global indicator. Springer, Dordrecht
Hughes KA, Convey P, Maslen NR, Smith RIL (2010) Accidental transfer of non-native soil organisms into Antarctica on construction vehicles. Biol Invasions 12:875–891
Hughes KA, Lee JE, Tsujimoto M, Imura S, Bergstrom DM, Ware C, Lebouvier M, Huiskes AHL, Gremmen NJM, Frenot Y, Bridge PD, Chown SL (2011) Food for thought: risks of non-native species transfer to the Antarctic region with fresh produce. Biol Conserv 144:1682–1689
Hughes KA, Cary SC, Cowan DA, Lovejoy C, Vincent WF, Wilmotte A (2013a) Pristine Antarctica: threats and protection. Antarct Sci. doi:10.1017/S0954102013000047
Hughes KA, Convey P, Huiskes AHL (2013b) Global movement and homogenisation of biota: challenges to the environmental management of Antarctica? In: Tin T, Liggett D, Maher P, Lamers M (eds) Antarctic Futures. Human engagement with the Antarctic environment: Human impacts, strategic planning and values for conservation. Springer, Dordrecht. doi:10.1007/978-94-007-6582-5_5
Hughes KA, Pertierra LR, Walton DWH (2013c) Area protection in Antarctica: how can conservation and scientific research goals be managed compatibly? Environ Sci Policy 31:120–132
Hughes KA, Worland MR, Thorne MAS, Convey P (2013d) The non-native chironomid *Eretmoptera murphyi* in Antarctica: erosion of the barriers to invasion. Biol Invasions 15:269–281
Kennedy AD (1995) Antarctic terrestrial ecosystem response to global environmental change. Annu Rev Ecol Syst 26:683–704
Kerry E (1990) Microorganisms colonising plants and soil subjected to different degrees of human activity, including petroleum contamination, in the Vestfold Hills and MacRobertson Land. Polar Biol 10:423–430
Kriwoken LK, Rootes D (2000) Tourism on ice: environmental impact assessment of Antarctic tourism. Impact Assess Proj Apprais 18:138–150
Lee JE, Chown SL (2009a) Breaching the dispersal barrier to invasion: quantification and management. Ecol Appl 19:1944–1959
Lee JE, Chown SL (2009b) Quantifying the propagule load associated with the construction of an Antarctic research station. Antarct Sci 21:471–475
Lewis PN, Bergstrom DM, Whinam J (2006) Barging in: a temperate marine community travels to the sub Antarctic. Biol Invasions. doi:10.1007/s10530-005-3837-6
Marshall WA (1996) Biological particles over Antarctica. Nature 383:680
Molina-Montenegro M, Carrasco-Urra F, Rodrigo C, Convey P, Valladares F, Gianoli E (2012) Occurrence of the non-native annual bluegrass (*Poa annua*) on the Antarctic mainland and its negative effects on native plants. Conserv Biol 26:717–723
Nedwell DB, Russell NJ, Cresswell-Maynard T (1994) Longterm survival of microorganisms in frozen material from early Antarctic base camps at McMurdo Sound. Antarct Sci 6:67–68
Olech M (1996) Human impact on terrestrial ecosystems in West Antarctica. NIPR symposium on polar biology, National Institute of Polar Research, Tokyo, Japan, Proceedings 9, pp 299–306

Olech M, Chwedorzewska KJ (2011) The first appearance and establishment of an alien vascular plant in natural habitats on the forefield of a retreating glacier in Antarctica. Antarct Sci. doi:10.1017/S0954102010000982

Pearce DA, Newsham KK, Thorne MAS, Calvo-Bado L, Krsek M, Laskaris P, Hodson A, Wellington EMH (2012) Metagenomic analysis of a southern maritime Antarctic soil. Front Microbiol 3:403. doi:10.3389/fmicb.2012.00403

Pertierra LR, Lara F, Benayas J, Hughes KA (2013) *Poa pratensis* L., current status of the longest-established non-native vascular plant in the Antarctic. Polar Biol 36:1473–1481

Peter H-U, Braun C, Janowski S, Nordt A, Nordt A, Stelter M (2013) The current environmental situation and proposals for the management of the Fildes Peninsula Region. Federal Environment Agency (Umweltbundesamt), Dessau-Roßlau. Available at: http://www.umweltdaten.de/publikationen/fpdf-l/4424.pdf

Smith RIL (1996) Introduced plants in Antarctica: potential impacts and conservation issues. Biol Conserv 76:135–146

Smith RIL (2005) The bryophyte flora of geothermal habitats on Deception Island, Antarctica. J Hattori Bot Lab 97:233–248

Smith RIL (2014) A fern cultured from Antarctic glacier debris. Antarct Sci. doi:10.1017/S0954102013000606

Smith RIL, Richardson M (2011) Fuegian plants in Antarctica: natural or anthropogenically assisted immigrants. Biol Invasions 13:1–5

Terauds A, Chown SL, Morgan F, Peat HJ, Watts D, Keys H, Convey P, Bergstrom DM (2012) Conservation biogeography of the Antarctic. Divers Distrib 18:726–741

Tsujimoto M, Imura S (2012) Does a new transportation system increase the risk of importing non-native species to Antarctica? Antarct Sci 24:441–449

Turner J, Bindschadler R, Convey P, di Prisco G, Fahrbach E, Gutt J, Hodgson D, Mayewski P, Summerhayes C (eds) (2009) Antarctic climate change and the environment. Scientific Committee on Antarctic Research, Cambridge, xi + 526

Turner J, Barrand NE, Bracegirdle TJ, Convey P, Hodgson D, Jarvis M, Jenkins A, Marshall G, Meredith MP, Roscoe H, Shanklin J, French J, Goosse H, Guglielmin M, Gutt J, Jacobs S, Kennicutt MC II, Masson-Delmotte V, Mayewski P, Navarro F, Robinson S, Scambos T, Sparrow M, Speer K, Summerhayes C, Klepikov A (2013) Antarctic climate change and the environment – an update. Polar Rec. doi:10.1017/S0032247413000296

Vincent WF (1988) Microbial ecosystems of Antarctica. Cambridge University Press, Cambridge

Volonterio O, Ponce de León R, Convey P, Krzeminska E (2013) First record of Trichoceridae (Diptera) in the maritime Antarctic. Polar Biol. 36:1125–1131

Vyverman W, Verleyen E, Wilmotte A, Hodgson DA, Willem A, Peeters K, Van de Vijver B, De Wever A, Leliaert F, Sabbe K (2010) Evidence for widespread endemism among Antarctic micro-organisms. Polar Sci 4:103–113

Wall DH, Lyons WB, Convey P, Howard-Williams C, Quesada A, Vincent WF (2011) Long term ecosystem networks to record change: an international imperative. Antarctic Sci 23:209

Walther G-R, Post E, Convey P, Parmesan C, Menzel M, Beebee TJC, Fromentin J-M, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389–395

Whinam J, Chilcott N, Bergstrom DM (2004) Subantarctic hitchhikers: expeditioners as vectors for the introduction of alien organisms. Biol Conserv 121:207–219

Wynn-Williams DD (1993) Microbial processes and the initial stabilisation of fellfield soil. In: Miles J, Walton DWH (eds) Primary succession on land. Blackwell, Oxford

Wynn-Williams DD (1996a) Antarctic microbial diversity: the basis of polar ecosystem processes. Biodivers Conserv 5:1271–1293

Wynn-Williams DD (1996b) Response of pioneer soil microalgal colonists to environmental change in Antarctica. Microb Ecol 31:177–188

# Chapter 28
# Meeting Future Challenges of Antarctic Research

## International and Interdisciplinary Cooperation

**David Carlson**

**Abstract** The preceding chapters have indicated the breadth, innovation and urgency of Antarctic research. However, polar research faces substantial challenges. These include obtaining funding, overcoming technological difficulties associated with operating in the Antarctic environment, making research results readily available to the wider public and philosophical issues around research methods and priorities. Continuing rapid change in Antarctica leaves little time for relaxation or contemplation. New models for international and interdisciplinary cooperation will need to evolve to support efficient and effective polar research. This chapter examines international and interdisciplinary cooperation during the most recent International Polar Year, the challenges for polar science, and some advantages and assets of polar science, with concluding views on the future of international research cooperation.

