Management Plan for Antarctic Specially Protected Area No. 122

ARRIVAL HEIGHTS, HUT POINT PENINSULA, ROSS ISLAND

Introduction

The Arrival Heights Antarctic Specially Protected Area (ASPA) is situated near the south-western extremity of Hut Point Peninsula, Ross Island, at 77° 49' 41.2" S, 166° 40' 2.8" E, with an approximate area 0.73 km^2. The primary reason for designation of the Area is its value as an electromagnetically 'quiet' site for the study of the upper atmosphere and its close proximity to logistical support. The Area is used for a number of other scientific studies, including trace gas and ultraviolet (UV) radiation monitoring, auroral and geomagnetic studies and air quality surveys. As an example, the longevity and quality of the numerous atmospheric datasets makes the Area of high scientific value. Since its designation in 1975 numerous projects have been located in or near the Area with a potential to degrade the electromagnetically quiet conditions at Arrival Heights. The interference generated by these activities appears to have an acceptably low impact on scientific experiments, with one known exception, discussed below. The continued use of the Area is favored by its geographical characteristics, unobstructed low viewing horizon, clean air and its proximity to logistical support and high costs associated with relocation. The Area was proposed by the United States of America and adopted through Recommendation VIII-4 [1975, Site of Special Scientific Interest (SSSI) No. 2]; date of expiry was extended through Recommendations X-6 (1979), XII-5 (1983), XIII-7 (1985), and XIV-4 (1987), Resolution 3 (1996) and Measure 2 (2000). The Area was renamed and renumbered through Decision 1 (2002); a revised management plan was adopted through Measure 2 (2004), Measure 3 (2011) and Measure 3 (2016). The degradation of electromagnetically 'quiet' conditions within the Area was recognized by SCAR Recommendation XXIII-6 (1994).

The Area lies within 'Environment S – McMurdo – South Victoria Land geologic', as defined in the Environmental Domains Analysis for Antarctica (Resolution 3 (2008)). Under the Antarctic Conservation Biogeographic Regions classification (Resolution 3 (2017)) the Area lies within ACBR9 – South Victoria Land.

1. Description of values to be protected

An area at Arrival Heights was originally designated in Recommendation VIII-4 (1975, SSSI No. 2), after a proposal by the United States of America on the grounds that it was "an electromagnetic and natural 'quiet site' offering ideal conditions for the installation of sensitive instruments for recording minute signals associated with upper atmosphere programs." For example, electromagnetic recordings have been carried out at Arrival Heights as part of long term scientific studies, yielding data of outstanding quality because of the unique characteristics of the geographic location with respect to the geomagnetic field combined with relatively low levels of electromagnetic interference. The electromagnetically quiet conditions and the longevity of data collection at Arrival Heights make the data obtained of particularly high scientific value.

In recent years, however, increases in science and support operations associated with Scott Base and McMurdo Station have raised the levels of locally generated electromagnetic noise at Arrival Heights and it has been recognized that the electromagnetically 'quiet' conditions have to some degree been degraded by these activities, as identified in SCAR Recommendation XXIII-6 (1994).

Scientific research within the Area appears to operate within an acceptably low level of electromagnetic interference (EMI) from other activities in the vicinity and the aims and

objectives set out in the management plan for Arrival Heights therefore remain relevant. However, recent site visits and deployment of new instruments have shown that there is some elevated very-low frequency (VLF) noise in the 50 Hz – 12 kHz range from sources located outside of the Area (associated with the wind turbines that are installed ~1 km from the Area). Analysis of the noise source indicates that inserting power filters into the electrical lines between the wind turbines and the power grid would significantly reduce the level of interference, but this solution has not yet been implemented. The review also produced evidence of increased VLF noise in the 12 - 50 kHz frequency range, which was mitigated by modifying the configuration and grounding of the electrical power grid local to Arrival Heights, and by decommissioning demonstrably electrically noisy equipment, such as some specific types of uninterruptable power supplies (UPS).

Notwithstanding these observations, the original geographical characteristics of the site, such as its elevated position and thus broad viewing horizon, the volcanic crater morphology, and the close proximity to the full logistic support of nearby McMurdo Station (US) 1.5 km south and Scott Base (NZ) 2.7 km SE, continue to render the Area valuable for upper atmospheric studies and boundary layer air sampling studies. Moreover, there are scientific, financial and practical constraints associated with any proposed relocation of the Area and the associated facilities. Thus, the current preferred option for management is to minimize sources of EMI to the maximum extent practicable, and to monitor these levels routinely so that any significant threat to the values of the site can be identified and addressed as appropriate.

Since original designation the site has been used for several other scientific programs that benefit from the restrictions on access in place within the Area. In particular, the broad viewing horizon and relative isolation from activities (e.g. vehicle movements, engine exhausts) has been valuable for measurement of greenhouse gases, trace gases such as ozone, spectroscopic and air particulate investigations, UV radiation and total column ozone monitoring, pollution surveys, and auroral and geomagnetic studies. It is important that these values are protected by maintenance of the broad and unobstructed viewing horizon and that anthropogenic gas emissions (in particular long-term gaseous or aerosol emissions from sources such as internal combustion engines) are minimised and where practicable avoided.

In addition, the protected status of Arrival Heights has also had the effect of limiting the extent and magnitude of physical disturbance within the Area. As a result, soils and landscape features are much less disturbed than is the case in the surrounding areas of Hut Point where station developments have taken place. In particular, sand-wedge polygons are far more extensive than elsewhere in the Hut Point vicinity, covering an area of approximately 0.5 km^2. The relatively undisturbed nature of the environment at Arrival Heights makes the Area valuable for comparative studies of impacts associated with station developments, and valuable as a reference against which to consider changes. These additional values are also important reasons for special protection at Arrival Heights.

The Area continues to be of high scientific value for a variety of high quality and long-term atmospheric data sets that have been collected at this site. Despite the acknowledged potential for interference from local and surrounding sources, the long-term data series, the accessibility of the site for year-round observations, its geographical characteristics, and the high cost of relocation, warrant that the site receive ongoing and strengthened protection. The vulnerability of this research to disturbance through chemical and noise pollution, in particular electromagnetic interference and potential changes to the viewing horizon and/or shadowing of instrumentation, is such that the Area requires continued special protection.

2. Aims and objectives

Management at Arrival Heights aims to:

- avoid degradation of, or substantial risk to, the values of the Area by preventing unnecessary human presence, disturbance and sampling within the Area;
- allow scientific research in the Area, in particular atmospheric research, while ensuring protection from incompatible uses and equipment installation that may jeopardize such research;

- minimize the possibility of generation of excessive electromagnetic noise interference within the Area through regulating the types, quantity and use of equipment that can be installed and operated in the Area;
- avoid degradation of the viewing horizon and shadowing effects by installations on instrumentation reliant on solar and sky viewing geometries;
- avoid / mitigate as far as practicable anthropogenic gaseous or aerosol emissions from sources such as internal combustion engines to the atmosphere within the Area;
- encourage the consideration of the values of the Area in the management of surrounding activities and land uses, in particular to monitor the levels, and encourage the minimization of sources of electromagnetic radiation that may potentially compromise the values of the Area;
- allow access for maintenance, upgrade and management of communications and scientific equipment located within the Area;
- minimize the possibility of introduction of alien plants, animals and microbes to the Area;
- allow visits for management purposes in support of the aims of the management plan; and
- allow visits for education or public awareness purposes associated with the scientific studies being conducted in the Area that cannot be fulfilled elsewhere.

