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The Effects of Weather Shocks on Economic Activity: What are the Channels of Impact?

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ABSTRACT

Global temperatures have increased at a historically unprecedented pace. This paper finds that the negative effect of temperature on output in countries with hot climates runs through reduced investment, depressed labor productivity, poorer human health, and lower agricultural and industrial output. We find that hot low-income countries suffer the largest costs. In a median low-income country, aggregate output is about 2 percent lower and investment is about 10 percent lower seven years after a 1 degree increase in average annual temperature. We also find that economic development, in general, helps to shield countries from temperature shocks, with hot regions in high-income countries on average sustaining less economic damage from rising temperatures than hot regions in low-income countries.

1. Introduction

Since the turn of the 20th century, the Earth's average surface temperature has increased at a speed that is unprecedented for at least the past 20,000 years (Figure 1).[1] Most scientists agree that global temperatures are set to rise further. A rise in average temperatures by 4°C or more is projected by the end of the century in the absence of further action to restrain greenhouse gas (GHG) emissions. To limit warming to less than 2°C, dramatic cuts to current emissions would be needed (IPCC, 2014). In either case, both the speed and the eventual magnitude of the increase in average temperature will be historic.

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[1] Climate refers to a distribution of weather outcomes for a given location, while weather refers to a realization from that distribution. Climate change typically implies that the whole distribution of outcomes shifts, with a possible increase in the likelihood of extreme outcomes. As argued by Weitzman (2011), the fattening of the tails—the increase in the probability of potentially irreversible and catastrophic damages—justifies aggressive policy actions to stabilize greenhouse gas (GHG) concentrations in the atmosphere ("climate change mitigation") and adjust to the changing climate ("adaptation").

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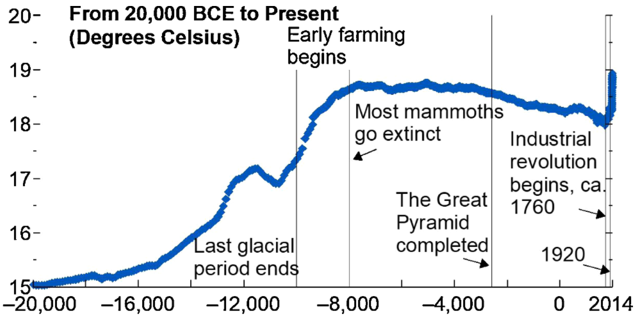

Fig. 1. Average Global Temperature: From 20,000 BCE to Present
Sources: Shakun and others (2012); and authors' calculations.

The pioneering work of Dell, Jones, and Olken (2012) and Burke et al. (2015a) offered evidence that higher temperatures significantly reduce economic growth in low income and warm countries.[2] But less is known about the specific channels through which growth is affected at the aggregate level. Having a detailed understanding of the main channels of impact—on a macroeconomic level, both empirically and theoretically—is necessary as governments and multilateral institutions seek a robust defense system against global warming over the next 100 years. Yet, the vast majority of prior empirical studies that consider various channels of the economic impact are done at the micro-level (see reviews in Dell, Jones and Olken, 2014; Carleton and Hsiang, 2016).

We provide new evidence on the effects of weather shocks on economic activity, the persistence of these effects, and the channels through which they operate. We offer a unified empirical framework, with a more flexible specification than Dell, Jones and Olken (2012) or Burke et al. (2015a), and use an expanded dataset from more than 180 economies over 1950–2015. We exploit the annual variation in temperature and precipitation to estimate their causal effect on aggregate economic activity, sectoral output and each of the key inputs of the aggregate production function: productivity, capital investment, and labor supply.

We contribute to the literature in several ways. To the best of our knowledge, we are the first to demonstrate that temperature shocks negatively impact investment globally, in both the short and long run. Since investment drives capital deepening and economic growth in the long run, understanding how climate change affects investment is vital.[3] We show that in a median low-income country, seven years after a 1 degree increase in average annual temperature, investment is 10 percent lower, an economically large impact. For comparison, seven years after the same temperature shock, aggregate output is about 2 percent lower.

For productivity and labor supply, prior studies documented the negative effect of temperature increases only in specific micro settings, such as experiments, or within individual countries.[4] Similarly, for sectoral output—agriculture and industry—the prior literature tended to focus on narrower samples, considering regions, countries, or specific crops.[5] The likelihood of finding statistically significant results within micro settings is much greater than in our macro case, and may leave room for skeptics to question the generalizability of the findings. The strong negative findings we report, taken together, dispel any notion that these effects might be localized, sporadic, or economically small.[6]

Second, our findings demonstrate that hot countries, which are overwhelmingly low-income, suffer the most from an increase in temperature. We thus confirm the findings by Dell, Jones and Olken (2012) and Burke et al. (2015a) of the uneven effects of temperature increases. But we are also able to demonstrate that the large and long-lasting aggregate damages are due to reduced

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[2] Dell, Jones, and Olken (2012) find that higher temperatures significantly reduce economic growth in low-income countries. Burke et al. (2015a) provide evidence that productivity peaks at about 13°C and declines strongly at higher temperatures. Since low-income countries are concentrated in geographic areas with hotter climates, the Burke et al. (2015a) findings suggest that a rise in temperature would be particularly harmful for this set of economies.

[3] Previously, in their main specification (Dell, Jones and Olken, 2012 found a negative but statistically insignificant effect of temperature shocks on investment. Anttila-Hughes and Hsiang (2013) found that typhoons reduce investment in health and human capital in the Philippines. Burke et al. (2015a) and Hallegate and Vogt Schilb, (2016) explored this channel theoretically, and the latter focused only on natural disasters.

[4] For studies on the effect of temperature on labor productivity see Seppanen, Fisk and Faulkner (2003) and Niemala (2002) for experimental evidence; see Park (2018) for evidence of the effect on high-stakes exam performance; see Graff Zivin and Neidell (2014) and Graff Zivin and Kahn (2016) for evidence from time use data and industrial productivity in the United States; see Somanathan et al. (2017) and Zhang et al (2018) for evidence on productivity in Indian and Chinese manufacturing, respectively. Regarding the effect of temperature on labor supply, and human health more specifically, see studies that focus on individual countries, for example, Barreca (2012) for the United States, (Burgess et al., 2014) for India, or Kudamatsu, Persson and Stromberg (2012) for a group of African countries, as well as a review in Deschenes (2014). Maccini and Yang (2009) document the negative effect of rainfall for long-term health in Indonesia.

[5] Among the prior literature that estimates the effect of weather shocks on sectoral output, some are focused on specific countries (e.g. Schlenker and Roberts 2009; Fisher et al., 2012; Burke and Emerick, 2016; and Wang et al., 2017 for the US; Guiteras, 2009 for India; Feng, Krueger and Oppenheimer, 2010 for Mexico; Levine and Yang, 2006 for Indonesia), or specific crops (e.g. Lobell, Schlenker and Costa-Roberts, 2011; Welch et al., 2010; Schlenker and Lobell, 2010).

[6] For agriculture and industrial value added, (Dell, Jones and Olken, 2012) also provide evidence of the negative effect of temperature increases in a large sample of countries, but only for poor countries and only in the short run. We, for completeness, chose to consider agriculture, manufacturing and the service sector all using the sample specification and most recent data, finding consistently negative results.

capital accumulation, depressed labor productivity in heat-exposed sectors, poorer human health, and lower agricultural and industrial output.

Finally, we also shed light on the debate whether economic development shields countries from the negative effects of climate change (Burke and Tanutama, 2019). Using subnational data, we find that hot regions in high-income countries on average sustain less economic damage than hot regions in low-income countries. This is an important finding, as it suggests that general economic development policies could complement any climate adaptation strategy.

The rest of the papers is organized as follows. Section 2 presents some key stylized facts about historical patterns of temperature and precipitations as well as scientific projections of future changes. Section 3describes the data and lays out the empirical strategy used to assess the macroeconomic effect of weather shocks. Section 4 presents the main findings and several robustness checks of the empirical results, while Section 5 looks at the channels through which aggregate economic output is affected. Section 6 presents results on the role of development based on subnational data. Section 7 concludes.

2. Temperature and Precipitation: Historical Patterns and Projections

Global temperatures have increased by roughly 1°C compared with the 1880 – 1910 average.[7] The rise started in earnest in the 1970s, following a large increase in carbon dioxide (CO_2) emissions,[8] that led to an increase in average annual temperature in all income groups (Figure 2, panels A, C, and E).

The median temperature over the first 15 years of this century, compared with the first 15 years of the past century, was 1.4°C higher in advanced economies, 1.3°C higher in emerging market economies, and 0.7°C higher in low-income countries. Even though most of the warming happened in advanced economies, by 2015 the temperature in the median low-income country (25°C) was more than twice that of the median advanced economy (11°C). Trends in precipitation are generally less clear (Figure 2, panels B, D, and F). Precipitation has increased somewhat in the northern hemisphere since the 1950s, and precipitation in the median low-income country has declined since the 1970s.

3. Empirical Strategy and Data

In the absence of historical experience with climate change that may be relevant for countries today, we build on the existing literature and identify how annual fluctuations in temperature and precipitation affect macroeconomic performance. Using the approach of Dell, Jones, and Olken (2012) and Burke et al. (2015a), we use within-country and across-country year-to-year fluctuations in temperature and precipitation to identify their causal effect on aggregate outcomes, both contemporaneously and over the medium term. We build on these studies by expanding the geographic and temporal coverage of the analysis to more than 180 economies during 1950 – 2015 (see Table Annex 2 for a list of countries and territories), examining the effects of weather shocks on a larger set of outcome variables, establishing the robustness of findings to different sources of weather data and alternative, more flexible empirical specifications.

We use Jordà's (2005) local projection method to trace the impulse response function of real per capita GDP to a weather shock. This approach was advocated by Stock and Watson (2007), among others, as a flexible alternative that does not impose the dynamic restrictions embedded in vector autoregressions or autoregressive distributed lag specifications and is particularly suited to estimating nonlinearities in the dynamic response. We derive the impulse response by estimating a set of regressions:

$$y_{i,t+h} - y_{i,t-1} = \beta_1^h c_{i,t} + \beta_2^h c_{i,t}^2 + \gamma_1^h c_{i,t-1} + \gamma_2^h c_{i,t-1}^2 + \varphi_1^h \Delta y_{i,t-1} + \mu_i^h + \theta_{r,t}^h + \varepsilon_{i,t}^h, \tag{1}$$

in which i indexes countries, t indexes years, and h indexes the estimation horizon (from horizon 0, which captures the contemporaneous effect, up to horizon 7, which captures the effect 7 years after the shock). Regressions for each horizon are estimated separately. The dependent variable is the cumulative growth of the outcome of interest between horizons $t-1$ and $t+h$, measured as the difference in the natural logarithms ($y_{i,t}$).[9] Following Burke et al. (2015a), the estimated regression has a quadratic specification in the weather variables, $c_{i,t}$, which comprise average annual temperature and precipitation. The regressions control for one lag of the dependent and the weather variables. Country fixed effects (μ_i^h) control for all time-invariant country differences, such as latitude and average growth rates, while time fixed effects interacted with region dummies ($\theta_{r,t}^h$) control for the common effect of all annual shocks across countries within a region.[10] The analysis also explores an alternative fixed-effects structure proposed by Burke et al. (2015a), which includes time fixed effects (τ_t^h) and country-specific linear and quadratic time trends ($\theta_i^h t + \theta_i^h t^2$) to account for

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[7] A description of the historical and forecast temperature and precipitation series used in the analysis is presented in Section III. The Annex lists all data sources, sample coverage and country groupings.

