CHAPTER 3

THE EFFECTS OF WEATHER SHOCKS ON ECONOMIC ACTIVITY: HOW CAN LOW-INCOME COUNTRIES COPE?

Global temperatures have increased at an unprecedented pace over the past 40 years, and significant further warming could occur, depending on our ability to restrain greenhouse gas emissions. This chapter finds that increases in temperature have uneven macroeconomic effects, with adverse consequences concentrated in countries with relatively hot climates, such as most low-income countries. In these countries, a rise in temperature lowers per capita output, in both the short and medium term, by reducing agricultural output, suppressing the productivity of workers exposed to heat, slowing investment, and damaging health. To some extent, sound domestic policies and development, in general, alongside investment in specific adaptation strategies, could help reduce the adverse consequences of weather shocks. But given the constraints faced by low-income countries, the international community must play a key role in supporting these countries' efforts to cope with climate change—a global threat to which they have contributed little. And while the analysis of the chapter focuses on the impact of weather shocks in low-income countries, most countries will increasingly feel direct negative effects from unmitigated climate change through warming above optimal levels in currently cooler countries, more frequent natural disasters, rising sea levels, loss of biodiversity, and adverse spillovers from vulnerable countries. Looking ahead, only continued international cooperation and a concerted effort to stem the man-made causes of global warming can limit the long-term risks of climate change.

Introduction

Since the turn of the 20th century, the Earth's average surface temperature has increased significantly. Sizable swings in global temperatures used to happen over long periods, such as fluctuations in and out of the Ice Ages. However, the speed at which the climate has changed over the past 30–40 years appears to be unprecedented in the past 20,000 years (Figure 3.1).[1] Most scientists agree that global temperatures are set to rise further, at a scale and pace very much dependent on our ability to restrain greenhouse gas emissions, the central cause of global warming (IPCC 2013). Extreme weather events, such as heat waves, droughts, and floods, are likely to become more frequent, and sea levels will rise. Although considerable uncertainty surrounds temperature projections, the scientific consensus predicts that without further action to tackle climate change, average temperatures could rise by 4°C or more by the end of the 21st century. Very substantial cuts to current emissions will be needed to limit warming to less than 2°C. Will climate change have significant macroeconomic consequences, especially in low-income developing countries that tend to be more exposed to the vagaries of the weather? And how can these countries cope with the rises in temperature they are set to experience over the coming decades?

Pinning down the economic consequences of climate change is difficult. Temperature increases of the magnitude that could potentially occur over the next century—and many other aspects of climate change, such as rapid rise in sea levels, ocean acidification, and the like—sit well outside recent (and relevant) historical experience and could affect a large number of countries. Extrapolating from the historically observed relationship between activity and weather patterns could also be problematic as populations adapt to persistent changes in climate. Yet studying the macroeconomic effects of annual variation in weather patterns

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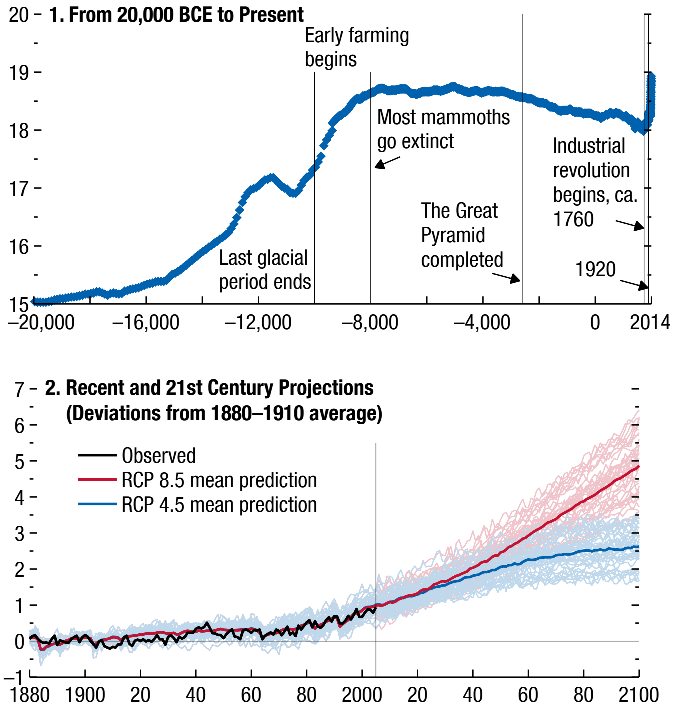
[1]Climate refers to a distribution of weather outcomes for a given location, while weather refers to a realization from that distribution. Climate change typically implies that the whole distribution of outcomes shifts, with a possible increase in the likelihood of extreme outcomes. As argued by Weitzman (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 concentrations in the atmosphere ("climate change mitigation") and adjust to the changing climate ("adaptation").

Figure 3.1. Average Global Temperature
(Degrees Celsius)

The average global temperature has risen at an extraordinary pace over the past century, and significant further warming could occur.



Sources: 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; Royal Netherlands Meteorological Institute Climate Change Atlas; Shakun and others (2012); and IMF staff calculations.
Note: In panel 2, the thin lines represent each of the 40 models in the IPCC WG1 AR5 Annex I Atlas, where a model with different parametrization is treated as a separate model. The thick lines represent the multimodel mean. Representative Concentration Pathways (RCP) are scenarios of greenhouse gas concentrations, constructed by the IPCC. RCP 4.5 is an intermediate scenario, which assumes increased attention to the environment, with emissions peaking around 2050 and declining thereafter. RCP 8.5 is an unmitigated scenario in which emissions continue to rise throughout the 21st century.

could produce useful insights.[2] In an influential study, Dell, Jones, and Olken (2012) find that higher temperatures significantly reduce economic growth in low-income countries. Burke, Hsiang, and Miguel (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, Hsiang, and Miguel (2015a) findings suggest that a rise in temperature would be particularly harmful for this set of economies.

Countries negatively affected by climate change will need to increase their resilience to rising temperatures and extreme weather events, both by enhancing their ability to smooth out shocks, which could become more frequent, and by investing in adaptation strategies, such as activity diversification, infrastructure investment, and technology innovation, that reduce the harm they do. Populations may also respond to changing climatic conditions by relocating geographically, which could have important cross-border ramifications. But the evidence on which policies may help countries and individuals cope with weather shocks is limited.

Understanding the macroeconomic effects of weather shocks and the scope for policy actions to moderate them will be crucial for low-income developing countries to achieve durable growth in the long term—a precondition for convergence and implementation of the United Nations Sustainable Development Goals.

Drawing from and building on the existing literature, this chapter contributes to the policy debate by examining the following questions:

- What has been the historical relationship between temperature and precipitation shocks and economic activity in both the short and the medium term? Are low-income countries particularly vulnerable? Through what channels do weather fluctuations affect the economy? And has the sensitivity of growth to weather shocks changed over time?
- How can countries, particularly low-income ones, cope with weather shocks? Can policies and other country characteristics mitigate the macroeconomic response to weather fluctuations?
- Given the projected path of temperature by the end of the 21st century, what might be the impact of climate change on low-income countries?

To address these questions, the chapter starts by documenting the historical evolution and projected change in temperature and precipitation patterns across broad country groups according to leading climate change models, as well as these groups' contributions to greenhouse gas emissions. It then examines the historical evidence on the macroeconomic effects of annual variation in temperature and precipitation

[2]Dell, Jones, and Olken (2014); Carleton and Hsiang (2016); and Heal and Park (2016) provide surveys of the new climate literature, which explores the impact of weather fluctuations on a broad range of economic variables.

across a large sample of economies, highlighting the channels through which climatic conditions affect the macroeconomy. The chapter offers evidence on how various policies and country characteristics influence the sensitivity of growth to weather variations, using both empirical analysis and model simulations, and presents case studies of various climate change adaptation strategies. Finally, the chapter incorporates the empirical estimates of economic loss from weather shocks and projected changes in temperature into a dynamic general equilibrium model to trace the potential long-term effects of climate change.

The chapter's main findings are as follows:

- The rise in temperature over the past century has been broad based. No country has been spared from the warming of the Earth's surface, and no country is projected to be spared further temperature increases, with the largest increases in temperature expected in countries with relatively colder climates. The contribution of low-income developing countries—which tend to be situated in some of the hottest geographic areas on the planet—to atmospheric greenhouse gas concentrations is negligible, both in absolute terms and on a per capita basis.
- The macroeconomic effect of temperature shocks is uneven across countries. Confirming the global nonlinear relationship between annual temperature and growth uncovered by Burke, Hsiang, and Miguel (2015a) using an expanded data set, the empirical analysis suggests that rising temperatures lower per capita output in countries with relatively high annual average temperature, such as most low-income countries. In these economies, the adverse effect is long-lasting and operates through several channels: lower agricultural output, depressed labor productivity in sectors more exposed to the weather, reduced capital accumulation, and poorer human health. Moreover, data indicate that macroeconomic outcomes have not become any less sensitive to temperature shocks in recent years, pointing to significant adaptation constraints.
- To some extent, sound policies and institutional frameworks, investment in infrastructure, and other adaptation strategies can reduce the damage from temperature shocks in hot countries. Although causal interpretation is difficult, empirical evidence suggests that countries with better-regulated capital markets, higher availability of infrastructure, flexible exchange rates, and more democratic institutions recover somewhat faster from the negative impacts of temperature shocks. Higher temperatures also constrain growth in hot regions of emerging market and developing economies significantly more than in hot regions of advanced economies, which corroborates the importance of development in reducing vulnerability.
- The temperature increase projected by 2100 under a scenario of unmitigated climate change implies significant economic losses for most low-income countries. Under the conservative assumption that weather shocks have permanent effects on the level, rather than the growth rate, of per capita output, model simulations suggest that the per capita GDP of a representative low-income country would be 9 percent lower in 2100 than it would have been in the absence of temperature increases, with the present value of output losses amounting to more than 100 percent of current GDP when discounted at the growth-adjusted rate of 1.4 percent.

Taken together, these findings paint a worrisome picture. Rising temperatures would have vastly unequal effects across the world, with the brunt of adverse consequences borne by those who can least afford it. In all likelihood, most countries will increasingly feel the direct impact of unmitigated climate change, through warming above optimal temperatures, more frequent (and more damaging) natural disasters, rising sea levels, loss of biodiversity, and many other hard-to-quantify effects. In addition, climate change is likely to create economic winners and losers at both individual and sectoral levels, even in countries where the effect might be moderate or positive on average. However, low-income countries will suffer disproportionately from further temperature increases—a global threat to which they have contributed little. And within low-income countries, the poor would likely be the most heavily affected by climate change (Hallegatte and Rozenberg 2017). Having little influence on the future course of climate, how can these countries cope with the challenges they face as temperatures rise?

The findings of this chapter suggest that domestic policies can partially dampen the adverse effects of weather shocks. Improving buffers and strengthening well-targeted social safety nets that can deliver support when needed would help countries smooth some of the instantaneous effects of weather shocks, while policies and institutions that make capital and labor markets more flexible and foster structural economic transformation could help countries recover somewhat faster and reduce their vulnerability to future shocks. Adaptation strategies that reduce specific climate change effects and risks, such as targeted infrastructure projects, adoption of appropriate technologies, and mechanisms to transfer and share these risks through financial markets, could also be part of the toolkit for reducing the economic damage caused by climate change.

But putting in place the right policies will be particularly difficult in low-income countries, which have huge spending needs and limited ability to mobilize the resources necessary for adaptation in a challenging economic environment. In some cases, political uncertainty and security issues exacerbate the challenge. Moreover, even when in place, domestic policies alone cannot fully insulate low-income countries from the adverse consequences of climate change, as higher temperatures push the biophysical limits of these countries' ecosystems, potentially triggering more frequent epidemics, famines, and other natural disasters, along with armed conflict and refugee flows. The international spillovers from these difficult-to-predict effects of climate change could be very considerable.

Climate change is a negative global externality of potentially catastrophic proportions, and only collective action and multilateral cooperation can effectively address its causes and consequences. Mitigating climate change requires radically transforming the global energy system, including through the use of fiscal instruments to better reflect environmental costs in energy prices and promote cleaner technologies as discussed in Box 3.6. Adapting to the consequences of climate change necessitates vast investments, including in boosting infrastructure, reinforcing coastal zones, and strengthening water supply and flood protection (Margulis and Narain 2010; UNEP 2016). The international community will have a key role to play in fostering and coordinating financial and other types of support for affected low-income countries. With advanced and emerging market economies contributing the lion's share to the warming that has occurred so far and is projected to continue, helping low-income countries cope with its consequences is a humanitarian imperative and sound global economic policy. In the future, only continued international cooperation and a concerted effort to stem the man-made causes of global warming can limit the long-term risks of climate change (IPCC 2014; IMF 2015; Stern 2015; Farid and others 2016; Hallegatte and others 2016).

It is important to highlight from the outset the inherent difficulty of quantifying the potential macroeconomic consequences of climate change. Extrapolating from historically observed weather responses of GDP to the long-term effect of global warming is challenging for several reasons.[3] On one hand, such an extrapolation may overstate the impact as governments and other economic agents take ameliorative actions, make investments, or develop new technologies that help populations adapt to persistent changes in climate. On the other hand, the actual impact could be larger if there are nonlinearities in the response as the climate shifts to conditions beyond recent experience.[4] Moreover, the chapter does not separately quantify the effects of natural disasters, whose higher projected frequency may amplify the damages they cause; it does not analyze distributional impacts across sectors and households within countries, which may be quite sizable; nor does it shed light on the consequences of many aspects of climate change, such as a rapid rise in sea levels, ocean acidification, and the like, that have no historical precedent but could have very large macroeconomic consequences.[5] Nevertheless, as long as the Earth continues to warm over the rest of the 21st century in the same pattern as over the past 50 years—a stochastic series of annual shocks along an upward trend—this chapter may provide valuable guidance on climate change vulnerabilities and adaptation needs under the current production technologies and geographic distribution of populations (Dell, Jones, and Olken 2012).

[3]Dell, Jones, and Olken (2014); Carleton and Hsiang (2016); Hsiang (2016); and Lemoine (2017) provide discussions of the conditions under which empirical estimates of the effect of weather shocks based on historical data can shed light on the consequences of climate change.

[4]For example, the historically observed natural year-to-year temperature variability for countries located in the tropics is roughly 0.5°C. The projected increase in temperature for these countries between 2005 and 2100 under the extreme unmitigated climate change scenario is 4.1°C—in other words, more than 8.5 times larger than the current natural variability, implying a totally new climatic regime (see also World Bank 2013).

[5]A large body of literature studies the macroeconomic impact of natural disasters (see, for example, Noy 2009; Cavallo and others 2013; Acevedo 2014; Felbermayr and Gröschl 2014; Cabezon and others 2015; IMF 2016a; IMF 2016b; Gerling, forthcoming; and Gerling, Moreno Badia, and Toffano, forthcoming). The chapter focuses on direct measures of the weather because natural disaster data may suffer from reporting and mismeasurement issues. Mismeasurement could be a particular problem in low-income countries, which typically have lower capacity to accurately evaluate, record, and report damage (Jennings 2011).

Temperature and Precipitation: Historical Patterns and Projections

This section sets the context for the rest of the chapter by summarizing the scientific consensus on how climate and one of its key man-made drivers—greenhouse gas emissions—have evolved over the past century. The section then presents scientists' projected changes for the rest of the 21st century and discusses the link between temperature, precipitation, and weather-related disasters.

Historical Patterns

Global temperatures have increased by roughly 1°C compared with the 1880–1910 average (Figure 3.2). The rise started in earnest in the 1970s, following a large increase in carbon dioxide (CO_2) emissions.[6] 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).

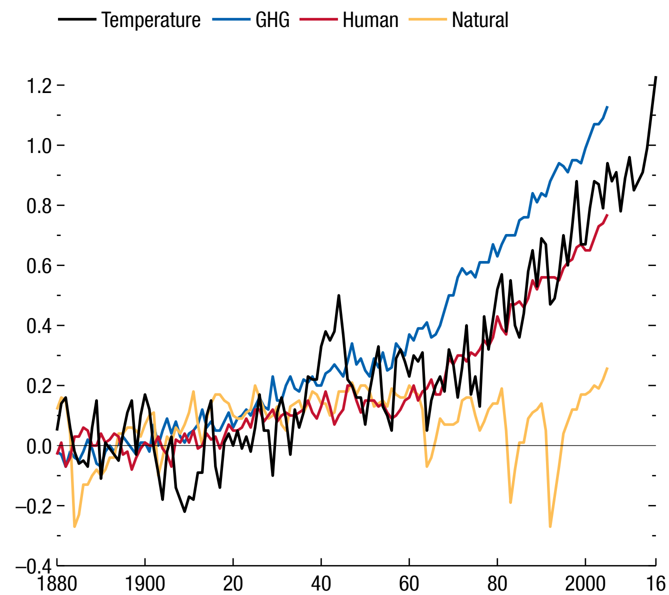
The increase in temperature has occurred in all regions, with the same accelerating trend, starting in the 1970s (Figure 3.3).[7] The median temperature over the first 15 years of this century, compared with the first 15 years of the past century, was 1.4°C higher in advanced economies, 1.3°C higher in emerging market economies, and 0.7°C higher in low-income developing countries. Even though most of the warming occurred in advanced economies, by 2015 the temperature in the median low-income developing country (25°C) was more than twice that of the median advanced economy (11°C).

Other aspects of the climate have also changed appreciably. Since 1900, the global mean sea level has risen by 17–21 centimeters. As with temperature, there has been an increase in the pace at which the sea level is rising: from 0.17 centimeter a year throughout most of the 20th century to 0.32 centimeter a year over the past 20 years (IPCC 2014).

Figure 3.2. Increase in Average Global Temperature and Contributions of Key Factors

(Deviations from 1880–1910 average, degrees Celsius)

According to the Intergovernmental Panel on Climate Change, most of the increase in temperature since 1950 can be attributed to human factors.



Sources: Carbon Dioxide Information Analysis Center; National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies; Roston and Migliozzi (2015); and IMF staff calculations.

Note: The lines present the actual increase in land and ocean surface air temperature relative to 1880–1910 and the increase predicted by different factors. Human factors include land use, ozone emissions, aerosol emissions, and GHG emissions. Natural factors include orbital changes, solar output, and volcanic activity. The contribution of each factor is estimated by "ModelE2" by NASA Goddard Institute for Space Studies. GHG = greenhouse gases.

CO_2 emissions have grown rapidly since the 1950s across all income groups, along with rising incomes and populations (Figure 3.4). However, emissions in low-income developing countries are still a fraction of those in advanced and emerging market economies, in both aggregate and per capita terms. And although advanced economies have managed to contain their overall emissions over the past decade, in per capita terms they still contribute vastly more than the rest of the world.

Projections

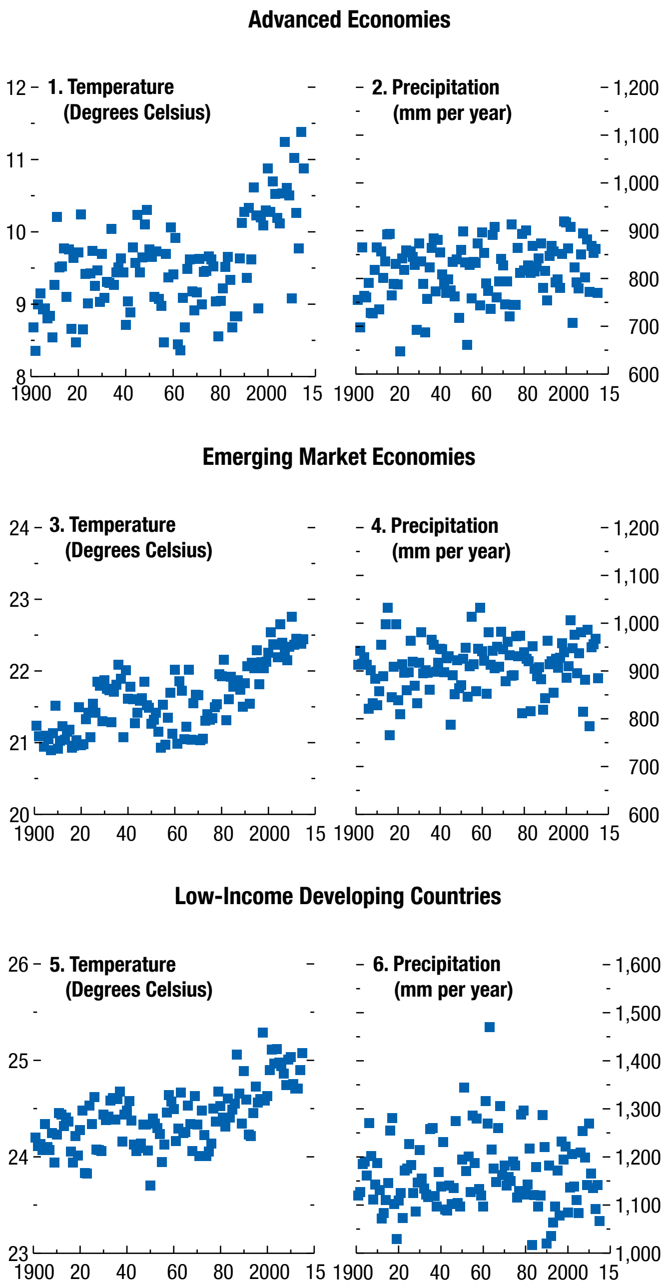
The overwhelming majority of scientists agree that future climate change depends largely on the path of CO_2 emissions, which in turn hinges on demo-

[6]The three most important greenhouse gases, 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.

[7]Trends in precipitation are generally less clear (Figure 3.3, panels 2, 4, and 6). Precipitation has increased somewhat in the northern hemisphere since the 1950s, and average precipitation in low-income developing countries has declined since the 1970s.

Figure 3.3. Temperature and Precipitation across Broad Country Groups

Temperature has risen across all country groups, while precipitation does not exhibit a clear pattern.

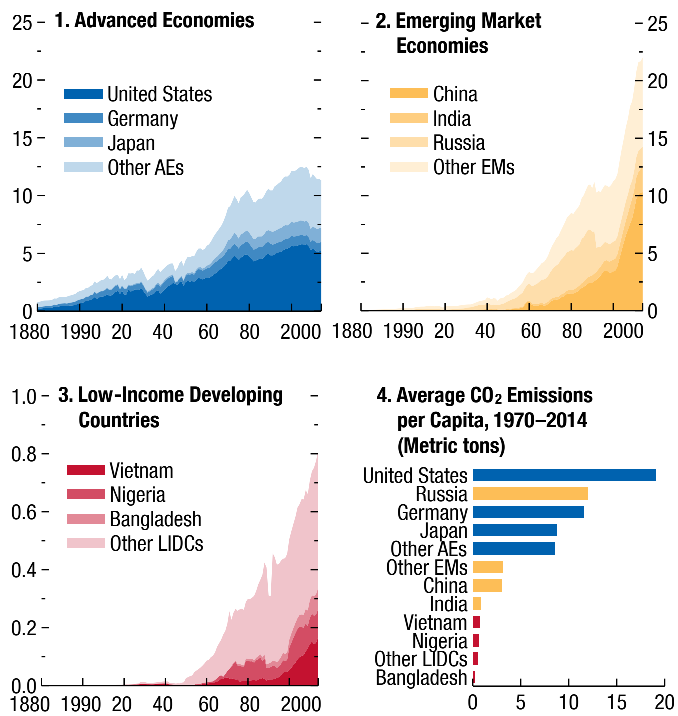


Sources: Climate Research Unit (v. 3.24); and IMF staff calculations.
Note: Terrestrial median annual temperature and precipitation data at grid level are aggregated to the country-year level using 1950 population weights. See Annex 3.1 for data sources and country groupings. mm = millimeter.

Figure 3.4. Annual CO_2 Emissions across Broad Country Groups

(Billion metric tons, unless noted otherwise)

CO_2 emissions have grown rapidly since the 1950s across all income groups, but emissions by low-income developing countries are negligible in both absolute and per capita terms.



Sources: Carbon Dioxide Information Analysis Center; and IMF staff calculations.
Note: AEs= advanced economies; CO_2 = carbon dioxide; EMs = emerging markets; LIDCs = low-income developing countries.

graphic changes, economic development, technological advances, and the vigor with which countries implement mitigation measures.[8] Yet, given the significant buildup and persistence of greenhouse gas concentration in the atmosphere, even with immediate and substantial cuts to current greenhouse gas emissions, temperatures are projected to rise for some time, albeit at a slower pace. The IPCC constructed four possible scenarios, called Representative Concentration Pathways (RCP), using alternative greenhouse gas concentration assumptions to project likely ranges

[8]Surveying 12,000 peer-reviewed scientific papers on climate change, Cook and others (2013) find that 97 percent of the studies expressing a position on the reasons behind global warming agree that it is influenced by man-made causes. See also Cook and others (2016).

of temperatures over the 21st century. The rest of the chapter focuses on two of these scenarios: an intermediate path (RCP 4.5) and an unmitigated path (RCP 8.5), as shown in Figure 3.1, panel 2.[9]

Under the RCP 8.5 scenario of unmitigated climate change, the average global temperature by 2081–2100 could rise by 3.7°C (with a projected range of 2.6°C–4.8°C).[10] Warming would occur all over the globe, with larger increases over the northern hemisphere, where some regions could experience temperatures almost 12°C higher than in 2005 (Figure 3.5). Between 2005 and 2100, the increase for the median advanced economy is projected to be 4.4°C, and 4.5°C for the median emerging market economy and median low-income developing country. Increases are projected to be smaller in absolute terms closer to the equator, but are very significant when set against the historical year-to-year and intrayear variability in temperature observed in those locations. Change in precipitation will vary by region, with dry areas generally expected to become drier and wet regions expected to experience an increase in rainfall.

Under this scenario, the global mean sea level is projected to rise by almost 0.8 meter by the end of the 21st century, exposing coastal areas, including some large population centers, to higher risk of flooding and erosion. Sea level rise will not be uniform across regions—it is projected to be higher than the global mean closer to the equator and less than the global mean at high latitudes (IPCC 2014; World Bank 2013).

It is important once again to stress the large uncertainty surrounding climate change projections. Future emissions depend on many factors that are difficult to predict and, even for the same emission scenario, climate models differ widely in their temperature and precipitation projections (Figure 3.1, panel 2). However, it is precisely this uncertainty and the possibility of fat tails—the probability that catastrophic climate change can occur—that is behind calls for strong mitigation actions to reduce emissions and for adaptation to prepare for significant shocks (Weitzman 2011).

Weather-Related Disasters

As temperatures rise, the risks of extreme weather events, such as floods, droughts, and heat waves, will increase (IPCC 2014). New statistical analysis suggests that projected climate change will likely bring more frequent weather-related disasters—events that cause great damage or loss of life.[11] This likelihood is particularly important for low-income developing countries and small states, which historically have been much more likely, relative to their land area, to experience natural disasters than advanced and emerging market economies (Figure 3.6, panel 1).[12]

Using monthly data from 1990 to 2014 on 8,000 weather-related disasters, a statistical analysis uncovers the historical relationship between the occurrence of a disaster and temperature and precipitation.[13] It then combines the estimated elasticities and the projected monthly temperature and precipitation in 2050 and 2100 under the RCP 8.5 scenario to forecast the likelihood of natural disasters. The results indicate that most disaster types will be more common by the end of the century, across all country income levels. As depicted in Figure 3.6, the frequency of disasters caused by heat waves or tropical cyclones will increase considerably (see Box 3.1, which explores the effect of tropical cyclones on economic activity).[14] Similarly,

[9]The Paris Agreement aims to contain the rise in temperature to less than 2°C (ideally to less than 1.5°C) relative to the preindustrial average, which would require policy efforts beyond those assumed under the RCP 4.5 scenario. Under the RCP 4.5 scenario, 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 relative to 1986–2005 (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). Under the RCP 8.5 scenario, CO_2 emissions grow throughout the 21st century.

[10]Under this scenario, the average increase in population-weighted temperature between 2005 and 2100 across the countries in the sample is projected to be 4.4°C, with the median country experiencing warming of 4.5°C.

[11]The International Disaster Database (EM-DAT) defines a natural disaster as an event in which at least one of the following criteria is met: 10 or more people are reported killed, 100 or more people are reported affected, and either a declaration of a state of emergency or a call for international assistance is made (Guha-Sapir, Below, and Hoyois 2015).

[12]Low-income developing countries and small states, respectively, are five and 200 times more likely to be hit by a weather-related natural disaster than the rest of the world, after controlling for country size.