**Keywords** Collaboration • Funding • Data sharing • APECS • PEI

## 28.1 History of Collaboration

Research focused on the polar regions has a long history. In the late 1800s, Austrian naval lieutenant Karl Weyprecht, himself an Arctic explorer, called for simultaneous and coordinated observations conducted through collaboration and international cooperation. His motivations included a genuine sense that understanding the vast polar regions required much more than a sequence of random and uncoordinated explorations. Weyprecht's timely vision stimulated the first International Polar Year from 1882 to 1883. Twelve countries participated and 15 expeditions took place (13 to the Arctic, and 2 to the Antarctic). The effort represented one

D. Carlson (✉)
World Climate Research Programme, 7bis, avenue de la Paix Case postale 2300
CH-1211, Geneva 2, Switzerland
e-mail: dcarlson@wmo.int; http://www.wcrp-climate.org



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_28

of the first instances of international cooperation and coordination in modern science.

Concentrated global focus on polar research continued on three subsequent occasions. From 1932 to 1933 the second International Polar Year resulted in the US establishing the first research station inland from Antarctica's coast, and produced advances in meteorology, magnetism, atmospheric science and ionospheric research that improved radioscience and technology. When ideas of a third polar year arose, compelling global issues in geophysics, astrophysics and oceanography almost immediately expanded the polar model into an International Geophysical Year (IGY 1957/1958). The IGY prompted an enormous effort in Antarctica with the result that strengthened polar coordination – a step forward in international scientific cooperation (Carlson 2013) – then and since, and initial efforts at polar protection represented two of its many legacies. The most recent International Polar Year, IPY 2007–2008, again focused on international cooperation with consortiums of up to 20 nations involved in many wide-ranging, interdisciplinary Antarctic research projects.

## 28.2 International and Interdisciplinary Cooperation

In the opening sentence of their framework document, the planners of the most recent IPY advocated international and interdisciplinary cooperation:

> The concept of the International Polar Year 2007–2008 is of an intensive burst of internationally coordinated, interdisciplinary, scientific research and observations focused on the Earth's polar regions. (ICSU 2004)

These two components - working together across national and interdisciplinary boundaries - present a similar set of challenges. In both cases, languages, habits, cultures and resources have developed strong conventions, either national or disciplinary. Does science offer a universal language, transcending national boundaries? Those involved in the IPY often found it easier to translate scientific information on, for example, the ozone hole or glacial retreat, into different languages, than to communicate basic scientific concepts from one discipline to another. Researchers with different native languages can very likely converse using English but have a more difficult task to converse across disciplines if one is an ecologist and the other a geologist. Scientific cooperation on the scale of an IPY necessarily includes both international and interdisciplinary facets.

## 28.3 Challenges for Polar Science

The recent IPY served to refresh international and interdisciplinary partnerships, but it also inspired better definition of urgent issues for Antarctic research, issues that in turn require the highest levels of interdisciplinary and international cooperation. How fast can ice sheets ablate and erode, and how fast can sea levels rise? Answering these questions requires collaborative expertise in glaciology, meteorology, and especially hydrology and oceanography. Which country can handle that problem alone? What international teams of oceanographers, geographers, geologists, geochemists, hydrographers, microbiologists and biochemists will quantify the complicated physical, geochemical and ecological controls on carbon processing in the Southern Ocean? What teams of biologists, ecologists, economists, hydrologists, geographers and oceanographers will predict the evolution and future health of Antarctic ecosystems? How will these researchers structure their inquiries, share their data and communicate their findings (Box 28.1)?

**Box 28.1: Science in an Age of Global Environmental Issues**

In 1998, Jane Lubchenco called for a ‘new social contract for science’ in response to global environmental concerns. She issued three challenges, requesting scientists of the twenty-first century “to address the most urgent needs of society, in proportion to their importance, to communicate their knowledge and understanding widely in order to inform decisions of individuals and institutions, and to exercise good judgment, wisdom and humility” (Lubchenko 1998). In this view, science as an academic pursuit, as an entitlement, recedes, while science motivated by social relevance advances. Creativity, innovation, curiosity and insight remain the key elements of this new science, but with greater engagement with local and global issues and with the public, and often with greater interdisciplinary and international collaboration. The IPY 2007–2008 aspired to meet all three challenges – relevance, communication and good judgement, the latter perhaps best reflected in IPY’s free and open data access policies. Periodic global events such as this IPY play an important role in stimulating new thinking and new practices in the world of science.

For international interdisciplinary cooperation to succeed, polar science will need to meet the following challenges.

### *28.3.1 Funding*

In every country and in every budget cycle, research competes for sufficient resources. As environmental, health and debt costs rise around the globe, that competition becomes more difficult under even the most optimistic scenarios. In systems where salaries and research funds derive from separate sources or separate jurisdictions, researchers and institutions will struggle to sustain sufficient funding.

The recent IPY enjoyed good luck on timing: one can hardly imagine replicating the multinational IPY-induced funding increments for polar science in the fiscal situation that arose immediately after. Political interest in both the Arctic and Antarctic notwithstanding, polar science will have to continually compete for priority and resources (Box 28.2).

**Box 28.2: Thoughts on Blue Skies Research**

The idea of 'blue skies' research has almost always represented an illusion. If a scientist has federal funding in any nation, that funding comes with expectations of social return on investment. US federal science funding increased after the Second World War, with clear expectations that science would contribute to a national effort to win future wars – geopolitical wars, wars on disease, the race to space. A scientist at his or her desk may have dreamed of self-motivated research, but if they had federal support (and most of them did), that support came on the basis of anticipated medical, defense or economic benefit. In Jane Lubchenco's article (written as she assumed the presidency of the American Association for the Advancement of Science) she called for a revision of that social contract. She wrote that the "roles of science – to discover, communicate, and use knowledge and train the next generation of scientists – have not changed, but the needs of society have been altered dramatically". In her article, science always had a social contract, but in an age of vast human alteration of Earth systems, social needs had changed. Her call for a focus on the most urgent needs of society does not represent a call for a new social contract where none had existed, but a call for a new social contract different to the pre-existing contract, different in its focus on the global environment.

Did science change after publication of the Lubchenco article? Not really, I suppose. The US National Science Foundation implemented 'broader impacts' criteria, to supplement its 'intellectual merit' criteria. If you label the former 'relevance' and the latter 'curiosity-driven', then the new criteria made explicit the need for every new proposal to address both innovation and application. To gain prominence and attract resources on the international scene, science must address urgent themes.

### *28.3.2 Relevance*

The traditional products of science – journal articles, scholarly books and regular and periodic assessments – have minimal relevance to the general public. The public increasingly confronts and learns science, in selected form third hand, from public media such as television or magazines. Science appears as merely another stream of information, indistinguishable from and no more interesting or relevant than any other form of infotainment. The defining scientific mechanisms of rigorous formulation and testing of hypotheses, of data sharing, of critical review, and of iterative refinement of initial ideas into reliable observations, theories or concepts remain poorly understood and have almost no validity in the public's estimation. One may assign the stark and persistent policy failures of the United Nations Framework Convention on Climate Change conferences to a lack of public interest and concern resulting from a long-standing and fundamental failure to engage the public in the processes of science. Despite its attractive iconic animals and compelling visual imagery, polar science faces these same urgent challenges.

### *28.3.3 Information Technology*

Increasingly, the data and communication technologies of science diverge from and fall behind the information tools of the modern world. The dry and characterless publications that commonly result from scientific research do not compete favourably with rapid, colourful, three-dimensional communications the general public now experience and expect. Users expect real-time communication of everyday information. Few will navigate to obscure sites to download year-old text files of sea-ice data or of future temperature projections from climate models. Thousands of students in computer and electrical engineering departments around the globe develop search algorithms, pattern matching, shortest distance algorithms and cool visualisation technologies, while most of our national and world data centres lack useful geographic interfaces.

### *28.3.4 Speed of Change*

The most recent IPY emphasised the surprising rate of change in all facets of Antarctic systems: glacial, oceanographic and ecological. Whether due to an acceleration of the underlying processes or merely a consequence of closer attention during the IPY, the speed of the changes challenges the normal scientific process, which usually involves:

- Four to five years of education to develop skills;
- Three to five additional years to gain funding and collect data;
- A further 2–3 years to analyse and understand;
- Iteration of the previous two steps;
- And then 5–7 more years to see this work incorporated into regional or global assessments.

Which polar systems or processes or paradigms remain stable or unchanging on these time scales?