[8] The three most important GHGs, which are regulated under the Kyoto Protocol, are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Among those, CO_2 has so far been the largest contributor to global warming. Although natural factors explain some of the warming over the past century, according to the Intergovernmental Panel on Climate Change (IPCC) more than half of the temperature increase since 1950 can be attributed to human activity (IPCC, 2014). Although CO_2 emissions have grown rapidly since the 1950s across all income groups, along with rising incomes and populations, emissions from low-income countries are still a fraction of those in advanced and emerging market economies, in both aggregate and per capita terms.

[9] Note that a difference in logs between period *t-1* and period $t+h$ approximates a growth rate over that period.

[10] We use indicators for six regions as defined by the World Bank: East Asia and Pacific, Europe and Central Asia, Latin America and the Caribbean, Middle East and North Africa, North America, South Asia, and Sub-Saharan Africa.

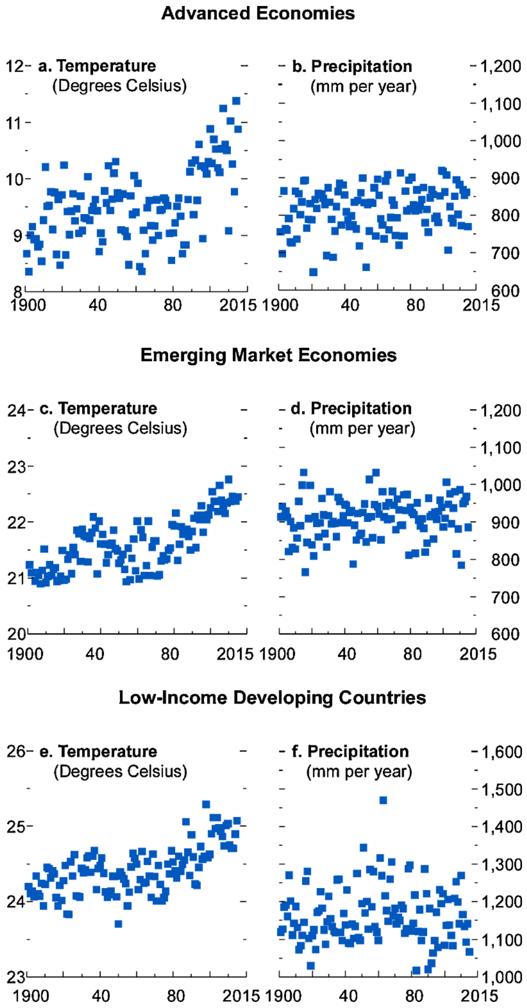

Fig. 2. Temperature and Precipitation across Broad Country Groups

Sources: Climate Research Unit (v. 3.24); and authors' calculations.

Note: Terrestrial median annual temperature and precipitation data at grid level are aggregated to the country-year level using 1950 population weights. See the Annex for data sources and country groupings.

within-country changes over time, such as demographic shifts, instead of the region-year fixed effects ($\theta^h_{r,t}$) of the baseline specification. Standard errors are clustered at the country level.

To avoid bias associated with "bad controls" (or overcontrolling), the specification is purposefully parsimonious: many of the determinants of growth, typically included in standard growth regressions (for example, institutional quality, educational achievement, policies, and so forth), may themselves be shaped by weather shocks and are thus not part of the baseline estimation. Of course, to the extent that these are time-invariant and country-specific, they are subsumed in the fixed effects.

Within this estimation framework, the effect of a weather shock, such as a 1°C increase in temperature, on the level of output at horizon h can be obtained by differentiating equation (1) with respect to temperature:

$$\frac{\partial(y_{i,t+h} - y_{i,t-1})}{\partial T_{i,t}} = \beta_1^h + 2\beta_2^h T_{i,t}. \tag{2}$$

Evaluating equation (2) for each horizon separately and using the 2015 annual average temperature, $T_{i,\ 2015}$, allows us to obtain the impulse response functions of per capita GDP to a temperature shock for each country. The marginal effect of an increase in precipitation is computed analogously. The threshold temperature at which the effect on the outcome variable switches from positive to negative, that is, the optimal level of temperature for per capita output, can be obtained by setting equation (2) to zero.

As discussed below, we use this empirical framework to examine the effect of weather shocks on per capita GDP, as well as on sectoral output (crop production, agricultural value added, services value added, and industrial value added), and the key elements of the aggregate production function (investment as a proxy for capital stock, infant mortality, and the human development index as a proxy for labor supply). We rely on an extended version of this empirical strategy to capture productivity effects using more disaggregated data on industry outcomes.

Our primary data sources for the outcome variables are the IMF World Economic Outlook and the World Bank World Development Indicators databases, from which we construct our measures of per capita GDP, broad sectoral value added and index of agricultural production. We rely on the Groningen Growth and Development Centre 10-sector database for more disaggregated data on sectoral real value added and employment in 40 countries over the period 1950–2012 when analyzing productivity effects.

Historical temperature and precipitation are from the University of East Anglia's Climate Research Unit (CRU). We construct average annual temperature and precipitation by aggregating weather data at the grid-cell level, provided by CRU at 0.5 × 0.5 degree resolution, to the level of the country using the 1950 population in each cell as weights. This method allows us to account for differences in population density within countries and captures the average weather experienced by a person in the country.

Data on subnational GDP per capita are from Gennaioli et al. (2014). These are used to examine the robustness of the key findings, as well as to explore the role of development in shaping the effects of temperature increases on per capita output. All data sources used in the paper are listed in Table Annex 1.

4. Results

4.1. Short-term Effect on Per Capita Output

The results from estimating equation (1) are presented in Table 1. The main specification results are in column (5), while the other columns present robustness checks using alternative sources of weather data; alternative population weights; and alternative samples, controls, and estimation approaches. Columns 1–8 use country-level data, while column 9 uses subnational data. Panel A contains the estimated coefficients for the weather variables at horizon 0 (that is, the contemporaneous effects of weather shocks). Panel B shows the effect of a 1°C increase in temperature estimated, following equation (2), at the median 2015 temperature for advanced economies (median T = 11°C), emerging market economies (median T = 22°C), and low-income countries (median T = 25°C), on impact and after seven years. Similarly, Panel C shows the effect of a 100 millimeter increase in precipitation estimated at the median 2015 precipitation for the three groups of economies.

Across all specifications, we find that the estimated coefficient on temperature is positive and the coefficient on temperature squared is negative, confirming the nonlinear relationship between growth and temperature shocks uncovered by Burke et al. (2015a). At low temperatures, an increase in temperature can boost growth, whereas at high temperatures, it hurts growth, with the threshold estimated to be about 13°C–15°C, using country-level data. These results suggest highly uneven effects of warming across the globe, depending on the initial climate of a particular location.

Figure 3 illustrates the findings from our baseline specification presented in column 5 of Table 1, by overlaying the marginal effect of a 1°C increase in temperature on contemporaneous per capita GDP by initial temperature, with the distribution of advanced, emerging market and low-income countries according to their average annual temperature. For the median emerging market economy, a 1°C increase from a temperature of 22°C lowers growth in the same year by 0.9 percentage point. For the median low-income country, with temperature of 25°C, the effect is even larger: growth falls by 1.2 percentage points. Figure 4, panel A, summarizes the estimated contemporaneous effect of an increase in temperature by 1°C on per capita GDP around the world. Even though low-income countries, which are projected to be significantly negatively affected by an increase in temperature, produced only about one-fifth of global GDP in 2016, they are home to close to 60 percent of current global population, as depicted in Figure 4, panel B, which rescales countries in proportion to their population.

We confirm broadly the same relationship between temperature and per capita GDP using subnational data on output from Gennaioli et al. (2014) (see column 9 of Table 1, which is analogous to column 5 with country-level data). With subnational data we estimate a smaller threshold temperature, at around 5°C, which is broadly consistent with estimates obtained by Burke and Tanutama (2019) and Kalkuhl and Wenz (2018). The difference in threshold temperature compared to country-level estimates is primarily driven by differences in the sample, as subnational data on per capita output are available for less than half of the countries included in the country-level regressions.[11] In Section 6, we leverage the subnational data to explore the impact of development on the ability of countries to cope with temperature shocks.

Figure 4, panel A, shows the estimated impact of a 1°C increase in temperature across all grids in the world, based on their average annual temperature in 2005. As indicated on the map, in a number of economies where the effect on aggregate growth may be statistically indistinguishable from zero, such as the United States, there are areas where a temperature rise would significantly lower output.

Unlike temperature, our analysis reveals no consistently significant relationship between precipitation and per capita GDP growth at either the country- or subnational-level (Table 1, Panel C). The lack of robust relationship could reflect potentially larger measurement error in the precipitation variable as discussed in Auffhammer et al. (2011). The measurement error may be further amplified by temporal aggregation. For example, if the only channel through which precipitation affects aggregate outcomes is through its effect on agriculture, then only precipitation during crops' growing period—poorly proxied by annual precipitation—may be relevant.

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[11] Our sample of countries with subnational GDP data covers 83 countries (including advanced, middle and low-income countries) and 1528 regions. Burke and Tanutama (2019) cover 37 countries (mostly advanced) with about 11,000 geographically smaller regions and use a specification that is similar to ours. Kalkhul and Wenz (2018) include 77 countries and 1545 regions, with some different countries compared to our sample, and focus on incorporating both annual and 30-year averages of climate variables in their specification.

Table 1
Effect of Weather Shocks on Output
Source: Authors' calculations.

