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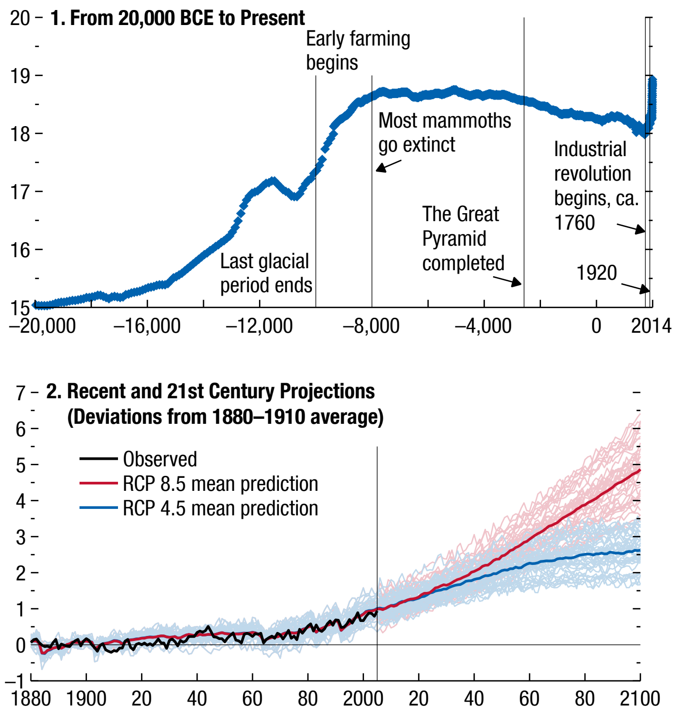
[1]Climate refers to a distribution of weather outcomes for a given location, while weather refers to a realization from that distribution. Climate change typically implies that the whole distribution of outcomes shifts, with a possible increase in the likelihood of extreme outcomes. As argued by Weitzman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

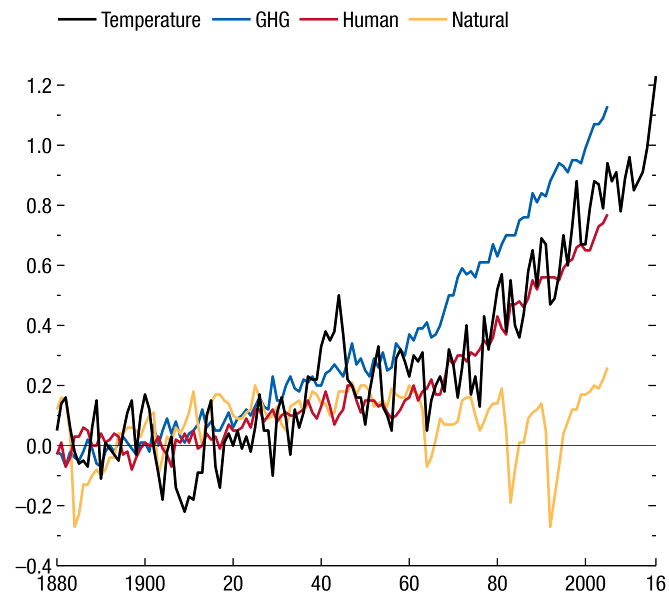
[6]The three most important greenhouse gases, which are regulated under the Kyoto Protocol, are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Among those, CO_2 has so far been the largest contributor to global warming.

[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 3.2. 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.

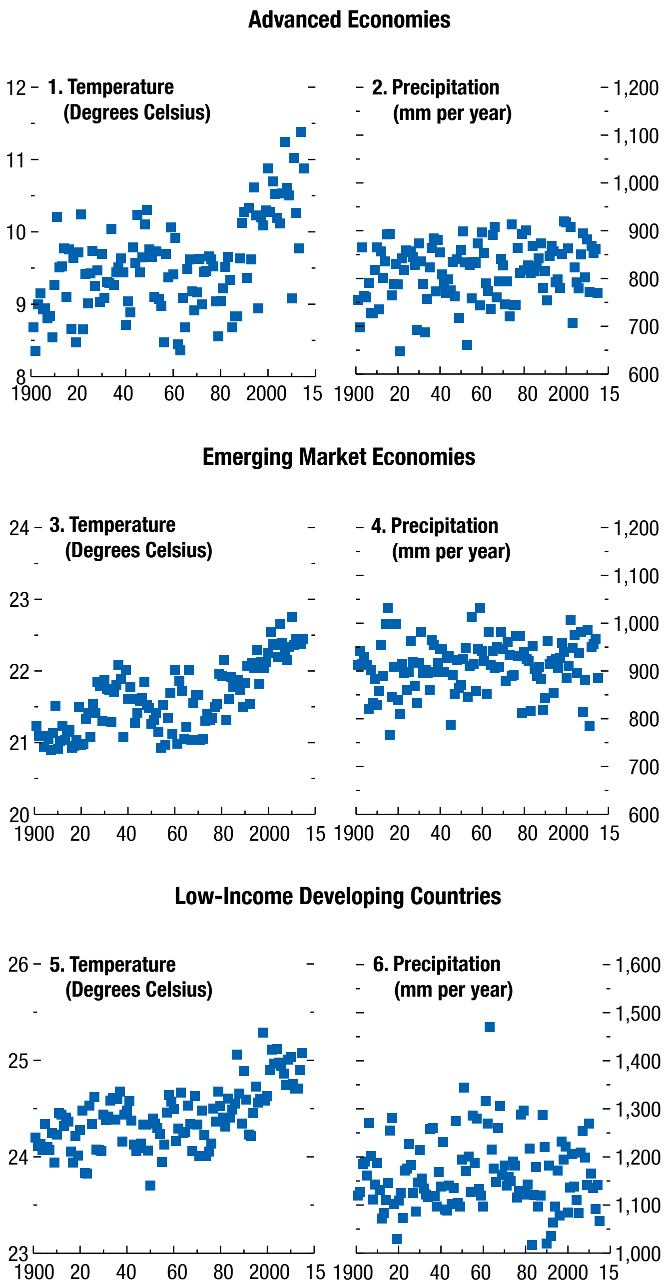
CO_2 emissions have grown rapidly since the 1950s across all income groups, along with rising incomes and populations (Figure 3.4). However, emissions in low-income developing countries are still a fraction of those in advanced and emerging market economies, in both aggregate and per capita terms. And 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-

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.

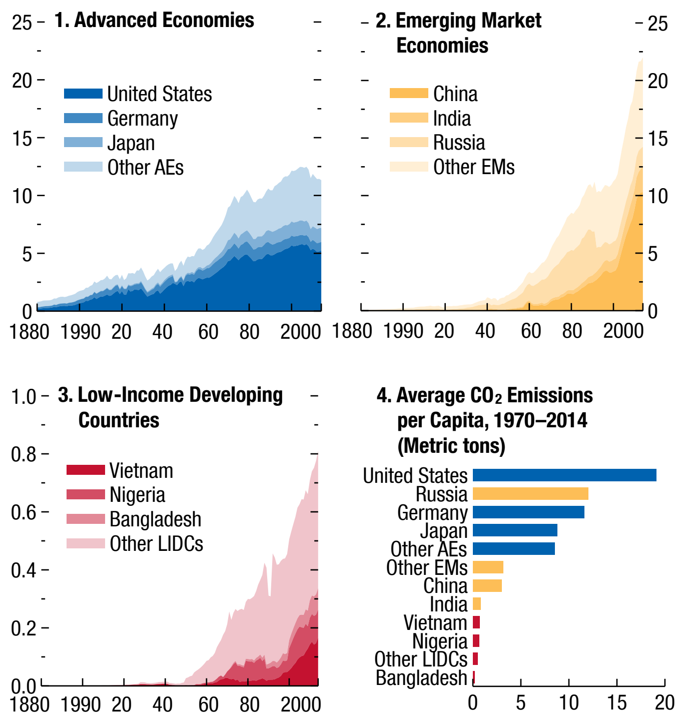


Sources: Climate Research Unit (v. 3.24); and IMF staff calculations.
Note: Terrestrial median annual temperature and precipitation data at grid level are aggregated to the country-year level using 1950 population weights. See Annex 3.1 for data sources and country groupings. mm = millimeter.

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.

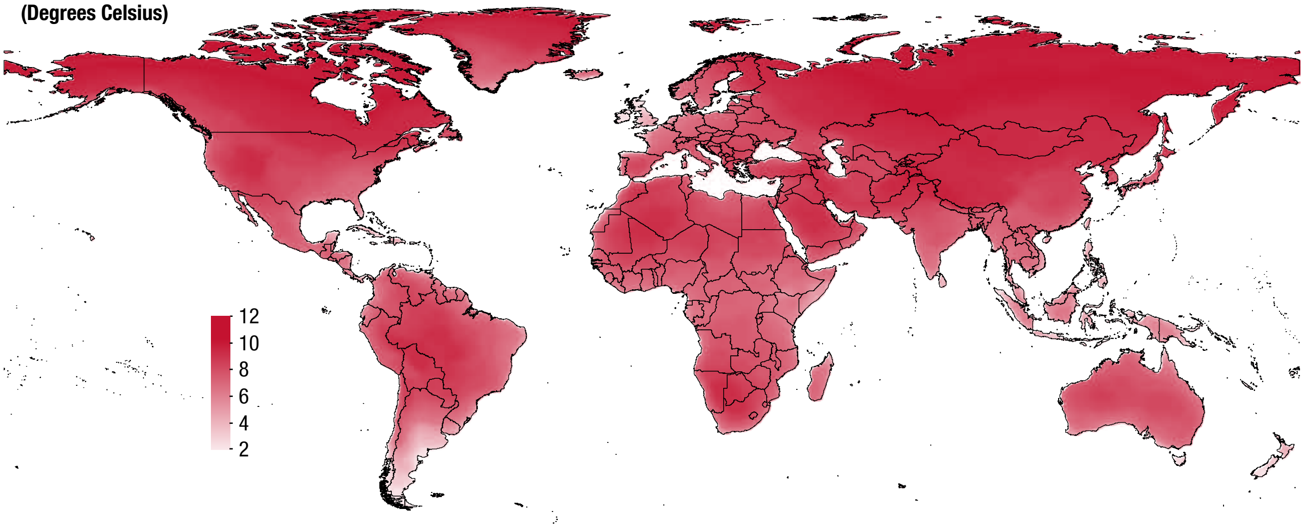
[13]The probability of each disaster type (flood, tropical cyclone, and so on) is estimated using a panel logit with country fixed effects, in which temperature and precipitation are the main explanatory variables. The analysis expands on Thomas and Lopez (2015) by modeling each disaster type separately 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.

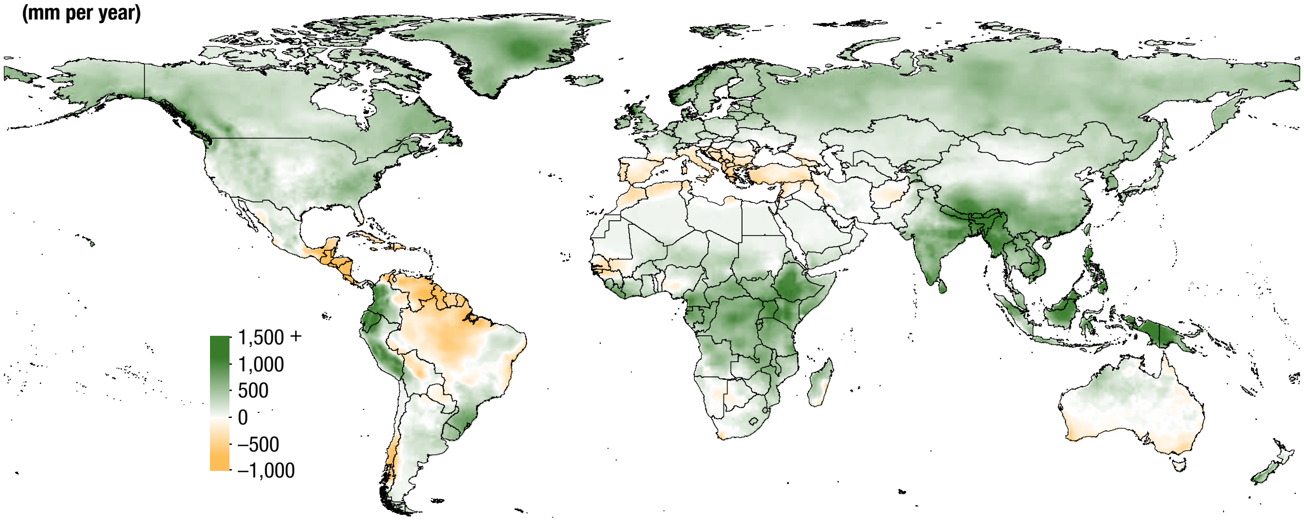
Figure 3.5. Temperature and Precipitation Projections under the RCP 8.5 Scenario

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)



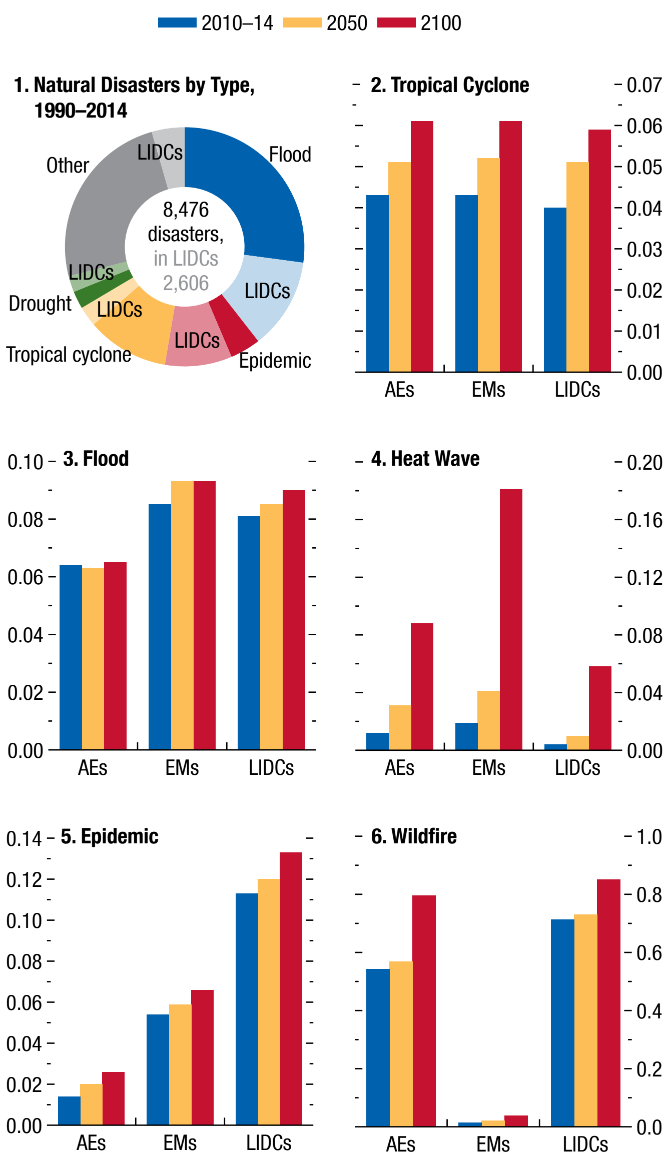
2. Precipitation Change between 2005 and 2100 (mm per year)



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.

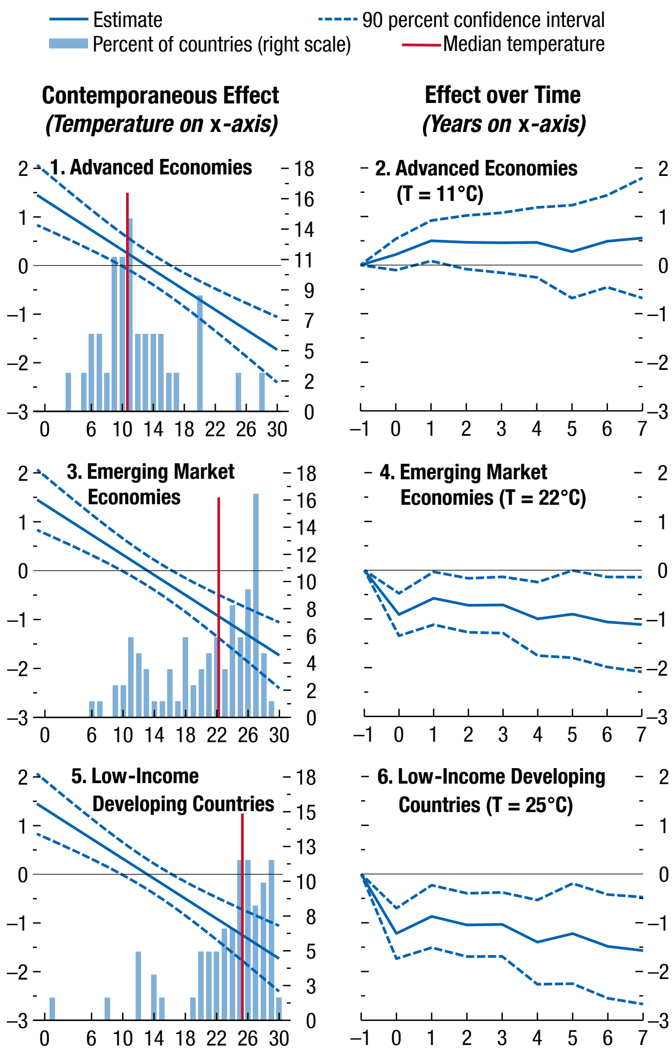
Short- and Medium-Term Effects

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).

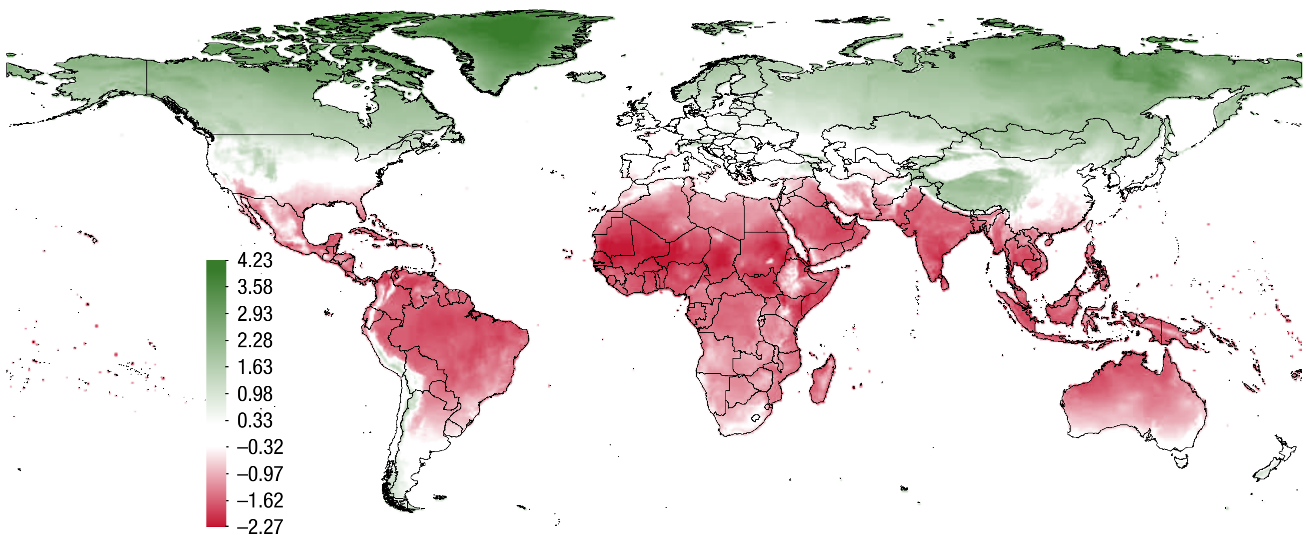
[17]Even if the effects on overall GDP in these countries are negligible, this may mask large losses and gains, with some sectors facing large investment needs to cope with higher temperatures, rising sea levels, or more damaging disasters. Moreover, the analysis focuses on the macroeconomic effects 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

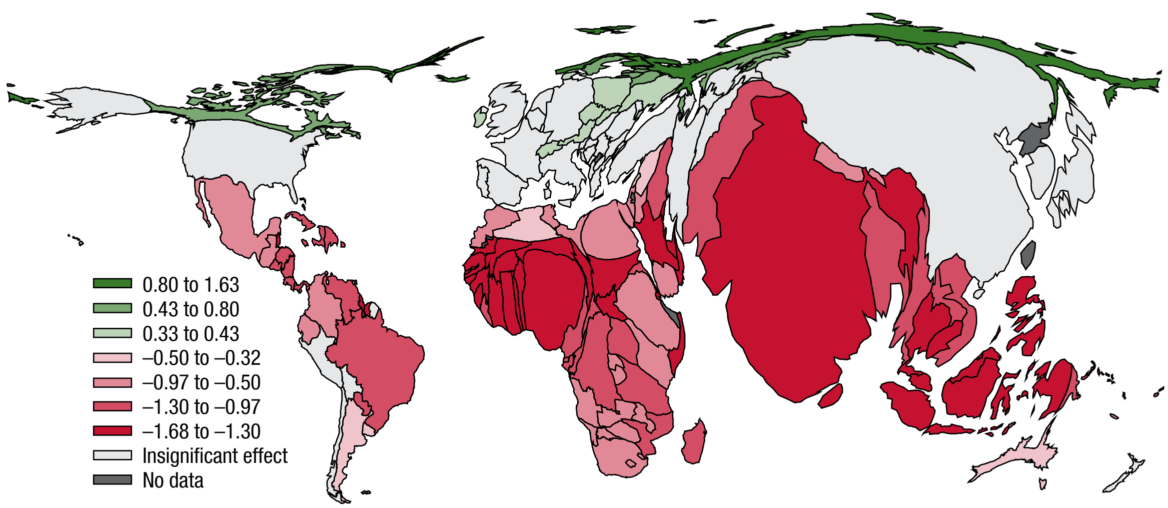
(Percent)

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

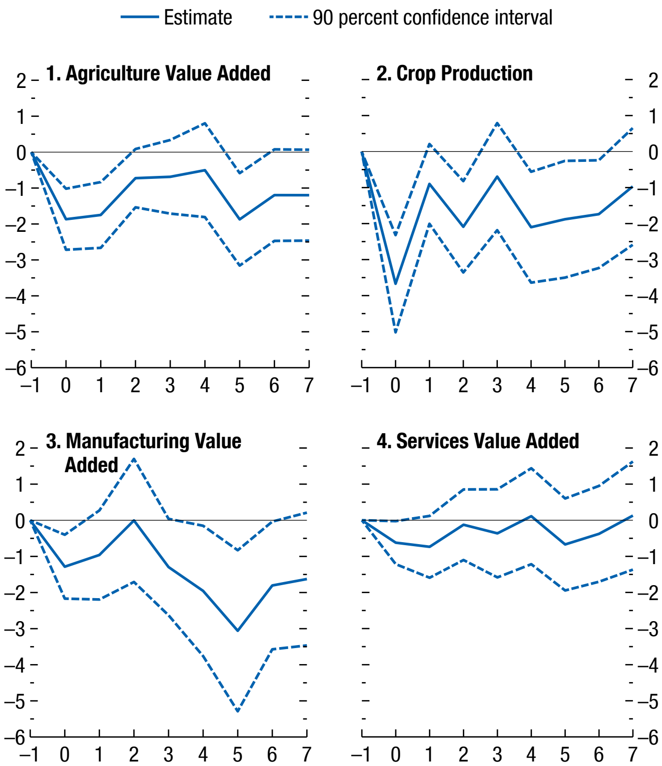
The weather can influence economic activity through various channels. The most obvious one is agricultural output, given that temperature and precipitation are direct inputs in crop production. However, studies show evidence of broader impacts, including on labor productivity, mortality, health, and conflict.[21] The literature 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

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.