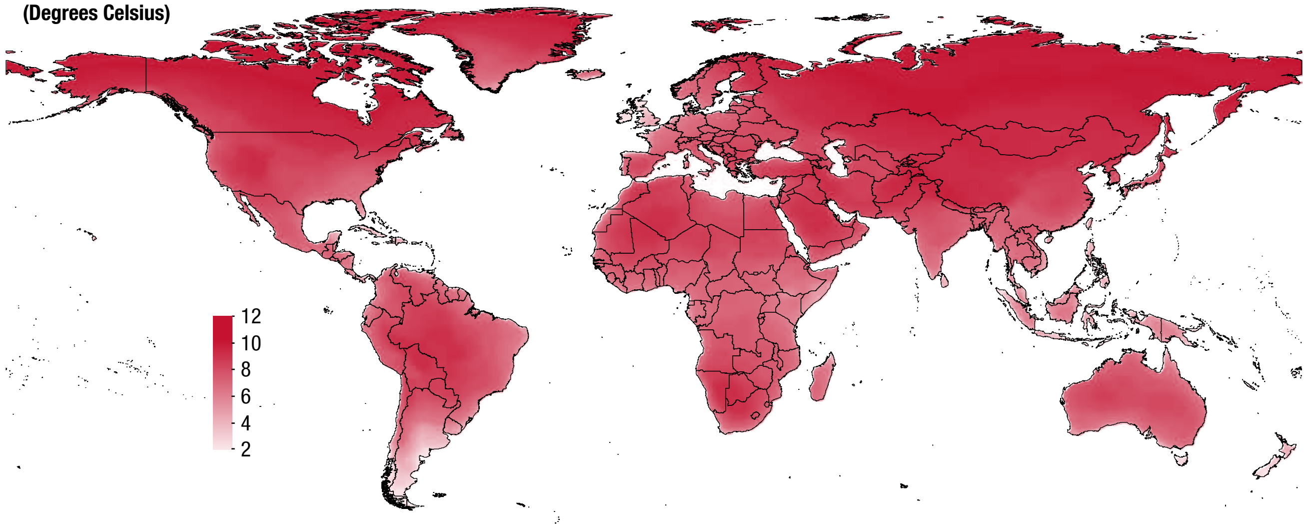
[13]The probability of each disaster type (flood, tropical cyclone, and so on) is estimated using a panel logit with country fixed effects, in which temperature and precipitation are the main explanatory variables. The analysis expands on Thomas and Lopez (2015) by modeling each disaster type separately and relying on monthly rather than annual data. See Annex 3.2 for further details.

[14]Scientists project that the frequency of tropical cyclone storms will decrease, but their strength and intensity will rise in a warmer world (Knutson and others 2010). This could lead to more natural disasters caused by more intense tropical cyclones despite the overall lower frequency of storms.

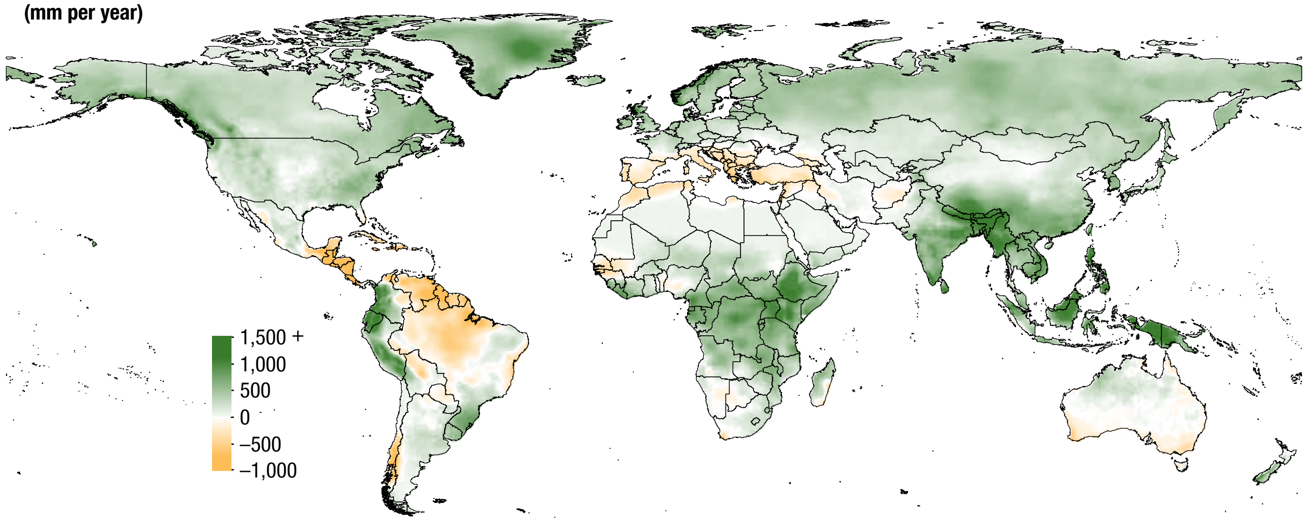
Figure 3.5. Temperature and Precipitation Projections under the RCP 8.5 Scenario

Under the scenario of continued increase in greenhouse gas emissions, temperatures across the globe are projected to rise significantly.

1. Temperature Change between 2005 and 2100 (Degrees Celsius)



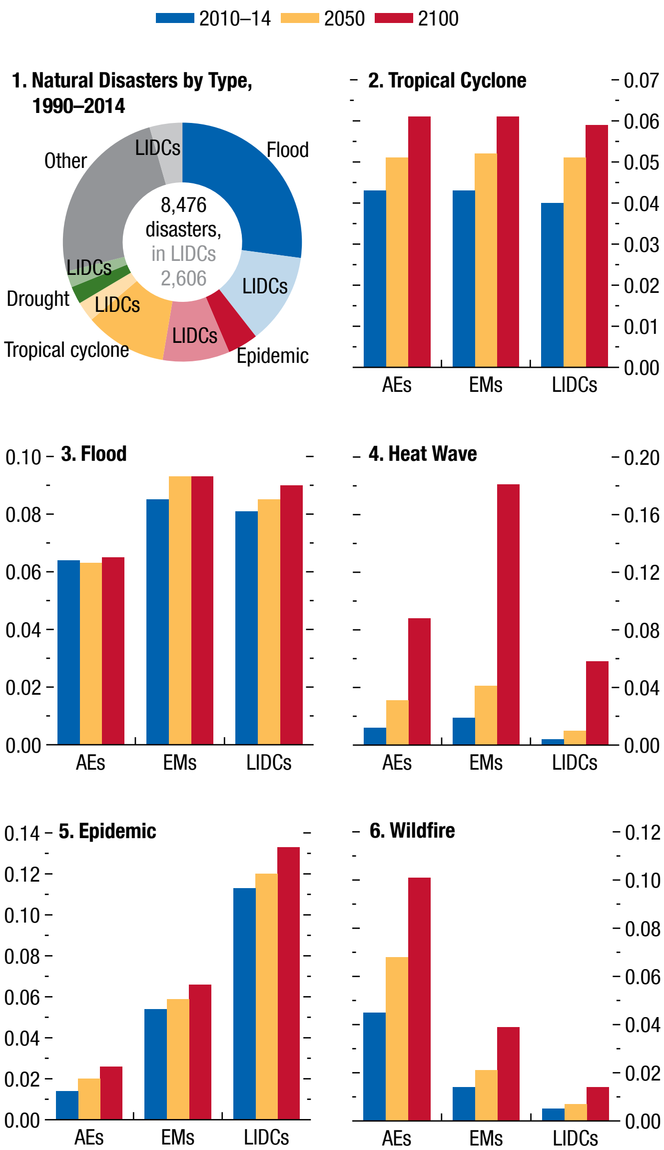
2. Precipitation Change between 2005 and 2100 (mm per year)



Sources: National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP); World Bank Group Cartography Unit; and IMF staff calculations.
Note: The NEX-GDDP data set comprises downscaled climate scenarios for the globe that are derived from the General Circulation Model (GCM) runs conducted under the Coupled Model Intercomparison Project Phase 5 (CMIP5) and for two Representative Concentration Pathways (RCP) greenhouse gas emissions scenarios (4.5 and 8.5). The CMIP5 GCM runs were developed for the Intergovernmental Panel on Climate Change Fifth Assessment Report. The data set includes downscaled projections from the 21 models and scenarios for daily maximum temperature, minimum temperature, and precipitation for 1950–2100. The spatial resolution of the data set is 0.25 degrees (~25 km x 25 km). mm = millimeter.

Figure 3.6. Natural Disasters: Historical and Projected Monthly Probability of Occurrence

Natural disasters, which have historically occurred with greater frequency in low-income developing countries relative to their land area, could become more common by the end of the 21st century under the scenario of continued increase in greenhouse gas emissions.



Sources: International Disaster Database (EM-DAT); and IMF staff calculations.
Note: In panel 1, the colors indicate the different types of natural disasters, with the lighter shades of each color specifying the portion that has occurred in low-income developing countries (LIDCs). Panels 2–6 show the predicted monthly probability of a disaster in 2050 and 2100, based on the Representative Concentration Pathways 8.5 scenario. Most of the predicted probabilities for individual months are not statistically significant, therefore the results should only be interpreted as indicative of the potential increase in the frequency of disasters with climate change. AEs = advanced economies; EMs = emerging markets; LIDCs = low-income developing countries.

floods and epidemics, which mainly affect low-income developing countries, will also become more common. More frequent weather-related disasters, without a corresponding increase in reconstruction capabilities, could amplify the damages they cause because economies may have insufficient time to recover between events (Hallegatte, Hourcade, and Dumas 2007).

The Macroeconomic Impact of Weather Shocks

The design of appropriate policies to cope with climate change requires an understanding of its potential macroeconomic consequences. In the absence of historical experience with climate change that may be relevant for countries today, the analysis in this section builds on existing literature and identifies how annual fluctuations in temperature and precipitation affect macroeconomic performance in the short and medium term. The channels through which macroeconomic effects occur and the changes in the sensitivity of growth to weather shocks are explored, motivated by evidence that higher temperatures constrain per capita GDP growth in countries with hot climates.

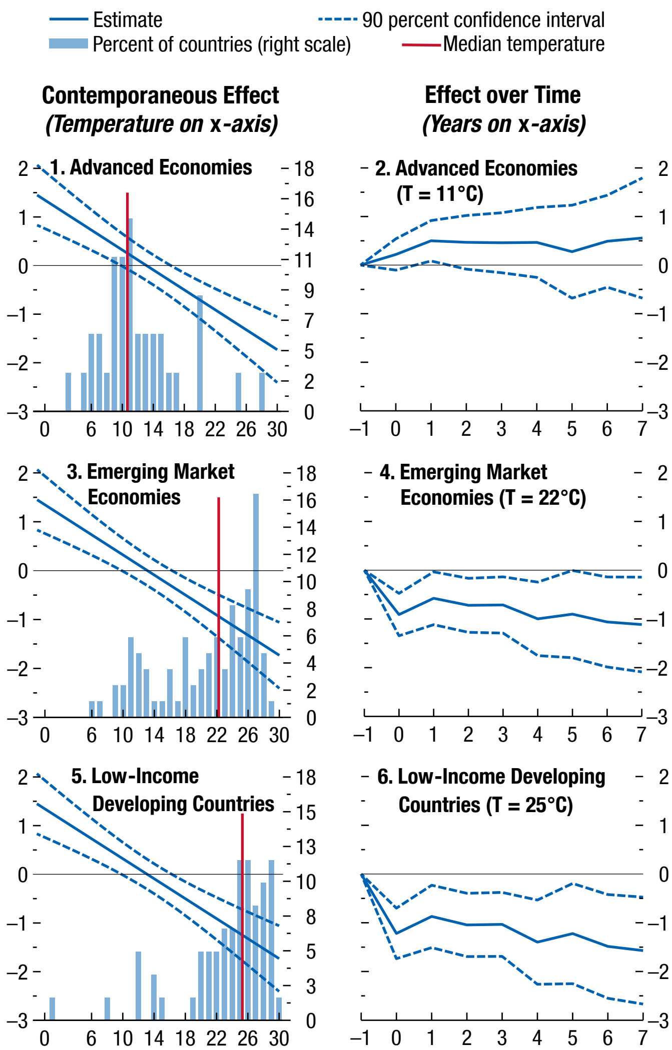
Short- and Medium-Term Effects

To measure the impact of weather shocks, this section examines the historical relationship between weather patterns and economic activity, using the approach of Dell, Jones, and Olken (2012) and Burke, Hsiang, and Miguel (2015a). Similar to these studies, the analysis uses within-country and across-country year-to-year fluctuations in temperature and precipitation to identify the causal effect of weather on aggregate outcomes, both contemporaneously and over the medium term. It builds on these studies by expanding the geographic and temporal coverage of the analysis, examining the effects of weather shocks on a larger set of outcome variables and establishing the robustness of findings to different sources of weather data and alternative, more flexible empirical specifications.

The baseline analysis uses Jordà's (2005) local projection method to trace the impulse response function of real per capita GDP to a weather shock in a sample of more than 180 economies during 1950–2015. Weather is measured as the country's average annual temperature and precipitation, along with the squared terms of temperature and precipitation to account for the global nonlinear relationship between temperature

Figure 3.7. Effect of Temperature Increase on Real per Capita Output
(Percent)

In relatively hot countries, such as most low-income developing countries, an increase in temperature has a negative, statistically significant, and long-lasting effect on per capita output.



Source: IMF staff calculations.
Note: Left-hand-side panels superimpose the contemporaneous effect of a 1°C increase in temperature on per capita output at different temperature levels computed as per equation (3.3) over the distribution of average annual temperatures recorded in 2015 in advanced economies (panel 1), emerging markets (panel 3), and low-income developing countries (panel 5). 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. Right-hand-side panels depict the impulse response of per capita output to a 1°C increase in temperature estimated at the median temperature of advanced economies (panel 2), emerging markets (panel 4), and low-income developing countries (panel 6). Horizon 0 is the year of the shock. T = temperature.

and growth, as demonstrated by Burke, Hsiang, and Miguel (2015a).[15]

The analysis confirms the existence of a statistically significant nonlinear effect of temperature on per capita economic growth, first established by Burke, Hsiang, and Miguel (2015a), in this chapter's substantially larger sample. In countries with high average temperatures, an increase in temperature dampens economic activity, whereas it has the opposite effect in much colder climates. The threshold temperature is estimated to be about 13°C to 15°C (see Annex Table 3.3.1).[16] These results suggest highly uneven effects of warming across the globe (Figures 3.7 and 3.8).

Because most advanced economies are in colder locations, with annual average temperatures close to the threshold, a marginal temperature increase does not materially affect their contemporaneous growth (Figure 3.7, panel 1).[17] Emerging market economies and particularly low-income developing countries tend

[15]Average annual temperature and precipitation are constructed by aggregating weather data at the grid-cell level to the level of the country using the population in each cell as weights to account for differences in population density within countries and capture the average weather experienced by a person in the country (see Annexes 3.1 and 3.3). The empirical approach consists of regressing contemporaneous and future output growth on temperature and precipitation and the squared terms to estimate an impulse response function at various horizons, controlling for country fixed effects, region-year fixed effects, lags and forwards of weather shocks, and lagged growth. See Annex 3.3 for further details.

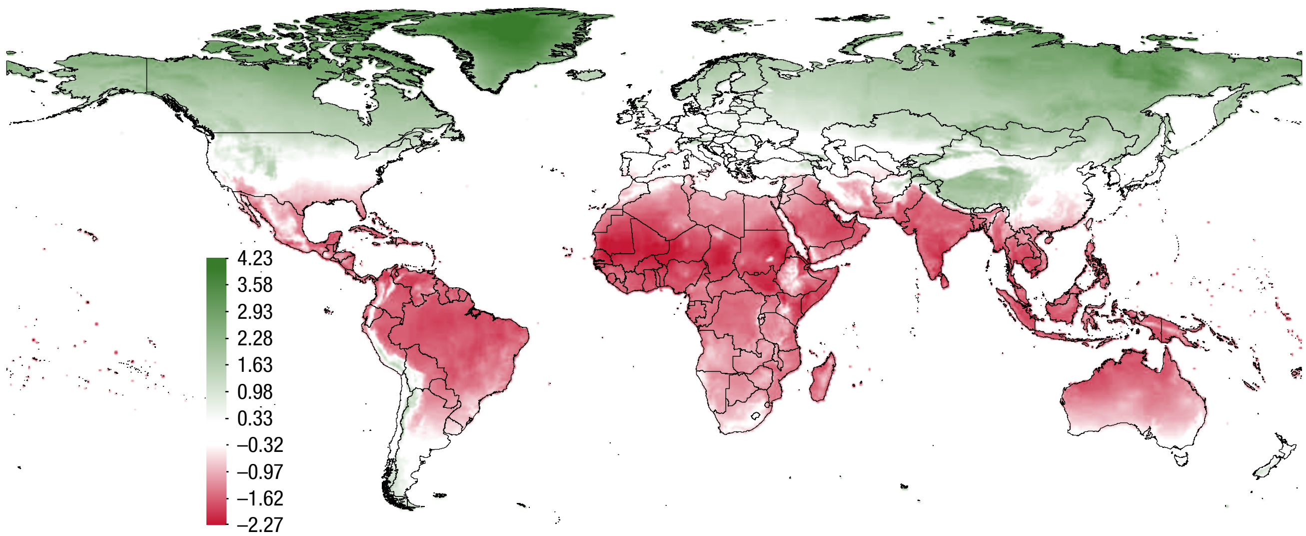
[16]The finding is robust to, among other things: (1) using alternative sources of raw grid-level weather data, (2) aggregating grid-level weather data to country averages with population weights from different decades, (3) estimation through an autoregressive distributive lag specification instead of a local projection method, (4) using country-specific linear and quadratic time trends as opposed to region-year fixed effects, and (5) controlling for the occurrence of natural disasters. The analysis does not find a consistently significant relationship between precipitation and per capita GDP growth, although it uncovers an effect of precipitation on agricultural output (Annex Tables 3.3.1 and 3.3.2).

[17]Even if the effects on overall GDP in these countries are negligible, this may mask large losses and gains, with some sectors facing large investment needs to cope with higher temperatures, rising sea levels, or more damaging disasters. Moreover, the analysis focuses on the macroeconomic effects of a limited set of weather characteristics, namely temperature and precipitation. The negative impact of other aspects of the climate, such as the rise in sea levels or the occurrence of extreme weather events, may be less unequal across broad income groups, as demonstrated in Box 3.1, which documents similar output losses from tropical cyclones across advanced and emerging market economies. The estimates also abstract from potential spillovers to advanced economies from famines, epidemics, social conflicts, and other difficult-to-predict effects of weather shocks in vulnerable economies. Moreover, under the scenario of unconstrained CO_2 emissions, most advanced economies will cross the threshold temperature and would start suffering the negative effects of higher temperatures on economic output (Annex Figure 3.6.1).

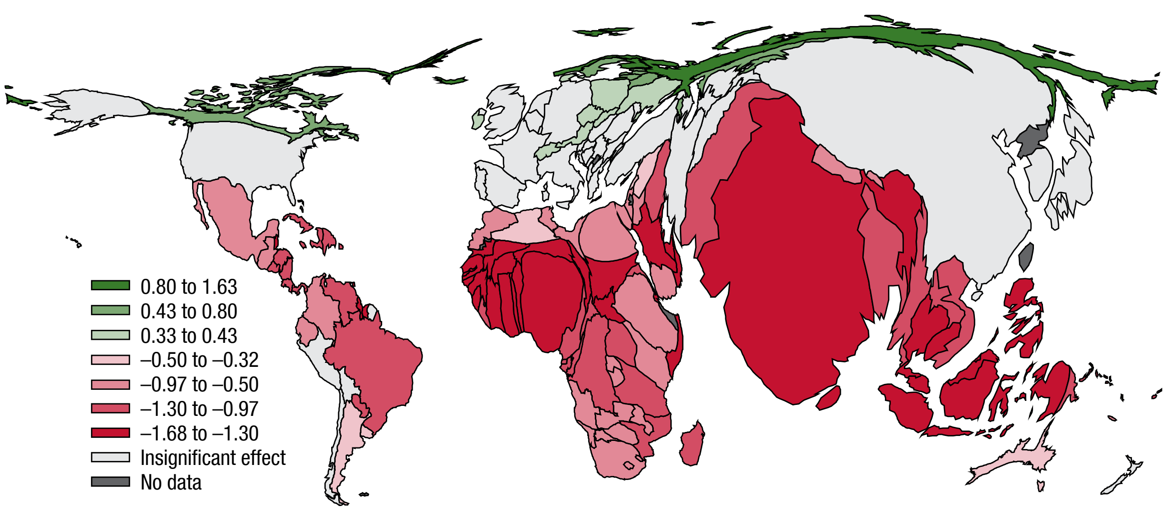
Figure 3.8. Effect of Temperature Increase on Real per Capita Output across the Globe
(Percent)

An increase in temperature has a highly uneven effect across the globe, with adverse consequences concentrated in the parts of the world where the majority of the world's population lives.

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



2. 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



Sources: Natural Earth; ScapeToad; United Nations World Population Prospects Database: the 2015 Revision; World Bank Group Cartography Unit; and IMF staff calculations.
Note: The maps depict the contemporaneous effect of a 1°C increase in temperature on per capita output computed as per equation (3.3). Panel 1 uses 2005 grid-level temperature, while panel 2 uses the recent 10-year average country-level temperature together with estimated coefficients in Annex Table 3.3.1, column (5). In the cartogram in panel 2, each country is rescaled in proportion to its 2015 population. Gray areas indicate the estimated impact is not statistically significant.

to have much hotter climates, and a rise in temperature significantly lowers per capita GDP growth. 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 developing country, with a temperature of 25°C, the effect of a 1°C increase in temperature is even larger: growth falls by 1.2 percentage points (Figure 3.7, panels 3 and 5).[18] And even though countries projected to be significantly 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 and more than 75 percent of the projected global population at the end of the century (Figure 3.8 and Annex Figure 3.3.1).

Does economic activity in countries with warmer climates recover quickly after a rise in temperature? The analysis suggests not. Even seven years after a weather shock, per capita output is 1 percent lower for the median emerging market economy and 1.5 percent lower for the median low-income country (Figure 3.7, panels 2, 4, and 6).[19] A deepening in the shape of the estimated impulse response of output to a temperature shock hints at the possibility of a growth effect (and consequently much larger economic losses from higher temperatures). However, statistically, it is not possible to reject the hypothesis that the contemporaneous and medium-term effects of a temperature shock on per capita output are identical.[20]

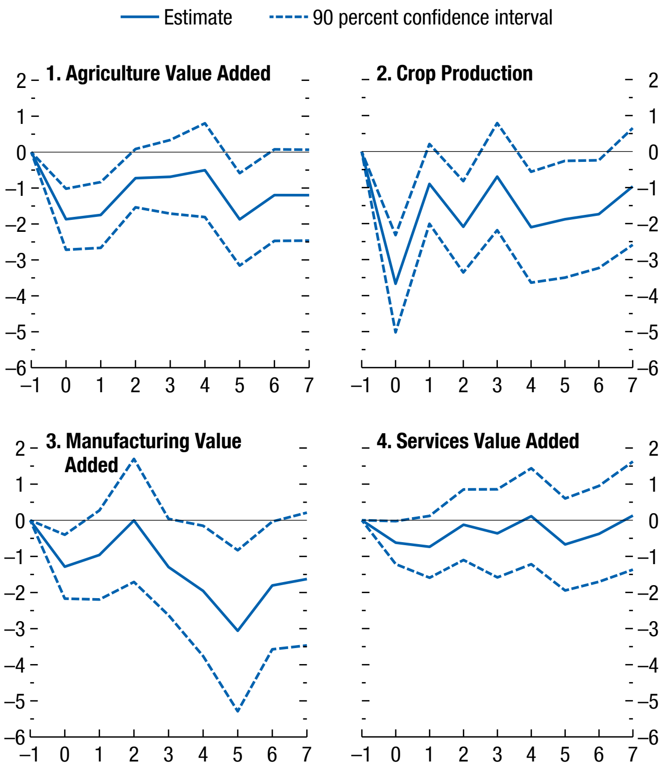
Channels of Impact

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 labor productivity, mortality, health, and conflict.[21] The literature

Figure 3.9. Effect of Temperature Increase on Sectoral Output Estimated at the Temperature of the Median Low-Income Developing Country

(Percent; years on x-axis)

An increase in temperature lowers agricultural output, but also has adverse effects on manufacturing value added in hot countries.



Source: IMF staff 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.

so far has often studied these effects within a specific country or through laboratory experiments; this chapter examines whether these channels are also at work in a cross-country setting. Box 3.1 extends the analysis in this section by examining the macroeconomic effects of another aspect of the weather—tropical cyclones.

The main analysis begins by studying whether weather shocks influence only agricultural production or also affect other economic sectors. As shown

[18]There are also substantial differences in the estimated effects of temperature increases within each broad country group, which reflect the wide distribution of average temperature across countries (Figure 3.7, panels 1, 3, and 5; Figure 3.8).

[19]The persistence of the estimated effects 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. A 1°C degree increase in annual temperature leads to significantly higher temperatures over the subsequent eight years.

[20]Dell, Jones, and Olken (2012) and Burke, Hsiang, and Miguel (2015a) argue in favor of a growth effect, although it is difficult to pin down the precise channel through which weather shocks persistently influence economic growth.

[21]See Dell, Jones, and Olken (2014); Carleton and Hsiang (2016); and Heal and Park (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.

in Figure 3.9, at the temperatures prevailing in the median low-income developing country, agricultural value added and crop production drop with higher temperatures, recover somewhat in subsequent years, and generally remain depressed over the medium term—much as expected and as documented in a large body of work.[22]

However, the analysis also confirms findings that industrial 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, Hsiang, and Miguel 2015a). Only services sector output appears to be sheltered from the weather.

To shed light on the reasons weather shocks affect sectors besides agriculture, the analysis concentrates on how key elements of the aggregate production function—productivity and labor and capital inputs—respond to weather shocks. As in other studies, the analysis aims to capture the net reduced-form effects of weather on various outcomes rather than uncover the potentially complex structural relationships that may exist among these variables.

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.[23] The analysis therefore examines whether higher temperatures in parts of the world that are hot decrease labor 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.[24]

Analysis of sectoral data on value added per worker reveals that, at the temperatures prevailing in the median low-income developing country, productivity of workers in heat-exposed industries falls significantly after a rise in temperature (Figure 3.10, panels 1 and 2). However, labor productivity is unaffected in industries in which work is performed mostly indoors.

Overall productivity may also decline if weather shocks provoke political instability, incite conflict, or undermine governing institutions in other ways. Although a more detailed analysis would be beyond the scope of this chapter, numerous studies document a strong link between weather shocks and these outcomes.[25] Since conflict is one of the key triggers of refugee flows, as discussed in Chapter 1 of the April 2017 *World Economic Outlook* (WEO), weather shocks could result in substantial spillovers to neighboring countries and ultimately to advanced economies through this channel.

Capital Accumulation

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.[26] Using national accounts data, the analysis examines the response of the main components of aggregate demand—gross capital formation, consumption, exports, and imports—to weather shocks within the empirical framework described above. At the tem-

[22]See, among others, Barrios, Bazoumana, and Strobl (2010); Barrios, Bertinelli, and Strobl (2006); Feng, Krueger, and Oppenheimer (2010); Schlenker and Lobell (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 and others (2017) for evidence from the United States. Unlike per capita output, agricultural value added and crop production respond to precipitation, in addition to temperature shocks, with more precipitation generally boosting production. See Annex Table 3.3.2.

[23]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, Deryugina and Hsiang (2014) for evidence from the United States, and Somanathan and others (2017) for recent evidence on labor productivity from India. 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).

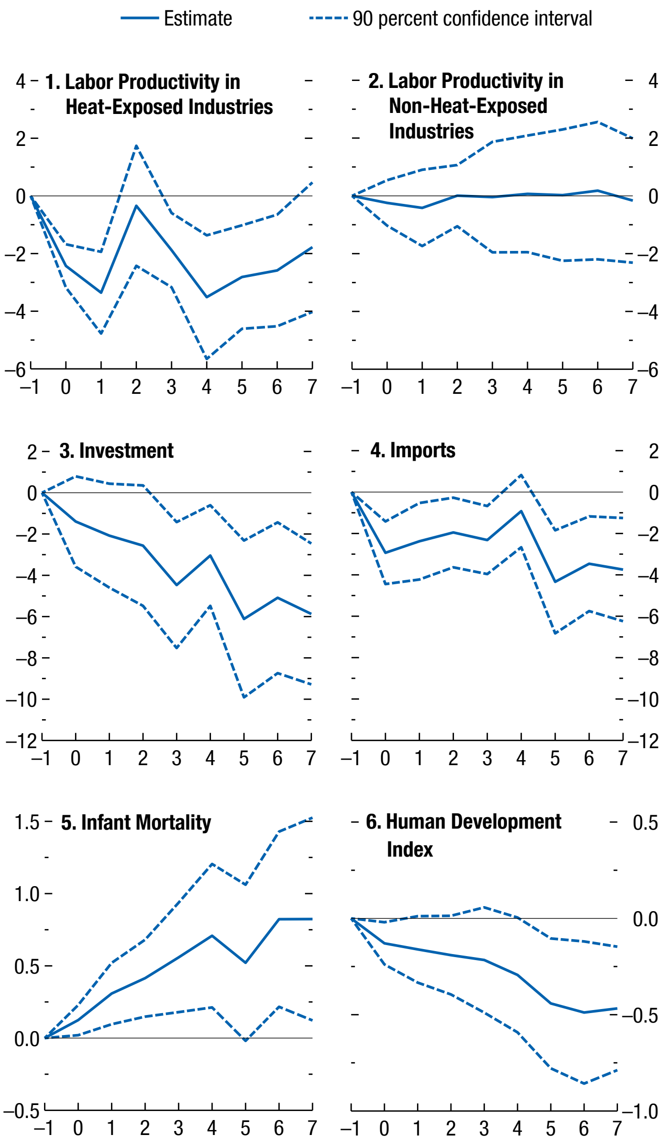
[24]The analysis follows Graff Zivin and Neidell (2014) and uses the National Institute for Occupational Safety and Health definitions of heat-exposed industries. Heat-exposed industries include agriculture, forestry, fishing and hunting, construction, mining, transportation, and utilities, as well as manufacturing in facilities that may not be climate controlled in low-income countries and whose production processes often generate considerable heat.