Panel A	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Temperature	1.399 ***	1.443 ***	1.428 ***	1.343 ***	**1.347** ***	1.347 ***	1.342 ***	1.249 ***	0.261
	(0.359)	(0.367)	(0.366)	(0.355)	**(0.357)**	(0.357)	(0.355)	(0.380)	(0.274)
Temperature^2	–0.049 ***	–0.049 ***	–0.048 ***	–0.052 ***	**–0.051** ***	–0.051 ***	–0.051 ***	–0.044 ***	–0.028 ***
	(0.012)	(0.011)	(0.011)	(0.011)	**(0.011)**	(0.011)	(0.011)	(0.011)	(0.009)
Precipitation	0.056	0.103 *	0.163 *	0.045	**0.110**	0.110	0.119	0.082	0.040
	(0.097)	(0.061)	(0.085)	(0.058)	**(0.104)**	(0.104)	(0.104)	(0.112)	(0.035)
Precipitation^2	–0.002	–0.002 **	–0.004 **	–0.001	**–0.003**	–0.003	–0.003	–0.002	–0.002 **
	(0.002)	(0.001)	(0.002)	(0.001)	**(0.002)**	(0.002)	(0.002)	(0.002)	(0.001)
Any Disaster							–0.406 **		
							(0.180)		
Threshold Temperature (°C)	14	15	15	13	**13**	13	13	14	5
Weather Source	UDEL	CRU	CRU	CRU	**CRU**	CRU	CRU	CRU	CRU
Population Weight	2010	2010	1950	2010	**1950**	1950	1950	1950	1950
Year Fixed Effects	Y	Y	Y	N	**N**	N	N	N	N
Region x Year Fixed Effects	N	N	N	Y	**Y**	Y	Y	Y	Y
Country Time Trends	Y	Y	Y	N	**N**	N	N	N	N
At Least 20 Years of Data	N	N	N	N	**N**	N	N	N	N
Adjusted R^2	0.15	0.15	0.15	0.14	**0.14**	0.14	0.14	0.11	0.11
Number of Countries	177	198	189	198	**189**	189	189	189	79
Number of Provinces									1,463
Number of Observations	8,147	9,114	8,815	9,114	**8,815**	8,815	8,815	8,917	40,835
Panel B: Impact of a 1°C Increase in Temperature									
Horizon 0:									
AE (T = 11°C)	0.331 *	0.370 *	0.365 *	0.197	**0.218**	0.218	0.217	0.277	–0.356 ***
	(0.196)	(0.196)	(0.195)	(0.191)	**(0.196)**	(0.196)	(0.195)	(0.212)	(0.108)
EM (T = 22°C)	–0.736 **	–0.703 ***	–0.697 ***	–0.949 ***	**–0.911** ***	–0.911 ***	–0.907 ***	–0.695 ***	–0.974 ***
	(0.309)	(0.223)	(0.223)	(0.266)	**(0.264)**	(0.264)	(0.263)	(0.243)	(0.176)
LIDC (T = 25°C)	–1.027 ***	–0.996 ***	–0.987 ***	–1.261 ***	**–1.219** ***	–1.219 ***	–1.214 ***	–0.960 ***	–1.142 ***
	(0.370)	(0.268)	(0.267)	(0.318)	**(0.315)**	(0.315)	(0.313)	(0.287)	(0.225)
Horizon 7 (cumulative):									
AE (T = 11°C)	0.856	0.647	0.584	0.905	**1.015**	0.558	1.009	0.023	–0.802 **
	(0.745)	(0.666)	(0.662)	(0.962)	**(0.980)**	(0.752)	(0.978)	(0.478)	(0.326)
EM (T = 22°C)	–1.636	–1.355 *	–1.389 *	–1.358	**–1.363**	–1.115 *	–1.374	–0.547	–3.286 ***
	(1.076)	(0.753)	(0.734)	(0.910)	**(0.892)**	(0.591)	(0.895)	(0.386)	(0.662)
LIDC (T = 25°C)	–2.316 *	–1.901 **	–1.926 **	–1.975 *	**–2.011** *	–1.571 **	–2.023 *	–0.702	–3.963 ***
	(1.275)	(0.877)	(0.854)	(1.083)	**(1.058)**	(0.667)	(1.062)	(0.450)	(0.810)
Panel C: Impact of a 100 millimeter per Year Increase in Precipitation									
Horizon 0:									
AE (P = 800 millimeter per year)	0.018	0.066	0.101 *	0.028	**0.066**	0.066	0.073	0.050	0.011
	(0.067)	(0.046)	(0.059)	(0.046)	**(0.071)**	(0.071)	(0.071)	(0.077)	(0.025)
EM (P = 900 millimeter per year)	0.013	0.061	0.093 *	0.026	**0.060**	0.060	0.067	0.046	0.007
	(0.063)	(0.045)	(0.056)	(0.045)	**(0.067)**	(0.067)	(0.067)	(0.072)	(0.024)
LIDC (P = 1,100 millimeter per year)	0.004	0.052	0.078	0.022	**0.049**	0.049	0.056	0.038	0.000
	(0.057)	(0.041)	(0.050)	(0.042)	**(0.059)**	(0.059)	(0.059)	(0.064)	(0.022)
Horizon 7 (cumulative):									
AE (P = 800 millimeter per year)	0.247	0.106	0.089	–0.146	**–0.214**	–0.187	–0.237	–0.287	0.077
	(0.200)	(0.181)	(0.196)	(0.226)	**(0.259)**	(0.223)	(0.260)	(0.229)	(0.078)

(*continued on next page*)

Table 1 (*continued*)

Panel C: Impact of a 100 millimeter per Year Increase in Precipitation									
EM (P = 900 millimeter per year)	0.245	0.104	0.090	–0.133	**–0.193**	–0.166	–0.215	–0.267	0.087
	(0.191)	(0.173)	(0.186)	(0.215)	**(0.244)**	(0.209)	(0.245)	(0.216)	(0.075)
LIDC (P = 1,100 millimeter per year)	0.240	0.100	0.091	–0.107	**–0.150**	–0.126	–0.171	–0.227	0.107
	(0.173)	(0.158)	(0.168)	(0.196)	**(0.218)**	(0.182)	(0.218)	(0.191)	(0.071)

Note: The table presents results from estimating equation (1), with separate regressions for each horizon. Panel A reports the estimated coefficients on the weather variables for horizon 0. Panels B and C show the marginal impact of a change in temperature and precipitation computed as per equation (2) at the median temperature (T) and median precipitation (P) of advanced economies (AE), emerging markets (EM), and low-income developing countries (LIDC) contemporaneously (horizon 0) and cumulatively seven years after the shock. The specifications in columns (1)–(8) control for country fixed effects; lag of temperature, precipitation, and their squared terms; and lag of growth. Columns (1)–(3) in addition control for country-specific time trend and time trend squared, whereas columns (3)–(8) control for region-year fixed effects (where region is defined based on the World Bank classification: Europe, Sub-Saharan Africa, etc.). Column (6) controls for observations of the weather variables within the forecast horizon, following Teulings and Zubanov (2014). Column (7) controls for occurence of natural disasters. Column (8) shows results from an auto-regressive distributed lag model with seven lags of the weather variables. Column (9) presents subnational regression results, where country fixed effect are replaced with province fixed effects. In all specifications, standard errors are clustered at the country level. CRU = University of East Anglia, Climate Research Unit; UDEL = University of Delaware.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

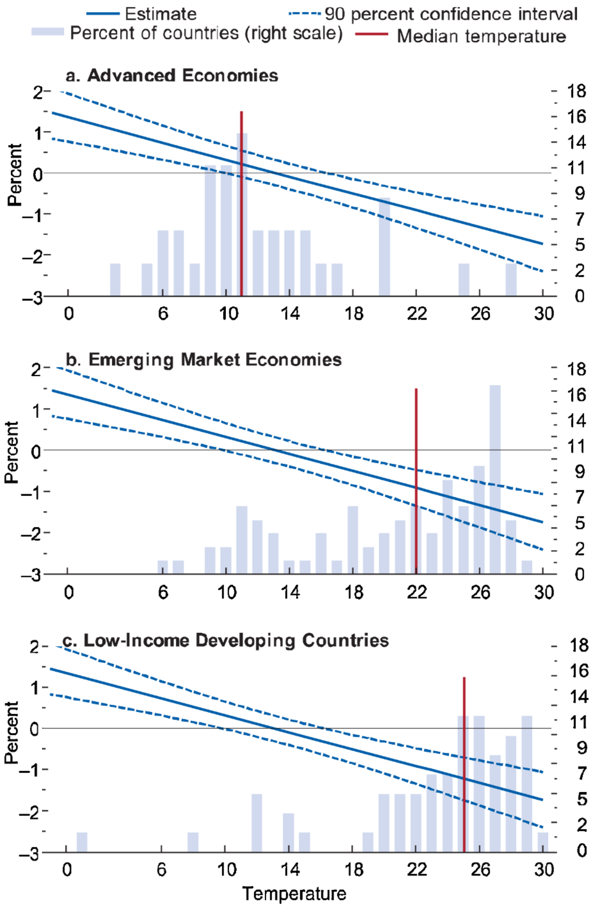
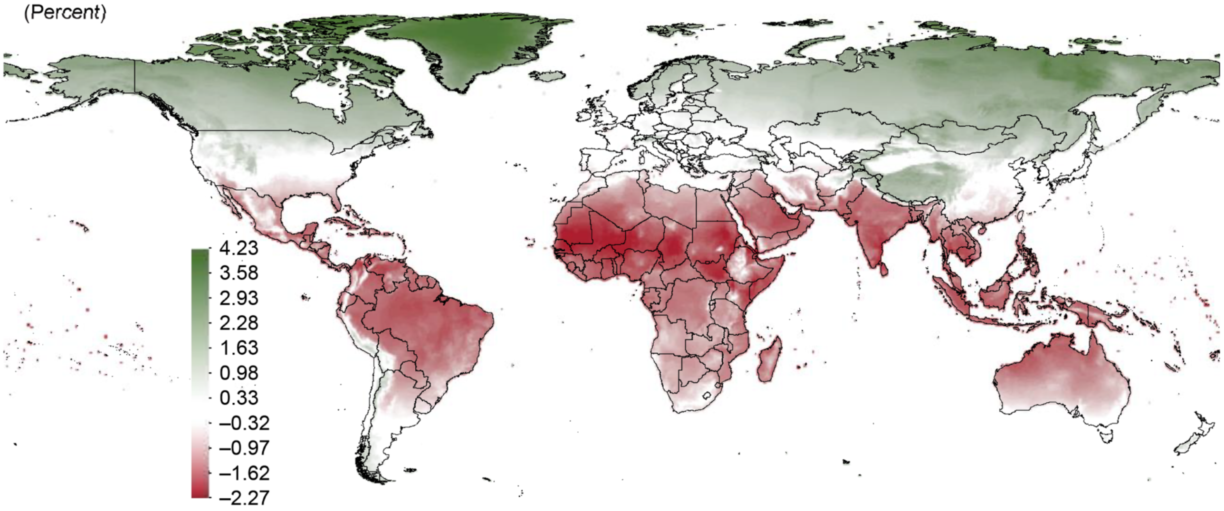


Fig. 3. The Contemporaneous Effect of Temperature Increase on Real per Capita Output
Source: Authors' calculations.
Note: The panels superimpose the contemporaneous effect of a 1°C increase in temperature on per capita output at different temperature levels computed as per equation (1) over the distribution of average annual temperatures recorded in 2015 in advanced economies, emerging markets and low-income countries. The blue lines show the point estimates and 90 percent confidence intervals, while the light blue bars denote the percent of countries at each temperature level. The vertical red line is the median temperature for the country group.

a. Effect of a 1°C Increase in Temperature on Real per Capita Output at the Grid Level
(Percent)



b. Effect of a 1°C Increase in Temperature on Real per Capita Output at the Country Level, with Countries Rescaled in Proportion to Their Population
(Percent)