[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).

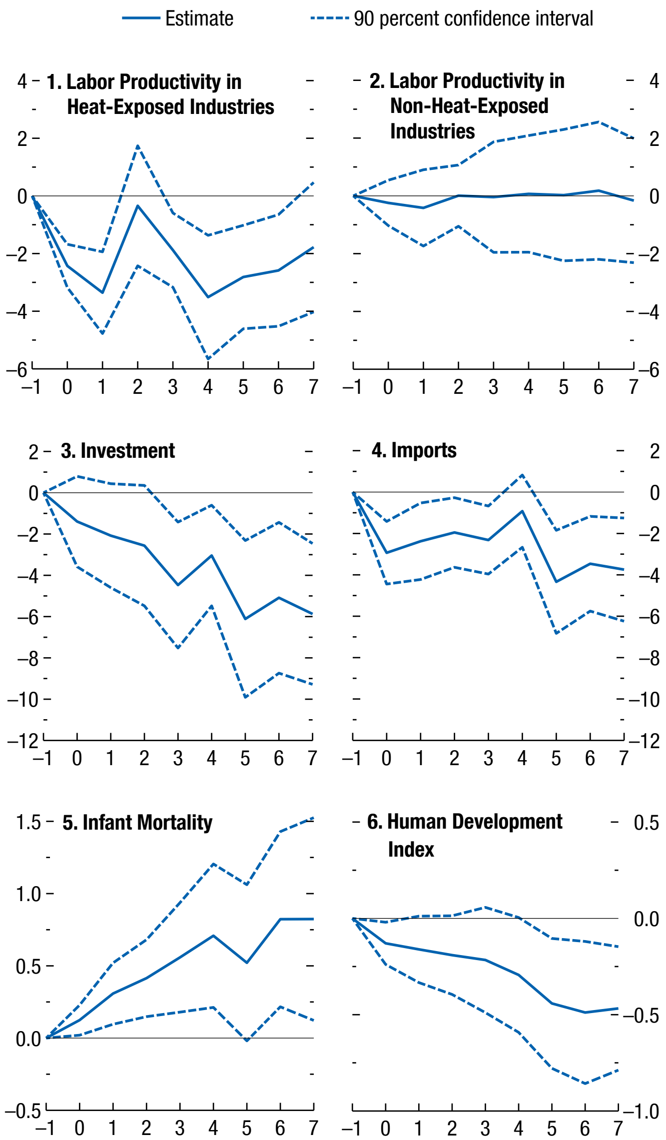
[24]The analysis follows Graff Zivin and Neidell (2014) and uses the National Institute for Occupational Safety and Health definitions of heat-exposed industries. Heat-exposed industries include agriculture, forestry, fishing and hunting, construction, mining, transportation, and utilities, as well as 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.

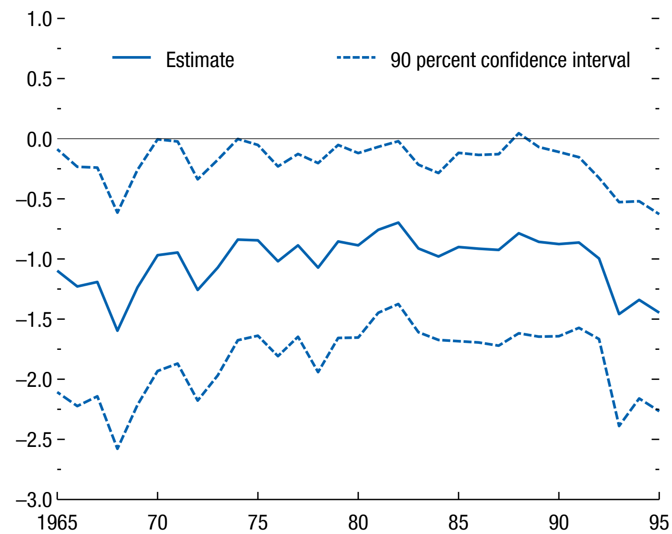
A Toolkit

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

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.

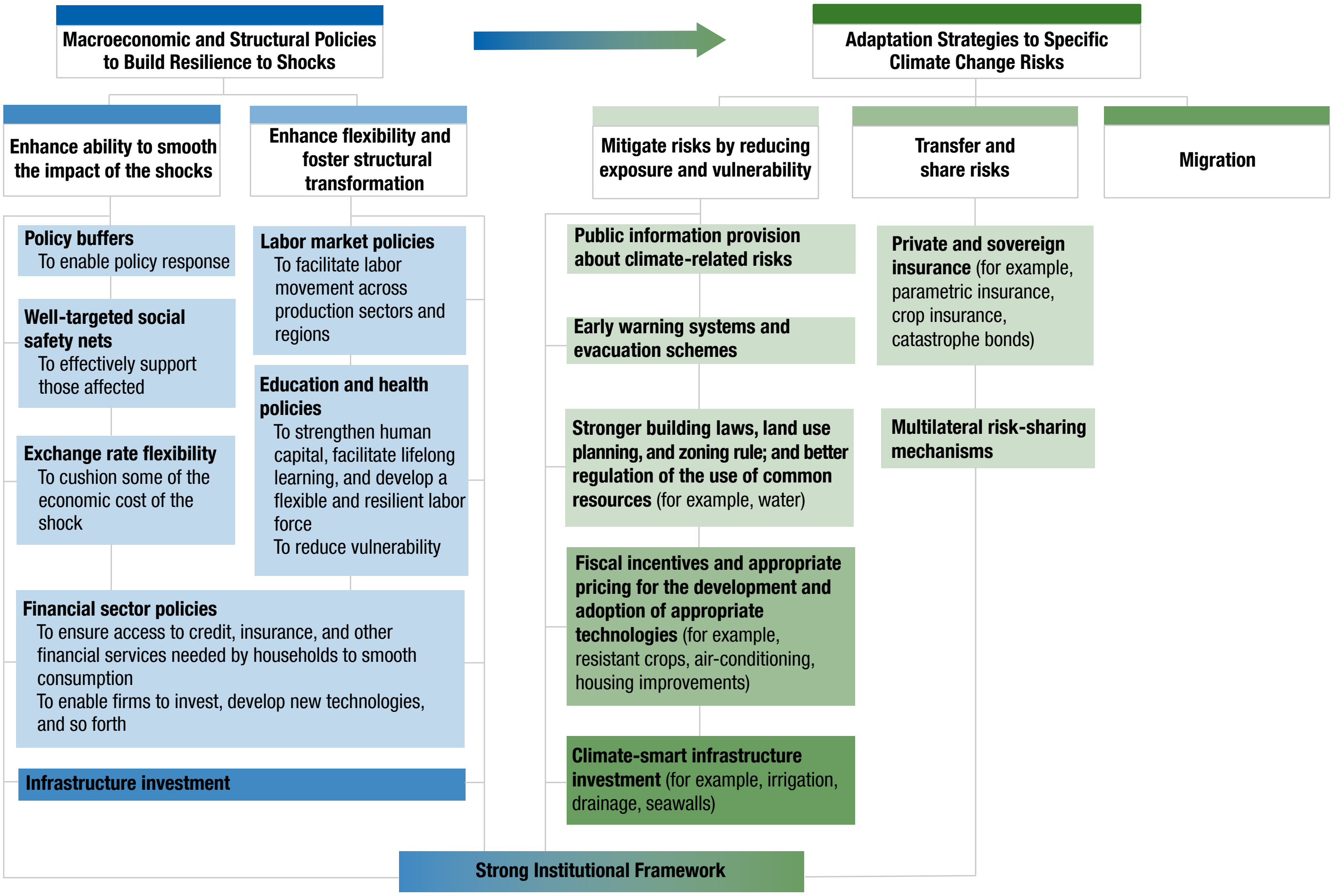
Note: The figure depicts the effect of a 1°C increase in temperature at horizon 0 estimated at the median low-income developing country temperature (25°C), over a 20-year rolling window. Each point estimate is for a period (t, t + 20).

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

[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 3.12. 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.

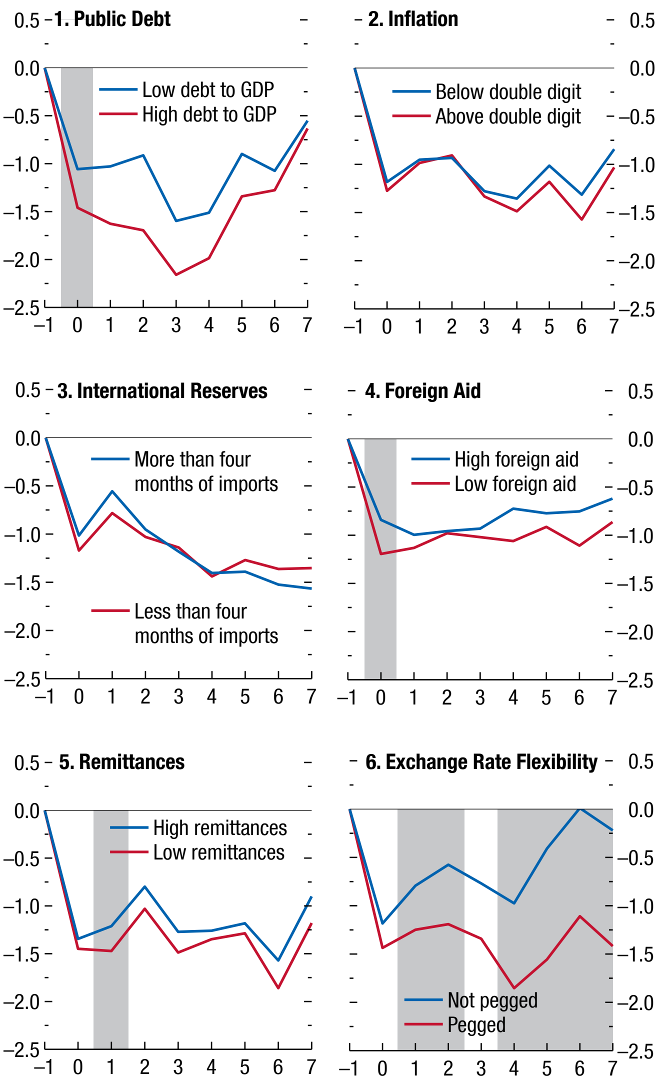
[33]See Kahn (2005); Noy (2009); McDermott, Barry, and Tol (2013); Burgess and others (2014); and Felbermayr and Gröschl (2014) for the role of financial development, and Von Peter, Dahlen, and Saxena (2012); Breckner and others (2016); and Lee, Villaruel, and Gaspar (2016) for the role of insurance 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.

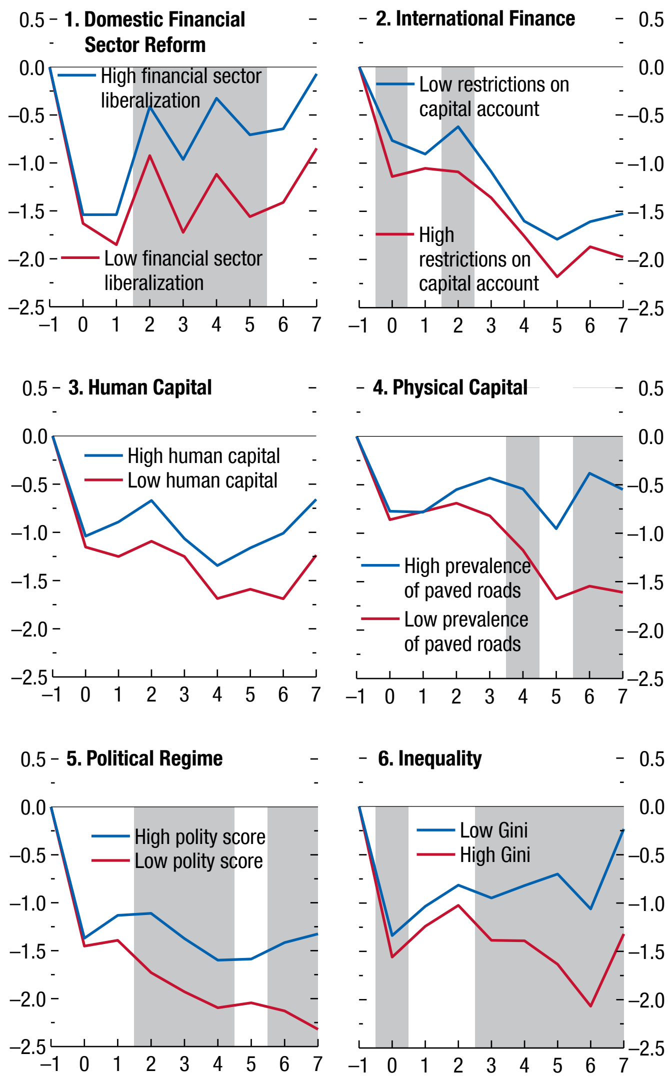


Source: IMF staff calculations.
Note: The panels depict how the effect of a 1°C increase in temperature on per capita output in the sample of countries with average temperature exceeding 15°C varies with the empirical proxy of a policy buffer. Horizon 0 is the year of the shock. Gray areas indicate that 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.

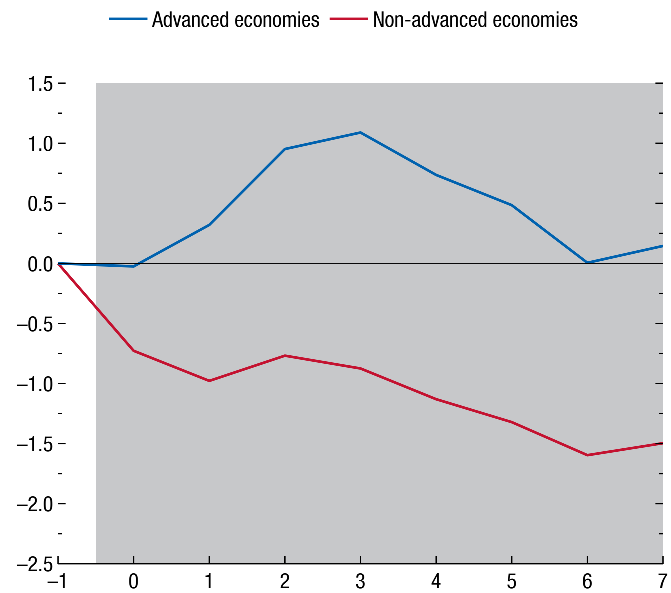


Source: IMF staff calculations.
Note: The panels depict how the effect of a 1°C increase in temperature on per capita output in the sample of countries with average temperature exceeding 15°C varies with the empirical proxies of structural policies and institutional settings. Horizon 0 is the year of 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]

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.

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

[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).

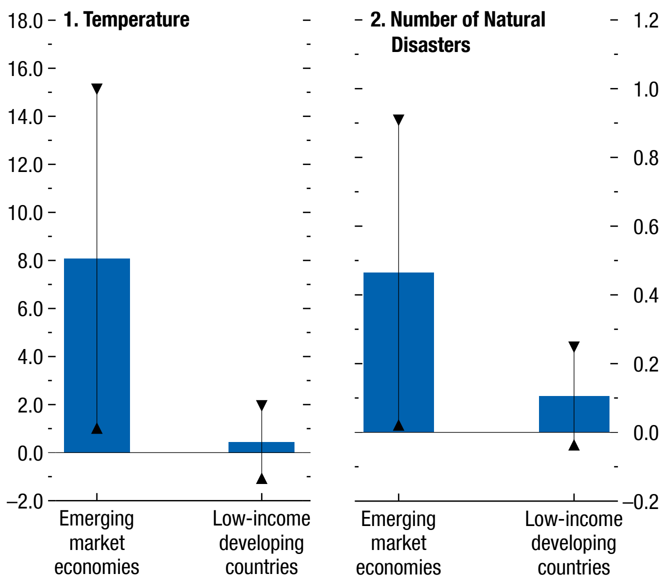
[37]Lack of knowledge and uncertainty about the risks caused by slowly changing climate conditions (Lee and others 2015) as well as the provision of government assistance to disaster-prone areas may also result in minimal behavioral change (Baez and others 2017).

[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).

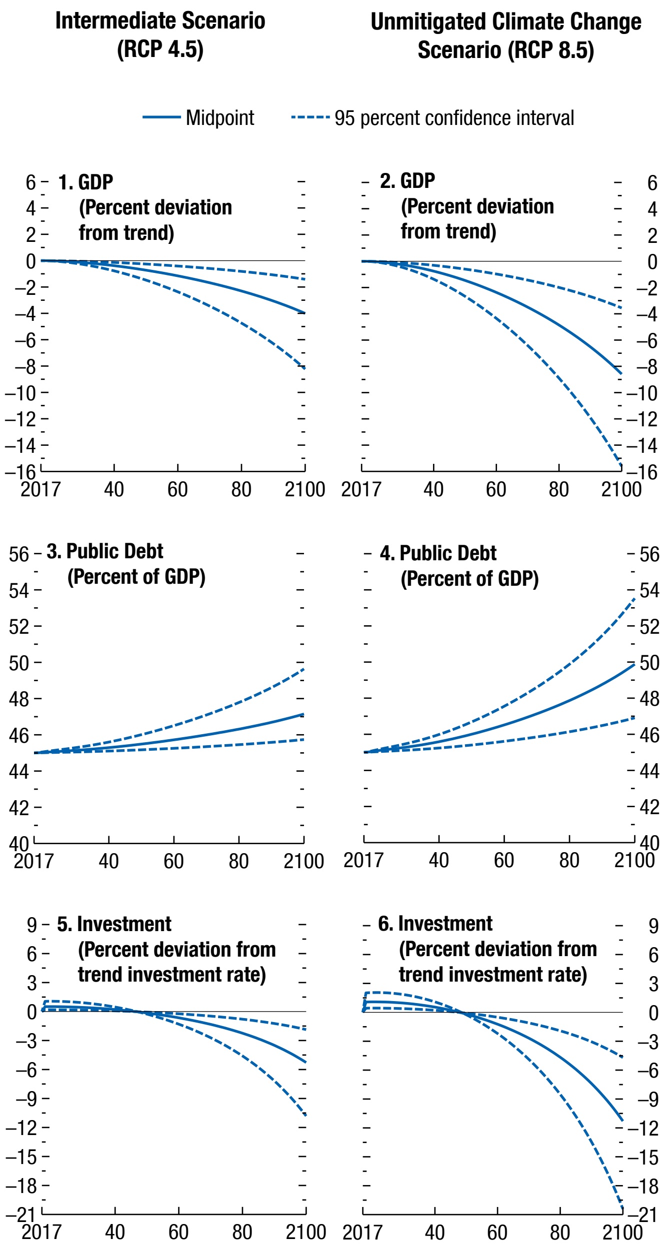
[43]For a detailed description of the model, see Buffie and others (2012) and Annex 3.5.

[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.

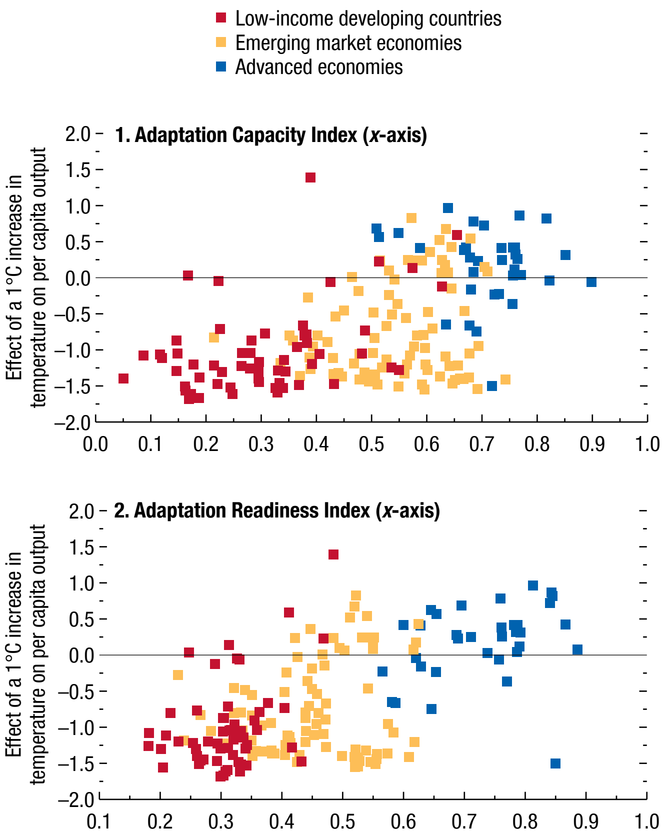
How can low-income countries cope with the rise in temperatures they are set to experience over the coming decades? Although causal interpretation is difficult, the chapter finds that the sensitivity of per capita output to temperature shocks varies with several mediating factors, and these factors are 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)
Temperature^2	–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)
Precipitation^2	–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:

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

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.