3. Management activities

The following management activities are to be undertaken to protect the values of the Area:

- Signs showing the location and boundaries of the Area with clear statements of entry restrictions shall be placed at appropriate locations at the boundaries of the Area to help avoid inadvertent entry. The signs should include instructions to make no radio transmissions and to turn vehicle headlights off within the Area, unless required in an emergency.
- Notices showing the location of the Area (stating the special restrictions that apply) shall be displayed prominently, and a copy of this management plan shall be kept available, in the principal research hut facilities within the Area and at McMurdo Station and Scott Base.
- National programs shall take steps to ensure the boundaries of the Area and the restrictions that apply within are marked on relevant maps and nautical / aeronautical charts;
- Markers, signs or other structures should not be installed within the Area except for essential scientific or management purposes. If installed, they shall be recorded, secured and maintained in good condition and removed when no longer required by the responsible National Antarctic program;
- Visits shall be made as necessary (no less than once every five years) to assess whether the Area continues to serve the purposes for which it was designated and to ensure management and maintenance measures are adequate.
- Electromagnetic noise surveys shall be undertaken within the Area bi-annually to detect equipment faults and to monitor levels of interference that may have potential to compromise the values of the Area unacceptably, for the purposes of identification and mitigation of their sources.
- Potentially disruptive activities that are planned to be conducted outside of but close to the Area, such as blasting or drilling, or the operation of transmitters or other equipment with the potential to cause significant electromagnetic interference within the Area, or activities that produce significant changes to the power grid (whether supplying or loading), should be notified in advance to the appropriate representative(s) of national authorities operating in the region, with a view to coordinating activities and / or

undertaking mitigating actions in order to avoid or minimize disruption to scientific programs.

- National Antarctic Programs operating in the region shall appoint an Activity Coordinator who will be responsible for inter-program consultation regarding all activities within the Area. The Activity Coordinators shall keep a log of visits to the Area by their programs, recording number of personnel, time and duration of visit, activities, and means of travel into the Area, and shall exchange this information to create a consolidated log of all visits to the Area annually.
- National Antarctic Programs operating in the region shall consult together with a view to ensuring the conditions in this management plan are implemented, and take appropriate measures to detect and enforce compliance where the conditions are not being followed.

4. Period of designation

Designated for an indefinite period.

5. Maps

Map 1: ASPA No. 122 Arrival Heights – Regional overview, showing Hut Point Peninsula, nearby stations (McMurdo Station, US; and Scott Base, NZ), installations (SuperDARN, satellite receptors and wind turbines) and routes (roads and recreational trails). Projection Lambert Conformal Conic: Standard parallels: 1st 77° 40' S; 2nd 78° 00' S; Central Meridian: 166° 45' E; Latitude of Origin: 77° 50' S; Spheroid WGS84; Datum McMurdo Sound Geodetic Control Network. Data sources: Topography: contours (10 m interval) derived from digital orthophoto and DEM from aerial imagery (Nov 1993); Permanent ice extent digitized from orthorectified Quickbird satellite image (15 Oct 2005) (Imagery © 2005 Digital Globe); Infrastructure: station layout CAD data USAP (Feb 09 / Mar 11), ERA (Nov 09) and USAP (Jan 11) field survey; Recreational trails PGC field survey (Jan 09 / Jan 11).

***Inset 1*:** The location of Ross Island in the Ross Sea. ***Inset 2*:** The location of Map 1 on Ross Island and key topographic features.

Map 2: ASPA No. 122 Arrival Heights – topographic map, showing protected area boundaries, site facilities, nearby installations (SuperDARN, satellite receptors) and routes (access roads and recreational trails). Projection details and data sources are the same as for Map 1.

6. Description of the Area

6(i) Geographical coordinates, boundary markers and natural features

Arrival Heights (77° 49' 41.2" S, 166° 40' 2.8" E; Area: 0.73 km^2) is a small range of low hills located near the southwestern extremity of Hut Point Peninsula, Ross Island. Hut Point Peninsula is composed of a series of volcanic craters extending from Mount Erebus, two of which, namely First Crater and Second Crater, respectively form part of the southern and northern boundaries of the Area. The Area is predominantly ice-free and elevations range from 150 m to a maximum of 280 m at Second Crater. Arrival Heights is located approximately 1.5 km north of McMurdo Station and 2.7 km northwest of Scott Base. The Area has a broad viewing horizon and is comparatively isolated from activities at McMurdo Station and Scott Base, with the majority of McMurdo Station being hidden from view.

Boundaries and coordinates

The southeastern boundary corner of the Area is defined by Trig T510 No.2, the center of which is located at 77° 50' 08.4" S, 166° 40' 16.4" E at an elevation of 157.3 m. Trig T510 No.2 replaced and is 0.7 m from the former boundary survey marker (T510), which no longer exists. The replacement T510 No.2 marker is an iron rod (painted orange) installed into the ground approximately 7.3 m west of the access road to Arrival Heights, and is surrounded by a small circle of rocks. The boundary of the Area extends from Trig T510 No.2 in a straight line 656.0 m northwest over First Crater to a point located at 77° 49' 53.8" S, 166° 39' 03.9" E at 150 m

elevation. The boundary thence follows the 150 m contour northward for 1186 m to a point (77° 49' 18.6" S, 166° 39' 56.1" E) due west of the northern rim of Second Crater. The boundary thence extends 398 m due east to Second Crater, and around the crater rim to a US Hydrographic Survey marker (a stamped brass disk) which is installed near ground level at 77° 49' 23.4" S, 166° 40' 59.0" E and 282 m elevation, forming the northeastern boundary of the Area. The boundary thence extends from the US Hydrographic Survey marker southward for 1423 m in a straight line directly to Trig T510 No.2.

Geology, geomorphology and soils

Hut Point Peninsula is 20 km long and is formed by a line of craters that extend south from the flanks of Mt. Erebus (Kyle 1981). The basaltic rocks of Hut Point Peninsula constitute part of the Erebus volcanic province and the dominant rock types are alkali basanite lavas and pyroclastics, with small amounts of phonolite and occasional outcrops of intermediate lavas (Kyle 1981). Aeromagnetic data and magnetic models indicate that the magnetic volcanic rocks underlying Hut Point Peninsula are likely to be <2 km in thickness (Behrendt *et al*. 1996) and dating studies suggest that the majority of basaltic rocks are younger than ~ 750 ka (Tauxe *et al*. 2004).

The soils at Arrival Heights consist mostly of volcanic scoria deposited from the eruptions of Mount Erebus, with particle size ranging from silt to boulders. The thickness of surface deposits ranges from a few centimetres to tens of metres, with permafrost underlying the active layer (Stefano, 1992). Surface material at Arrival Heights also includes magma flows from Mount Erebus, which have been weathered and reworked over time. Sand-wedge polygons cover an area of approximately 0.5 km^2 at Arrival Heights and, because physical disturbance has been limited by the protected status of the Area, are far more extensive than elsewhere in the southern Hut Point Peninsula vicinity (Klein *et al*. 2004).

Climate

Arrival Heights is exposed to frequent strong winds and conditions are generally colder and windier than at nearby McMurdo Station and Scott Base (Mazzera *et al.* 2001). During the period February 1999 to April 2009, the maximum temperature recorded within the Area was 7.1ºC (30 Dec 2001) and the minimum was -49.8ºC (21 July 2004). During this period, December was the warmest month, with mean monthly air temperatures of -5.1ºC, and August was the coolest month, averaging –28.8ºC (data sourced from National Institute of Water and Atmospheric Research (NIWA), New Zealand, http://www.niwa.co.nz, 21 May 2009).

The mean annual wind speed recorded at Arrival Heights between 1999 and 2009 was 6.96 ms-1, with June and September being the windiest months (data sourced from NIWA, http://www.niwa.co.nz, 21 May 2009). The highest recorded gust at Arrival Heights between 1999-2011 was 51 m/s (~184 km/h) on 16 May 2004. The prevailing wind direction at Arrival Heights is north-easterly, as southern air masses are deflected by the surrounding topography (Sinclair 1988). Hut Point Peninsula lies at the confluence of three dissimilar air masses, predisposing the area to rapid onset of severe weather (Monaghan *et al*. 2005).

Scientific research

Numerous long-term scientific investigations are conducted at Arrival Heights, with the majority of research focusing on the earth's atmosphere and magnetosphere. Radio observations from the ultra low frequency band through the visible light spectrum support scientific research into lightning processes, lightning-ionosphere interactions, thunderstorm-generated atmospheric gravity waves, auroral events, geomagnetic storms, as well as other forms of space weather and heliospherical drivers of global climate change. Other instruments support research into meteorological phenomena and variations in UV radiation and trace gas levels, particularly ozone, ozone precursors, ozone destroying substances, biomass burning products and greenhouse gases. The Area has good access and logistical support from nearby McMurdo Station and Scott Base, which are important to facilitate research within the Area.