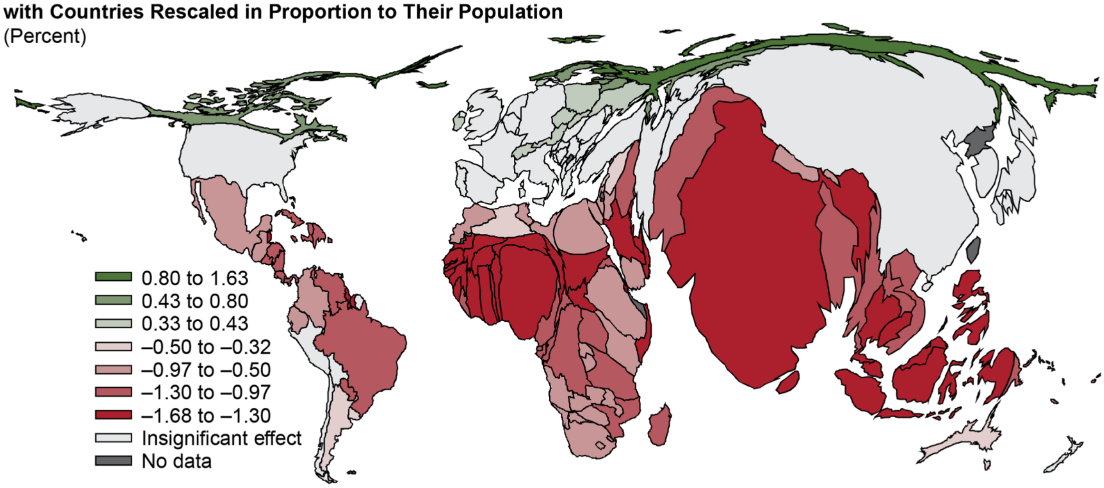


Fig. 4. Effect of Temperature Increase on Real per Capita Output across the Globe
Sources: Natural Earth; ScapeToad; United Nations World Population Prospects Database: the 2015 Revision; World Bank Group Cartography Unit; and authors' calculations.
Note: The maps depict the contemporaneous effect of a 1°C increase in temperature on per capita output computed as per equation (2). Panel A uses 2005 grid-level temperature, while panel B uses the recent 10-year average country-level temperature together with estimated coefficients in Table 1, column (5). In the cartogram in panel B, each country is rescaled in proportion to its 2015 population. Gray areas indicate the estimated impact is not statistically significant.

4.2. Medium-term Effect on Per Capita Output

Our empirical analysis suggests that the effects of temperature increase are long-lasting. The cumulative effects of a 1°C increase in temperature seven years after the shock is shown in the lower half of Panel B in Table 1. Even seven years after a weather shock, per capita output is 1.4 percent lower for the median emerging market economy and 2 percent lower for the median low-income country as depicted in Figure 5.

The estimated persistence may reflect the relatively persistent nature of temperature shocks. Univariate time series regression analysis shows that temperature shocks decay slowly, especially in relatively hot locations, with a 1°C degree increase in annual temperature leading to significantly higher temperatures in the subsequent years. Some authors, such as Dell, Jones, and Olken (2012) and Burke et al. (2015a), have argued that temperature shocks may have a negative growth effect—rather than just level effect—on GDP (and consequently much larger economic losses from higher temperatures). However, statistically, we are unable to reject the hypothesis that the contemporaneous and medium-term effects of a temperature shock on per capita output are identical, hence we only find evidence of a level effect on GDP.

4.3. Robustness

To establish the robustness of these findings at the country level, we present results from estimating numerous alternative specifications

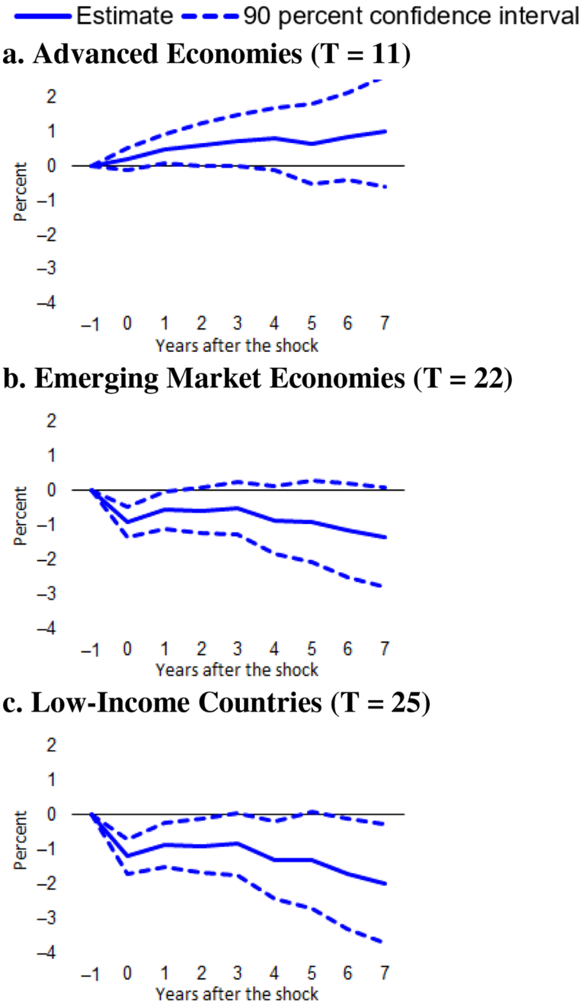


Fig. 5. Effect of Temperature Increase on Real per Capita Output over Time
Source: Authors' calculations.
Note: The panels depict the impulse response of per capita output to a 1°C increase in temperature estimated at the median temperature of advanced economies, emerging markets and low-income developing countries. Horizon 0 is the year of the shock. T = temperature.

in Table 1. In column (1), we replicate the specification of Burke et al. (2015a), using our substantially larger sample (relative to their study, our paper expands the sample both geographically and temporally by about 25 percent). In this specification, we include country-specific linear and quadratic time trends, we use University of Delaware (UDEL) weather data, and aggregate weather variables using the 1990 population weights. Column (2) uses the same empirical approach as in column (1) but an alternative source of weather data, CRU instead of UDEL, and obtains similar coefficients on the temperature and precipitation variables.

The choice of population weights used to aggregate gridded weather data to the country level could play an important role since migration within and across country borders is one of the potential strategies for coping with adverse weather conditions. Since historical data show an increase in average annual temperatures starting in the 1970s (Figure 2), column (3) presents results with 1950 population weights to account for migration responses that could have already taken place.

Column (4) and column (5) (main specification for the paper) present results for the baseline specification with region-year fixed effects, following Dell, Jones, and Olken (2012), using 2010 and 1950 population weights, respectively. As suggested by Teulings and Zubanov (2014), column (6) controls for observations of the weather variables occurring within the forecast horizon, which is more robust to dynamic misspecification. Column (7) controls separately for the occurrence of natural disasters[12] since temperature and precipitation fluctuations might affect economic activity through their effect on the incidence of natural disasters. Controlling for

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[12] Natural disasters indicator is based on disasters reported in the Emergency Events International Disaster Database (EM-DAT). Disasters are reported when at least one of these conditions is met: 1) ten or more people killed, 2) hundred or more people affected, 3) state of emergency declared, 4) international call for assistance made.

Table 2
Effect of Weather Shocks on Sectoral Output
Source: Authors' calculations.

Panel A	Agriculture (1)	Manufacturing (2)	Services (3)	Crop Production (4)
Temperature	0.283	1.281	–0.268	3.860 *
	(0.871)	(1.035)	(0.585)	(2.085)
Temperature^2	–0.043 *	–0.051 *	–0.007	–0.151 ***
	(0.023)	(0.027)	(0.016)	(0.050)
Precipitation	0.705 ***	0.108	–0.000	1.287 ***
	(0.228)	(0.149)	(0.111)	(0.332)
Precipitation^2	–0.015 ***	–0.002	–0.001	–0.028 ***
	(0.005)	(0.003)	(0.002)	(0.007)
Adjusted R^2	0.10	0.13	0.12	0.09
Number of Countries	174	168	174	185
Number of Observations	5,847	5,225	5,730	8,836
Panel B: Impact of a 1°C Increase in Temperature				
Horizon 0:				
AE (T = 11°C)	–0.664	0.152	–0.423	0.547
	(0.464)	(0.532)	(0.303)	(1.077)
EM (T = 22°C)	–1.610 ***	–0.977 **	–0.578 *	–2.767 ***
	(0.431)	(0.439)	(0.298)	(0.664)
LIDC (T = 25°C)	–1.868 ***	–1.285 **	–0.621 *	–3.671 ***
	(0.517)	(0.538)	(0.362)	(0.820)
Horizon 7 (cumulative):				
AE (T = 11°C)	2.497 ***	1.550	–0.495	1.188
	(0.896)	(2.207)	(2.082)	(1.166)
EM (T = 22°C)	–0.838	–2.723 **	–0.082	–0.480
	(1.152)	(1.359)	(0.997)	(1.296)
LIDC (T = 25°C)	–1.747	–3.889 **	0.031	–0.935
	(1.414)	(1.678)	(1.380)	(1.613)
Panel C: Impact of a 100 millimeter per Year Increase in Precipitation				
Horizon 0:				
AE (P = 800 millimeter per year)	0.458 ***	0.076	–0.013	0.835 ***
	(0.149)	(0.105)	(0.075)	(0.223)
EM (P = 900 millimeter per year)	0.428 ***	0.072	–0.015	0.778 ***
	(0.139)	(0.100)	(0.071)	(0.210)
LIDC (P = 1,100 millimeter per year)	0.366 ***	0.065	–0.018	0.665 ***
	(0.121)	(0.090)	(0.063)	(0.185)
Horizon 7 (cumulative):				
AE (P = 800 millimeter per year)	–0.277	0.102	–0.117	–0.220
	(0.246)	(0.377)	(0.278)	(0.296)
EM (P = 900 millimeter per year)	–0.259	0.108	–0.104	–0.200
	(0.233)	(0.358)	(0.261)	(0.279)
LIDC (P = 1,100 millimeter per year)	–0.224	0.119	–0.077	–0.160
	(0.208)	(0.321)	(0.229)	(0.246)

Note: The table presents results from estimating equation (1) using the same specification as in Table 1, column (5), for different dependent variables, with separate regressions estimated for each horizon. In all specifications, standard errors are clustered at the country level. Panel A reports the estimated coefficients on the weather variables for horizon 0. Panels B and C show the marginal impact of a change in temperature and precipitation computed as per equation (2) at the median temperature (T) and median precipitation (P) of advanced economies (AE), emerging markets (EM), and low-income developing countries (LIDC) contemporaneously (horizon 0) and cumulatively seven years after the shock.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

natural disasters does not materially alter the estimated coefficients on temperature and precipitation. In columns (1)–(7), impulse responses were estimated using Jordà’s (2005) local projection method. Column (8), however, tests the robustness of the findings to using the autodistributed lag model with seven lags of the weather variables and their squared terms, as in Dell, Jones, and Olken (2012), who tested different models from no lags up to 10 lags and found that across different lag specifications results are broadly consistent in magnitude and statistical significance. Column (9) is analogous to column (5) using subnational data.