[25]Burke, Hsiang, and Miguel (2015b) review the literature that links climate to conflict. Forcible removal of rulers has also been linked to fluctuations in climate (Burke and Leigh 2010; Dell, Jones, and Olken 2012; Chaney 2013; Kim 2014), and several historical cases of societal collapse have been compellingly attributed to climate change (Cullen and others 2000; Haug and others 2003; Buckley and others 2010; Büntgen and others 2011).

[26]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.

Figure 3.10. Effect of Temperature Increase on Productivity, Capital, and Labor Input Estimated at the Temperature of the Median Low-Income Developing Country
(Percent; years on x-axis)

In hot countries, an increase in temperature dampens labor productivity in heat-exposed industries, depresses investment and imports, and has damaging health effects.



Source: IMF staff 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).

perature of the median low-income country, all four components respond negatively to a 1°C increase in temperature. However, in the medium term, the effect is most pronounced for investment, which is estimated to be 6 percent lower seven years after the shock (Figure 3.10, panel 3). Imports, which are typically closely tied to investment, also exhibit a significant and long-lasting drop as temperature rises (Chapter 2 of the October 2016 WEO).[27]

Labor Supply

The analysis also reveals that, in hot climates, higher temperatures may reduce (future) labor supply because of their influence on mortality rates (Figure 3.10, panel 5). 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 of numerous studies of links between weather and mortality, prenatal health, and other health outcomes in various countries.[28] The adverse effects on the health and educational attainment of children could be one of the key reasons behind the long-lasting nature of weather's consequences.

Effects over Time

As countries repeatedly face weather fluctuations, it is reasonable to expect them to take measures that lessen the impact of temperature shocks on the economy. However, the analysis does not find any obvious evidence of such adaptation over the past 60 years. Estimates of the response of per capita output

[27]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 and others 2016).

[28]Deschênes (2012) and Guo and others (2014) provide comprehensive reviews of the literature on the link between temperature and mortality and health. See, for example, Deschênes and Greenstone (2011), Barreca (2012), and Barreca and others (2016) for evidence from the United States; Kudamatsu, Persson, and Strömberg (2012) for evidence from a subset of African countries; and Burgess and others (2014) for evidence from India. Carleton (2017) documents a significant increase in suicide rates when higher temperatures threaten agricultural yields in India. Deryugina and Hsiang (2014), Graff Zivin and Neidell (2014), Park (2016), and Somanathan and others (2017) find a direct effect of higher temperature on labor supply and productivity.

to temperature shocks over rolling 20-year periods suggest that the relationship between the two variables has remained constant (Figure 3.11).[29] The reasons behind this apparent lack of adaptation are not well understood, but high costs, limited access to credit for financing adaptation, insufficient information about the benefits of adaptation, limited rationality in planning for future risks, and inadequate access to technology are likely constraints, as discussed in Carleton and Hsiang (2016).

Coping with Weather Shocks and Climate Change

This section examines how policies, institutions, and other country characteristics can mitigate the adverse consequences of temperature shocks and climate change. It begins by discussing the toolkit available to policymakers and private agents with which to cope with weather shocks. It then presents illustrative evidence of the extent to which, historically, some policies (along with the overall level of development) have shaped the link between macroeconomic performance and temperature shocks. The empirical evidence is complemented in Box 3.2 by dynamic general equilibrium model scenarios of the response of macroeconomic aggregates to weather shocks under various proxies for relevant policies. Case studies of specific adaptation strategies occupy Boxes 3.3 and 3.4. The section also examines migration as a response to persistent changes in climate as adaptation strategies reach their limits. Finally, the role of international cooperation in supporting countries' efforts to cope with weather shocks and climate change is discussed.

A Toolkit

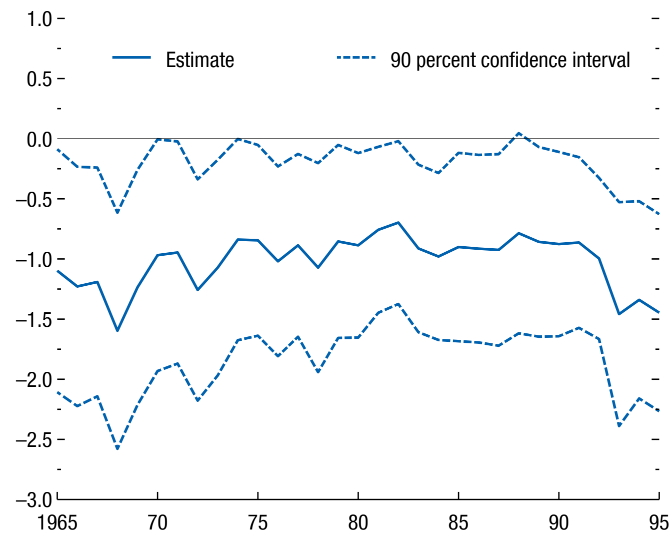
To structure the discussion, this subsection lays out a toolkit of possible domestic policy actions and private choices that may help insulate economic activity

[29]Studies reveal large differences in the ability of individual sectors to adapt to specific weather shocks. For example, Hsiang and Narita (2012) and Hsiang and Jina (2014) find that countries more frequently exposed to tropical cyclones experience less damage, which suggests that they have learned to cope with these extreme events. Mortality caused by high temperatures has declined significantly over time with the introduction of air-conditioning in the United States (Barreca and others 2016). But there is little evidence of declining sensitivity of agricultural yields (Burke and Emerick 2016) or overall output (Dell, Jones, and Olken 2012; Deryugina and Hsiang 2014; Burke, Hsiang, and Miguel 2015a) to temperature fluctuations.

Figure 3.11. Effect of Temperature Increase on Real per Capita Output Estimated at the Temperature of the Median Low-Income Developing Country over Time

(Percent; years on x-axis)

The contemporaneous effect of temperature shocks on per capita output has remained relatively constant over time.



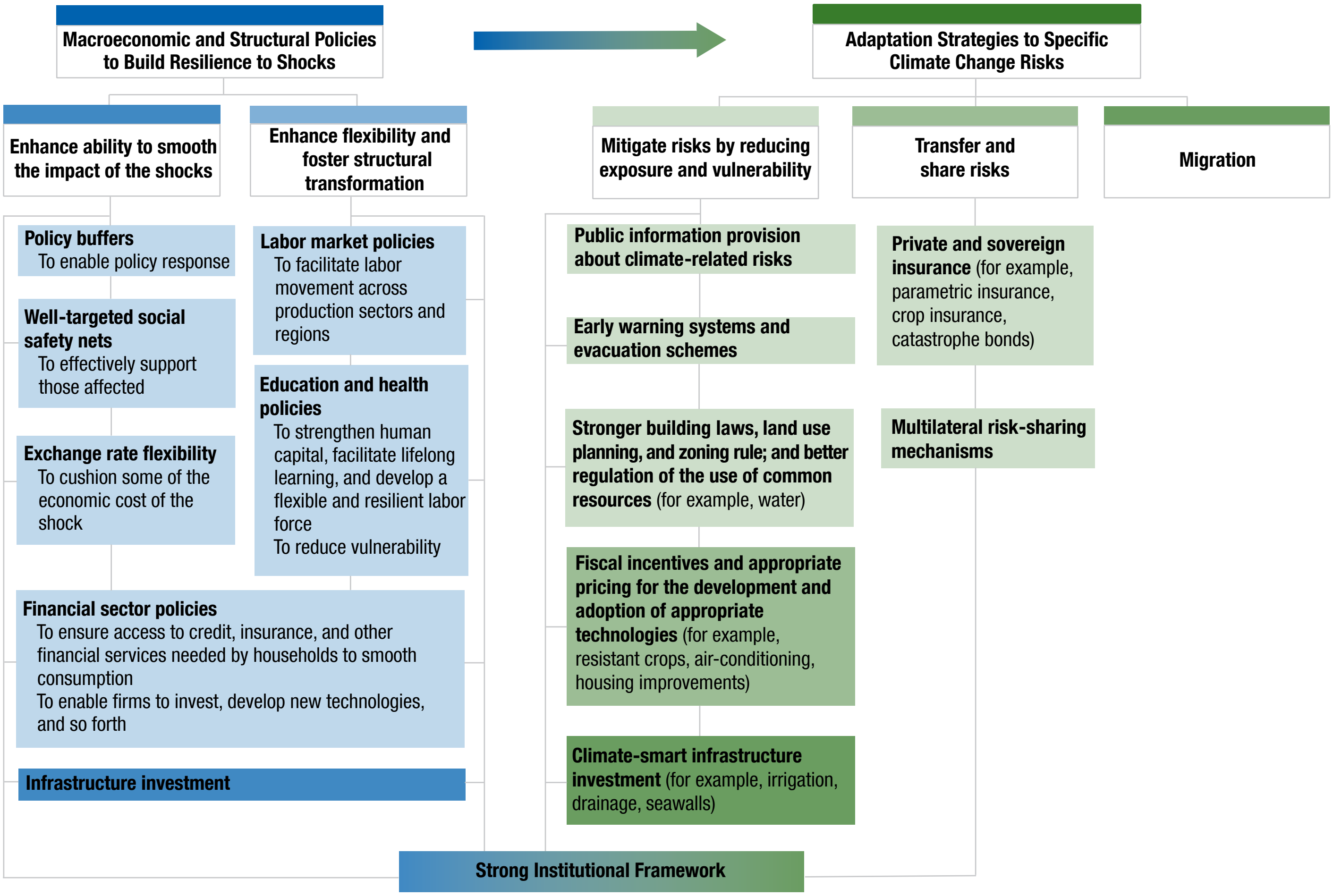
Source: IMF staff calculations.

Note: The figure depicts the effect of a 1°C increase in temperature at horizon 0 estimated at the median low-income developing country temperature (25°C), over a 20-year rolling window. Each point estimate is for a period (t, $t + 20$).

from weather shocks and from the risks that accompany climate change (Figure 3.12).

Fluctuations in weather can be viewed as one of many shocks that affect macroeconomic performance. As such, their consequences could be attenuated by general macroeconomic and structural policies and institutions that enhance countries' ex ante and ex post resilience to shocks. While priorities will vary depending on each country's specific circumstances and weather-related threats, policies may include those that seek to limit the short-term impact when shocks occur, help the economy recover faster, and reduce vulnerability to future shocks. Policies reinforce each other to achieve these goals. For example, countries with buffers (fiscal and monetary space, large international reserves, access to foreign aid) and well-targeted social safety nets may be better placed to deliver support to people affected by weather shocks, thus smoothing consumption in the short term. Adjusting to weather shocks and climate change will likely require reallocating people and capital across sectors and regions as production and trade patterns shift. Policies and institutions that

Figure 3.12. Coping with Weather Shocks and Climate Change: A Toolkit



Source: IMF staff compilation.

facilitate the needed reallocation, such as those that ensure access to finance, labor market flexibility, and investment in human capital and infrastructure, could speed up recovery and foster the structural transformation necessary to reduce vulnerability.[30]

Mitigating the risks associated with climate change will also require some very specific adaptation policies to help countries reduce their exposure and vulnerability to climatic events. Once the key climate change risks are identified for a particular location, both "soft" and "hard" adaptation measures can be applied (Hallegatte 2009). Soft measures may include strengthening public information provision, building codes, and land use and zoning laws, and devising warning and evacuation systems, along with targeted incentives for climate-related technologies (such as air-conditioning) and transferring and sharing risks related to weather events (such as natural disasters, which may increase in frequency) through financial markets. Hard measures may include investment in climate-smart infrastructure, such as retrofitting properties and building (or upgrading) irrigation or drainage systems, building seawalls, and the like.[31] Appropriate adaptation measures are highly specific to the climate-related risks in

[30]The classification of policies presented in Figure 3.12 is rather loose. Greater financial access could help farmers both smooth consumption when higher temperatures damage crops and invest in the technology needed to prevent future damage (such as buying heat-resistant seeds).

[31]See Hallegatte (2009); Hallegatte, Lecocq, and de Perthuis (2011); IPCC (2014); Cabezon and others (2015); OECD (2015a); Farid and others (2016); Hallegatte and others (2016); IMF (2016a); and IMF (2016b) for a comprehensive discussion of various climate change adaptation strategies.

each location and national circumstances; the infrastructure requirements for a flood-prone area would be vastly different from those of an area that is frequently exposed to droughts. This specificity, together with lack of comparable data on adaptation measures, precludes cross-country empirical analysis. Case studies of adaptation strategies, however, could prove insightful and are presented in Box 3.3. Box 3.4 discusses the role of financial markets in sharing and transferring weather-related risks.

Important synergies exist between general macroeconomic and structural policies and specific adaptation strategies: economic and institutional development will likely strengthen a country's capacity to cope with climate change and to invest in specific adaptation strategies. For example, stronger institutions will make enforcement of soft measures more effective, while fiscal space will enable the investment in needed infrastructure. Conversely, some adaptation strategies, such as efficient water use, climate-resilient housing, or activity diversification could facilitate development even in the absence of climate change (Farid and others 2016).

Finally, as adaptation strategies reach their limits, economic agents could respond to persistent changes in climate and the associated loss in income by relocating geographically.

The Role of Domestic Policies and Institutions: Empirical Evidence

To study the extent to which macroeconomic and structural policies and country characteristics mute the effect of weather shocks, the analysis extends the empirical approach described above. It does so by allowing the response of per capita output to weather shocks to vary with various proxies for these policy and institutional settings, which are included one at a time in the analysis.[32] It is important to emphasize that, whereas fluctuations in temperature and precipitation are truly exogenous, which allows their causal impact to be identified, variations in policies and institutions across countries and over time are not. Accordingly, estimated correlations should be interpreted as being merely suggestive of causal impact.

The results suggest that having the right policies and institutions in place may help attenuate the effects of temperature shocks, to some extent. The instantaneous effect of a temperature shock is slightly smaller in countries with lower public debt, higher inflows of foreign aid, and greater exchange rate flexibility. The presence of monetary buffers (proxied by having below double-digit inflation) or international reserves makes no notable difference (Figure 3.13). However, the extent of attenuation that buffers provide is estimated to be small and short lived.

The evidence is somewhat more compelling for structural policies and country characteristics that are typically deemed important for easing sectoral reallocation of factors of production and structural transformation in general. Although the uncertainty surrounding the empirical estimates is often very large, the medium-term adverse effect of a temperature increase appears to fade when domestic and international financial markets are better regulated, the exchange rate is flexible, infrastructure is widely available, democratic institutions are strong, and the distribution of income is fairly even—that is, in more-developed economies (Figure 3.14).

Patterns uncovered in the data broadly mirror simulations of a dynamic structural general equilibrium model, which can properly isolate the causal effects of the availability of buffers, costs of capital adjustment, quality of institutions, and investment in adaptation strategies (Box 3.2). They are also in line with the empirical findings that show less damage from extreme weather events and natural disasters in countries where exchange rates are flexible, financial services are readily available, and institutions are strong.[33,34]

[32]More specifically, the estimated specification augments equation (3.2) to include an interaction term between the weather shock and the policy variable. For simplicity, the sample is restricted to countries with average temperature exceeding 15°C, in which an increase in temperature has a statistically significant linear negative impact on economic activity. See Annex 3.3 for further details.

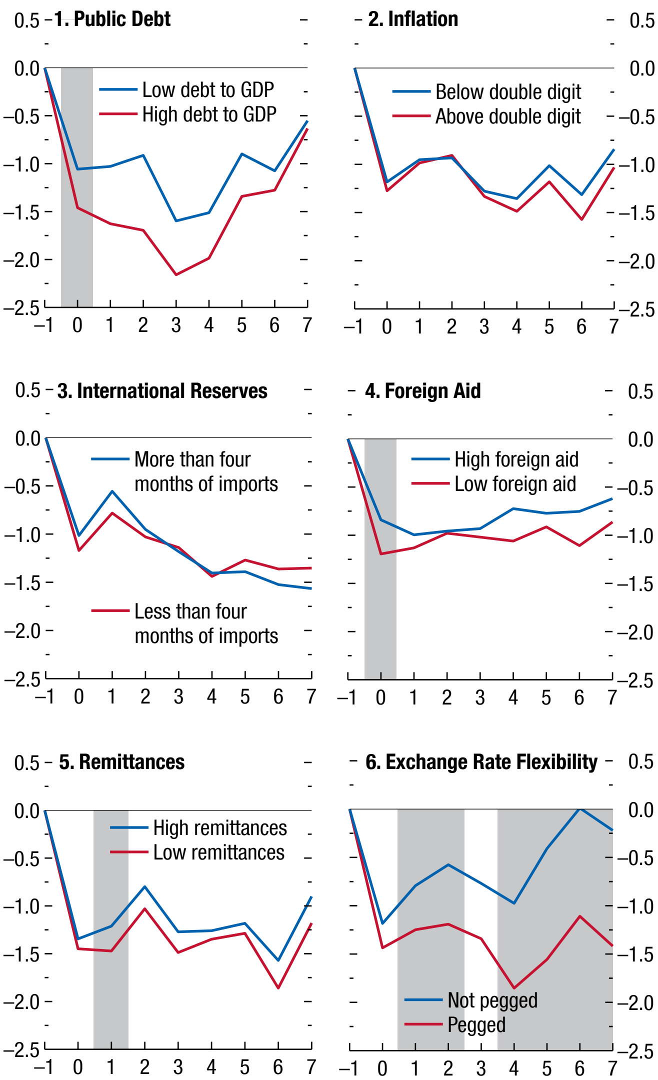
[33]See Kahn (2005); Noy (2009); McDermott, Barry, and Tol (2013); Burgess and others (2014); and Felbermayr and Gröschl (2014) for the role of financial development, and Von Peter, Dahlen, and Saxena (2012); Breckner and others (2016); and Lee, Villaruel, and Gaspar (2016) for the role of insurance penetration. Kahn (2005), Noy (2009), and Felbermayr and Gröschl (2014) find evidence for the role of institutions, and Ramcharan (2009) examines the role of exchange rates in reducing damage from extreme weather events and natural disasters.

[34]Two studies make a compelling case for the importance of sectoral reallocation in alleviating output losses from climate change. When quantifying the effects of climate change on agricultural markets using micro data from 1.7 million fields around the world, Costinot, Donaldson, and Smith (2016) find that the welfare losses would be three times larger if farmers were unable to switch production in response to changing climatic conditions and comparative advantage. In an empirical study, Colmer (2016) establishes that labor movements from agriculture into manufacturing in India can significantly offset the aggregate economic losses associated with weather-driven changes in agricultural productivity.

Figure 3.13. Role of Policy Buffers

(Percent; years on x-axis)

There is some suggestive evidence that the contemporaneous effect of temperature on per capita output is marginally lower in countries with lower public debt, greater foreign aid inflows, and flexible exchange rates.

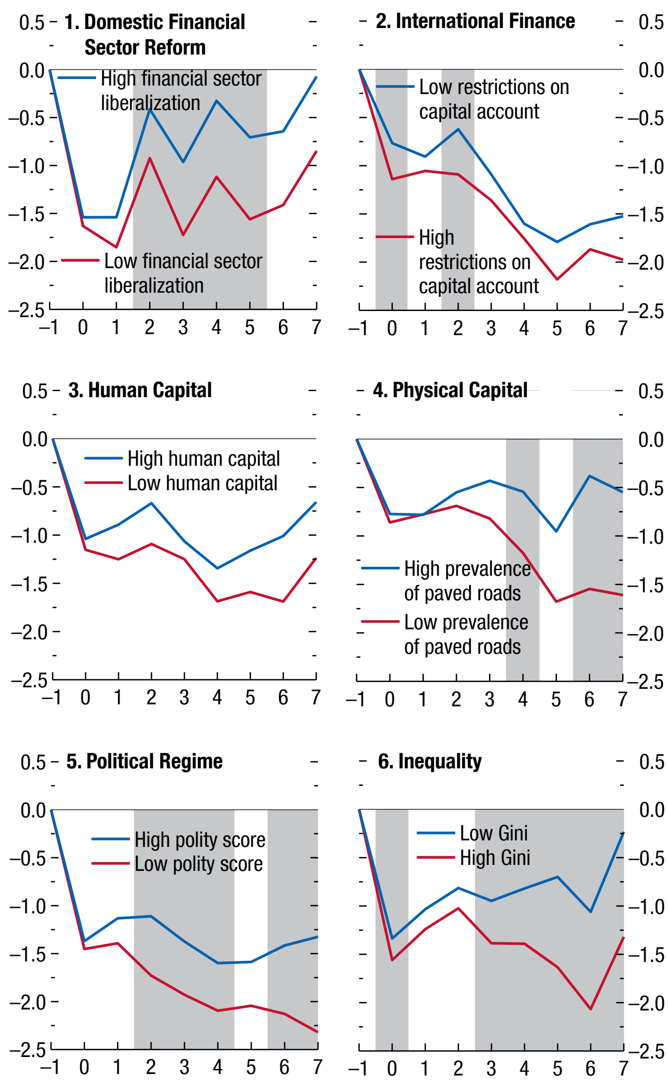


Source: IMF staff calculations.
Note: The panels depict how the effect of a 1°C increase in temperature on per capita output in the sample of countries with average temperature exceeding 15°C varies with the empirical proxy of a policy buffer. Horizon 0 is the year of the shock. Gray areas indicate that the blue and red lines are significantly different from each other at the 15 percent level. See Annex 3.3 for the exact definition of policy variables.

Figure 3.14. Role of Structural Policies and Institutions

(Percent; years on x-axis)

There is some suggestive evidence that the medium-term effect of an increase in temperature on per capita output is marginally lower in countries with better-regulated financial markets, greater physical capital, more democratic institutions, and lower income inequality.



Source: IMF staff calculations.
Note: The panels depict how the effect of a 1°C increase in temperature on per capita output in the sample of countries with average temperature exceeding 15°C varies with the empirical proxies of structural policies and institutional settings. Horizon 0 is the year of the shock. Gray areas indicate that the blue and red lines are significantly different from each other at the 15 percent level. See Annex 3.3 for the exact definition of policy variables.

An alternative approach to assessing whether development more broadly reduces vulnerability to weather shocks takes advantage of subnational cross-country 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. However, some of the larger advanced economies, such as the United States, span several climate zones.[35] This within-country geographic heterogeneity makes it possible to compare whether economic activity in the "hot" states or provinces of advanced economies responds to a temperature increase in the same way as economic activity does in states or provinces of emerging market and developing economies with a similar average temperature. Indeed, analysis suggests that temperature shocks hurt hot areas in emerging market and developing economies significantly more than those in advanced economies (Figure 3.15). Thus, economic development seems, to some extent, to insulate countries from the vagaries of the weather.[36]

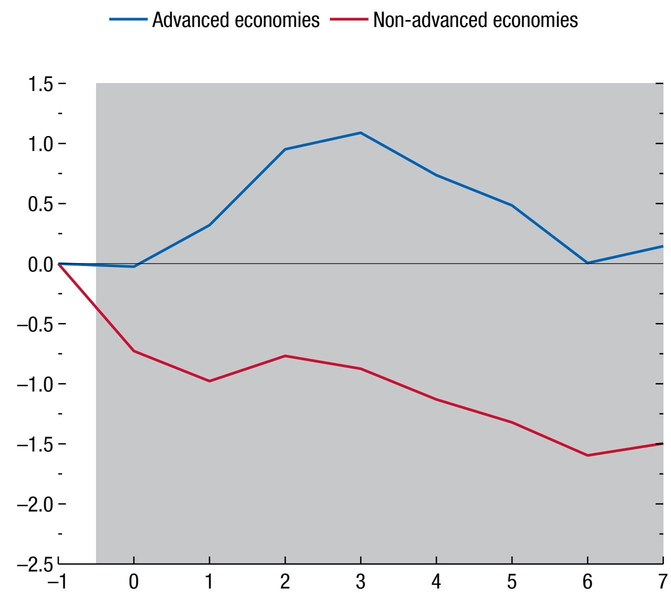
The Role of Migration

Migration is another possible adaptation strategy for households hurt by weather shocks and persistent changes in climate—one with important cross-border spillovers. Theoretically, the impact of weather shocks on migration is ambiguous (see Dell, Jones, and Olken 2014). Although lower incomes, safety concerns, and physiological discomfort are powerful incentives to relocate, the adverse income effect of weather shocks may undermine households' ability to pay for transport and other relocation expenses (Bryan, Chowdhury, and Mobarak 2014; Carleton and Hsiang 2016).[37] Several empirical studies have documented adaptation to weather shocks and natural disasters through migration within country borders.[38] Evidence of international migration responses is scarcer and typically focuses on flows from individual countries.[39]

The analysis builds on Cattaneo and Peri (2016) and examines whether weather shocks and natural

Figure 3.15. Role of Development: Evidence from Subnational Data
(Percent; years on x-axis)

The adverse effect of an increase in temperature on output is more pronounced in non-advanced economies.



Source: IMF staff calculations.
Note: The figure depicts how the effect of a 1°C increase in temperature in the sample of states or provinces with average temperature exceeding 15°C varies with an indicator of whether the state or province is located in an advanced economy. Horizon 0 is the year of the shock. Gray area indicates that the blue and red lines are significantly different from each other at the 15 percent level.

[35]Average annual temperatures in the US states of Maine and Texas are about 7°C and 21°C, respectively.

[36]Data constraints prevent the identification of 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 given that 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, and the like).

[37]Lack of knowledge and uncertainty about the risks caused by slowly changing climate conditions (Lee and others 2015) as well as the provision of government assistance to disaster-prone areas may also result in minimal behavioral change (Baez and others 2017).

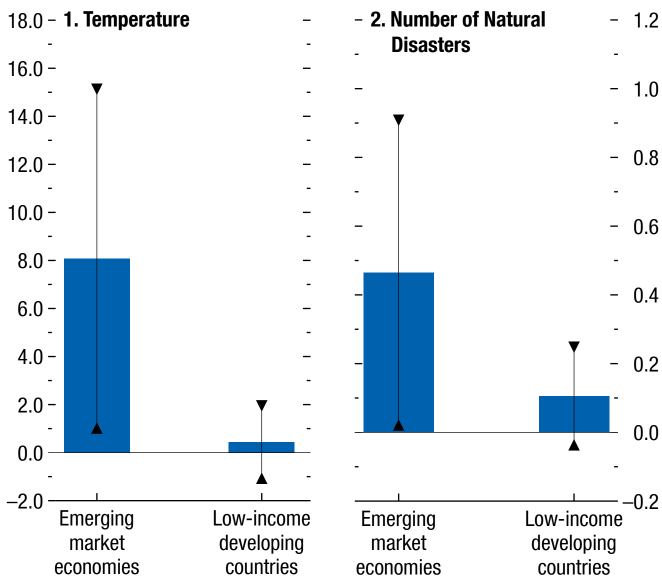
[38]See Gray and Mueller (2012b) for evidence from Bangladesh; and Boustan, Kahn, and Rhode (2012); Feng, Oppenheimer, and Schlenker (2012); Hornbeck (2012); and Hornbeck and Naidu (2014), among others, for evidence from the United States. Deryugina (2011), on the other hand, finds no population response in the 10 years following a hurricane landfall in the United States, but documents a substantial increase in government transfer payments.

[39]Munshi (2003), for example, finds that more migrants move from Mexico to the United States when rainfall is lower in a given Mexican community—a pattern also confirmed by Feng, Krueger, and Oppenheimer (2010). Country-specific evidence also includes Ethiopia (Gray and Mueller 2012a), Indonesia (Bohra-Mishra, Oppenheimer, and Hsiang 2014), Pakistan (Mueller, Gray, and Kosec 2014), and Syria (Kelley and others 2015). Barrios, Bertinelli, and Strobl (2006) and Marchiori, Maystadt, and Schumacher (2012) provide evidence from several countries in sub-Saharan Africa.

Figure 3.16. Effect of Temperature and Natural Disasters on International Migration

(Percentage points of origin country's total population)

Among the sample of countries with average temperature exceeding 15°C, an increase in temperature and greater incidence of natural disasters induce migration, but only from non-low-income developing countries.



Source: IMF staff calculations.
Note: Estimates from a panel regression of the effects of a 1°C increase in 10-year average temperature and number of natural disasters on the share of emigrants. See Annex 3.4 for further details on the data, specification, and estimation. Vertical lines denote 90 percent confidence intervals.

disasters trigger emigration.[40] The findings suggest that a rise in temperature and greater incidence of weather-related disasters induce emigration, but only from countries where people can generally afford to leave, which confirms Cattaneo and Peri's (2016) results (Figure 3.16; Annex Table 3.4.1). Households in low-income developing countries, which tend to have limited access to savings and credit, appear trapped by weather-induced income shocks (see Black and others 2011; Chen and others 2017). This interpretation is consistent with the findings of Hallegatte and others (2016) that the poorest households in low-income countries tend to be the most exposed and vulnerable to climate change. These are also precisely the households with the fewest resources available to finance relocation.