The extremely-low-frequency and very-low-frequency (ELF/VLF) data have been continuously collected at Arrival Heights since the austral summer of 1984/1985 (Fraser-Smith *et al*. 1991). The ELF/VLF noise data are unique in both length and continuity for the Antarctic and were recorded concurrently with ELF/VLF data at Stanford University and now at the University of Florida, allowing for comparison between polar and mid-latitude time series. The lack of electromagnetic interference and remote location of Arrival Heights allow researchers to measure background ELF/VLF noise spectra and weak ELF signals, such as Schumann resonances, which are associated changes in the magnetosphere and ionosphere (Füllekrug & Fraser-Smith 1996). ELF/VLF and Schumann resonance data collected within the Area have been studied in relation to space weather: fluctuations in sun spots, solar particle precipitation events, and planetary-scale meteorological phenomenon (Anyamba *et al*. 2000; Schlegel & Füllekrug 1999; Fraser-Smith & Turtle 1993). Observations of narrowband VLF transmitter signals at Arrival Heights have been used to track and analyze the ionospheric response to a solar eclipse in the Northern hemisphere (Moore & Burch 2018). Furthermore, ELF data have been used as a proxy measure of global cloud-to-ground lightning activity and thunderstorm activity (Füllekrug *et al*. 1999) and VLF data provide input to global networks which monitor lightning activity and conditions in the ionosphere (Clilverd *et al.* 2009; Rodger *et al*. 2009). Current ELF and VLF research investigates which types of lightning have the most impact on the magnetosphere and (separately) on the Schumann resonances. High quality electromagnetic data from Arrival Heights has enabled determination of an upper limit for the photon rest mass of $\sim 10^{-52}$ kg (Füllekrug 2004) based on detection of minute global ionospheric reflection height measurements (Füllekrug *et al.* 2002), and it has also provided a critical link between lightning at mid- and tropical latitudes and surface temperature variations in moderate and tropical climates (Füllekrug & Fraser-Smith 1997). Recent research has developed novel measurement technologies with a sensitivity of μV/m over the broad frequency range from ~4 Hz to ~400 kHz (Füllekrug 2010), which has promising scientific potential requiring conditions of electromagnetic quiescence such as are present at Arrival Heights.

The Fe-Boltzmann and Na Lidars at Arrival Heights provide laser-based remote sensing of the upper atmosphere (and thereby space weather) by measuring the temperature and density of metallic particles between 30 and 200 km altitude. Observations at Arrival Heights demonstrate that Iron and Sodium layers respond with significantly different dynamics to external stimuli, specifically aurora (Chu *et al*. 2020). They determined that the auroral affected the iron/sodium mixing ratio, and thereby directly impacted the transport and dissipation of wave energy in the mesosphere. The lidar record is now greater than 10 years in length and will be used to study the atmospheric response over a complete solar cycle.

The southerly location of Arrival Heights results in several weeks of total darkness during the austral winter, allowing low intensity auroral events and dayside emissions to be observed (Wright *et al*. 1998). Data recorded at Arrival Heights have been used to track the motion of polar cap arcs, a form of polar aurora, and results have been related to solar wind and interplanetary magnetic field conditions. Auroral observations made at Arrival Heights by researchers for the University of Washington have also been used to calculate the velocity and temperature of high altitude winds by analyzing the Doppler shift of auroral light emissions. In addition to auroral research, optical data collected within the Area have been used to monitor the response of the thermosphere to geomagnetic storms (Hernandez & Roble 2003) and medium frequency radar has been used to measure middle atmospheric (70-100 km) wind velocities (McDonald *et al*. 2007).

A range of trace gas species are measured at Arrival Heights, including carbon dioxide, ozone, bromine, methane, nitrogen oxides, hydrogen chloride and carbon monoxide, with records commencing as early as 1982 (McKenzie *et al*. 1984; Zeng *et al*. 2012; Kolhepp *et al.* 2012). Measurements made at Arrival Heights in the 1980s provided key data to support the (now verified) depletion of ozone from man-made chlorofluorocarbon (CFC) compounds (Solomon *et al.* 1987).

Arrival Heights represents a key site in the Network of the Detection of Atmospheric Composition Change (NDACC), Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN) and the WMO Global Atmosphere Watch (GAW) program, with data

being used to monitor changes in the stratosphere and troposphere, including long-term evolution of the ozone layer, Southern Hemisphere greenhouse gas concentrations and changes in overall atmospheric composition (Allan *et al*. 2005; Lowe *et al*. 2005; Manning *et al*. 2005). The measurements made at Arrival Heights are vital for Southern Hemisphere and Antarctic satellite comparison (e.g. Vigouroux *et al*. 2007; Sha *et al*. 2021), atmospheric chemistry model validation (Risi *et al.* 2012), ozone hold monitoring (Klekociuk *et al*. 2021) and global-scale stratospheric circulation trend studies (Strahan *et al*. 2020). Arrival Heights has also been used as one of several Antarctic reference stations for intercomparisons of surface air measurements (Levin *et al*. 2012; Schaefer *et al*. 2016). UV radiation has been continuously monitored at Arrival Heights since 1989 (Booth *et al*. 1994). These measurements quantified the effect of the ozone hole on UV radiation at the surface (Bernhard *et al*. 2006, 2010; McKenzie *et al*. 2019) and elucidated the interdependent effects of surface albedo and clouds on UV levels (Nichol *et al*. 2003).

Tropospheric and stratospheric ozone concentrations as well as total ozone columns have been recorded at Arrival Heights since 1988 and are used to monitor both long-term and seasonal variations in ozone (Oltmans *et al*. 2008; Nichol *et al*. 1991; Nichol 2018), as well as in estimations of stratospheric ozone loss (Kuttippurath *et al*. 2010). In addition to longer-term trends, sudden and substantial ozone depletion events have been recorded during spring-time at Arrival Heights, which occur over a period of hours and thought to result from the release of bromine compounds from sea salt (Riedel *et al*. 2006; Hay *et al*. 2007). Tropospheric bromine levels have been continuously recorded since 1995 within the Area and have been studied in relation to ozone depletion, stratospheric warming and changes in the polar vortex, as well as being used in validation of satellite measurements (Schofield *et al*. 2006). Nitrogen oxide (NO_2) data collected at Arrival Heights have also been used to investigate variations in ozone levels and results show substantial variations in NO_2 at daily to interannual timescales, potentially resulting from changes in atmospheric circulation, temperature and chemical forcing (Struthers *et* al. 2004; Wood *et al*. 2004). In addition, ground-based Fourier transform spectroscopy has been used at Arrival Heights to monitor 16+ atmospheric trace gas species. Examples of science include: carbonyl sulfide levels, HCl fluxes from Mount Erebus and observing the effects of sudden stratospheric warmings on the ozone hole (Kremser *et al*. 2015; Keys *et al*. 1998; Smale *et al*. 2021).

Vegetation

Lichens at Arrival Heights were surveyed in 1957 by C.W. Dodge and G.E. Baker, with species recorded including: *Buellia alboradians, B. frigida, B. grisea, B. pernigra, Caloplaca citrine, Candelariella flava, Lecanora expectans, L. fuscobrunnea, Lecidella siplei, Parmelia griseola, P. leucoblephara* and *Physcia caesia*. Moss species recorded at Arrival Heights include *Sarconeurum glaciale* and *Syntrichia sarconeurum* (BAS Plant Database, 2009), with *S. glaciale* documented within drainage channels and disused vehicle tracks (Skotnicki *et al*. 1999).

Human activities and impact

The Arrival Heights facilities are used year-round by personnel from McMurdo Station (US) and Scott Base (NZ). In addition to two laboratory buildings, numerous antenna arrays, aerials, communications equipment, and scientific instruments are located throughout the Area, along with associated cabling.

The scientific instruments used for atmospheric research in the Area are sensitive to electromagnetic noise and interference, with potential local noise sources including VLF radio transmissions, powerlines, vehicle emission systems and also laboratory equipment. Noise sources generated outside of the Area that may also affect electromagnetic conditions at Arrival Heights include radio communications, entertainment broadcast systems, ship, aircraft, or satellite radio transmissions, or aircraft surveillance radars. Any significant source or sink connected to the power grid has the potential to affect observations at Arrival Heights. A site visit report from 2006 suggested that levels of interference at that time were acceptably low, despite activities operating out of McMurdo Station and Scott Base. On the other hand, the

installation of wind turbines in 2009/10 introduced electrical noise to the power grid, which in turn affected measurements at Arrival Heights. In order to provide some degree of protection from local radio transmissions and station noise, some of the VLF antennas at Arrival Heights are located within Second Crater.

