CHAPTER 4

CLIMATE CHANGE AND THE GLOBAL ECONOMY

This chapter uses a global dynamic model to examine the macroeconomic and financial consequences of policies to address climate change. Although these consequences can be rapid and wide-ranging, this chapter finds that the overall costs of mitigation could be minimized if policies are well designed and accepted by a broad group of countries.

Climate change is a potentially catastrophic global externality and one of the world's greatest collective action problems. The distribution of causes and effects is highly uneven across countries and across generations. Enormous uncertainty surrounds existing estimates of future damages that may result from climate change, but these potential damages are to a considerable extent irreversible and may be catastrophic if global warming is unchecked. The costs of abating climate change also have a sunk component—that is, cannot be fully recovered—and are contingent on a multitude of factors, including the rate at which the global economy grows over the long term and the pace at which low-emission technologies emerge and diffuse across the global economy. The discount rate chosen to aggregate damages from climate change and the costs of abating them across generations also has important implications for how various policy options are weighed by policymakers.

The macroeconomic consequences of policies to abate climate change can be immediate and wide-ranging, particularly when these policies are not designed carefully. The promotion of biofuels provides a good example. Expansion of biofuel production in the United States and western Europe in recent years has pushed up food prices and boosted inflation, creating serious problems for poor food-importing countries around the world and limiting the ability of central banks to ease monetary policy in response to recent financial turbulence. The main cause of these negative effects is the fact that advanced economies have placed trade restrictions on imports of biofuels, constraining the production of biofuels in lower-cost countries such as Brazil.[1]

This chapter focuses on examining the macroeconomic and financial implications, for the global economy and for individual countries, of policies to address climate change.[2] First, the chapter reviews available estimates of damages from climate change, illustrating the potentially significant benefits of abatement and highlighting the key variations among these estimates.[3] Next, the chapter briefly discusses the need for countries to adapt their ecological, social, and economic systems to climate change. The costs of such adaptation will have significant

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[1]Production of biofuels also needs to be environmentally sustainable. For more details on biofuels, see the October 2007 *World Economic Outlook.*

[2]This study builds on the review of climate change issues in the October 2007 *World Economic Outlook.* For an analysis of the fiscal implications of climate change, see IMF (2008).

[3]Abatement is defined here as the reduction in greenhouse gas (GHG) emissions. This term is used interchangeably with the term "mitigation." Adaptation means adjustment to climate change.

bearing on the estimates of potential losses from climate change, and macroeconomic policies and financial markets can play a role in reducing these costs.

The main contribution of this chapter is its analysis of the macroeconomic and financial implications of alternative mitigation policies across countries, using a global dynamic macroeconomic model. An effective mitigation policy must be based on setting a price path for the greenhouse gas (GHG) emissions that drive climate change. The overall costs of such carbon-pricing policies—a global carbon tax, a global cap-and-trade system, or a hybrid policy—could be moderate, provided the policies are well designed.

- Carbon pricing should be credible and long term. If it is, then even small and gradual increases in carbon prices will be sufficient to induce businesses and people to shift away from emission-intensive products and technologies.
- Carbon pricing should be global. It is not feasible to contain climate change unless all major GHG emitters start pricing their emissions.
- Carbon pricing should seek to equalize the price of GHG emissions across countries to maximize the efficiency of abatement. Emissions would then be reduced more where it is cheaper to do so.
- Carbon pricing should be flexible, allowing firms to adjust the amount of abatement in response to changes in economic conditions, to avoid excessive volatility in carbon prices. High carbon price volatility could augment macroeconomic volatility and generate spillovers across the world. Policy frameworks should also provide scope to adjust policy parameters in response to new scientific information and experiences with policy implementation.
- Carbon pricing should be equitable. No undue burdens should be put on countries least able to bear them.

All in all, the analysis highlights the importance of carefully designing mitigation policies to take into account their macroeconomic and financial effects, and thereby to ensure the sustainability of any future international agreement on climate change.[4]

How Will Climate Change Affect Economies?

The global climate is projected to continue to warm in coming decades, as new GHG emissions augment the already large stock of past emissions. Increases in energy-related emissions of carbon dioxide, the largest and fastest-growing source of GHG emissions, are driven by growth in GDP per capita and increases in population, and these increases are only partially offset by improvements in the intensity of energy use (Figure 4.1).[5] Catching-up economies, especially large and fast-growing countries such as China and India, contribute most to the growth in emissions (Box 4.1). Advanced economies account for most past energy-related emissions and thus for most of the current stock of these emissions. However, when changes in land use and deforestation are considered, a different conclusion emerges: advanced economies account for less than half of the current stock of total emissions (den Elzen and others, 2005; Baumert, Herzog, and Pershing, 2005).

Outlook for Climate Change

Without changes in policy, GHG emissions are projected to accelerate. However, these projections are wide-ranging, given uncertainty about the rates at which productivity will grow, energy intensity will improve, and emerging and developing economies will converge toward the living standards of advanced economies. For

[4]Commitments under the central international agreement on emission levels—the Kyoto Protocol—are set to expire in 2012. At a recent conference in Bali, Indonesia, signatories to the United Nations Framework Convention on Climate Change (UNFCCC)—most of which are IMF members—agreed on the agenda for two years of negotiations on a new agreement, with a 2009 deadline.

[5]Intensity of energy use is defined as energy use per unit of output and calculated as the ratio of total energy use to GDP.

example, even studies based on the widely used Special Report on Emissions Scenarios (SRES) developed by the United Nations Intergovernmental Panel on Climate Change (IPCC) show significant variations in projected emission growth. Emission projections in studies based on this source range from 22 percent to 88 percent between 2000 and 2030, and from –40 percent to 237 percent between 2000 and 2100. The estimates based on more recent, “post-SRES” scenarios exhibit a similar range, although the median is lower in 2030 and higher in 2100 (Figure 4.2).

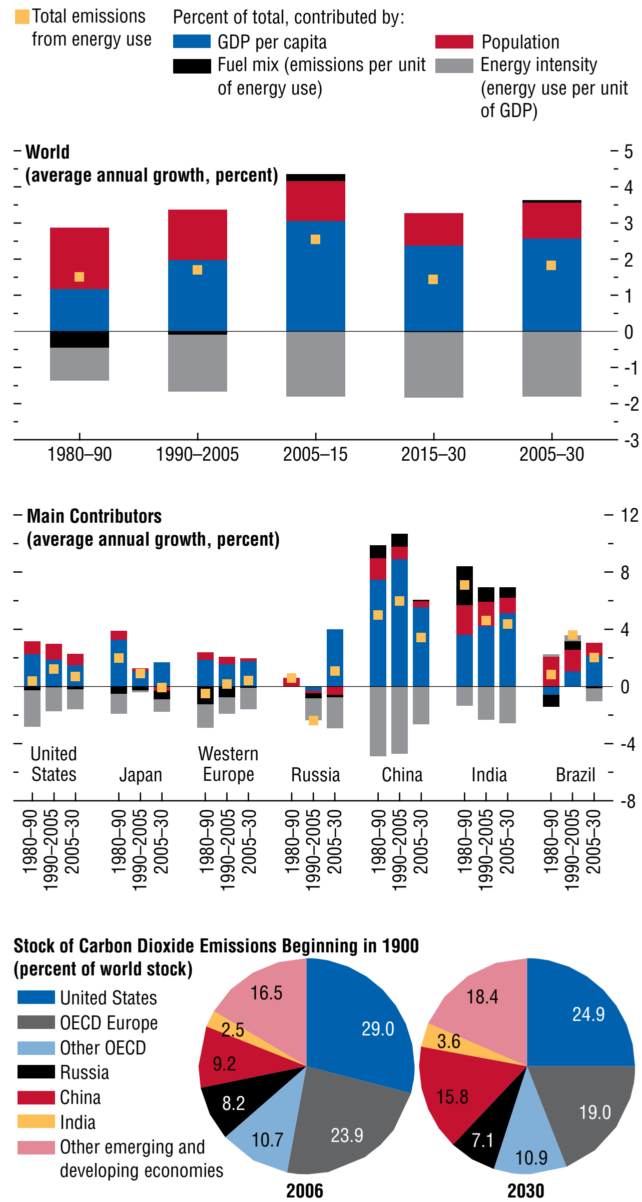
Business-as-usual (BAU) projections imply a sizable risk that global climate would change dramatically by the end of the century. The IPCC projects that, in the absence of emission control policies, global temperatures will increase by 2.8°C on average over the next century, with best-guess increases ranging from 1.8°C to 4°C across SRES scenarios (IPCC, 2007). The probability of higher temperature increases is not negligible. Stern (2008) points out that if BAU concentrations of GHGs stabilize at or above 750 parts per million (ppm) in carbon-dioxide-equivalent (CO_2e) terms by the end of the century, as implied by the latest IPCC scenarios, there would be at least a 50 percent chance that global temperatures would increase by more than 5°C, with potentially disastrous consequences for the planet (also see Weitzman, 2008, on the analysis of catastrophic risks from climate change).[6]

Global warming would have a multifaceted and potentially devastating impact on climate patterns (IPCC, 2007). Precipitation would increase at high latitudes and decrease in most subtropical land regions. Other likely manifestations of warming include increasing acidification of the ocean; melting of snow and sea ice; and

[6]Stern (2008) notes that the latest scenarios may be too optimistic about the likelihood of stabilizing GHG concentrations at these levels, because they do not take into account important feedbacks in the carbon cycle, such as release of methane from permafrost, collapse of the Amazon, and reduction in the absorptive capacity of the oceans.

Figure 4.1. Carbon Dioxide Energy-Related Emissions[1]

Emissions increases are driven by GDP growth per capita and population increases, with improvements in the energy intensity of output providing only a partial offset. Emerging and developing economies contribute most to emissions growth, and advanced economies account for most of past emissions.

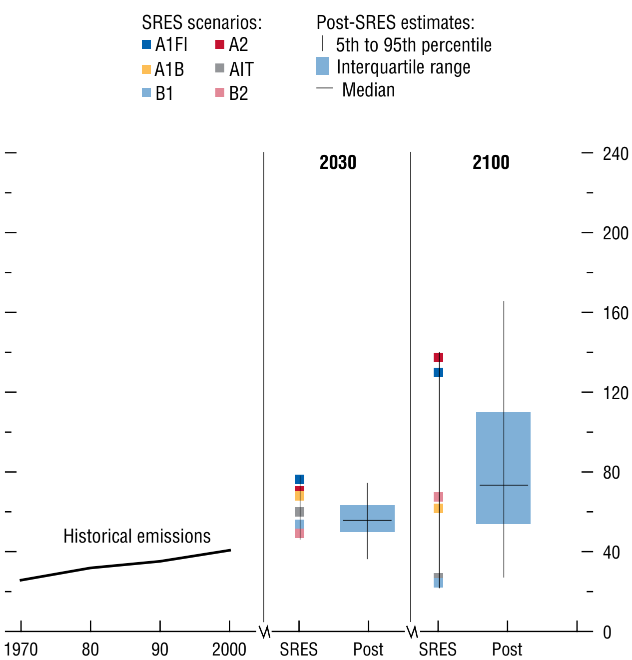


Sources: Energy Information Administration, *International Energy Annual* (2005) and *International Energy Outlook* (2006); International Energy Agency, *World Energy Outlook* (2007); and World Resources Institute's Earth Trends database.
[1]The figure plots emissions of carbon dioxide from energy use.