### *28.3.5 Prediction*

Despite the urgency expressed in many IPY proposals, the natural tendency of science to follow its philosophical roots and focus on research publications as the final product represents a barrier to rapid development of useful predictive skills. A further barrier arises from the lack of suitable and capable predictive models for polar systems. Meanwhile, economists and policy makers and negotiators, who focus on carbon and other natural resources, need robust predictive skills for key questions about ice, carbon and ecosystems. Reliance on long-term climate averages or the extrapolation of recent trends will not provide sufficient guidance. Those not immediately involved in the science can ask with justification: "What did we get out of the IPY?"

Antarctic research needs a prediction focus and framework, covering the physical, biological and cultural features of Antarctic systems, to quickly and effectively exploit scientific results for the benefit of all.

### *28.3.6 Protection*

Some IPY projects focused on ecosystems undergoing rapid change and envisioned their data contributing to, or motivating, the establishment or enhancement of protections at population, ecosystem and regional levels. Many IPY biology results from Antarctica will eventually improve the scientific basis for ecosystem management under the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), but even that enlightened and precautionary convention arrived long after the major depletions of Antarctic marine mammals and struggles to keep up with current industrial fishing activities in Antarctic waters. In addition, many researchers operate under the concern that ecosystems will change (some will disappear) before we have even identified all their components, much less developed a sense of their complexity or resilience. Illegal, unregulated and unreported fishing already occurs and will likely increase (Chap. 21). As farmed fish constitute increasingly large portions of humanity's protein need and as fish farmers search more widely and aggressively for fish food, pelagic marine crustaceans of Antarctic waters will come under increasing pressure.

### *28.3.7 Timely Prediction and Protection: An Unobtainable Ideal?*

The desire to achieve an ideal presents opportunity and stimulus for innovative redesign, re-evaluation and creative problem solving. At the close of the IPY 2007–2008 Antarctic researchers identified a need for additional time and continued funding to exploit discoveries, to resolve complexities and to seek unequivocal data. At the same time they recognised urgent responsibilities to produce meaningful predictions of imminent changes in the geophysical and ecological systems. Pursuing definitive data sets while simultaneously producing timely and accurate prognoses seems impossible. In policy, devoting the persistence necessary to achieve durable territorial, political and economic consensus expressed within various laws, conventions and treaties requires sustained attention and substantial time. To do this while also instituting timely and effective protections for vulnerable ecosystems that extend well beyond the terms of current regulations, and while the publicity associated with the IPY keeps the Antarctic in the public eye, seems unobtainable.

However, by building on the international and interdisciplinary assets of the IPY, particularly the international cooperation, the new options and tools for data access and prediction, and the strong engagement of energetic young scientists and educators, visible and plausible solutions emerge.

## 28.4 Assets

### *28.4.1 International Cooperation*

The operations portion of an Antarctic Treaty Consultative Meeting involves attendees, seated by national delegation, tilting their country cards upward to catch the chair's attention, often speaking through translators, beginning by thanking each other for cooperation over the past year.

> Chile would like to thank New Zealand and the USA for . . .
> The Russian Federation takes this opportunity to record its pleasure in the cooperation by Argentina and India on the issue of . . .

Steadily (the chair does not hurry this procedure), the room and the record fill with formal expressions of thanks from one country to one or several others. A substantial portion of these interventions reference serious issues: cooperation on urgent provision or movement of fuel, or on timely ice breaking, or even on emergency health and rescue. By devoting the opening minutes of their meeting to expressions of cooperation and gratitude, the Treaty Parties recognise the fundamental and essential role that cooperation plays in Antarctic research, and they start their discussions on a genuine cooperative note.

Listings of numbers of participating nations (close to 50 in the Antarctic Treaty, 60 or so in the IPY) provide only the context in which international cooperation occurs. The exchanges described above demonstrate actual bilateral or multi-lateral interactions at a relatively high working level. Throughout the IPY countless unofficial and informal exchanges across languages and cultures occurred at the working levels of researchers, students, engineers and technicians. At almost every Antarctic base and in nearly every field camp and ship cruise, international participation at the individual level exceeded official national participation statistics. For example, a national icebreaker, working as part of an official six-country IPY project, had on board individuals from at least another three countries as part of its student and technical staff. Multiply those working-level interactions, often enhanced by recognition of participation in a larger effort, across the number of IPY projects, and one gets a sense of the real international impact of an event like the IPY.

This working-level international cooperation extended throughout a wide range of meetings and conferences and workshops held by the polar organisations SCAR (Scientific Committee for Antarctic Research) and IASC (International Arctic Sciences Committee), by the treaty organisations, by parliamentarians, by associations of museums, artists and teachers. Under the extra workload and extra urgency of the IPY, international cooperation survived and thrived.

### *28.4.2 Interdisciplinary Cooperation*

Unlike its predecessors, the IPY 2007–2008 included a broad range of research in biology and social sciences. All 30 science unions of the International Council for Science (ICSU) claimed some involvement in the IPY. Again, lists of specialities or lists of unions understate actual working-level interdisciplinary interactions. In many instances of field research, interdisciplinary interaction happened as freely and naturally as international interaction. The logistics constraints of Antarctic research, which require team efforts in collective locations and much logistical cooperation, favoured close and extended interaction among various researchers.

At these bases and on these ships, astronomers met archaeologists, economists met ecologists, and glaciologists met geneticists. The deliberate IPY effort to involve every possible discipline in the effort to understand Antarctica became accepted as necessary and desirable. Interdisciplinary connections and partnerships will endure as the normal daily disciplinary pressures of funding, promotion and publication re-assert themselves, sustained in part by the multidisciplinary approaches of post-IPY organisations such as the International Association for Cryospheric Science and the SCAR-IASC Bipolar Action Group.

### *28.4.3 Data Access and Sharing*

Most IPY participants accepted the free and open data access policy, and numerous national and disciplinary data centres provide initial browse and access systems for some IPY data. However, widespread seamless data access across national and disciplinary boundaries remains a goal rather than an accomplishment, and options for the long-term preservation of the Antarctic IPY data sets remain unknown. Several initiatives have the potential to substantially change the ways in which Antarctic scientists access and share data. The Polar Information Commons (PIC), an ICSU-funded initiative started by a group of international colleagues, drew inspiration from Antarctica as a global commons, used only for peaceful purposes and scientific endeavours. A new journal, Earth System Science Data (ESSD), also a product of IPY 2007–2008, advances the parallel issues of open data access and professional credit for data assembly and sharing. Working often in partnership with polar science journals, ESSD represents a notable success toward the IPY goals of openly accessible data, shared widely.

Useful examples of access and sharing concepts on smaller, more regional scales exist, particularly in web portals that have evolved as components of community monitoring. Community-monitoring networks operate over a substantial part of North America and Eurasia and monitor, for instance, birds, mammals, fish, plants and lake and river ice. They often directly examine and report conditions and health of animals. During the IPY 2007–2008, they increasingly collected samples for later disease, contaminant and genetic analysis. Most of these community networks will continue their activities for at least a decade and share their information through multi-language websites. These community-based information systems support many of the IPY goals of engagement, partnership and communication, and provide working examples that contribute to larger questions of international and interdisciplinary data sharing.

### *28.4.4 Prediction Teams and Tools*

In the Southern Ocean, observers and modellers cooperated to use the Southern Ocean State Estimate (SOSE) model to plan, guide and analyse results from an ocean experiment involving an inert tracer inserted west (upstream) of the Drake Passage. Using this modelling framework to synthesise a wide range of Southern Ocean observations seems quite feasible and will represent a step forward in understanding and predicting the biology, chemistry and dynamics of the Southern Ocean. This example of international and interdisciplinary cooperation represents the tip of an iceberg. Many groups develop independent descriptions and models of polar processes such as regional ice-ocean-atmosphere coupling, vegetation propagation, snow accumulation or fishery adaptation. Compiling these separate activities into an integrated prediction skill for polar systems, while enormously difficult, will represent an important enabling step for other regional and global prediction efforts. Applying these prediction systems and efforts to the Antarctic will force us to think operationally, to assess the timeliness and quality of observations, and to develop and use data assimilation schemes. Producing predictions for the Antarctic will entail risk and require changes in thinking and funding but will focus attention on quality and on understanding and meeting user, including public, expectations.