Unauthorised access to the Area, both by vehicle and on foot, is thought to have resulted in damage to cabling and scientific instruments, although the extent of damage and impact upon scientific results is unknown. A camera was installed at the USAP building in early 2010 to monitor traffic entering the Area via the road leading to the laboratories.

Recent installations within and close to the Area include an FE-Boltzmann LiDAR in the New Zealand Arrival Heights Research Laboratory in 2010, the Super Dual Auroral RADAR Network (SuperDARN) Antenna Array (2009-10) and two satellite earth station receptors (Map 2). The SuperDARN Antenna Array transmits at low frequencies (8 – 20 MHz), with the main transmission direction to the southwest of the Area, and its location was selected in part to minimize interference with experiments at Arrival Heights. Two satellite earth station receptors (Joint Polar Satellite System (JPSS) and MG2) are located nearby. One of the receptors has the ability to transmit (frequency range 2025 – 2120 Hz) and measures have been taken to ensure that any irradiation of the Area is minimal.

Three wind turbines were constructed approximately 1.5 km east of the Area and close to Crater Hill during austral summer 2009-10 (Map 1). EMI emissions from the turbines should comply with accepted standards for electrical machinery and utilities. As referenced above, EMI originating from the new wind turbines has been detected in very low frequency datasets at Arrival Heights, with potential sources of EMI including turbine transformers, generators and power lines. Interference in the VLF range has been sufficient to render Arrival Heights unsuitable for scientific studies measuring radio pulses from lightning (e.g. the AARDVARK experiment), and for this reason a second antenna was established at Scott Base where disturbance in the VLF range is much lower.

Air quality monitoring has been regularly carried out at Arrival Heights since 1992 and recent studies suggest that air quality has been reduced, most likely due to emissions originating from McMurdo or Scott Base (Mazzera *et al*. 2001), for example from construction and vehicle operations. Investigations found that air quality samples contained higher concentrations of pollution derived species (EC, SO_2, Pb, Zn) and PM_{10} (particles with aerodynamic diameters less than 10 μm) aerosols than other coastal and Antarctic sites.

6(ii) Access to the Area

Access to the Area may be made over land by vehicle or on foot. The access road to the Area enters at the south-east and extends to the research laboratories. Several vehicle trails are present within the Area and run from the Satellite Earth Station in First Crater to the foot of Second Crater. Pedestrian access may be made from the access road.

Access by air and overflight of the Area are prohibited, except when specifically authorized by permit, in which case the appropriate authority supporting research programs within the Area must be notified prior to entry.

6(iii) Location of structures within and adjacent to the Area

Both New Zealand and United States maintain research and living facilities within the Area. New Zealand opened a new research laboratory at Arrival Heights on 20 January 2007, replacing an old building which has been removed from the Area. The United States maintains one laboratory within the Area. A range of antenna arrays and aerials designed to meet scientific needs are located throughout the Area (Map 2), and a new VLF antenna was installed at Arrival Heights in December 2008. A Satellite Earth Station (SES) is located several meters inside the boundary of the Area on First Crater (Map 2).

The SuperDARN Antenna Array is located approximately 270 m SW of the Area, while two satellite earth station receptors are installed approximately 150 m SW of the Area (Map 2).

6(iv) Location of other protected areas in the vicinity

The nearest protected areas to Arrival Heights are on Ross Island: Discovery Hut, Hut Point (ASPA No.158), is the closest at 1.3 km southwest; Cape Evans (ASPA No. 155) is 22 km north; Backdoor Bay (ASPA No. 157) is 32 km north; Cape Royds (ASPA No. 121) is 35 km NNW; High Altitude Geothermal sites of the Ross Sea region (ASPA No. 175) near the summit of Mt. Erebus is 40 km north; Lewis Bay (ASPA No. 156) the site of the 1979 DC-10 passenger aircraft crash is 50 km NE; New College Valley (ASPA No. 116) is 65 km north at Cape Bird; and Cape Crozier (ASPA No. 124) is 70 km to the NE. NW White Island (ASPA No. 137) is 35 km to the south across the Ross Ice Shelf. Antarctic Specially Managed Area No. 2 McMurdo Dry Valleys is located approximately 50 km to the west of the Area.

6(v) Special zones within the Area

A Restricted Zone has been designated to provide spatially explicit restrictions on access, installations and emissions within a part of the Area. The Restricted Zone is intended for application to meet particular needs, for example at substantial and / or long-term facilities with special management requirements, rather than for general application to every experiment or installation within the Area (provisions elsewhere within the Management Plan cover these more general circumstances).

New Zealand installed a new Geomagnetic Observatory at Arrival Heights in 2021/22, which is located ~200 m NE of the main United States laboratory (Map 2). The objective of the Observatory is to capture data continuously on natural changes in the regional Earth's magnetic field as part of a global recording network. The Observatory comprises a Variometer hut and an Absolute hut, with power and data service cables extending to the existing New Zealand laboratory. Instruments collecting data at the Observatory are particularly sensitive. A Restricted Zone has been designated around the Observatory to help minimize potential interference.

Geomagnetic Observatory Restricted Zone: boundary extent and conditions for access and installations:

1) The Restricted Zone is designated with a maximum radius of 140 m around the Observatory (Map 2).
2) Installation of any new facilities, antennae, scientific instruments or any other structure is prohibited within the Restricted Zone unless authorized by permit after consultation with the operator responsible for the Observatory.
3) An inner part of the Restricted Zone is designated with a radius of ~100 m around the Observatory where access should be only for compelling reasons that cannot be served elsewhere within the Area. A minor variation to this inner zone boundary is defined to align parallel with and 5 m to the east of the road to Second Crater to allow for access along the road (Map 2).
4) Vehicles and machinery are generally prohibited within the inner part of the Restricted Zone, except as required for essential scientific or maintenance purposes specified by a permit. Access into the inner part of the Restricted Zone shall thus generally be on foot. However, in winter (01 Mar – 31 Oct) vehicles may approach the Observatory along the designated foot access route (Map 2) to within 50 m of the huts to facilitate safe access. Winter visitors should observe all restrictions on use of headlights and radios as specified in other sections of the Management Plan.
5) Visitors traversing through the outer part of the zone by vehicle (e.g. *en route* to Second Crater or the northern part of the Area) shall record vehicle movement times in a log book held at the main NZ laboratory.
6) Disturbance of rocks within a 10 m radius of each hut at the Observatory is prohibited, unless specifically authorized by permit.
7) Pedestrian entry within a 10 m radius of the huts at the Observatory shall be recorded in the log book held at the main NZ laboratory.

7. Terms and conditions for entry permits

7(i) General permit conditions

Entry into the Area is prohibited except in accordance with a permit issued by an appropriate national authority. Conditions for issuing a permit to enter the Area are that:

- it is issued only for scientific study of the atmosphere and magnetosphere, or for other scientific purposes that cannot be served elsewhere; or
- it is issued for operation, management and maintenance of science support facilities (including safe operations), on the condition that movement within the Area be restricted to that necessary to access those facilities; or
- it is issued for educational or public awareness activities that cannot be fulfilled elsewhere and which are associated with the scientific studies being conducted in the Area, on the condition that visitors are accompanied by permitted personnel responsible for the facilities visited; or
- it is issued for essential management purposes consistent with plan objectives such as inspection or review;
- the actions permitted will not jeopardize the scientific or educational values of the Area;
- any management activities are in support of the objectives of the Management Plan;
- the actions permitted are in accordance with the Management Plan;
- the permit, or a copy, shall be carried within the Area;
- a visit report shall be supplied to the authority or authorities named in the permit;
- permits shall be valid for a stated period.

7(ii) Access to, and movement within or over, the Area

Access to the Area is permitted by vehicle and on foot. Landing of aircraft and overflight within the Area, including by both piloted and Remotely Piloted Aircraft Systems (RPAS), is prohibited unless specifically authorized by permit. Prior written notification must be given to the appropriate authority or authorities supporting scientific research being conducted in the Area at the time of the proposed aircraft activity. The location and timing of the aircraft activity should be coordinated as appropriate in order to avoid or minimize disruption to scientific programs, including the preservation of unobstructed viewing horizons. RPAS use within the Area should follow the Environmental Guidelines for Operation of Remotely Piloted Aircraft Systems (RPAS) in Antarctica (Resolution 4 (2018)).