5. Channels of Impact

The weather can influence economic activity through various channels. The most obvious one is agricultural output, given that temperature and precipitation are direct inputs in crop production. However, studies show evidence of broader impacts, including on

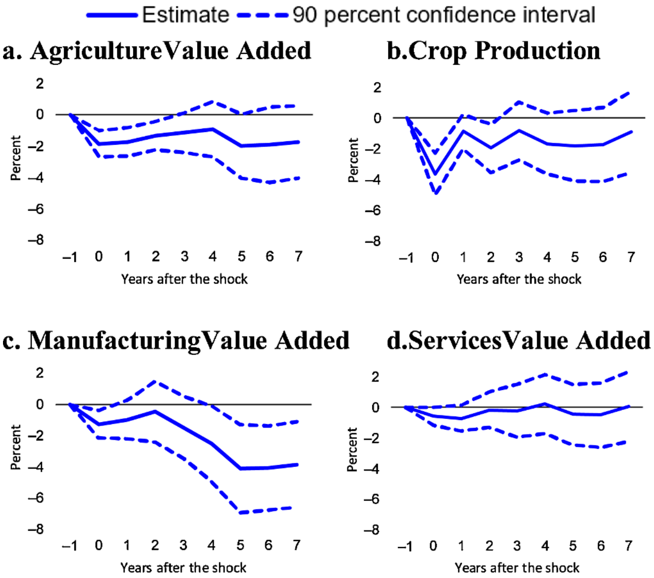

Fig. 6. Effect of Temperature Increase on Sectoral Output Estimated at the Temperature of the Median Low-Income Developing Country
Source: Authors' calculations.
Note: The panels depict the effect of a 1°C increase in temperature estimated at the median low-income developing country temperature (25°C). Horizon 0 is the year of the shock. Crop production is an index, produced by the Food and Agriculture Organization, of price-weighted quantities of agricultural commodities produced excluding production for seeds and fodder.

labor productivity, mortality, health, and conflict.[13] The literature so far has often studied these effects within a specific country or through laboratory experiments. We examine whether these channels are also at work in a cross-country setting.

5.1. Sectoral Output: Agriculture, Manufacturing, Services

We begin by studying whether weather shocks influence only agricultural production or also affect other economic sectors, by estimating equation (1) but with real value added of agricultural, manufacturing, and services sectors, and crop production as our outcomes of interest. Regression results are presented in Table 2. Figure 6 depicts the impulse response function of the four outcomes considered at the temperatures prevailing in the median low-income country.

We find that agricultural value added and crop production drop with higher temperature, recover somewhat in subsequent years, but generally remain depressed over the medium term. This is consistent with a large body of work which documents the negative effect of temperature and/or precipitation shocks on agricultural output.[14] However, the analysis also confirms findings that manufacturing output is similarly hurt as temperatures rise in countries with hot climates, although the estimates are more imprecise (see also Dell, Jones, and Olken, 2012; Burke et al., 2015a). Only the services sector output appears to be sheltered from the weather.

It is important to note that, unlike aggregate output, agricultural production is significantly affected by precipitation in addition to temperature shocks. Although the results suggest a concave relationship between agricultural output and precipitation, at the typical levels of precipitation of all three country groups, an increase in precipitation unambiguously improves agricultural productivity (Table 2, Panel C). The effects of precipitation are also short-lived; agricultural output seven years down the line is not affected by a precipitation shock today, which is different from the effect of temperature.

To shed light on the reasons why weather shocks affect sectors besides agriculture in such a broad and long-lasting manner, we examine how key elements of the aggregate production function—productivity, and labor and capital inputs—respond to weather shocks. As in other studies, we aim to capture the net reduced-form effects of weather on various outcomes rather than uncover the potentially complex structural relationships that may exist between these variables.

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[13] See Dell, Jones, and Olken (2014); Burke et al. (2015b); Heal and Park (2016); Carleton and Hsiang (2016) for literature reviews. Weather shocks can also indirectly affect economic activity through their impacts on third markets. See Cashin, Mohaddes, and Raissi (2017) for an analysis of the international macroeconomic transmission of El Niño within a dynamic multicountry framework.

[14] See, among others, Barrios, Ouattara, and Strobl (2008), Barrios, Bertinelli, and Strobl (2006, 2010), Schlenker and Lobell (2010), Feng, Krueger, and Oppenheimer (2010), Lobell, Schlenker, and Costa-Roberts (2011), and Lanzafame (2014) for evidence from emerging market and developing economies and Schlenker and Roberts (2009), Burke and Emerick (2016) and Wang et al. (2017) for evidence from the United States.

Table 3
Effect of Weather Shocks on Productivity, Capital, and Labor

Panel A	Capital Input		Labor Input		Labor Productivity	
	Investment	Imports	Infant Mortality	HDI	Non-Heat Exposed	Heat Exposed
	(1)	(2)	(3)	(4)	(5)	
Temperature	0.850	0.467	–0.147	0.269 ***	0.246	1.902 *
	(2.042)	(0.943)	(0.117)	(0.078)	(0.681)	(1.002)
Temperature^2	–0.045	–0.068 **	0.005 *	–0.008 ***	–0.010	–0.087 ***
	(0.059)	(0.033)	(0.003)	(0.002)	(0.018)	(0.026)
Precipitation	–0.377	–0.654 **	–0.001	0.000	0.047	0.272
	(0.398)	(0.271)	(0.024)	(0.018)	(0.201)	(0.195)
Precipitation^2	0.003	0.006	0.001	–0.000	–0.003	–0.008 *
	(0.009)	(0.007)	(0.001)	(0.000)	(0.005)	(0.004)
Adjusted R^2	0.03	0.08	0.64	0.31	0.03	
Number of Countries	169	178	182	181	40	
Number of Observations	6,093	6,866	8,685	3,864	17,848	
Panel B: Impact of a 1°C Increase in Temperature						
Horizon 0:						
AE (T = 11°C)	–0.138	–1.029 **	–0.028	0.094 **	0.030	–0.003
	(0.976)	(0.455)	(0.067)	(0.043)	(0.396)	(0.502)
EM (T = 22°C)	–1.126	–2.525 ***	0.092 *	–0.082	–0.185	–1.909 ***
	(1.064)	(0.753)	(0.055)	(0.056)	(0.412)	(0.363)
LIDC (T = 25°C)	–1.395	–2.934 ***	0.124 *	–0.129 *	–0.244	–2.428 ***
	(1.331)	(0.919)	(0.063)	(0.067)	(0.478)	(0.456)
Horizon 7 (cumulative):						
AE (T = 11°C)	1.672	2.149	–0.382	0.484 *	0.639	–1.391
	(2.389)	(1.886)	(0.558)	(0.263)	(1.906)	(1.712)
EM (T = 22°C)	–7.623 ***	–5.181 **	1.511 ***	–0.518 **	–0.655	–3.185
	(2.778)	(2.070)	(0.566)	(0.259)	(1.861)	(1.955)
LIDC (T = 25°C)	–10.158 ***	–7.180 ***	2.027 ***	–0.792 ***	–1.008	–3.675
	(3.256)	(2.444)	(0.658)	(0.297)	(2.216)	(2.513)
Panel C: Impact of a 100 millimeter per Year Increase in Precipitation						
Horizon 0:						
AE (P = 800 millimeter per year)	–0.329	–0.558 ***	0.008	–0.007	–0.009	0.148
	(0.262)	(0.180)	(0.015)	(0.013)	(0.133)	(0.136)
EM (P = 900 millimeter per year)	–0.323	–0.547 ***	0.009	–0.008	–0.016	0.132
	(0.246)	(0.170)	(0.015)	(0.012)	(0.125)	(0.130)
LIDC (P = 1,100 millimeter per year)	–0.311	–0.523 ***	0.011	–0.010	–0.030	0.101
	(0.216)	(0.151)	(0.013)	(0.011)	(0.109)	(0.118)
Horizon 7 (cumulative):						
AE (P = 800 millimeter per year)	–0.303	–0.890 *	0.082	–0.090	–0.277	0.161
	(0.681)	(0.506)	(0.181)	(0.057)	(0.772)	(0.512)
EM (P = 900 millimeter per year)	–0.257	–0.871 *	0.086	–0.086	–0.243	0.137
	(0.640)	(0.480)	(0.165)	(0.054)	(0.719)	(0.484)
LIDC (P = 1,100 millimeter per year)	–0.165	–0.834 *	0.092	–0.078 *	–0.174	0.089
	(0.563)	(0.429)	(0.134)	(0.047)	(0.615)	(0.430)

Source: Author's calculations.

Note: Columns (1–4) present results from estimating equation (1) using the same specification as in Table 1, column (5), for different dependent variables. Specification in column (5) presents results from estimating equation (3) where an indicator for heat exposed sectors is interacted with temperature and precipitation, their squared terms, and their lags; also controlling for country-sector and region-year fixed effects, and lag of growth. Separate regressions are estimated for each horizon. In all specifications, standard errors are clustered at the country level. Panel A reports the estimated coefficients on the weather variables for horizon 0. Panels B and C show the marginal impact of a change in temperature and precipitation computed as per equation (2) at the median temperature (T) and median precipitation (P) of advanced economies (AE), emerging markets (EM), and low-income developing countries (LIDC), contemporaneously (horizon 0) and cumulatively seven years after the shock. HDI = Human Development Index.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

5.2. *Productivity*

Evidence from surveys and other sources shows that exposure to heat above a certain point reduces people's performance on both cognitive and physical tasks.[15] We therefore examine whether higher temperatures in parts of the world that are hot decrease labor

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[15] Seppänen, Fisk, and Faulkner (2003) report a productivity loss of about 2 percent for every 1°C increase in temperature above 25°C, based on a survey of laboratory experiments. See also Seppänen, Fisk, and Lei (2006) for a meta-analysis of the literature, (Somanathan et al., 2017) for recent

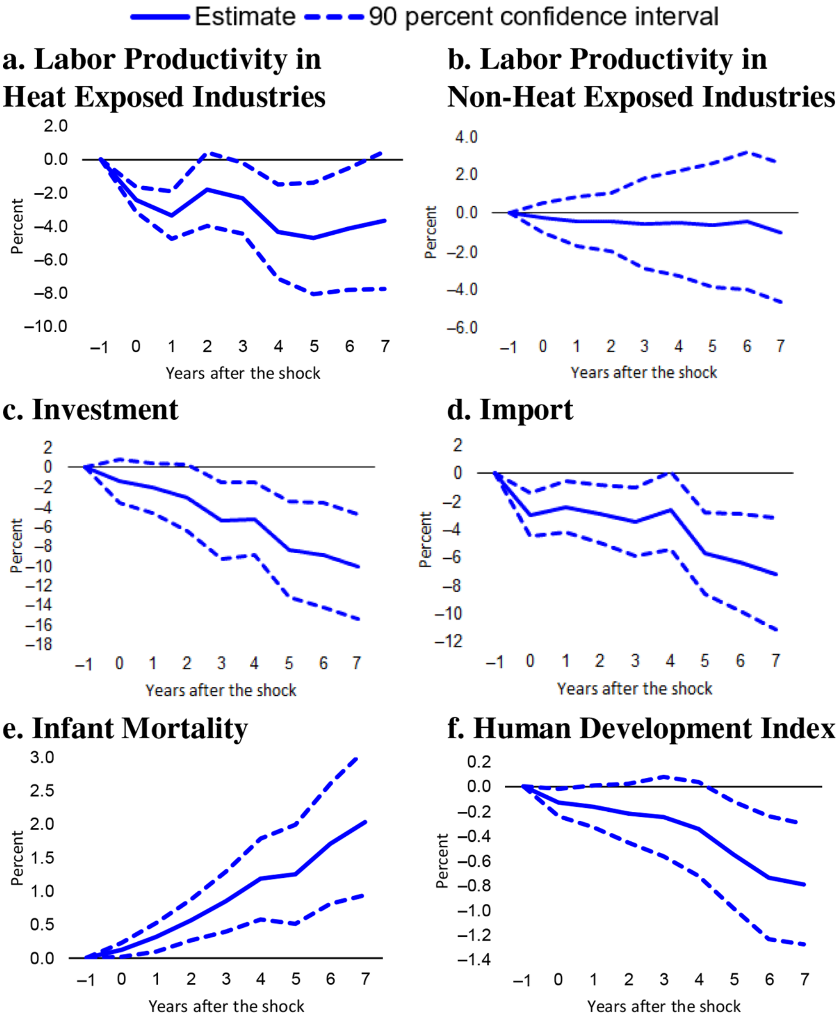


Fig. 7. Effect of Temperature Increase on Productivity, Capital, and Labor Input Estimated at the Temperature of the Median Low-Income Developing Country

Source: Authors' calculations.