### *28.4.5 Protection Options*

Partly due to the declining health of marine fisheries, and partly due to some demonstrated successes, the concept of marine reserves as mechanisms for protection and restoration has gained interest and momentum. Advocacy groups for the Southern Ocean have proposed a Marine Protected Area for the Ross Sea. The most recent IPY has reminded many people of the benefits of existing environmental protection and fisheries resource management protocols in and around Antarctica, in contrast to the absence of either in the Arctic. However, present protocols provide only partial protection, and the recent proposals represent small and hesitant protection efforts, unlikely to prevent illegal unregulated and unreported fishing.

During the IPY the success of the Census of Antarctic Marine Life (CAML), with its strong links to the ocean-wide Census of Marine Life, indicated the increasing integration of Antarctica with global biodiversity and conservation activities. The IPY also highlighted the substantial importance of Antarctic marine ecosystems in the global carbon cycle. Many of the IPY biodiversity and ecology studies used innovative and skillful integration of data sets and GIS analysis tools and provided an open-access approach to data and to products. These products, along with extensive maps of species or population distributions, have substantial regional ecological value, but the processes used to produce the models behind the maps, coupled with rigorous open-access practices for the data and for the analytical tools, have high relevance for polar biology and for global ecosystem analysis. The sharing and use of these integrating models and analysis techniques offer powerful tools for proposing and evaluating systematic options for the protection of Antarctic systems.

### *28.4.6 The Association of Polar Early Career Scientists (APECS)*

The most recent IPY included a deliberate recruitment goal, to “inspire a new generation of polar scientists and engineers”. As shown by their growing membership and documented by their many activities on their website, the new Association of Polar Early Career Scientists (APECS) has seized this opportunity and seems very likely to follow their motto to “shape the future of polar research”.

Reasons for this success emerge by examining APECS at a working level. As its members necessarily undergo rapid changes in career status, the organisation itself manages a frequent turnover of leadership, offering more opportunities to more future leaders and providing an organisational response and adaptation, time-scaled appropriately to the rapid changes in polar systems. Through various workshops and schools, the APECS members learn career planning and communication skills as well as teaching and faculty survival techniques. Unlike within chemistry departments or engineering schools, where expectations and practices propagate within long-held departmental and disciplinary norms, the APECS participants learn and exchange their ideas in an overtly interdisciplinary setting and format. They interact, learn, explore and discover as Antarctic scientists, respecting but also merging their specialised training into shared interests and goals. The polar community has yet to recognise the magnitude or impact of this change for polar science, specifically and for interdisciplinary science generally (Box 28.3).

**Box 28.3: Perspective: By Megan Berg, Outreach for ANDRILL**

The rich global history of Antarctica affords an invaluable perspective for young generations. As a student, I was invited to be part of ANDRILL, a major Antarctic geologic drilling effort, and got to see the world through this unique lens, working side by side with Italians, New Zealanders, Germans and Americans in a place that, on paper, is owned by no one. Every day was lush with lingual, cultural, political and scientific discussion, which continues beyond the field season and into the fabric of our collaborations and lifelong friendships. One scientist who particularly had an impact on me was Peter Webb, who had travelled to Antarctica in 1957 on a mission to map the Dry Valleys. Growing up in Wellington, New Zealand, Peter arrived on the Antarctic scene just in time to be in contact with some of the early geologic explorers of the late nineteenth and early twentieth centuries, including Frank Debenham, Griffith Taylor and Raymond Priestley. Our stories crossed paths at an opportune time. I was preparing for my first trip to Antarctica at the age of 19. Peter had also spent his first season on the ice at the same age 50 years prior. On a continent that has experienced more exploration and development in the last 50 years than ever in human history, I was enthralled by his stories of Antarctica during the ‘wild west’ years, before the bureaucracy, before satellites were launched, back in the days when the US Navy ran the whole crazy operation. His sharp sense of wit and curiosity inspired me. His discussions often led to the idea that the exploration of a scientific question will never lead to a solid, neatly packaged understanding of our planet, but will result in more of an unravelling, a deeper set of more complex questions that require a broad imagination and infinite patience (Fig. 28.1).

(continued)

**Box 28.3** (continued)

**Fig. 28.1** Peter Webb with Paola Montone, in Antarctica (With kind permission from Megan Berg)

### *28.4.7 Polar Educators International (PEI)*

Polar Educators International, started during IPY and growing as of this writing to include more than 400 members from 24 countries, collaborates internationally and across disciplines to convey both the relevance and urgency of polar research. Adopting a broad definition of educator, they intentionally include scientists and students along with professional educators, covering a wide range of formal and informal education options and activities.

Members of PEI work uniquely at the interfaces between rapidly evolving polar science and new directions in education and communication, in and beyond classrooms. They share skills and experiences to rekindle student and public engagement with global environmental change. They develop and use powerful images and messages from polar regions to stimulate, guide and promote fundamental changes in public interest, attitudes and policies toward the health and well-being of our planet and our neighbours.

## 28.5 A Final View of Collaboration

For better or worse, the IPY chart, encompassing both Antarctic and Arctic programmes, developed into a much-used symbol of the IPY 2007–2008. Originally developed as a tool to identify programmatic gaps, the hexagonal array evolved into a useful way to show the abundance, variety and breadth of the IPY, across disciplines and across hemispheres, on a single page. Gradually, the chart became identified as the definitive map of the IPY. The presence of a project hexagon on the chart and indications of national participation in many projects/hexagons became IPY status symbols. A continuing sequence of updates and improvements led to this final version (Fig. 28.2).

In these views, we see no hats or jackets with national logos, no flags, and not even a face. At this working level, we all became hands-on partners in the great adventure we called the IPY. Out of this shared connection to a special region of our planet, many good ideas will grow.

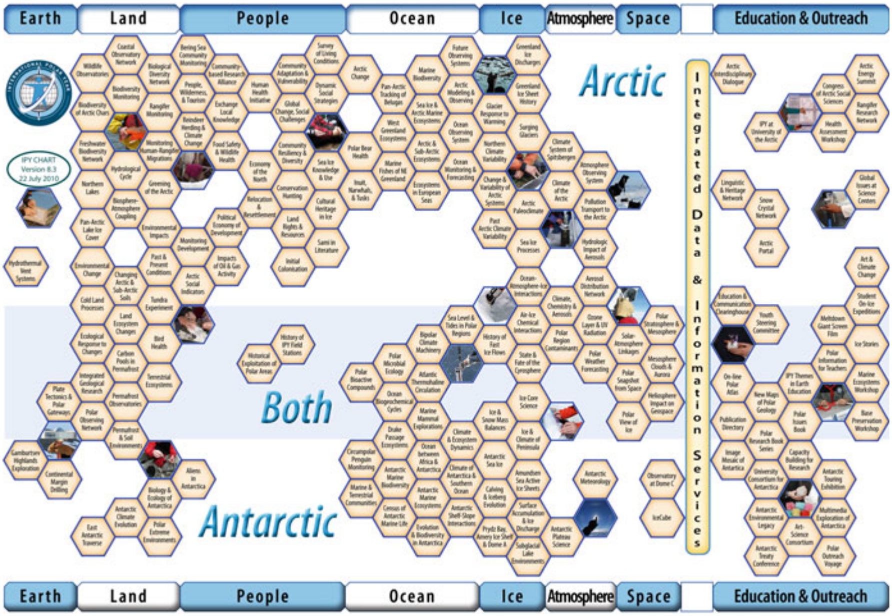



**Fig. 28.2** This version of the IPY project chart preserves only the active, funded IPY projects. It no longer shows disciplinary boundaries aligned with the land, ocean or space labels, and it shows examples of IPY participants at work (With kind permission from the IPY International Programme Office)

**Fig. 28.3** The international young scientific talent of the latest IPY, aboard the German vessel *PolarStern* during the first cruise of the IPY Census of Antarctic Marine Life (CAML) project (With kind permission from Victoria Wadley and Gauthier Chapelle of the International Polar Foundation)

## 28.6 Conclusions

Early-career Antarctic researchers (including APECS and its members) with new ideas and techniques represent one key to future international and interdisciplinary research. Nevertheless, the long-standing barriers to rapidly convert understanding into prediction or to see our knowledge reflected in protection policies will take time and effort to overcome. The variety and energy and strengths of the IPY at the working level give rise to optimism for meeting the challenges ahead. The IPY energy persists as researchers feel that they have just started to discover, to build their teams, to develop international and interdisciplinary partnerships, to really do Antarctic science and to cautiously advance toward prediction and protection. These researchers may worry about what comes next, particularly for continued funding, but they do not want the collaboration and cooperation of the IPY to end. Out of that enthusiasm, perhaps with APECS catalysing some real changes, will come the legacy of the most recent IPY (Fig. 28.3).