Figure 4.2. Emission Forecasts[1]

(Gigatons of carbon dioxide equivalent per year)

Emission forecasts cover a wide range of potential scenarios and outcomes, ranging from rapid output growth with developments of new energy technologies (the A1 scenario), less regional development convergence (A2), rapid shifts toward information- and services-based economies (B1), and fewer technological improvements (B2). All these scenarios are considered equally plausible, with no probabilities assigned to them. Even within each type of scenario, there is a wide range of emission projections (not shown), typically diverging by hundreds of percentage points by 2100.



Sources: EDGAR-HYDE 1.4 database; IPCC (2007); Netherlands Environmental Assessment Agency; Olivier and Berdowski (2001); Van Aardenne and others (2001); and IMF staff calculations.

[1]Global greenhouse gas emissions for 1970–2000 and projected baseline emissions for 2030 and 2100 are from the IPCC's *Special Report on Emissions Scenarios* (SRES) and post-SRES literature. The figure shows emissions from the six illustrative SRES scenarios.

an increase in the intensity of extreme events such as heat waves, droughts, floods, and tropical cyclones. At higher temperatures, the probability of catastrophic climate changes would rise (for example, melting of the west Antarctic ice sheet or permafrost; a change in monsoon patterns in south Asia; or a reversal of the Atlantic Thermohaline Circulation, which would cool the climate of Europe).

Economic Costs of Climate Change

Economic estimates of the impact of climate change are typically based on "damage functions" that relate GDP losses to increases in temperature. The estimates of GDP costs embodied in the damage functions cover a variety of climate impacts that are usually grouped as market impacts and nonmarket impacts. Market impacts include effects on climate-sensitive sectors such as agriculture, forestry, fisheries, and tourism; damage to coastal areas from sea-level rise; changes in energy expenditures (for heating or cooling); and changes in water resources. Nonmarket impacts cover effects on health (such as the spread of infectious diseases and increased water shortages and pollution), leisure activities (sports, recreation, and outdoor activities), ecosystems (loss of biodiversity), and human settlements (specifically because cities and cultural heritage cannot migrate).

Existing studies tend to underestimate economic damages from climate change, particularly the risk of worse-than-expected outcomes. The three main benchmark studies (Mendelsohn and others, 2000; Nordhaus and Boyer, 2000; and Tol, 2002) and the review of the literature in the *Stern Review* (2007) point to mean GDP losses between 0 percent and 3 percent of world GDP for a 3°C warming (from 1990–2000 levels) (Figure 4.3).[7] However, these estimates of damages are often incomplete—they rarely cover nonmarket damages, the risk of local

[7]See IPCC (2007) for a detailed review of the literature on damages.

extreme weather, socially contingent events, or the risk of large temperature increases and global catastrophes.[8] Moreover, available estimates tend to be based on a smaller increase in global temperatures than projected in the IPCC's latest scenarios. Studies typically calculate damages for a doubling of CO_2e concentration from pre-industrial levels. Yet the latest IPCC's BAU scenarios are expected to result in a tripling or quadrupling of concentrations by the end of the century, implying higher temperatures than those assumed in most studies. More recent, risk-based approaches to the analysis of damages from climate change point to significantly higher estimates than those suggested in the earlier literature (Stern, 2008).

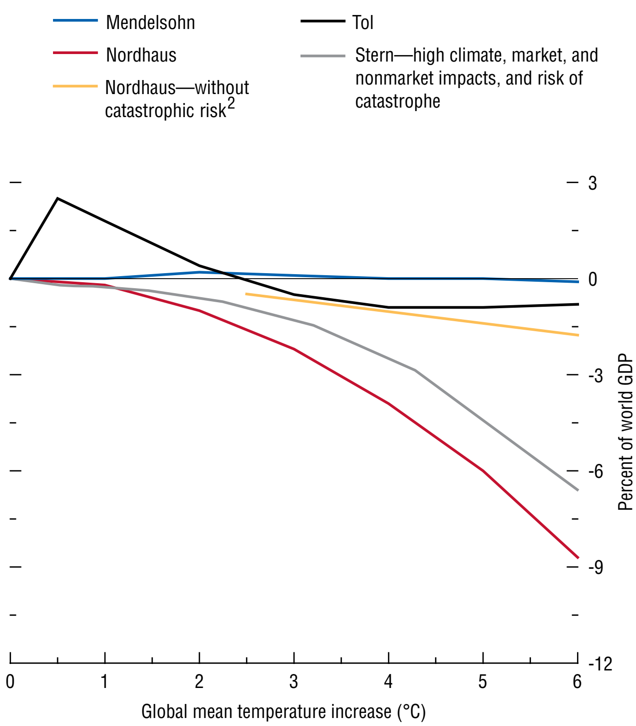
Estimates of total global damages also mask large variations across countries and regions. Damages tend to be greater for countries with higher initial temperatures, greater climate change, and lower levels of development (Figure 4.4). A moderate rise in temperature increases agricultural productivity in countries with low initial temperatures, but decreases it in hotter countries. Similarly, warming reduces deaths from cold in countries with initially colder climates, but increases mortality and morbidity in countries with warmer climates. Although warming reduces expenditures on winter heating in countries with an initially cooler climate, such countries may incur additional expenditures on summer cooling. Countries with initially warmer climates also incur additional costs for cooling.

Beyond initial temperature, the level of development has a strong effect on the extent of damages from climate change. First, a

[8]Studies are also incomparable in methodology. Mendelsohn covers only market impacts; Tol covers market and nonmarket impacts; Nordhaus and Boyer and the *Stern Review* cover market and nonmarket impacts as well as catastrophic risks. The studies differ in their assumptions about the extent of adaptation to climate change (large in Mendelsohn; smaller in Tol), and about the underlying economy (future or current). Mendelsohn's estimates are based mostly on U.S. data and extrapolated for other countries.

Figure 4.3. Mean GDP Losses at Various Levels of Warming[1]

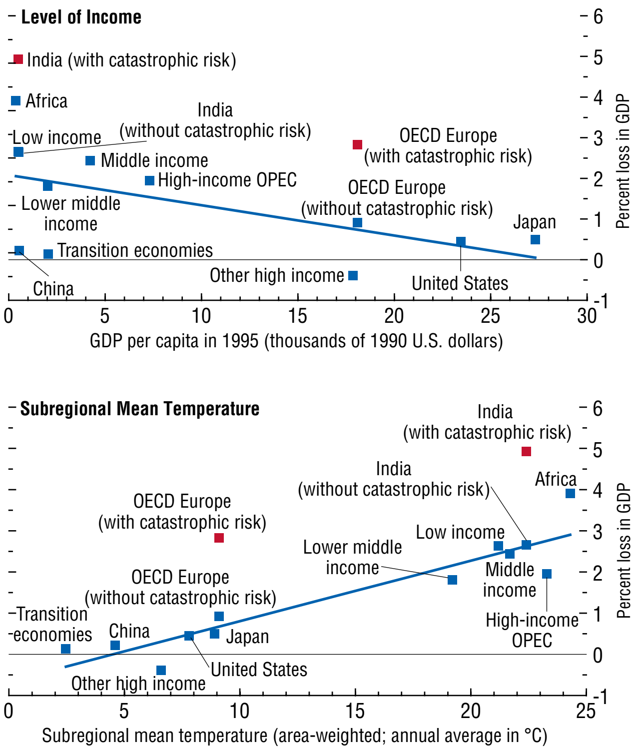
Estimates of GDP losses from climate change vary depending on the methodology and coverage of impacts and risks. GDP losses increase with temperature.



Source: Stern (2007).
[1]The studies presented in the *Stern Review* are from Mendelsohn, Schlesinger, and Williams (2000), Nordhaus and Boyer (2000), and Tol (2002).
[2]Nordhaus and Boyer (2000) data adjusted for catastrophic risk are available only for 2.5°C and 6°C. Observations were interpolated using a linear trend.

Figure 4.4. Damages from 2.5°C Warming by Region[1]

Losses from climate change fall disproportionately on emerging and developing economies.



Source: Nordhaus and Boyer (2000).
[1]OECD is the Organization for Economic Cooperation and Development. OPEC is the Organization of Petroleum Exporting Countries. See Nordhaus and Boyer (2000) for information on country group composition. The regression line includes only observations without catastrophic risk.

lower level of development typically implies a larger dependence on climate-sensitive sectors, particularly agriculture. Second, populations in these countries are typically more vulnerable to climate change because of lower income per capita, limited availability of public services (such as health care), less-developed financial markets, and poor governance. Third, the same factors also restrain the adaptive capacity of the economy. Some estimates of damages from climate change explicitly specify costs as a function of income level (Nordhaus and Boyer, 2000). Often, higher initial temperatures and lower levels of development go hand in hand, compounding the damaging impact of climate change on developing economies.

All three of the main benchmark studies suggest a similar distribution of the climate change impact across regions, shown in Figure 4.5 by adjusting regional impacts for the study-specific global impact. The regions likely to experience the most negative effects include Africa, south and southeast Asia (especially India), Latin America, and Organization for Economic Cooperation and Development (OECD) Europe (if catastrophic risk is included). In contrast, China, North America, OECD Asia, and transition economies (especially Russia) should suffer smaller impacts and may even benefit, depending on the actual extent of warming. In India, the large negative impact is due to catastrophic risk (such as a change in the monsoon pattern), agricultural damages, and deteriorating health. In Africa, the main effect estimated by Nordhaus and Boyer is deteriorating health from the spread of tropical disease; however, recent estimates of the likely effects on agricultural potential (discussed herein) also project substantial agricultural damages (Cline, 2007). OECD Europe is largely affected by the risk of catastrophic impact and damages to coastal areas.

Physical estimates of the impact of climate change confirm that Africa and Asia are particularly vulnerable. In these regions, almost 1 billion people would experience shortages of water by 2080, more than 9 million could fall victim to coastal floods, and many could face increased hunger (Figure 4.6). Pacific island countries are perhaps the most immediately vulnerable among the poor countries, as even a small further rise in sea level would dramatically affect their environment.

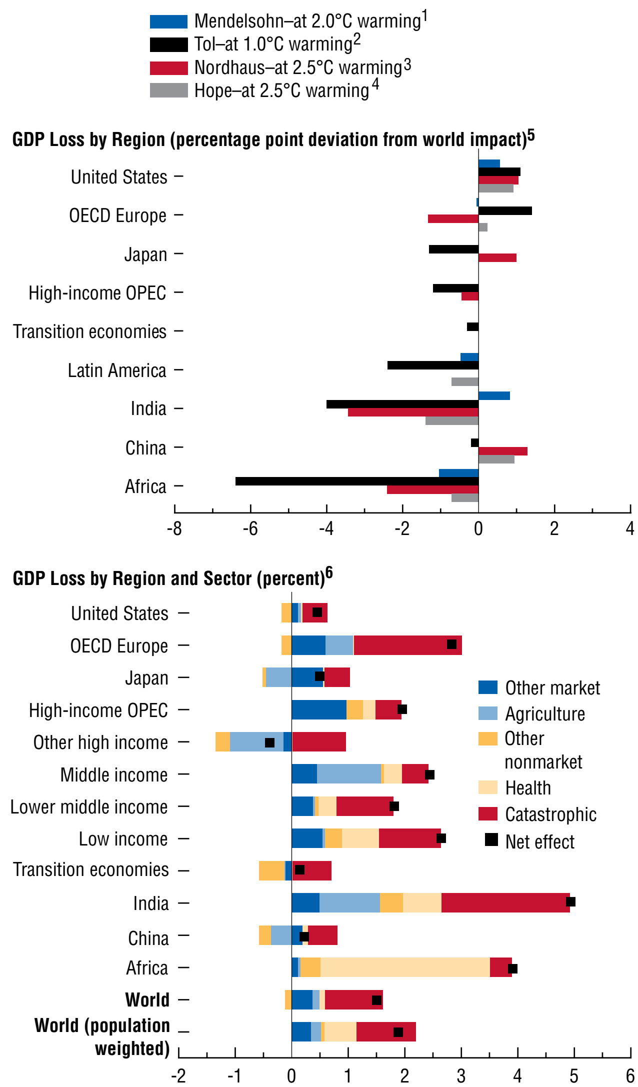
Two main areas of uncertainty plague estimates of damages from climate change at all levels, as is reflected in the large variation in the present value of damages. The first is the limitation of current scientific knowledge about the physical and ecological processes underlying climate change. For example, there is only incomplete information about how rapidly GHG concentrations will grow in the future, how sensitive climate and biological systems will be to increased concentrations of GHGs, and where the "tipping points" are, beyond which catastrophic climate events can occur.[9]