Substantial migration flows, potentially spilling across country borders, could arise if climate change leads to a significant rise in sea levels. Hundreds of millions of people in low-lying areas could become vulnerable to flooding, forcing them to abandon their homes and relocate (Usery, Choi, and Finn 2007, 2009). In the United States alone, more than 4 million people living in coastal areas could be affected if oceans rise the 80 centimeters the IPCC projects by 2100 under the unmitigated climate change scenario. If the rise in sea levels is twice as much, the affected population would exceed 13 million (Hauer, Evans, and Mishra 2016).

International Support

Climate change is a global externality, and countries will not be able to deal with its causes or its consequences on their own. Both equity and efficiency arguments call for active support from the international community in helping low-income countries plan, fund, and implement adaptation measures to cope with the consequences of climate change without compromising developmental objectives. On equity grounds, low-income countries have contributed only marginally to greenhouse gas emissions, yet they are the most vulnerable to their harmful consequences, as this chapter demonstrates. On efficiency grounds, requiring countries that have and/or are currently contributing substantially to the atmospheric greenhouse gas concentration to bear some of the adaptation costs of low-income countries will help offset polluters' failure to fully internalize the cost of greenhouse gas emissions. And while the benefits of adaptation are largely domestic, successfully coping with weather shocks and climate change could avert significant cross-border spillovers, for example by stemming climate-induced population migration.

Support from the international community in the form of concessional climate finance will be crucial to mobilize the resources necessary to build resilience to climate change in low-income countries (see Box 3.6). The commitment by advanced economies to jointly contribute $100 billion a year by 2020 for mitigation and adaptation in developing economies, which was further strengthened by the 2015 Paris Agreement,

[40]Focusing on the sample of countries with average annual temperature of at least 15°C, as in the section titled "The Role of Domestic Policies and Institutions: Empirical Evidence," the analysis relates the share of emigrants from a country to its average temperature, precipitation, and incidence of natural disasters over a 10-year period, controlling for time-invariant country characteristics and global and region-specific decadal shocks. See Annex 3.4 for further details.

is an important step in that regard.[41] In addition to financial assistance, the transfer of appropriate adaptation and clean technologies to low-income countries can further enhance their efforts to cope with climate change by improving access to state-of-the-art technology, skills, and knowledge. Several initiatives under the United Nations Framework Convention on Climate Change have promoted the international exchange of knowledge related to good practices in adaptation (such as the Adaptation Learning Mechanism), which can be integrated into national and local plans. Multilateral risk-sharing mechanisms, such as the Caribbean Catastrophic Risk Insurance Facility and the African Risk Capacity, can also help countries with emergency response in the immediate aftermath of a disaster, as discussed in Boxes 3.3 and 3.4.

Cognizant of the challenges posed by climate change, the IMF, among other international financial institutions, offers direct technical and financial support to small states and other countries that are vulnerable to weather conditions. To foster adaptation, it provides policy advice and capacity building on how to enhance macroeconomic and risk management frameworks, determine the appropriate balance between self-insurance and risk transfer, and strengthen investment and growth to build resilience.[42] The IMF has also increased vulnerable countries' annual access limits under the Rapid Credit Facility and Rapid Financing Instrument to provide rapid assistance to countries with urgent payment needs, including as a result of natural disasters (IMF 2016b).

Long-Term Effects of Temperature Increase—A Model-Based Approach

Empirical work in this chapter so far has assessed the macroeconomic effects of weather shocks in the short and medium term. This section incorporates these estimates into a dynamic general equilibrium model to shed light on the potential long-term effects of temperature increases on GDP, investment, and public debt for a representative small open low-income country. The model also highlights the role that structural transformation of low-income countries (that is, making the transition from agriculture to a more services-based economy) could play in attenuating the impact of climate change. Box 3.5 complements the analysis by reviewing the evidence on the long-term effects of historical climate on economic performance.

Simulations are based on the Debt, Investment, and Growth (DIG) model of Buffie and others (2012), which captures aspects pertinent to low-income countries—such as low public investment efficiency and high capital adjustment costs—and can be extended easily to incorporate the structural transformation process.[43] These aspects of the DIG model make it preferable for studying the impact of climate change in low-income countries relative to the Integrated Assessment Models (IAMs) more commonly used to assess climate change effects.[44]

In the DIG model, firms combine labor, private capital, and infrastructure to produce output. Consumers supply labor and derive utility from consuming traded and nontraded goods, while the government collects revenue, redistributes income, and invests in infrastructure, which it funds through domestic and external borrowing, grants, and remittances. Based on the empirical results, changes in the exogenously-given sector-specific total factor productivity (TFP) levels are modeled as quadratic functions of temperature, while all other parameters are calibrated broadly as in Buffie and others (2012).[45]

[41]Estimates vary, but there is general agreement that adaptation needs in developing economies are on the order of billions of dollars a year (Margulis and Narain 2010; UNEP 2016). The Paris Agreement reiterates and extends developed economies' commitment to jointly mobilize $100 billion a year by 2020: advanced economies are strongly urged to scale up their efforts with a concrete road map for achieving the goal and, by 2025, are expected to set a new collective, quantified goal from a floor of $100 billion a year (Farid and others 2016).

[42]The IMF completed its first Climate Change Policy Assessment in June 2017 in collaboration with the World Bank for Seychelles (IMF 2017).

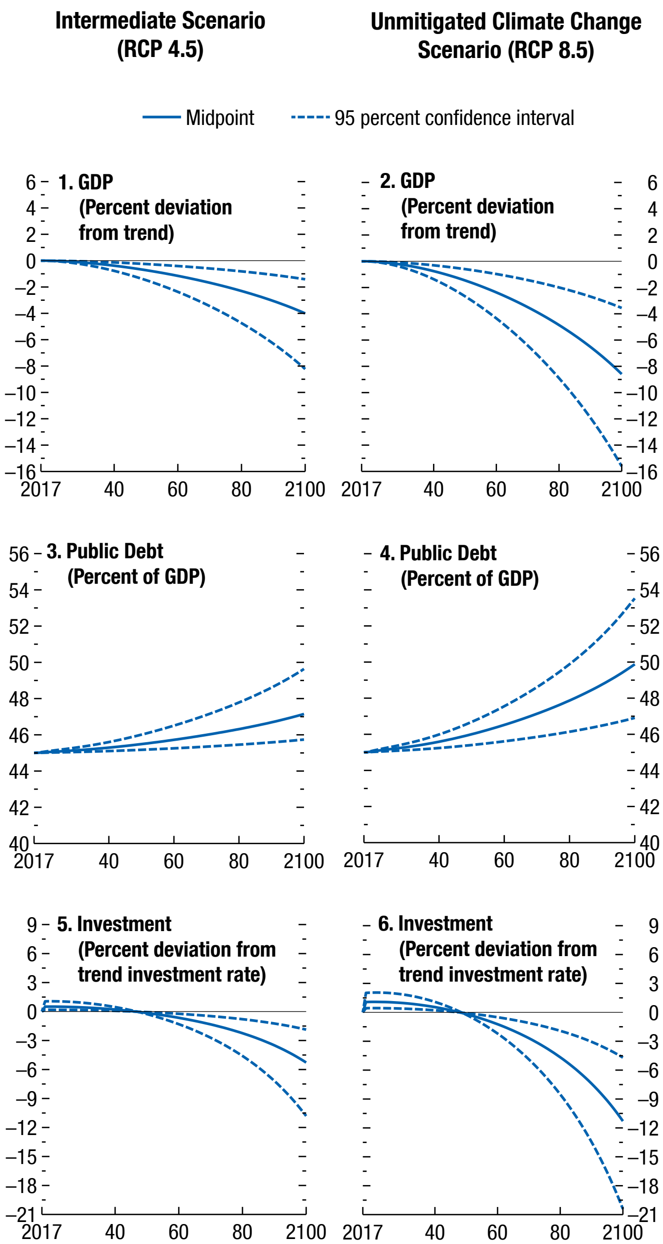
[43]For a detailed description of the model, see Buffie and others (2012) and Annex 3.5.

[44]The three best-known IAMs are the Dynamic Integrated Climate-Economy (DICE) model; the Climate Framework for Uncertainty, Negotiation, and Distribution model; and the Policy Analysis of the Greenhouse Effect model. RICE is a DICE model that includes regions and AD-DICE is a variant of DICE that includes adaptation. Anthoff and Tol (2010), Hope (2011), and Nordhaus and Sztorc (2013) provide descriptions of these models. Existing IAMs are typically not geographically granular enough, lumping together economies with different income levels and average temperatures. They include various feedback loops among emissions, growth, and climate that are less relevant for low-income countries. And they are typically not well suited to analyzing sectoral issues and structural economic transformation.

[45]In particular, $TFP_{t+1} - TFP_t = \beta_1^1 (T_{t+1} - T_t) + 2\beta_2^1 (T_{t+1} - T_t) T_t + \Delta TFP_t^*$, in which ΔTFP_t^* is the TFP growth rate that would prevail under no climate change, assumed to be 2.8 percent based on the WEO medium-term growth forecast for low-income countries. β_1^1 and β_2^1 are the estimated coefficients on the linear and squared temperature terms in equation (3.2), as reported in column (5) of Annex Table 3.3.1, rescaled to match the modeled decline of GDP when temperature increases by 1°C, and T_t is the average annual temperature for the median low-income country at time t, where the initial temperature is set at 25°C.

Figure 3.17. Long-Term Impact of Temperature Increase for a Representative Low-Income Developing Country: Model Simulations

Model simulations suggest that the increase in temperature projected under the intermediate and the unmitigated climate change scenarios could have significant economic consequences for a representative low-income developing country, with sizable downside risks.



Source: IMF staff calculations.
Note: RCP = Representative Concentration Pathways.

The effects of climate change are examined through simulations of the macroeconomic response of output, the public-debt-to-GDP ratio, and private investment to the temperature increases projected under two of the scenarios prepared by the IPCC, as discussed in the "Projections" subsection of this chapter. The simulations suggest that under both scenarios, the representative low-income country will experience sizable economic losses relative to a baseline of no changes in temperature, with significant downside risks (Figure 3.17).

Under the milder scenario, the increase in temperature will lower output by 4 percent by 2100 and depress private investment by 5 percent as firms respond to lower productivity from rising temperatures by cutting back capital spending. The relative decline in output implies an increase in the public-debt-to-GDP ratio of 2 percentage points by 2100. Under the unmitigated climate change scenario, the macroeconomic effect would be much larger. Output would fall short by close to 9 percent relative to no climate change, private investment would fall by 11 percent, and the public-debt-to-GDP ratio would rise by 5 percentage points by 2100.[46]

Conversely, the adverse effect would be significantly smaller if the rise in temperature is successfully contained to less than 2°C, as stipulated in the 2015 Paris Agreement, underscoring the critical importance of mitigation efforts in limiting climate change damage. Box 3.6 discusses recent developments in climate mitigation efforts.

There is great uncertainty surrounding these central projections because empirical estimates of the effect of temperature shocks are imprecise and temperature projections are uncertain. As a result, wide confidence intervals surround this chapter's central projections.[47] There is a 2.5 percent chance of output declining more than 8 percent below the trend under the milder scenario and more than 16 percent under the unmitigated climate change scenario. In line with lower output, public debt would increase significantly relative to output (about 10 percent of GDP under the worst-case scenario), and the private-investment-to-GDP

[46]These results are broadly in line with other model-based estimates of the impact of climate change as discussed in Tol (2009). For a survey of estimates of climate change damage at the global level, see Tol (2014) and Nordhaus and Moffat (2017).

[47]The construction of confidence intervals is detailed in Annex 3.5. These intervals do not account for stochastic variations in the weather or fat-tail events.

ratio could plummet by as much as 20 percent below the trend.

An alternative way to quantify climate change damage for a representative low-income country is to compute the present value of the shortfall in economic output relative to the baseline of no climate change and to express this present value as a share of current output.[48] Using a moderate growth-adjusted discount rate of 1.4 percent, the present value of output losses is large, at 48 percent and 100 percent of current output under the RCP 4.5 and RCP 8.5 scenarios, respectively.

The above simulations assume a static economic structure. However, as seen in the "Channels of Impact" subsection, rising temperatures affect some economic sectors more than others. For example, compared with agriculture, the services sector is relatively sheltered from the adverse effects of higher temperature. Hence, structural economic transformation from a mostly agrarian to a more services-based economy could lower the economic cost of climate change. The analysis extends the baseline DIG model to include an exogenous process of reallocating labor from agriculture and manufacturing to services. The pace of structural transformation is assumed to be moderate and replicates past trends for low-income countries: in the absence of shocks, the employment share of the services sector rises by 2.5 percentage points a decade. Simulations in this extended model indicate that over the long term, for the median low-income country, structural transformation can reduce the cost of climate change by about 25 percent and 30 percent under the RCP 4.5 and RCP 8.5 scenarios, respectively.

The potential impact of climate change quantified in this section is subject to important caveats. First, extrapolating from the short- to medium-term causal effects of weather shocks estimated from historical data to the long-term impact of potential global warming may overstate the case if persistent changes in climate induce agents to adapt their economic activity to the new environment. Conversely, permanent changes in climate may have consequences that fluctuations in annual weather do not. Moreover, the model does not capture the effects of extreme weather events, which inflict long-lasting macroeconomic damage, as demonstrated in Box 3.1 in the case of tropical cyclones, and could increase in frequency, potentially amplifying the damage they cause. Certain expected or possible events (such as rising sea levels) have no historic precedents from which to draw inference but may have very significant economic consequences for many low-income countries, which are also not quantified in the simulations. Moreover, the long-term projections do not incorporate several of the channels through which temperature increases, and climate change in general, could affect economic activity, such as declining labor supply from higher mortality and migration.

Even abstracting from these difficulties, considerable uncertainty exists about how to incorporate the empirical estimates of economic losses into the dynamic general equilibrium model. The analysis in this chapter has taken a very conservative approach and assumes that weather shocks have a permanent effect on the *level* of output. However, several studies have argued that the empirical evidence is not inconsistent with a persistent effect on the *growth rate* of output (Dell, Jones, and Olken 2012; Burke, Hsiang, and Miguel 2015a). Because even a small growth effect would ultimately dwarf a level effect, the adverse consequence of temperature increases for the median low-income country would be many times larger if rising temperatures were incorporated into the model as affecting the growth path of output.[49]

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 developing economies. This chapter documents the extraordinarily fast rise in temperature over the past century across advanced, emerging market, and low-income developing economies and the significant warming that could occur by the end of this century, depending on the international community's ability

[48]In line with Nordhaus (2010), the real interest rate is assumed to be 4.25 percent, giving a growth-adjusted discount rate of 1.4 percent. A more extreme discount rate of 0.1 percent, proposed by Stern (2007), would increase the present value of damage by an order of magnitude.

[49]Burke, Hsiang, and Miguel (2015a) estimate much larger damages from climate change for hot countries: they model temperature increases as having a persistent effect on the growth rate, rather than the level of output. Permanent growth effects could arise if weather shocks scar productivity growth through their effects on institutions, innovation, or human capital accumulation. Several studies have found evidence of effects of weather shocks on outcomes that could plausibly shape productivity growth (for example, the link between weather and conflict or weather and educational attainment), but it is difficult to establish empirically how long the growth damage through this channel lasts.

to contain greenhouse gas emissions. Low-income developing countries, which tend to be in some of the hottest parts of the planet and are projected to experience sizable increases in temperature, have contributed very little to the atmospheric concentration of greenhouse gases.

Yet 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 developing countries. The chapter finds 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 capital accumulation, and damage health. 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 and others 2016; Hallegatte and Rozenberg 2017; IMF 2016b). Despite the significant warming that has occurred over the past century, the sensitivity of per capita output to temperature shocks has not changed materially, pointing to significant constraints to adaptation.

The negative effects of projected climate change for low-income countries could be large. Focusing on one particular aspect of climate change—namely, the projected rise in temperature—and under the conservative assumption that temperature increases affect the level rather than the growth path of output, model simulations suggest that, absent efforts to reduce global emissions, the output of a representative low-income country could be 9 percent lower than without an increase in temperature, with considerable downside risks.[50] The significant uncertainty about the magnitude and effects of climate change—not only how much temperatures will rise, but also how the environment will react—calls for careful consideration of these downside risks.

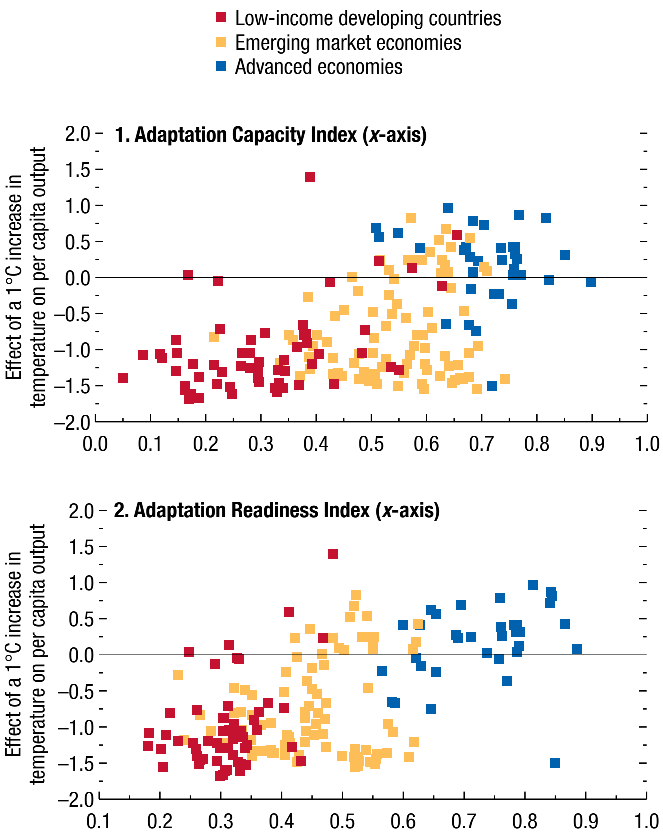
How can low-income countries cope with the rise in temperatures they are set to experience over the coming decades? Although causal interpretation is difficult, the chapter finds that the sensitivity of per capita output to temperature shocks varies with several mediating factors, and these factors are fundamental to teasing out the chapter's policy implications. Sound domestic policies and institutions, and development in general, could play a role in partially reducing the adverse effects of weather shocks. Having policy buffers in place can help cushion some of the negative effects of weather shocks by helping sustain public investment at adequate levels. Policies and institutional settings that facilitate the reallocation of factors of production across economic sectors and geographic regions and that foster development—such as better access to domestic and international financial markets, high-quality infrastructure, and stronger institutions—can increase resilience to weather shocks to some extent. These policies and institutional settings enable countries to recover faster from the negative consequences of temperature increases and reduce their exposure and vulnerability in the future. Investment in adaptation strategies and projects—such as, for example, well-targeted social safety nets that can promptly deliver support where needed, climate-smart infrastructure, and appropriate technology—could also reduce some of the damage from climate change, as illustrated by selected case studies.

But low-income countries have huge spending needs and scarce resources to undertake the investments necessary to cope with climate change. According to United Nations estimates, attaining the Sustainable Development Goals would require low-income countries to increase public spending by up to 30 percent of GDP—an amount that likely exceeds the fiscal space available in most countries (Baum and others 2017; Schmidt-Traub 2015). Low-income countries also often lack the institutional setting, administrative capacity, or political stability to implement appropriate macroeconomic policies or adaptation strategies (Figure 3.18). Moreover, domestic policies alone cannot fully insulate low-income countries from the consequences of climate change as higher temperatures push the biophysical limits of these countries' ecosystems, potentially triggering more frequent epidemics, famines, and other natural disasters, at the same time fueling migration pressure and conflict risk. The international spillovers from these impacts of climate change in vulnerable countries could be very sizable.

[50]Moreover, the negative welfare consequences of changing climate conditions will likely exceed output losses. Uncomfortably high temperatures could spur investment as households adapt, but the increase in economic activity may not improve welfare.

Figure 3.18. Vulnerability to Temperature Increase and Adaptation Prospects

Low-income developing countries, where the effect of temperature increase is estimated to have the most pernicious effect, tend to have much lower climate change adaptation capacity and readiness.



Sources: Notre Dame Global Adaptation Index; and IMF staff calculations.
Note: The figure depicts the estimated effect of a 1°C increase in temperature on per capita output at horizon 0 against countries' score for adaptation readiness and adaptation capacity. A higher score indicates better adaptation capacity and more readiness.

Given that low-income countries' potential to address the climate change challenge by themselves is limited, the international community must play a key role in providing and coordinating financial and nonfinancial support to these countries (see Box 3.6). Advanced and emerging market economies have contributed the lion's share to actual and projected climate change. Hence, helping low-income developing countries cope with the consequences of climate change is both a humanitarian imperative and sound global economic policy that helps offset countries' failure to fully internalize the costs of greenhouse gas emissions.

While the analysis in this chapter focused on the impact of global warming in 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 more damaging) natural disasters (see Box 3.1), rising sea levels, 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 (see Annex Figure 3.6.1). 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 and others 2016; Hallegatte and others 2016; IMF 2015; Stern 2015; IPCC 2014).

Box 3.1. The Growth Impact of Tropical Cyclones

Tropical cyclones, commonly known as hurricanes in the Atlantic and as typhoons in the northwest Pacific, are one of the most destructive forces of nature.[1] They caused damage of $548 billion (constant 2010 dollars) worldwide during 2000–14 (International Disasters Database [EM-DAT]; Guha-Sapir, Below, and Hoyois 2015), almost three-quarters of which occurred in advanced economies.[2] This box estimates the effect of tropical cyclones on economic activity and discusses the possible consequences of climate change through its effects on tropical cyclones under an unconstrained greenhouse gas emissions scenario (Representative Concentration Pathway 8.5).

Measuring Tropical Cyclones and Empirical Estimation

Several studies have examined the macroeconomic impact of tropical cyclones, typically finding significant economic damage.[3] The analysis in this box combines detailed data on maximum sustained wind speed and settlements' population to construct a comprehensive database of tropical storms that took place near centers of economic activity.[4] Between 1950 and 2016, 4,597 storms passed within 100 miles of a city, affecting 3,113 cities in 132 countries or territories.

Tropical cyclones affect countries of different sizes, from small islands in the Caribbean and the Pacific to large countries such as China, Mexico, and the United States. When a storm strikes a small country, it generally affects a large portion of its territory and population, while the impact in larger countries can be contained to relatively smaller areas. To account for this difference, the wind variable—the maximum sustained wind in knots within 100 miles of a country ($Wind_{i,t}$)—is weighted by the share of the population exposed to all tropical cyclones in a year ($P_{i,t}$). Storms also differ in the speed at which they move, with slow-moving storms being potentially more destructive. Thus, the wind variable is also weighted by the share of a country's time endowment exposed to all storms within a year ($TE_{i,t}$), in which the time endowment is given as the product of the number of hours in a year and the number of cities in a country. Table 3.1.1 summarizes the key elements of the cyclone variables.

To estimate the effect of tropical cyclones on per capita output, the analysis extends the local projection empirical approach used in the chapter to include the

The author of this box is Sebastian Acevedo.

[1]A tropical cyclone is a rotating, organized system of clouds and thunderstorms that originates over tropical or subtropical waters and has a closed low-level circulation (NOAA 2017b). Hurricane-strength winds (greater than 64 knots) can extend beyond 200 miles for the largest storms.

[2]Storms cause more absolute damage in advanced economies because their capital stocks tend to be more valuable; however, as a percentage of GDP, damage is generally higher in small states and low-income developing countries. The EM-DAT reports damage for about half of the disasters caused by storms. Acevedo (2016) finds that, in the Caribbean, economic damage caused by tropical cyclones could be 1.6 to 3.6 times higher than reported.

[3]Raddatz (2009); Fomby, Ikeda, and Loayza (2013); and Acevedo (2014) use data from the EM-DAT to estimate the effects of different types of natural disasters (including storms) on growth, while a parallel body of literature (Strobl 2012; Bertinelli and Strobl 2013; Hsiang and Jina 2014) uses wind-field models to estimate the effects of storm winds on growth. Bakkensen and Barrage (2016) use maximum wind speed at landfall, which is closer to the approach used here.

[4]The International Best Track Archive for Climate Stewardship contains data on 7,140 tropical cyclones, with information on maximum sustained wind speed between 1950 and 2016 (Knapp, Applequist, and others 2010; Knapp, Kruk, and others 2010). These data are combined with the CIESIN (2016) settlements' population in 2000, which contains data for 67,682 cities that range in population from one person to 18.5 million people.

Table 3.1.1. Characteristics of the Average Tropical Cyclone by Country Group

	MSW within 100 Miles (knots)	Exposed Population	Exposed Time Endowment	Distance (miles)
World	51.30	0.34	0.0005	77.05
Advanced Economies	58.56	0.28	0.0004	77.78
Emerging Market Economies	49.84	0.28	0.0004	76.27
Low-Income Developing Countries	42.45	0.20	0.0003	79.66
Small States	47.02	0.58	0.0009	71.26
Islands	54.43	0.49	0.0007	75.69

Sources: CIESIN GRUMPv1 Settlement Points r01; Ibtracs v03r09; and IMF staff calculations.
Note: Maximum sustained winds (MSW) one minute average in knots per hour. Exposed population as a share of total population. Exposed time endowment as a share of the total hours available in each country (24 hours × 365 days × cities). Distance is the average distance from each city (within 100 miles of the storm) to the storm position where the wind was at its maximum.

Box 3.1 *(continued)*

Table 3.1.2. Effect of Weather and Wind Shocks on Economic Activity

Real GDP per Capita Growth	(1)	(2)	(3)
Temperature	1.347***	0.931***	0.920***
	(0.357)	(0.222)	(0.223)
Temperature²	–0.051***	–0.038***	–0.037***
	(0.011)	(0.010)	(0.010)
Precipitation	0.110	0.051	0.047
	(0.104)	(0.104)	(0.106)
Precipitation²	–0.003	–0.002	–0.001
	(0.002)	(0.002)	(0.002)
Wind × Population × Time Endowment			–26.750**
			(12.912)
Adjusted R^2	0.14	0.18	0.18
Number of Countries	189	96	96
Number of Observations	8,815	4,696	4,696

Source: IMF staff calculations.
Note: All regressions control for country and region-year fixed effects; lags and forwards of temperature, precipitation, and their squared terms; and lag of growth. Column (3) also controls for the contemporaneous wind variable, as well as its lags and forwards. Column (1) replicates the chapter's baseline specification (column (5) in Annex Table 3.3.1). Columns (2) and (3) include only countries exposed to tropical cyclones. Standard errors clustered at the country level.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

wind variable weighted by the share of population and time exposed. The specification estimated is as follows:

$$
\begin{aligned}
y_{i,t+h} - y_{i,t-1} &= \alpha_1^h\left(\text{Wind}_{i,t} P_{i,t}\, TE_{i,t}\right) \\
&+ \alpha_2^h\left(\text{Wind}_{i,t-1} P_{i,t-1}\, TE_{i,t-1}\right) \\
&+ \textstyle\sum_{j=1}^{h-1} \alpha_3^h \left(\text{Wind}_{i,t+h-j} P_{i,t+h-j}\, TE_{i,t+h-j}\right) \\
&+ \beta_1^h c_{i,t} + \beta_2^h c_{i,t-1} + \textstyle\sum_{j=1}^{h-1} \beta_3^h c_{i,t+h-j} \\
&+ \varphi_1^h \Delta y_{i,t-1} + \mu_i^h + \theta_{r,t}^h + \varepsilon_{i,t}^h, \qquad (3.1.1)
\end{aligned}
$$

in which h indexes the estimation horizon, μ_i^h are country fixed effects, $\theta_{r,t}^h$ are region-year fixed effects, $y_{i,t}$ is the log of GDP per capita, and $c_{i,t}$ refers to average annual temperature and precipitation and their squared terms.

The results presented in Table 3.1.2 indicate that if the wind speed increased by one knot throughout the entire country (that is, the entire population is exposed), and for an entire year, real GDP per capita would decline by 26.7 percent the year the storm strikes. This, of course, is not a very useful indicator of the effect of a typical storm on a country; a better measure is the marginal effect of increasing wind speed as captured by $\alpha P_{i,t} TE_{i,t}$.

Findings

Tropical cyclones have a significant negative effect on output, with the biggest impact felt in small states and islands that are generally more exposed to this type of storm (Figure 3.1.1).[5] By income group, advanced economies are the hardest hit by tropical cyclones because they tend to be exposed to higher wind speeds.

The estimates are not only statistically, but also economically, significant. Seven years after an average storm strikes, per capita output is almost 1 percent lower than if the storm had not happened, with 2.5 times larger losses experienced by small states (Figure 3.1.2).[6] The effects of storms are very persistent: even after 20 years, the economy has not fully recovered from the shock.[7] Notably, the effect of tropical cyclones on economic activity is separate and in addition to the effects of temperature (Table 3.1.2). Introducing the wind variable does not materially change the coefficients on temperature and precipitation for the same sample of countries.