## References


Association of Polar Early Career Scientists. http://apecs.is/

Carlson D (2013) Reading and thinking about International Polar Years: five recent books. Polar Res 32. http://dx.doi.org/10.3402/polar.v32i0.20789

Census of Antarctic Marine Life. http://www.caml.aq/

Earth System Science Data (Copernicus). http://www.earth-system-science-data.net/
International Council for Science (2004) A framework for the International Polar Year 2007–2008, produced by the ICSU IPY 2007–2008 Planning Group
Lubchenko J (1998) Entering the century of the environment: a new social contract for science. Science 279(5350):491–497. doi:10.1126/science.279.5350.491
Polar Information Commons. http://www.polarcommons.org/
Southern Ocean State Estimate. http://www.mit.edu/~mmazloff/SOSE.html

# Chapter 29
# Antarctic Scientific Collaboration

## The Role of the SCAR

**David W.H. Walton, Mahlon C. Kennicutt, and Colin P. Summerhayes**

**Abstract** The early national expeditions to Antarctica were short-term, with science usually driven by the interests and opportunities of those scientists who were taken along. Some expeditions made important collections of both data and specimens that proved crucial in establishing why more research should be funded. However, in those early days, there was little coordination other than attempts to use similar instruments and protocols for collecting physical data such as magnetic and meteorological records. With our present-day sophisticated communications, aerial and oceanic surveys, regular access to scientific stations and ships across Antarctica and the Southern Ocean, and research on and around the continent by many nations, collaboration is essential to make the most of the resources. Establishing the Scientific Committee on Antarctic Research (SCAR) in 1958 proved to be a crucial step in developing the Antarctic scientific community and maximising the value of research across all scientific fields. In parallel to this, SCAR has also developed a major role as the primary scientific advisor to the Antarctic Treaty Parties on scientific and environmental matters.

**Keywords** Scientific Committee on Antarctic Research • Antarctic Treaty • International Geophysical Year • International Polar Year • APECS

D.W.H. Walton (✉)
British Antarctic Survey, Cambridge, UK
e-mail: dwhw@bas.ac.uk

M.C. Kennicutt
Texas A & M University, College Station, TX, USA
e-mail: mckennicutt@gmail.com

C.P. Summerhayes
Scott Polar Research Institute, Cambridge, UK
e-mail: cps32@cam.ac.uk



D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5_29

## 29.1 Finding a Common Purpose

The first two Polar Years in 1882/1983 and 1932/1933 had shown that it was possible to agree on international research goals in the polar regions, but they achieved much less than had been hoped, not least because of global economic problems, the limited range of fields investigated and a failure to synthesise and publish much of the data afterwards (Barr and Lüdecke 2010; Summerhayes 2008).

During 1944, the UK had established several permanent stations on the Antarctic Peninsula, and this initiative was soon followed by Argentina, Chile, France and Australia, all nations claiming territory on the continent. Their early scientific activities were driven by opportunity and some national planning, but there was little attempt to coordinate or collaborate. Indeed, for much of the first 10 years relations between Argentina, Chile and the UK were strained as each country tried to improve its legal claim to territory, a much more important objective to those nations at the time than the science being undertaken.

Various suggestions were put forward for an international solution to the growing tension, but none met with general support (Jacobsen 2011). The idea for a third Polar Year first surfaced in 1950, promoted by two physicists, Lloyd Berkner from the USA and Sidney Chapman from the UK. They understood that the predicted high in solar activity would make 1957/1958 an advantageous period for many geophysical observations at the poles. Technological developments resulting from the Second World War, such as rocketry and radar, had also provided scientists with a whole range of new instruments for research. Their original idea finally morphed into a more general programme called the International Geophysical Year (IGY), which included scientists from around the globe, but with an emphasis on two frontiers – space and Antarctica.

The coordinating committee for the IGY (Comité Spécial de l'Année Géophysique Internationale, CSAGI) did an outstanding job in avoiding the politics, especially the Cold War distrust between the USA and the USSR, which bedevilled most international relations at the time. A focus on science that needed to be done was the objective of the IGY, and not political or territorial aspirations. In the end, 12 nations established active Antarctic research stations during the IGY, and while most were on the coast for ease of logistics, two major stations were established inland for the first time at the South Pole (Amundsen-Scott, USA) and the Pole of Inaccessibility (Polyus Nedostupnosti, USSR).

The success of the wide range of research conducted during the IGY cemented relationships amongst a fledgling community of Antarctic scientists. The major scientific discoveries of the IGY lent credence to petitions by scientists for their governments to continue to fund Antarctic science and maximise the return on the considerable logistics investments they had made. Such pleas were welcomed in the USA where President Eisenhower was looking for a way to keep the Antarctic continent from becoming militarised by the USA and the USSR in their continuous competition for hegemony. An international treaty building on the continuing value of science and including controls on military activities was clearly the answer, and so the USA took the initiative and called together the original 12 nations to develop the agreement that ultimately became the Antarctic Treaty (Berkman 2011).

By 1 December 1959, the future of Antarctica was assured as the Antarctic Treaty was signed in Washington DC. Not only did it reserve the continent for peace and science but it specifically excluded all military activities and developments and allowed for international inspections to ensure compliance. In science it required continuing collaborations, international cooperation and data sharing, building on the success of the IGY and providing a beacon of hope for the international science community in what were grim political times internationally.

Scientists were excited by the achievements of the IGY, and at the fourth CSAGI meeting in June 1957 discussed asking for funds for a further year of research from all their governments. Politics began to intrude and the UK, Chile and Australia all opposed the extension to the IGY, while the USA, USSR, Argentina and Belgium were supportive. So the scientists decided to directly approach the International Council of Scientific Unions (ICSU) and request support at least for the establishment of a permanent committee to continue the planning and collaborative work of CSAGI. By September 1957, this had been agreed and the 12 nations as well as four ICSU scientific unions were invited to propose members for the Special Committee on Antarctic Research (SCAR), which held its first meeting in The Hague in February 1958, well before the Antarctic Treaty had been agreed by the politicians (Fig. 29.1).

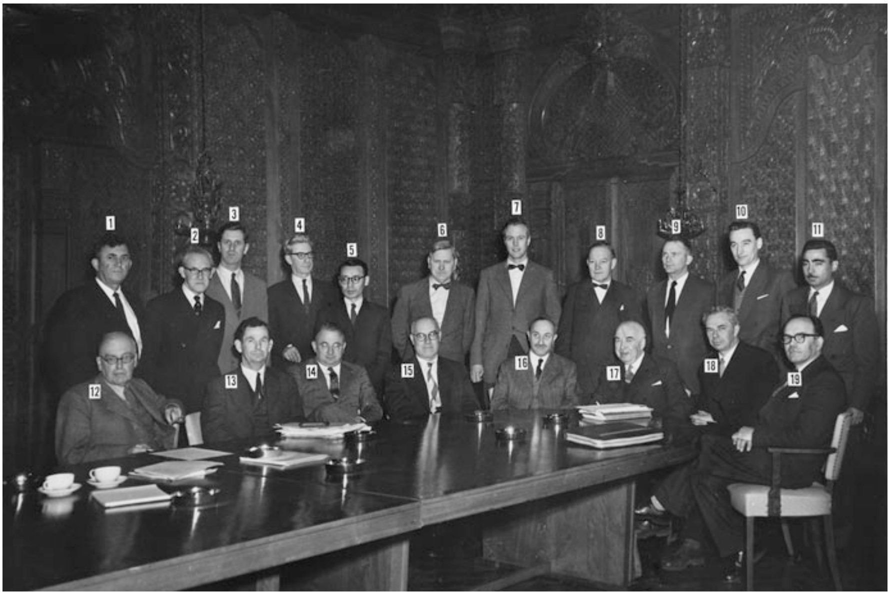


**Fig. 29.1** The first meeting of SCAR at The Hague, 3–5 February 1958. Nine of the 12 countries were represented and George Laclavère (15) from France became the first president (With kind permission from the Scientific Committee on Oceanic Research)

The establishment of SCAR by middle-aged men smoking pipes was to be an abiding feature of the early development of the committee. At this first meeting, a constitution was drawn up that made SCAR independent of governments, decided that its area of interest would be determined by scientific rather than political features, set the annual subscription and began the establishment of working groups (based on specific disciplines) to coordinate scientific initiatives. A president was elected and this prestigious post has continued to be critical in leading SCAR's disparate membership in the right direction. As SCAR membership grew, vice presidents were appointed to form, together with the secretary/treasurer, an executive committee.