The second source of uncertainty relates to how best to quantify the economic impact of climate change. The magnitude of losses from climate change depends, for example, on how well people and firms adapt and at what cost, as well as on the extent to which technological innovation can reduce the impact. For example, health effects from the spread of tropical disease may be lower if the spread of malaria can be reduced. Similarly, losses in agricultural yields may be limited if heat- and drought-resistant crops can be developed. Conventional approaches to evaluating damage from climate change also tend to neglect dynamic macroeconomic linkages. Climate change is largely a supply-side shock, but it may have significant effects on trade, capital flows, and

[9]This has implications for measures of economic damage. For example, the effect of climate change on productivity in agriculture and forestry depends to a large extent on the magnitude of carbon fertilization effects (a process by which higher concentrations of carbon dioxide in the atmosphere could result in increased crop yields), which is not known with certainty. Recent downward revisions to carbon fertilization effects have led to higher estimates of diminished world agricultural potential (Cline, 2007).

Figure 4.5. Impact of Warming by Region and Sector

Africa, south and southeast Asia (especially India), Latin America, and European OECD countries are likely to be most affected by climate change.



Sources: Hope (2006a); Mendelsohn, Schlesinger, and Williams (2000); Nordhaus and Boyer (2000); and Tol (2002).

[1]Shows the median impact of the Ricardian and Reduced-Form models for a 2°C warming. South and southeast Asia includes Middle East and China. No data are available for Asian Organization for Economic Cooperation and Development (OECD) countries and high-income OPEC (Organization of Petroleum Exporting Countries) countries.

[2]Impact of a 1°C warming. High-income OPEC refers to the Middle East. China includes other centrally planned Asian economies. No data are available for transition economies.

[3]Impact of a 2.5°C warming. North America refers only to the United States. OECD Asia refers only to Japan. South and southeast Asia refers only to India. No data are available for Latin America.

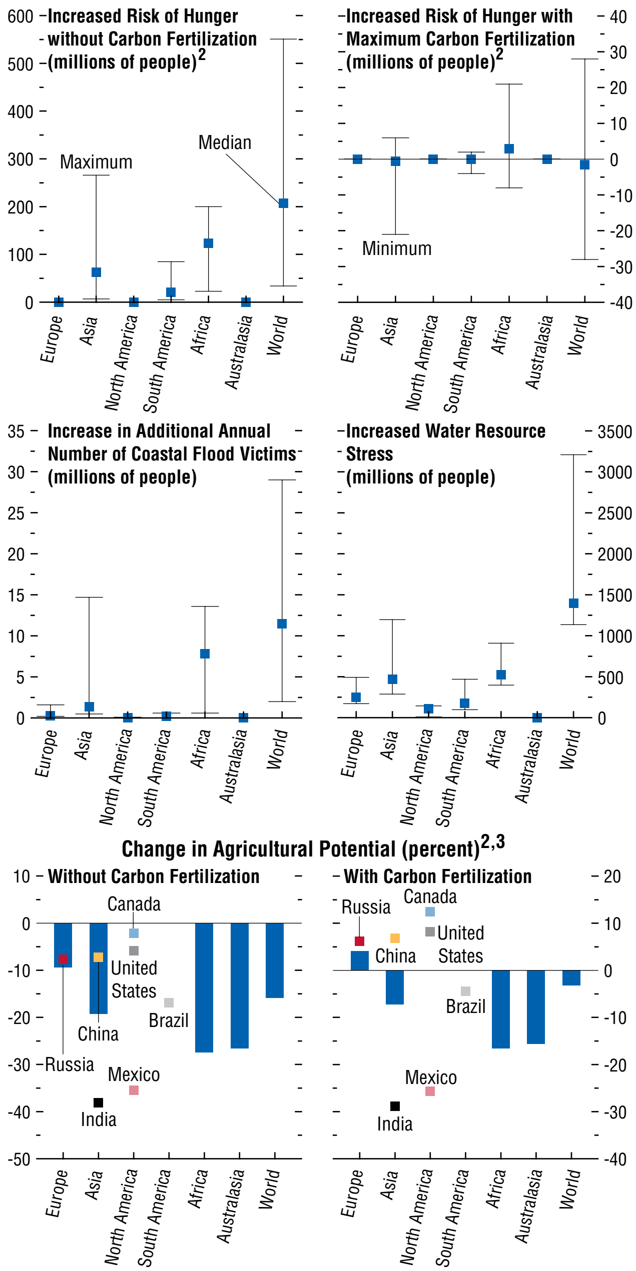
[4]Shows the median impact of models with and without adaptation at 2.5°C warming. North America refers only to the United States. South and southeast Asia refers only to India. No data are available for OECD Asia and high-income OPEC countries.

[5]World impact is estimated as follows: Mendelsohn at 0.13, Tol at 2.30, Nordhaus at -1.50, and Hope at -1.15 percent of GDP.

[6]Estimates from Nordhaus and Boyer (2000).

Figure 4.6. Physical Impact by 2080[1]

Physical estimates of climate change impact confirm that Asia and Africa are particularly vulnerable to climate change.



Sources: Cline (2007); and Yohe and others (2007).

[1]Data for panels 1–4 are from Yohe and others (2007); sample includes estimates from A1FI, A2, B1, and B2 *Special Report on Emissions Scenarios* (IPCC, 2007). Data for panels 5–6 are from Cline (2007). All impacts are measured relative to the situation in 2080 with no climate change. Regional compositions may not be comparable across panels.

[2]Carbon fertilization refers to the increase in crop productivity as a result of the effect of carbon dioxide on crops.

[3]Estimates without carbon fertilization are weighted averages of the estimates from a Ricardian model and crop models. Estimates with carbon fertilization include the effect of a uniform boost of 15 percent in yield. See Cline (2007) for more information.

migration, as well as on investment and savings (Box 4.2).[10]

Quantifying the aggregate losses across generations involves use of a single welfare measure and bears on the present value estimates of global losses. The rate at which the welfare of future generations should be discounted to the present (which relates to the marginal product of capital) is the subject of considerable debate. The *Stern Review*'s estimate that climate change would produce a large welfare cost—equivalent to a permanent reduction in consumption of about 14 percent of world output over the next two centuries—is much higher than the average annual estimated output loss.[11] This reflects a low elasticity of marginal utility to consumption and an assumed pure rate of time preference of approximately zero, both of which give a large weight to consumption losses from distant generations.[12] Many consider these assumptions unpersuasive because they imply a much higher-than-observed savings rate and a lower-than-observed rate of return on capital (Nordhaus, 2007a; and Dasgupta, 2007). Stern (2008) points out that discount rates are conditional on the path of future growth in consumption, implying that a lower discount rate should apply in a world with climate change than in a world without it, all other things equal. He also underscores that basing discount rates on market rates is fundamentally inappropriate in cases involving welfare trade-offs across far-apart generations and across countries with different levels of income. Technological change (DeLong, 2006) and uncer-

[10]For instance, as climate lowers output now and in the future, investment may fall because there are fewer resources to invest and because the rate of return on capital is lower. Using simulations, Fankhauser and Tol (2005) show that the capital accumulation effect is important, especially if technological change is endogenous, and may be larger than the direct impact of climate change.

[11]Under the *Stern Review*'s "high-climate scenario" with catastrophic, market, and nonmarket impacts, the mean losses are less than 1 percent of world output in 2050, 2.9 percent in 2100, and 13.8 percent in 2200.

[12]Raising the pure rate of time preference from 0.1 to a still modest 1.5 reduces the range of expected damage costs from 5–20 percent to 1.4–6 percent of global consumption (see the October 2007 *World Economic Outlook*).

tainty over future discount rates may also justify using lower discount rates (Pindyck, 2007).

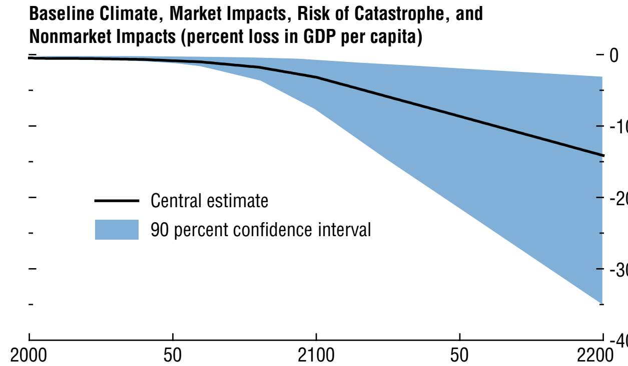
What is the relative importance of the different sources of variation in damage estimates? The *Stern Review*'s estimate of the percent loss in GDP per capita by 2200 under its baseline climate scenario (which assumes relatively high emissions and includes market impacts, nonmarket impacts, and catastrophic risk) ranges from about 3 percent to 35 percent (90 percent confidence interval), with a central estimate of 15 percent (Figure 4.7). Hope (2006b) finds that the two most important sources of variation in estimates of welfare losses are the climate sensitivity parameter and the pure rate of time preference.[13] Uncertainty surrounding the nonmarket impacts and the elasticity of marginal utility with respect to income also ranks high, whereas uncertainty about market impacts ranks lower. Weitzman (2007a) concludes that the choice of the discount rate overshadows any uncertainty about the costs and benefits of climate change a century from now. He also argues that the most important source of variation is uncertainty over probability and scale of catastrophes. Webster and others (2003) find that nearly half of the variation is attributable to uncertainty about emission forecasting.

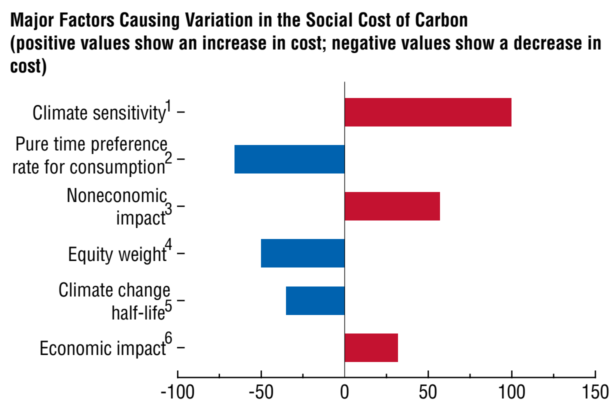
Non-negligible tail risks of large damages from climate change would justify an early and significant policy action. Uncertainty generally increases the benefits of policy delay, but because both the damages from climate change and its costs are irreversible, policy implications of uncertainty are more ambiguous (Pindyck,

[13]Hope uses the PAGE 2002 model, but focuses on the social cost of carbon (SCC)—the present value of future climate change damages caused by one extra ton of carbon emissions—as an indicator of damages. Like GDP-based measures, SCC estimates fluctuate widely. In a recent survey, Tol (2005) found a mean SCC of $43 per ton of carbon, with a standard deviation of $83. Using standard assumptions about discounting and aggregation, he concluded that the SCC is unlikely to exceed $50 per ton of carbon. Other surveys, however, point to higher values (a central value of $105 in Clarkson and Deyes, 2002, and a lower benchmark of $50 in Downing and others, 2005). Also see IPCC (2007).