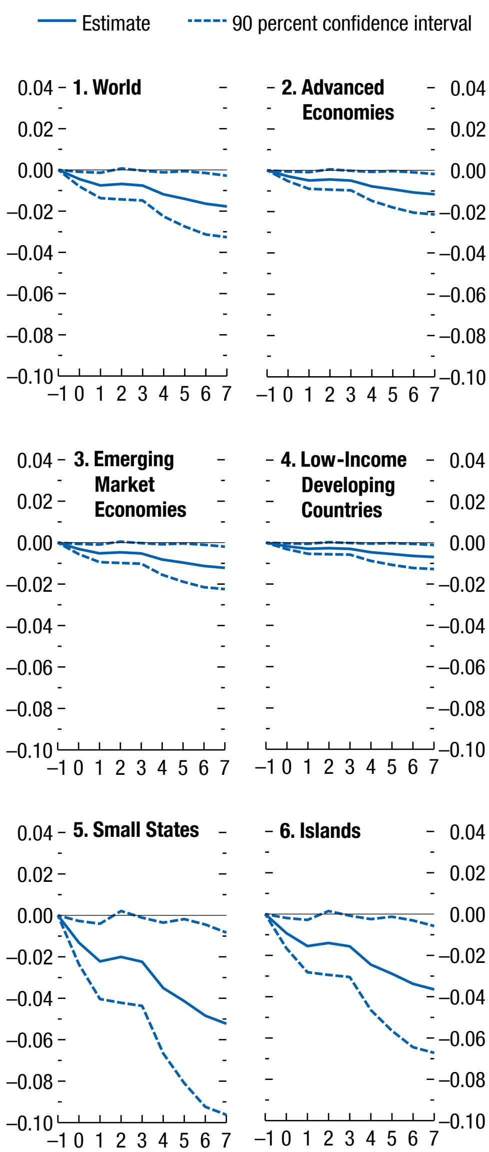
Climate Change and Tropical Cyclones

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.

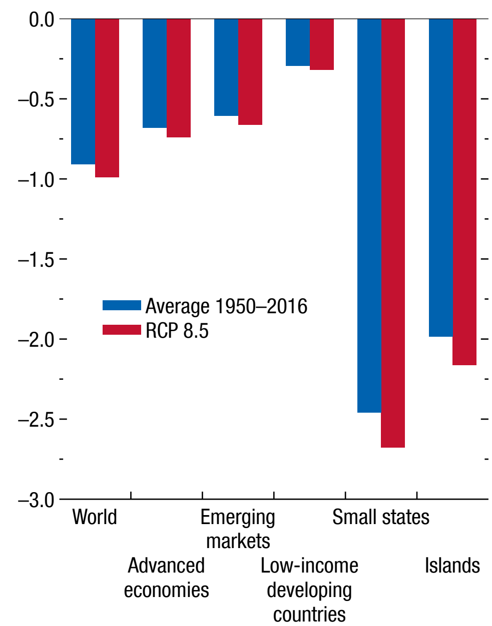
Box 3.1 *(continued)*

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

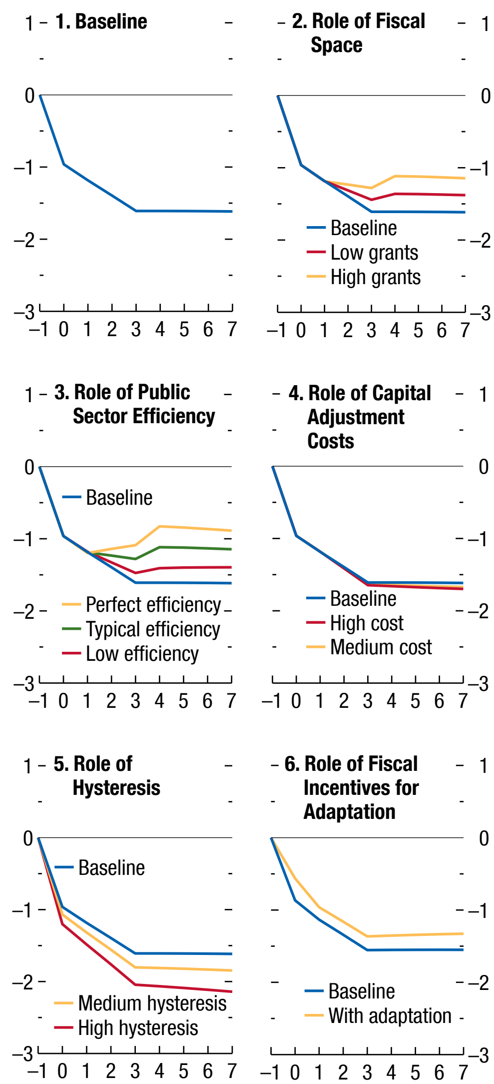
To illustrate how policies can help moderate the consequences of weather shocks in low-income countries, this box uses the Debt, Investment, and Growth (DIG) model developed by Buffie and others (2012) and simulates the macroeconomic effects of temperature increases under various assumptions for key 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

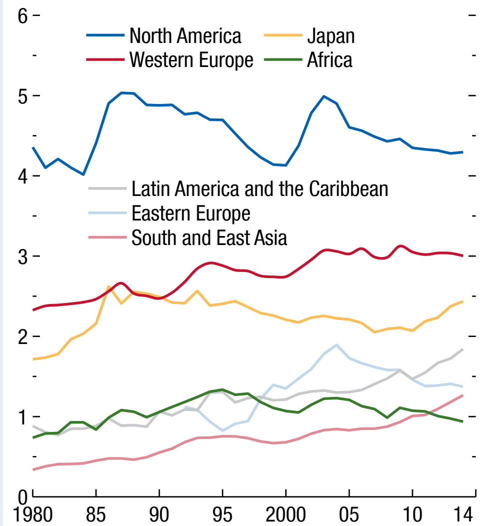
Financial markets can reduce the adverse consequences of weather shocks by reallocating the costs and risks of such shocks to those most willing and able to bear them. Insurance products, such as weather derivatives, can help households and firms vulnerable to short-term fluctuations in temperature and 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

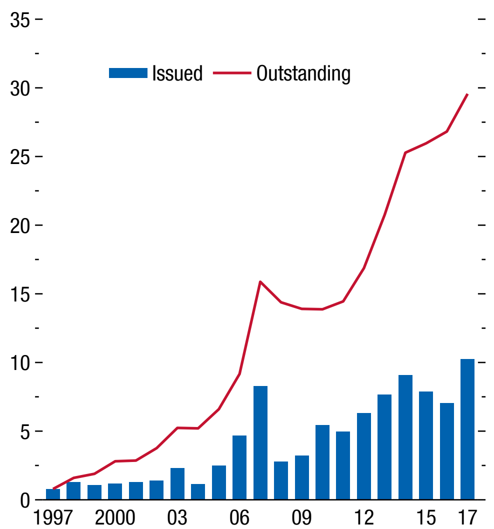
The author of the box is Alan Xiaochen Feng.

[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.

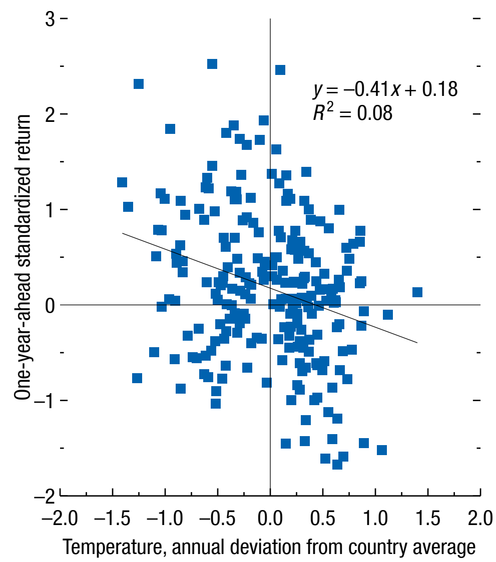
Box 3.4 *(continued)*

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) *(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 nonmonotonic 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

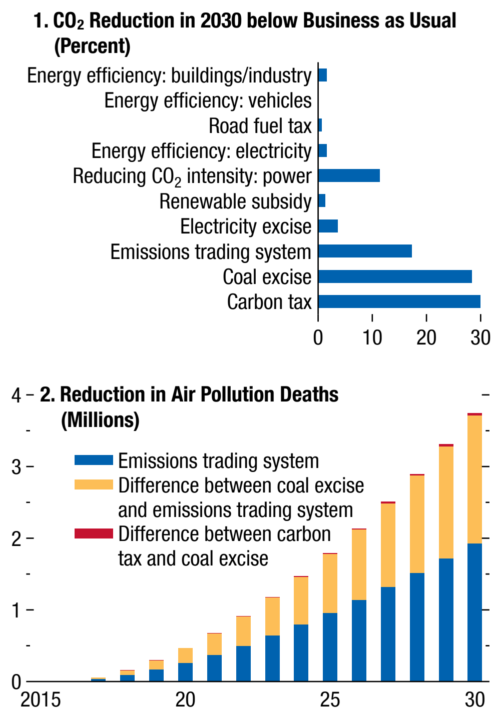
China, the largest emitter of carbon dioxide (CO_2), accounted for 29 percent of global emissions in 2013. According to IMF estimates, phasing in an emissions tax of $70 a ton of CO_2 in China by 2030 would raise the prices of coal, electricity, and road fuels by about 70 percent, 15 percent, and 7 percent, 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)*

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.

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.

[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

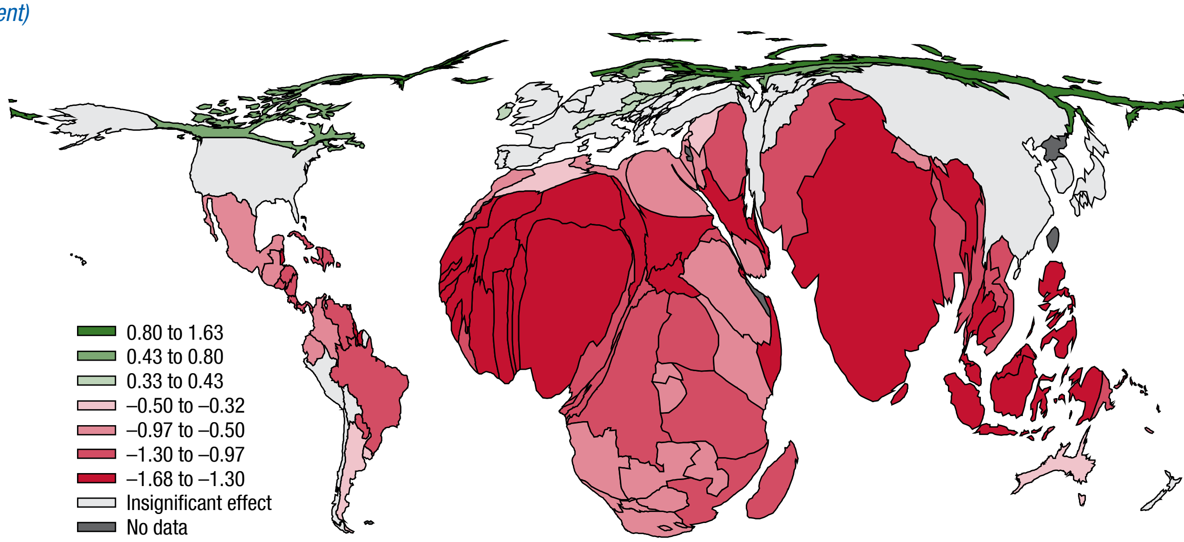
A. Real Output per Capita Growth	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Temperature	1.399***	1.443***	1.428***	1.343***	1.347***	1.248***	1.342***	1.249***	–1.154***
	(0.359)	(0.367)	(0.366)	(0.355)	(0.357)	(0.339)	(0.355)	(0.380)	(0.320)
Temperature^2	–0.049***	–0.049***	–0.048***	–0.052***	–0.051***	–0.044***	–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)
Temperature²	–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)
Precipitation²	–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)
Temperature^2	–0.045	–0.068**	0.005*	–0.008***	–0.010	–0.087***
	(0.059)	(0.033)	(0.003)	(0.002)	(0.018)	(0.026)
Precipitation	–0.377	–0.654**	–0.001	0.000	0.047	0.272
	(0.398)	(0.271)	(0.024)	(0.018)	(0.201)	(0.195)
Precipitation^2	0.003	0.006	0.001	–0.000	–0.003	–0.008*
	(0.009)	(0.007)	(0.001)	(0.000)	(0.005)	(0.004)
Adjusted R^2	0.03	0.08	0.64	0.31	0.03	
Number of Countries	169	178	182	181	40	
Number of Observations	6,093	6,866	8,685	3,864	17,848	
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

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Impact of a 1°C Increase in Temperature on per Capita Output	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:

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

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:

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

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

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

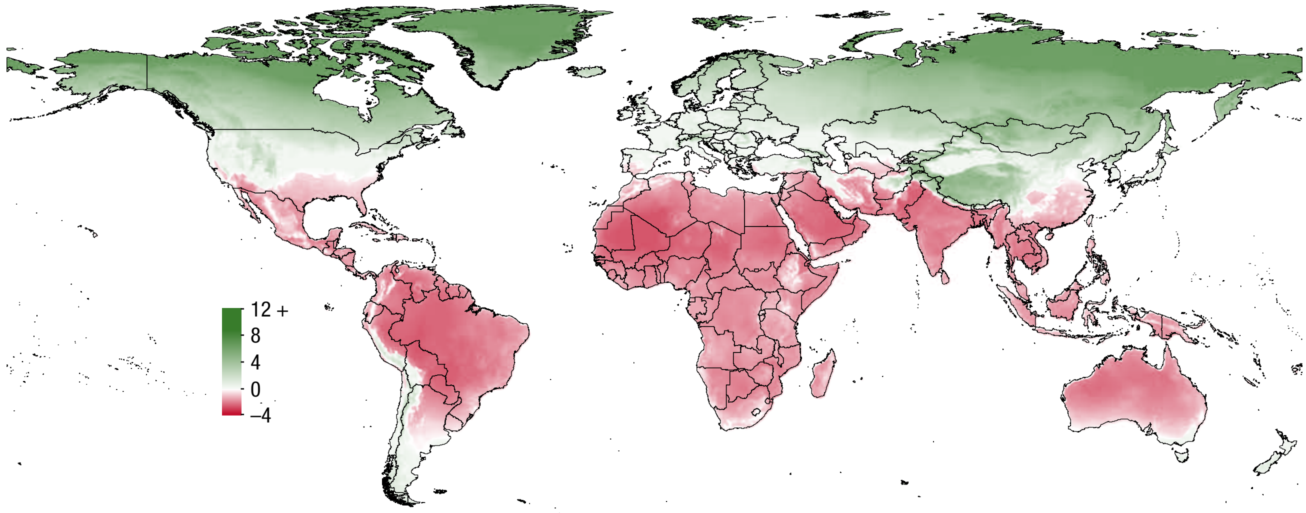
Annex 3.6. Reduced Form Approach to Estimating Potential Long-Term Effects of Climate Change

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.

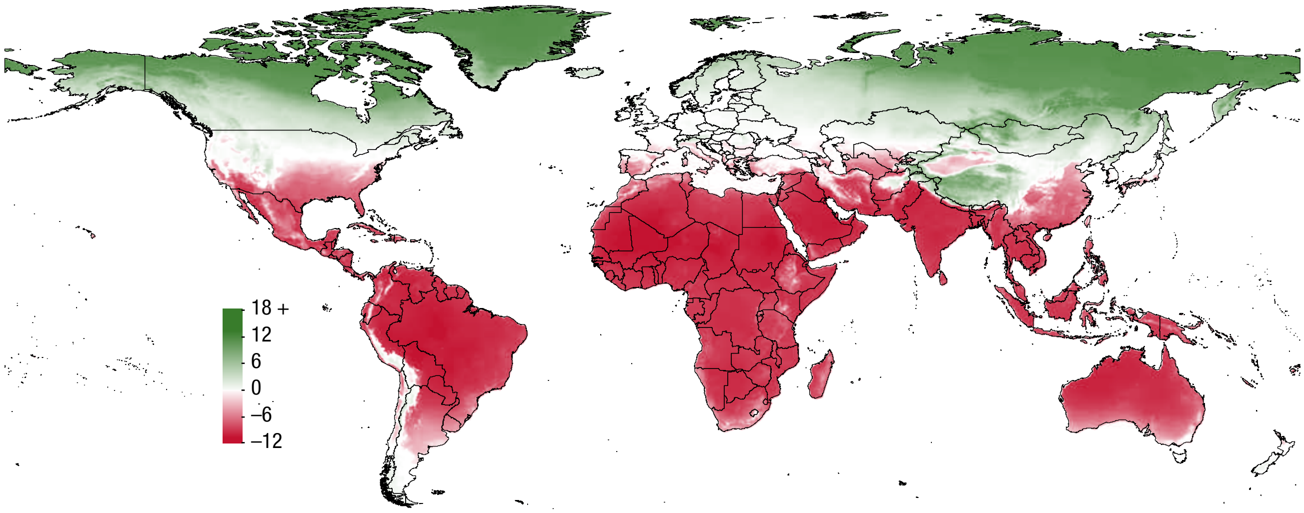
The analysis suggests that the projected warming will have uneven effects across the globe. However, the increase in temperature, especially under the RCP 8.5 scenario, will push many advanced economies beyond the threshold temperature level, thus triggering direct economic losses for these countries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

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

1. RCP 4.5 Scenario



2. RCP 8.5 Scenario



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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CHAPTER 4

CROSS-BORDER IMPACTS OF FISCAL POLICY: STILL RELEVANT?

Positive cross-country spillovers from collective fiscal action by the world's largest economies helped speed the recovery from the global financial crisis nearly a decade ago. But do fiscal spillovers still matter today? The answer is yes—but the extent depends on circumstances in both the countries that generate fiscal shocks and in those that are recipients of the shocks. This chapter combines new empirical research and model-based simulations to show that fiscal spillovers tend to be low when a fiscal shock originates from a country without output gaps, but the impact intensifies when a source or recipient country is in recession and/or benefiting from accommodative monetary policy—which suggests that spillovers are large when domestic multipliers are also large. The chapter also finds that spillovers from government spending shocks are larger than those associated with tax shocks, that the transmission of fiscal shocks may be stronger among countries with fixed exchange rates, and that fiscal spillovers impact the external positions of source and recipient countries alike. Model-based simulations suggest that the cross-border effects of budget-neutral fiscal reforms are generally modest, though large reforms can trigger spillovers, especially if they affect cross-border investment decisions. Overall, this evidence draws attention to the cross-border repercussions of corporate tax reform in the United States, for example, or of an increase in public investment in Germany.

Introduction

What is the potential for fiscal policy to affect macroeconomic outcomes in other economies through cross-border spillovers? This question has been at the center of the policy debate, especially in the aftermath of the global financial crisis, when many countries experienced persistent economic slack, and monetary policy interest rates approached the effective lower bound. Fiscal stimulus was then advocated widely, especially in major economies with sufficient fiscal space. This was not least because excess capacity and low interest rates would help limit crowding out of private spending and the expected positive spillovers would make collective efforts to boost activity more effective.

More recently, the global effects of fiscal policy have been discussed amid possible changes in the macroeconomic policy mix in Japan and the United States. Debate is also ongoing about the role of fiscal policies in addressing excess external imbalances, including whether euro area countries with excess current account surpluses should raise fiscal spending, which could also support growth in the currency union.

Recent improvements in economic conditions in many countries and their implications for monetary policy raise questions about the size of potential spillovers from fiscal stimulus today. Cyclical positions have improved across the board over the past few years, although with differences across countries (Figure 4.1). For example, the United States is operating at close to full employment and, as a result, the Federal Reserve has begun to normalize monetary policy conditions. At the same time, although euro area economies and Japan are experiencing an encouraging cyclical recovery, output gaps remain negative in many of these countries and core inflation is stubbornly low, prompting monetary authorities to commit to accommodative policies for an extended period. As the chapter discusses, cyclical conditions and the associated ability or willingness of monetary policy to act, both in countries emitting and receiving the fiscal shock, are key determinants of the magnitude of its impact.[1] Considerations regarding fiscal space in source countries are also relevant—if term premiums increase and financial conditions tighten following a fiscal stimulus, spillovers could be smaller.

Against this backdrop, the chapter aims to answer the following questions:

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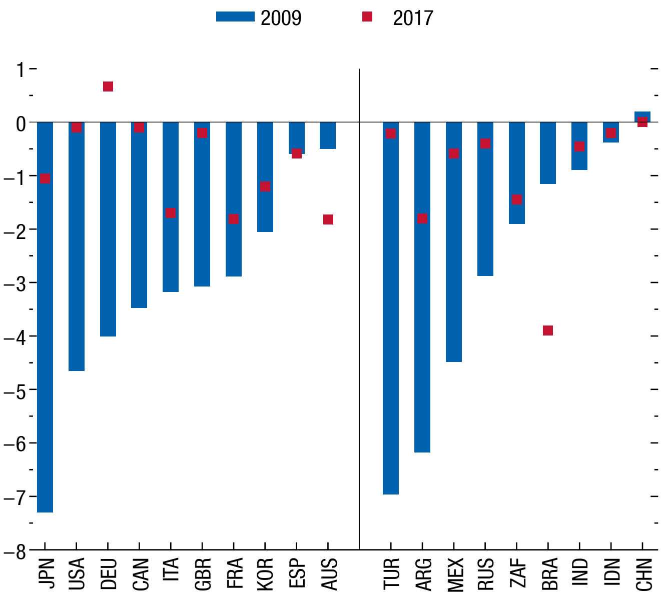
[1]Throughout the chapter, countries from which fiscal shocks originate are referred to as "source" or "shock-emitting"; countries affected by these shocks are referred to as "recipient" or "shock-receiving."

Figure 4.1. Output Gap in Selected Countries
(Percent)



Source: IMF staff estimates.
Note: Data labels in the figure use International Organization for Standardization (ISO) country codes.

- Are fiscal spillovers large from a global or regional perspective? How do they depend on the fiscal instruments involved (for example, government spending or taxes)? How do they depend on fiscal space in source countries?
- To what extent does the size of fiscal spillovers depend on cyclical and monetary policy conditions, in both source and recipient countries?
- How do fiscal spillovers depend on exchange rate regimes?
- What is the impact of fiscal shocks on external positions and exchange rates in source and recipient countries?
- Do fiscal reforms generate spillovers, even if the reforms are budget neutral?

The chapter sheds light on these issues by looking at the implications of fiscal policy changes in some major advanced economies for activity across a large group of advanced and emerging market economies. The empirical analysis is based on a newly constructed data set of government spending and tax revenue shocks for five systemic economies between the first quarter of 2000 and the second quarter of 2016, identified using the structural vector autoregression methodology of Blanchard and Perotti (2002). Information from the five source-country shocks is combined using the strength of trade links with a range of advanced and emerging market recipient countries to assess global spillovers.