Climate Change and Tropical Cyclones

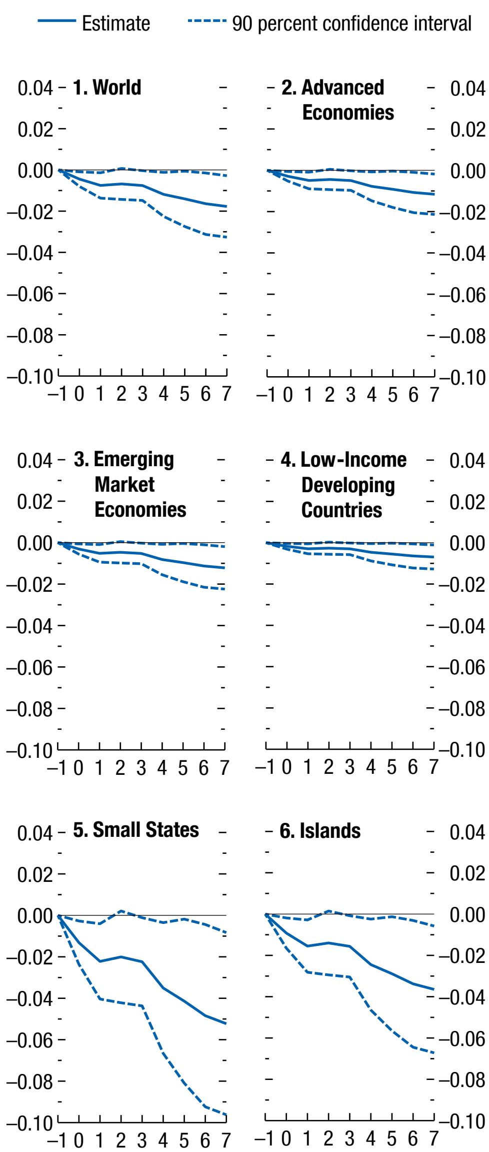
Climate scientists predict that, with climate change, there will be fewer tropical cyclones that form, but the

[5]For a discussion of small states' vulnerability to natural disasters and climate change, see IMF (2016b).
[6]A storm strike includes any tropical cyclone that passed within 100 miles of a city in a country.
[7]Hsiang and Jina (2014) find a similar response; in their case, the decline in GDP is much larger, but the partial recovery starts after 15 years.

Box 3.1 *(continued)*

Figure 3.1.1. Effect of Tropical Cyclone Exposure on Real GDP per Capita

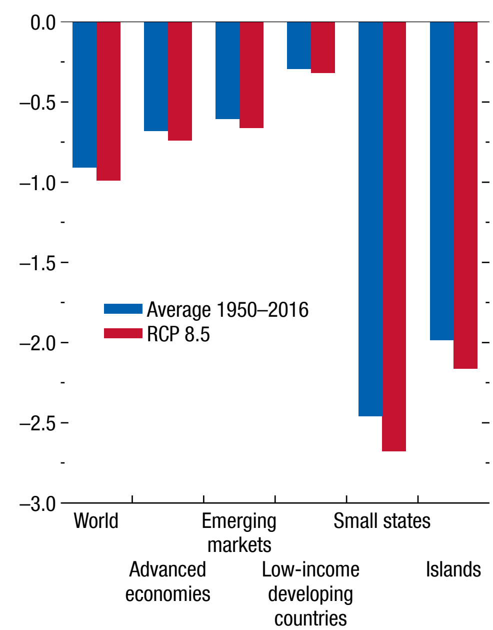
(Percent; years on x-axis)



Source: IMF staff calculations.
Note: Cumulative impact of a one-knot increase in tropical cyclone winds on real GDP per capita. Horizon 0 is the year of the shock.

Figure 3.1.2. Cumulative Effect of Average Tropical Cyclone on Real GDP per Capita after Seven Years

(Percent)



Source: IMF staff calculations.
Note: Cumulative effect after seven years on real GDP per capita of the average tropical cyclone that each country group is exposed to in terms of maximum wind speed, exposed population, and exposed time endowment. RCP = Representative Concentration Pathways.

ones that do will be more intense and destructive (Knutson and others 2010). In the unmitigated climate change scenario (Representative Concentration Pathway 8.5), sea surface temperature in 2090–2100 is expected to increase by 2.6°C relative to 1995–2005, which suggests that the maximum wind speed of tropical cyclones could increase by 9 percent.[8] The analysis in this box suggests that the average country would suffer an additional 0.1 percent of per capita output loss every time it is hit by an average tropical cyclone, with smaller states experiencing 0.2 percent greater damage (Figure 3.1.2).

[8]Sea surface temperature is a key ingredient in the formation and development of tropical cyclones (Landsea 2004). A 1°C increase in sea surface temperature raises maximum wind speed by 3.5 percent (Knutson and Tuleya 2004).

Box 3.2. The Role of Policies in Coping with Weather Shocks: A Model-Based Analysis

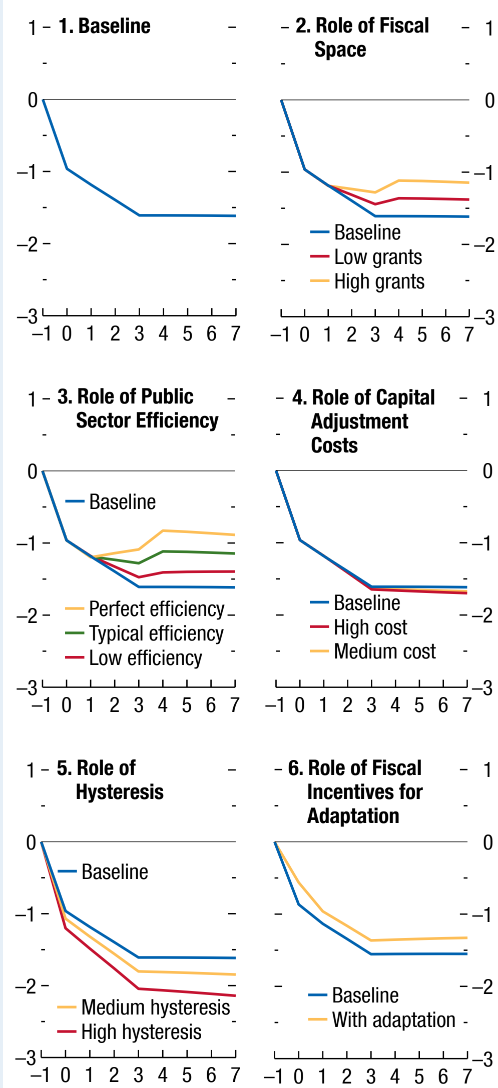
To illustrate how policies can help moderate the consequences of weather shocks in low-income countries, this box uses the Debt, Investment, and Growth (DIG) model developed by Buffie and others (2012) and simulates the macroeconomic effects of temperature increases under various assumptions for key policy variables.[1] As demonstrated empirically in the chapter, in hot countries, an increase in temperature reduces productivity. Moreover, a temperature increase could precipitate the loss of productive land. Consequently, the analysis calibrates the weather damage to total factor productivity and private capital to broadly match the estimated response of GDP to a 1°C increase in temperature in a representative low-income country with a baseline temperature of 25°C and examines how this damage can be shaped by macroeconomic and structural policies (Figure 3.2.1).[2]

Policy Space and the Role of Institutions

Weather shocks can weigh significantly on the public purse of low-income countries. Government revenues can be adversely affected by the reduction in agricultural and industry output at the same time that spending may need to be ramped up to deliver support to affected households if weather shocks compromise food security, to rebuild transport or communication infrastructure if they are damaged by natural disasters, and potentially to retrain the workforce. Because fiscal space is often tight in many low-income countries, expanding transfers from advanced economies—for instance, through the transfers agreed to under the Paris Agreement—could strengthen countries' ability to reduce the impact of weather shocks. Model simulations suggest that receiving additional transfers used to build up public investment for three years, starting a

Figure 3.2.1. Role of Policies: A Model-Based Analysis

(Real GDP, deviation from steady state; years on x-axis)



Source: IMF staff calculations.
Note: The baseline assumes no additional grants in panels 2 and 3, low adjustment cost in panel 4, no hysteresis in panel 5, and no adaptation in panel 6. In panel 2, additional grants amount to 0.5 percent of GDP in low grants scenario, and 1 percent of GDP in high grants scenario. In panel 3, all simulations, except the baseline, assume high additional grants.

The authors of this box are Manoj Atolia, Claudio Baccianti, Ricardo Marto, and Mico Mrkaic.

[1]The DIG model is a real, neoclassical, dynamic open economy framework with two production sectors that use public and private capital as input and many features that are pertinent to low-income countries, such as low public investment efficiency, limited fiscal space, and capital adjustment costs. The model is also used to simulate the long-term effects of climate change in the section of the chapter titled "Long-Term Effects of Temperature Increase—A Model-Based Approach."

[2]For simplicity, the traded and nontraded sectors are assumed to react equally to weather shocks. The findings are robust to this modeling choice. Most other parameters are calibrated as in Buffie and others (2012), except the real interest rate on public debt, which is lower than in the original paper because of the decline in global interest rates. See Annex 3.5 for further details.

Box 3.2 *(continued)*

year after the weather shock, could limit the damage of weather shocks to output (Figure 3.2.1, panel 2). Additional transfers of 1 percent of the recipient country's GDP reduce the depth of the recession by about 0.5 percent throughout the simulation period. Encouragingly, because the transfers increase the stock of public infrastructure, thereby boosting productive capacity in both sectors, they increase output not only in the short term, but also in the long term.

Additional transfers benefit the recipient country, but the size of the benefit depends crucially on the efficiency of investment in public sector infrastructure, in particular, and on the quality of public sector governance in general. Efficiency of public investment is low in many low-income countries, with estimates of the share of expenditures on public infrastructure that truly increase the stock of public capital ranging from 20 percent to 60 percent (Hulten 1996; Pritchett 2000; Foster and Briceno-Garmendia 2010). The results of the simulations show that, in countries with high public investment efficiency, the receipt of additional transfers can effectively dampen the adverse consequences of a weather shock (Figure 3.2.1, panel 3). In countries with low public investment efficiency, however, there is little difference between receiving and not receiving additional transfers. In sum, the simulation shows convincingly that low-income countries must continue to improve the efficiency of public investment and strengthen their institutional frameworks to reap the full benefit of having buffers to counteract the effects of changing weather conditions.

Policies that Ease Factor Reallocation and Structural Transformation

Weather shocks disrupt production, especially in certain sectors of the economy, and adjusting to these shocks would require reallocating workers and capital across and within sectors. The speed and cost at which these factors of production can be reallocated will influence how fast the economy can recover after adverse shocks to total factor productivity or the stock of capital.

In low-income countries, reallocation of capital (and factors of production in general) can be hampered by rigid economic environments and suboptimal policies, for example, limited access to financial markets, bureaucratic impediments (such as difficulties in obtaining building permits), and legal uncertainties.[3] Simulations indicate that higher costs of capital reallocation slow the recovery from weather shocks (Figure 3.2.1, panel 4).[4]

The speed at which affected workers can be reallocated to alternative productive activities also matters. Unemployment can cause hysteresis or permanent "scarring" of productivity, given that workers lose skills during long unemployment or underemployment episodes. This in turn could have long-lasting consequences for economic performance. In the DIG model, this channel is captured in the sensitivity of productivity to lagged negative output gaps.[5] The results from simulations that vary this sensitivity suggest that hysteresis could significantly prolong and deepen the effects of weather shocks. Hence, policies should aim to preserve human capital, including by instituting programs that provide incentives to the unemployed to participate in human-capital-preserving activities, such as public works projects, as in the Ethiopian Productive Safety Net Program, discussed in Box 3.3.

Investment in Adaptation Strategies

In addition to the general macroeconomic and structural policies discussed above, governments, households, and firms engage in direct investments in adaptation strategies in response to changing weather conditions (for example, by planting more-heat-resistant crops or investing in green infrastructure). Many adaptation measures, however, have the nature of public goods. Setting up an early-warning system for extreme heat, instituting information campaigns about water conservation, or increasing vegetation in public areas and other green infrastructure investments all have nonrival

[3]In the DIG model, the ease of factor reallocation is captured in the cost of private capital adjustment parameter. The cost of capital adjustment is inversely proportional to elasticity of investment with respect to Tobin's q, in which higher elasticity implies lower capital adjustment costs.

[4]The quantitative impact appears small, but the simulation should be seen as a qualitative guide only. The size of the GDP decline depends on the cost of capital adjustment as well as on the shape and timing of the shock. If the climate shock results mostly in the destruction of private capital and, to a lesser extent in lowering total factor productivity, then the recovery is slower and damage to GDP larger because of slower rebuilding of capital.

[5]The size of the effect is calibrated by using the estimated elasticity of current wages to lagged hours worked by Altuğ and Miller (1998). Their estimated elasticity of 0.2 stands for the high degree of hysteresis in the model specification.

Box 3.2 *(continued)*

and nonexcludable payoffs. Because households and firms are unable to internalize the full social benefits, government involvement may be needed to provide incentives to private agents to undertake adaptation efforts toward socially optimal levels. In an extension of the DIG model, the government introduces fiscal incentives for the adoption of resilience-improving technologies and finances the provision of public goods related to weather risks, which lowers the sensitivity of output to temperature increases. Assuming that private adaptation expenditure falls 20 percent short of the social optimum, and that government policy aims at restoring optimality, simulations suggest that over 20 years, each $1 spent on adaptation by the government reduces total weather damage by $2. The mechanism behind this finding is private investment's response to the reduced weather-related productivity losses, which boosts GDP in the medium and long term. The simulation illustrates a general principle that improving resilience through public adaptation spending can reduce weather-driven downturns and accelerate recoveries (Figure 3.2.1, panel 6).

Box 3.3. Strategies for Coping with Weather Shocks and Climate Change: Selected Case Studies

Adverse effects of weather shocks and climate change have motivated local communities and countries to adapt and counter these unfavorable consequences. As demonstrated in Figure 3.12, a wide range of strategies could dampen the negative impacts of weather shocks and natural disasters by reducing exposure and vulnerability or by transferring and sharing weather-related risks. The purpose of this box is to showcase some examples of successful coping strategies.

Social Safety Nets

Approximately 85 percent of the Ethiopian population is employed in agriculture, mostly on small family-owned farms. Climate change and associated droughts, delayed rains, and flooding weigh on agricultural productivity and food security. Furthermore, in some areas, the land has become degraded due to overuse. Consequently, approximately 10 percent of the rural population is chronically food insecure.

To assist the at-risk population, the Ethiopian government and international partners instituted the Productive Safety Net Program (PSNP) in 2006. The PSNP provides cash or food to households unable to feed themselves all year, particularly in the lean season (June–August). The aid is contingent on active participation in local productivity-enhancing or environmental programs—for example, land rehabilitation, improvement of water sources, and construction of infrastructure such as roads and hospitals. A complementary program, the Household Asset Building Program, which targets the same households as the PSNP, helps households diversify their income sources and increase productive assets, including by offering technical assistance, with the goal of achieving lasting food security.

With more than 7.6 million participants (or almost 8 percent of the Ethiopian population) and 47,000 small community projects every year, the PSNP is the largest climate change adaptation program in Africa. The community projects, which are mostly devoted to environmental restoration, are offering measurably positive results. The PSNP has reduced soil loss by more than 40 percent and improved the quality and quantity of available water. Studies suggest that land productivity has consequently increased by up to 400 percent. In addition, the PSNP has reduced the damage from seasonal flooding. The program has also improved the food security of vulnerable households—beneficiaries of the PNSP experienced a 25 percent smaller drop in consumption relative to those that were not covered by the program in the aftermath of droughts (Porter and White 2016). The PSNP has also reduced the number of people in need of humanitarian intervention and the cost of such intervention. Finally, the PSNP has increased savings of vulnerable households and has facilitated improved access to educational and health services.

Technology Adoption

High temperatures significantly lower labor productivity and could lead to adverse health outcomes—such as increased incidence of hyperthermia and worsening chronic cardiovascular or respiratory diseases—and mortality, as demonstrated in a large body of work and the analysis in this chapter. Governments and individuals have various options for reducing these adverse economic and health impacts, such as green infrastructure (to increase the presence of vegetation in cities) and specific construction technologies (for example, roofs that are highly solar reflective). Among all options, modern air-conditioning, invented at the turn of the 20th century, is the most common solution adopted by households and firms to deal with excessive heat.

The benefits of climate control, both in the workplace and for health outcomes, are well documented. In a 1957 survey, 90 percent of American firms named cooled air as the single biggest boost to their productivity (Cooper 2002), and Singapore's founding father, Lee Kuan Yew, credited air-conditioning as the most important factor in his country's development success. The dramatic decline in heat-related mortality over the 20th century in the United States has also been attributed to the adoption of residential air conditioning (Barreca and others 2016).

Nevertheless, the negative effects of air-conditioning cannot be ignored. Increased adoption of indoor climate control increases energy consumption and greenhouse gas emissions. Exhaust from air-conditioning machines and facilities can give rise to local pockets of hot air, which can present significant negative externalities for nearby populations. High up-front costs and infrastructure requirements make this technology out of reach for poor and vulnerable populations, especially in low-income developing countries.[1]

The authors of this box are Claudio Baccianti and Mico Mrkaic.

[1]As of 2012, slightly more than one-third of households had access to electricity in the median low-income developing country.

Box 3.3 *(continued)*

Intelligent planning and implementation of air-conditioning could reduce some of the negative spillovers of this otherwise effective strategy for adapting to rising temperatures. A case in point is district cooling—a centralized air-conditioning system—which has been adopted in major cities in advanced economies and is currently under construction in the Gujarat International Finance Tec-City, a new business district in Gujarat, India. With district cooling, chilled water is produced at a central source and is distributed to final consumers through underground pipes.

A centralized cooling system has clear environmental and economic advantages over decentralized air-conditioning. The centralized production of chilled water consumes 35 to 50 percent less energy than individual air cooling units, reducing cost and pollution. Higher energy efficiency, in turn, eases the pressure the diffusion of air-conditioning puts on the local electricity sector, which often lags the rapidly growing demand for energy in emerging market and developing economies. Finally, district cooling eliminates the up-front cost for final users, making indoor climate control more accessible.

As in the provision of other types of infrastructure, such as energy and water distribution, public sector involvement could speed up the development and expansion of district cooling systems, which could be held back by low energy prices, insufficient demand density, economic uncertainty, and other risks related to the substantial up-front investment. The government of Gujarat has taken direct control of the construction of the cooling distribution network, as have the governments of the Republic of Korea, Qatar, and Singapore.

Climate-Smart Public Infrastructure Investment

Flash floods in Kuala Lumpur, Malaysia, have caused considerable property damage, impassable traffic congestion, contamination of the water supply, and loss of human life. To alleviate these problems, the authorities embarked on an ambitious dual-purpose infrastructure project that would help with both traffic and flood water management.

The Stormwater Management and Road Tunnel (SMART Tunnel) is a dual-purpose structure designed to combat flash floods. A three-level tunnel combines a two-level road tunnel and a storm drainage system underneath. Under normal conditions, the drainage level is closed and the tunnel is used as an ordinary road traffic tunnel. However, the tunnel is designed so that one or both traffic-carrying levels can be temporarily repurposed by being allowed to flood for use as storm drains.

During moderate storms, the system reallocates the lower traffic level to carry storm water, while the top level can still be used by motorists. If the rainfall is expected to be extreme, both traffic-carrying levels can be closed to traffic, evacuated, and used as drains.

Cost-benefit analysis has demonstrated the effectiveness of the tunnel system. At a cost of about $500 million, it is expected to prevent more than $1.5 billion in flood damage and reduce the costs of traffic congestion by more than $1 billion over the next 30 years.

Early-Warning Systems and Evacuation Programs

Situated in the Ganges delta, Bangladesh is one of the countries most vulnerable to climate change. Annual floods typically inundate about one-fifth of the country, leading to loss of life and property damage.[2] Over the past 70 years, storms have caused thousands of deaths and millions of tons of crop damage, and, because of climate change, the problems are expected to worsen.

After the extraordinary damage caused by Cyclone Sidr, the authorities and international partners embarked on the Emergency Cyclone Recovery and Restoration Project (ECRRP).[3] The goals of the ECRRP are to improve agricultural infrastructure and long-term disaster preparedness, including by building and reconstructing cyclone shelters and reinforcing embankments. The program has meaningfully reduced the risk of cyclone exposure of the vulnerable population by rebuilding about 240 cyclone shelters and repairing more than 100 kilometers of embankments.

The ECRRP has also helped increase agricultural resilience to climate shocks and helped improve the livelihoods of the affected populations. In addition to providing farmers with agricultural equipment, saline-tolerant rice seeds, and training in crop diversification for better farm management, investments in grain silos and livestock protection have reduced the exposure of the agricultural production chain to weather-related shocks.

[2]In extreme years, floods can affect up to three-quarters of the land area in Bangladesh.

[3]The cyclone destroyed 1.5 million houses and damaged 1.3 million tons of crops.

Box 3.3 *(continued)*

Multilateral Risk-Sharing Mechanisms

Caribbean Catastrophic Risk Insurance Facility

Caribbean countries are regularly affected by tropical storms, extreme rainfall, earthquakes, and volcanic eruptions. Because these shocks are, at least in part, uncorrelated, risk sharing in the form of a regional insurance pool can offer welfare improvements relative to self-insurance or purchase of reinsurance by individual countries. The Caribbean Catastrophic Risk Insurance Facility (CCRIF) is the world's first regional risk-pooling financial institution, offering insurance for the most prevalent natural disasters in the region. It was formed in 2007 and currently includes 17 members.[4]

The CCRIF insures against tropical cyclones, excessive rainfall, and earthquakes. All 17 participating countries can purchase up to $100 million of coverage for each category of risk. The program is designed to finance emergency response, over the weeks and months after the disaster, rather than provide comprehensive insurance against asset losses or infrastructure damages. The insurance is parametric—payouts are based on parameterized models for each category of insured events: tropical cyclones, excessive rainfall, and earthquakes. For example, the payout after an earthquake is proportional to its intensity, location, and estimated losses. Predetermined payouts, based on publicly observable data, obviate the need for time-consuming and costly damage assessments and insurance adjustments. A downside of parametric insurance in response to the effects of basis risk; that is, calculated payouts might not match the actual damage.[5]

During 2007–15, the CCRIF made 13 payouts to eight members in the total amount of $38 million, most of which was in response to the effects of tropical cyclones. The payouts ranged from 0.1 to 0.3 percent of GDP for the recipient country. While the payouts do not cover all losses, they offer important support to insured countries, including from the rapid disbursement of funds—payouts have been disbursed, at the latest, two weeks after the insured event. In addition, CCRIF members are given complete freedom regarding the use of the funds received.

The CCRIF has proved to be an effective risk-pooling mechanism. Its effectiveness is recognized by both the insured countries, which can obtain coverage at a lower cost than they could individually from commercial insurers, and from the participants in the reinsurance market.

African Risk Capacity

The African Risk Capacity (ARC) is a mutual insurance facility whose aim is to strengthen food security. The ARC, a Specialized Agency of the African Union, was established in 2012 to help African Union members insure against crop failure caused by extreme weather events, such as droughts and floods, by pooling climate-related risks. Initially, 18 African Union members signed the establishment agreement; since then, membership has grown to more than 35 countries.

The ARC provides parametric insurance. When an insured event occurs, the payout is based on models and satellite input data to predict the extent of crop failures and the associated costs. Using parametric instead of indemnity insurance accelerates the payouts, which is of particular importance to the most vulnerable populations. By pooling their risks, participating countries reduce the cost of insurance by about half, given that drought is very unlikely to affect the whole country pool.

Evidence points to the benefits of the ARC, but challenges remain. The ARC has reduced the volatility of food consumption for the most vulnerable households. Furthermore, it has helped reduce the need for fire sales of assets in distressed regions. However, the risk pool is still relatively small (for example, in comparison with the CCRIF) and could be expanded further to better diversify the risks. In addition, misallocation of insurance may decrease with accumulated experience.

[4]Anguilla, Antigua and Barbuda, The Bahamas, Barbados, Belize, Bermuda, the Cayman Islands, Dominica, Grenada, Haiti, Jamaica, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Trinidad and Tobago, and the Turks and Caicos Islands joined at the inception; Nicaragua joined in 2015. The CCRIF is contemplating expanding beyond the Caribbean.

[5]Indemnity insurance avoids this problem, but suffers from costly assessments and adjustments.

Box 3.4. Coping with Weather Shocks: The Role of Financial Markets

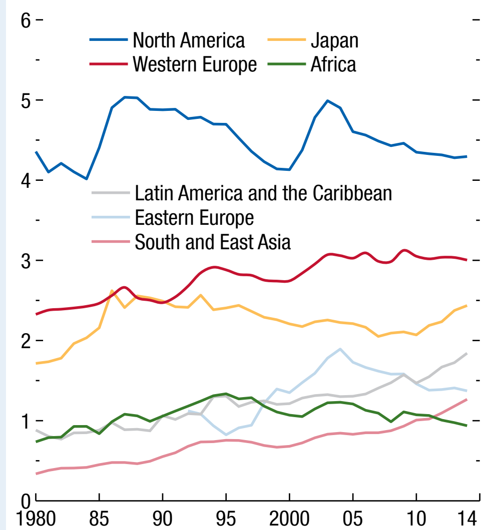
Financial markets can reduce the adverse consequences of weather shocks by reallocating the costs and risks of such shocks to those most willing and able to bear them. Insurance products, such as weather derivatives, can help households and firms vulnerable to short-term fluctuations in temperature and precipitation hedge their idiosyncratic weather exposure. Catastrophe (Cat) bonds can help disperse catastrophic weather risk to capital markets. However, the degree to which financial markets can mitigate the impacts of weather shocks hinges on the level of insurance penetration and on the capacity to correctly price weather-related risks. This box reviews recent developments in the market for weather-related financial products and provides new evidence on the extent to which stock markets efficiently price weather-related risks.

Insurance

Recent studies highlight the important role that insurance markets could play in facilitating economic recovery in the aftermath of weather-related natural disasters. A higher degree of insurance penetration can limit the fiscal burden of natural disasters (Lloyd's 2012) and reduce their negative macroeconomic consequences (Von Peter, Dahlen, and Saxena 2012), especially in countries with strong institutions (Breckner and others 2016). Parametric insurance products, developed in the early 2000s, also hold promise for providing protection from various weather-related risks to households and firms in low-income countries.[1] Overcoming important barriers to the provision of traditional insurance to small farmers, these products minimize transaction costs, are easy to enforce, and limit potential adverse selection and moral hazard issues.

Yet, insurance penetration, as captured in non-life insurance premiums as a percentage of GDP, remains low, especially in developing economies (Figure 3.4.1). And despite its advantages, the take-up of parametric insurance has been disappointing (Hallegatte and others 2016). Many factors have likely contributed to the slow adoption of the novel financial instruments, including limited financial literacy or experience with similar financial products, insufficient understanding of the product, high cost, and residual basis risk (see, among others, Cole and others 2012, 2013; Karlan and others 2014).

Figure 3.4.1. Insurance Penetration: Non-Life Insurance Premium
(Percent of GDP)



Sources: Haver Analytics; Swiss Re, Sigma database; and IMF staff calculations.

Catastrophe Bonds

The market for Cat bonds, a financial instrument that transfers catastrophe risk from the issuing primary insurers and reinsurance companies to the capital markets, has grown rapidly in recent years, reaching an outstanding volume of nearly $30 billion at the end of 2016 (Figure 3.4.2).[2] Cat bonds are attractive to investors because they have relatively higher yields and low correlation with the returns of most other financial assets. The low-interest-rate environment since

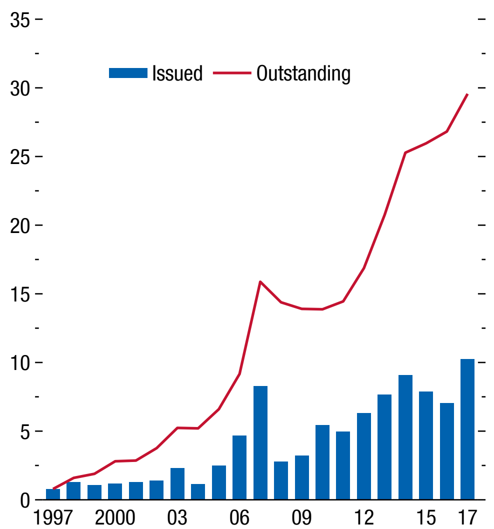
The author of the box is Alan Xiaochen Feng.

[1]Unlike traditional indemnity insurance for natural hazards, parametric insurance products offer payments that are based on a publicly observable index, such as rainfall or temperature. While their design offers numerous advantages over traditional products, parametric insurance can leave a fair amount of residual risk uncovered ("basis risk"), given that the actual loss may differ from the payment received by contract holders.

[2]Cat bonds pay interest, principal, or both during normal times, but absorb losses if a predefined catastrophe occurs. They were first introduced in the mid-1990s, in the aftermath of Hurricane Andrew.