Figure 4.7. Variation in Estimates of Damages from Climate Change

There is considerable uncertainty about estimates of the economic impact of climate change.





Sources: Hope (2006b); and Stern (2007).
[1]Equilibrium temperature rise for a doubling of carbon dioxide concentration.
[2]Pure time preference for consumption now rather than in one year's time.
[3]Valuation of noneconomic impact for a 2.5°C temperature rise.
[4]Negative of the elasticity of marginal utility with respect to income.
[5]Half-life in years of global response to an increase in radiative forcing.
[6]Valuation of economic impact for a 2.5°C temperature rise.

Box 4.1. Rising Car Ownership in Emerging Economies: Implications for Climate Change

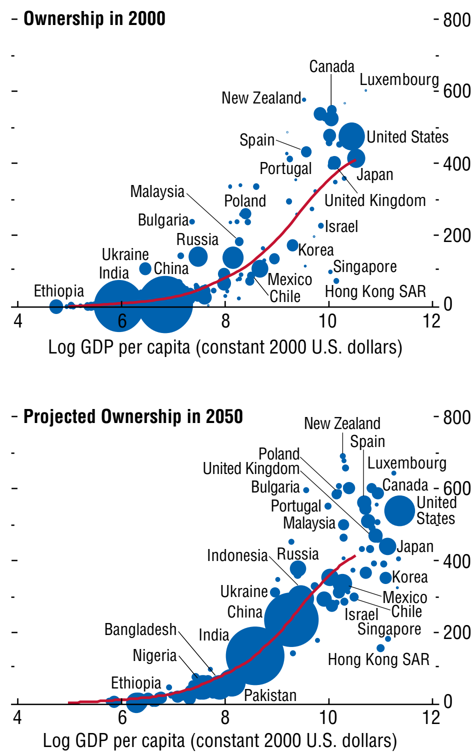
Economic history suggests that as people get richer, they increase their use of private transportation. Accordingly, rapid economic growth in a number of large emerging economies has recently been accompanied by an impressive acceleration in the demand for cars, and these countries may be expected to move quickly toward mass car ownership in the decades ahead. Greater car usage will improve the well-being and broaden the economic opportunities of millions who are being lifted out of poverty, but it will also have major implications for climate change. Cars currently account for 6½ percent of global GHG emissions and a sizable share of oil consumption—for example, gasoline accounts for as much as 45 percent of oil consumption in the United States, one of the most gasoline-reliant economies.

Car ownership is amenable to econometric analysis, and the exercise yields reasonably accurate projections, thereby providing a quantitative illustration of the scale of future challenges related to keeping GHG emissions in check. Indeed, over the past few decades, car ownership has displayed a relatively robust relationship with GDP per capita. More specifically, both the historical experience of economies that are now advanced and cross-country regression analysis suggest that car ownership remains low up to per capita incomes of about $5,000 (a threshold identified through an iterative search for the best regression fit) and then takes off rapidly as incomes grow beyond that threshold.

Several emerging economies—including China and India, the most populous countries in the world—are currently at the stage of development usually associated with such a takeoff (figure). Indeed, while a wide range of consumer durables are commonplace in most urban Chinese households, car ownership remains relatively low beyond a handful of major urban centers. This is indicative of the potential for rising car ownership in the next few decades, as per capita income grows beyond $5,000 in key emerging and developing economies. Projections derived from regressions based on a panel of countries suggest that the number of cars worldwide will increase by 2.3 billion between 2005 and 2050, and that the number of cars in emerging and developing economies will increase by 1.9 billion.[1] Compa-

Car Ownership

(Cars per 1,000 people on the y-axis; size of bubble represents population)



Sources: International Road Federation, *World Road Statistics;* World Bank, *World Development Indicators* (2007); and projections from Chamon, Mauro, and Okawa (2008).

Note: The main authors of this box are Marcos Chamon and Paolo Mauro, based on Chamon, Mauro, and Okawa (2008).

[1]The projections are based on a regression model relating car ownership in a panel of countries to the share of the population earning more than $5,000 per capita a year and a trend that captures technological

rable projections are supported by microeconometric estimates based on two surveys of tens of thousands of households in China and India. The results confirm that as more and more households reach income levels that allow them to afford a car, ownership should rise by ½ billion cars in China and ⅓ billion cars in India between now and 2050. The projected increase in car ownership in these emerging market giants (and other countries at a similar stage of development) will not only have substantial fiscal consequences for these countries—which are likely to require infrastructure investment to support such increased demand for transportation—but will also have major implications for emissions and climate change.

A simple back-of-the-envelope calculation regarding GHG emissions may help gauge the implications of an increase in the worldwide car fleet from 0.5 billion in 2000 to 2.9 billion in 2050. According to the *Stern Review* (2007), cars (and vans) accounted for emissions equivalent to 2.6 gigatons of carbon dioxide (GtCO_2) in 2000. Relating the projected increase in the number of cars to additional emissions requires strong simplifying assumptions about future improvements in fuel efficiency. Over the past two and a half decades, the average number of miles per gallon has been broadly stable in most advanced economies, as technological improvements have been accompanied by increases in average car weight. Assuming that the growth rate of car emissions is the same as the growth rate of cars, worldwide emissions by cars would amount to 6.8 GtCO_2 in 2050. To put this in perspective, the *Stern Review*'s business-as-usual scenario foresees that total emissions (flow) from all sources will rise from 42 GtCO_2 in 2000 to 84 GtCO_2 in 2050. Emissions from cars as a share of total CO_2 emissions from all sources would thus rise from 6.3 percent in 2000 to 8.1 percent in 2050. To sum up, cars could contribute significantly—and more than proportionately—to an increase in emissions from all sources that would have profound implications for climate change.

Policymakers in emerging and developing economies have an opportunity to "lean against the wind" of greater car ownership that inevitably results from economic development by promoting investment in appropriate subway, rail, and/or public transportation infrastructure. Local pollution concerns also have become an important driver for policy change. The wide variation in gasoline taxes across countries—ranging from $0.4 a gallon in the United States (and even less in some developing economies) to more than $3 a gallon in the United Kingdom—suggests that there may be significant room to increase fuel taxation in various parts of the world. Some countries also have begun to make substantial use of fuel efficiency standards. Notably, China introduced such standards in 2005 and will make them more stringent in 2008. At present, China's fleet average fuel economy standards are more strict than those in Australia, Canada, and the United States, though somewhat less strict than those in Europe and Japan. Additional policy measures include higher taxes on less-fuel-efficient cars.

While such policies seem necessary, they are likely to be insufficient. Ultimately, much will depend on progress with respect to new technologies—such as plug-in hybrids or other breakthroughs that we are unable to foresee—and incentives for innovation may also be considered in this area.

improvements; long-term projections for economic growth are based on published sources. For more details on the methodology and sources, see Chamon, Mauro, and Okawa (2008).

2007). The significant probability of climate catastrophes strengthens the case for earlier abatement—that is, reduction of GHG emissions—with abatement initiatives increasing in intensity as learning progresses (Stern, 2008; and Weitzman, 2008). Even with aggressive abatement, however, it will be necessary to pursue adaptation—adjustments in ecological, social,

Box 4.2. South Asia: Illustrative Impact of an Abrupt Climate Shock

This box presents some scenarios that illustrate the economic effects on an open economy of an abrupt change in climate. This example examines the impact of changes in the monsoon pattern on a representative south Asian country that is heavily reliant on agriculture, but the arguments are relevant to other countries exposed to major climate shocks.

These scenarios were developed using a six-country[1] annual version of the Global Integrated Monetary and Fiscal Model (GIMF).[2] GIMF is a multicountry dynamic stochastic general equilibrium model that has been designed for multilateral surveillance. It includes strong non-Ricardian features whereby fiscal policies have significant real effects. It also includes significant nominal and real rigidities, making it a useful tool to study both the short- and long-term implications of supply and demand shocks.

Abrupt Climate Shock

The baseline climate change scenario, shown as the red lines in the leftmost column of the figure, assumes that a sudden and permanent deterioration in climate leads to failed harvests and therefore higher mortality rates and emigration to neighboring countries. In the first year 1 percent of the population either perishes or emigrates, followed by 0.2 percent a year over the subsequent five years, leading to a population decline of 2 percent over the long term.

In addition to the population effects, drastic changes in climate could also make obsolete many existing agricultural, distributional, and associated industrial patterns, forcing the relocation or decommissioning of existing capital stocks and the relocation or retraining of labor. This represents a large shock to the stock of a country's technology, which would likely result in a significant decline in total factor productivity.[3] For this south Asian economy, productivity growth would be significantly reduced over the medium term in both the tradable and the nontradable sectors of the economy. This would be accompanied by negative effects on foreign demand for the country's products, due to reduced competitiveness in the new industries in which the country is forced to specialize.

Relative to baseline, these shocks cause an immediate 2 percent and ultimately more than 8 percent contraction in GDP, accompanied by a 2 percent real depreciation as domestic goods prices fall. Policy is accommodative, through both a lowering of interest rates and a deterioration in the fiscal deficit.[4] Both measures reduce national savings and drive the current account into deficit.

Financial Market Response

The blue lines in the leftmost column of the figure show a scenario that adds to the direct climate-related shocks a risk premium shock of 1 percentage point a year, as financial markets respond to the country's deteriorating performance and prospects. Higher interest rates reduce capital accumulation and therefore GDP, which ultimately ends up 3 percent lower than in the baseline scenario. Because a higher risk premium raises domestic savings, it leads to depreciation of the real exchange

Note: The main authors of this box are Michael Kumhof and Douglas Laxton, with support from Susanna Mursula.

[1]The country blocks are emerging Asia, euro area, India, Japan, United States, and the remaining countries. Trade linkages among these countries were calibrated using the 2006 matrix of world trade flows.