To analyze the role that economic slack, constraints on monetary policy, and exchange rate regimes play in transmission, the chapter uses an econometric framework that can flexibly test for the presence of nonlinear effects. Model-based simulations then help to illustrate the complex cross-border transmission channels of fiscal shocks. This approach offers insights into potential changes in the external positions of source and recipient countries, as well as the dynamic behavior of key macroeconomic variables, and elucidates spillovers from different types of fiscal reforms.

The chapter's findings add to the existing empirical literature on fiscal spillovers by expanding the scope of the analysis. Previous empirical studies focus on a relatively small sample of recipient countries—often those of the Organisation for Economic Co-operation and Development (OECD) or euro area (Beetsma and Giuliodori 2004; Beetsma, Klaassen, and Wieland 2006; Auerbach and Gorodnichenko 2013; Nicar 2015; Blanchard, Erceg, and Lindé 2016; Goujard 2017; Poghosyan 2017), and several studies consider only one fiscal instrument (government spending) and/or only fiscal consolidation episodes. The chapter also adds to the literature, extending the analysis of economic slack, monetary policy accommodation, and the role of exchange rate regimes in determining spillovers from fiscal shocks.

The chapter suggests that fiscal spillovers still matter, but their size depends on the type of fiscal action and on economic circumstances in both source and recipient countries:

- *Fiscal spillovers are larger for spending shocks.* On average, a 1 percent of GDP fiscal stimulus in a major advanced economy can raise output in recipient countries by 0.08 percent over the first year. But spillovers are larger for government spending shocks than for tax shocks, consistent with the literature that points to higher domestic multipliers for spending shocks—output in recipients can increase by 0.15 percent following a spending hike, versus 0.05 percent after a tax cut. Model simulations reinforce this message and provide more granular evidence—for example, changes in public investment tend to have larger cross-border effects than changes in public consumption.

- *Relatively weak cyclical positions imply larger spillovers.* Although modest in normal times, spillovers are larger when cyclical conditions are weak, likely due to the reduced crowding-out effects of public spending on private sector activity.
- *Monetary policy constraints also increase spillovers.* When monetary policy in either source or recipient countries does not counteract fiscal shocks—for example, because the effective lower bound is binding—spillovers are much larger than during normal times.
- *Currency pegs between source and recipient countries may amplify spillovers.* There is some evidence suggesting that fiscal shocks tend to have larger spillovers on recipient countries with currencies pegged to the source country's currency than on those with flexible exchange rates.
- *Fiscal policy can change external positions in source and recipient countries.* Trade balances deteriorate in source countries following a fiscal expansion, with a consequent improvement in recipients' external positions.
- *An increase in term premiums may dampen spillovers.* If fiscal stimulus at the source increases the term premium—for instance, because of concerns about debt sustainability—spillovers are somewhat lower compared with a constant term premium scenario.
- *Under some circumstances, fiscal reforms come with spillovers as well.* Most budget-neutral fiscal reforms have limited cross-border effects, although large reforms can generate significant spillovers. For example, a reform that substantially reduces corporate income tax rates and is offset by higher consumption taxes in major economies can have repercussions in the rest of the world, including through higher global interest rates and cross-border reallocation of investment and profits.

These results point to several important policy lessons that are relevant now. Although fiscal space is currently more limited, and improved cyclical conditions in many countries mean that spillovers from fiscal policy are likely to be lower than during the global financial crisis, the analysis suggests that fiscal stimulus in major economies can nonetheless be important in lifting economic activity abroad, although not everywhere. For example, given the cyclical position and gradually less accommodative monetary policy conditions in the United States, a US fiscal stimulus would likely have relatively modest cross-border spillovers, especially if stimulus takes the form of tax policy measures. In the euro area—where there is fiscal space in some countries—stimulus could have larger spillovers. This is in the context of prospects for continued monetary policy accommodation and still-significant slack in some recipient countries.

The impact on external imbalances would also depend on the source of fiscal stimulus, as stimulus in the United States is likely to increase imbalances, whereas stimulus in some surplus euro area countries could reduce them. Where countries are considering significant reductions in corporate income tax rates, the analysis suggests associated changes in investment-location and profit-reporting decisions by multinational corporations could have significant negative spillovers on activity and the fiscal position of nonreforming countries.

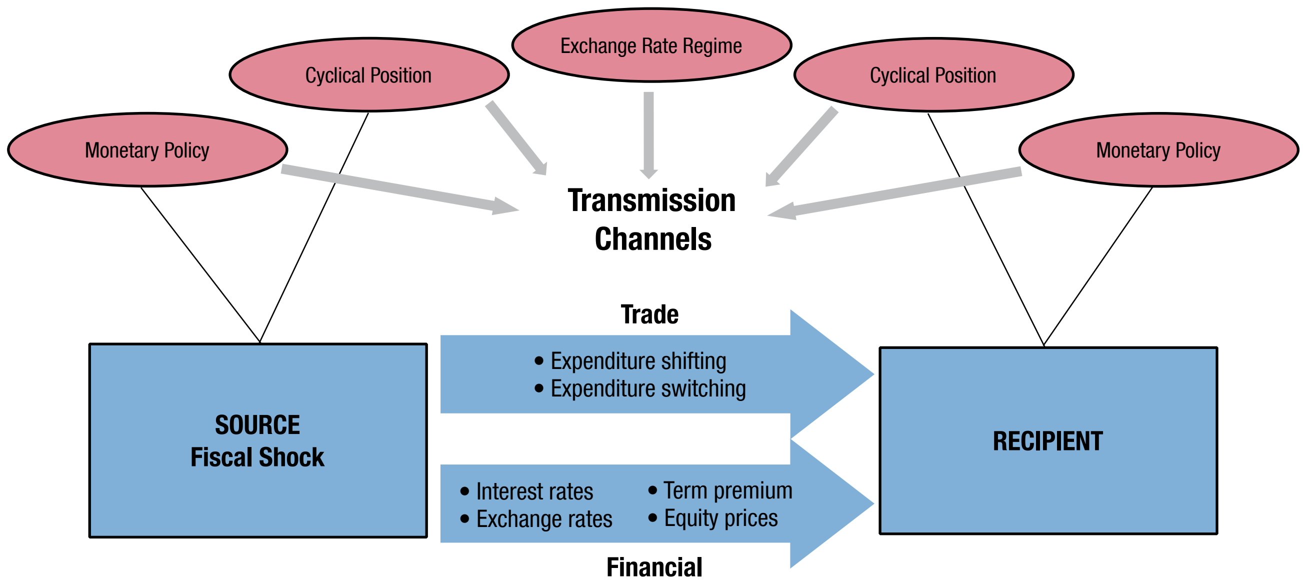
Spillovers from Fiscal Policy—A Conceptual Framework

The cross-border impact of fiscal policy changes in a given country depends on their initial domestic effects and the transmission mechanisms of shocks. This means that factors affecting the source's domestic fiscal multiplier are relevant for determining spillovers on recipient countries. The fiscal shock is propagated through different channels—primarily associated with trade links—with the final impact also depending on the economic and policy conditions in the recipient countries (Figure 4.2). This section provides a brief overview of the domestic impact of fiscal shocks, outlines their possible transmission channels, and discusses the factors affecting transmission.

Domestic Impact of a Fiscal Shock

A large body of literature on domestic fiscal multipliers suggests that cyclical and policy conditions play a role in the response of a domestic economy to fiscal shocks. In general, multiplier estimates vary significantly across countries, sample periods, and methodologies. While a comprehensive summary is beyond the scope of this chapter (see, for example, Batini and others 2014), dynamic stochastic general equilibrium and structural vector autoregression models developed since the early 1990s suggest that the size of multipliers tends to be modest (between zero and one over the first year) in "normal times"—generally understood as circumstances in which the economy

Figure 4.2. The Transmission of a Fiscal Shock



Source: IMF staff compilation.

does not have a significant output gap—and depends on a number of structural characteristics, including a country's trade openness, exchange rate regime, labor market rigidities, and size of public debt.[2] Outside normal times, multipliers can vary with the state of the business cycle (generally larger in a downturn than in an expansion, although the empirical evidence is not conclusive) or the degree of monetary accommodation (larger when monetary policy is unresponsive, such as at the effective lower bound).[3] All else equal, a larger domestic multiplier should be associated with greater cross-border spillovers.

The composition of the fiscal intervention—whether it is based on government spending or revenue measures—also influences the size of the domestic multiplier. Many studies have found that, for advanced economies, short-term spending multipliers tend to be larger than revenue multipliers (for example, see a survey in Mineshima, Poplawski-Ribeiro, and Weber 2014). This has been explained using traditional Keynesian theory—for example, while an additional dollar of government spending contributes directly to higher aggregate demand, a dollar of tax cuts can be either spent or saved by firms and/or households (that is, the marginal propensity to consume can be less than one). Recent empirical evidence using the narrative approach has found somewhat larger tax multipliers than spending multipliers, although narrative-based evidence on the latter is primarily limited to defense-related spending.[4] Yet other studies suggest that the relative magnitude of the

[2]For example, see Cole and Ohanian (2004); Kirchner, Cimadomo, and Hauptmeier (2010); Corsetti, Meier, and Müller (2012); Gorodnichenko, Mendoza, and Tesar (2012); Born, Juessen, and Müller (2013); and Ilzetzki, Mendoza, and Vegh (2013). A multiplier of one would suggest that a change in the fiscal balance translates—dollar for dollar—into a similar change in GDP.

[3]For example, see Erceg and Lindé (2010); Christiano, Eichenbaum, and Rebelo (2011); Eggertsson (2011); Woodford (2011); Auerbach and Gorodnichenko (2012a, 2012b); Owyang, Ramey, and Zubairy (2013); Nakamura and Steinsson (2014); Riera-Crichton, Vegh, and Vuletin (2015); Blanchard, Erceg, and Lindé (2016); and Canzoneri and others (2016). However, Ramey and Zubairy (forthcoming) found little evidence of state dependence of the government spending multiplier based on historical data from the United States.

[4]The narrative method, pioneered by Romer and Romer (2010), makes use of narrative records, such as budget documents and speeches, to identify the size, timing, and principal motivation for fiscal actions. The Romer and Romer (2010) data set also divides fiscal policy changes into those made for reasons related to prospective economic conditions and discretionary actions (for example, actions aimed at reducing public debt), thereby allowing for a causal analysis of the impact of fiscal policy on output. See also Ramey (2011); Cloyne (2013); Mertens and Ravn (2013); and Guajardo, Leigh, and Pescatori (2014).

spending and revenue multipliers may differ between consolidation and expansion episodes and among different degrees of monetary accommodation.[5]

Channels of Cross-Border Transmission

In standard open-economy macroeconomic models, a fiscal shock is transmitted abroad primarily through the trade channel, which consists of two effects:[6]

- *Expenditure shifting* (sometimes referred to as "leakages") refers to the direct impact of a fiscal policy change on the source country's import demand through changes in domestic consumption and investment, which affects trading partners. Here, the marginal propensity to import by both the public and private sectors plays a key role—if most spending changes are in nontradable sectors and do not translate into a higher or lower level of imports, spillovers from expenditure shifting may be smaller. Larger and more open economies tend to import more, suggesting that fiscal policy changes in these countries will have larger spillovers on others through the expenditure shifting channel.
- *Expenditure switching* refers to the impact of a fiscal shock operating through changes in the real exchange rate, which can trigger substitution between domestic and foreign goods consumption. For example, in a Mundell-Fleming-Dornbusch framework, fiscal expansion puts upward pressure on interest rates, the nominal exchange rate appreciates in the source country, and domestic prices increase.[7] The resulting real appreciation boosts import demand as foreign goods become cheaper. This effect will be more significant, especially in the short term, when the nominal exchange rate is fully flexible; where nominal exchange rates are fixed, relative price—and hence real exchange rate—adjustments can take longer. Either way, expenditure switching effects imply that a fiscal shock can have nontrivial cross-border spillovers, even if its domestic impact is muted, because the boost to import demand can occur without an increase in domestic income.

In addition to the trade channel, the response of financial variables to a fiscal shock can trigger spillovers through changes in global financial conditions. A fiscal policy change in a large economy can impact global interest rates, exchange rates, and the slope of the yield curve—the latter stemming from any perceived or actual impact of the policy change on long-term fiscal sustainability in the source country. The financial channel can work in the opposite direction to the trade channel. For example, the higher interest rates and exchange rate appreciation associated with an expansionary fiscal shock in the source country can increase the cost of foreign currency borrowing and worsen the balance sheets of corporations and households in recipient countries if there are currency mismatches, generating negative spillovers. Equity prices may also adjust, with cross-border repercussions.

Overall, the relative strength of each transmission channel will depend on the extent of trade and financial linkages between the source and recipient countries. Thus, the net spillover impact of a fiscal shock is an empirical question.

Factors Affecting the Transmission

Like the domestic fiscal multiplier, cross-border spillovers from fiscal actions tend to vary with economic circumstances. Two factors play particularly important roles:

- *Cyclical position:* The domestic multiplier—and hence spillovers through expenditure shifting—may be larger when the source country has more economic slack. For example, a fiscal stimulus that boosts public employment would be more likely to crowd out private employment when labor markets are tight (Michaillat 2014), resulting in smaller domestic and spillover impacts; the same logic applies to the case of fiscal tightening. Another possibility is that a fiscal stimulus relaxes borrowing constraints (which tend to be tighter during a downturn), for example, by raising the value of collateralizable assets along with demand, helping to increase credit and investment (Canzoneri and others 2016). Somewhat similarly, if the recipient country is operating close to full capacity when an external fiscal shock hits, greater demand in tradable sectors may crowd out activity in the rest of the economy, resulting in a more muted impact on overall economic activity.
- *Monetary policy constraints:* Whether monetary policy accommodates the fiscal shock matters, and it is relevant for both source and recipient countries.

[5]For example, see Eggertsson (2011); and Erceg and Lindé (2013).

[6]For example, see Fleming (1962); Mundell (1963); Dornbusch (1976); and Obstfeld and Rogoff (1995).

[7]Notice that other frameworks can deliver different exchange rate predictions (see Obstfeld and Rogoff 1995).

Under normal circumstances, monetary policy reacts to counter the demand and price effects of a fiscal shock. However, when monetary policy is stuck at the effective lower bound, the domestic and spillover effects can be greater. For example, if nominal interest rates in the source country do not rise in response to higher expected inflation following an expansionary fiscal shock, real interest rates decline, crowding in domestic demand and increasing the multiplier (Blanchard, Erceg, and Lindé 2016).[8] In this case, the reduction in the real interest rate in the source country may lead its real exchange rate to depreciate, changing the direction of the expenditure switching effect. In a recipient country, when at the effective lower bound, monetary policy will do little to dampen the effect of the external shock.

Aside from conjunctural factors, institutional or structural features such as the *exchange rate regime* can also affect the transmission of fiscal shocks and hence the size of spillovers. On one hand, most theoretical frameworks predict that lack of nominal exchange rate flexibility delays real exchange rate adjustments to a fiscal shock, dampening the expenditure switching effect and hence the size of spillovers. On the other hand, currency pegs can strengthen expenditure shifting between the source and recipient—for example, by reducing expected exchange rate volatility and cross-border transaction costs, which is helpful in forming trade relationships (Klein and Shambaugh 2006; Qureshi and Tsangarides 2010; Aglietta and Brand 2013)—and potentially increase spillovers. This may be particularly relevant in currency unions, as long-standing economic and institutional integration and the use of a common currency can strengthen trade (Rose and van Wincoop 2001; Berger and Nitsch 2008). The exchange rate regime also matters for the transmission of fiscal shocks through the financial channel. For example, under flexible regimes, spillovers from an expansionary fiscal shock can be dampened if currency mismatches in balance sheets of households and corporations in the recipient country make depreciations contractionary. Ultimately, which of these considerations dominates is an empirical question.

[8]This insight works for both contractionary and expansionary shocks. Low interest rates prevent the central bank from counteracting a contractionary shock by reducing rates further, while in the case of an expansionary shock, it may be fully accommodated if the central bank aims for a more accommodative stance than feasible; in either case, spillovers are amplified.

Spillovers on Economic Activity: Empirical Evidence

This section examines the relevance of fiscal spillovers in practice and how they vary with economic circumstances. It does so by looking at a very broad sample of source and recipient countries and analyzing different types of shocks under both fiscal consolidations and expansions. It first describes the empirical strategy used to estimate spillovers and then presents the estimated impact on economic activity in recipient countries.

Empirical Strategy

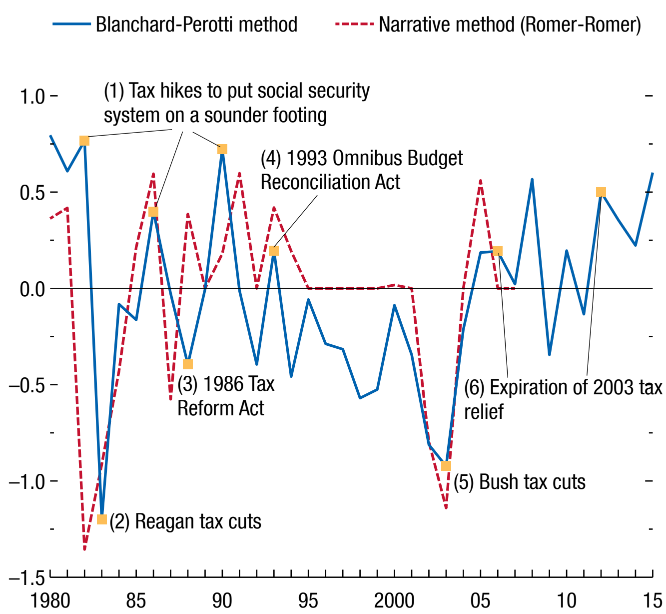
The baseline approach jointly identifies government spending and revenue shocks in five major advanced economies—France, Germany, Japan, the United Kingdom, and the United States—using the structural vector autoregression methodology of Blanchard and Perotti (2002).[9] A key assumption is that discretionary fiscal policy does not respond contemporaneously to unexpected changes in output, as it takes time for policymakers to assess the output shock and make spending and/or tax decisions, including passing and implementing new legislation. The assumption is more likely to hold in the short term, and therefore the identification uses quarterly data.[10]

The shocks identified by this approach offer a sensible narrative of the fiscal policies adopted over the past several decades. Comparison of structural shocks with historical policy records (quantified using the narrative approach in the literature) shows that structural shocks can broadly reflect major policy changes in timing and order of magnitude. For example, for the United States, the structural tax shocks capture tax cuts enacted under the Ronald Reagan and George W. Bush administrations as well as their subsequent expiration. The same is true of tax hikes during the 1980s, which

[9]Although spillovers from fiscal policy in China are potentially important, data limitations prevent the inclusion of China as a source country in the empirical analysis. Later in the chapter, model-based simulations help shed light on the potential spillover effects from China's fiscal policy.

[10]Although the use of quarterly fiscal data comes with challenges, it is instrumental to implementing the identification method used by Blanchard and Perotti (2002). These data (in real terms and seasonally adjusted) are used for shock identification only and for major advanced economies with high-quality statistics. As discussed later in the chapter, it is also reassuring that alternative identification methods that do not rely on quarterly fiscal data yield similar results for spillovers.

Figure 4.3. Tracking Tax Shocks in the United States
(Percent of GDP)



Sources: Romer and Romer (2010); and IMF staff calculations.

were put in place following the Greenspan Commission's recommendations to shore up financing of the social security system (Figure 4.3).[11]

The structural shocks also have a statistically and economically significant domestic impact. Consistent with traditional Keynesian theory and previous empirical work that uses a similar methodology, estimates of domestic multipliers using the structural shocks tend to be larger for spending instruments (slightly above one) than for tax instruments (slightly below one). Some differences are seen in the size of domestic tax multipliers across the five source countries, with the multiplier of the United States being larger than that of European peers or Japan, possibly reflecting different tax structures and the specific tax instruments used (Blagrave and others, forthcoming).

The spillover effects from the fiscal shocks are estimated using the local projections method.[12] The econometric specification relates an economic outcome in a recipient country, such as the level of output, to a fiscal shock from the five source countries—constructed by pooling together shocks from source countries and weighting them by the strength of trade links between the source and the recipient.[13] The baseline specification controls for factors that affect the normal short-term dynamics of output in the recipient country, such as past growth rates and external demand developments. The specification is estimated using quarterly data from the first quarter of 2000 through the second quarter of 2016, and the sample of 55 advanced and emerging market economies represents almost 85 percent of world output. Thus, the panel estimation gives spillover estimates for an "average" country in the sample.[14] For the panel estimation, the shocks are expressed as a share of recipient countries' output to facilitate aggregation across sources. For ease of interpretation of the economic magnitude, results are presented with shocks normalized to an average 1 percent of GDP change in the fiscal position across source countries (see details in Annex 4.2, which shows how panel results are rescaled using relative GDP levels and trade links).

Spillovers on Economic Activity

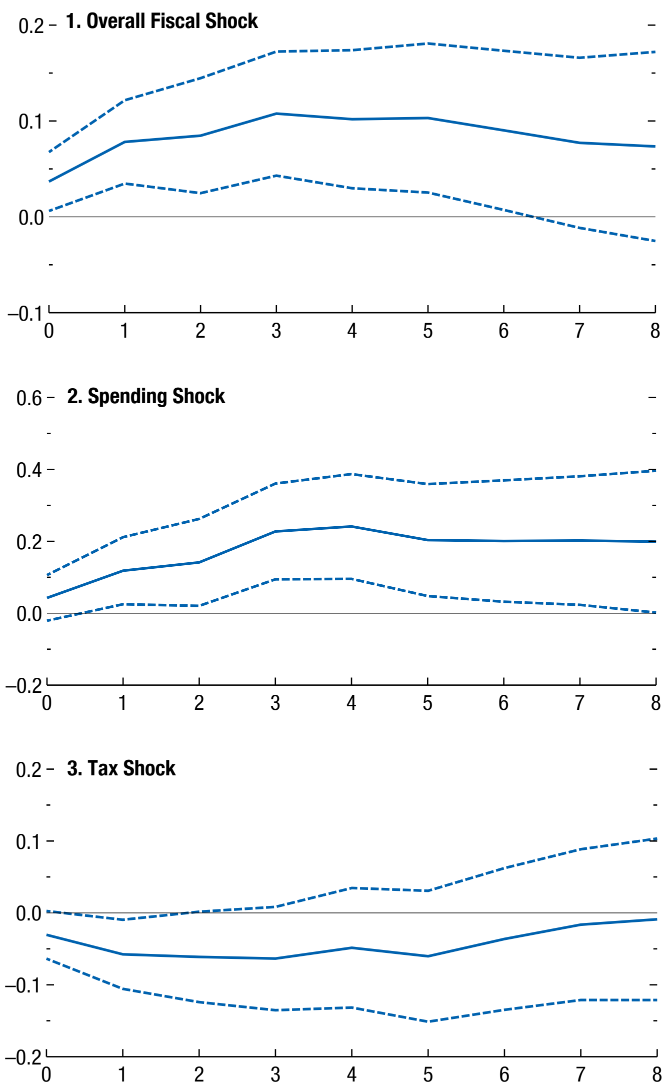
The results point to significant spillover effects from fiscal policy, especially from government spending shocks. Figure 4.4 shows the estimated response to a foreign fiscal shock of an average recipient country's output over eight quarters. A shock to the fiscal balance—henceforth referred to as the *overall fiscal shock*—is constructed as a shock to government spending minus a shock to tax revenues, such that a positive shock implies a *reduction* in the source country's fiscal balance (or an increase in the deficit). An overall fiscal shock would increase recipient output on impact, reaching a peak around the third quarter after the shock before starting to dissipate (Figure 4.4, panel 1). Estimations for specific fiscal instruments show that spillovers from a government spending shock are larger, more persistent, and more precisely estimated

[11]See Blagrave and others (forthcoming) for more examples.
[12]See Jordà (2005).