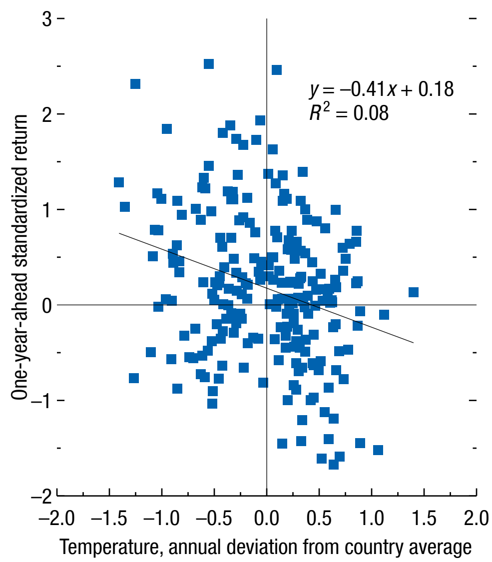
Box 3.4 *(continued)*

Figure 3.4.2. Catastrophe Bond Market
(Billions of US dollars)



Source: Artemis Insurance-Linked Securities and Catastrophe Bond Market Report (www.artemis.bm).
Note: Years ending June 30.

Figure 3.4.3. Temperature Shocks and Stock Price Predictability: Food and Beverages Sector



Sources: Datastream; Peng and Feng (forthcoming); and IMF staff calculations.
Note: One-year-ahead food and beverages sector returns are regressed on annual average temperature (deviation from the country average, degrees Celsius). Sample is restricted to countries with an average annual temperature above 15°C.

the global financial crisis, as well as new regulations that recognize the relief of capital through Cat bond issuance, have potentially contributed to the growth of the Cat bond market. Cat bonds have become an increasingly popular tool for private insurance and reinsurance companies in Europe, Japan, and the United States to transfer away their risk exposures to earthquakes, storms, and hurricanes.

As discussed in the chapter, low-income developing countries and small states are especially vulnerable to catastrophic risks. Mexico, in 2006, was the first country to issue Cat bonds; since then, several low-income developing countries have issued Cat bonds covering hurricanes, earthquakes, and other extreme events. The World Bank issued its first-ever Cat bond in 2014 to provide reinsurance to the Caribbean Catastrophe Risk Insurance Facility, a risk-pooling facility designed to limit the financial impact on 16 Caribbean country governments after possible earthquakes and hurricanes (see also Box 3.3). A similar arrangement—the Extreme Climate Facility—is being developed by the African Risk Capacity (see Box 3.3) to allow for the issuance of Cat bonds to alleviate the impact of extreme weather conditions on member African countries.

Do Financial Markets Correctly Price Weather-Related Risks?

The optimal level of insurance against abnormal weather conditions requires accurate assessments of weather-related risk. There is growing evidence that investors in financial markets do not fully understand, at least immediately, the impact of weather shocks on output and productivity. Hong, Li, and Xu (2016) show that the stock indices of the food industry in the United States and in a few other advanced economies respond to changes in drought indices only with a delay. This finding suggests that markets do not incorporate weather information into prices until several months later, perhaps after the losses incurred are reflected in food companies' annual reports. The

Box 3.4 *(continued)*

initial underreaction to weather shocks may indicate the possibility of underinsurance, even in the presence of easily accessible insurance products.

The analysis in this box examines the response of investors to temperature variations. As demonstrated in the chapter, an increase in temperature in countries with relatively hot climates has a negative effect on output and productivity, especially in certain sectors of the economy. Using data on equity market returns across 17 sectors in 42 countries and annual fluctuation in temperature, the analysis studies whether financial markets correctly price in these adverse temperature effects. If markets are efficient, fluctuations in temperature should have no predictive power on equity returns because stock prices instantaneously reflect the impact of temperature shocks on firm performance. Empirical analysis suggests that this is not the case. Higher temperature can predict negative future (12-month-ahead) stock returns for the food and beverages sector, suggesting that investors respond to temperature shocks with a delay (Figure 3.4.3).[3] These effects are particularly strong for countries at lower latitudes (for example, those with average annual temperature greater than 15°C) and are insignificant for industrial, technology, utilities, and oil and gas sectors. The predictability of stock returns in the food and beverages sector suggests that the impact of temperature shocks on productivity is not well priced by investors until several months later (possibly only after earnings reports reflect these losses), consistent with the hypothesis of underreaction to these shocks.

[3]The one-year-ahead equity return for the food and beverages sector is regressed on current-year average temperature in the country, controlling for country-year fixed effects as well as the dividend yield of the sector. Equity returns are normalized by the standard deviation of yearly sector returns in each country. Results are robust to controlling for one-year-ahead average temperature in the country. Similar effects are found for retail and personal goods sectors (Peng and Feng forthcoming).

Box 3.5. Historical Climate, Economic Development, and World Income Distribution

As argued in the chapter, climate change may have very long-lived effects on economic performance, although the exact magnitudes depend on many factors, including economic agents' adaptability and the ability of the economy to structurally adjust. Empirically, it is very difficult to disentangle whether weather shocks have permanent level or growth effects on output based on recent data (since 1950); if they reflect permanent growth rather than level effects, then the consequences may be many times larger than the initial effects, but this impact would manifest only over a very long time.

This box reviews a relatively new and growing literature that attempts to directly assess whether historical climate can have a large and permanent effect on economic performance. Enabled by the rising availability and granularity of historical data, the literature examines the relationship between modern outcomes and historical climate, starting from the hypothesis that historical events (potentially in the very deep past) interact with the physical environment and can have permanent effects on economic development and performance.[1]

Leveraging the exogeneity of historical climate, Bluedorn, Valentinyi, and Vlassopoulos (2009) estimate the reduced-form relationship between a country's temperature over different periods from 1730 to 2000 and its modern income per capita, uncovering some striking patterns. A simple bivariate regression confirms the strong negative correlation between income in 2000 and the average temperature during 1970–99 (Table 3.5.1, regression 1). However, after controlling for historical average temperature in the 18th and 19th centuries, a time-varying and non-monotonic effect of temperature on current country incomes is revealed, with 18th century temperature exhibiting a positive and large effect while 19th century temperature shows an even larger negative effect (Table 3.5.1, regression 2). Interestingly, once historical climate is introduced, 20th century temperature no longer shows a strong, negative association with current income, suggesting that it may be serving as a proxy for the combined effects of historical climate, rather than capturing a direct impact of the current temperature level in the simple regression.

What might account for the estimated nonmonotonic relationship between temperature and income? Bluedorn, Valentinyi, and Vlassopoulos (2009) postulate that it could reflect interactions between temperature and historical events across centuries. For example, the large negative effect of 19th century temperature on current incomes could be linked to a slower diffusion of technologies from the United Kingdom and Europe, which were at the technological frontier then, and generally at the cooler end of the global temperature distribution. If the technologies these countries developed were more suitable for

The author of this box is John C. Bluedorn.

[1]Nunn (2014) provides an excellent exposition of the idea, which is central to recent empirical research on historical development.

Table 3.5.1. Effect of Historical Climate on Current Real Output

	Mean Temperature		Mean Temperature				
	1970–99	R^2	1970–99	1830–59	1730–59	R^2	N
Sample	(1)		(2)				
Full Sample	–0.061**	0.16	0.177	–2.100*	1.864**	0.27	167
	(0.011)		(0.073)	(0.315)	(0.301)		
Visual Outliers Excluded	–0.058**	0.15	0.179	–2.591**	2.353**	0.24	162
	(0.011)		(0.180)	(0.484)	(0.446)		
Sub-Saharan Africa Excluded	–0.026*	0.04	0.126**	–1.660**	1.505**	0.16	128
	(0.011)		(0.047)	(0.262)	(0.257)		
Neo-Europes Excluded	–0.057**	0.14	0.169*	–2.652**	2.423**	0.25	163
	(0.011)		(0.068)	(0.461)	(0.453)		

Source: IMF staff calculations.
Note: Dependent variable is log real GDP per capita in 2000, purchasing power parity adjusted. Robust standard errors appear underneath coefficient estimates in parentheses. Visual outliers are Australia, Bolivia, Eritrea, Ethiopia, and the United States. Neo-Europes = Australia, Canada, New Zealand, and the United States. N = number of countries in the cross-sectional sample. See Bluedorn, Valentinyi, and Vlassopoulos (2009).
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Box 3.5 *(continued)*

cooler climates, the negative correlation between 19th century temperature and current incomes could arise from historically slower technological adoption. Alternative interpretations are possible, such as a negative relationship between historical temperature and the quality of institutions adopted in European colonies in the 19th century (see Acemoglu, Johnson, and Robinson 2001).

The positive effect of 18th century temperature on current incomes is more difficult to interpret. Fenske and Kala (2015) provide a compelling hypothesis for Africa, where the level of a region's participation in the 18th century slave trade may have been shaped by climate conditions. Given the adverse effects higher temperatures have on agricultural productivity and mortality in hotter climates, as documented in the chapter, Fenske and Kala (2015) argue that a region's slave supply costs fell when temperatures were lower, leading to greater slave exports, which, in turn, is strongly associated with poorer incomes today (Nunn 2008).

Climate may have also affected the timing of transitions along the economic development path. Ashraf and Michalopoulos (2015) argue that climatic volatility thousands of years ago affected the willingness of human societies to experiment with farming as a solution to unpredictable foraged food sources. They find a statistically significant and robust hump-shaped relationship between the standard deviation of historically experienced temperatures in a region and the timing of the adoption of agriculture—areas with more volatile climate (assuming that the volatility was not so large as to precipitate social collapse) tended to make the transition to farming earlier, partly accounting for differences in income today.

Andersen, Dalgaard, and Selaya (2016) consider another characteristic of climate—the historical intensity of ultraviolet radiation (UV-R) experienced in a location. They argue that higher UV-R intensity affects mortality and thereby the willingness to engage in human capital investment. This, in turn, affected the time at which a society experienced the fertility transition (the decline of fertility associated with a rise in incomes; see Galor 2011). A slower fertility transition is associated with lower incomes at the country level today. In a mix of empirical and theoretical work, they find a positive relationship between UV-R and the transition timing, consistent with the link they hypothesize.

As shown by these studies, historical climate can have very long-lived effects on economic development through its interaction with historical events.

Box 3.6. Mitigating Climate Change

Although the primary focus of the chapter is the macroeconomic consequences of climate change and potential for adaptation in low-income countries, only a concerted global effort to cut greenhouse gas emissions and slow the pace of rising temperatures can limit the long-term threat of climate change. This box reviews recent developments in climate change mitigation efforts and describes the crucial role fiscal policies could play in abating climate change and mobilizing financing for mitigation and adaptation, drawing on recent IMF work.[1]

The 2015 Paris Agreement

In December 2015 parties to the United Nations Framework Convention on Climate Change agreed to the aspirational goal of containing global warming to 2°C above preindustrial levels (and to strive to keep warming to 1.5°C), thus laying the foundation for meaningful progress on addressing climate change at the global level. Mitigation pledges were submitted by 195 countries in their Nationally Determined Contributions (NDCs) under the 2015 Paris Agreement, with many pledges aiming to reduce emissions in 2030 by about 30 percent relative to emissions in some baseline year. Starting in 2018 parties are required to report progress on meeting mitigation pledges every two years, and to submit updated (and preferably more stringent) NDCs every five years. The pledges are not legally binding, however, and there is some risk of backtracking, given that the United States is withdrawing from the agreement.

The Paris Agreement strengthens previous commitments by developed economies to jointly mobilize $100 billion a year by 2020 for adaptation and mitigation in developing economies. By 2025 the parties to the agreement are expected to set a new collective quantifiable goal from a floor of $100 billion a year—many developing countries' more ambitious mitigation commitments are contingent on receiving external finance.

The Role of Fiscal Instruments in Climate Change Mitigation

It is widely accepted that carbon pricing—charging for the carbon emissions from fossil fuels—should be front and center in implementing mitigation pledges in both advanced and emerging market economies. Charging for carbon emissions increases the price of energy from fossil fuels (especially carbon-intensive coal) and provides incentives for mitigation, including replacing coal with less-carbon-intensive natural gas as well as carbon-free renewables and nuclear energy. In addition, carbon pricing stimulates improvements in energy efficiency, reduces the demand for energy-consuming products, and promotes innovation (for example, in the areas of carbon capture and storage technologies).

Carbon pricing can be implemented through carbon taxes or emissions trading systems. Carbon taxes are imposed on fossil fuels in proportion to the fuel's carbon content. Implementing carbon taxes is a straightforward extension of already-established taxes on fossil fuels and can be easily administered in most countries. Emissions trading systems put an upper limit on emissions by issuing emissions allowances. Firms are required to obtain allowances to cover their emissions, and the trading of allowances among emitters establishes the price of emissions. Emissions trading systems are typically implemented downstream on power generators and large industrial firms and need to be accompanied by other measures to cover smaller sources of emissions, for example, from vehicles and buildings.

China

China, the largest emitter of carbon dioxide (CO_2), accounted for 29 percent of global emissions in 2013. According to IMF estimates, phasing in an emissions tax of $70 a ton of CO_2 in China by 2030 would raise the prices of coal, electricity, and road fuels by about 70 percent, 15 percent, and 7 percent, respectively, and reduce 2030 emissions by about 30 percent, relative to the no-tax scenario (Figure 3.6.1, panel 1). An alternative with almost equal effectiveness would simply involve the addition of a carbon charge to existing taxes on domestic and imported coal. An emissions trading system would be about 40 percent less effective than a carbon tax. Given that China is moving ahead with an emissions trading system in any case, combining it with an up-front coal charge (perhaps with rebates for entities covered by the emissions trading system) would ensure more comprehensive pricing. Despite being less effective than carbon taxes, an emissions trading

The author of this box is Ian Parry.

[1]See, for example, Chapter 4 of the October 2008 *World Economic Outlook*; Parry, de Mooij, and Keen (2012); Parry, Morris, and Williams (2015); Farid and others (2016); and Parry and others (2016).

Box 3.6 *(continued)*

system is nonetheless much more effective than a variety of other mitigation policies, such as incentives for energy efficiency or renewables and taxes on road fuels and electricity.

Coal and carbon taxes, if phased in between 2017 and 2030, would also substantially reduce air pollution in China and save almost 4 million lives. The emissions trading system is about half as effective in this regard, with about 2 million lives saved (Figure 3.6.1, panel 2). The carbon tax would also raise substantial revenues of about 3 percent of GDP in 2030. In other countries, typically less coal intensive than China, reduced CO_2 emissions, lower domestic air pollution, and increased fiscal revenues would be less striking (in proportionate terms). However, the key policy lessons would remain unchanged: carbon taxes are the most effective mitigation instrument. Furthermore, carbon taxes—because of their domestic environmental and fiscal benefits—can be (up to a point) in countries' own interests.

Easing the Transition to Carbon Pricing

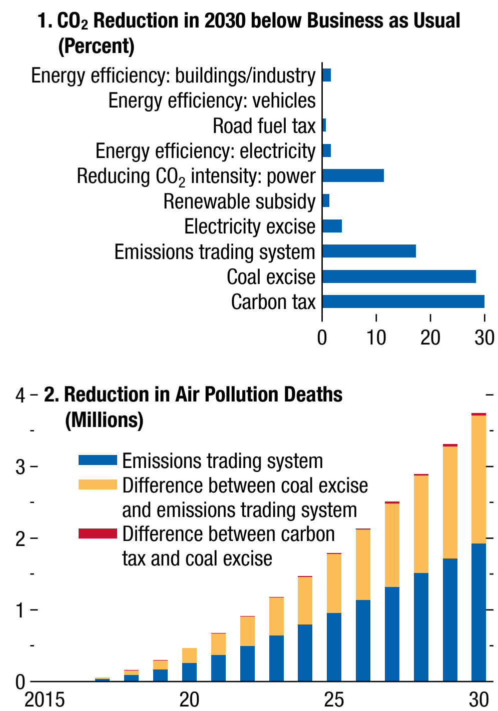
At the domestic level, undesirable effects of carbon pricing need to be mitigated to ease its adoption. Some carbon-intensive industries might become uneconomical as a result of carbon pricing, and their employees will require help with retraining and reallocation to other sectors. Using a fraction of revenues from carbon pricing to enhance social safety nets and to offer other forms of fiscal relief to low-income households would smooth the transition as well.[2]

At the international level, policymakers might consider imposing carbon price floor requirements for large emitters to reinforce the Paris Agreement and provide some reassurance against losses in competitiveness. Countries could elect to set carbon prices above the floor for fiscal or domestic environmental reasons, thus becoming environmental leaders—a prototype for this type of arrangement is the recently announced requirement that Canadian provinces phase in a price of Can$50 a ton of CO_2 by 2022.

Progress on Climate Mitigation

Carbon pricing mechanisms have proliferated—about 40 national governments and more than 20 subnational governments have implemented, or are implementing, some form of carbon pricing. Much more remains to be done, however. Only 12 percent of global greenhouse gases are currently priced (although China's emissions trading system will double this figure). Current prices are also too low. CO_2 prices for emissions trading systems are less than \$15 a ton of CO_2, and carbon taxes are mostly less than \$25 a ton, with the notable exceptions of Canada and the Scandinavian countries (World Bank, Ecofys, and Vivid Economics 2016). In contrast, average global prices of about \$40–\$80 a ton by 2020 would be consistent with limiting projected warming to 2°C (Stern and Stiglitz 2017). This shortfall in appropriate pricing could result in large-scale future climate change and underscores the pressing need for adaptation investment.

Figure 3.6.1. Effectiveness of Mitigation Policies in China



Source: Parry and others (2016).
Note: The price is \$70 per ton of CO_2 for emissions trading system, coal excise, and carbon tax. CO_2 = carbon dioxide.

[2]For example, Parry and others (2016) and Parry, Mylonas, and Vernon (2017) show that, at least initially, this assistance will require about 10 percent or less of the carbon pricing revenues.

Box 3.6 *(continued)*

The Role of Fiscal Instruments in Climate Finance

Financing needs for climate adaptation investment in developing economies have been estimated at upward of $80 billion a year until 2050 (Margulis and Narain 2010), which greatly exceeds current finance from advanced economies. The volume of public and private climate finance mobilized by developed economies for developing economies reached $62 billion in 2014 (of which only 15 percent was for adaptation), compared with the $100 billion goal set in 2009 and reiterated in the Paris Agreement (OECD 2015b). On equity grounds, there is some appeal in linking climate finance donations from advanced economies to their contribution to climate change. If the Group of Twenty economies, excluding the five members with lowest per capita income, donated $5 for each ton of projected CO_2 emissions, an additional $70 billion for climate finance could be raised in 2020.[3] Funding these contributions from national budgets would provide a more robust source of finance than apportioning a fraction of revenues from future (and highly uncertain) carbon pricing. The onus, however, is on recipient countries to carefully cost and prioritize adaption projects and to attract finance through resilient macro-fiscal frameworks and strong governance.

[3]IMF staff calculations, assuming emissions are reduced linearly over time to meet countries' Paris Agreement mitigation pledges. Carbon charges for international aviation and maritime fuels are another promising source of climate finance—a $30 a ton CO_2 charge on these fuels could raise revenues of $25 billion in 2020, even with full compensation for developing economies (Farid and others 2016).

Annex 3.1. Data Sources and Country Groupings

Data Sources

The primary data sources for this chapter are the IMF World Economic Outlook database and the World Bank World Development Indicators database. The main data sources on temperature and precipitation are the University of East Anglia's Climate Research Unit (historical data, 1901–2015) and National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections data set (forecast, present–2100). All data sources used in the chapter's analysis are listed in Annex Table 3.1.1.

For real GDP per capita, investment, and imports, the sources are listed in the order in which they are spliced (which entails extending the level of a primary series using the growth rate of a secondary series).

Data Definitions

The main historical temperature and precipitation series used in the chapter's analysis are constructed by aggregating grid cell data at 0.5 × 0.5 degree resolution (approximately 56 kilometers × 56 kilometers at the equator) to the level of individual countries or subnational regions at annual or monthly frequency.

Annex Table 3.1.1. 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 data set (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)
Population 2010, 1990, 1950 (Grid level)	Center for International Earth Science Information Network (CIESIN v.3 and v.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, 2015 Revision
CO_2 Emissions	Carbon Dioxide Information Analysis Center
Temperature Forcings	Carbon Dioxide Information Analysis Center; NASA GISS; Roston and Migliozzi (2015)
Natural Disasters	Centre for Research on the Epidemiology of Disasters, International Disaster Database (EM-DAT)
Global Ocean Temperature	NOAA (2017a)
Migration	Global Bilateral Migration Database, World Bank Group; Özden and others (2011)
Real GDP per Capita	IMF, World Economic Outlook database; World Bank, World Development Indicators database
Subnational GDP per Capita	Gennaioli and others (2014)
Crop Production Index	Food and Agriculture Organization; 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 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, Human Development Report database
Consumer Price Index	IMF, World Economic Outlook database
Debt-to-GDP Ratio	IMF, Historical Public Debt database
Reserves Minus Gold	Lane and Milesi-Ferretti (2017); External Wealth of Nations database, updated to 2015
Net Official Development Assistance and Official Aid Received	World Bank, World Development Indicators database
Personal Remittances Received	World Bank, World Development Indicators database
Exchange Rate Regime Indicator	Reinhart and Rogoff (2004); Ilzetzki, Reinhart, and Rogoff (2008), updated to 2015
Adaptation Readiness and Capacity	Notre Dame Global Adaptation Initiative; Chen and others (2015)
Domestic Financial Sector Liberalization Index	Abiad, Detragiache, and Tressel (2008)
Quinn-Toyoda Capital Control Index	Quinn (1997); Quinn and Toyoda (2008)
Human Capital Index	Penn World Tables 9.0
Paved Roads Kilometers per Capita	Calderón, Moral-Benito, and Servén (2015); World Bank, World Development Indicators database; Chapter 3 of the October 2014 *World Economic Outlook*
Revised Combined Polity Score (Polity2)	Polity IV Project
Gini Coefficient	Standardized World Income Inequality Database

Source: IMF staff compilation.

The estimates are weighted by grid-level population (exploring three alternatives: population distribution as of 1950, 1990, and 2010) to account for differences in population density (Dell, Jones, and Olken 2014).

Temperature and precipitation projections are from two of the four scenarios, called Representative Concentration Pathways (RCP), constructed by the Intergovernmental Panel on Climate Change. The RCP 4.5 scenario assumes increased attention to the environment with slow growth of carbon dioxide (CO_2) emissions until 2050 and a decline of emissions thereafter, resulting in a mean temperature increase of 1.8°C by 2081–2100 relative to 1986–2005 (in a range of 1.1°C–2.6°C, with a greater than 50 percent chance of an increase exceeding 2°C by 2100). In the RCP 8.5 scenario, CO_2 emissions continue to grow unconstrained, and the average 2081–2100 temperature is expected to be 3.7°C higher (in a range of 2.6°C–4.8°C) relative to 1986–2005. The chapter uses the average of the maximum and minimum daily temperature and total daily precipitation data from 2005 and projections for 2050 and 2100 at the 0.25 x 0.25 degree resolution, averaged across the 21 models of the Coupled Model Intercomparison Project Phase 5 for each scenario. Annual temperatures are computed as the average of the daily temperature; annual precipitation is the sum of daily precipitation.

Country Groupings

Annex Table 3.1.2. 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, Macedonia FYR, Malaysia, Maldives,* Marshall Islands,* Mauritius, Mexico, Micronesia,* Montenegro, Morocco, Namibia, Nauru,* 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 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, Kenya, Korea, Kyrgyz Republic, Latvia, Lesotho, Lithuania, Macedonia FYR, Malaysia, Mexico, Mongolia, Morocco, Mozambique, Nepal, Netherlands, Nicaragua, Nigeria, Norway, Pakistan, Panama, Paraguay, 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
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

Source: IMF staff compilation.
* Not included in the main regression analysis.

Annex 3.2. Weather Shocks and Natural Disasters

Although there is a clear link between weather conditions and the occurrence of extreme weather events, the relationship between weather shocks and natural disasters—extreme events associated with significant economic damage and loss of life—has not been studied in detail. The analysis in this section examines how weather conditions influence the frequency of various types of weather-related natural disasters.

A logit panel specification with country fixed effects is used to estimate the effect of the weather variables $c_{i,t}$ (temperature and precipitation) on the probability of a natural disaster taking place in country i in a given month t.

$$\Pr\left(\text{disaster}_{i,t} = 1\right) = \Phi\,(\beta_1 c_{i,t} + \beta_2 c_{i,t}^2 + \gamma_1 Dev_{i,t}^T + \gamma_2 Dev_{i,t}^P + \gamma_3 Dev_{i,t}^{Ocean} + \delta_1 \ln(GDP)_{i,t-12} + \delta_2 \ln(Pop)_{i,t-12} + \mu_i + \varepsilon_{i,t}), \quad (3.1)$$

in which the nonlinear function $\Phi(\cdot) = \exp(\cdot)/(1+\exp(\cdot))$ captures the effect of the regressors on the probability of a natural disaster. Country fixed effects (μ_i) capture time-invariant country characteristics, such as the size and geographic location of the country and its topology, that may influence the exposure and vulnerability of countries to different types of disasters.[51] The specification controls for the level of real GDP per capita and population, as well as for global weather conditions—specifically the deviation in global ocean surface temperature from the 1901–2000 average—that might affect the incidence of disasters. The sample includes monthly data during 1990–2014 for 228 countries and territories on more than 8,000 weather-related disasters. Equation (3.1) is estimated separately for each type of natural disaster, improving on Thomas and Lopez (2015), who perform a similar exercise on annual data, but group together all disasters.

Annex Table 3.2.1 presents the estimation results for each disaster type. Weather conditions have a very strong impact on the occurrence of disasters. More precipitation reduces the occurrence of disasters caused by droughts, wildfires, and heat waves, but increases the probability of disasters triggered by floods, landslides, cold waves, tropical cyclones, and other storms. The effects of temperature are also as expected, with higher temperatures resulting in more disasters caused by droughts, wildfires, heat waves, tropical cyclones, and other storms, but reducing the probability of cold waves. The results also show that precipitation has nonlinear effects on the probability of most disasters.

Interestingly, the estimations suggest that the weather conditions over the preceding 12 months have a significant effect on the occurrence of most types of disasters. Weather anomalies during the previous year, as captured in the cumulative deviation of temperature and precipitation from its monthly 10-year average, are important determinants of all types of disasters, except those caused by landslides or tropical cyclones, which are entirely a function of short-term weather patterns. Epidemics, however, are not affected by short-term weather conditions, but respond to temperature deviations in the year before the event is triggered.

To quantify the likely impact of climate change, the analysis combines the estimation results and projected temperature and precipitation in 2050 and 2100 under Representative Concentration Pathway 8.5 to predict the likelihood of each type of natural disaster. These predicted probabilities in 2050 and 2100 are compared with the predicted incidence of natural disasters over 2010–14 in Figure 3.6.

Annex 3.3. Empirical Analysis of the Macroeconomic Effects of Weather Shocks and the Role of Policies

This annex provides further details on the empirical model used to quantify short- and medium-term effects of weather on economic activity to identify the channels through which these effects occur, investigate evidence or lack thereof of adaptation over time, and study the role of various policy measures in attenuating the effects of temperature shocks.

The baseline analysis uses Jordà's (2005) local projection method to trace out the impulse response functions of various outcomes to weather shocks based on the following equation:

[51]Given the large time dimension of the sample (each country has about 300 observations), a panel logit specification is preferred to conditional logit models because it allows for the estimation of predicted and marginal effects accounting for country fixed effects. The results are robust to the use of conditional logit regression models developed by Chamberlain (1980) to avoid the incidental parameters problem that may arise from estimating fixed effects with a small time sample.