By 1962, there were eight working groups, providing a general framework for discussing the science. The working group model persisted for many years, with several groups being reconfigured or renamed as fashions and priorities in science changed. Several (biology, upper atmosphere physics, geology, geodesy and cartography, glaciology, oceanography, meteorology, logistics) persisted unchanged for decades. Each SCAR country could appoint a representative to each working group, within which current activities were reported and new ideas were discussed. In addition, each country appointed a delegate to attend the formal SCAR meeting that determined organisational policies and decisions. By 1968, it was recognised that dedicated groups were needed to discuss particular topics on a continuing basis. These were to be small, appointed directly by the executive committee on the basis of expertise rather than national representation, and named groups of specialists. The number of these groups of specialists has fluctuated over the years but they have had a major influence on specific areas of science such as environmental affairs and conservation, seals, Southern Ocean ecosystems and ecology, subglacial lake exploration, climate and global change (Walton and Clarkson 2011).

With only 12 countries taking part for the first 20 years, the community in each area of science was not large, and close friendships were formed that greatly facilitated the exchange of information and joint planning of projects.

## 29.2 Providing Initiatives for the Antarctic Treaty

Many of the same people (men only of course in those days) transferred from CSAGI to the new SCAR, providing both continuing expertise from the IGY experience and a strong commitment to Antarctic science right from the start. The Antarctic Treaty countries had rejected a suggestion that SCAR be given a seat at their meetings to provide them with independent and expert scientific advice, but the diplomats did recognise the need for such advice from the start. At their first meeting in Canberra in 1961, their first recommendation dealt with SCAR programmes and their fourth with the need for SCAR to provide scientific advice. With no direct connection with the treaty meetings, SCAR had to transmit its advice through national delegations, which was helped by several countries regularly appointing senior SCAR scientists as advisors to their delegations. This pattern


**Fig. 29.2** The logo of BIOMASS (Biological Investigations of Marine Antarctic Systems and Stocks), which was the first large-scale marine programme organised by SCAR (With kind permission from SCAR)

was to continue until 1987 when SCAR was finally appointed as an observer to the Antarctic Treaty Consultative Meeting (ATCM), allowing the tabling of its own papers. This continues today.

During the last 50 years, SCAR has provided the Antarctic Treaty with authoritative scientific advice on many different issues and topics. SCAR drafted the outlines of most of the policies on conservation and environmental management, and it often fell to SCAR to remind treaty parties of the need for strong objective scientific evidence to support decision and policy making. SCAR served as a voice for the scientific community by analysing and reporting on the effects of treaty decisions on scientific research. In pursuit of SCAR's own objectives, such as the need for maps and names for geographic features, SCAR developed the only systematic gazetteer for the continent, and rules for mapping that have played a major role in guiding and supporting the national mapping activities (Walton 2011).

One area of actions deserves particular mention. There is only a passing mention of conservation in the Antarctic Treaty and yet this was identified as early as 1959 as needing urgent attention. It was a SCAR draft that provided the foundations for the Agreed Measures for the Conservation of Antarctic Animals and Plants in 1964, and it was SCAR scientists who raised the issues associated with uncontrolled fishing by the USSR in the 1970s. The scientific findings of the SCAR BIOMASS Program resulted in the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), which now provides fisheries management for the Southern Ocean (Chap. 21) (Fig. 29.2).

## 29.3 Reorganising to Meet the Twenty-First Century

Science is always in a state of flux, with evolving objectives, methods and structures to meet new and emerging challenges. SCAR appeared to manage change over the years quite well by frequently making small adjustments to its structure, but had not made any major change to the organisation for most of its first 40 years. The increasing political interest in minerals in the 1980s apparently prompted a sudden increase in applications to join SCAR and the Antarctic Treaty so that membership increased from the original 12 in 1977 to 24 by 1990 (Orheim et al. 2011). This created considerable pressures on the existing organisation, which had become insular and overly based on personal relationships, but the only response was to simply expand the existing structure rather than consider anew how to become more effective and strategic with twice as many members.

A major change, symptomatic of an outdated structure, occurred in 1988, when the logisticians (National Antarctic Programs) decided that they needed an organisation of their own and left SCAR to form the Council of Managers of National Antarctic Programs (COMNAP) (Fowler 2000). Some felt this was an indication of the end of SCAR, but many simply took this event as a wake-up call, drawing attention to questions raised amongst the science community about the relevance, need and functioning of SCAR.

As usual in large international organisations, it took some time for change to get under way. It was not until 1998 that newer members and younger delegates eventually found common purpose in demanding that the old system must be changed and that a fresh face and structure were critical for the survival of SCAR into the twenty-first century. The inertia to stay the same was finally overcome at a meeting in 1998 in Concepcion, where suggestions that SCAR might cease to exist resulted in the establishment of an international review committee and a mechanism to move SCAR in a new direction. Consulting widely with Antarctic scientists around the world, the committee came back with 20 recommendations that would provide a complete restructuring of SCAR. A new strategy was devised, new responsibilities were given to delegates and to vice presidents, and chief officers of the principal committees were included ad hoc in the executive committee meetings. A restructured secretariat was established with a full-time executive director, major new peer-reviewed international programmes were established, and all scientific activities became subject to time limits and regular reviews to determine relevance, effectiveness and efficiency. A quest began to find new sources of funding for a range of new initiatives and a system of awards was devised with medals for achievement in both science and the international coordination of science. SCAR also began to work on its first ever strategic plan (Fig. 29.3).

For scientists interested in working in Antarctica, the most important changes were the new international programmes that promoted participation and interdisciplinary collaboration on a much more organised and broader basis than ever before. These were the SCAR Scientific Research Programs (SRPs) that served to re-emphasize science and encourage better information flow, networking and mentoring. A biennial Open Science Conference was created to foster cross-disciplinary approaches complementing the quadrennial SCAR disciplinary Symposia (e.g., Biology, Earth Sciences, and Glaciology) (Fig. 29.4).

**Fig. 29.3** SCAR groups meet all over the world. This is a marine ecology EASIZ workshop meeting in Croatia (With kind permission from Andrew Clarke, BAS)

**Fig. 29.4** Every 2 years, SCAR organises a major meeting for all its scientific groups and the national delegates. This photo shows the national delegates from over 28 countries at XXVII SCAR in Shanghai in 2002 (With kind permission from SCAR)

The growing international environmental movement and the increasing political interest in global climate change in the 1970s and 1980s, coupled with the development of new glaciological techniques for collecting and analysing ice cores, had the effect of placing Antarctica and its surrounding Southern Ocean centre stage as key elements in understanding and modelling the Earth and its global climate system. In response, SCAR gradually increased its efforts to work with ICSU's new International Geosphere-Biosphere Program (IGBP), and with the World Climate Research Program (WCRP) co-sponsored by the World Meteorological Organization (WMO), ICSU and UNESCO's Intergovernmental Oceanographic Commission (IOC). In parallel with this, data from national activities in Antarctica began to be used by the Intergovernmental Panel on Climate Change (IPCC).

SCAR's involvement in climate change studies expanded considerably with SCAR's restructuring. In 2004, SCAR decided to embark on a review of Antarctic Climate Change and the Environment (ACCE) that would be the south polar equivalent of the Arctic Climate Impact Assessment (ACIA) that had been started in the north by the Arctic Council and the International Arctic Science Committee (IASC).

The restructuring of SCAR had created Standing Scientific Groups (SSGs) for life sciences, geosciences and physical sciences, collapsing the numerous working groups into these three groups. All expert groups were disbanded, and reconstituted based solely on need and participation to deal with long-standing questions. Action groups were created to deal with shorter-term issues. While SSGs were populated by national members, expert and action groups and Scientific Research Programs (SRPs) were populated by those with scientific expertise appropriate to the group's objectives. All groups, appointments and leadership positions were assigned finite appointment terms subject to regular review and replacement or renewal, and larger projects were given a finite termination date to ensure renewal on a regular basis.