[13]The use of trade links to weight the shock is instrumental to obtaining country-specific external fiscal shocks, but it does not preclude spillovers through channels other than trade given that the estimates capture the overall response of recipient-country GDP regardless of the channel of transmission. Combining shocks from several source countries is important to use the variability emanating from different sources, given that trade patterns differ. In particular, while some source countries—such as the United States—can have a global impact, the impact of others is more regional; for example, Germany's and France's trading partners are more concentrated in Europe.
[14]More details about the data and empirical methodology are provided in Annexes 4.1 and 4.2, respectively, as well as in Blagrave and others, forthcoming.

Figure 4.4. Dynamic Responses of Recipient Countries' Output to Fiscal Shocks

(Impact on output level, percent; quarters on x-axis)



Source: IMF staff calculations.
Note: $t = 0$ is the quarter of the respective shocks. Solid lines denote point estimates and dashed lines denote 90 percent confidence bands. Shocks are normalized to an average of 1 percent of GDP across source countries.

than those from a tax shock of equal size (Figure 4.4, panels 2 and 3).[15] This is consistent with the evidence pointing to larger domestic spending multipliers than domestic tax multipliers—as discussed earlier. Data constraints prevent a more detailed empirical examination of spillovers from specific spending or tax instruments, such as government consumption or investment—an issue assessed later in the chapter through model-based simulations.

Spillovers are economically significant and in line with earlier estimates. For example, a 1 percent of GDP overall fiscal shock in an average major advanced economy would raise output in the average recipient country by about 0.08 percent over the first year. For a government spending increase of the same magnitude, the average spillover impact in recipient countries increases to 0.15 percent over the first year; for a tax hike of similar size, output falls by about 0.05 percent (Figure 4.5). As expected, spillovers from fiscal shocks are substantially lower than domestic fiscal multipliers in source countries, but still relevant.[16] These are of the same order of magnitude as those found in previous work—for example, Beetsma, Klaassen, and Wieland (2006)—although differences in country and time samples as well as shock identification make a direct comparison challenging.[17] While the spillover estimates in this section are averages across different economic and policy conditions, subsequent analysis also shows that there is a large difference between estimates in normal times and those in times of economic slack, for example.

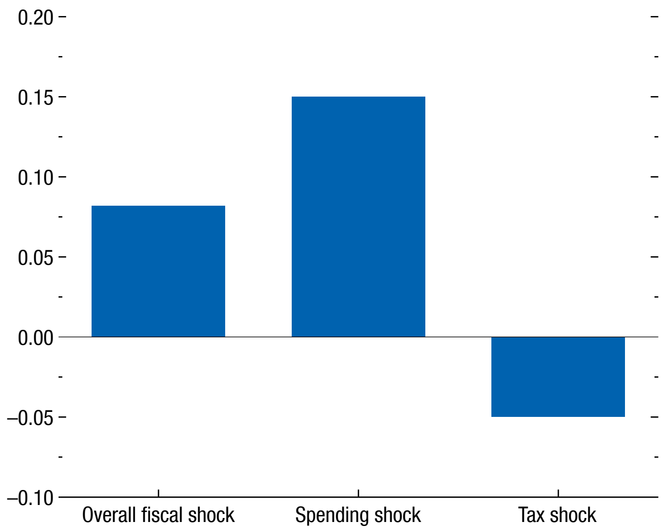
Further analysis of components of recipient-country output corroborates the importance of trade for the transmission of fiscal shocks (Figure 4.6), consistent with the conceptual framework outlined above. In particular, a positive fiscal shock from abroad is estimated to raise recipient-country bilateral exports to the source countries. With higher export demand, firms expand investment to build production capacity, generating a second-round effect on recipient-country investment, whereas the impact on consumption appears negligible. The boost to exports and investment increases imports, some of which come from source countries. With bilateral imports rising by much less than bilateral exports, however, the recipient's trade balance with the source countries improves following the fiscal shock.

[15]These effects are assumed to be symmetric during fiscal expansions and consolidations—the panel analysis cannot disentangle a potential asymmetry from different policy actions.

[16]As discussed earlier, fiscal shocks in the chapter yield domestic spending multipliers slightly above one and tax multipliers slightly below one, on average, across the source countries.

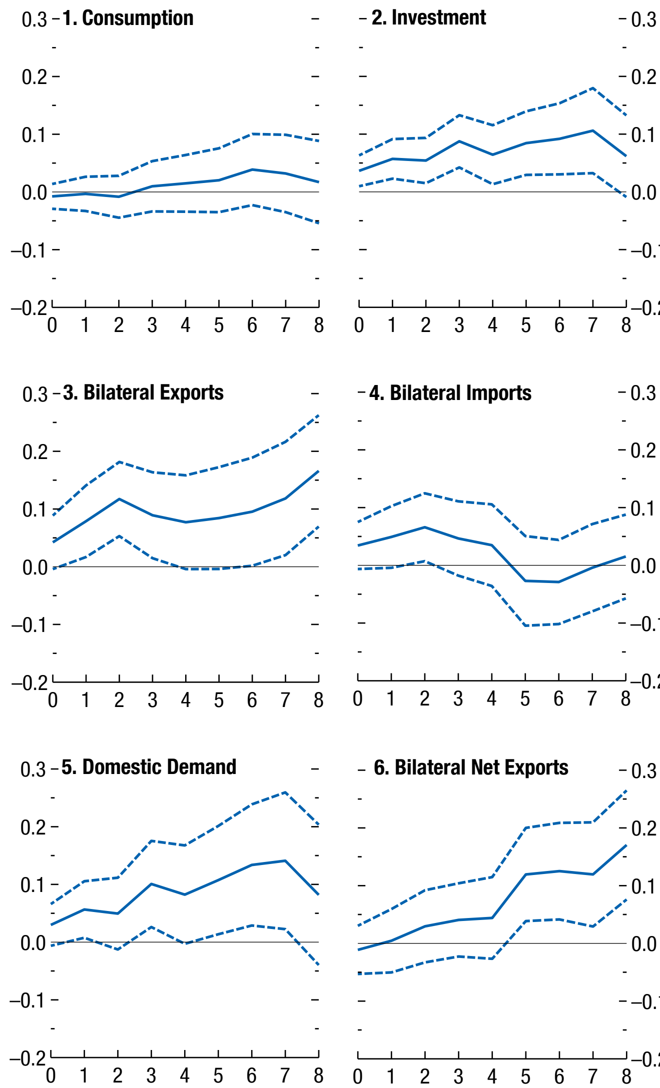
[17]Beetsma and others (2006) find that a 1 percent of German (French) GDP shock to government spending results in a European GDP response of about 0.14 (0.08) percent after two years. For a tax shock, spillovers are about –0.05 (–0.03) percent. Compared with studies that express shocks in units of recipient-country GDP (Auerbach and Gorodnichenko 2013; Goujard 2017), estimates are also broadly similar. A detailed comparison to the literature is provided in Blagrave and others, forthcoming.

Figure 4.5. Spillovers of Fiscal Shocks on Recipient Countries' Output
(One-year average impact on output; percent)



Source: IMF staff calculations.
Note: Shocks are normalized to an average of 1 percent of GDP across source countries.

Figure 4.6. Dynamic Responses of Components of Recipient Countries' Output to a Fiscal Shock
(Percent of output; quarters on x-axis)



Source: IMF staff calculations.
Note: $t = 0$ is the quarter of the shock. Solid lines denote point estimates, and dashed lines denote 90 percent confidence bands. Responses to an overall fiscal shock are presented. Shocks are normalized to an average of 1 percent of GDP across source countries.

The empirical spillover estimates are robust to alternative specifications and shock-identification strategies. For example, the baseline results do not change much with the inclusion of additional control variables (for example, the recipient-country short-term interest rate, output gap, unemployment rate, and fiscal stance).[18] Estimates are also similar—though slightly larger—using a panel vector autoregression estimation methodology that allows for potential feedback effects of exchange rates and interest rates on output. In addition, estimates using comparable fiscal shocks obtained from alternative identification strategies—namely forecast errors and narrative approach—also yield spillover estimates that are similar in size and dynamics. This provides reassurance that the baseline results are not driven by the structural vector autoregression methodology for identifying fiscal shocks.[19] Annex 4.3 gives more details about robustness tests.

[18]These robustness checks can be found in Blagrave and others (forthcoming).

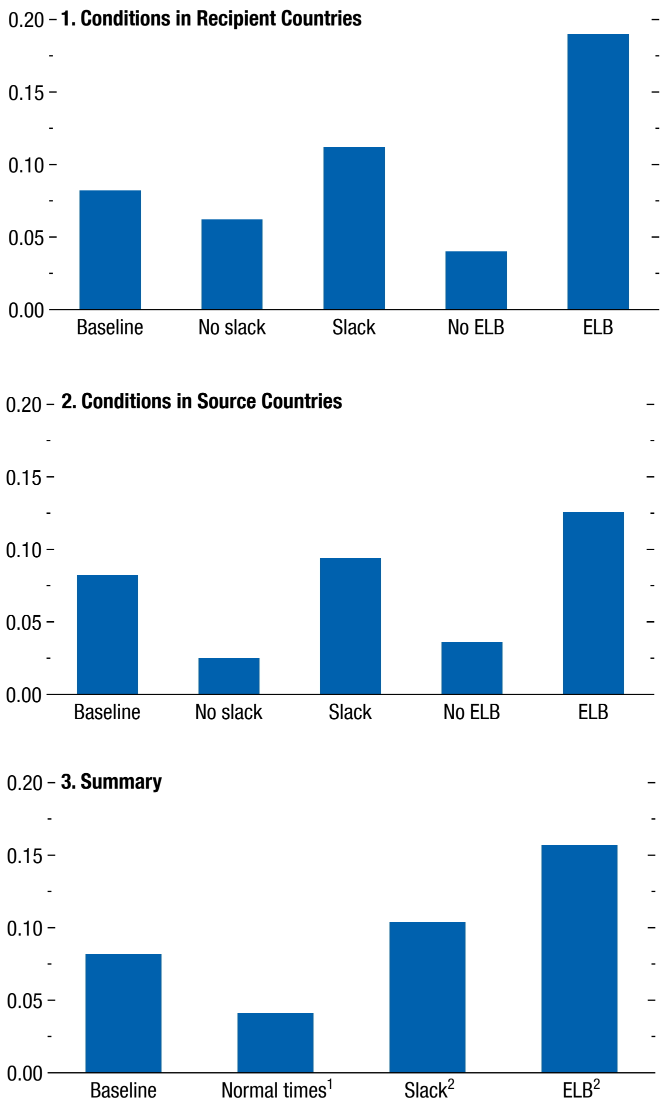
[19]Forecast errors are constructed as the difference between actual and projected values of the relevant fiscal variable (spending or tax revenues). The shocks based on forecast errors are identified as residuals from a regression of the spending- or tax-based forecast errors on GDP forecast errors and lagged macroeconomic variables.

Spillovers under Different Economic and Policy Conditions

Business cycle and monetary policy conditions in both source and recipient countries, along with the bilateral exchange rate regime, can affect the magnitude of spillovers from fiscal policy. As outlined earlier in the conceptual framework, these factors are expected to affect the domestic impact of fiscal shocks—if

Figure 4.7. Spillovers under Various Economic and Policy Conditions

(One-year average impact on output; percent)



Source: IMF staff calculations.
Note: ELB = effective lower bound. Slack is defined as output gap below zero; and ELB corresponds to short-term interest rates in the bottom 25 percent of cross-country historical distribution. Responses to an overall fiscal shock are presented. Shocks are normalized to an average of 1 percent of GDP across source countries.
[1]Normal times refer to average of no slack and no ELB in both source and recipient countries.
[2]Average estimates for conditions in source countries and conditions in recipient countries.

they pertain to the source country—as well as their cross-border transmission. In general, a larger impact in the source country is expected to give rise to more significant spillovers.

Cyclical Position and Monetary Policy Constraints

To test how cyclical positions and monetary policy affect the impact of fiscal shocks, the baseline econometric framework is augmented to allow for potential regime dependence (see Annex 4.2 for details). The definitions of regimes are based on the prevailing output gap or the level of the short-term interest rate in either source or recipient countries. Specifically, a negative output gap is assumed to represent economic slack, and a short-term interest rate below the 25th percentile of the relevant cross-country distribution is a proxy for monetary policy constrained by the effective lower bound.[20] Results are robust to using alternative definitions of slack, including the unemployment gap or smooth-transition probability as in Auerbach and Gorodnichenko (2013). For the effective lower bound, results are also robust to using an absolute interest rate threshold that is common to all countries.

Consistent with theory and empirical findings in the domestic multiplier literature, spillovers are estimated to be larger during episodes of economic slack than in normal times. For example, if the recipient country has slack when the external fiscal shock hits, its output would rise by 0.11 percent over the first year in response to a 1 percent of GDP overall fiscal shock in an average major advanced economy. By contrast, the response to the same shock would be almost halved—to 0.06 percent—when there is no economic slack (Figure 4.7, panel 1). Differential effects are also observed when the *source* economy has slack, compared with when it does not—with estimates varying between 0.09 percent and 0.03 percent, respectively (Figure 4.7, panel 2).

Spillovers can be even larger when monetary policy is constrained by the effective lower bound, either in the source or the recipient country (Figure 4.7, panels 1 and 2). For example, subject to a 1 percent of GDP overall fiscal shock in an average major advanced economy, the response of recipient-country output can be more than four times greater when its interest rate is exceptionally lower than in normal times.[21] Monetary

[20]Separate distributions are applied for advanced and emerging market economies.

[21]These results—for both slack and effective lower bound cases, in both recipient and source countries—also extend to disaggregated spending and tax shocks (see Blagrave and others, forthcoming, for more details).

policy constraints in source countries have a similar effect on spillovers, as they can amplify the domestic impact of fiscal shocks. Although slack and the effective lower bound have distinct mechanisms to amplify spillovers, it is often difficult to clearly distinguish the two states in empirical estimation because they can coincide in practice, as has occurred in recent years.[22] This caveat should be kept in mind when interpreting the results.

The response of GDP components under monetary policy constraints offers further insights into how a fiscal shock is transmitted to recipient countries (Figure 4.8). Faced with a positive fiscal shock from abroad, consumption—and particularly investment—in a recipient country responds much more strongly when the domestic nominal interest rate is close to the effective lower bound, likely reflecting declining real interest rates associated with higher expected inflation. This is consistent with results from theoretical models (see section on factors affecting transmission) and is confirmed by the results of the model-based simulations presented in the next section. The responses of exports to and imports from the source countries are also stronger when monetary policy accommodates the fiscal shock, in line with the domestic response of investment.

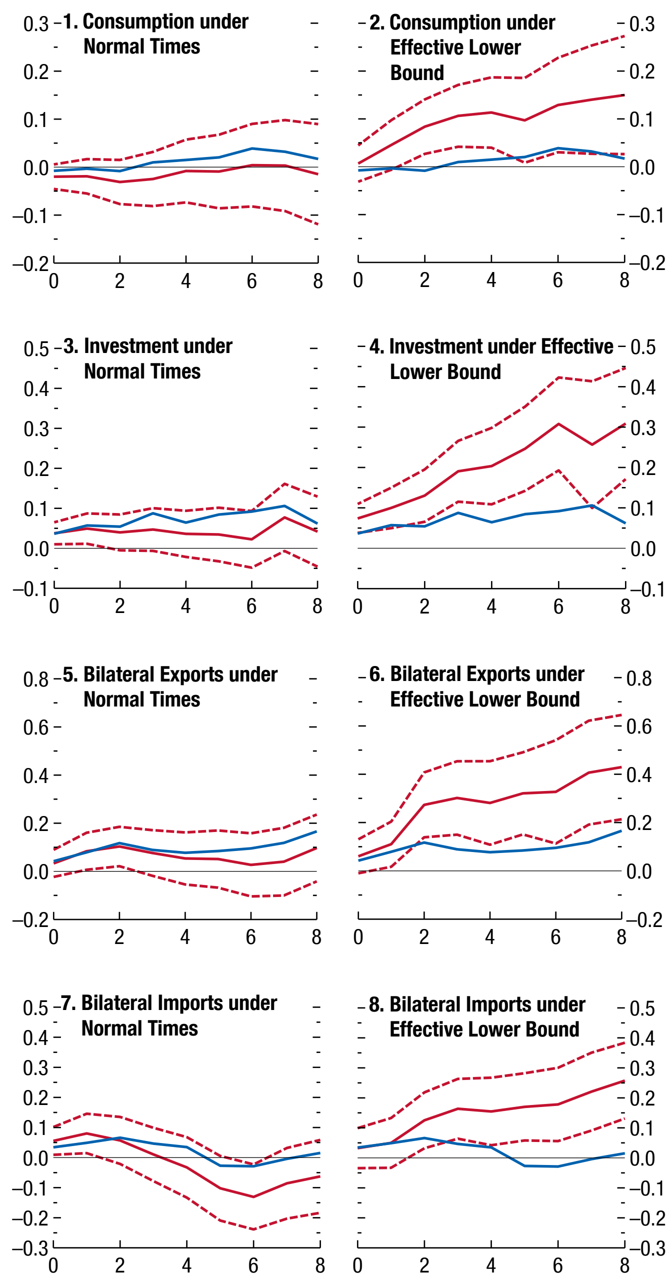
Exchange Rate Regime

As discussed in the section on factors affecting transmission, the exchange rate regime can also impact the size of fiscal spillovers. To investigate this question, this section analyzes whether the impact of a fiscal shock in the United States varies for recipient countries with fixed and flexible exchange rate regimes vis-à-vis the US dollar. The United States—with its global currency and systemic trade importance—is a suitable source country for this exercise. Countries do not typically peg to the British pound or the Japanese yen. In the case of the euro, Germany's and France's trade importance is mostly within Europe, where most sample countries are

[22]In the post-2000 sample considered in this empirical exercise, about 26 percent of country-quarter observations fall under the definition of "effective lower bound," three-quarters of which coincide with economic slack. Similarly, about 55 percent of observations fall under the definition of "slack," 35 percent of which coincide with the effective lower bound. For example, many advanced economies experienced both severe slack and very low interest rates in the aftermath of the global financial crisis. Japan, in particular, experienced both slack and effective lower bound for 84 percent of the observations during the sample period.

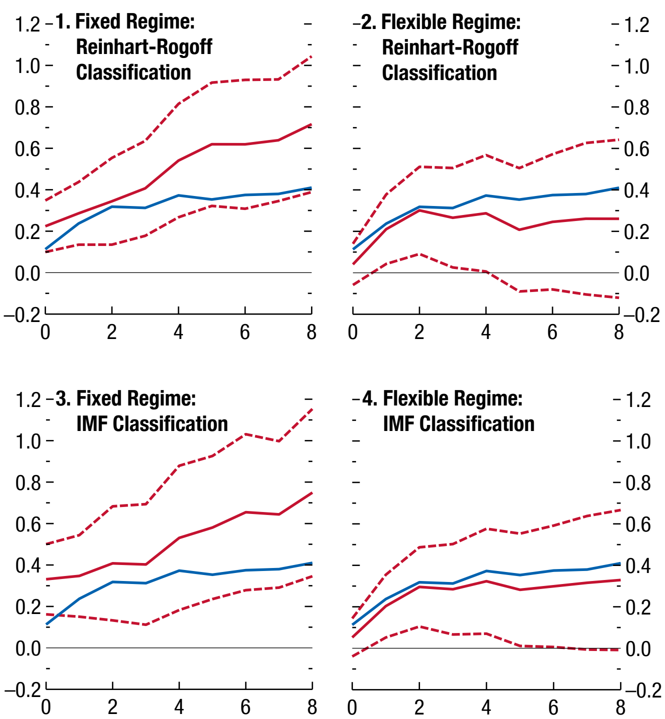
Figure 4.8. Dynamic Reponses of Components of Recipient Countries' Output under Normal Times and Effective Lower Bound in Recipient Countries

(Percent of output; quarters on x-axis)



Source: IMF staff calculations.
Note: Normal times = no effective lower bound. $t = 0$ is the quarter of the shock. Solid red lines denote point estimates under different conditions; dashed red lines denote 90 percent confidence bands; and solid blue lines represent the unconditional response. Effective lower bound corresponds to short-term interest rates in the bottom 25 percent of cross-country historical distribution. Responses to an overall fiscal shock are presented. Shocks are normalized to an average of 1 percent of GDP across source countries.

Figure 4.9. Dynamic Reponses of Recipient Countries' Output to US Spending Shock under Various Exchange Rate Regimes
(Impact on output, percent; quarters on x-axis)



Source: IMF staff calculations.
Note: $t = 0$ is the quarter of the shock. Solid red lines denote point estimates conditional on exchange rate regime; dashed red lines denote 90 percent confidence bands; and solid blue lines represent the unconditional estimates. Shocks are normalized to an average of 1 percent of GDP across source countries (note that this represents a less than 1 percent of US GDP shock).

either euro area members or peg to the euro, not allowing for enough variation in the data to identify the effect for those with flexible regimes.