Vehicle and pedestrian traffic should be kept to the minimum necessary to fulfil the objectives of permitted activities and every reasonable effort should be made to minimize potential impacts on scientific research: e.g. personnel entering the Area by vehicle should coordinate travel so vehicle use is kept to a minimum.

Vehicles shall keep to the established vehicle tracks as shown on Map 2, unless specifically authorized by permit otherwise. Pedestrians should also keep to established tracks wherever possible. Care should be taken to avoid cables and other instruments when moving around the Area, as they are susceptible to damage from both foot and vehicle traffic. During hours of darkness, vehicle headlights should be switched off when approaching the facilities, in order to prevent damage to light-sensitive instruments within the Area.

For conditions applying to access within the Restricted Zone see Section 6(v).

7(iii) Activities which may be conducted in the Area

- scientific research that will not jeopardize the scientific values of the Area or interfere with current research activities;
- essential management activities, including monitoring, inspection, and the installation of new facilities to support scientific research;

- Activities with educational aims (such as documentary reporting (visual, audio or written) or the production of educational resources or services) that cannot be served elsewhere. Activities for educational and / or outreach purposes do not include tourism;
- use of hand-held and vehicle radios by visitors entering the Area is allowed; however, their use should be minimized and shall be restricted to communications for scientific, management or safety purposes;
- surveys of electromagnetic noise to help ensure that scientific research is not significantly compromised.

7(iv) Installation, modification or removal of structures

- No structures are to be erected within the Area except as specified in a permit.
- All structures, scientific equipment or markers installed within the Area, outside of research hut facilities, must be authorized by permit and clearly identified by country, name of the principal investigator and year of installation. All such items should be free of organisms, propagules (e.g. seeds, eggs) and non-sterile soil, and be made of materials that can withstand the environmental conditions and pose minimal risk of contamination or of damage to the values of the Area
- Installation (including site selection), maintenance, modification or removal of structures or equipment shall be undertaken in a manner that minimizes environmental disturbance and installations should not jeopardize the values of the Area, particularly the electromagnetically 'quiet' conditions and the current viewing horizon. The time period for removal of equipment shall be specified in the permit.
- No new Radio Frequency (RF) transmitting equipment other than low power transceivers for essential local communications may be installed within the Area. Electromagnetic radiation produced by equipment introduced to the Area shall not have significant adverse effects on any on-going investigations unless specifically authorized. Precautions shall be taken to ensure that electrical equipment used within the Area is adequately shielded to keep electromagnetic noise to a minimum.
- Installation or modification of structures or equipment within the Area is subject to an assessment of the likely impacts of the proposed installations or modifications on the values of the Area, as required according to national procedures. Details of proposals and the accompanying assessment of impacts shall, in addition to any other procedures that may be required by appropriate authorities, be submitted by investigators to the activity coordinator for their national program, who will exchange documents received with other activity coordinators for the Area. Activity coordinators will assess the proposals in consultation with national program managers and relevant investigators for the potential impacts on the scientific or natural environmental values of the Area. Activity coordinators shall confer with each other and make recommendations (to proceed as proposed, to proceed with revisions, to trial for further assessment, or not to proceed) to their national program within 60 days of receiving a proposal. National programs shall be responsible for notifying investigators whether or not they may proceed with their proposals and under what conditions.
- The planning, installation or modification of nearby structures or equipment outside the Area that emit EMR, obstruct the viewing horizon or emit gases to the atmosphere should take into account their potential to affect the values of the Area.
- Removal of structures, equipment or markers for which the permit has expired shall be the responsibility of the authority which granted the original permit, and shall be a condition of the permit.
- For conditions applying to installation, modification or removal of structures within the Restricted Zone see Section 6(v).

7(v) Location of field camps

Camping within the Area is prohibited. Overnight visits are permitted in buildings equipped for such purposes.

7(vi) Restrictions on materials and organisms which may be brought into the Area

- anthropogenic gaseous or aerosol emissions to the atmosphere from sources such as internal combustion engines within the Area shall be minimised or where practicable avoided. Long-term or permanent anthropogenic gaseous or aerosol emissions within the Area would jeopardize scientific experiments and are prohibited;
- Deliberate introduction of animals, plant material, micro-organisms and non-sterile soil into the Area is prohibited. Precautions should be taken to minimize the accidental introduction of animals, plant material, micro-organisms and non-sterile soil from other biologically distinct regions (within or beyond the Antarctic Treaty area);
- Herbicides and pesticides are prohibited from the Area;
- Any other chemicals, including radio-nuclides or stable isotopes, which may be introduced for scientific or management purposes specified in the permit, shall be removed from the Area at or before the conclusion of the activity for which the permit was granted;
- Fuel, food, and other materials shall not be stored in the Area, unless required for essential purposes connected with the activity for which the permit has been granted. In general, all materials introduced shall be for a stated period only and shall be removed at or before the conclusion of that stated period;
- All materials shall be stored and handled so that risk of their introduction into the environment is minimized;
- If release occurs which is likely to compromise the values of the Area, removal is encouraged only where the impact of removal is not likely to be greater than that of leaving the material *in situ*.

7(vii) Taking of, or harmful interference with, native flora or fauna

Taking or harmful interference with native flora and fauna is prohibited, except in accordance with a permit issued under Article 3 of Annex II of the Protocol on Environmental Protection to the Antarctic Treaty. Where animal taking or harmful interference is involved, this should, as a minimum standard, be in accordance with the SCAR Code of Conduct for the Use of Animals for Scientific Purposes in Antarctica.

7(viii) Collection or removal of materials not brought into the Area by the permit holder

- Material may be collected or removed from the Area only in accordance with a permit and should be limited to the minimum necessary to meet scientific or management needs. This includes biological samples and rock or soil specimens.
- Material of human origin likely to compromise the values of the Area, which was not brought into the Area by the permit holder or otherwise authorized, may be removed from any part of the Area unless the impact of removal is likely to be greater than leaving the material *in situ*. If this is the case the appropriate authority should be notified and approval obtained.
- The appropriate national authority should be notified of any items removed from the Area that were not introduced by the permit holder.

7(ix) Disposal of waste

All wastes, including human wastes, shall be removed from the Area.

7(x) Measures that may be necessary to continue to meet the aims of the Management Plan

1) Permits may be granted to enter the Area to carry out scientific monitoring and site inspection activities, which may involve the collection of data for analysis or review, or for protective measures.

2) Any specific sites of long-term monitoring shall be appropriately marked.
3) Electromagnetic bands of particular scientific interest and that warrant special protection from interference should be identified by parties active within the Area. As far as practically possible, the generation of electromagnetic noise should be limited to frequencies outside of these bands.
4) The intentional generation of electromagnetic noise within the Area is prohibited, apart from within agreed frequency bands and power levels or in accordance with a permit.
5) Research or management should be conducted in a manner that avoids interference with long-term research and monitoring activities or possible duplication of effort. Persons planning new projects within the Area are strongly encouraged to consult with established programs working within the Area, such as those of New Zealand or the United States, before initiating the work.

7(xi) Requirements for reports

- The principal permit holder for each visit to the Area shall submit a report to the appropriate national authority as soon as practicable after the visit has been completed in accordance with national procedures.
- Such reports should include, as appropriate, the information identified in the visit report form contained in the Guide to the Preparation of Management Plans for Antarctic Specially Protected Areas (Resolution 2 (2011)). If appropriate, the national authority should also forward a copy of the visit report to the Parties that proposed the Management Plan, to assist in managing the Area and reviewing the Management Plan.
- Parties should, wherever possible, deposit originals or copies of such original visit reports in a publicly accessible archive to maintain a record of usage, for the purpose of any review of the Management Plan and in organising the scientific use of the Area.
- The appropriate authority should be notified of any activities/measures that might have exceptionally been undertaken, and / or of any materials released and not removed, that were not included in the authorized permit.

8. Supporting documentation

Allan, W., Lowe, D.C., Gomez, A.J., Struthers, H. & Brailsford, G.W. 2005. Interannual variation of 13C in tropospheric methane: Implications for a possible atomic chlorine sink in the marine boundary layer. *Journal of Geophysical Research: Atmospheres* **110** (D11): D11306.