Proposals for SRPs were generated by self-organisation of interested communities, subjected to peer review before creation, and internal and external performance reviews every 2 and 4 years, respectively. SRPs were designed to end in 8 years or less, and continuation was not an option without significant re-formulation and a new proposal. The first five agreed major international science programmes were:

- Antarctica and the Global Climate System (AGCS), a study of the present ocean-atmosphere-ice system in the Antarctic;
- Antarctic Climate Evolution (ACE), a study of climate change over the last 35 million years;
- Evolution and Biodiversity in the Antarctic (EBA), a study of the responses of life to change;
- Subglacial Lake Exploration (SALE), the chemistry and biology of lakes buried beneath the ice sheet;
- Interhemispheric Conjugacy Effects in Solar-Terrestrial and Aeronomy Research (ICESTAR), a study of the response of the outer atmosphere to the changing impact of the solar wind.


**Fig. 29.5** As well as the official SCAR delegation to Antarctic Treaty Consultative Meetings every year, there are normally many SCAR scientists included in national delegations. Informal consultations over a beer are taking place here at the ATCM in Lima, Peru (With kind permission from Peter Clarkson, SCAR)

These mostly interdisciplinary programmes encouraged the development of linkages between geologists and biologists, between glaciologists and meteorologists, and between oceanographers and atmospheric chemists (Fig. 29.5).

By the time of its restructuring, SCAR had begun to realise that it could not, as in the past, take on most Antarctic scientific studies by itself. To be fully effective, and to avoid duplication of effort, it needed to form partnerships with other organisations with a global remit that included an interest in Antarctic science, such as the IGBP and the WCRP. In addition, SCAR had realised that many of the scientific questions it addressed were common also to the Arctic and required bipolar solutions that would benefit from developing partnerships with groups such as the International Permafrost Association and the International Arctic Science Committee. Partnerships with these organisations were duly developed, allowing SCAR to strengthen and extend its vision and mission through cooperative and bipolar initiatives.

Meanwhile the new executive director was travelling the world breathing new life and enthusiasm into groups everywhere while promoting SCAR as the key forum for the discussion and development of Antarctic science. These new activities were recognised in various ways. Initially the award to SCAR of Spain's Prince of Asturias Prize for International Cooperation in 2002 presented a problem. What to do with the prize money of 50,000 Euros? This prompted the establishment of a new annual opportunity for young scientists to become SCAR Fellows and gain


**Fig. 29.6** In 2002, SCAR was awarded the Prince of Asturias Foundation Prize for International Cooperation. Here in the back row, with Queen Sofia and Prince Felipe, are the SCAR representatives at the award ceremony (With kind permission from SCAR)

experience of working at overseas research facilities. A second major opportunity was the success of an application to the Tinker Foundation for SCAR to administer the annual Martha Muse Award of US$100,000, given to a leading mid-career scientist with great potential for future leadership in Antarctic science and/or policy. A third major step forward was the selection of SCAR to manage the Southern Ocean component of the Census of Antarctic Marine Life funded by the Alfred P Sloan Foundation, which reached its conclusion in 2010 (Fig. 29.6).

SCAR began thinking about the preparations for an International Polar Year (IPY) as early as 2000, seeing this as a major opportunity to develop bipolar and interdisciplinary initiatives and to encourage much wider participation in polar science from the global community. By 2004, ICSU had established a planning committee for the IPY, and development of new ideas was already under way. The WMO quickly became a co-sponsor of the IPY, and SCAR was invited to join the IPY organising committee. When the IPY started in March 2007, there were 228 endorsed programmes, 170 in science, 57 in education and outreach and 1 in data management. In the end, 97 of the programmes involved SCAR either in Antarctic or bipolar studies, raising the profile of the newly revitalised organisation, including the naming of all 5 SCAR SRPs as IPY programmes.

While the details of the IPY are dealt with in Chap. 28, it is noteworthy that the timing of this international activity could not have been better for the re-invention of SCAR. The IPY was a perfect opportunity for testing the efficiency and effectiveness of new SCAR management structures and for highlighting two areas where SCAR had particular concerns, long-term data management and the importance of education and public outreach in building a better understanding of the global importance of Antarctica.

Alongside the many workshops and symposia organised by SCAR, the various disciplines have produced important, openly available products for the benefit of all. Amongst the most important have been the detailed map of the rocky continent underlying the Antarctic ice sheets (BEDMAP), the Antarctic digital database of maps, the Composite Gazetteer, the International Antarctic Weather Forecasting Handbook, the synthesis volume on Antarctic Climate Change and the Environment (ACCE), the Antarctic Seismic Data Library, the Antarctic Marine Biodiversity Database, the Continuous Plankton Recorder database, and the READER project to rescue historic climate data. Most recently, in 2012, SCAR launched with its partner SCOR (ICSU's Scientific Committee on Oceanic Research) a Southern Ocean Observing System (SOOS) that will make a significant contribution to the Global Ocean Observing System organised by UNESCO's IOC on behalf of the WMO, ICSU and the United Nations Environment Program (UNEP).

## 29.4 Scientific Highlights

Since it is national programmes that actually fund research in Antarctica, it might be asked just what SCAR can claim to have achieved scientifically over the past 50 years. It is as an independent science forum, as a global network of interested scientists, as the principal scientific advisor to the Antarctic Treaty Parties and as a facilitator of meetings and symposia that SCAR has made its greatest contribution, in much the same way as the scientific committees of ICSU, the Royal Society in the UK and the National Academy of Sciences in the USA have facilitated the development of national scientific agendas and directions.

While not a funder of science, there are still many achievements in which SCAR has played a major role in synthesizing data and bringing together observations and models. Just to cite a few examples, in the case of climate, the establishment of the Reference Antarctic Data for Environmental Research (READER) database has shown the exceptional warming of the western side of the Antarctic Peninsula; multiple shallow snow cores from transects across the East Antarctic Ice Sheet (ITASE) have provided an important insight into the variability of climate reconstructions based on ice cores; and the development of a sea-ice database has linked with satellite observations to characterise changes in sea-ice thickness around the whole continent. In the Southern Ocean, SCAR's most important early contribution was the BIOMASS programme, which focused on the key role krill play in the marine ecosystem (El Sayed 1994). Most recently, in 2009, SCAR produced the Antarctic

Climate Change and the Environment (ACCE) report (Turner et al. 2009), which is updated regularly in reports to the annual Antarctic Treaty Consultative Meeting. Further achievements are documented in detail elsewhere (Summerhayes 2007).

## 29.5 Future Opportunities

As of 2015, SCAR comprised 31 full national members, 8 associate national members and 9 ICSU scientific union members. How things have changed since the original 12 countries sat around the table and formed SCAR. However, the independence of SCAR from governments and its insistence on the quality and excellence of science, the need for authoritative objective scientific advice to inform policy making, the importance of international collaboration and cooperation, and the imperative to nurture and mentor the next generation of scientists are unchanged. The future direction of SCAR is set through 6-year strategic plans with the latest one covering 2011–2016, and more recently, the initiation of the first Antarctic and Southern Ocean Science Horizon Scanning exercise that will bring together leading Antarctic scientists, researchers, policy makers, national Antarctic programmes, funders of Antarctic science and visionaries to discern future directions in Antarctic science over the next two decades. The scan has produced a collective, community-based vision of the 100 highest priority scientific questions to assist in strategic planning, influence future directions in Antarctic research, highlight opportunities for collaborations and synergies, identify future critical infrastructure, logistical, and technological needs and inform international decisions about investments in the Antarctic scientific enterprise (Kennicutt et al. 2014a, b).

SCAR's Scientific Research Programs (SRPs) are subject to renewal on a regular basis and cannot extend beyond 8 years. This ensures that SCAR's science portfolio remains timely, addressing key scientific areas that are topical, multidisciplinary and of political and societal importance in a global context. It also ensures renewal of the portfolio of science and encourages wide participation. The latest SRPs include:

- **State of the Antarctic Ecosystem**: this programme has been designed to explain biodiversity on land and in the sea (including sea ice), answering questions about how ecosystems evolved and what threatens them. A primary product of this programme will be recommendations for biodiversity management and conservation.
- **Antarctic Thresholds – Ecosystem Resilience and Adaptation**: The extreme environment, and the marked difference in community complexity between the polar regions and much of the rest of the planet may mean that consequences of stress for ecosystem function and services, and their resistance and resilience, will differ from elsewhere. The main goal of this programme is to determine the resistance, resilience and vulnerability to change of Antarctic biological systems, including in particular the likelihood of cataclysmic shifts or tipping points in Antarctic ecosystems.