The empirical framework is again modified to allow for regime dependence of the fiscal shock—now originating only in the United States—where the regime definition is based on the prevailing bilateral exchange rate arrangement between the United States and the recipient country in a particular period. Specifically, a "fixed" exchange rate regime is defined as encompassing de facto pegs or crawling pegs, classified using two alternative methods: (1) Reinhart and Rogoff (2004) updated by Ilzetzki, Reinhart, and Rogoff (2017a, 2017b)—henceforth called "Reinhart-Rogoff" classification; and (2) the IMF's *Annual Report on Exchange Arrangements and Exchange Restrictions* ("IMF" classification).[23] More details are provided in Annex 4.1.

The evidence suggests that a government spending shock in the United States generates stronger and more persistent impacts on countries whose exchange rates are pegged to the US dollar than on those whose exchange rates are more flexible (Figure 4.9). This is the case regardless of which exchange regime classification is used. The difference in the output responses between fixed and flexible regimes is statistically significant on impact under both classifications and also during the second year under the Reinhart-Rogoff classification. At the same time, no difference in spillovers is observed between fixed and flexible regimes from an overall fiscal shock or a tax shock (not shown). Taken at face value, this result seems to point to relatively weak expenditure switching effects in the transmission of spending shocks. This weakness could reflect that, for a significant portion of the sample, US monetary policy was constrained by the effective lower bound, limiting interest rate and hence exchange rate movements. Another possibility is that, as discussed earlier, trade integration may be stronger under pegs—beyond what can be captured by the simple import ratios used in weighting the shocks.

The Transmission of Fiscal Shocks—Model-Based Analysis

To complement the empirical analysis, the chapter presents model-based simulations using a multiregion general equilibrium model—the IMF's G20 Model. The model simulations are intended to be illustrative and offer further insights into the macroeconomic adjustment to fiscal shocks—including the response of exchange and interest rates—and more granularity on the impacts of various fiscal instruments. Overall, simulations serve as theory-based cross-checks on the empirical results and provide insights into how fiscal shocks are propagated.[24]

The results are generally consistent with the empirical findings in this chapter: simulations show that spillovers from temporary fiscal shocks can differ

[23]In 2015, for example, the Reinhart-Rogoff classification has more recipient countries classified as having "fixed" exchange rates compared with the IMF classification. The number of fixed-rate countries varies over time. In general, there tend to be more fixed exchange rate regimes in earlier years of the sample.

[24]Additional details on the G20 Model are available in Andrle and others (2015).

substantially depending on the monetary policy response and the fiscal instruments used. In addition, the responses of GDP components under different assumptions on monetary accommodation closely resemble those identified empirically.[25] In all cases, fiscal shocks are expressed as a share (generally 1 percent) of a particular source country's GDP—this differs from how results were presented in the empirical section and implies that, all else equal, shocks emanating from larger countries will have larger spillover effects.

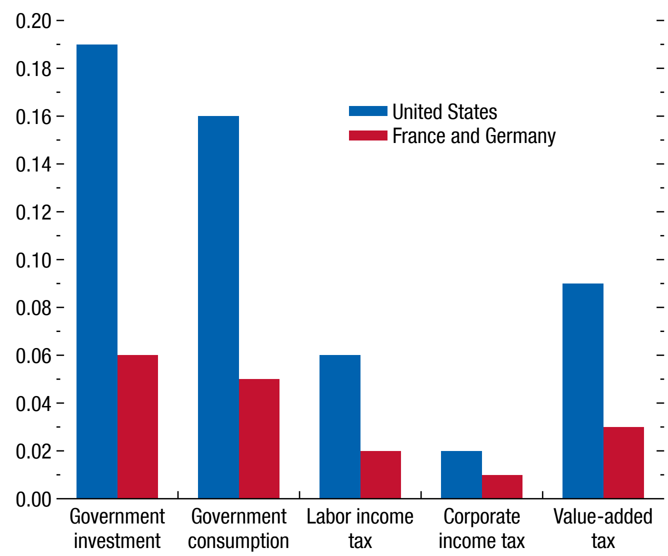
Spillovers on Output: Fiscal Instruments and Policy Accommodation

The model simulations confirm substantial spillovers from government spending shocks. Specifically, they show that spending shocks have larger spillover effects than do tax shocks.[26] This coincides with results from the empirical analysis described in this chapter. However, structural models offer insights into the impact of specific fiscal instruments as well, as shown in Figure 4.10:

- *Spending instruments:* Government investment shocks in the G20 Model have larger domestic and spillover effects than shocks to government consumption. This is because government investment increases the public capital stock, which is assumed to increase private sector productivity, stimulating private investment and labor demand and in turn raising wages and labor income. By contrast, government consumption does not affect private sector productivity.
- *Tax instruments:* Model simulations suggest that temporary changes in consumption taxes have the largest domestic and spillover effects among tax instruments. Unlike cuts in labor income or corporate taxes, where benefits can be saved, households must increase their current-period spending to take advantage of temporarily lower consumption taxes.[27] In addition, because investment decisions have a long planning horizon and investment can be costly to adjust (Christiano, Eichenbaum, and Evans 2005), the impact of temporary corporate income tax changes is smaller than that of temporary labor income tax changes—the latter affect liquidity-constrained households, which fully adjust consumption in response.

Figure 4.10. Impact of Fiscal Shocks on Global GDP Based on Various Instruments

(Two-year average impact, percent)



Source: IMF, G20 Model (G20MOD) simulations.
Note: All shocks are 1 percent of source-country GDP, lasting two years.

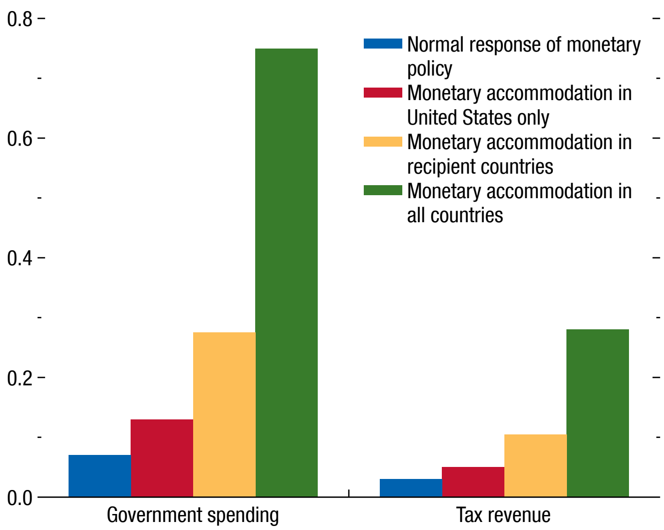
Consistent with the empirical analysis, model simulations show that spillovers on output can vary widely, depending on the response of monetary policy, in both source and recipient countries. Figure 4.11 depicts the impact of the same temporary two-year US government spending and tax shocks considered in Figure 4.10—using the *average* across spending and tax instruments—on recipient-country GDP under different monetary policy assumptions: (1) a rule-based response in both source and recipient countries, (2) accommodation in the United States during the first two years following the fiscal shock, (3) accommodation in recipient countries during the first two

[25]The domestic and spillover effects of permanent fiscal shocks may differ from those of temporary shocks, partly because of their effects on interest rates. For example, permanent fiscal consolidations in large countries may lower global interest rates, thereby crowding in investment and boosting GDP over the long term. Some permanent fiscal reform scenarios are considered in the next section.

[26]For simplicity, the analysis presented here is conducted for France, Germany, and the United States; the intention is to draw broad lessons about the heterogeneity of spillovers across different fiscal instruments. The findings presented here apply equally to other countries' fiscal shocks.

[27]Conversely, when consumption taxes increase temporarily, households can avoid some of the burden by postponing consumption.

Figure 4.11. Spillovers from US Fiscal Shocks with and without Monetary Accommodation
(Two-year average impact on rest of the world GDP, percent)



Source: IMF, G20 Model (G20MOD) simulations.
Note: Normal response of monetary policy is a rule-based response, in countries without fixed exchange rate regimes, where monetary policy responds to an increase in expected future inflation by increasing nominal interest rates to reduce demand and return inflation to target.

years, and (4) accommodation in both the United States and recipient countries during the same period. Spillovers vary markedly depending on the response of monetary policy—for example, they can be about four times larger if monetary policy in recipient countries fully accommodates the shock, as compared with when monetary policy follows the inflation-forecast targeting rule in each country.[28,29] These results are closely aligned with the empirical analysis presented in Figure 4.7—when interest rates in the recipient country are at or near the effective lower bound, spillover effects are estimated to be about four times larger than they are during normal times.

Model-based simulations can also offer insights in terms of regional patterns of the impact of fiscal shocks. Spillovers from stimulus in the United States have the broadest global reach—due to the large size of the US economy and its moderately strong trade links with most regions (Figure 4.12).[30] Spillovers from the United States are largest on countries in Latin America and Canada—all of which account for significant shares of US import demand. For shocks from France and Germany, spillovers are largest on Europe, given deep trade integration, but relatively small on other regions. Finally, fiscal measures in China have meaningful spillovers on each region due to the size and openness of the Chinese economy. By region, spillovers are slightly larger on countries in Asia—given strong trade links—though spillovers on Europe, Canada, and Latin America are not trivial. China's economy, given its growing global clout, is playing an important role in driving spillovers onto neighboring countries through the trade channel and the impact of fluctuations in demand on commodity prices (IMF 2016).

Macroeconomic Adjustment and the Role of Financial Variables

Model simulations can give a richer description of the macroeconomic dynamics behind fiscal spillovers. In particular, simulations allow for an examination of the dynamics of interest rates and exchange rates—because these variables are forward-looking in nature, they respond to changes in the expected future state of the economy, so when a change in fiscal policy is announced or expected, these variables react immediately. This makes it difficult to capture their behavior in empirical exercises using structural shocks, which typically assess the impact of the implementation of fiscal changes.[31] The chapter uses both model-based analysis and an alternative empirical approach that isolates anticipation effects to assess the impact of fiscal shocks on exchange rates and external positions in recipient countries.

To shed light on the dynamics of adjustment following fiscal shocks, Figure 4.13 presents the response of several variables in the United States and the global

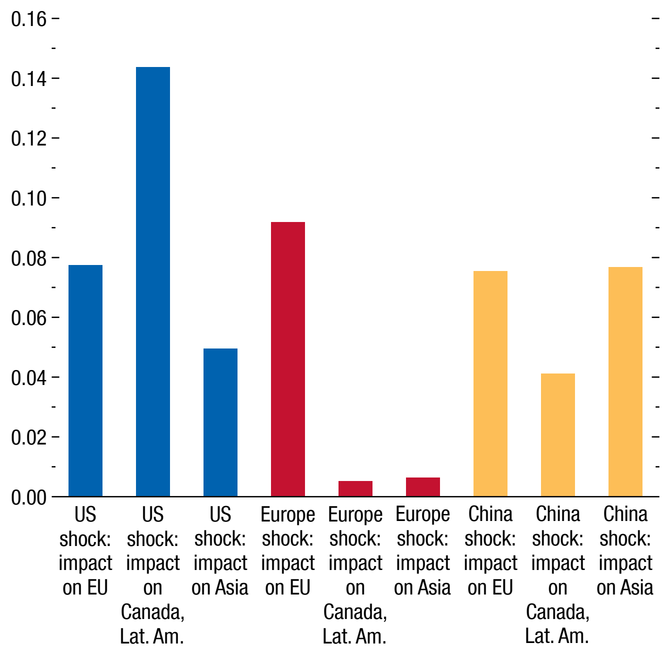
[28]In the G20 Model, monetary policy in countries with flexible exchange rate regimes responds to an increase in expected future inflation by increasing nominal interest rates to reduce demand and return inflation to target.

[29]Spillovers are even larger under the full accommodation scenario—they should be viewed as an upper bound, as such a scenario would require an exceptional coordinated accommodation by monetary policy in all countries.

[30]The regional distribution of spillovers predicted by model simulations closely resembles those implied by the empirical analysis presented earlier. See Blagrave and others (forthcoming) for more details.

[31]Several studies estimating fiscal shocks in structural vector autoregression models find that increases in government spending trigger exchange rate *depreciations*—see, for example, Corsetti and Müller (2006); Kim and Roubini (2008); Monacelli and Perotti (2010); Enders, Müller, and Scholl (2011); and Ravn, Schmitt-Grohé, and Uribe (2012). This empirical result runs counter to the predictions of the Mundell-Fleming-Dornbusch framework, although it is consistent with some new open-economy macroeconomic models (Obstfeld and Rogoff 1995).

Figure 4.12. Regional GDP Impact of Government Spending Shocks from the United States, Europe, and China
(Two-year average impact, percent)

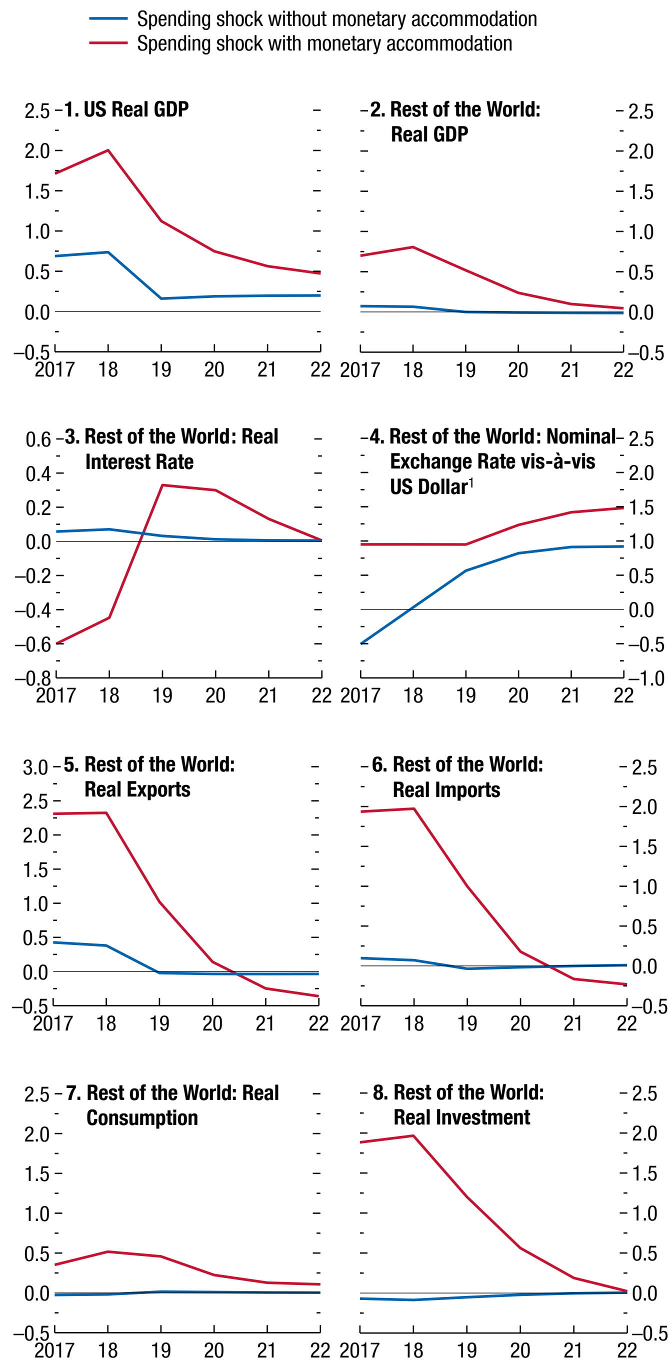


Source: IMF, G20 Model (G20MOD) simulations.
Note: EU = European Union; Lat. Am. = Latin America (Argentina, Brazil, Mexico). Europe shock refers to France and Germany shocks. Shock to government spending is equivalent to 1 percent of GDP, lasting two years. Average level impact over two years with no monetary accommodation in any country is presented.

economy to a temporary government spending increase in the United States. Given the importance of the monetary policy reaction, it presents a two-year stimulus scenario under both a normal monetary policy response (blue line) and monetary policy accommodation in all countries (red line).

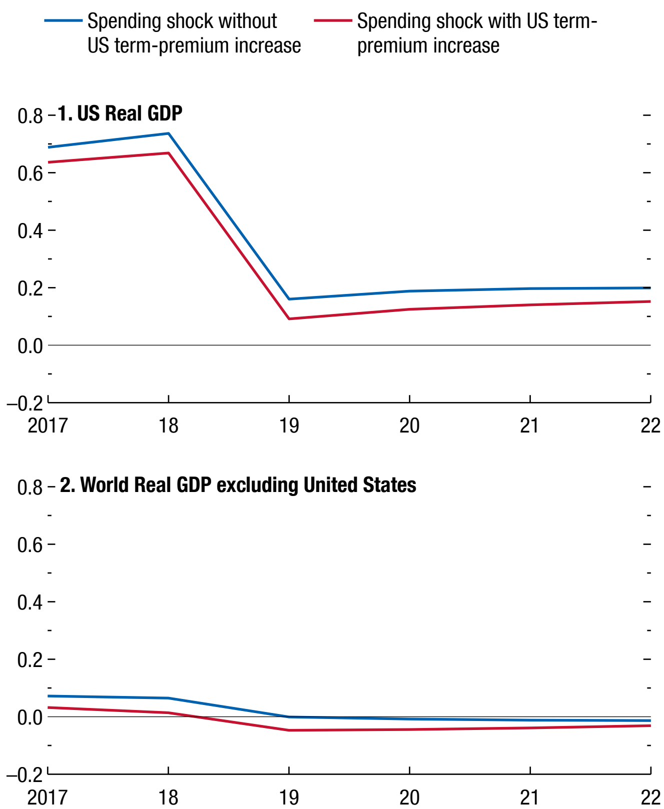
- *Monetary policy response:* Following the fiscal shock, policy rates increase to curb inflationary pressures from the demand shock both in the United States and in recipient countries. The uncovered interest parity condition implies that bilateral nominal exchange rates in relation to the US dollar depreciate in the short term given that the response of US monetary policy is more pronounced than elsewhere—being the source of the shock, inflationary pressures are greater there. The increase in US external demand and the nominal exchange rate depreciation in recipient countries induce a modest increase in exports from the rest of the world, and thus a slight improvement in the corresponding trade balances. However,

Figure 4.13. Dynamic Reponses to a US Government Spending Shock
(Percent deviation from baseline)



Source: IMF, G20 Model (G20MOD) simulations.
Note: Red lines denote the response to a 1 percent of GDP US government spending shock lasting two years with monetary accommodation in both source and recipient countries lasting two years, and blue lines represent the response to the same shock without monetary accommodation in any country.
[1]Increase represents appreciation.

Figure 4.14. Spillovers from US Spending Shock with and without a US Term-Premium Increase
(Percent deviation from baseline)



Source: IMF, G20 Model (G20MOD) simulations.
Note: Red lines denote the response to a 1 percent of GDP US government spending shock lasting two years, with a 25 basis point increase in the US term premium and subsequent spillovers to term premiums in other countries. Blue lines represent the response to the same spending shock with no term-premium increase. No monetary accommodation is assumed for any country.

the increase in world interest rates reduces consumption and investment in the rest of the world. The net effect on GDP is small but positive.

- *Monetary accommodation:* In this scenario, the positive impact on inflation goes unchecked, causing real interest rates to decline. This triggers a strong positive response in both consumption and investment in the rest of the world as the cost of capital and current-period consumption declines. The contrast between the dynamics of consumption and investment under monetary accommodation, as opposed to normal times, is consistent with the empirical findings shown in Figure 4.8. Monetary accommodation also implies a much larger impact on both exports—due to stronger external demand conditions—and imports, due to stronger domestic activity in recipients. The expenditure switching channel operates in the opposite direction under monetary accommodation, with recipient countries' real exchange rates *appreciating* against the US dollar. This occurs because the negative impact on US real interest rates is more pronounced than elsewhere. Recipients' trade balances still improve because of the strong increase in demand from the United States. Overall, as shown in Figure 4.11, the cumulative effect on global GDP is amplified under monetary accommodation.

If the term premium increases following a fiscal impulse—capturing potential concerns about debt sustainability or higher future inflation—and monetary policy responds normally, the impact of stimulus in the United States is reduced and spillovers are marginally smaller (Figure 4.14). In this case, higher interest rates than in the baseline scenario discourage investment and consumption in the United States. Therefore, the net effect on GDP in the rest of the world is slightly smaller, illustrating the potential for an adverse reaction of financial markets to an increase in spending to reduce spillovers.[32] This possibility underscores the importance of having a credible medium-term macroeconomic framework, which gives market participants confidence that inflation will be held in check because debt dynamics are sustainable.

An empirical examination of how exchange rates and external positions respond to fiscal shocks is presented in Box 4.1. To capture anticipation effects, the analysis constructs fiscal shocks based on the methodology of Forni and Gambetti (2016), which identifies these shocks at announcement dates, as captured by changes in professional forecasts. It shows that an increase in government spending in the United States leads to a real appreciation of the dollar and a worsening of the US trade balance, as predicted by standard macroeconomic models.

Fiscal Reforms

The model-based analysis also facilitates the examination of spillovers from so-called fiscal reforms—defined

[32]In this scenario, the increase in the US term premium is assumed to drive up term premiums in other countries as well, according to historical correlations between these variables across countries.

as permanent budget-neutral shifts in the composition of the public sector budget. The scenarios considered so far in the chapter deal with temporary fiscal impulses associated with a change in the fiscal stance in the source country. However, budget-neutral fiscal reforms may also have spillover effects. To demonstrate these differences, the following two scenarios are considered: (1) a budget-neutral corporate income tax reform and (2) a budget-neutral infrastructure spending increase. These illustrative scenarios suggest that fiscal reforms have limited cross-border effects, though significant changes can still generate large spillovers.