Note: The panels depict the effect of a 1°C increase in temperature estimated at the median low-income developing country temperature (25°C). Horizon 0 is the year of the shock. Heat exposed industries include agriculture, forestry, fishing and hunting, construction, mining, transportation, utilities, and manufacturing, following Graff Zivin and Neidell (2014).

productivity. If productivity is a channel through which weather shocks affect aggregate GDP, the effect should be significantly larger for sectors in which workers are directly exposed to the weather. We explore this hypothesis using the Groningen Growth and Development Centre 10-sector database, which provides sectoral real value added and employment in 40 countries over the period 1950–2012. We follow Graff Zivin and Neidell (2014) and classify sectors into those that are "heat-exposed" and not[16] to estimate the following specification:

$$y_{i,s,t+h} - y_{i,s,t-1} = \beta_1^h c_{i,t} + \beta_2^h c_{i,t}^2 + \gamma_1^h c_{i,t-1} + \gamma_2^h c_{i,t-1}^2 + \alpha_1^h c_{i,t} \times H_s + \alpha_2^h c_{i,t}^2 \times H_s + \omega_1^h c_{i,t-1} \times H_s + \omega_2^h c_{i,t-1}^2 \times H_s + \varphi_1^h \Delta y_{i,s,t-1} + \mu_{i,s}^h + \theta_{r,t}^h + \varepsilon_{i,s,t}^h, \quad (3)$$

(footnote continued)

evidence on labor productivity from India, and (Deryugina and Hsiang, 2014) for evidence from the United States. Heat stress may also reduce cognitive function as captured in student performance (Wargocki and Wyon, 2007; Graff Zivin, Hsiang and Neidell, 2015; Garg, Jagnani, and Taraz, 2017; Park, 2017).

[16] According to Graff Zivin and Neidell (2014), who follow definitions from the National Institute for Occupational Safety and Health, heat-exposed industries include agriculture, forestry, fishing, and hunting; construction; mining; transportation; and utilities—as well as manufacturing in which facilities may not be climate-controlled in low-income countries and production processes often generate considerable heat.

Table 4
The Role of Development: Evidence from Subnational Data
Source: IMF staff calculations.

	Regions with temperature above 15°C				Regions with temperature between 15°C and 20°C			
	Full Sample (1)	Advanced Economies (2)	Non-Advanced Economies	P-value	Full Sample (3)	Advanced Economies (4)	Non-Advanced Economies	P-value
Horizon 0	–0.705 ***	–0.025	–0.727 ***	0.01	–0.448 *	–0.002	–0.666 **	0.09
	(0.174)	(0.159)	(0.210)		(0.234)	(0.193)	(0.334)	
Horizon 1	–0.908 ***	0.320	–0.978 ***	0.00	–0.806 **	0.425	–1.282 **	0.00
	(0.263)	(0.232)	(0.315)		(0.364)	(0.301)	(0.508)	
Horizon 2	–0.963 ***	0.625 *	–1.089 ***	0.00	–0.715	0.782 *	–1.275 **	0.01
	(0.350)	(0.350)	(0.418)		(0.467)	(0.435)	(0.637)	
Horizon 3	–0.910 **	0.703 **	–1.134 **	0.00	–0.513	0.789 *	–1.164	0.02
	(0.429)	(0.323)	(0.516)		(0.548)	(0.412)	(0.735)	
Horizon 4	–1.242 **	0.342	–1.592 **	0.01	–0.236	0.445	–0.699	0.20
	(0.508)	(0.354)	(0.621)		(0.574)	(0.429)	(0.786)	
Horizon 5	–2.130 ***	0.001	–2.313 ***	0.01	–1.697 **	0.331	–2.086 **	0.04
	(0.612)	(0.477)	(0.740)		(0.741)	(0.562)	(0.998)	
Horizon 6	–2.266 ***	–0.507	–2.763 ***	0.02	–1.379 *	–0.226	–2.014 *	0.16
	(0.674)	(0.488)	(0.836)		(0.788)	(0.575)	(1.146)	
Horizon 7	–2.321 ***	–0.485	–2.684 ***	0.04	–1.963 **	0.011	–2.812 *	0.08
	(0.749)	(0.555)	(0.938)		(0.960)	(0.624)	(1.463)	
Median Temperature,°C	22.86	16.65	24.06		17.02	16.53	17.52	
Mean Temperature,°C	22.22	17.00	23.00		17.20	16.60	17.51	
Adjusted R^2	0.18	0.20			0.26	0.33		
Number of Countries	44	7	37		28	7	21	
Number of Provinces	607	51	556		167	47	120	
Number of Observations	16,148	16,148			5,719	5,719		

Note: The table presents results from estimating equation (4) using subnational data on a sample of provinces with average annual temperature (i) above 15°C or (ii) between 15°C and 20°C. In the regressions in columns (2) and (4), indicator for whether a province is located in an advanced economy is interacted with temperature, precipitation, their lags, lag of growth, and region-year fixed effects. Regressions include province fixed effects. Separate regressions are estimated for each horizon. Regression summary statistics are reported for horizon 0. In all specifications, standard errors are clustered at the province level.
* $p<0.1$; ** $p<0.05$; *** $p<0.01$.

in which $y_{i,s,t}$ is the log of real sectoral value added per worker, H_s is an indicator for sectors that are "heat-exposed," $\mu_{i,s}^{h}$ are country-sector fixed effects, and $\theta_{r,t}^{h}$ are region-year fixed effects. Standard errors are clustered at the country level.

Specification (5) in Table 3 summarizes the results of this estimation. Panel A contains the estimated coefficients on temperature and precipitation and their squared terms for non-heat-exposed sectors (β_1^h, β_2^h) and heat-exposed sectors ($\beta_1^h + \alpha_1^h$, $\beta_2^h + \alpha_2^h$). Panels B and C present the estimated impacts of temperature and precipitation evaluated for the median advanced, emerging market and low-income country in the year of the shock, as well as seven years later. Panels A and B in Figure 7 plot the impulse response function of real output per worker to a 1°C increase in temperature for heat-exposed and non-heat-exposed sectors evaluated at the average annual temperature of the median low-income country.

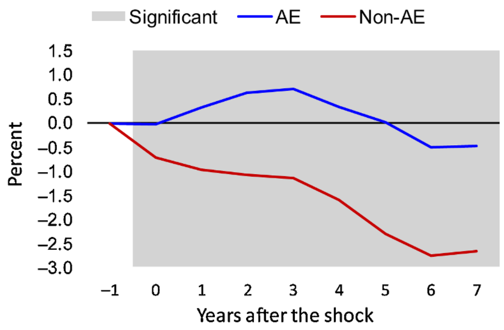
Our analysis suggests that at higher temperatures, an increase in temperature significantly lowers labor productivity in heat-exposed industries. Temperature increases, however, have no discernible effect on the productivity of workers in non-heat-exposed sectors, even in countries with hot climates.

5.3. *Investment*

Temperature increases are largely supply-side shocks, but they could lead to persistent output losses and affect growth if they influence the rate of factor accumulation. Investment may fall in response to temperature shocks because there are fewer resources to invest, because the rate of return on capital is lower, and/or because the temporary negative shock to income raises the cost of financing investment in an environment of imperfect capital markets (see, for example, Fankhauser and Tol, 2005). When access to formal savings, credit, or insurance is limited, households may also sell productive assets to smooth consumption in response to weather shocks.

Using national accounts data, we examine the response of the main components of aggregate demand—gross capital formation, consumption, exports, and imports—to weather shocks using the empirical framework given by equation (1). At the temperature of the median low-income country, all four components respond negatively to a 1°C increase in temperature, although the uncertainty

a. Regions with temperature above 15°C



b. Regions with temperature between 15°C and 20°C

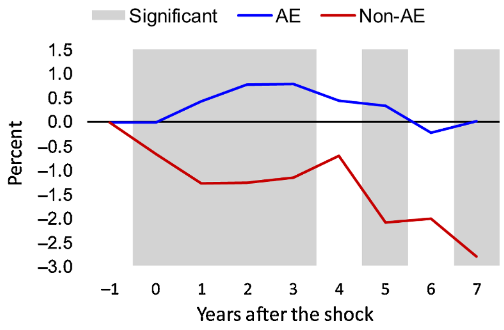


Fig. 8. The Role of Development: Evidence from Subnational Data
Source: Authors' calculations.
Note: The figure depicts how the effect of a 1°C increase in temperature varies with an indicator of whether the state or province is located in an advanced economy (AE). Horizon 0 is the year of the shock. Gray areas indicates that the blue and red lines are significantly different at the 15 percent level.

surrounding the estimated contemporaneous effects is large. However, in the medium term, the effect is most pronounced for investment (Table 3, column 1). Seven years after the shock, investment is estimated to be 10 percent lower than it would have been in the absence of the shock as depicted in Figure 7, panel C. Imports, which are typically closely tied to investment, also exhibit a significant and long-lasting drop as temperature rises (Table 3, column 2 and Figure 7, panel D).

The negative effect of temperature shocks on aggregate investment is consistent with evidence from household-level studies, which find that weather shocks could slow or even reverse capital accumulation as households try to smooth consumption or perceive investment as too risky (Hallegatte et al., 2016).

5.4. Labor Supply

Finally, we examine whether labor supply may be affected by weather fluctuations, for example, through their effect on health. In the absence of comprehensive and comparable data on adult health outcomes, we focus on infant mortality as an imperfect proxy. Estimating equation (1) with infant mortality as dependent variable reveals that, in hot climates, higher temperatures may reduce (future) labor supply because of their influence on mortality rates (Table 3, column 3 and Figure 7, panel E). A 1°C increase in temperature raises infant mortality by 0.12 percentage point in the year of the shock. The effect grows through the estimation period as weather-related lower income (and potential food insecurity) reinforces the direct physiological impact of higher temperatures in hot climates.