Anyamba, E., Williams, E., Susskind, J., Fraser-Smith, A. & Fullerkrug, M. 2000. The Manifestation of the Madden-Julian Oscillation in Global Deep Convection and in the Schumann Resonance Intensity. *American Meteorology Society* **57**(8): 1029–44.

Behrendt, J. C., Saltus, R., Damaske, D., McCafferty, A., Finn, C., Blankenship, D.D. & Bell, R.E. 1996. Patterns of Late Cenozoic volcanic tectonic activity in the West Antarctic rift system revealed by aeromagnetic surveys. *Tectonics* **15**: 660–76.

Bernhard G., Booth, C.R., Ehramjian, J.C. & Nichol, S.E. 2006. UV climatology at McMurdo Station, Antarctica, Based on Version 2 data of the National Science Foundation's Ultraviolet Radiation Monitoring Network. *Journal of Geophysical Research* **111:** D11201.

Bernhard, G., Booth C.R., & Ehramjian, J.C. 2010. Climatology of Ultraviolet radiation at high latitudes derived from measurements of the National Science Foundation's Ultraviolet Spectral Irradiance Monitoring Network. In W. Gao, D.L. Schmoldt & J.R. Slusser (eds), *UV Radiation in Global Climate Change: Measurements, Modeling and Effects on Ecosystems*. Tsinghua University Press, Beijing; Springer, New York.

Booth, C.R., Lucas, T.B., Morrow, J.H., Weiler, C.S. & Penhale, P.A. 1994. The United States National Science Foundation's polar network for monitoring ultraviolet radiation. In C.S. Weiler & P.A. Penhale (eds) *Ultraviolet radiation in Antarctica: Measurements and biological effects.* AGU, Washington, DC: 17-37.

Chu, X., Nishimura, Y., Xu, Z., Yu, Z., Plane, J. M. C., Gardner, C. S., & Ogawa, Y. (2020). First simultaneous lidar observations of thermosphere- ionosphere Fe and Na (TIFe and TINa) layers at McMurdo (77.84°S, 166.67°E), Antarctica with concurrent measurements of aurora activity, enhanced ionization layers, and converging electric field. Geophysical Research Letters, 47, e2020GL090181. https://doi.org/10.1029/2020GL090181.

Clilverd, M.A., Rodger, C.J., Thomson, N.R., Brundell, J.B., Ulich, Th., Lichtenberger, J., Cobbett, N., Collier, A.B., Menk, F.W., Seppl, A., Verronen, P.T., & Turunen, E. 2009. Remote sensing space weather events: the AARDDVARK network. *Space Weather* **7** (S04001). DOI: 10.1029/2008SW000412.

Connor, B.J., Bodeker, G., Johnston, P.V., Kreher, K., Liley, J.B., Matthews, W.A., McKenzie, R.L., Struthers, H. & Wood, S.W. 2005. Overview of long-term stratospheric measurements at Lauder, New Zealand, and Arrival Heights, Antartica. *American Geophysical Union, Spring Meeting 2005.*

Deutscher, N.M., Jones, N.B., Griffith, D.W.T., Wood, S.W. and Murcray, F.J. 2006. Atmospheric carbonyl sulfide (OCS) variation from 1992-2004 by ground-based solar FTIR spectrometry. *Atmospheric Chemistry and Physics Discussions* **6**: 1619–36.

Fraser-Smith, A.C., McGill, P.R., Bernardi, A., Helliwell, R.A. & Ladd, M.E. 1991. Global Measurements of Low-Frequency Radio Noise *in Environmental and Space Electromagnetics* (Ed. H. Kikuchi). Springer-Verlad, Tokyo.

Fraser-Smith, A.C. & Turtle, J.P.1993. ELF/VLF Radio Noise Measurements at High Latitudes during Solar Particle Events. Paper presented at the 51st AGARD-EPP Specialists meeting on *ELF/VLF/LF Radio Propagation and Systems Aspects.* Brussels, Belgium; 28 Sep – 2 Oct, 1992.

Füllekrug, M. 2004. Probing the speed of light with radio waves at extremely low frequencies. *Physical Review Letters* **93**(4), 043901: 1-3.

Füllekrug, M. 2010. Wideband digital low-frequency radio receiver. *Measurement Science and Technology*, **21**, 015901: 1-9. doi:10.1088/0957-0233/21/1/015901.

Füllekrug , M. & Fraser-Smith, A.C.1996. Further evidence for a global correlation of the Earth-ionosphere cavity resonances. *General Assembly of the International Union of Geodesy and Geophysics No. 21, Boulder, Colorado, USA.*

Füllekrug, M. & Fraser-Smith, A.C. 1997. Global lightning and climate variability inferred from ELF magnetic field variations. *Geophysical Research Letters* **24**(19): 2411.

Füllekrug, M., Fraser-Smith, A.C., Bering, E.A. & Few, A.A. 1999. On the hourly contribution of global cloud-to-ground lightning activity to the atmospheric electric field in the Antarctic during December 1992. *Journal of Atmospheric and Solar-Terrestrial Physics* **61**: 745-50.

Füllekrug, M., Fraser-Smith, A.C. & Schlegel, K. 2002. Global ionospheric D-layer height monitoring. *Europhysics Letters* **59**(4): 626.

Hay, T., Kreher, K., Riedel, K., Johnston, P., Thomas, A. & McDonald, A. 2007. Investigation of Bromine Explosion Events in McMurdo Sound, Antarctica. *Geophysical Research Abstracts.* Vol. 7.

Hernandez, G. & Roble, R.G. 2003. Simultaneous thermospheric observations during the geomagnetic storm of April 2002 from South Pole and Arrival Heights, Antarctica. *Geophysical Research Letters* **30** (10): 1511.

Keys, J.G., Wood, S.W., Jones, N.B. & Murcray, F.J. 1998. Spectral Measurements of HCl in the Plume of the Antarctic Volcano Mount Erebus. *Geophysical Research Letters* **25** (13): 2421–24.

Klein, A.G., Kennicutt, M.C., Wolff, G.A., Sweet, S.T., Gielstra, D.A. & Bloxom, T. 2004. Disruption of Sand-Wedge Polygons at McMurdo Station Antarctica: An Indication of Physical Disturbance. *61st Eastern Snow Conference*, Portland, Maine, USA.

Klekociuk, A.R., Tully, M.B., *et al*. 2021. The Antarctic ozone hole during 2018 and 2019. *Journal of Southern Hemisphere Earth Systems Science* **71** (1): 66-91.

Kohlhepp, R., Ruhnke, R., Chipperfield, M.P., De Mazière, M., Notholt, J., & 46 others 2012. Observed and simulated time evolution of HCl, ClONO2, and HF total column abundances, *Atmospheric Chemistry & Physics* **12**: 3527-56.

Kremser, S., Jones, N.B., Palm, M., Lejeune, B., Wang, Y., Smale, D. & Deutscher, N.M. 2015. Positive trends in Southern Hemisphere carbonyl sulfide, *Geophysical Research Letters* **42**: 9473–80.

Kyle, P. 1981. Mineralogy and Geochemistry of a Basanite to Phonolite Sequence at Hut Point Peninsula, Antarctica, based on Core from Dry Valley Drilling Project Drillholes 1,2 and 3. *Journal of Petrology.* **22** (4): 451 – 500.

Kuttippurath, J., Goutail, F., Pommereau, J.-P., Lefèvre, F., Roscoe, H.K., Pazmiño A., Feng, W., Chipperfield, M.P., & Godin-Beekmann, S. 2010. Estimation of Antarctic ozone loss from ground-based total column measurements. *Atmospheric Chemistry and Physics* **10**: 6569–81.

Levin, C., Veidt, C., Vaughn, B.H., Brailsford, G., Bromley, T., Heinz, R., Lowe, D., Miller, J.B., Poß, C.& White, J.W.C. 2012 No inter-hemispheric δ13CH4 trend observed. *Nature* **486:** E3–E4.

Lowe, D.C., Levchenko V.A., Moss, R.C., Allan, W., Brailsford, G.W. & Smith A.M. 2002. Assessment of "storage correction" required for in situ ^{14}CO production in air sample cylinders. *Geophysical Research Letters* **29** (7): 43/41-43/4.

Manning, M.R., Lowe, D.C., Moss, R.C., Bodeker, G.E. & Allan, W. 2005. Short-term variation in the oxidizing power of the atmosphere. *Nature* **436** (7053): 1001-04.