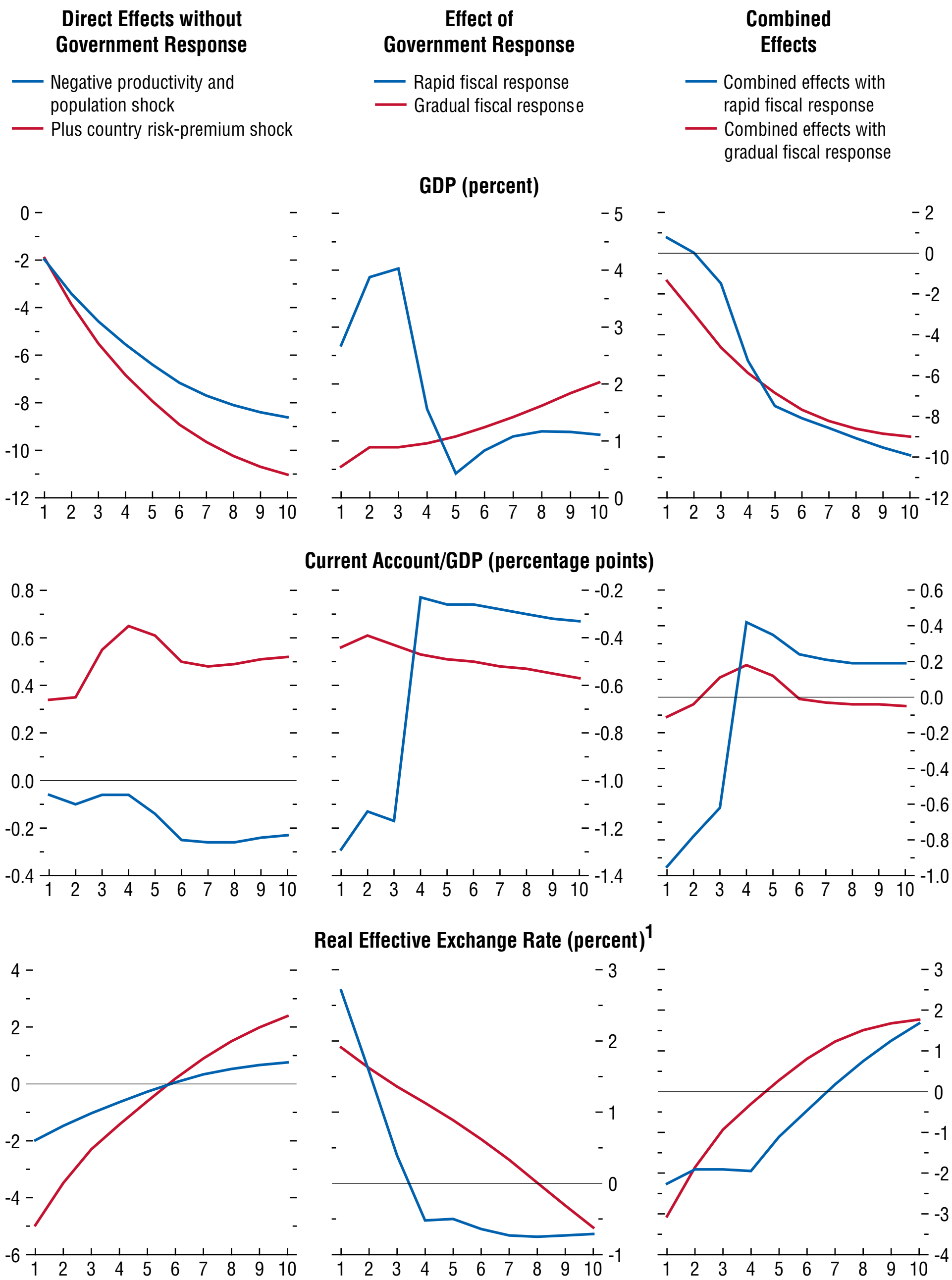
[2]For a description of the structure of the model see Kumhof and Laxton (2007).

[3]For estimates of the long-run effects on productivity see Nordhaus (2007b).

[4]Fiscal policy is assumed to target a structural interest-inclusive deficit consistent with the preexisting stock of government debt, with the government's estimate of the permanently sustainable tax base reduced only slowly in response to lower realized tax revenue. As a result, tax rates are raised only gradually when the economy contracts, resulting in several years of deficits and increases in debt. Relative to a balanced budget rule, such a policy is expansionary.

Illustrative Impact of Climate Change

(Deviations from control; x-axis in years)



Source: IMF staff calculations.

[1] A positive value represents an appreciation relative to the baseline.

Box 4.2 *(concluded)*

rate in the short run and causes the current-account-to-GDP ratio to be around 0.7 percentage point higher than in the baseline scenario. After a few years, the improving external asset position causes the real exchange rate to appreciate.

Government Response

Because sufficiently large climate shocks can cause a country's stock of technology to deteriorate significantly, the question arises of how best to rebuild that technology. Clearly, the private sector will have a significant role to play, but private investment may be hampered by the disincentives to capital accumulation stemming from higher real interest rates. Furthermore, the affected economy would require a large-scale investment in public goods such as relief facilities to protect the population, rebuild transportation and communications infrastructure, and retrain the workforce. The middle column of the figure illustrates two such scenarios.[5]

The red lines show the incremental effects of an increase in public investment by 3.3 percent of GDP over a period of three years. This is financed by the issuance of additional government debt, which is allowed to increase by 10 percent of GDP in the long run, accompanied by a 0.5 percent permanent increase in the government-deficit-to-GDP ratio from year four onward. The model assumes that private agents do not save sufficiently to offset such changes in public sector savings. This implies that the issuance of additional government debt crowds out private sector investment in other assets, in this case principally by reducing net foreign assets by 9 percent of GDP in the long run.

[5]It may be possible to phase in some public investment ahead of a climate shock. But in order to be effective, this would require advance knowledge of exactly when and where such a shock will hit. Given the tremendous uncertainties associated with climate change, there would seem to be only limited scope for such preemptive action.

Higher public investment increases the stock of public capital by 15 percent at the end of year three. The scenario predicts that GDP increases throughout, initially by about 4 percent as a result of increased government demand, and after a few years by about 1 percent because of the productivity-enhancing effects of a larger public capital stock.[6] The large increase in demand and corresponding decline in national savings causes an initial current account deficit of more than 1 percent of GDP and a 3 percent real appreciation. The current account remains negative as a result of permanently lower government savings, eventually causing the real exchange rate to depreciate enough to generate an export volume sufficient to service the increased external debt.

A policy of rapid government investment may be necessary if the climate shock causes an especially dramatic collapse in activity at the outset. If it does not, as in our baseline scenario, then a more gradual approach may be in order. This is illustrated by the blue lines in the middle column of the figure, which show an increase of public investment by 1 percent of GDP over a period of 10 years. The effects on GDP are similar but are realized much more gradually. The differences are due to the different implications of the two public investment scenarios on the cumulative public capital stock and on the effect of the rate of depreciation.

The red and blue lines in the rightmost column of the figure combine the climate change scenario, including the risk premium response, with either of the two public investment scenarios. Public investment accomplishes two objectives: (1) mitigating the impact of the climate shock, which is most effective when the investment is concentrated in the period immediately following the shock, and (2) mitigating the long-run effects of the shock, which is most effective when the investment is spread over a longer time period.

[6]The elasticity of output with respect to public capital has been calibrated to be consistent with the empirical literature. See Ligthart and Suárez (2005).

or economic systems in response to climatic impacts.[14] If serious efforts to cut emissions were undertaken immediately, some climate warming would still occur, making adaptation unavoidable. However, adaptation is an inadequate response on its own, because there are natural limitations to humans' ability to adapt at higher degrees of warming.

How Can Countries Best Adapt to Climate Change?

Societies have historically adapted to changing environmental conditions, and individuals and firms can be expected to continue altering their behavior in response to changing climate conditions (for example, by planting more drought-resistant crops). However, government involvement is also likely to be needed to spur adaptation, in order to overcome market failures (individual firms and households unable to incorporate the full social benefits of adaptation into their decision making), to meet the need for public goods and services to support adaptation (for example, coastal protection or investment in public health infrastructure), and to augment the private sector's capacity to adapt, for example, in poor countries.

Quantitative analyses of adaptation costs are scant, but studies focusing on public sector costs suggest that adaptation may put a strain on government budgets, especially in developing economies that have weak adaptation capacities and are likely to be more severely affected by climate change. Based on simple extrapolations of current expenditure patterns, the United Nations Framework Convention on Climate Change (2007) estimates additional annual adaptation investment in agriculture, health, water, and coastal protection of about $40 billion a year in 2030, perhaps half of which might be expected to fall on the public sector. The study also projects additional infrastructure needs of $8 billion–$130 billion, some of which would fall directly on governments.[15] Further refinements of adaptation cost estimates are needed in order to try to narrow the wide range of uncertainty surrounding these estimates and to broaden their coverage where possible—factoring in, for example, the need to adapt to increased climate variability.

Economic and institutional development is perhaps the best means of improving climate-related adaptive capacity. Development promotes diversification away from heavily exposed sectors; improves access to health, education, and water; and reduces poverty. To be effective in fostering adaptation, development strategies need to take climate change vulnerabilities into account, while seeking to avoid maladaptation (IPCC, 2007). Higher-quality institutions also strengthen countries' ability to adapt to climate change (Kahn, 2005).

Fiscal self-insurance against climate change is also needed. Government budgets must include room for adaptation expenditures, and social safety nets must be strengthened, especially in countries that will be severely affected. External financing may be needed to complement domestic resources in cases where the demands of adaptation overwhelm poor countries' capacity.[16] The recent launch of a UN fund to provide

[14]More ambitiously, "geoengineering," that is, technological efforts to stabilize the climate system by direct intervention in the energy balance of the Earth, could be used to reduce global warming. But these technologies are at a very early stage of development and, although promising, open a vast range of potential risks to the environment. See Barrett (2006) for a discussion of geoengineering.

[15]The World Bank (2006) puts the cost of "climate-proofing" development investments at $3 billion–$54 billion a year, and the United Nations Development Program (2007) estimates this cost at $44 billion a year in 2015. An additional $2 billion would be needed for disaster response and $40 billion a year to strengthen social safety nets. By comparison, the Japanese government puts the total cost of building coastal defenses to one meter of sea level rise at $93 billion (Government of Japan, 2002). The United Kingdom also reports high cost estimates for flood prevention—about $1 billion annually and a further $8 billion to strengthen the Thames Barrier (UKCIP, 2007).

[16]For example, Easterling and others (2007) conclude that a 3°C regional warming would likely exceed the ability of emerging economies to adapt to the impact on crop yields.

Box 4.3. Macroeconomic Policies for Smoother Adjustment to Abrupt Climate Shocks

Economic theory suggests that macroeconomic policies such as exchange rate flexibility can help reduce the macroeconomic cost of the extreme weather events that are likely to accompany climate change. Such shocks typically destroy capital and disrupt production, and adjusting to them requires reallocating people and capital across and within sectors. Currency depreciation helps reduce the cost of the shock and enables the economy to move more quickly to the new equilibrium by raising the domestic price of exports, while a higher price level facilitates adjustment in real wages (Friedman, 1953; and Mundell, 1961). Adjustment to a negative shock in a fixed-rate regime tends to take longer, with economic activity declining until (sticky) wages and prices fall to their new equilibrium levels (Obstfeld and Rogoff, 2002). The empirical evidence in Ramcharan (2007a) is consistent with these ideas.

However, there are some important caveats to this literature. In part because of concerns about their commitment to price stability, some central banks in developing economies may not have the ability to effectively pursue countercyclical monetary policy. Thus, an important component of the adjustment process in flexible rate regimes may be limited in practice. Also, prices may not be particularly rigid in many developing economies, making adjustment through the nominal exchange rate superfluous. Moreover, fixed-rate regimes can reduce exchange rate variability and lower transaction costs, thereby stimulating trade, investment, and growth. And depending on the balance-sheet exposure of firms, nominal exchange rate movements can exacerbate the impact of real shocks.

The reallocation of production factors after a shock also depends on credit market imperfections and labor market rigidities (Caballero and Hammour, 2005; and Matsuyama, 2007). Intuitively, the aggregate economic cost of a shock such as a flood that destroys agricultural production may be lessened if the dislocated farm labor can be readily absorbed in the manufacturing sector. But rigid labor contracts may prevent such a reallocation, idling labor and worsening the shock. Likewise, financial market imperfections that deny firms liquidity to help finance shocks can lead to inefficient closures and economic contractions (Bernanke and Gertler, 1989; Kiyotaki and Moore, 1997; and Wasmer and Weil, 2004). There is also econometric evidence that highlights the importance of flexible financial sector policies in shaping the impact of extreme weather shocks.