Annex Table 3.2.1. Effect of Weather Shocks on Natural Disasters, 1990–2014

Dependent Variable	Drought (1)	Epidemic (2)	Flood (3)	Landslide (4)	Wildfire (5)	Cold Wave (6)	Heat Wave (7)	Tropical Cyclone (8)	Other Storms (9)
Precipitation	–0.002***	0.000	0.022***	0.018***	–0.023***	0.014***	–0.009***	0.012***	0.012***
	(0.001)	(0.001)	(0.002)	(0.003)	(0.004)	(0.005)	(0.003)	(0.003)	(0.004)
Precipitation^2	0.000***	0.000	–0.000***	–0.000***	0.000***	–0.000**	0.000***	–0.000*	–0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Temperature	0.024*	0.009	0.051***	–0.010	0.109***	–0.286***	0.282*	0.168***	–0.063***
	(0.013)	(0.012)	(0.020)	(0.025)	(0.012)	(0.049)	(0.144)	(0.039)	(0.014)
Temperature^2	–0.000	0.000	–0.001	–0.000	0.001	–0.007***	0.005	–0.001	0.000
	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.002)	(0.005)	(0.001)	(0.001)
Precipitation Deviations (12 months)	–0.005***	–0.000	0.001***	0.001	–0.001*	–0.001*	–0.003***	0.000	0.000
	(0.001)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.000)
Temperature Deviations (12 months)	0.037*	0.024**	–0.008	–0.013	0.022	–0.042***	0.026	0.003	0.033***
	(0.019)	(0.012)	(0.006)	(0.013)	(0.020)	(0.015)	(0.019)	(0.009)	(0.007)
Global Ocean Temperature Deviations	–0.127	1.014**	0.274	0.028	1.566*	1.098	0.861	–1.441***	0.395
	(1.002)	(0.486)	(0.298)	(0.578)	(0.870)	(0.781)	(1.025)	(0.549)	(0.370)
Log GDP per Capita$_{t-12}$	–0.975*	–0.589**	–0.059	0.033	–1.029	2.486***	0.045	–0.076	–0.303
	(0.500)	(0.267)	(0.158)	(0.383)	(0.711)	(0.627)	(0.382)	(0.302)	(0.279)
Log Population$_{t-12}$	0.869	2.361***	2.575***	0.650	0.821	–1.026	0.273	2.617***	0.058
	(0.878)	(0.364)	(0.318)	(0.662)	(1.211)	(1.392)	(1.267)	(0.582)	(0.575)
Constant	10.481*	5.529*	1.646	–5.050	9.982	–31.876***	–9.242**	0.504	3.519
	(6.145)	(3.087)	(1.896)	(4.746)	(8.525)	(7.772)	(4.416)	(3.683)	(3.352)
Number of Observations	29,976	35,772	43,632	19,620	18,732	17,844	12,924	20,652	33,684
Number of Countries	101	120	147	66	63	61	44	69	114

Source: IMF staff calculations.
Note: The dependent variable is an indicator that takes the value of 1 if a natural disaster of a particular type is taking place. All specifications control for country fixed effects. Standard errors are clustered at the country level.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

$$y_{i,t+h} - y_{i,t-1} = \beta_1^h c_{i,t} + \beta_2^h c_{i,t}^2 + \gamma_1^h c_{i,t-1} + \gamma_2^h c_{i,t-1}^2 + \sum_{j=1}^{h-1} \delta_1^h c_{i,t+h-j} + \sum_{j=1}^{h-1} \delta_2^h c_{i,t+h-j}^2 + \varphi_1^h \Delta y_{i,t-1} + \mu_i^h + \theta_{r,t}^h + \varepsilon_{i,t}^h, \quad (3.2)$$

in which i indexes countries, t indexes years, and h indexes the estimation horizon (from horizon 0, which represents the contemporaneous regression, up to horizon 7). Regressions for each horizon are estimated separately. The dependent variable is the cumulative growth rate of the outcome of interest between horizons $t - 1$ and $t + h$, measured as difference in the natural logarithms ($y_{i,t}$). Following Burke, Hsiang, and Miguel (2015a), the estimated regression has a quadratic specification in the weather variables $c_{i,t}$, which comprise average annual temperature (T) and precipitation (P). The regressions control for one lag of the dependent and weather variables and for forwards of the weather variables, as suggested by Teulings and Zubanov (2014). Country fixed effects (μ_i^h) control for all time-invariant country differences, such as latitude, initial macroeconomic conditions, 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. The analysis also explores an alternative fixed-effects structure proposed by Burke, Hsiang, and Miguel (2015a), which includes time fixed effects (τ_i^h) and country-specific linear and quadratic time trends ($\theta_i^h t + \theta_i^h t^2$) to account for within-country changes over time, such as demographic shifts, instead of the region-year fixed effects ($\theta_{r,t}^h$) 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, as documented below, and are thus not part of the baseline estimation.

Within this estimation framework, the effect of a 1°C increase in temperature on the level of output at horizon h can be obtained by differentiating equation (3.2) with respect to temperature:

$$\frac{\partial (y_{i,t+h} - y_{i,t-1})}{\partial T_{i,t}} = \beta_1^h + 2\beta_2^h T_{i,t}. \quad (3.3)$$

Evaluating equation (3.3) 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 can be obtained by setting equation (3.3) to zero.

The Effect of Weather Shocks on Economic Activity

Annex Table 3.3.1 presents the key results for the effect of weather shocks on per capita output, along with numerous robustness checks. 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 at the median 2015 temperature for advanced economies (median T = 11°C), emerging market economies (median T = 22°C), and low-income developing 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 advanced economies, emerging market economies, and low-income developing countries on impact and after seven years.

Annex Table 3.3.1 begins by replicating Burke, Hsiang, and Miguel's (2015a) specification and establishes its robustness to using alternative sources of weather data; alternative population weights that are used to aggregate gridded weather data at the country level; alternative sets of fixed effects; and alternative samples, controls, and estimation approaches. Column (1) estimates the specification used in Burke, Hsiang, and Miguel (2015a) and includes country-specific linear and quadratic time trends, University of Delaware weather data, and 1990 population weights in the chapter's substantially larger sample (the chapter expands the sample both geographically and temporally by about 25 percent). Column (2) uses an alternative source of weather data, the University of East Anglia Climate Research Unit instead of the University of Delaware, 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 given that migration within and across country borders is one of the potential strategies for coping with adverse weather conditions. Given that historical data show an increase in average annual temperatures starting in the 1970s (Figure 3.3), column (3) presents results with 1950 population weights to account for migration responses that could have already taken place.

Following Dell, Jones, and Olken (2012), column (4) and column (5) (main specification for the chapter)

Annex Table 3.3.1. Effect of Weather Shocks on Output

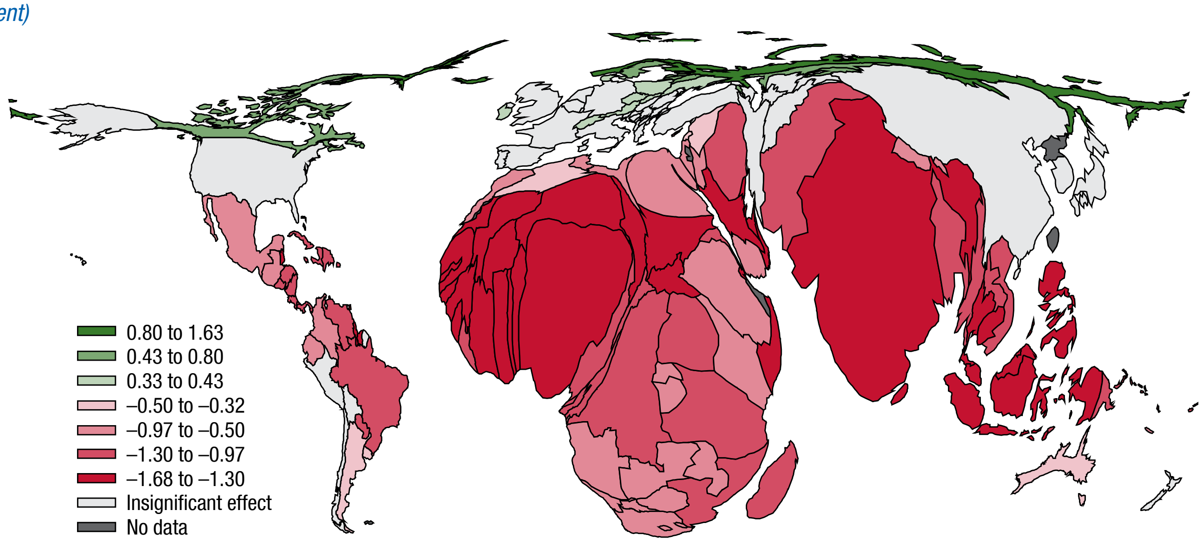
A. Real Output per Capita Growth	(1)	(2)	(3)	(4)	**(5)**	(6)	(7)	(8)	(9)
Temperature	1.399***	1.443***	1.428***	1.343***	**1.347*****	1.248***	1.342***	1.249***	–1.154***
	(0.359)	(0.367)	(0.366)	(0.355)	**(0.357)**	(0.339)	(0.355)	(0.380)	(0.320)
Temperature^2	–0.049***	–0.049***	–0.048***	–0.052***	**–0.051*****	–0.044***	–0.051***	–0.044***	
	(0.012)	(0.011)	(0.011)	(0.011)	**(0.011)**	(0.010)	(0.011)	(0.011)	
Precipitation	0.056	0.103*	0.163*	0.045	**0.110**	0.127	0.119	0.082	0.005
	(0.097)	(0.061)	(0.085)	(0.058)	**(0.104)**	(0.103)	(0.104)	(0.112)	(0.034)
Precipitation^2	–0.002	–0.002**	–0.004**	–0.001	**–0.003**	–0.003	–0.003	–0.002	
	(0.002)	(0.001)	(0.002)	(0.001)	**(0.002)**	(0.002)	(0.002)	(0.002)	
Any Disaster							–0.406**		
							(0.180)		
Threshold Temperature (°C)	14	15	15	13	**13**	14	13	14	
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**	Y	N	N	N
Adjusted R^2	0.15	0.15	0.15	0.14	**0.14**	0.14	0.14	0.11	0.09
Number of Countries	177	198	189	198	**189**	184	189	189	127
Number of Observations	8,147	9,114	8,815	9,114	**8,815**	8,756	8,815	8,917	6,135
B. Impact of a 1°C Increase in Temperature on Real Output per Capita Level at Horizon 0									
AE (T=11°C)	0.331*	0.370*	0.365*	0.197	**0.218**	0.280	0.217	0.277	
	(0.196)	(0.196)	(0.195)	(0.191)	**(0.196)**	(0.190)	(0.195)	(0.212)	
EM (T=22°C)	–0.736**	–0.703***	–0.697***	–0.949***	**–0.911*****	–0.687***	–0.907***	–0.695***	
	(0.309)	(0.223)	(0.223)	(0.266)	**(0.264)**	(0.228)	(0.263)	(0.243)	
LIDC (T=25°C)	–1.027***	–0.996***	–0.987***	–1.261***	**–1.219*****	–0.951***	–1.214***	–0.960***	
	(0.370)	(0.268)	(0.267)	(0.318)	**(0.315)**	(0.270)	(0.313)	(0.287)	
Impact of a 1°C Increase in Temperature on Real Output per Capita Level at Horizon 7									
AE (T=11°C)	0.898	0.889	0.822	0.457	**0.558**	0.560	0.552	0.023	
	(0.705)	(0.701)	(0.697)	(0.744)	**(0.752)**	(0.744)	(0.751)	(0.478)	
EM (T=22°C)	–1.173	–0.957	–1.048	–1.117*	**–1.115***	–1.088*	–1.138*	–0.547	
	(0.852)	(0.665)	(0.651)	(0.604)	**(0.591)**	(0.595)	(0.589)	(0.386)	
LIDC (T=25°C)	–1.738*	–1.461*	–1.558**	–1.547**	**–1.571****	–1.537**	–1.599**	–0.702	
	(1.002)	(0.761)	(0.745)	(0.686)	**(0.667)**	(0.670)	(0.664)	(0.450)	
C. Impact of a 100 mm per Year Increase in Precipitation on Real Output per Capita Level at Horizon 0									
AE (P=800 mm per year)	0.018	0.066	0.101*	0.028	**0.066**	0.076	0.073	0.050	
	(0.067)	(0.046)	(0.059)	(0.046)	**(0.071)**	(0.070)	(0.071)	(0.077)	
EM (P=900 mm per year)	0.013	0.061	0.093*	0.026	**0.060**	0.070	0.067	0.046	
	(0.063)	(0.045)	(0.056)	(0.045)	**(0.067)**	(0.066)	(0.067)	(0.072)	
LIDC (P=1,100 mm per year)	0.004	0.052	0.078	0.022	**0.049**	0.057	0.056	0.038	
	(0.057)	(0.041)	(0.050)	(0.042)	**(0.059)**	(0.058)	(0.059)	(0.064)	
Impact of a 100 mm per Year Increase in Precipitation on Real Output per Capita Level at Horizon 7									
AE (P=800 mm per year)	0.304	0.171	0.179	–0.173	**–0.187**	–0.207	–0.209	–0.287	
	(0.198)	(0.216)	(0.227)	(0.214)	**(0.223)**	(0.225)	(0.224)	(0.229)	
EM (P=900 mm per year)	0.295	0.166	0.174	–0.156	**–0.166**	–0.187	–0.188	–0.267	
	(0.188)	(0.205)	(0.215)	(0.200)	**(0.209)**	(0.210)	(0.210)	(0.216)	
LIDC (P=1,100 mm per year)	0.278	0.155	0.164	–0.121	**–0.126**	–0.148	–0.146	–0.227	
	(0.169)	(0.185)	(0.192)	(0.174)	**(0.182)**	(0.182)	(0.183)	(0.191)	

Source: IMF staff calculations.

Note: The table presents results from estimating equation (3.2), 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 (3.3) 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; lags and forwards of temperature, precipitation, and their squared terms; and lag of growth. Column (8) shows results from estimating an autoregressive distributed lag model with seven lags of the weather variables and their squared terms. Column (9) reports the coefficients on temperature and precipitation from a linear specification estimated on a sample of countries with average temperature above 15°C, also including controls for country fixed effects and lag of growth. In all specifications, standard errors are clustered at the country level. CRU = University of East Anglia, Climate Research Unit; mm = millimeter; UDEL = University of Delaware.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Annex Figure 3.3.1. Effect of Temperature Increase on Real per Capita Output across the Globe, with Countries Rescaled in Proportion to Their Projected Population as of 2100
(Percent)



Sources: Natural Earth; ScapeToad; United Nations World Population Prospects database: the 2015 revision; and IMF staff calculations.
Note: The map depicts the contemporaneous effect of a 1°C increase in temperature on per capita output computed as per equation (3.3) using recent 10-year average country-level temperature together with estimated coefficients in Annex Table 3.3.1, column (5). Each country is rescaled in proportion to the projected population as of 2100. Using projected population as of 2100, 76 percent of world population will live in countries that experience a negative impact from 1°C increase. Gray areas indicate the estimated impact is not statistically significant.

present results for the baseline specification with region-year fixed effects instead of country-specific time trends. Column (6) limits the sample to countries with at least 20 years of data.

Column (7) controls separately for the occurrence of natural disasters given that temperature and precipitation fluctuations might affect economic activity through their effect on the incidence of natural disasters, as discussed in Annex 3.2. Controlling for natural disasters does not materially alter the estimated coefficients on temperature and precipitation.[52]

In columns (1)–(7), impulse responses were estimated using Jordà's (2005) local projection method. This approach is advocated by Stock and Watson (2007), among others, as a flexible alternative that does not impose the dynamic restrictions embedded in vector autoregressions (autoregressive distributed lag) specifications and is particularly suited to estimating nonlinearities in the dynamic response. 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 test different models from no lags up to 10 lags and find that, across different lag specifications, results are broadly consistent in magnitude and statistical significance.

Across all specifications, 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, Hsiang, and Miguel (2015a). At low temperatures, an increase in temperature boosts growth, whereas at high temperatures, an increase in temperature hurts growth, with the threshold average annual temperature estimated to be about 13°C–15°C. As an additional robustness check, column (9) presents results of a linear regression without the squared terms of the weather variables in which the sample is limited to countries with average annual temperature above 15°C. Indeed, within the sample of relatively hot countries, the coefficient on temperature is negative and statistically significant. The effect of temperature increase across the globe is shown in Figure 3.8 panel 1 at grid level; in panel 2, where countries are rescaled in proportion to their 2015 population; and in Annex

[52]To further explore the robustness of these results, weather variables were transformed using natural logarithms or normalized by subtracting the country mean and dividing by the country standard deviation. Availability of data on subnational per capita GDP and annual average temperature and precipitation allows us to estimate the same regression at a subnational level using province fixed effects. Through all three specifications the main finding persists: there is a nonlinear relationship between temperature and economic performance (results available on request).

Figure 3.3.1, where countries are rescaled in proportion to projected 2100 population.

There is no consistently significant relationship between precipitation and per capita GDP growth across the various specifications. The lack of robust relationship could reflect potentially larger measurement error in the precipitation variable, as discussed in Auffhammer and others (2011), which could 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.

Annex Table 3.3.1 also reveals the very persistent effects of temperature shocks. The lower half of panel B presents the cumulative effects of a 1°C increase in temperature estimated at the median temperature of advanced, emerging market, and low-income developing countries seven years after the shock. All but one specification show evidence of a long-lasting and potentially deepening adverse impact of temperature shocks on per capita output at the temperatures experienced by the median low-income developing country.

To examine how widespread the effects of temperature may be, equation (3.2) is estimated using sectoral value added and agricultural production as the outcomes of interest. Real value added of the agricultural, manufacturing, and services sectors from the World Bank's World Development Indicators database is complemented with an index of crop production volume compiled by the United Nations Food and Agriculture Organization. Results are presented in Annex Table 3.3.2. There is a concave relationship between temperature and output in both the agricultural and manufacturing sectors, whereas services value added appears to be relatively protected from the effects of higher temperature. In other words, at the median temperature of low-income countries, an increase in temperature significantly reduces agricultural value added and crop production and lowers manufacturing output.

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. 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.

Channels

The chapter examines the potential channels through which temperature shocks affect the macroeconomy in a broad and long-lasting manner by studying the relationship between temperature and each of the main components of the aggregate production function.

Investment

As hypothesized by Fankhauser and Tol (2005), weather shocks could have long-lasting effects on output if they influence investment decisions, and hence capital input. Equation (3.2) is estimated using real gross fixed capital formation as the outcome of interest. The analysis also examines weather's impacts on imports, given the tight link between imports and investment. Results, presented in Annex Table 3.3.3, columns (1)–(2), confirm the idea that temperature shocks suppress investment. Although the uncertainty surrounding the estimated contemporaneous effects is large, seven years after a temperature increase, both investment and imports are significantly lower in countries with relatively hot climates (see also Figure 3.10).

Labor Input

The analysis also examines whether labor supply may be affected by temperature increases. Using infant mortality as the outcome of interest, equation (3.2) is estimated, uncovering a convex relationship between temperature and current (or future) labor supply (Annex Table 3.3.3, column [3]). In hot countries, an increase in temperature raises infant mortality instantaneously, with the effect growing over time. In these countries, 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 (column [4]).

Productivity

Motivated by the body of evidence of reduced human cognitive and physical performance at high temperatures from laboratory experiments and country-specific studies, the analysis examines whether reduced labor productivity may underpin the negative temperature–aggregate output relationship in countries with hot climates. If this is indeed

Annex Table 3.3.2. Effect of Weather Shocks on Sectoral Output

	Agriculture	Manufacturing	Services	Crop Production
A. Dependent Variable	(1)	(2)	(3)	(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
B. Impact of a 1°C Increase in Temperature on Dependent Variable Level at 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)
Impact of a 1°C Increase in Temperature on Dependent Variable Level at Horizon 7				
AE (T=11°C)	2.070***	1.642	–0.220	1.177
	(0.753)	(1.798)	(1.445)	(0.889)
EM (T=22°C)	–0.498	–0.926	0.054	–0.509
	(0.654)	(0.939)	(0.734)	(0.812)
LIDC (T=25°C)	–1.198	–1.626	0.129	–0.969
	(0.769)	(1.117)	(0.910)	(0.985)
C. Impact of a 100 mm per Year Increase in Precipitation on Dependent Variable Level at Horizon 0				
AE (P=800 mm per year)	0.458***	0.076	–0.013	0.835***
	(0.149)	(0.105)	(0.075)	(0.223)
EM (P=900 mm per year)	0.428***	0.072	–0.015	0.778***
	(0.139)	(0.100)	(0.071)	(0.210)
LIDC (P=1,100 mm per year)	0.366***	0.065	–0.018	0.665***
	(0.121)	(0.090)	(0.063)	(0.185)
Impact of a 100 mm per Year Increase in Precipitation on Dependent Variable Level at Horizon 7				
AE (P=800 mm per year)	–0.228	0.024	–0.141	–0.237
	(0.257)	(0.390)	(0.286)	(0.284)
EM (P=900 mm per year)	–0.213	0.030	–0.125	–0.217
	(0.243)	(0.371)	(0.269)	(0.267)
LIDC (P=1,100 mm per year)	–0.184	0.041	–0.094	–0.177
	(0.217)	(0.332)	(0.235)	(0.235)

Source: IMF staff calculations.
Note: The table presents results from estimating equation (3.2) using the same specification as in Annex Table 3.3.1, 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 (3.3) 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. mm = millimeter.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

the case, sectors where workers are more exposed to heat should see a bigger decrease in labor productivity when temperatures rise in relatively hot countries. The analysis uses the Groningen Growth and Development Centre 10-sector database, which provides sectoral real value added and employment in 40 countries over 1950–2012, and Graff Zivin and Neidell's (2014) classification of sectors into those that are "heat-exposed" and others to estimate the following specification:[53]

[53]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.

Annex Table 3.3.3. Effect of Weather Shocks on Productivity, Capital, and Labor

	Capital Input		Labor Input		Labor Productivity	
	Investment	Imports	Infant Mortality	HDI	Non-Heat Exposed	Heat Exposed
A. Dependent Variable	(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)
Temperature²	–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)
Precipitation²	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	
B. Impact of a 1°C Increase in Temperature on Dependent Variable Level at 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)
Impact of a 1°C Increase in Temperature on Dependent Variable Level at Horizon 7						
AE (T=11°C)	1.812	2.361	–0.364	0.609**	0.305	–1.142
	(2.029)	(1.494)	(0.427)	(0.259)	(1.183)	(0.986)
EM (T=22°C)	–4.225**	–2.439*	0.569	–0.237	–0.063	–1.642
	(1.803)	(1.303)	(0.375)	(0.175)	(1.114)	(1.119)
LIDC (T=25°C)	–5.871***	–3.747**	0.824*	–0.467**	–0.163	–1.778
	(2.074)	(1.516)	(0.426)	(0.195)	(1.306)	(1.365)
C. Impact of a 100 mm per Year Increase in Precipitation on Dependent Variable Level at Horizon 0						
AE (P=800 mm 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 mm 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 mm 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)
Impact of a 100 mm per Year Increase in Precipitation on Dependent Variable Level at Horizon 7						
AE (P=800 mm per year)	–0.478	–0.984**	0.071	–0.102*	–0.295	0.072
	(0.689)	(0.498)	(0.163)	(0.061)	(0.832)	(0.554)
EM (P=900 mm per year)	–0.423	–0.961**	0.074	–0.097*	–0.265	0.041
	(0.649)	(0.472)	(0.149)	(0.057)	(0.776)	(0.524)
LIDC (P=1,100 mm per year)	–0.313	–0.914**	0.080	–0.087*	–0.206	–0.022
	(0.573)	(0.422)	(0.123)	(0.050)	(0.666)	(0.467)

Source: IMF staff calculations.
Note: Columns (1–4) present results from estimating equation (3.2) using the same specification as in Annex Table 3.3.1, column (5), for different dependent variables. Specification in column (5) presents results from estimating equation (3.4) where an indicator for heat exposed sectors is interacted with temperature and precipitation, their squared terms, and their lags and forwards; 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 (3.3) 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; mm = millimeter.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

$$y_{i,s,t+h} - y_{i,s,t-1} = \beta_1^h c_{i,t} + \beta_2^h c_{i,t}^2 + \gamma_1^h c_{i,t-1} + \gamma_2^h c_{i,t-1}^2 + \sum_{j=1}^{h-1} \delta_1^h c_{i,t+h-j} + \sum_{j=1}^{h-1} \delta_2^h c_{i,t+h-j}^2 + \alpha_1^h c_{i,t} \times H_s + \alpha_2^h c_{i,t}^2 \times H_s + \omega_1^h c_{i,t-1} \times H_s + \omega_2^h c_{i,t-1}^2 \times H_s + \sum_{j=1}^{h-1} \tau_1^h c_{i,t+h-j} \times H_s + \sum_{j=1}^{h-1} \tau_2^h c_{i,t+h-j}^2 \times H_s + \varphi_1^h \Delta y_{i,s,t-1} + \mu_{i,s}^h + \theta_{r,t}^h + \varepsilon_{i,s,t}^h, \quad (3.4)$$

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.

Annex Table 3.3.3, specification (5) summarizes the results of this estimation. 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.

The Role of Policies and Institutional Settings

To study the extent to which macroeconomic and structural policies and country characteristics mediate the effect of weather shocks, the analysis extends the empirical approach described above by allowing the response of per capita output to weather shocks to vary with various proxies for these policies. The estimated specification augments equation (3.2) to include an interaction term between the weather shock and the policy variable:

$$y_{i,t+h} - y_{i,t-1} = \beta_1^h c_{i,t} + \gamma_1^h (c_{i,t} \times p_{i,t-1}) + \delta_1^h p_{i,t-1} + \beta_2^h c_{i,t-1} + \gamma_2^h (c_{i,t-1} \times p_{i,t-2}) + \delta_2^h p_{i,t-2} + \sum_{j=1}^{h-1} \beta_3^h c_{i,t+h-j} + \varphi_1^h \Delta y_{i,t-1} + \mu_i^h + \theta_{r,t}^h + \varepsilon_{i,t}^h. \quad (3.5)$$

The sample is restricted to countries with average annual temperature exceeding 15°C, in which an increase in temperature has a statistically significant linear negative impact on economic activity, as in Annex Table 3.3.1, column (9). Consequently, the weather shock $c_{i,t}$ refers to average annual temperature and precipitation. Most of the policy variables $p_{i,t}$ are lagged to minimize reverse causality concerns and are included one at a time. As emphasized in the chapter, it is difficult to interpret causally the coefficients on the interaction terms, given that the variation in policies and institutions across countries and over time is not random. Policies and institutions could also be correlated with relevant country attributes that are not controlled for in the regression. Moreover, policy data availability varies significantly in both temporal and country coverage, resulting in sizable differences in the estimation sample.

For ease of interpretation, in the baseline results, each policy variable is transformed into an indicator variable depending on whether, in year *t*, the country is above or below the median value of this particular policy in the estimation sample.[54] An exception to this approach is the measurement of buffers. A country is considered to have (1) fiscal buffers if public debt as a share of GDP is less than the 75th percentile, (2) monetary buffers if annual inflation is less than 10 percent, (3) high international reserves if international reserves minus gold can cover at least four months of imports, (4) high foreign aid if foreign aid inflows as a share of GDP are in the 75th percentile, and (5) high remittances if per capita remittances in real dollars received are greater than the 75th percentile. For exchange rate policy, the analysis uses an indicator if the de facto exchange rate regime of a country is not pegged based on the coarse classification of Reinhart and Rogoff (2004).

Annex Tables 3.3.4 and 3.3.5 present the main findings. For each policy, the tables report the estimated effect of a 1°C increase in temperature on per capita output at horizons 0 through 7, where the policy is not in place and where the policy is in place. The tables also report the *p*-value of a statistical test of the difference between the effect of temperature in different policy scenarios.

The short-term negative effects of temperature shocks tend to be larger in countries with lower buffers, as evidenced by the larger estimated responses in columns (2), (5), and (8) in Annex Table 3.3.4. However, the differences are typically not statistically significant, and in the few cases in which they are (fiscal buffers, foreign aid, and remittances), they tend to be very short lived. Exchange rate regime, however, seems to be significantly associated with the extent of damage caused by weather shocks. Countries with nonpegged exchange rates tend to recover faster from these shocks. A similar pattern was documented by Ramcharan (2009), who finds that exchange rate flexibility helps economies adjust better in the aftermath of windstorms and earthquakes.

[54]Results from an alternative specification in which the policy variables are used in their continuous forms rather than transformed into indicators are available on request.