- **Antarctic Climate Change in the twenty-first century**: The goals of this programme are to deliver improved regional predictions of likely change in key elements of the Antarctic atmosphere, ocean and cryosphere for the next 20–200 years, and to understand the likely responses of the physical and biological systems to natural and anthropogenic forcing factors. Palaeo-climate reconstructions of selected time periods, recognised as past analogues for future climate predictions, will be used to validate model performances for the Antarctic region.
- **Past Antarctic Ice Sheet Dynamics** (**PAIS**): PAIS aims to improve our understanding of ice-sheet dynamics during past warm world conditions by looking at vulnerable areas around the continent (both on the west and east Antarctic margin), linking ice data with coastal and offshore records and integrating data into the latest generation of coupled Glacial Isostatic Adjustment (GIA)-Ice Sheet-Climate models that will assist in estimating likely changes in sea level both locally and globally.
- **Solid Earth Response and Influence on Cryosphere Evolution** (**SERCE**): SERCE aims to improve understanding of the solid earth response to cryospheric and tectonic forcing by studying the interactions between the solid earth and the cryosphere, including Glacial Isostatic Adjustment (GIA) and ice-mass change and the influence of solid earth parameters (such as heat flow, disposition of sediments) on ice-sheet dynamics. This will include work with other groups on ice-mass change, ice-sheet contributions to global sea-level rise, and glacial isostatic adjustment models of Greenland and other ice caps.
- **Astronomy and Astrophysics in Antarctica**: This programme aims to coordinate astronomical activities in Antarctica in a way that ensures the best possible outcomes from international investment in Antarctic astronomy, and maximizes the opportunities for productive interaction with other disciplines.

In addition SCAR's leading role in the development of the Southern Ocean Observing System will enable us to learn more about the physical, chemical and biological complexity of this 10 % of the world's oceans, and its role in climate change in the Southern Hemisphere. A new program, the ANtarctic Terrestrial Observing System (ANTOS) is now emerging to supplement SOOS.

For many years, SCAR focused only on the natural science component of Antarctica. The human element was assumed to be the responsibility of others. However, more recently SCAR has facilitated the growth of a history and social sciences group with a steadily expanding membership. Their investigations into the history of Antarctic science as well as values and human perceptions of the continent (e.g. Lüdecke 2007) have been matched by the recent cultural activities organised alongside the Open Science meeting in Portland in 2012 that celebrated the continent in music, art and photography.

The continued upgrading of the SCAR website (www.scar.org) has provided not only a link to SCAR activities being undertaken but also a basis for announcing new scientific highlights from the many national programmes working on, from and around the continent. In addition there are valuable sections on education and outreach in several languages, making the science accessible for schools in many


**Fig. 29.7** The first of the invited SCAR lectures at the Antarctic Treaty Consultative Meeting in Spain, in 2003, was delivered by Anna Jones, entitled 'Antarctic Science Global Relevance' (With kind permission from SCAR)

countries. Recruiting and Educating the next generation of Antarctic scientists is a key element of SCAR's mission (Fig. 29.7).

There is much still to do to ensure that SCAR remains the preeminent forum for Antarctic research, the source of authoritative scientific advice and an organisation that advances and champions multilateral and interdisciplinary collaborations. In its 55-year history, the organisation has been dominated by men, and the majority of its senior officers have been provided by a small subset of countries. There is a noticeable lack of Middle Eastern and African countries among the treaty parties and SCAR nations. This pattern is slowly changing. It needs to continue to move forward with gender equality in senior positions, and with an increasing emphasis on making the science more widely available and understood. Assistance can be provided through mentoring and joint projects to strengthen the science in those countries that have more limited resources for Antarctic research. The increasing use of social media to promulgate information and ideas worldwide is matched by the steady increase in the proportion of young scientists who are attending SCAR meetings and are interested in a career in Antarctic research. The close links between SCAR and the Association of Polar Early Career Scientists (APECS) form an essential partnership for keeping enthusiasm high and the momentum for change.

SCAR has always provided a forum for the exchange of ideas, been a facilitator of new initiatives and acted as an independent source of the latest and best Antarctic

**Fig. 29.8** The SCAR logo: the continuing indicator of independence and cooperation in Antarctic science (With kind permission from SCAR)

science. Its small budget has never allowed it to provide direct financial support for research itself, and its very limited secretariat is best used to support meetings, publish and disseminate information, and provide linkages across the widely spread community of over 35 nations that are active in SCAR. The success of SCAR now and in the future will always be reliant on the goodwill and unpaid work of many individual scientists who believe that by working together in SCAR they can achieve much more than the sum of their individual efforts. It is this sense of community and personal friendships that has always made SCAR more important and more effective than either its budget or its staffing would suggest. It is the enthusiasm of the participants, the excitement of the research and their love of working in Antarctica that will continue to ensure that SCAR plays a pivotal role in facilitating the best and highest quality science on global problems from an Antarctic perspective for years to come. While the world and Antarctic politics have become increasingly complicated over the years, the fundamental commitment to science, peace and international cooperation remains as compelling now as it was more than 50 years ago. The need for an organisation like SCAR has never been greater (Fig. 29.8).

## References

Barr S, Lüdecke C (eds) (2010) The history of the International Polar Years. Springer, Berlin

Berkman PA (2011) President Eisenhower, the Antarctic Treaty and the origin of international spaces. In: Berkman PA, Lang MA, Walton DWH, Young OR (eds) Science diplomacy. Smithsonian Institution Scholarly Press, Washington, DC, pp 17–27

El Sayed SZ (ed) (1994) Southern ocean ecology: the BIOMASS perspective. Cambridge University Press, Cambridge, p 399

Fowler AN (2000) COMNAP – the National Managers in Antarctica. American Literary Press Inc., Baltimore

Jacobsen M (2011) Building the international legal framework for Antarctica. In: Berkman PA, Lang MA, Walton DWH, Young OR (eds) Science diplomacy. Smithsonian Institution Scholarly Press, Washington, DC, pp 1–15

Kennicutt MC et al (2014a) Polar research: six priorities for Antarctic science. Nature 512 (7512):23–25. doi:10.1038/512023a

Kennicutt MC et al (2014b) A roadmap for Antarctic and southern ocean science for the next two decades and beyond. Antarctic Sci 26. doi:10.1017/S0954102014000674

Lüdecke C (ed) (2007) Steps of Foundation of Institutionalized Antarctic Research. In: Proceedings of the 1st SCAR workshop on the history of Antarctic research, Bavarian Academy of Sciences and Humanities, Munich, 2–3 June 2005. Berichte zur Polar und Meeresforchung 560, pp 1–228

Orheim O, Press A, Gilbert N (2011) Managing the Antarctic Environment: the evolving role of the Committee for environmental protection. In: Berkman PA, Lang MA, Walton DWH, Young OR (eds) Science diplomacy. Smithsonian Institution Scholarly Press, Washington, DC, pp 209–221

Summerhayes CP (2007) Achievements of SCAR to 2006. SCAR Report No. 29:38

Summerhayes CP (2008) International collaboration in Antarctica: the International Polar Years, the International Geophysical Year and the Scientific Committee on Antarctic Research. Polar Rec 44(231):321–334

Turner J, Bindschadler RA, Convey P, Di Prisco G, Fahrbach E, Gutt J, Hodgson DA, Mayewski PA, Summerhayes CP (2009) Antarctic climate change and the environment. Scientific Committee on Antarctic Research, Cambridge, ISBN 978-0-948277-22-1, p 526. www.scar.org/publications/occasionals/acce.html

Walton DWH (2011) SCAR and the Antarctic Treaty. In: Berkman PA, Lang MA, Walton DWH, Young OR (eds) Science diplomacy. Smithsonian Institution Scholarly Press, Washington, DC, pp 75–88

Walton DWH, Clarkson PD (2011) Science in the snow: fifty years of international collaboration through the Scientific Committee on Antarctic Research. SCAR, Cambridge, p 258

# Index




D. Liggett et al. (eds.), *Exploring the Last Continent*,
DOI 10.1007/978-3-319-18947-5

## E



## F



## G

## H



## I