However, identifying the role of economic policy in shaping the aggregate economic response to climate change and other adverse shocks can be very difficult. Policymakers often choose policies and regulations based in part on the expected impact of economic events, potentially blurring the lines between cause and effect. For example, because policymakers may choose exchange rate flexibility when they expect costly changes to the terms of trade, more flexible regimes may coincide with sharp output losses, masking the potential impact of floating exchange rate regimes in smoothing these shocks. Bias can also arise because policy choices can determine the frequency and intensity of economic shocks. In this case, exchange rate or financial sector policies may determine

Note: The main author of this box is Rodney Ramcharan.

Disasters across High- and Low-Income Countries

Country Income Category	Number of Disasters	Population (million)	Killed in Disasters	Total Damage, as a Percent of GDP	GDP per Capita
High income	1,476	828	75,425	0.007	23,021
Low income	1,533	869	907,810	0.55	1,345

Sources: Centre for Research on the Epidemiology of Disasters; and Stromberg (2007). Disasters include earthquakes, droughts, floods, windstorms, and volcanic eruptions. Total damage is computed for windstorms and floods only.

Regional Differences in Disaster Incidence and Impact

	Number of Disasters	Killed per 100,000	Affected per 100,000
Africa	861	2.61	1,453
Asia	2,352	0.74	4,303
Americas	1,626	0.59	564
Europe	863	0.60	206
Oceania	324	0.46	2,363

Sources: Centre for Research on the Epidemiology of Disasters; and Stromberg (2007).

specialization patterns and thus the intensity and frequency of terms-of-trade shocks.

Natural disasters can, however, provide credible insight into the impact of economic policy in shaping the aggregate economic response to climate change and other shocks. In particular, disasters are easily observed and yet highly unpredictable. They are also, at least in the short run, not determined by economic choices. Thus, in economics jargon, they can be treated as conditionally exogenous with respect to policy choices. That said, these events do cluster geographically (first and second tables), and the general susceptibility of some countries to natural shocks may influence both economic policy and the response to such shocks. But susceptibility is an observable phenomenon that can be included in the estimation framework, reducing the possibility of bias. And even after accounting for geographic clustering, these shocks remain mostly low-probability and unpredictable events for many countries, and therefore are unlikely to be a powerful force in determining economic policy. The Caribbean, for example, is notoriously hurricane prone, yet an Atlantic hurricane on average has struck one of these islands just seven times in the past 100 years.

The methodology in Ramcharan (2007a) can be used to estimate the role of financial sector policies in shaping the output impact of natural disasters. In the case of floods, for example, let S_{it-1} denote a variable that takes on the value of zero if there are no floods in country i in year $t-1$ (the previous year) and the ratio of affected land area to the country's total land

Financial Sector Reforms and the Impact of Floods on Output Growth

(Dependent variable: real per capita GDP growth)

(a)	(b) Baseline	(c) "Constant Policies"	(d) Fixed Effects
Flood ($t-1$)	37.945	70.707	32.146
	[40.916]	[62.509]	[51.284]
Index*Flood ($t-1$)	–7.343	–75.724	–0.244
	[24.954]	[100.034]	[27.582]
Flood ($t-2$)	13.043	2.490	4.323
	[35.767]	[36.658]	[33.569]
Index*Flood ($t-2$)	27.832	40.557	30.428
	[33.379]	[32.498]	[28.258]
Flood ($t-3$)	89.142**	104.159	86.924**
	[36.503]	[102.895]	[40.527]
Index*Flood ($t-3$)	–10.844	–150.389	–13.505
	[26.197]	[169.852]	[25.770]
Flood ($t-4$)	–37.606	–73.439**	–39.671*
	[25.417]	[27.862]	[23.146]
Index*Flood ($t-4$)	86.859**	127.332***	92.125**
	[37.567]	[35.185]	[36.152]
Flood ($t-5$)	–77.633**	–226.517***	–83.121**
	[35.548]	[47.327]	[35.773]
Index*Flood ($t-5$)	94.267***	70.670***	97.687***
	[14.572]	[10.574]	[14.122]
Observations	989	842	989
R-squared	0.28	0.30	0.37

Source: Ramcharan (2007b).
Note: Standard errors, in brackets, are clustered at the country level. *, **, and *** denote significance at the 10 percent, 5 percent, and 1 percent level, respectively.

area if a flood does occur. Let R_{it} denote the Abiad, Detragiache, and Thierry Tressel (2007) de jure financial liberalization index observed in country i on year t. The vector $\mathbf{X}_{it}$ denotes the set of control variables observed for country i in year t.

The estimating equation is

$$y_{it} = \sum_{j=1}^{5}[\alpha_j S_{it-j} + \lambda_j R_{it} + \gamma_j S_{it-j} * R_{it} + \mathbf{X}_{it-j} S_{it-j} \theta_j] + \mathbf{X}_{it}\beta + \nu_t + u_{it},$$

where the parameters γ_j test whether the impact of a shock on the outcome variable, y_{it}, depends on the market orientation of the financial system. Because the financial system as well as the shock can affect the equilibrium level of y_{it}, the specifi-

Box 4.3 *(concluded)*

cation also linearly includes R_{it}, as well as S_{it}. In addition, other variables that are correlated with the decision to reform the financial system might also shape the output response to the shock, and to reduce this potential source of bias, we also estimate these interaction terms, yielding the coefficient θ_j. We consider the effects of the shock over a five-year horizon, beginning in the year immediately after the event is reported. The variable ν_t denotes year effects; u_{it} is a residual term that is allowed to be correlated across years for the same country in all regressions.

The third table excerpts some of the main results reported in Ramcharan (2007b). The sample consists of an unbalanced panel of 43 countries, beginning in 1973. The results confirm that financial liberalization can alleviate the impact of a flood on growth. Column b suggests that for two economies experiencing a similar flood, output growth is about 0.65 percentage point higher in the economy scoring one standard deviation higher on the liberalization index.[1] However, these results can be biased if policymakers systematically respond to these shocks by changing financial sector policies. Thus, column c excludes those floods that coincided with changes to the liberalization index over a six-year period, beginning in the year prior to the shock. The results are little changed. Finally, column d includes country-specific dummies to absorb time-invariant unobserved heterogeneity among countries. Again, the cumulative effect of financial sector reforms in shaping the output response to the shock is little changed.

[1]The fraction of land area affected by the typical flood in the sample is 0.014, and the standard deviation of the liberalization index is 0.246. Thus, using the significant coefficients from the third table, the estimated impact is (94.267+86.859)*0.014*0.246.

dedicated financing to such countries is a welcome step in this regard.

A flexible exchange rate regime and policies that make capital and labor more flexible may help reduce the macroeconomic cost of the types of abrupt shocks (such as extreme weather events) that are likely to accompany climate change (Box 4.3). Such shocks typically destroy capital and disrupt production, and adjusting to them requires reallocating people and capital across and within sectors. Many of these policies can be implemented fairly quickly and at a small cost to the budget, making them part of an effective adaptation strategy that can dampen the macroeconomic impact of climate shocks.

How Financial Markets Can Foster Adaptation

Financial markets can reduce the macroeconomic costs of adaptation by generating price signals to incentivize the relocation of people to lower-risk areas (for example, through lower insurance premiums) and reallocation of capital to newly productive sectors and regions (factoring in climate-adjusted costs and risks).[17] The financial markets' capacity to reallocate costs and risks to those most willing and able to bear them also will help reduce the social costs of adaptation. However, this capacity is dependent on the quality of macroeconomic and financial policies.

Two types of financial instruments are particularly relevant in the context of responding to climate change.

- Weather derivatives offer a way for producers vulnerable to short-term fluctuations in temperature or rainfall to hedge their exposure.[18] Exchange-traded contracts are typically linked to the number of days hotter or colder than the seasonal average within a future period,

[17]The recent strong performance of water distribution companies suggests that such factors are already being reflected in equity prices (Geman and Kanyinda, 2007).

[18]A weather swap is the transfer of payments between parties under a contract determined by the outcome of a weather-related index. The party who is "long" on the swap pays if the realized index is above the strike price and gets paid if it is below the strike price.

and trading in these contracts has grown strongly (Figure 4.8). Trading has focused on temperatures in selected U.S. and European cities, with liquidity now concentrated in near-term contracts because hedge funds and banks hold a larger share of such positions. Weather derivatives are now complemented by weather swaps and insurance contracts that can be used to hedge adverse weather and agricultural outcomes. Governments in some lower-income countries (for example, India and Mongolia) now offer crop and livestock insurance as a way to protect their most vulnerable farmers. Ethiopia pioneered drought insurance in 2006.

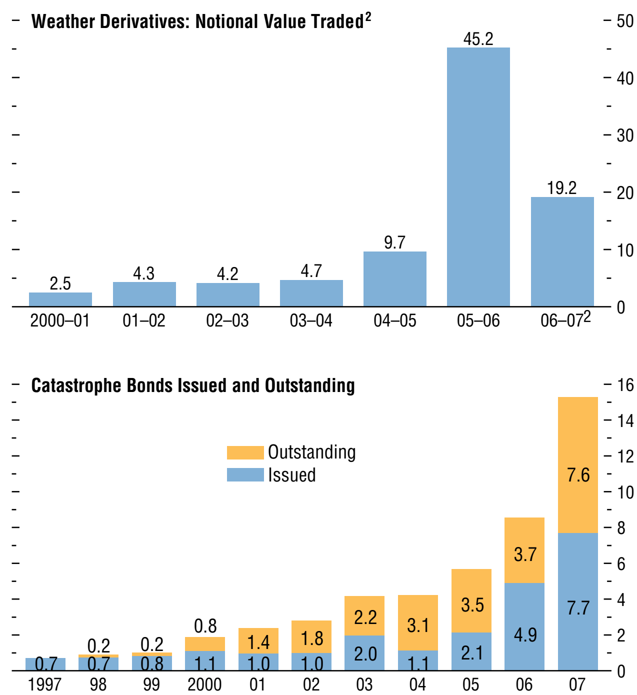
- Catastrophe (Cat) bonds help disperse catastrophic weather risk (Box 4.4). Following Hurricane Katrina, Cat bond issuance rose sharply (see Figure 4.8), benefiting vulnerable sectors, for example, agriculture and coastal property, by offering insurers more flexible instruments to transfer risk, thereby extending insurability and stabilizing premiums.

Nonetheless, there is a possibility that rising climate-related risks may overwhelm the financial sector's capacity (ABI, 2005). What can governments do to help preserve insurability and risk-management capacity? First, governments should refrain from subsidizing or capping flood or hurricane insurance premiums, in order to avoid promoting risky behavior and increasing fiscal risks. Development in areas vulnerable to flooding or wind damage may need to be discouraged in some cases where a high likelihood of damage makes insurance unavailable. In other cases, government investment in flood defenses or water conservation may enable insurers to continue providing flood or drought coverage. Finally, governments can foster the development of weather derivatives, insurance, and Cat bonds by providing reliable and independent data on weather patterns.

Although they are not a panacea—at this point, hedges against weather and catastrophic risks are available only out to five years—recent innovation and deepening in these markets

Figure 4.8. Weather Derivatives and Catastrophe Bonds[1]
(Billions of U.S. dollars)

There has been a strong rise in trading of weather derivatives and issuance of bonds transferring catastrophic risk.



Sources: PricewaterhouseCoopers; and Swiss Re Capital Markets.
[1]Notional value traded is the total value of the derivatives contract transacted, against which weather-related payments are calculated.
[2]Reduction in notional value traded in 2006–07 is largely the result of a move to monthly, rather than seasonal, contracts on the Chicago Mercantile Exchange.