This cross-country panel evidence corroborates findings in numerous studies of links between weather and mortality, prenatal health, and other health outcomes in different countries. Deschênes (2012) and Guo et al. (2014) provide comprehensive reviews of the literature on the link between temperature and mortality and health from a large number of countries.[17] Graff Zivin and Neidell (2014), Deryugina and Hsiang (2014), Park (2017), and Somanathan et al. (2017) find a direct effect of higher temperature on labor supply and productivity. The adverse effects on the health and educational attainment of children could be one of the key reasons

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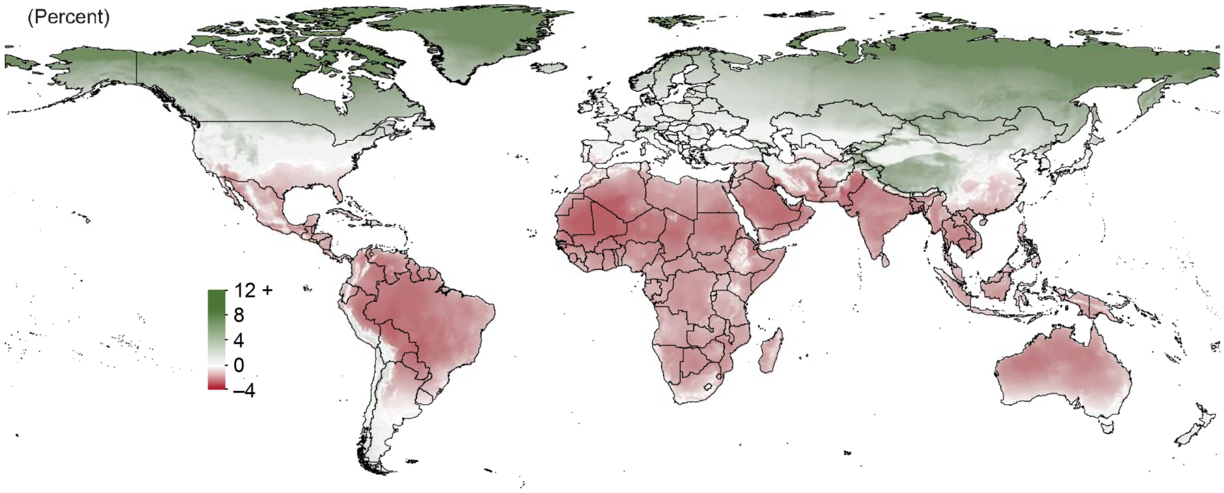
[17] See also Burgess et al. (2014) for evidence from India; Kudamatsu, Persson, and Strömberg (2012) for evidence from a subset of African countries; and Barreca (2012); Barreca et al. (2016); and Deschênes and Greenstone (2011) for evidence from the United States.

a. RCP 4.5 Scenario
(Percent)



b. RCP 8.5 Scenario
(Percent)

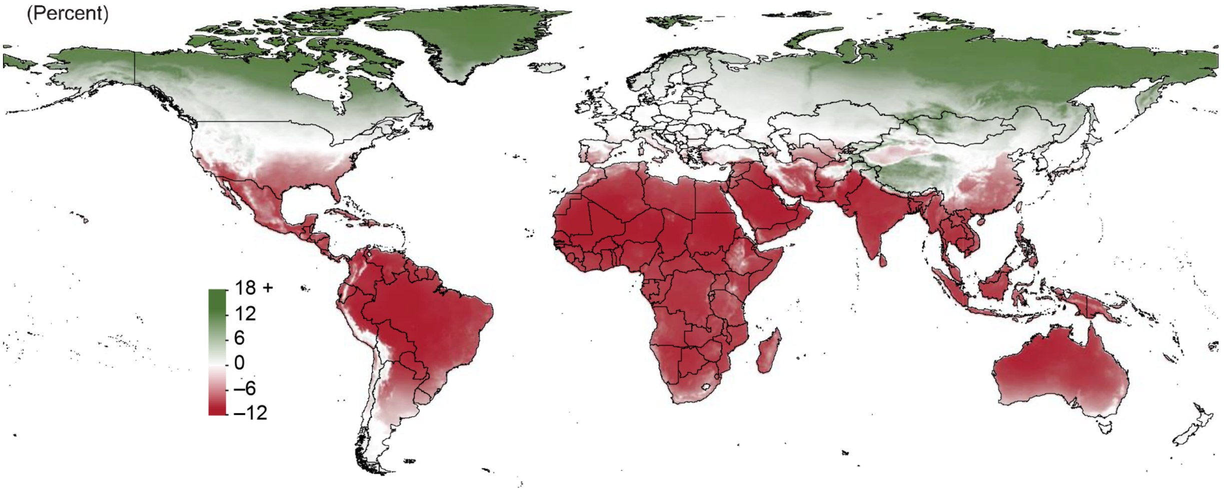


Fig. 9. The Long-Term Impact of Temperature Increase on Real per Capita Output across the Globe
Sources: National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP); World Bank Group Cartography Unit; and authors' calculations.
Note: The maps depict the effect of the projected increase in temperature between 2005 and 2100 under RCP 4.5 and RCP 8.5 scenarios on real per capita output in 2100. Gray areas indicate the estimated impact is not statistically significant. For each of these scenarios, we compute annual temperatures by (i) averaging the maximum and minimum daily temperatures for 21 models in NEX-GDDP, (ii) averaging across the 21 models, and (iii) averaging across all days of the year. The Representative Concentration Pathways (RCP) scenarios constructed by the Intergovernmental Panel on Climate Change (IPCC) use alternative GHG concentration assumptions to project likely ranges of temperatures over the 21st century. Under the RCP 8.5 scenario of unmitigated climate change, the average global temperature by 2081–2100 relative to 1986–2005 could rise by 3.7°C (with a projected range of 2.6°C–4.8°C), with larger increases over the northern hemisphere. Under the RCP 4.5 scenario or intermediate climate change, there is increased attention to the environment. CO_2 emissions peak around 2050 and decline thereafter, with a resulting temperature increase of 1.8°C by 2081–2100 (a likely range of 1.1°C to 2.6°C and a greater than 50 percent chance of an increase exceeding 2°C by 2100).

behind the long-lasting nature of weather's consequences. Indeed, we find that higher temperatures also have a negative effect on a broader measure of human well-being, the Human Development Index, a weighted average of per capita income, educational achievement, and life expectancy as documented in Table 3, column 4 and Figure 7, panel F.

6. The Role of Development

The level of development could directly influence countries' ability to cope with weather shocks and reduce the damages they cause. For example, in higher income countries, most people live in housing well equipped to withstand even severe weather shocks, thanks to good thermal insulation and air-conditioning, storm windows, high quality roofs and foundations. More developed countries may have better government policies that we cannot measure well individually, which can help them better withstand weather shocks. Yet, despite its wide-reaching policy implications, compelling evidence on the extent to which the level of development helps protect countries against climate change is scarce. The scarcity of evidence is perhaps not surprising. Using country-level data, it is difficult to establish definitively whether advanced economies experience a smaller marginal effect of heat on macroeconomic performance, because so few of them have hot climates.

We present new analysis to help shed light on the role of development in potentially dampening the negative effects of climate change. To do so, we leverage the fact that some of the larger advanced economies, such as the United States, span several climate zones. For example, while the average annual temperature in the U.S. state of Maine is about 7°C, it is 20°C in Texas. This within-country geographic heterogeneity makes it possible to compare whether economic activity in the hot states or provinces of advanced economies responds in the same way to a temperature increase as it does in the hot states or provinces of emerging market and developing economies.

We thus combine subnational GDP per capita from Gennaioli et al. (2014) with annual temperature and precipitation data at the same level of aggregation (based on CRU data with 1950 population weights). As presented in Table 1 column 9, we first estimate the quadratic specification following equation 1. We then zoom in on a set of hot regions with average temperature above 15°C and estimate a linear regression (i.e. without the squared terms of the weather variables). As shown in Table 4 column 1, within this set of hot regions, the coefficient on temperature is negative and statistically significant.

Next, we include an interaction term (AE_i) that takes the value of 1 for regions located in advanced economies, resulting in the following specification:

$$y_{i,t+h} - y_{i,t-1} = \beta_1^h c_{i,t} + \gamma_1^h (c_{i,t} \times AE_i) + \beta_2^h c_{i,t-1} + \gamma_2^h (c_{i,t-1} \times AE_i) + \varphi_1^h \Delta y_{i,t-1} + \varphi_2^h (\Delta y_{i,t-1} \times AE_i) + \mu_i^h + \theta_{AE,r,t}^h + \varepsilon_{i,t}^h, \tag{4}$$

where μ_i^h denotes province fixed effects, and region-year fixed effects ($\theta_{r,t}^h$) are allowed to vary across advanced and non-advanced economies.[18] Standard errors are clustered at the province level. Our goal here is simply to establish whether the overall development level can indeed modify the relationship between weather shocks and GDP, without attempting to disentangle the specific channels in which this may take place. [19]

Column 2 of Table 4 and Figure 8 (panel A) present the estimated effects for subnational regions in advanced and non-advanced economies, as well as the p-value of a test of their difference. The analysis suggests that temperature shocks hurt hot areas in emerging market and developing economies significantly more than those in advanced economies. Thus, economic development seems, to some extent, to insulate countries from the vagaries of the weather.

One potential pitfall in this analysis might stem from the fact that hot regions in emerging market and developing economies tend to be hotter than hot regions in advanced economies. To address this concern, we limit the sample to regions with temperatures between 15°C and 20°C. For this sample, the median and mean temperatures are around $17(\pm 0.5)$°C, alleviating the concerns that the results might be driven by remaining heterogeneity in temperatures across regions in advanced and non-advanced economies. We observe the same pattern: there is a statistically significant difference in the ability of developed and developing countries to respond to temperature shocks.

7. Summary and Policy Implications

Coping with climate change is one of the fundamental challenges of the 21st century, and this challenge looms particularly large for low-income economies. We document the extraordinarily fast rise in temperature over the past century across advanced, emerging market, and low-income economies. Low-income countries, which tend to be in some of the hottest parts of the planet and are projected to experience sizable increases in temperature depending on our ability to contain future GHG emissions, have contributed very little to the atmospheric concentration of GHGs.

The analysis suggests that rising temperatures have highly uneven macroeconomic effects, with the adverse consequences borne disproportionately by countries with hot climates, such as most low-income countries. We find that a rise in temperature lowers per capita output in countries with high average temperatures, in both the short and medium term, through a wide array of channels. In areas with hot climates, higher temperatures reduce agricultural output, lower productivity of workers exposed to the heat, slow the rate of investment, and damage health.[20]

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[18] In this exercise we split the sample in two groups—advanced and non-advanced economies—for three reasons: first, previous results presented in the paper show that the GDP response to temperature shocks is relatively similar in emerging markets and low-income countries; second, the empirical specification for this exercise is much simpler, and the estimated coefficient easier to interpret, if we use a dummy variable for the interaction term in equation 4 (i.e. splitting countries into two groups, rather than three groups); finally, the number of low-income countries for which we have subnational data is relatively small, and the time series short, making it difficult to precisely estimate effects for that group.