Budget-Neutral Corporate Income Tax Reform

The direct spillovers of a (simultaneous) budget-neutral reduction in corporate income tax rates in France, Germany, and the United States—the "source" countries in this scenario—would be slightly negative.[33] The scenario's main assumptions are that corporate tax rates are reduced by 15 percentage points, consumption-tax rates rise to offset the revenue loss, and monetary policy responds normally.[34] The direct impact of the reform is captured by the blue lines in Figure 4.15. As shown in the figure,

- Real GDP increases gradually as lower corporate income tax rates raise the return to capital in the source countries, stimulating investment. This positive effect on reform-country GDP is only partly counteracted by the increase in the consumption tax rate, which depresses consumption. Although these reforms are initially budget neutral, the expansion of investment increases tax revenues over time, which reduces the deficit and the debt stock in source countries.[35] Their trade balances deteriorate slightly due to investment-driven import demand.
- Given the lack of fiscal stimulus in the short term, the direct spillovers on recipient countries are limited. Over the medium term, GDP in recipient countries is slightly reduced, as recipient countries are now at a

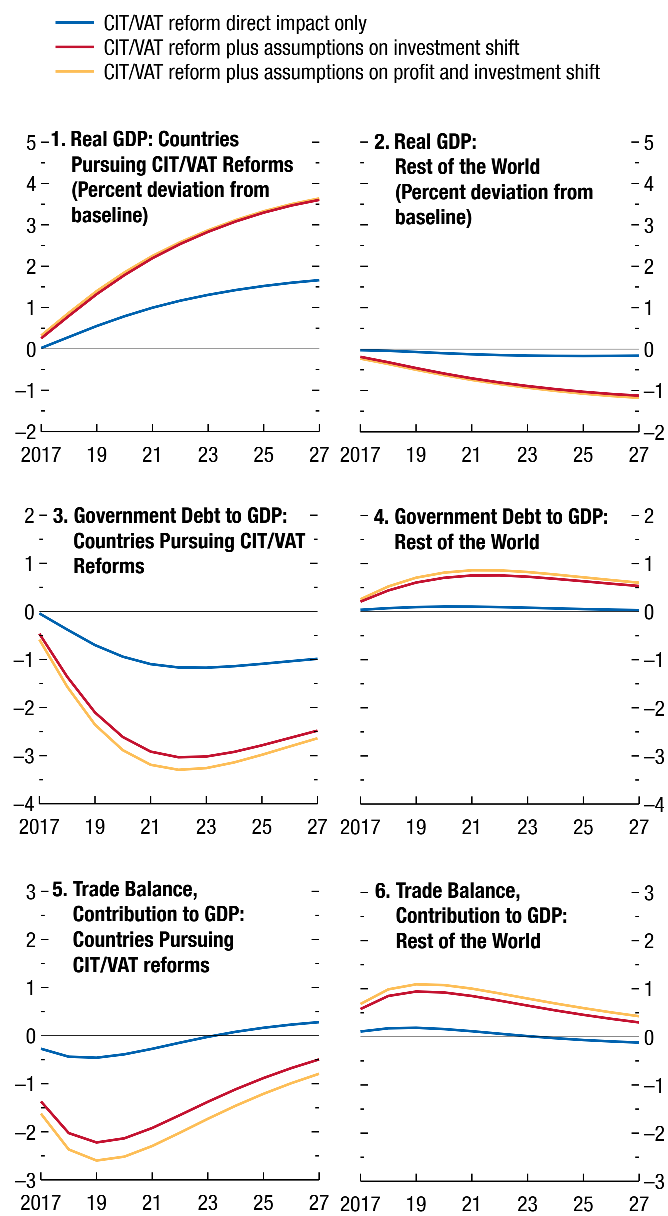
[33]France, Germany, and the United States are considered in this scenario given that they currently have corporate income tax rates above the OECD average, giving them scope for a substantial reduction. Reforms are budget neutral, contingent on the baseline path of output.

[34]In the case of the United States, which has no federal consumption tax, this would imply enacting such a tax.

[35]Absent the offsetting increase in consumption taxes, the corporate income tax reduction would result in a net loss of tax revenues, even after accounting for the increase in the tax base due to stronger investment.

Figure 4.15. Spillovers from Corporate Income Tax Reduction Financed by an Offsetting Increase in Value-Added Tax

(Percentage-point deviation from baseline, unless noted otherwise)



Sources: IMF, G20 Model (G20MOD) simulations; and IMF staff estimates.
Note: Blue lines denote the response to CIT/VAT reforms only, red lines denote the response to CIT/VAT reforms plus assumptions on investment shift, and yellow lines denote the response to CIT/VAT reforms plus assumptions on profit and investment shift. No monetary accommodation is assumed for any country. For rest of the world, no reforms are assumed. CIT = corporate income tax; VAT = value-added tax.

competitive disadvantage with respect to their return to capital, and real interest rates are slightly higher—implying lower investment. This negative impact more than offsets the small impetus to exports associated with increased demand from source countries.

However, beyond this direct effect, fiscal reforms may also affect investment and profit-reporting decisions. As discussed in Devereux (2008) and De Mooij and Ederveen (2008), corporate tax rates influence both intensive and extensive (discrete or location) decisions of firms, suggesting that multinational companies may relocate operations when faced with significant changes in relative tax rates in different jurisdictions. In addition, both studies note that it is feasible for multinational companies to shift profits between countries. In the scenario, the lower corporate income tax rates prompt these firms to shift operations—both investment and the jurisdiction in which profits are reported—to source countries, to the detriment of recipients.

The effect of investment and profit shifting are illustrated by the red (investment shifting only) and yellow (investment and profit shifting together) lines of Figure 4.15. Based on estimates in the literature on profit and investment shifting, the scenario assumes that foreign direct investment in countries not pursuing reforms could decline by about $400 billion—this loss is assumed to be distributed equally across all countries as a share of GDP.[36] By contrast, the countries pursuing reforms are assumed to benefit by a similar amount, above and beyond the immediate impact on investment from the corporate income tax reduction discussed above.[37] Profit shifting is assumed to be a pure fiscal revenue gain for source countries and a corresponding loss for other countries.[38]

The results suggest that investment shifting and profit shifting could trigger more significant spillovers on activity and affect fiscal positions. Activity in source countries would be considerably higher—with GDP increasing by almost 4 percent after 10 years—although significantly reduced elsewhere, by about 1 percent. Corresponding changes in trade balances would imply a material deterioration for corporate-tax-reforming countries—as import demand rises significantly—and an improvement for the rest of the world, due to import compression and export growth. Both investment shifting and profit shifting can also have an impact on fiscal positions, improving the primary balance of source countries and undermining the balance of others, above and beyond the direct effects of the corporate income tax reform itself. The marginal impact of profit shifting on public debt stocks can be seen by comparing the red and yellow lines in panels 3 and 4 of Figure 4.15—it is clear that the impact of investment shifting (measured by comparing the blue and the red lines) is much larger than that of profit shifting.[39]

Budget-Neutral Permanent Increase in Public Investment

Compared with corporate income tax reforms that trigger investment and profit shifting, a budget-neutral permanent increase in public investment would have very modest spillovers.[40] The scenario assumes a ½ percent of GDP increase in public investment in the five large economies considered in the empirical exercise—France, Germany, Japan, the United Kingdom, and the United States—which is financed by an increase

[36]This is a simplifying assumption. Countries that currently benefit from a significant corporate income tax gap relative to the source countries, or those with a significant presence of multinational corporations based in countries pursuing corporate income tax reforms, may be more adversely affected by investment shifting.

[37]The assumed impact of investment shifting is derived by applying an estimated semielasticity of the corporate tax base to tax rate changes from De Mooij and Ederveen (2008)—taken to be –3.2—to foreign direct investment inflows and outflow data for France, Germany, and the United States, which proxy the foreign portion of the corporate tax base subject to relocation. Under a large corporate income tax rate reduction, foreign direct investment inflows would increase as foreign multinationals choose to locate more production in the countries pursuing reforms, and outflows would decline as domestic multinationals choose to develop more production capacity domestically. It is important to note that semielasticities in the literature vary widely and that the estimated investment-shifting impact of corporate income tax reform is sensitive to these assumptions.

[38]The assumed impact of profit shifting is derived by applying an estimated semielasticity of profits with respect to the tax rate—a value of 2, taken from De Mooij and Ederveen (2008)—to estimates of the share of multinational firms in each country, which is assumed to be approximately 0.6 in Germany and France and 0.3 in the United States, and to the corporate income tax rate reduction being considered (15 percentage points). The same caveats mentioned for investment shifting regarding elasticities apply.

[39]The impact on public debt in this scenario is only transitory, with all debt-to-GDP ratios returning to baseline in the long term. The speed of adjustment back to baseline depends on assumptions regarding the aggressiveness of the model's fiscal rule—other assumptions would lead to different adjustment dynamics.

[40]This result is broadly consistent with results reported in Bussière and others (2017), who find that most budget-neutral fiscal reforms do not have large cross-border trade spillovers, except in the case of coordinated reforms in periods of accommodative monetary policy.

in consumption taxes. Such a reform would boost the capital stock in source countries, thereby increasing output permanently—the increase in investment resulting from the higher productivity associated with an expansion of the public capital stock outweighs the negative impact on domestic consumption of higher consumption taxes. However, as shown in Figure 4.16, although there would be some modest cross-border impact due to expenditure shifting, the impact would be muted by an exchange rate depreciation in source countries, implying that the expenditure switching channel will eventually offset the positive effect.[41] The impact on recipient countries' trade balances is small, but negative.

Conclusions

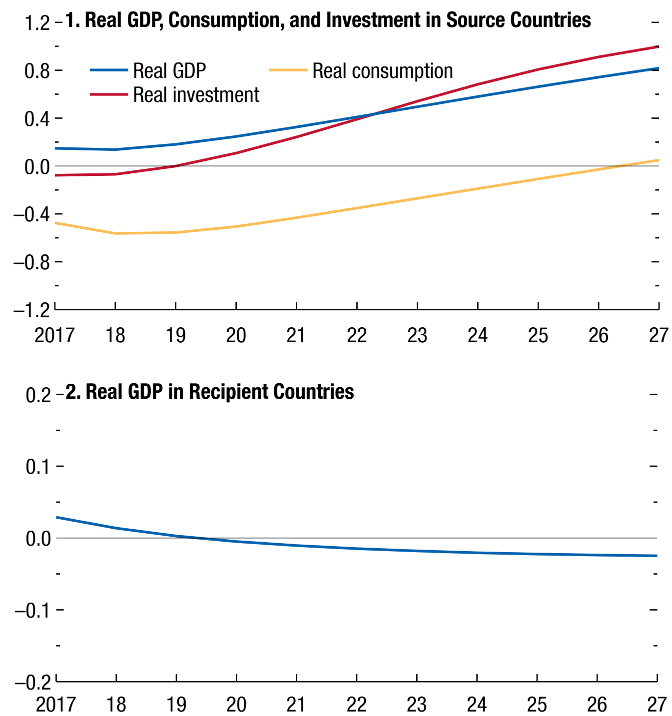
Positive cross-country spillovers from collective fiscal policy actions helped the global economy recover from the global financial crisis, but do fiscal spillovers still matter under much-improved economic conditions today? The chapter finds that spillovers continue to be relevant, but to what extent depends on circumstances in both source and recipient countries. It shows that fiscal spillovers tend to be lower when a fiscal shock originates from a country where GDP is at its potential, but that the impact intensifies when either the source or recipient country is in recession and/or benefiting from accommodative monetary policy. This suggests that spillovers are generally large when domestic multipliers are also large. The chapter also finds that spillovers from government spending shocks are larger than those associated with tax shocks, that the transmission of fiscal shocks may be greater among countries with fixed exchange rates, and that transmission may be dampened if the fiscal impulse at the source tightens global financial conditions.

While the chapter does not offer conclusions about how individual countries should conduct fiscal policy from a domestic perspective, it provides information about potential cross-country effects from such action. The current juncture suggests that positive cross-border effects from stimulus in countries with broadly closed output gaps will generally be smaller than during the crisis, but there could still be benefits. For example, in the euro area, spillovers from a more expansionary fiscal stance in countries with fiscal space—such as higher public investment to raise potential output in Germany—on some trading partners experiencing weak cyclical positions might still be important due to continued accommodative monetary policy and evidence suggesting that spillovers tend to be amplified by currency pegs. More generally, the fiscal instrument also matters: spending on public investment is likely to produce greater cross-border dividends than tax cuts.

The chapter also presents illustrative scenarios of fiscal reforms in which a change in the makeup of the government budget that does not generate a short-term change in the fiscal stance come with small spillovers. However, substantial fiscal reforms, such as large budget-neutral corporate income tax rate reductions—compensated with increases in consumption taxes—that affect the investment-location and

[41]A permanent productivity shock in source countries increases supply by more than demand, implying that the relative price of source-country goods must fall in equilibrium.

Figure 4.16. Spillovers from Increase in Government Investment in Five Major Economies
(Percent deviation from baseline)



Source: IMF, G20 Model (G20MOD) simulations.
Note: Spillovers from a permanent 0.5 percent of GDP increase in government investment in five major economies (France, Germany, Japan, United Kingdom, United States) financed via value-added tax. No monetary accommodation is assumed for any country.

profit-reporting decisions of multinational firms, could have large spillovers.

Finally, and not surprisingly, fiscal actions with economically meaningful cross-border effects can also impact trade balances. For example, the chapter suggests that fiscal stimulus tends to lead to a deterioration in the trade balance of the country where it occurs, with corresponding improvements in the positions of trading partners. This implies that a fiscal expansion in the United States could exacerbate global current account imbalances, while stimulus in Germany would tend to reduce them.

Box 4.1. The Spillover Impact of US Government Spending Shocks on External Positions

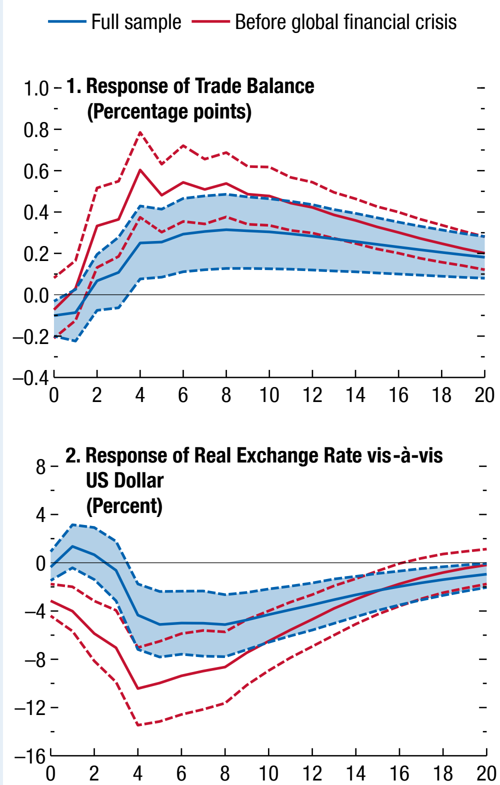
Consensus on the effect of government spending shocks on a country's exchange rate and external balance remains elusive in the empirical literature.[1] This may stem partly from the difficulty of isolating agents' anticipation of fiscal policies, given both legislative and implementation lags, as highlighted by Ramey (2011), among others. This box and a related spillover note (Popescu and Shibata, forthcoming) examine the impact of fiscal spending shocks from the United States on the US trade balance and real exchange rate, from both a multilateral and a bilateral perspective, while carefully taking into consideration the issue of fiscal foresight.

To capture anticipation effects, the approach follows Forni and Gambetti (2016) and relies on professional forecasters' surveys to identify fiscal shocks at the announcement rather than implementation date.[2] Methodologically, the fiscal foresight ("news") shock is identified in a vector autoregression using US data from the first quarter of 1981 through the fourth quarter of 2016.[3] The analysis further extends Forni and Gambetti (2016) to a cross-country perspective to account for recipients' macroeconomic conditions, which is the main unique contribution of this exercise.

The results suggest that news of future government spending leads to a real appreciation of the US dollar and deterioration of the US trade balance—in line with theory and solving the "depreciation puzzle" found in most previous studies. As discussed in Forni and Gambetti (2016), the key intuition is that the inclusion of additional information on fiscal expectations and forecasts improves the estimation of the effects of fiscal spending shocks by capturing more precisely the timing of the impact. The timing is likely significant in assessing the response of fast-moving variables, such as the exchange rate, which react quickly to perceived changes in future conditions.

Moving on to the analysis of spillovers, a panel vector autoregression analysis makes it possible to take into account the recipient country's macro and policy variables (such as cyclical positions, monetary policy, and domestic fiscal policy). The estimation uses an unbalanced panel of 30 US trading partners (23 advanced economies and 7 emerging market economies representing about 80 percent of US imports) from the fourth quarter of 1982 through the third quarter of 2016. Results suggest that an anticipated increase in US government spending triggers real

Figure 4.1.1. Response of Recipient Countries' Trade Balance and Real Exchange Rate vis-à-vis US Dollar
(Quarters on x-axis)



Source: IMF staff calculations.
Note: $t = 0$ is the quarter of the shock. Dashed lines denote 90 percent confidence bands.

The authors of this box are Adina Popescu and Ippei Shibata.

[1]For example, while the theoretical literature tends to predict that increases in government spending would trigger exchange rate appreciations, the empirical literature often finds the opposite in the case of the United States; this is usually referred to as the "depreciation puzzle."

[2]More specifically, the Survey of Professional Forecasters forecasts of government spending are used to capture preannounced or anticipated (also called "news" or "foresight") fiscal spending by exploiting the change in forecast expectations.

[3]The vector autoregression includes, in this order: real federal government consumption expenditures and gross investment, the fiscal news variable based on Survey of Professional Forecasters forecasts, real GDP, private consumption, the federal surplus divided by GDP, net exports of goods and services divided by GDP, the 10-year Treasury constant maturity rate, and the real effective exchange rate.

Box 4.1 *(continued)*

exchange rate depreciations in other countries and improvements in their trade balances with the United States. More specifically, an announcement of a 1 percent of US GDP increase in government spending will depreciate a trading partner's exchange rate by about 5 percent after one and a half years while improving the partner's net exports vis-à-vis the United States by 0.3 percentage point of its own GDP after two years (Figure 4.1.1, blue lines).

Estimation over subsamples reveals that the impact on exchange rates and trade balances may have diminished following the global financial crisis. The red lines in Figure 4.1.1 plot the response of the trade balance and real exchange rates vis-à-vis the United States before the global financial crisis (before 2007), suggesting that responses were significantly larger before the onset of the crisis. These results may reflect constrained monetary policy in recent years, which could have dampened US exchange rate appreciation (in response to expansionary fiscal shocks), thus also potentially contributing to a smaller trade balance response.

Performing the same analysis for different groups of countries—only advanced economies or only Group of Twenty economies—suggests that the results are quantitatively robust. The results are also robust to variations in the methodology, including different variable ordering and the inclusion of additional variables, as well as to different weighting schemes (including time-varying weights).

Annex Table 4.1.1. Data Sources for Quarterly Fiscal Data by Source Country

Country	Fiscal Data	Data Source	Seasonal Adjustment	Note
France	Government spending	Eurostat[1]	SWDA by source	Sum of government final consumption and GFCF
	Tax revenue	Eurostat[1]	SWDA by source	Current taxes on income and wealth, excluding social contributions
Germany	Government spending	Deutsche Bundesbank	SWDA by source	Sum of government final consumption and GFCF
	Tax revenue	Eurostat[1]	X-12-ARIMA by IMF staff	
Japan	Government spending	Cabinet Office of Japan	SAAR by source	Sum of government final consumption and GFCF
	Government total revenue	Ministry of Finance and Cabinet Office	X-12-ARIMA by IMF staff	Extrapolated using Denton method
United Kingdom	Government spending	Office for National Statistics	Seasonally adjusted by source	Sum of government final consumption and GFCF
	Tax revenue	Eurostat[1]	X-12-ARIMA by IMF staff	
United States	Government spending	US Bureau of Economic Analysis	Seasonally adjusted by source	Sum of government final consumption and GFCF
	Tax revenue	US Bureau of Economic Analysis	Seasonally adjusted by source	

Source: IMF staff compilation.
Note: For government spending, nominal levels are deflated using the GDP deflator when real levels are not directly available from the source. For tax revenue (total revenue for Japan), real levels are calculated by deflating nominal levels using each country's GDP deflator. GFCF = gross fixed capital formation; SAAR = seasonally adjusted and annualized data; SWDA = seasonally and working-day adjusted data; X-12-ARIMA = US Census Bureau software package for seasonal adjustment.
[1]Quarterly nonfinancial accounts for general government database from Eurostat.

Annex 4.1. Data

Data for Shock Identification

Quarterly fiscal data used in shock identification for five shock-emitting (source) countries stem from national statistical bureaus, either directly or via Haver Analytics.[42] Quarterly real government spending and tax revenue data used in constructing fiscal shocks are expressed in local currency units, seasonally adjusted, and annualized for the sample period of 2000:Q1–2016:Q2. Government spending is calculated as the sum of quarterly general government consumption and general government gross fixed capital formation from national accounts. For tax revenue, quarterly general government total tax income is used, except for Japan. Data sources for each country are listed in Annex Table 4.1.1. See Blagrave and others, forthcoming, for more details on the data, as well as a discussion of data limitations and construction of fiscal shocks.

[42]France, Germany, Japan, United Kingdom, United States.

Data for Spillover Analysis

Quarterly data from 55 recipient countries for 2000:Q1–2016:Q2 include series on real output, consumption, investment, exports/imports, bilateral good exports/imports, external demand, short-term interest rates, output gaps, and exchange rate regimes, collected from multiple data sources. Data sources for each series are listed in detail in Annex Table 4.1.2, followed by a list of all the countries in the sample in Annex Table 4.1.3.

Data Description

- *Real GDP, consumption, investment:* Quarterly real levels are rebased to 2010 prices, expressed in local currency units, seasonally adjusted and annualized. Investment data refer to gross fixed capital formation.
- *Exports/imports:* Quarterly real levels are rebased to 2010 prices, expressed in local currency units, seasonally adjusted and annualized. Data from national accounts stem from Haver Analytics and refer to total exports/imports of goods and services.

Annex Table 4.1.2. Data Sources for Recipient Countries

Series	Data Sources	Estimation	Countries Missing Data	Note
Real Output	WEO; Haver Analytics	Rebased to 2010; deflated using GDP deflator	None in the sample	Seasonally adjusted, annualized, in national currency
Real Consumption, Investment, Exports, Imports	Haver Analytics	Rebased to 2010; deflated using respective deflators for each country and variable	Vietnam	Seasonally adjusted, annualized, in national currency; data from national accounts
Bilateral Goods Exports/Imports	DOTS	Average of values reported by the reporter and partner countries	None in the sample	Original data at monthly frequency, aggregated by sum
External Demand	WEO; DOTS; Haver Analytics	Export-weighted sum of partner countries' real GDP growth	None in the sample	Seasonally adjusted, quarter over quarter growth, log difference, percent
Short-Term Monetary Policy Rate	Bloomberg Finance L.P.; Haver Analytics	Three-month LIBOR, three-month Treasury bill rate, where available	Cyprus, Estonia, Luxembourg, Slovak Republic, Uruguay	Policy rate, deposit rate, target rate used where LIBOR and treasury bill rates were not available
Output Gap	WEO; Haver Analytics	Gap between real output and potential output estimated by HP filter	None in the sample	Denton method used to match annual output gap numbers in WEO

Source: IMF staff compilation.
Note: DOTS = IMF, *Direction of Trade Statistics*; HP = Hodrick-Prescott; LIBOR = London interbank offered rate; WEO = *World Economic Outlook*.