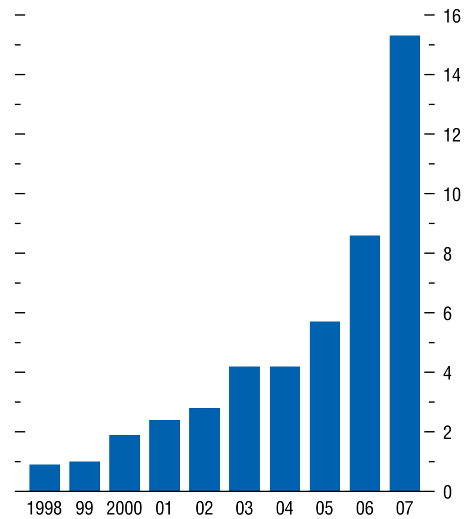
Box 4.4. Catastrophe Insurance and Bonds: New Instruments to Hedge Extreme Weather Risks

Climate change is likely to increase the incidence of extreme weather events. The *Stern Review* (2007) anticipates an increase in the frequency of severe floods, droughts, and storms. Likewise, the Intergovernmental Panel on Climate Change (IPCC) expects an increase in the intensity and duration of droughts and in the severity of hurricanes. Such events often have devastating effects, particularly in low-income and small countries. Financial markets can help these countries to insure against extreme weather risks. Although relatively unexploited to date, a variety of insurance instruments now allow for hedging almost any natural disaster risk.

Over the past decade, the market for global catastrophe reinsurance has grown strongly in volume and in the variety of financial structures, although its geographic coverage has expanded to a more limited degree. The global catastrophe reinsurance market is the wholesale segment of the insurance market. Typically, primary insurers (those that write policies to households and companies) seek coverage for their exposure to natural disasters (first figure). In addition, securitizations—such as catastrophe (Cat) bonds—can be used to transfer ("lay off") risk to the capital markets. Cat bonds are typically issued by reinsurance companies, but are sometimes issued by primary insurers or parties who seek self-insurance, such as governments. Although still relatively small, the Cat bond market has been growing rapidly in the past few years, reaching a total capitalization of more than $15 billion by end-2007. Market sources estimate the overall catastrophe reinsurance volume at about $150 billion.

Most Cat bonds and catastrophe reinsurance contracts are focused on a handful of major risks, but the covered events have widened some over the past two years. The major perils—U.S. wind, U.S. earthquake, European windstorm, Japanese earthquake, and Japanese typhoon—account for about 90 percent of the total market volume. Recently, insurers in a wider set of countries have started to seek disaster coverage, including in Australia and New Zealand (wind), and in Taiwan Province of China (earthquake).

Cat Bond Market Capitalization
(Billions of USD)



Source: Swiss Re Capital Markets.

A handful of Cat bonds have been issued by governments seeking to hedge the fiscal risks that arise from disasters. For example, in 2006, FONDEN, the Mexican government agency charged with providing relief following natural disasters, placed instruments to cover earthquake risks at three vulnerable locations, with total coverage of $450 million. The operation comprised a direct contract with a reinsurance company and the issuance of two Cat bonds. In 2007, the World Bank launched the Caribbean Catastrophe Risk Insurance Facility (CCRIF)—a regional disaster insurance facility to provide coverage against hurricane risk for 16 Caribbean countries. The countries purchased a total of $120 million in disaster insurance from CCRIF, which then laid off the risk

Note: The main author of this box is Eduardo Borensztein.

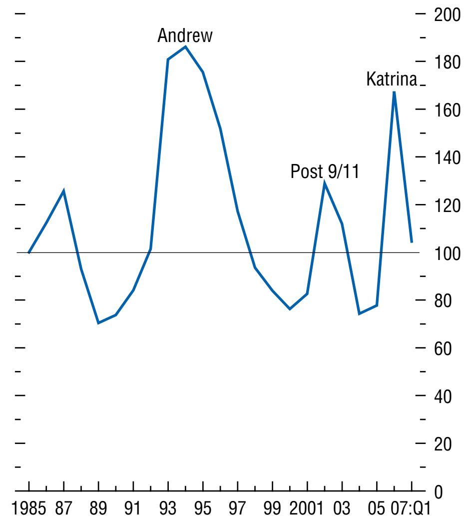
through reinsurers and capital markets. Scale is a significant advantage of pooling multicountry risk. The minimum economically feasible size for a Cat bond is estimated to be about $100 million.

Market instruments typically do not provide full insurance coverage for macro risks. The standard contract or Cat bond, including those used by FONDEN and CCRIF, applies a "parametric" trigger—the insurance payment is triggered by the occurrence of a natural event of a certain magnitude, rather than by a calculation of the losses suffered. The trigger can be a particular wind speed or a certain intensity and/or depth of an earthquake measured at a specified location. The parametric trigger simplifies enormously the monitoring and execution of the insurance contract and permits immediate payment upon the occurrence of the covered disaster.[1] The event can be monitored by a third party, such as the U.S. National Hurricane Center.

Parametric insurance, however, can leave a fair amount of residual risk uncovered ("basis risk" in insurance language). A natural phenomenon may cause considerable damage without crossing the parametric boundary. Indeed, Hurricane Dean, which caused significant damage in Belize and Jamaica in August 2007, did not trigger any payments under the CCRIF because winds did not reach the required speeds at the specified locations. As with any other insurance structure, there is a trade-off between cost and coverage in parametric insurance. Basis risk can be reduced but only at a higher cost, and the insured must choose their preferred trade-off between risk and cost.

Pricing in the Cat market has been punctuated by the impact of large disasters—particularly U.S. hurricanes Andrew in 1993 and Katrina in 2005 (second figure). There has also been an upward trend in insurance premiums, in part related to upward reassessments of disaster risk. The reason for the premium spikes is that, after a large disaster, reinsurance companies need to rebuild capital in order to preserve their solvency and credit ratings. This may be a long process if capital markets are not fluid, and in the meantime insurance premiums remain elevated. Yet the figure also suggests that the post-Katrina rise, although broadly commensurate with the post-Andrew increase, was fairly short lived. The reversal of the premium increase took place despite both a tightening of standards by credit rating agencies and an upward reassessment of disaster risk by weather modeling firms and market participants. Part of the reason for the quick reversal was the rapid entry of new investors such as hedge funds, banks, and private equity investors, who supplied additional capital through various market structures. In addition to Cat bonds, new market instruments include bank loans and equity, especially in the form of "sidecars"—legally

Detrended Catastrophe Insurance Premiums
(Index, 1985 = 100)



Source: IMF staff calculations based on Lane Financial, LLC.

[1]A more common feature of standard reinsurance contracts is an "indemnity" trigger—namely, the damage suffered by the insured. There are also intermediate options such as modeled losses and indices based on a parametric occurrence.

Box 4.4 *(concluded)*

separate, special-purpose reinsurance companies that raise short-term capital through private equity and debt.

An Unexploited Opportunity?

Low-income and small countries are especially vulnerable to natural disasters because of more limited geographical diversification, higher percentages of the population living in exposed areas, and higher dependence on natural rainfall and benign weather conditions for agricultural production. According to the World Health Organization's Emergency Events Database, two hurricanes that hit Belize in 2000 and 2001 each caused damage equivalent to more than 30 percent of GDP and impaired public debt sustainability (Borensztein, Cavallo, and Valenzuela, 2008).[2] Even less-extreme events can involve enormous indirect costs. Drought has been linked to higher incidence of armed conflict in low-income countries, essentially through its effect on economic growth and poverty (Miguel, Satyanath, and Sergenti, 2004).

Faced with such catastrophic risk, low-income countries tend to rely on foreign aid or some form of self-insurance (Borensztein, Cavallo, and Valenzuela, 2008). Aid flows, however, are unreliable, may arrive late, and seem somewhat dependent on the extent to which the media covers the disaster. Self-insurance strategies include borrowing when a disaster occurs or accumulating resources in a dedicated fund. But there is a critical difference between insurance and self-insurance. If a country purchases insurance (say by issuing a Cat bond), it will receive ensured payment in a disaster that offsets the loss suffered, albeit imperfectly. By resorting to borrowing, by contrast, the country can spread over time the cost of the disaster but still bears the full economic loss. Moreover, self-insurance strategies may have other problems. For example, self-insurance funds may be appropriated for other uses when they become sizable. There is, in fact, an optimal combination of insurance and borrowing (or self-insurance), which depends on many factors, including the size of the potential loss, the cost of insurance, interest rates, ease of access to external financing, and the extent to which credit rating agencies incorporate market insurance coverage in their evaluation.

Despite their advantages, few countries have issued Cat bonds or sought disaster insurance. One reason may be cost. Cat premiums can be high owing to various factors, including the required technical studies by modeling agencies, legal costs, and remuneration of the capital requirements for insurance and reinsurance companies under imperfect market conditions (see Froot, 2001). (To some extent, however, the cost of insurance for emerging and developing economies is tempered by the diversification value of these perils within the global financial market.) Another reason may be policymakers' fears of engaging in unusual and complex operations, which they may not fully understand. Politicians also tend to focus on the near term and hence are not motivated to spend money on insurance that may mainly benefit their successors in office.

Catastrophe insurance instruments also can be useful for international financial institutions that seek to provide broad support for such insurance programs, as in the case of CCRIF. The World Bank has other projects under way to provide insurance to farmers in various countries, including India and Mongolia, and it is hedging these risks in global markets. Disaster insurance is a means for aid agencies to deal with the budget limitations that can arise in years when they must respond to several large disasters. In this regard, the United Nations' World Food Program (WFP), in collaboration with the World Bank, ran a pilot program for drought insurance in Ethiopia in 2006, which offered coverage to farmers who could be affected by insufficient rainfall. The WFP laid off the risk in the global reinsurance market. In the event, no payments were triggered because rains were adequate in all the covered areas.

[2]Cost estimates should be viewed with appropriate caution and are subject to significant revisions.

holds the promise that they have considerable potential to promote adaptation to climate change. The growth of hedge funds and the strong appetite for risks that are uncorrelated with other financial markets should ensure continuing demand for financial instruments that pay investors a premium for taking weather risk even in the face of climate change (van Lennep and others, 2004; and Bonaccolta, 2007).

All in all, countries' adaptive capacity is likely to increase in the future, as incomes rise, technologies emerge, financial markets develop, and understanding of climate change improves. Nonetheless, at high degrees of warming, the limitations of adaptation are likely to be reached relatively quickly. Together with the rising probability of catastrophic risk, this points to a need for mitigation.

How Can Countries Effectively and Efficiently Mitigate Climate Change?

A successful policy framework for mitigating climate change must satisfy several criteria.

- To be effective, mitigation policy must raise the prices of GHGs to reflect the marginal social damage from emissions. Higher GHG prices would help generate incentives for reducing production and consumption of emission-intensive goods and for development and adoption of new, low-emission technologies.
- Mitigation policy must be applied across all GHGs, firms, countries, sectors, and time periods in order to ensure that policy achieves the desired objectives at the lowest possible cost.
- It is important to address distributional considerations across firms, income groups, and generations, both for reasons of fairness and distributional justice as well as to ensure that policies remain politically viable.
- Mitigation policies must be flexible and robust to changing economic conditions and to new scientific information about climate change, because highly volatile outcomes could increase the economic costs of policies and reduce political support.
- Mitigation policies must be enforceable and have "dynamic consistency," meaning that governments have incentives to keep them in place, in order to induce the needed behavioral response.

Many policy instruments have been considered for reducing emissions. The most prominent have been emission taxes, tradable emission permits, performance standards, incentives for the adoption of energy-saving technologies, and subsidies for the reduction of emissions or introduction of clean technologies (Box 4.5).[19] Market-based policies, such as emission taxes (often called carbon taxes[20]) and permit-trading programs, have an important advantage over performance standards in that they create a common price for emissions. Common pricing encourages emissions to be concentrated in firms that can produce more efficiently.