Mazzera, D.M., Lowenthal, D.H., Chow, J.C. & Watson, J.G. 2001. Sources of PM_{10} and sulfate aerosol at McMurdo station, Antarctica. *Chemosphere* **45**: 347–56.

McDonald, A.J., Baumgaertner, A.J.G., Fraser, G.J., George, S.E. & Marsh, S. 2007. Empirical Mode Decomposition of the atmospheric wave field. *Annals of Geophysics* **25**: 375–84.

McKenzie, R.L. & Johnston, P.V. 1984. Springtime stratospheric NO_2 in Antarctica. *Geophysical Research Letters* **11.1**: 73-75.

McKenzie, R., Bernhard, G., *et al*. 2019. Success of Montreal Protocol demonstrated by comparing high-quality UV measurements with "World Avoided" calculations from two chemistry-climate models. *Scientific Reports* **9**: 12332,

Monaghan, A.J. & Bromwich, D.H. 2005. The climate of the McMurdo, Antarctica, region as represented by one year forecasts from the Antarctic Mesoscale Prediction System. *Journal of Climate.* **18:** 1174–89.

Moore, R.C. & Burch, H.C. 2018. The D region response to the August 2017 total solar eclipse and coincident solar flare. *Geophysical Research Letters* **45**: doi: 10.1029/2018GL080762.

Nichol, S.E., Coulmann, S. & Clarkson, T.S. 1991. Relationship of springtime ozone depletion at Arrival Heights, Antarctica, to the 70 HPA temperatures. *Geophysical Research Letters* **18** (10): 1865–68.

Nichol, S.E., Pfister, G., Bodeker, G.E., McKenzie, R.L., Wood, S.W. & Bernhard, G. 2003. Moderation of cloud reduction of UV in the Antarctic due to high surface albedo. *Journal of Applied Meteorology* **42** (8): 1174-83.

Nichol, S.E. 2018. Dobson spectrophotometer #17: past, present and future. *Weather & Climate* **38**: 16-26.

Oltmans, S.J., Johnson, B.J. & Helmig, D. 2008. Episodes of high surface-ozone amounts at South Pole during summer and their impact on the long-term surface-ozone variation. *Atmospheric Environment* **42**: 2804–16.

Riedel, K., Kreher, K., Nichol, S. & Oltmans, S.J. 2006. Air mass origin during tropospheric ozone depletion events at Arrival Heights, Antarctica. *Geophysical Research Abstracts* **8**.

Risi, C., Noone, D., Worden, J., Frankenberg, C., Stiller, G., & 25 others 2012. Process-evaluation of tropospheric humidity simulated by general circulation models using water vapor isotopologues: 1. Comparison between models and observations. *Journal of Geophysical Research* **117**: D05303.

Rodger, C. J., Brundell, J.B., Holzworth, R.H. & Lay, E.H. 2009. Growing detection efficiency of the World Wide Lightning Location Network. *American Institute of Physics Conference Proceedings* **1118**: 15-20.

Schaefer, H., Mikaloff Fletcher, S.E., *et al*. 2016. A 21st century shift from fossil fuel to biogenic methane emissions indicated by $^{13}CH_4$. *Science* **352**: 80-84.

Schlegel, K. & Füllekrug, M. 1999. Schumann resonance parameter changes during high-energy particle precipitation. *Journal of Geophysical Research* **104** (A5): 10111-18.

Schofield, R., Johnston, P.V., Thomas, A., Kreher, K., Connor, B.J., Wood, S., Shooter, D., Chipperfield, M.P., Richter, A., von Glasow, R. & Rodgers, C.D. 2006. Tropospheric and stratospheric BrO columns over Arrival Heights, Antarctica, 2002. *Journal of Geophysical Research* **111**: 1–14.

Sha, M.K., Langerock, B., *et al*. 2021. Validation of methane and carbon monoxide from Sentinel-5 Precursor using TCCON and NDACC-IRWG stations. *Atmospheric Measurement Techniques* **14**: 6249–304.

Sinclair, M.R. 1988. Local topographic influence on low-level wind at Scott Base, Antarctica. *New Zealand Journal of Geology and Geophysics.* **31**: 237–45.

Skotnicki, M.L., Ninham, J.A. & Selkirk P.M. 1999. Genetic diversity and dispersal of the moss *Sarconeurum glaciale* on Ross Island, East Antarctica. *Molecular Ecology* **8**: 753-62.

Smale, D., Strahan, S.E., *et al*. 2021. Evolution of observed ozone, trace gases, and meteorological variables over Arrival Heights, Antarctica (77.8° S, 166.7° E) during the 2019 Antarctic stratospheric sudden warming. *Tellus B: Chemical and Physical Meteorology* **73** (1): 1-18.

Solomon, S., Mount, G.H., Sanders, R.W. & Schemltekopf, A.L. 1987. Visible spectroscopy at McMurdo Station, Antarctica: 2. Observations of OClO. *Journal of Geophysical Research: Atmospheres* **92** D7: 8329-38.

Stefano, J.E. 1992. Application of Ground-Penetrating Radar at McMurdo Station, Antarctica. Presented at the Hazardous Materials Control Research Institute federal environment restoration conference, Vienna, USA, 15-17 April 1992.

Strahan, S.E., Smale, D. *et al*. 2020. Observed hemispheric asymmetry in stratospheric transport trends from 1994 to 2018. *Geophysical Research Letters* **47** (17): e2020GL088567.

Struthers, H., Kreher, K., Austin, J., Schofield, R., Bodeker, G., Johnston, P., Shiona, H. & Thomas, A. 2004. Past and future simulations of NO_2 from a coupled chemistry-climate model in comparison with observations. *Atmospheric Chemistry and Physics Discussions* **4**: 4545–79.

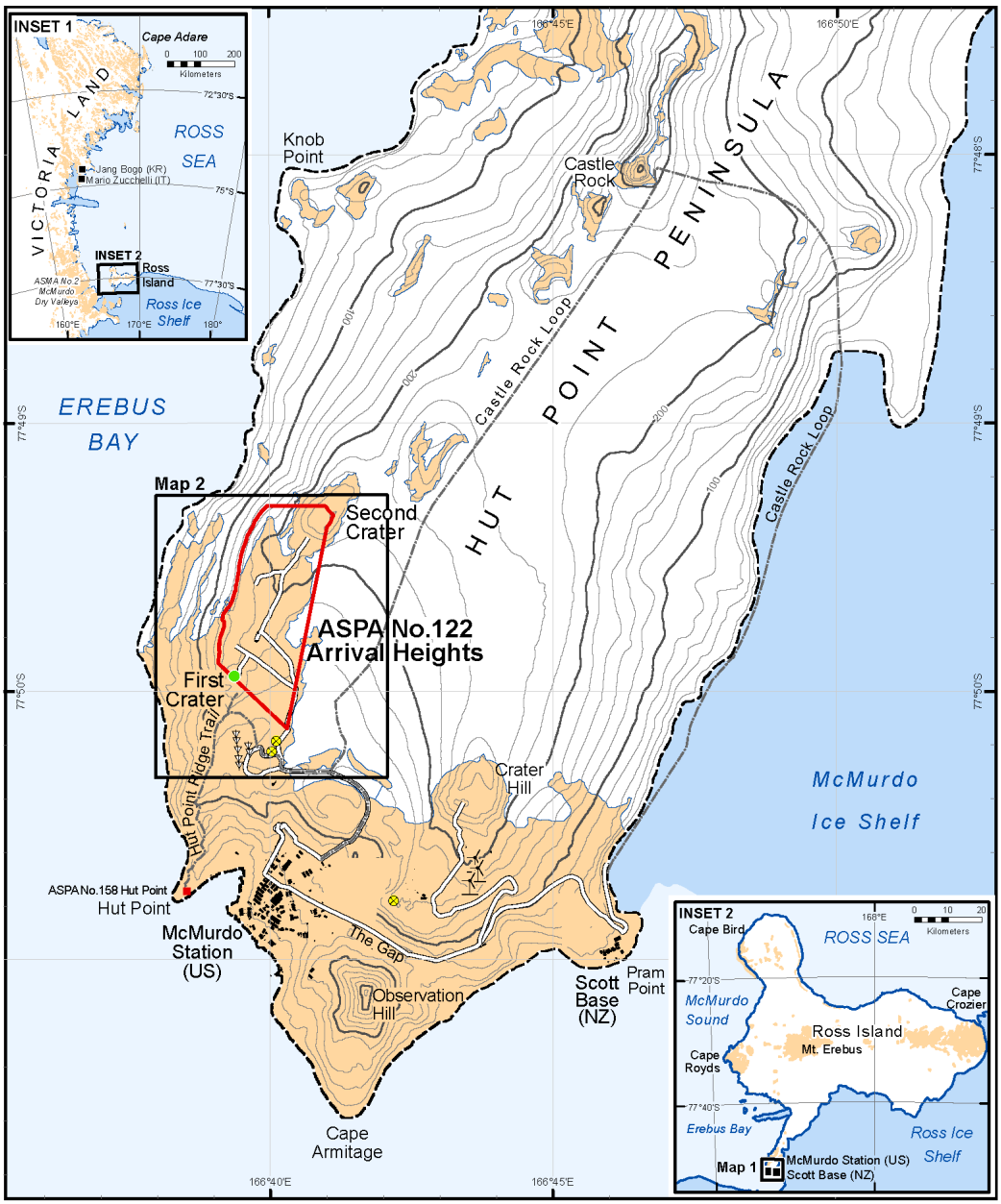
Tauxe, L., Gans, P.B. & Mankinen, E.A. 2004. Paleomagnetic and 40Ar/39Ar ages from Matuyama/Brunhes aged volcanics near McMurdo Sound, Antarctica. *Geochemical Geophysical Geosystems* **5** (10): 1029.