- *Bilateral goods exports/imports:* Bilateral weights are calculated using bilateral exports/imports of goods between 55 countries in the sample and five source countries (5 x 55 = 275 pairs). For each country pair, the average is that of reported values of both countries.
- *External demand:* This is calculated as a weighted sum of partner countries' real growth based on bilateral export weights.
- *Short-term interest rate:* The three-month London interbank offered rate (LIBOR) and three-month Treasury bill rate are used. For more comprehensive country and historical coverage, policy, deposit, and target rates are used where three-month LIBOR and Treasury bill data are not available.
- *Output gap:* The quarterly output gap is first calculated as the gap between real output and potential output, estimated by the Hodrick-Prescott filter. Then, to reconcile any potential difference between the estimated output gap and the annual output gap numbers published in the IMF's *World Economic Outlook* (WEO), the Denton proportional benchmarking method is used. This method both preserves the seasonality observed from quarterly estimated output gap series and matches the data published in the WEO when converted to annual basis.

Variables with notable trends over the sample period are detrended using country-specific linear

Annex Table 4.1.3. Recipient Countries in Sample

Region	Countries (55 total)
Africa	South Africa
Americas	Argentina, Brazil, Canada, Chile, Colombia, Costa Rica, Mexico, Peru, United States,* Uruguay
Asia	Australia, China, India, Indonesia, Japan,* Korea, Malaysia, New Zealand, Philippines, Thailand, Vietnam
Europe	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France,* Germany,* Greece, Hungary, Ireland, Israel, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Russia, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom*

Source: IMF staff compilation.
*Shock-emitting (source) country. Source country is excluded from the set of recipient countries when analyzing fiscal shocks from the same source.

trends. In addition, outliers—observations with quarter-over-quarter GDP growth rates higher than 10 percent or lower than –10 percent in any given quarter (very few observations)—are excluded.

Exchange Rate Regime Classification

A measure of bilateral exchange rate arrangement vis-à-vis the US dollar is constructed to estimate spillovers for different exchange rate regimes.

For the Reinhart-Rogoff classification, the exchange rate regime is expressed as a time-varying index based on the annual coarse de facto classification from Ilzetzki, Reinhart, and Rogoff (2017a, 2017b), ranging from 1 (most rigid) to 6 (most flexible). For each period, if a country is assigned a value of 1 (de facto peg) or 2 (de facto crawling peg), it is deemed a "fixed regime." The quarterly index is interpolated from annual data, assigning the same value for all four quarters within a year. For example, in 2015, this classification yields seven "fixed" rate countries (Argentina, China, Costa Rica, India, Peru, Philippines, Vietnam) out of the sample of 55 countries.[43]

The IMF pre-2008 classification (coarse) consists of six categories, with 1 being the most rigid and 6 the most flexible.[44] The classification changed in 2008, and post-2008 data are obtained from the IMF's website. As under the Reinhart-Rogoff classification, a country is generally classified as having a fixed exchange rate vis-à-vis the US dollar if it is assigned a value of 1 (de facto peg) or 2 (de facto crawling peg or crawling band narrower than or equal to ±2 percent). Again, the quarterly index is interpolated from annual data. For example, for 2015, this classification yields two fixed-rate countries (China, Vietnam) out of the sample of 55 countries, although there are more fixed-rate countries in earlier periods.

Annex 4.2. Empirical Strategy

Baseline Specification

As in Auerbach and Gorodnichenko (2013), the response of output in the recipient country to a fiscal shock abroad is estimated using the local projections method. This approach is particularly well suited to accommodate nonlinearity; that is, it allows estimation of spillovers under different states of the economy. Moreover, the method is more robust to misspecification of the data-generating process than a vector autoregression, for which the misspecification error is compounded at each horizon of the impulse response.

The following baseline linear model at time horizon h (for $h = 0, \ldots, H$) is estimated using a panel ordinary least squares estimator:

$$\frac{Z_{i,t+h} - Z_{i,t-1}}{Y_{i,t-1}} = \alpha_h \frac{Shock_{it}}{Y_{i,t-1}} + \sum_{l=1}^{L} \beta_{hl} X_{i,t-l} + \theta_{hi} + \mu_{ht} + \varepsilon_{iht}, \tag{4.1}$$

in which Z_{it} is the variable of interest (real GDP, consumption, investment, and the like) in recipient country i at quarter t, Y_{it} is real GDP in recipient country i at quarter t, $Shock_{it}$ is the foreign fiscal shock facing country i at time t (see below), and X_{it} is a vector of control variables including lags of the fiscal shock, lags of GDP growth, and lags of external demand, measured as a weighted average of trading partner growth rates (the number of lags $L = 4$ was chosen). Variables θ_{hi} and μ_{ht} capture the country and time fixed effects. Given that the foreign fiscal shock is expressed in units of recipient-country GDP ($Shock_{it}$ is scaled by lagged GDP Y_{it-1}), the coefficient α_h is analogous to a domestic multiplier of an external shock (Hall 2009; Barro and Redlick 2011). The impulse response for H periods is constructed from a sequence of estimates $\{\alpha_h\}_{h=0}^{H}$.

The baseline fiscal shock combines country-specific shocks from the five source countries (France, Germany, Japan, United Kingdom, United States) and weights them using trade links with recipient countries. The assumption behind the weighting system is that fiscal policy is transmitted mainly through trade—countries with tighter trade links to the source would be expected to receive larger shocks in the form of larger changes in export demand, and therefore larger spillovers. However, the estimated spillovers capture those from all transmission channels, including the financial channel. The external fiscal shock facing recipient country i in time t is given by

$$Shock_{it} = \sum_{j=1}^{5} \frac{M_{ij,t-1}}{M_{j,t-1}} \frac{s_{jt} E_{j,t-1}}{E_{i,t-1}}, \tag{4.2}$$

in which j denotes source country, M_{ijt} is country j's goods imports from country i at time t, M_{jt} is

[43]The number of countries classified as "fixed" can generally vary over time given that the exchange rate regime classification is time varying.

[44]Data for regime classification before 2008 is from Carmen Reinhart's website, http://www.carmenreinhart.com.

total goods imports by country j, s_{jt} is the identified fiscal shock in country j expressed in real terms in country j's currency, and E_{jt} is country j's US dollar real exchange rate. Therefore, the second term on the right side $\left(s_{jt}E_{j,t-1}/E_{i,t-1}\right)$ equals the real monetary value of the fiscal shock coming from country j converted into units of recipient country i's currency. This term is then scaled by the import share $\left(M_{ij,t-1}/M_{j,t-1}\right)$, which captures the relative importance of recipient country i as a supplier of the source country's imports.[45] Finally, the weighted shocks are added up across the five source countries.[46] The combined shocks are relatively small: for example, spending (tax) shocks average about 0.06 (0.1) percent of recipient-country GDP over the sample period.

Nonlinear Specifications

Role of Cyclical Conditions and Monetary Policy Constraints

To study the state-dependent effects for *recipient* countries, a nonlinear version of the baseline specification is estimated. Regression coefficients on the shock and the control variables are allowed to vary with different states. The state is defined with respect to the economic cycle ("slack/no slack") or with respect to monetary policy stance ("effective lower bound/no effective lower bound"). Slack corresponds to a negative output gap. Effective lower bound corresponds to short-term interest rate below the 25th percentile value of the cross-country distribution, which is about 0.57 percent for advanced economies and 3.0 percent for emerging market economies.

Following Auerbach and Gorodnichenko (2013), the baseline specification is modified in the following way:

$$\begin{aligned}\frac{Z_{i,t+h}-Z_{i,t-1}}{Y_{i,t-1}} &= \alpha_{1h} I_{i,t-1}\frac{Shock_{it}}{Y_{i,t-1}} \\ &+ \alpha_{2h}\left(1-I_{i,t-1}\right)\frac{Shock_{it}}{Y_{i,t-1}} \\ &+ \sum_{l=1}^{4}\beta'_{1hl} I_{i,t-1} X_{i,t-l} \\ &+ \sum_{l=1}^{4}\beta'_{2hl}\left(1-I_{i,t-1}\right)X_{i,t-l} \\ &+ \theta_{hi}+\mu_{ht}+\varepsilon_{iht},\end{aligned} \tag{4.3}$$

in which $I_{i,t}$ takes the values of either 1 or 0, indicating the state in recipient country i in period t. Spillovers in the two different states can then be analyzed by comparing the estimated parameters α_{1h} and α_{2h}.

For the *source* country, only the shock is partitioned according to the state of the economy, which can be again either the cyclical position or monetary policy near the effective lower bound. The states are defined in the same way as in the specification for recipient countries. The source-country shock therefore becomes

$$Shock_{it}^{j} : I_{t-1}^{j}\, Shock_{it}^{j} + \left(1 - I_{t-1}^{j}\right) Shock_{it}^{j}, \tag{4.4}$$

in which I_t^j is a {0;1} dummy variable indicating the state in the shock-emitting country. The assumption behind interacting only the shock with the state dummy is that although shocks in the source country and its domestic response might be regime dependent, their propagation to recipient countries is not.

Spillovers to Recipients with Different Exchange Rate Regimes

Similar to the nonlinear specification in which the shock is partitioned based on the source country's state, the shock is decomposed into two components according to the bilateral exchange rate arrangement between recipient i and the United States:

$$Shock_{it}^{US} : Fix_{i,t-1}^{US}\, Shock_{it}^{US} + \left(1 - Fix_{i,t-1}^{US}\right) Shock_{it}^{US}, \tag{4.5}$$

in which $Fix_{it}^{iUS} = 1$ if country i and the United States share a fixed regime in period t.

Spillover Estimates Expressed in Terms of Source-Country GDP

While the baseline specification expresses fiscal shocks in terms of *recipient-country GDP*—given the decision to combine shocks from different sources and following standard practice in the literature—this transformation might complicate the interpretation of the magnitude of spillovers. To facilitate the interpretation, the estimates presented in the chapter are rescaled as spillovers in response to a 1 percent of *source country GDP* fiscal shock. This is done by normalizing the estimated spillover coefficient α in the following way:

$$Spill_{i,j} = S_j \frac{M_{i,j}}{M_j}\frac{Y_j}{Y_i}\alpha, \tag{4.6}$$

in which S_j is the source-country shock as a percent of its own GDP (assumed to be 1); $\left(M_{i,j}/M_j\right)$ is the recipient country's share in the source country's total imports (the weighting factor in the baseline model);

[45]See Blagrave and others, forthcoming, for a discussion of alternative weighting systems.

[46]Estimated fiscal shocks are not correlated across countries.

and $\left(Y_j/Y_i\right)$ is the ratio of source to recipient-country GDP—both measured in US dollars.[47]

Annex 4.3. Robustness Tests

To ensure that the baseline results are not driven by the selected shock identification scheme or econometric approach, this section performs several robustness checks. The results are robust to (1) estimation of spillovers using a panel vector autoregression, which accounts for the endogenous response of exchange rates and monetary policy in recipient countries; and (2) the use of alternative fiscal shocks based on forecast error and narrative approaches.

Estimation with a Panel Vector Autoregression

Analysis in a panel vector autoregression is conducted to ensure that the results are not driven by the choice of the local projections method. A panel vector autoregression explicitly takes into account the endogenous response of key macro variables when estimating spillovers from a fiscal shock. The following six-variable panel vector autoregression model is estimated:

$$Y_{i,t} = c_i + \sum_{p=0}^{I} A_p Y_{i,t-p} + \mu_{i,t}, \qquad (4.7)$$

in which c_i is a vector of country-specific fixed effects, A_p is a reduced-form coefficient matrix, $\mu_{i,t}$ is a vector of shock terms, and $Y_{i,t}$ is a vector of six endogenous variables:

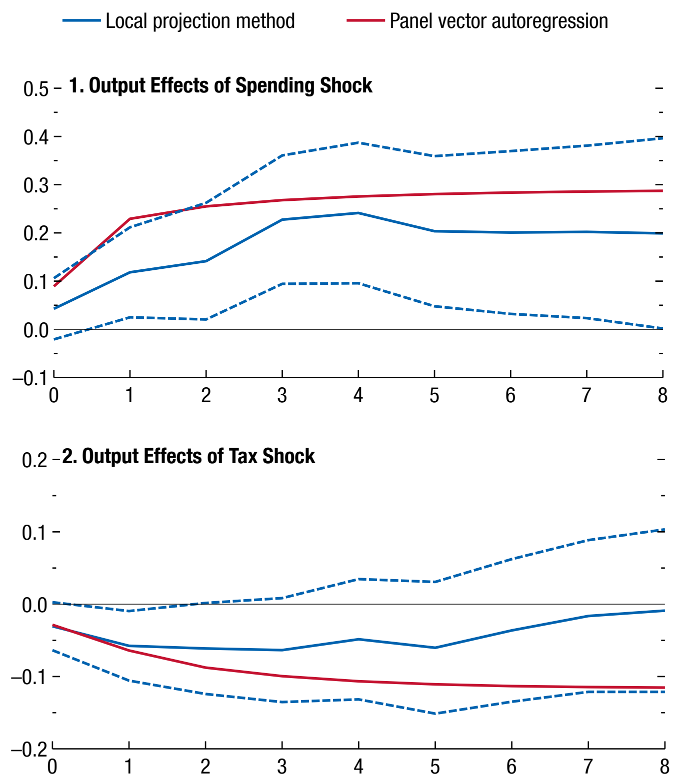
$$Y = \{Gshock; Tshock; effective\ ext.demand; GDP\ growth; interest\ rate; REER\}.$$

With the exceptions of *Gshock* and *Tshock*, which are identical to the weighted shocks used in the baseline analysis presented in equation 4.1, each variable is in (detrended) quarter-over-quarter growth rates and relates to the recipient country *i*'s domestic economy.[48] The sample period is the same as in the baseline local projections analysis.

Panel vector autoregression analysis confirms the findings from the baseline regression model estimated with the local projections method. The results, expressed in terms of the cumulative impulse response following a 1 percent of source-country GDP shock to government spending (tax revenue), are presented in Annex Figure 4.3.1 (red line). Spillovers from an increase in government spending at the source are larger than spillovers from a tax cut. The results are statistically different from zero at the 5 percent level, based on simulations conducted using standard (Monte Carlo) resampling methods.

Annex Figure 4.3.1. Effects of Spending and Tax Shock on Recipient Countries' Output: Comparison with Panel Vector Autoregression

(Percent; quarters on x-axis)



Source: IMF staff calculations.

Note: $t = 0$ is the quarter of respective shocks. Solid blue lines denote the baseline response to respective shocks using local projection method; dashed lines denote 90 percent confidence bands; and solid red lines represent the response to respective shocks using panel vector autoregressions. Shocks are normalized to an average of 1 percent of GDP across source countries.

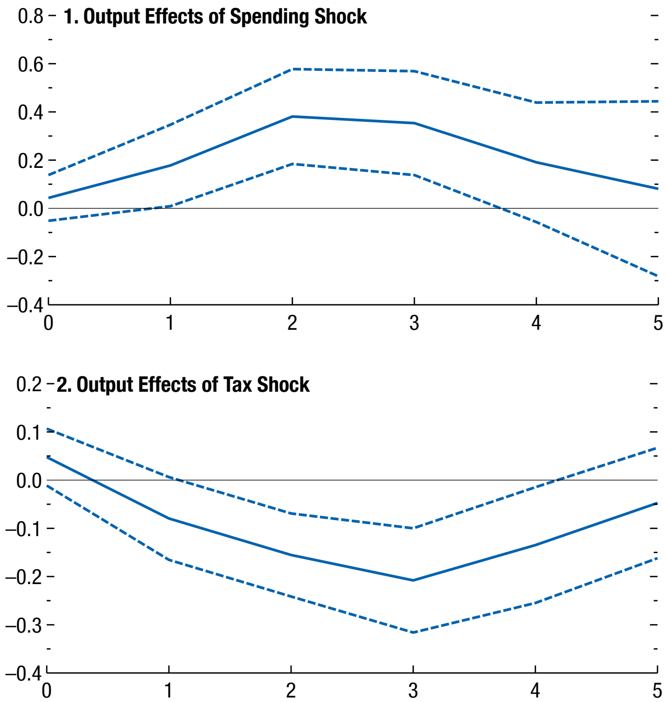
Identification Using Forecast Errors

The second robustness check focuses on the identification of fiscal shocks. The alternative methodology identifies shocks as forecast errors (the difference

[47]Plausible alternative weighting systems of the source-country shock would deliver the same results in terms of source-country GDP. Alternative weighting systems would also require recalculating the spillover coefficient estimated in the baseline (α), resulting in an equal and offsetting adjustment of this coefficient, given that any transformation applied to the *source* shock would be constant across all *recipient* countries.

[48]Results from the panel vector autoregression are robust to several alternative specifications, including not detrending the data.

Annex Figure 4.3.2. Effects of Spending and Tax Shock on Recipient Countries' Output: Forecast Errors
(Percent; years on x-axis)



Source: IMF staff calculations.
Note: $t = 0$ is the year of respective shocks. Solid lines denote the response to respective shocks, and dashed lines denote 90 percent confidence bands. Effects are estimated based on shocks derived from forecast errors. Shocks are normalized to an average of 1 percent of GDP across source countries.

between actual variable and its forecast from the previous period) in the growth rates of government spending or tax revenues, this way capturing only unanticipated fiscal changes. This differs from the structural shocks used in the baseline analysis, which are based on actual changes in fiscal variables and can be anticipated by agents if they were announced earlier. The presence of such anticipated shocks could bias the estimates because the information set of the econometrician is different from the information set of the agents. Because forecast errors capture unexpected changes, the problem with fiscal foresight is reduced under this approach, as the information set of the econometrician and private agents is more aligned.

The approach uses real-time fiscal projections by the Organisation for Economic Co-operation and Development and real-time actual data to construct the forecast error shocks at annual frequency on the sample from 2000 to 2012.[49] The forecast error for each variable $X = \{G, T, Y\}$ is constructed as

$$FE_t^X = X_t - X_{t|t-1}^f, \tag{4.8}$$

in which X_t is the growth rate of the variable from the contemporaneous data release and $X_{t|t-1}^f$ is the forecast one period earlier. A positive forecast error means an expansionary spending shock and a contractionary tax shock. Following Auerbach and Gorodnichenko (2013), the forecast errors of spending and taxes are regressed on the forecast errors of output to take into account any changes as a result of surprises in the business cycle. They are also regressed on lagged macroeconomic variables' growth rates (GDP, deflator, investment, government spending or tax revenues) to account for the portion of the innovation that can be predicted from past observations. The forecast error shocks for each source country are then constructed as residuals from this regression, converted to levels using base year (2010) expenditures or revenue, and replaced in equations (4.1) and (4.2).

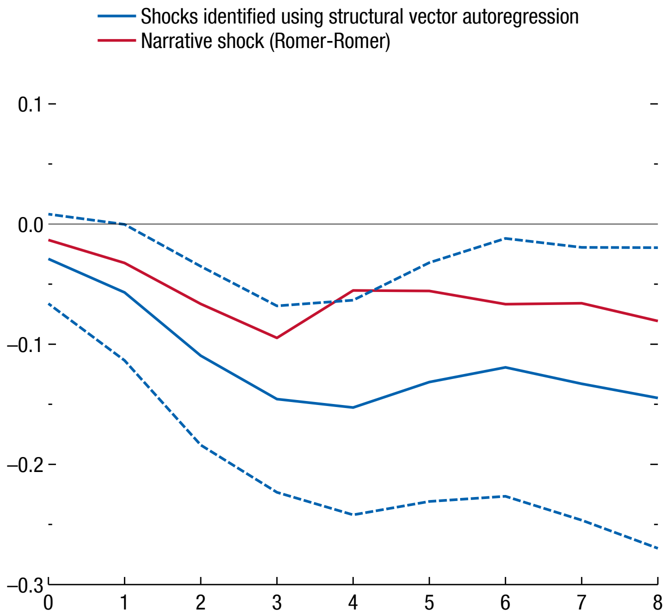
Spillover analysis using forecast error shocks confirms the baseline results—that spending shocks have larger spillovers than tax shocks (Annex Figure 4.3.2)—and provides a strong robustness check. These shocks are constructed using an entirely different methodology, a different database and estimated at a different frequency than the shocks used in the baseline specification. The size of spillovers is somewhat larger compared with the baseline, which can be explained, in part, by a stronger response of source-country spending and revenues to forecast error shocks compared with structural shocks (although these impulse responses are imprecisely estimated because of the small sample).

Identification Using Narrative Approach

To further confirm that the baseline results are not driven by the shock identification scheme, a robustness check using the narrative tax shocks of Romer and Romer (2010) is conducted. Several studies in the literature present narrative fiscal shocks (for example, DeVries and others 2011), but the data set of Romer and Romer (2010) is the most suitable for comparison with the baseline analysis of the chapter given that it covers both expansion and consolidation episodes.[50]

[49] After 2012 the forecast data are not continuous.
[50] Narrative shock databases for government spending are much less common in the literature, which precludes a robustness check of spillovers from spending shocks based on narrative shocks.

Annex Figure 4.3.3. Effects of US Tax Shock on Recipient Countries' Output: Comparison with US Narrative Tax Shock, 1995–2007
(Percent; quarters on x-axis)



Sources: Romer and Romer (2010); and IMF staff calculations.
Note: $t = 0$ is the quarter of the US tax shock. Solid blue line denotes the response to US tax shock using structural vector autoregression; dashed lines denote 90 percent confidence bands; and solid red line represents the response to US narrative tax shock based on Romer and Romer (2010). Shocks are normalized to an average of 1 percent of GDP across source countries (note that this will represent a less than 1 percent of US GDP shock).

The shock is simply replaced in equations (4.1) and (4.2), with analysis conducted only for the United States over the period 1995:Q1–2007:Q4 (2007:Q4 is last period for which the narrative shock is available). A comparable set of time-sample-modified baseline results is obtained by estimating spillovers from the United States on the same sample.

Results presented in Annex Figure 4.3.3 show similar spillovers from US tax shocks for shocks identified using a structural vector autoregression and those coming from the narrative approach. Although the spillovers identified using the narrative approach are somewhat smaller compared with the (time-sample-modified) baseline, they fall comfortably within the confidence bands of the baseline estimates. Given that the narrative shocks are based on a completely different identification scheme, these results provide another strong robustness check.

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