[19] Data constraints prevent us from identifying the precise channels through which development attenuates the link between weather and overall economic performance. Economic activity in hot areas in advanced economies may be more insulated from temperature shocks since households exposed to these shocks have better access to ex post coping mechanisms (such as social protection) or have reduced their vulnerability to shocks through ex ante adaptation strategies (such as activity diversification, adoption of air-conditioning, higher quality housing, and the like).

[20] These findings reflect impacts of weather shocks on average country outcomes. But weather shocks could also have sizable unfavorable distributional consequences within a country. Poor households tend to be more vulnerable to weather fluctuations as a result of their heavy reliance on agricultural income, higher proportion of income devoted to food items, and limited access to savings and credit (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017).

Yet, we find that a higher level of overall development is associated with a smaller negative effect of an increase in temperature. This finding suggests that advanced countries have somehow found ways to better insulate their "hot" regions from the negative effects of temperature. We cannot identify the specific ways in which these "hot" regions have adapted to their climates, but this finding offers some hope for effectiveness of climate adaptation strategies.

While our analysis emphasized the impact of global warming on low-income countries, it is important to note that all countries will increasingly feel direct negative effects from unmitigated climate change, through more frequent (and damaging) natural disasters, rising sea level, loss of biodiversity and many other difficult-to-quantify consequences. Warming will also begin to weigh on growth in many advanced economies, as their temperatures rise above optimal levels.

By combining our estimated sensitivity of per capita output to temperature increase, baseline annual temperatures and projected temperature increase under two Representative Concentration Pathway (RCP) scenarios of the Intergovernmental Panel for Climate Change, Figure 9 depicts the potential cumulative impacts on 2100 per capita GDP across the globe. This exercise confirms the highly uneven effects of warming across the globe, but also reveals that the projected increase in temperature, especially under the RCP 8.5 scenario of unmitigated climate change, will push many advanced economies beyond the threshold temperature levels, thus triggering direct economic losses for these countries as well. And even in countries where the effect might be moderate or positive on average, climate change will create winners and losers at both the individual and sectoral levels. Moreover, the international spillovers from the most vulnerable countries, through depressed economic activity and potentially higher conflict and migration flows, could be considerable. Going forward, only a global effort to contain carbon emissions to levels consistent with an acceptable increase in temperature can limit the long-term risks of climate change (Farid et al. 2016; Hallegatte et al. 2016; Stern, 2015; IPCC, 2014).

Declaration of Competing Interest

All authors declare that they have no relevant or material financial interest that related to the research described in the paper. During the conduct of this research, all authors were employees of the International Monetary Fund.

Annex. Data Sources and Country Groupings

Annex Tables 1–2

Table A1
Data Sources

Indicator	Source
Temperature, Historical	Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project Phase Five AR5 Atlas subset; Marcott and others (2013); Matsuura and Willmott (2007); National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS); Royal Netherlands Meteorological Institute (KNMI) Climate Change Atlas; Shakun and others (2012)
Temperature and Precipitation, Forecast (Grid level)	NASA Earth Exchange Global Daily Downscaled Projections Dataset (NEX-GDDP)
Temperature and Precipitation, Historical (Grid level)	University of East Anglia, Climate Research Unit (CRU TS v.3.24); University of Delaware (UDEL v.4.01)
Subnational GDP per Capita	Gennaioli et al. (2014)
Population 2010, 1990, 1950 (Grid level)	Center for International Earth Science Information Network (CIESIN) Columbia University, United Nations Food and Agriculture Programme (FAO), and Centro Internacional de Agricultura Tropical (CIAT) (2005), CIESIN Version 3; Center for International Earth Science Information Network (CIESIN) Columbia University (2016), CIESIN Version 4; History Database of the Global Environment (HYDE v3.2), Klein and others (2016)
Population 2015 and Projected Population 2100	United Nations World Population Prospects Database, the 2015 Revision
Disaster Indicator	EM-DAT: The Emergency Events Database - Université catholique de Louvain (UCLouvain) - CRED, D. Guha-Sapir - www.emdat.be, Brussels, Belgium
Real GDP per Capita	IMF, World Economic Outlook database; World Bank, World Development Indicators database
Crop Production Index	Food and Agriculture Organization (FAO); World Bank, World Development Indicators database
Sectoral Real Value Added (Agriculture, manufacturing, services)	World Bank, World Development Indicators database
Sectoral Labor Productivity	Groningen Growth and Development Centre (GGDC) 10-Sector database; Timmer, de Vries, and de Vries (2015)
Real Gross Capital Formation	IMF, World Economic Outlook database; World Bank, World Development Indicators database
Real Imports of Goods and Services	IMF, World Economic Outlook database; World Bank, World Development Indicators database
Infant Mortality Rate	World Bank, World Development Indicators database
Human Development Index	United Nations Development Programme (UNDP), Human Development Report database

Table A2
Country and Territory Groups

Advanced Economies	Australia, Austria, Belgium, Canada, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hong Kong SAR,* Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Macao SAR,* Malta, Netherlands, New Zealand, Norway, Portugal, Puerto Rico, San Marino,* Singapore, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Taiwan Province of China,* United Kingdom, United States
Emerging Market Economies	Albania, Algeria, Angola, Antigua and Barbuda, Argentina, Armenia, Azerbaijan, The Bahamas,* Bahrain, Barbados, Belarus, Belize, Bosnia and Herzegovina, Botswana, Brazil, Brunei Darussalam, Bulgaria, Cabo Verde, Chile, China, Colombia, Costa Rica, Croatia, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Fiji, Gabon, Georgia, Grenada, Guatemala, Guyana, Hungary, India, Indonesia, Iran, Iraq, Jamaica, Jordan, Kazakhstan, Kosovo,* Kuwait, Lebanon, Libya, Malaysia, Maldives,* Marshall Islands,* Mauritius, Mexico, Micronesia,* Montenegro, Morocco, Namibia, Nauru,* North Macedonia, Oman, Pakistan, Palau,* Panama, Paraguay, Peru, Philippines, Poland, Qatar, Romania, Russia, Samoa, Saudi Arabia, Serbia, Seychelles,* South Africa, Sri Lanka, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Suriname, Swaziland, Syria, Thailand, Timor-Leste, Tonga, Trinidad and Tobago, Tunisia, Turkey, Turkmenistan, Tuvalu,* Ukraine, United Arab Emirates, Uruguay, Vanuatu, Venezuela
Low-Income Developing Countries	Afghanistan, Bangladesh, Benin, Bhutan, Bolivia, Burkina Faso, Burundi, Cambodia, Cameroon, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Republic of Congo, Côte d'Ivoire, Djibouti, Eritrea, Ethiopia, The Gambia, Ghana, Guinea, Guinea-Bissau, Haiti, Honduras, Kenya, Kiribati,* Kyrgyz Republic, Lao P.D.R., Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Moldova, Mongolia, Mozambique, Myanmar, Nepal, Nicaragua, Niger, Nigeria, Papua New Guinea, Rwanda, Senegal, Sierra Leone, Solomon Islands, Somalia,* South Sudan, Sudan, São Tomé and Príncipe, Tajikistan, Tanzania, Togo, Uganda, Uzbekistan, Vietnam, Yemen, Zambia, Zimbabwe
Countries and Territories with Average Annual Temperature above 15°C	Algeria, American Samoa, Angola, Anguilla, Antigua and Barbuda, Argentina, Australia, Bahrain, Bangladesh, Barbados, Belize, Benin, Bhutan, Botswana, Brazil, Brunei Darussalam, Burkina Faso, Burundi, Cabo Verde, Cambodia, Cameroon, Central African Republic, Chad, Colombia, Comoros, Democratic Republic of the Congo, Republic of Congo, Costa Rica, Cuba, Curaçao,* Cyprus, Côte d'Ivoire, Djibouti, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Eritrea, Ethiopia, Fiji, Gabon, The Gambia, Ghana, Grenada, Guadeloupe,* Guatemala, French Guiana,* Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, India, Indonesia, Iraq, Israel, Jamaica, Jordan, Kenya, Kuwait, Lao P.D.R., Lebanon, Liberia, Libya, Madagascar, Malawi, Malaysia, Mali, Malta, Martinique,* Mauritania, Mauritius, Mexico, Montserrat, Morocco, Mozambique, Myanmar, Namibia, Nepal, New Caledonia, Nicaragua, Niger, Nigeria, Oman, Pakistan, Panama, Papua New Guinea, Paraguay, Philippines, Puerto Rico, Qatar, Reunion,* Rwanda, Samoa, Saudi Arabia, Senegal, Sierra Leone, Singapore, Solomon Islands, Somalia, South Africa, South Sudan, Sri Lanka, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Sudan, Suriname, Swaziland, Syria, São Tomé and Príncipe, Tanzania, Thailand, Timor-Leste, Togo, Tonga, Trinidad and Tobago, Tunisia, Turkmenistan, Turks and Caicos,* Uganda, United Arab Emirates, Uruguay, Vanuatu, Venezuela, Vietnam, Virgin Islands (US), West Bank and Gaza, Yemen, Zambia, Zimbabwe
Countries with Sectoral-Level Data	Argentina, Bolivia, Botswana, Brazil, Chile, China, Colombia, Costa Rica, Denmark, Egypt, Ethiopia, France, Germany, Ghana, Hong Kong SAR,* India, Indonesia, Italy, Japan, Kenya, Korea, Malawi, Malaysia, Mauritius, Mexico, Morocco, Netherlands, Nigeria, Peru, Philippines, Senegal, Singapore, South Africa, Spain, Sweden, Taiwan Province of China,* Tanzania, Thailand, United Kingdom, United States, Venezuela, Zambia
Countries with Province-Level Data	Albania, Argentina, Australia, Austria, Bangladesh, Belgium, Benin, Bolivia, Bosnia and Herzegovina, Brazil, Bulgaria, Canada, Chile, China, Colombia, Croatia, Czech Republic, Denmark, Ecuador, Egypt, El Salvador, Estonia, Finland, France, Germany, Greece, Guatemala, Honduras, Hungary, India, Indonesia, Iran, Ireland, Italy, Japan, Jordan, Kazakhstan, Korea, Kyrgyz Republic, Latvia, Lesotho, Lithuania, Malaysia, Mexico, Mongolia, Morocco, Mozambique, Netherlands, Nicaragua, Nigeria, North Macedonia, Norway, Pakistan, Panama, Peru, Philippines, Poland, Portugal, Romania, Russia, Serbia, Slovak Republic, Slovenia, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Tanzania, Thailand, Turkey, Ukraine, United Arab Emirates, United Kingdom, United States, Uruguay, Uzbekistan, Venezuela, Vietnam

*Not included in the main regression analysis.

Supplementary materials

Supplementary data associated with this article can be found, in the online version, at 10.1016/j.jmacro.2020.103207.

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