Vigouroux, C., De Mazière, M., Errera, Q., Chabrillat, S., Mahieu, E., Duchatelet, P., Wood, S., Smale, D., Mikuteit, S., Blumenstock, T., Hase, F. & Jones, N. 2007. Comparisons between ground-based FTIR and MIPAS N2O and HNO3 profiles before and after assimilation in BASCOE. *Atmospheric Chemistry & Physics* **7:** 377-96. .

Wood, S.W., Batchelor, R.L., Goldman, A., Rinsland, C.P., Connor, B.J., Murcray, F.J., Stephan, T.M. & Heuff, D.N. 2004. Ground-based nitric acid measurements at Arrival Heights, Antarctica, using solar and lunar Fourier transform infrared observations. *Journal of Geophysical Research* **109**: D18307.

Wright, I.M., Fraser, B.J., & Menk F.W. 1998. Observations of polar cap arc drift motion from Scott Base S-RAMP Proceedings of the AIP Congress, Perth, September 1998.

Zeng, G., Wood, S.W., Morgenstern, O., Jones, N.B., Robinson, J., & Smale, D. 2012. Trends and variations in CO, C2H6, and HCN in the Southern Hemisphere point to the declining anthropogenic emissions of CO and C2H6, *Atmospheric Chemistry & Physics* **12**: 7543-55.



Map 1: ASPA No.122 Arrival Heights - Regional overview

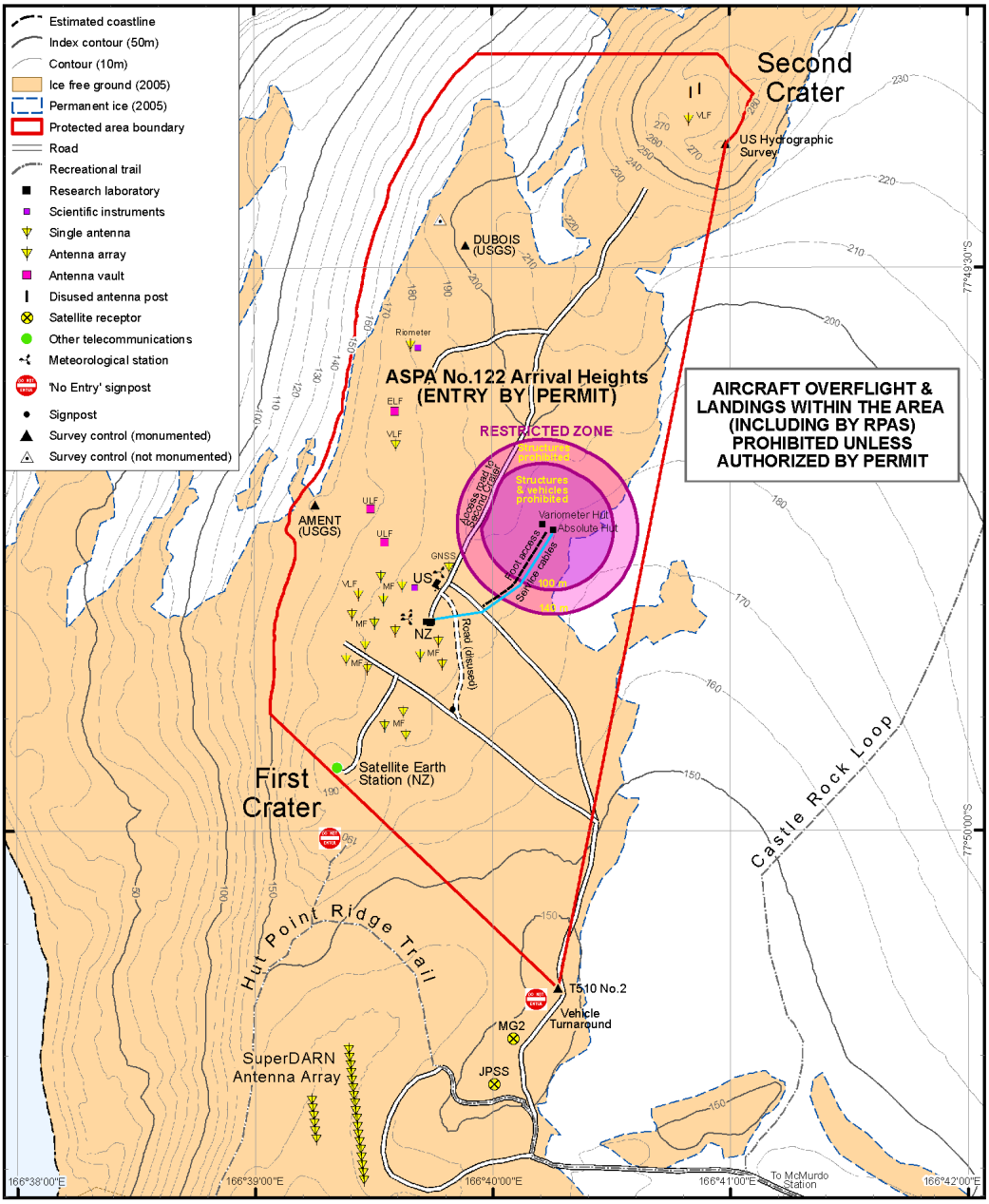
23 Mar 2023 (v1)
United States Antarctic Program
Environmental Research & Assessment

Estimated coastline
Index contour (100m)
Contour (20m)
Ice free ground (2005)
Permanent ice (2005)
Ice shelf
Protected area boundary
Road
Recreational trail
Buildings
SuperDARN antenna array
Satellite receiver
Satellite Earth Station
Wind turbine

0 0.5 1 Kilometers

N

Projection: Lambert Conic Conformal
Spheroid and horizontal datum: WGS84
Data sources: Contours: Derived from 2m DEM, contour interval 20m; Buildings: RPSC survey (Feb 09); Features: Derived from USAP (Feb 2009) & ERA (Nov 2009) field surveys; Recreational trails: PSC field survey 2009; Permanent ice: Digitised from Quickbird orthophoto (15 Oct 05); ASPA boundary: Management Plan (2022).



Map 2: ASPA No.122 Arrival Heights - Boundary & topography

23 Mar 2023 (v1)
United States Antarctic Program
Environmental Research & Assessment

Caution:
Overground cables are present throughout Arrival Heights and are not shown on this map. Care should be taken to avoid disturbing these cables.

N

0 100 200
Meters

Projection: Lambert Conic Conformal
Data sources: Contours: Derived from 2m DEM, contour interval 10m; Features: Derived from USAP (Feb 2009) & ERA (Nov 2009) field surveys; Recreational trails: PGC field survey 2009; Permanent ice digitised from orthorectified Quickbird image (15 Oct 05) (Imagery © Digital Globe); ASPA boundary: Management Plan (2022); Antennae / instruments / infrastructure: verified 2022.