Annex Table 3.3.4. Role of Policy Buffers

Impact of a 1°C Increase in Temperature on per Capita Output	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Public Debt			Inflation			International Reserves		
	Low	High	P-value	Low	High	P-value	High	Low	P-value
Horizon 0	−1.057***	−1.460***	0.09	−1.183***	−1.275***	0.40	−1.015**	−1.171***	0.52
	(0.387)	(0.352)		(0.295)	(0.322)		(0.414)	(0.314)	
Horizon 1	−1.029**	−1.627***	0.24	−0.952***	−0.985**	0.87	−0.556	−0.782**	0.36
	(0.471)	(0.466)		(0.362)	(0.425)		(0.492)	(0.395)	
Horizon 2	−0.914*	−1.695**	0.24	−0.933**	−0.907**	0.87	−0.952**	−1.030***	0.58
	(0.492)	(0.690)		(0.375)	(0.416)		(0.390)	(0.382)	
Horizon 3	−1.597***	−2.159***	0.34	−1.279***	−1.333***	0.79	−1.182***	−1.140***	0.78
	(0.525)	(0.758)		(0.419)	(0.429)		(0.404)	(0.411)	
Horizon 4	−1.512**	−1.986**	0.46	−1.355**	−1.487**	0.55	−1.404***	−1.440***	0.85
	(0.704)	(0.972)		(0.560)	(0.571)		(0.522)	(0.522)	
Horizon 5	−0.899	−1.341	0.42	−1.014*	−1.181*	0.46	−1.390**	−1.270**	0.66
	(0.758)	(0.936)		(0.583)	(0.628)		(0.609)	(0.603)	
Horizon 6	−1.075	−1.277	0.68	−1.315**	−1.572**	0.32	−1.524**	−1.362**	0.55
	(0.844)	(0.867)		(0.626)	(0.675)		(0.614)	(0.597)	
Horizon 7	−0.552	−0.633	0.87	−0.842	−1.032	0.52	−1.566**	−1.353**	0.49
	(0.819)	(0.859)		(0.610)	(0.628)		(0.629)	(0.611)	
Adjusted R^2		0.15			0.12			0.09	
Number of Countries		119			122			127	
Number of Observations		4,492			5,365			6,135	

Impact of a 1°C Increase in Temperature on per Capita Output	Foreign Aid			Remittances			Exchange Rate Flexibility		
	High	Low	P-value	High	Low	P-value	Not Pegged	Pegged	P-value
Horizon 0	−0.840**	−1.194***	0.06	−1.345***	−1.449***	0.34	−1.183***	−1.436***	0.16
	(0.380)	(0.334)		(0.337)	(0.312)		(0.321)	(0.315)	
Horizon 1	−0.996**	−1.132***	0.59	−1.212***	−1.472***	0.13	−0.792*	−1.249***	0.08
	(0.448)	(0.396)		(0.389)	(0.410)		(0.426)	(0.415)	
Horizon 2	−0.958**	−0.979**	0.94	−0.799*	−1.030**	0.31	−0.575	−1.191**	0.08
	(0.433)	(0.401)		(0.436)	(0.456)		(0.483)	(0.503)	
Horizon 3	−0.931*	−1.020**	0.74	−1.271**	−1.488***	0.45	−0.769	−1.342**	0.20
	(0.551)	(0.475)		(0.530)	(0.499)		(0.574)	(0.600)	
Horizon 4	−0.724	−1.061*	0.32	−1.260*	−1.348**	0.77	−0.975	−1.853**	0.08
	(0.672)	(0.539)		(0.678)	(0.664)		(0.781)	(0.801)	
Horizon 5	−0.772	−0.913*	0.70	−1.182*	−1.287**	0.76	−0.408	−1.556*	0.04
	(0.635)	(0.534)		(0.691)	(0.644)		(0.830)	(0.851)	
Horizon 6	−0.753	−1.108*	0.36	−1.571*	−1.860**	0.45	0.011	−1.109	0.06
	(0.731)	(0.598)		(0.842)	(0.751)		(0.828)	(0.780)	
Horizon 7	−0.620	−0.863*	0.59	−0.900	−1.179	0.49	−0.220	−1.418*	0.05
	(0.677)	(0.499)		(0.749)	(0.731)		(0.871)	(0.852)	
Adjusted R^2		0.16			0.14			0.10	
Number of Countries		120			115			115	
Number of Observations		5,175			3,441			3,942	

Source: IMF staff calculations.
Note: The table presents results from estimating equation (3.5) on a sample of countries with average annual temperature above 15°C. In the regressions, indicators for policy measures are interacted with temperature, precipitation, and their lags, controlling for country and region-year fixed effects, lags of growth and policy measure, forwards of temperature and precipitation. Separate regressions are estimated for each horizon. Regression summary statistics are reported for horizon 0. In all specifications, standard errors are clustered at the country level.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Annex Table 3.3.5. Role of Structural Policies and Institutions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Impact of a 1°C Increase in Temperature on per Capita Output	Domestic Financial Sector Reform Index			International Finance Restrictions			Human Capital		
	High	Low	P-value	Low	High	P-value	High	Low	P-value
Horizon 0	−1.540***	−1.631***	0.59	−0.766**	−1.139***	0.07	−1.039***	−1.152***	0.63
	(0.437)	(0.439)		(0.293)	(0.275)		(0.291)	(0.349)	
Horizon 1	−1.539***	−1.853***	0.17	−0.906**	−1.054***	0.50	−0.891**	−1.250***	0.25
	(0.518)	(0.598)		(0.391)	(0.367)		(0.411)	(0.420)	
Horizon 2	−0.413	−0.923	0.15	−0.622	−1.090**	0.10	−0.669	−1.092**	0.27
	(0.538)	(0.711)		(0.434)	(0.472)		(0.437)	(0.494)	
Horizon 3	−0.964	−1.724**	0.06	−1.089**	−1.359***	0.39	−1.065**	−1.250**	0.64
	(0.712)	(0.854)		(0.462)	(0.487)		(0.475)	(0.491)	
Horizon 4	−0.325	−1.118	0.10	−1.601***	−1.757***	0.69	−1.345**	−1.686***	0.49
	(0.829)	(0.855)		(0.502)	(0.529)		(0.527)	(0.576)	
Horizon 5	−0.707	−1.561*	0.13	−1.790**	−2.180***	0.41	−1.161	−1.590**	0.46
	(0.844)	(0.868)		(0.702)	(0.761)		(0.699)	(0.704)	
Horizon 6	−0.644	−1.412*	0.22	−1.608***	−1.868***	0.59	−1.009	−1.689**	0.34
	(0.805)	(0.807)		(0.594)	(0.615)		(0.685)	(0.724)	
Horizon 7	−0.071	−0.847	0.27	−1.525**	−1.975***	0.39	−0.657	−1.236*	0.44
	(0.888)	(0.818)		(0.682)	(0.718)		(0.736)	(0.715)	
Adjusted R^2		0.24			0.13			0.12	
Number of Countries		46			74			89	
Number of Observations		1,455			3,434			4,582	

Impact of a 1°C Increase in Temperature on per Capita Output	Physical Capital			Political Regime Index			Inequality		
	High	Low	P-value	High	Low	P-value	Low	High	P-value
Horizon 0	−0.773***	−0.861***	0.66	−1.370***	−1.452***	0.73	−1.336***	−1.559***	0.07
	(0.294)	(0.302)		(0.328)	(0.293)		(0.431)	(0.390)	
Horizon 1	−0.782*	−0.777*	0.99	−1.132***	−1.392***	0.27	−1.034*	−1.240**	0.26
	(0.405)	(0.423)		(0.393)	(0.367)		(0.580)	(0.588)	
Horizon 2	−0.550	−0.690	0.69	−1.110***	−1.729***	0.01	−0.814	−1.024*	0.35
	(0.442)	(0.459)		(0.416)	(0.433)		(0.584)	(0.591)	
Horizon 3	−0.430	−0.820	0.30	−1.374***	−1.929***	0.03	−0.947	−1.386*	0.09
	(0.411)	(0.497)		(0.466)	(0.464)		(0.714)	(0.738)	
Horizon 4	−0.543	−1.175**	0.15	−1.599***	−2.095***	0.09	−0.819	−1.391*	0.06
	(0.464)	(0.573)		(0.566)	(0.601)		(0.827)	(0.820)	
Horizon 5	−0.953	−1.677**	0.17	−1.587**	−2.044***	0.15	−0.699	−1.634*	0.01
	(0.625)	(0.755)		(0.671)	(0.705)		(0.899)	(0.877)	
Horizon 6	−0.381	−1.546**	0.09	−1.416**	−2.128***	0.06	−1.061	−2.067**	0.01
	(0.586)	(0.691)		(0.679)	(0.704)		(0.930)	(0.913)	
Horizon 7	−0.548	−1.610*	0.14	−1.325*	−2.320***	0.02	−0.233	−1.320	0.01
	(0.645)	(0.815)		(0.751)	(0.788)		(1.060)	(0.998)	
Adjusted R^2		0.13			0.10			0.28	
Number of Countries		114			106			95	
Number of Observations		3,905			5,056			1,798	

Source: IMF staff calculations.
Note: The table presents results from estimating equation (3.5) on a sample of countries with average annual temperature above 15°C. In the regressions, indicators for policy measures are interacted with temperature, precipitation, and their lags, controlling for country and region-year fixed effects, lags of growth and policy measure, forwards of temperature and precipitation. Separate regressions are estimated for each horizon. Regression summary statistics are reported for horizon 0. In all specifications, standard errors are clustered at the country level.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Annex Table 3.3.6. Role of Development: Evidence from Subnational Data

Impact of a 1°C Increase in Temperature on per Capita Output	Full Sample (1)	Advanced Economies	Non-Advanced Economies (2)	P-value
Horizon 0	−0.705***	−0.025	−0.727***	0.01
	(0.174)	(0.159)	(0.210)	
Horizon 1	−0.908***	0.320	−0.978***	0.00
	(0.263)	(0.232)	(0.315)	
Horizon 2	−0.599**	0.952***	−0.768**	0.00
	(0.290)	(0.350)	(0.357)	
Horizon 3	−0.543	1.089***	−0.875**	0.00
	(0.340)	(0.339)	(0.429)	
Horizon 4	−0.752*	0.736*	−1.130**	0.01
	(0.386)	(0.385)	(0.499)	
Horizon 5	−1.246***	0.485	−1.321**	0.04
	(0.460)	(0.510)	(0.588)	
Horizon 6	−1.156**	0.005	−1.596**	0.10
	(0.478)	(0.526)	(0.646)	
Horizon 7	−1.333**	0.145	−1.496**	0.13
	(0.527)	(0.601)	(0.714)	
Adjusted R^2	0.18	0.20		
Number of Countries	44	7	37	
Number of Provinces	607	51	556	
Number of Observations	16,148	16,148		

Source: IMF staff calculations.

Note: Regression (2) presents results from estimating equation (3.5) using subnational data on a sample of provinces with average annual temperature above 15°C. In the regression, the 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; controlling for province fixed effects and forwards of temperature and precipitation. 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.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

The medium-term negative effects of temperature shocks tend to be smaller in countries with better structural policies and institutions (Annex Table 3.3.5). Standard errors are again quite large, and it is often difficult to reject the hypothesis that policies do not have an effect, but the point estimates of the effect of temperature shocks in the outer horizons are substantially larger in columns (2), (5), and (8). This evidence is in line with findings in the literature on the role of policies in attenuating the effects of natural disasters. See, among others, Kahn (2005); Noy (2009); Cavallo and others (2013); Felbermayr and Gröschl (2014); and Breckner and others (2016) for the role of institutional strength and democracy; Noy (2009); Von Peter, Dahlen, and Saxena (2012); McDermott, Barry, and Tol (2013); Felbermayr and Gröschl (2014); and Breckner and others (2016) for the role of financial markets; and Noy (2009); Raddatz (2009); and Von Peter, Dahlen, and Saxena (2012) for the role of development status.

The Role of Development

The chapter examines whether the overall level of development attenuates the negative effects of temperature shocks in hot countries, using subnational cross-country data. Combining subnational growth data from roughly 1,460 provinces and states across 79 countries from Gennaioli and others (2014) and annual temperature and precipitation data at the same level of aggregation, the analysis confirms that there is a nonlinear relationship between subnational growth and temperature by estimating equation (3.2). It then zooms in on the set of provinces and states with average temperature greater than 15°C to examine whether economic activity in the "hot" states or provinces of advanced economies responds to a temperature increase in the same way as in states or provinces of emerging market and developing economies with a similar average temperature. Equation (3.5) is estimated with $p_{i,t}$ taking the value of 1 for states or provinces located in advanced economies. $p_{i,t}$ is also interacted with lag of growth, μ_i^h denote state or province fixed effects, and region-year fixed effects, $\theta_{r,t}^h$, are allowed to vary across advanced and non-advanced economies. Standard errors are clustered at the province level.

Annex Table 3.3.6 presents the estimated effects of a 1°C increase in temperature at horizons 0 to 7 in all subnational regions with temperature greater than 15°C in column (1). The subsequent columns present the estimated effects for subnational regions in advanced and non-advanced economies, as well as the

Annex Table 3.4.1. Effect of Weather Shocks and Natural Disasters on Emigration, 1980–2015

Percent of Emigrants in Total Population	(1)	(2)	(3)	(4)	(5)	(6)
Temperature	3.963	8.008*	8.067*	8.134*	8.127*	8.074*
	(2.522)	(4.477)	(4.476)	(4.357)	(4.480)	(4.287)
Precipitation	–0.206	–0.477	–0.484	–0.484	–0.491	–0.492
	(0.710)	(0.880)	(0.878)	(0.881)	(0.878)	(0.880)
Temperature × LIDC		–7.475*	–7.672*	–7.788*	–7.571*	–7.634*
		(4.253)	(4.255)	(4.092)	(4.249)	(4.088)
Precipitation × LIDC		0.935	0.918	0.929	0.972	0.992
		(1.022)	(1.018)	(1.024)	(1.039)	(1.033)
Number of Natural Disasters			0.228*	0.228*	0.458	0.465*
			(0.138)	(0.136)	(0.281)	(0.269)
War				0.409		–0.418
				(2.283)		(3.771)
Number of Natural Disasters × LIDC					–0.358	–0.359
					(0.309)	(0.296)
War × LIDC						1.216
						(4.034)
Adjusted R^2	0.04	0.06	0.06	0.06	0.06	0.05
Number of Observations	337	337	337	337	337	337

Source: IMF staff calculations.
Note: All specifications include country-of-origin fixed effects, decade-region fixed effects, and decade fixed effects interacted with a dummy for low-income developing country (LIDC). Standard errors are clustered at the country level.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

p-value of a test of their difference. The negative effects of temperature shocks are felt much more heavily in non-advanced economies.

Annex 3.4. The Impact of Weather Changes and Natural Disasters on International Migration

This annex provides additional details on the empirical analysis of the effect of temperature shocks and natural disasters on international migration. The analysis relies on data from Özden and others (2011) on emigrant stocks for 117 economies with average temperature greater than 15°C between 1980 and 2015. Migrant stocks, which are available at 10-year intervals, are differenced to compute net emigrant flows in each decade.

Building on Cattaneo and Peri (2016), the analysis estimates the following specification:

$$\begin{aligned} Emigrant_{i,d} = {} & \alpha + \gamma T_{i,d} + \beta\, T_{i,d} \times LIDC_i + \mu P_{i,d} \\ & + \theta\, P_{i,d} \times LIDC_i + \rho Disaster_{i,d} \\ & + \tau\, Disaster_{i,d} \times LIDC_i + \mu_i \\ & + \theta_{r,d} + \varphi_d \times LIDC_i + \epsilon_{i,d}, \end{aligned} \tag{3.6}$$

in which i indexes countries, d indexes decades,[55] *Emigrant* is the net flow of emigrants over the decade as a percentage of the total population of the origin (source) country, T is the average temperature and P the average precipitation for the decade, and *Disaster* is the average number of natural disasters for each country-decade. The latter three variables are further interacted with a dummy identifying low-income developing countries (*LIDC*) to capture potential differences in the emigration response to the weather fluctuations and natural disasters. As in Cattaneo and Peri (2016), the regression further controls for country fixed effects (μ_i), region-decade fixed effects ($\theta_{r,d}$), and decade fixed effects interacted with the *LIDC* dummy. The random error term $\epsilon_{i,d}$ is clustered at the country level.[56] The specification is purposefully parsimonious. Controls typically included as determinants of migrations, such as population size, sociopolitical environment, and others, could themselves be affected by weather fluctuations and natural disasters. In a robustness check, the exercise controls for the incidence of war, an important push factor for emigration, although arguably this could be yet another channel through which weather fluctuations trigger movements of people (see Burke, Hsiang, and Miguel 2015b).

Annex Table 3.4.1 reports the main findings from estimating equation (3.6). Higher average temperatures

[55]The 2010 decade includes data up to 2015.

[56]Following Dell, Jones, and Olken (2012), the specification includes only fixed effects as controls, since other potential controls, such as population size or sociopolitical environment, may themselves be affected by agricultural productivity—a key channel through which weather shocks may influence emigration—potentially producing a bias in the estimation by introducing an overcontrolling problem. The only exception is a dummy for wars (see Beaton and others 2017), which is included in some of the specifications and confirms the robustness of the findings.

over a decade do not have a significant effect on emigration in the full sample of countries (column [1]). However, once the response is allowed to vary across broad groups of countries, the results suggest that in countries that are not classified as low income, higher temperature is indeed associated with greater emigration flows (column [2]). A 1°C increase in average decadal temperature leads to an increase in the share of net emigrants of about 8 percentage points (which is equivalent to one standard deviation in the sample investigated).[57] Similarly, more natural disasters over a decade also increase net emigration flows, especially in countries not classified as low income.[58]

Annex 3.5. Model-Based Analysis

The model used to analyze the long-term impact of climate change and simulate the effects of policies in Box 3.2 is developed and presented in Buffie and others (2012). It is commonly known as the Debt, Investment, and Growth (DIG) model and has served as a workhorse in many IMF studies of low-income countries. The DIG is an optimizing intertemporal model with perfect foresight. It describes a two-sector small open economy model with private and public capital, learning by doing, and endogenous fiscal policies. Public capital is productive and is used in the production function in both sectors. Government spending can raise output directly by augmenting the stock of public capital and can crowd in and crowd out private investment.

Firms operate Cobb-Douglas technologies to combine labor, private capital, and public capital (infrastructure) into output in the traded and nontraded sectors. The evolution of total factor productivity (TFP) is exogenous in both sectors. Firms face separate prices for exports, and imports and are assumed to be profit maximizing.

Consumers supply labor and derive utility from consuming the domestic traded good, the foreign traded good, and the domestic nontraded good. These goods are combined into a constant elasticity of substitution basket, and savers maximize the present value of their lifetime utility. The model breaks Ricardian equivalence by including both savers and hand-to-mouth consumers.

The government spends on transfers, debt service, and (partially inefficient) infrastructure investment. It collects revenue from the consumption value-added tax and from user fees for infrastructure services. The deficit is financed through domestic borrowing, external concessional borrowing, or external commercial borrowing. Policymakers accept all concessional loans offered by official creditors. The borrowing and amortization schedule for these loans is fixed exogenously. Debt sustainability requires that the value-added tax and transfers eventually adjust to cover the entire deficit, given the exogenously determined upper limit on taxes and lower limit on transfers. The model incorporates shocks to the government external debt risk premium (or world interest rates).

The majority of the model parameters are set to the same values as in Buffie and others (2012), with few exceptions, mostly to reflect the decline in global interest rates, the projection of trend GDP growth in low-income countries, and the sample median of public-debt-to-GDP ratios. The parameters that differ from the ones in Buffie and others (2012) are presented in Annex Table 3.5.1.

Simulating the Long-Term Impact of Climate Change

To trace the long-term impact of climate change, the model incorporates the estimated relationship between temperature and per capita output discussed in Annex 3.3 and presented in Annex Table 3.3.1, column (5). The effect is assumed to occur through temperature's effect on TFP; therefore, the estimated parameters are rescaled so that the model matches the empirically estimated decline of GDP if temperature increases by 1°C.[59]

The temperature during 2017–2100 is assumed to follow one of two alternative scenarios: Representative Concentration Pathway (RCP) 4.5 or RCP 8.5. The temperature increases during 2017–2100 are calculated for the median low-income country in the sample and are equal to 2.0°C and 3.9°C for RCP 4.5 and RCP 8.5, respectively.

[57]The flow of emigrants as a share of population in countries that are not classified as low income in this sample is 2.5 percent, on average, with a standard deviation of 8.1 percentage points. For low-income countries, these statistics are 0.6 percent and 2.2 percentage points, respectively.

[58]Results (not shown here and available on request) are robust to the use of other proxies for low-income countries, such as a dummy identifying the countries in the bottom quartile of the average GDP per capita distribution of the country sample during the full sample period analyzed.

[59]Estimates of the damage to GDP cannot be used directly given that GDP is endogenous.

Annex Table 3.5.1. Parameterization of the Debt, Investment, and Growth Model

Parameter	Value (percent)
Initial Return on Infrastructure Investment	30
Public Domestic Debt-to-GDP Ratio	10
Public Concessional Debt-to-GDP Ratio	30
Public External Commercial Debt-to-GDP Ratio	5
Oil Revenues-to-GDP Ratio	2
Real Interest Rate on Public Domestic Debt	7
Real Interest Rate on Public External Commercial Debt	4
Trend per Capita Growth Rate	2.8

Sources: Buffie and others (2012); and IMF staff calculations.

There are two sources of uncertainty in the simulation—the uncertainty of RCP projections and the uncertainty of the effect of temperature on TFP. Both sources of uncertainty are combined in the analysis as follows. The upper-bound scenario is simulated assuming that the temperature increase is equal to the lowest 5th percentile for each RCP.[60] To account for the uncertainty of estimated parameters, the TFP parameters are set to the conditional expected value for the upper 50 percent of the TFP distribution. The worst lower-bound scenario is simulated analogously.

Modeling Structural Transformation

Structural transformation is generated in the DIG model by introducing diverging trends in sectoral TFP growth, along the lines of Ngai and Pissarides (2007). In their model, faster productivity growth in the traded goods sector goes along with a decline in the relative price of traded versus nontraded goods. Given complementarity in final demand, production in the former sector relative to the latter does not increase in the same proportion. The value share of the traded goods sector eventually shrinks, even in the presence of international trade. While this approach relies on only one potential driver of structural transformation, it generates the desired increase in employment and nominal-value-added shares of the nontraded goods sector, which is mostly composed of services. The gap in sectoral TFP growth rates is set to replicate the average increase in the service share of value added in low-income developing countries in 1990–2015, which has risen at the rate of 2.5 percentage points a decade. Given this calibration, in the scenario without rising temperatures, the employment share of nontraded goods increases from the baseline value of 42.27 percent to 65 percent over 90 years.

Modeling Optimal Adaptation

Box 3.2 extends the original DIG model to incorporate direct investment in adaptation strategies. The main addition is the inclusion of private adaptation and public subsidies to private adaptation, whereas damages are modeled as before. In the absence of any adaptation measure, increased temperature causes gross damage, denoted by GD_{jt}, at time t in sector j. The gross damage is expressed as a fraction of sectoral output:

$$gd_{jt} = \frac{GD_{jt}}{q_{jt}} = f\left(T\right).$$

Gross damage can be reduced by investing in adaptation. Firm i's capacity to adapt to climate change is denoted by $O_{i,jt}$. It is increasing in firm i's protection expenditures $AD_{i,jt}$ as well as in the total sectoral protection expenditures $\overline{AD}_{jt} = \int_0^1 AD_{i,jt}\,di$.[61] The residual damage for firm i in sector j is

$$\Omega_{i,jt} = \frac{gd_{jt}}{O_{i,jt}\left(AD_{i,jt}, \overline{AD}_{jt}\right)^{\phi}},$$

in which the marginal damage reduction from adaptation spending is decreasing. The positive parameter φ is the elasticity of damage reduction to the level of adaptation.

If the cost of a unit of protection is equal to $P_{AD,t}$ and the functional form for the capacity to adapt is $O_{i,jt}\left(AD_{i,jt}, \overline{AD}_{jt}; \varsigma\right) = AD_{i,jt}\overline{AD}_{jt}^{\varsigma}$ (with $0 \leq \varsigma \leq 1$), then cost minimization by firms in the symmetric

[60]Here, the 5–95 percent confidence intervals for the temperature increases are 1.2°C to 2.8°C and 2.8°C to 5.1°C for RCP 4.5 and RCP 8.5, respectively.

[61]Many adaptation measures have the nature of public goods; hence, firms benefit from total sectoral protection spending.

equilibrium $AD_{i,jt} = \overline{AD}_{jt}$ determines the optimal level of adaptation expenditure for each firm

$$AD_{i,jt} = \left(\phi \frac{GD_{jt}}{P_{AD,t}}\right)^{\frac{1}{1+\phi(1+\varsigma)}}$$

The optimal level of firm-specific residual damage is then

$$\Omega_{jt} = \frac{gd_{jt}}{AD_{jt}^{\phi(1+\varsigma)}},$$

which can be shown to be socially suboptimal.

The social planner's cost function, $TotD_{i,jt}$, differs from that of individual firms

$$TotD_{i,jt}^{SP} = GD_{jt}\left(AD_{jt}^{SP}\right)^{-\phi(1+\varsigma)} + P_{AD,t}AD_{jt}^{SP}.$$

Minimizing the social cost gives socially optimal adaptation expenditures

$$AD_{jt}^{SP} = \left[\phi\left(1+\varsigma\right)\frac{GD_{jt}}{P_{AD,t}}\right]^{\frac{1}{1+\phi(1+\varsigma)}}$$

It can be shown that private agents invest less than the socially optimal amount. The adaptation spending gap (as a fraction of the socially optimal adaptation spending) is equal to

$$1 - \left(\frac{1}{1+\varsigma}\right)^{\frac{1}{1+\phi(1+\varsigma)}}.$$

It can also be shown that the socially optimal amount of adaptation expenditures can be achieved if subsidies in the amount of $\upsilon_{\varsigma,jt}$ per unit cost of protection are paid by the government to the firms

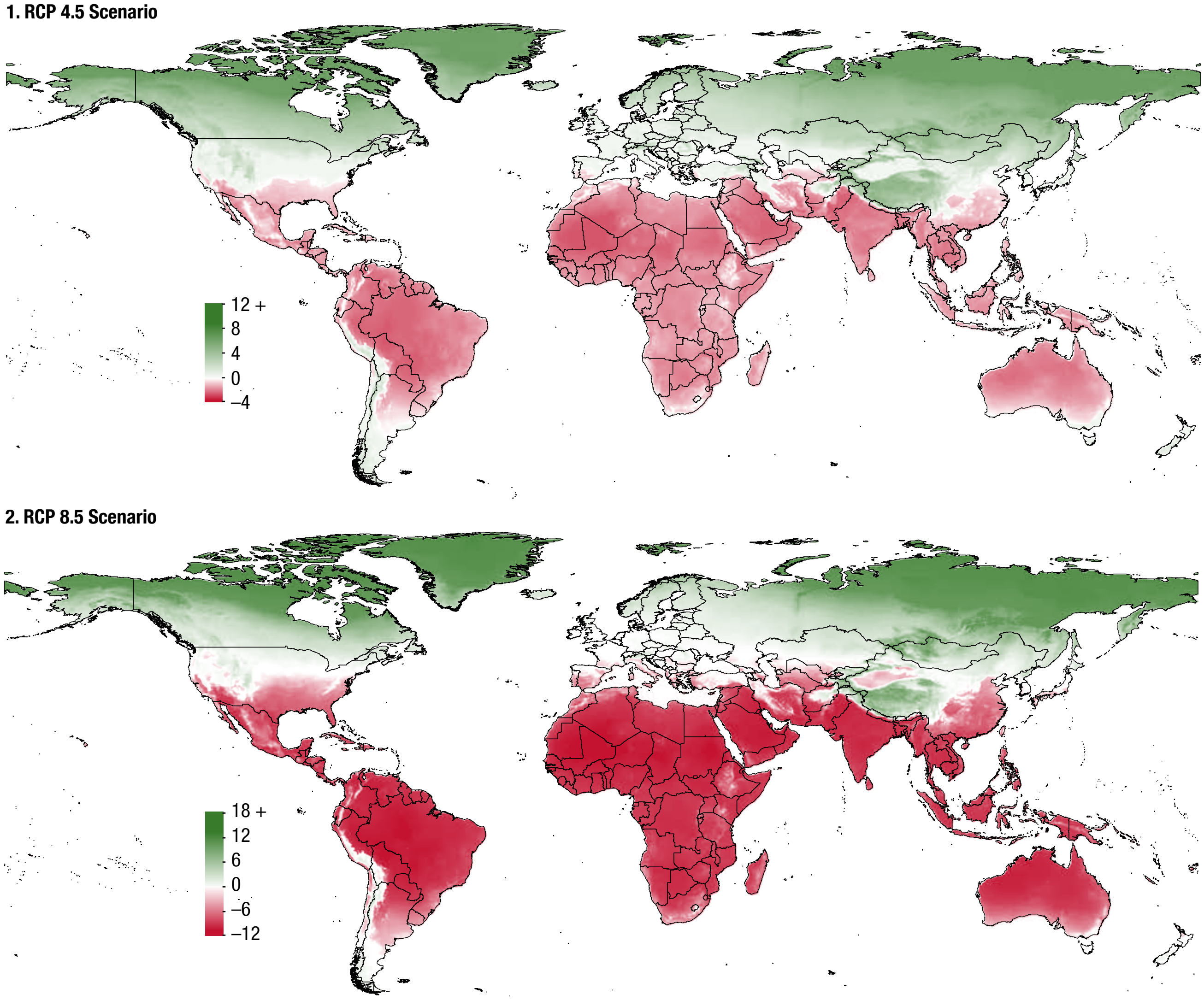
$$\upsilon_{\varsigma,jt} = \frac{\varsigma}{(1+\varsigma)}.$$

Annex 3.6. Reduced Form Approach to Estimating Potential Long-Term Effects of Climate Change

Indicative evidence of the potential impacts of climate change and their distribution across the globe could also be gleaned by combining the estimated sensitivity of per capita output to temperature increase (Annex Table 3.3.1, column [5]), baseline annual temperatures, and projected temperature changes for each geographic location. As in the modeling exercise, this analysis takes the most conservative approach and assumes temperature increases have a permanent level, rather than growth, effect on per capita output. The estimated cumulative impact on 2100 per capita GDP under the Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios are presented in Annex Figure 3.6.1. It is important to note that this exercise captures the likely impact of one particular aspect of climate change, namely temperature increases. The macroeconomic effects of many expected or possible events (such as higher incidence of natural disasters, rising sea levels, ocean acidification, and the like) are not quantified in this exercise. Furthermore, the analysis abstracts from cross-border spillovers that may arise if climate change triggers more frequent epidemics, famines, and other natural disasters along with social unrest, armed conflict, and associated refugee flows.

The analysis suggests that the projected warming will have uneven effects across the globe. However, the increase in temperature, especially under the RCP 8.5 scenario, will push many advanced economies beyond the threshold temperature level, thus triggering direct economic losses for these countries as well.

Annex Figure 3.6.1. The Long-Term Impact of Temperature Increase on Real per Capita Output across the Globe
(Percent)



Sources: National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP); World Bank Group Cartography Unit; and IMF staff 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. RCP = Representative Concentration Pathways.

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