The choice between carbon taxes and cap-and-trade systems is less clear cut. Carbon taxes have an important advantage over cap-and-trade systems in that they result in a stable price for emissions (cap-and-trade policies seek to stabilize the quantity of emissions, but allow prices to fluctuate). Stable prices for emissions are critical for firms making long-term decisions about investment and innovation in low-emission technologies. Carbon taxes also provide for greater flexibility in the face of changing economic conditions, allowing firms to reduce emissions more during periods of slow demand growth and less during periods of high demand growth, when the cost of doing so would be higher. In contrast, cap-and-trade systems could give rise to volatile emission pricing when demand conditions change. Carbon taxes also generate revenues that can be used to enhance efficiency

[19]Performance standards include, for example, limits on emissions per kilowatt hour of electricity and fuel-economy requirements on vehicles.

[20]Taxing the carbon content of emissions is equivalent to taxing carbon dioxide. Carbon dioxide accounts for the largest share of emissions. Emissions of other GHGs (methane, nitrous oxide, and fluorinated gases) are often expressed in terms of their carbon dioxide equivalents.

Box 4.5. Recent Emission-Reduction Policy Initiatives

Under Annex I of the Kyoto Protocol, signatory countries[1] agree to reduce their greenhouse gas (GHG) emissions by 8 percent relative to 1990 levels by 2008–12. This is the principal international policy framework providing incentives to mitigate the impact of global warming. The main implementation mechanism for the Kyoto Protocol in Europe is the European Union Emissions Trading Scheme (EU-ETS). Two additional compliance vehicles, the Clean Development Mechanism (CDM) and Joint Implementation, enable Annex I countries to gain credits for emission reductions arising from investments made in countries not subject to binding targets.

The EU-ETS is an international cap-and-trade system, projected to reduce emissions by 2.4 percent compared to a business-as-usual scenario by 2010,[2] although it needs further reform in order to realize its full potential for large-scale, efficient mitigation. During Phases I (2005–07) and II (2008–12), carbon dioxide (CO_2) emission rights were allocated to about 11,000 energy-intensive installations across the European Union (mostly electric power utilities and major industrial emitters), representing about 40 percent of total EU carbon emissions. The volume of trading in the market was about 1.6 billion tons of CO_2 in 2007 and was valued at about €28 billion (up 55 percent over 2006 values).[3] Intended to minimize abatement costs for a given emission target, the system is subject to a number of design flaws, which have reduced its effectiveness. First, excess quotas and market uncertainty have caused permit prices to be too low and volatile. In fact, prices fell to zero in the second half of 2007 (although prices are generally higher under Phase II). Second, the high share of free allocations (at least 95 percent in Phase I and 90 percent in Phase II) led to windfall profits and forgone public revenues and reduced abatement incentives by creating expectations of future free allocations based on current emissions.[4] These problems were exacerbated by rules under which exiting firms lose their free allocations while new firms typically receive free allocations.[5] Third, the carbon price is poorly coordinated with policies, taxes, and regulations implemented in markets outside the scope of the scheme, such as heating and transportation. Efforts to limit the extent of some of these (and other) problems are under way, for example, by expanding the system to include new industries (including, for example, aviation within the European Union) and new gases; preannouncing future constraints (starting with an 11 percent reduction in Phase III against the previous commitment framework); moving to full auctioning of permits (starting with at least 60 percent in 2013); and harmonizing the rules for cap-setting and entry and exit.

The CDM enables Annex I countries to gain credits for investment in less-carbon-intensive technologies in developing and emerging market economies (currently not subject to mitigation targets), facilitating access to lower-cost abatement opportunities and helping to promote development by adding to the capital stock in these economies. The CDM market has grown rapidly in recent years, with primary markets estimated at 950 million tons of CO_2 and valued at approximately €12 billion in 2007 (up almost 200 percent over 2006 values). Several issues, however, warrant attention. First, the capacity to monitor and verify the "additionality" of emission reductions, formally a condition for CDM project approval, is often unclear. Although emissions may be reduced through a

Note: The main authors of this box are Ben Jones and Jon Strand, with input from Paul Mills.

[1]A group of industrialized nations including eastern Europe, the OECD, Russia, and the United States (although the latter did not ratify the treaty).

[2]See Capoor and Ambrosi (2007).

[3]See Point Carbon Research (2008).

[4]See Böhringer and Lange (2005) and Rosendahl (2006) for discussion. Rosendahl points out that when future quotas are updated to reflect current emissions, the quota price could be several times the level of marginal emission abatement cost, indicating that very little abatement is taking place.

[5]See, for example, Åhman and Holmgren (2006); and Åhman, Burtraw, Kruger, and Zetterberg (2007).

particular CDM project, it is difficult to quantify overall emission reductions in economies that are not subject to overarching emission constraints or policies (such counterfactuals are in some sense impossible to ascertain, even given elaborate case-by-case administrative procedures). Second, given the high degree of policy risk after 2012, virtually no abatement has been achieved for projects subject to long investment-return periods, such as in energy supply markets—most investment has targeted emission reductions from industrial processes. Third, forgone deforestation has so far been left out of the CDM, and its inclusion will require overcoming complex administrative and governance problems, especially in relation to establishing a baseline, monitoring and enforcing compliance, and managing "leakage" risks. Finally, few CDM projects have yet been carried out in the poorest countries (with Brazil, China, and India so far dominating), which raises distributional concerns.

In addition, many countries, including nonsignatories to the Kyoto Protocol (such as the United States) and major developing economies that are not subject to binding targets under the agreement, have implemented domestic policies that reduce emissions. (The table summarizes these policies for a selected group of countries.) These policies are typically motivated less by climate change concerns than by other considerations, for example, productivity improvements, energy security, and the abatement of local pollution. However, other domestic policies, such as energy subsidies, may have opposing effects, leading to strong overall growth in emissions, particularly from expansion of fossil-fuel-based energy supply in developing economies. Although domestic efforts are welcome—indeed essential—thus far they have provided weak and often poorly coordinated incentives and have also lacked transparency. These factors have impeded effective and efficient international coordination of mitigation efforts. Two primary types of such domestic emission-reduction policies are performance standards and technology subsidies.

Performance standards, though often less attractive than market mechanisms, have resulted in substantial emission reductions in markets for vehicles, buildings, and appliances, for which emissions are diffuse, transaction costs from compliance with market incentives are high, and the credibility of carbon markets is still being established. In road transport, Japan's Top Runner program (see table) has yielded significant energy savings, estimated at 15 percent during 1995–2005 in the case of diesel passenger vehicles (Energy Conservation Centre Japan, 2005). In the United States, Corporate Average Fuel Economy (CAFE) standards, while less demanding than European or Japanese standards, have improved vehicle efficiency since their introduction in 1975. However, laxer restrictions on sport-utility vehicles and small trucks have constrained their overall effectiveness when consumer preferences shifted toward heavier vehicle classes. Regulatory codes applied to buildings, for example in California, are estimated to have saved approximately 10,000 gigawatt hours (GWh) of electricity annually, about 4 percent of total electricity use in 2003 (California Energy Commission, 2005). More stringent commitments to improve the energy efficiency of U.S. federal buildings were announced in December 2007. U.S. standards on appliances are projected to reduce annual residential emissions by about 37 metric tons of CO_2 ($MtCO_2$) by 2020, roughly 9 percent of household emissions (Meyers and others, 2002).

Technology subsidies (including tax incentives) have been widely used to support renewable electricity and biofuel production, but they are not a cost-effective substitute for proper carbon pricing. Even so, they may be an appropriate response to failures in technology markets. Support typically aims to reduce the cost of research and development and capital investment, or to guarantee higher end-user prices. In Germany, for example, a renewable electricity "feed-in" tariff system is expected to impose additional costs of €30 billion–€36 billion on consumers between 2000 and 2012 at a cost of approximately €0.10 a kilowatt hour

Box 4.5 *(concluded)*

Domestic Policy Measures Affecting Emissions

China	Domestic targets to reduce the energy intensity of GDP by 20 percent during 2005–10 and expand renewable energy generation to 30 percent of total capacity by 2020 • Reduced indirect taxation on renewable electricity generation and favorable customs duty rates on imported components • Central and local government research and development support, for example, \$28 million expenditure on development of renewables under 10th Five-Year Plan • Various investment subsidies, for example, in renewable village power systems as part of large-scale rural electrification programs • Energy-efficiency standards on vehicles, energy-using products, and some new urban buildings; residential appliances, for example, estimated to conserve about 9 percent of China's residential electricity in 2010[1] • Restructuring of (and closure of the most energy-inefficient) state-owned enterprises
European Union	Kyoto Protocol commitment to reduce emissions by 8 percent against 1990 levels by 2008–12; EU voluntary target of 20 percent below 1990 levels by 2020 • The EU Emissions Trading Scheme (EU-ETS), covering power generation and heavy industry, is projected to reduce emissions by an additional 2.4 percent compared with business as usual in 2010[2] • Extensive taxation of gasoline and diesel, particularly high in the United Kingdom • Support for climate research and technologies amounting to \$3 billion, and a further \$1.8 billion on nuclear research, under Framework Program 6, 2002–06[3] • Renewables obligations and "feed in" tariffs for diffusion of clean technologies • Regulation of buildings, appliances, and vehicles (for example, the Energy Performance of Buildings Directive) and proposed mandatory regulation of passenger vehicles[4]
India	Domestic targets, including a 20 percent increase in energy efficiency by 2016–17; expanded electricity supply to all villages by 2009; and 5 percent increase in tree and forest cover[5] • Planned subsidies for renewable energy sources, particularly in remote rural areas, totaling \$174 million during 2007–12[6] • \$38 million investment in research, design, and development in new and renewable energy • Increased forest cover through regulation, incentives, and information on improved forest management[7] • Building codes for large new commercial buildings and government buildings, designed to reduce energy consumption by 20–40 percent[8]
Japan	Kyoto Protocol commitment to reduce emissions by 6 percent from 1990 levels by 2008–12; national objective to reduce energy intensity by 30 percent from 2003 to 2030 • Taxes on gasoline (¥46,800/kiloliter), kerosene (aviation fuel) (¥26,000/kiloliter), coal (¥700/ton), and electricity (¥375/kilowatt-hour sold)[9] • Top Runner Program of performance standards on more than 20 classes of products (including vehicles and appliances), expected to realize savings of 16–25 percent of total national savings by 2010[10] • Supplier obligation to produce 8.7 terawatt hours (tWh) of renewable electricity in 2007, rising to 16 billion tWh by 2014[11] • Voluntary agreements with industry stakeholders covering 39 industries to subsidize one-third of greenhouse gas (GHG) reduction expenditure if targets are met
United States	Voluntary objective to reduce GHG intensity level to 18 percent below 2002 levels by 2012 • Tax incentives totaling \$3.6 billion over 2006–11 for use on cleaner, renewable energy and more energy-efficient technology • Support for research and development, domestic and international climate-related programs (for example, "Methane to Markets" and Asia Pacific Partnership) of \$37 billion during 2001–07 • Efficiency standards for buildings, vehicles, and appliances. ENERGY STAR performance labeling program covering 1,400 products, and extended through partnerships with six international markets

(International Energy Agency, 2007b). In the United States, repeal of excise taxes for biofuels implies a subsidy of approximately \$12 billion during 2007–11 (Metcalf, 2007). Analysis of the returns for various renewable energy subsidies in G7 countries indicates that costs are generally much higher than most current estimates of marginal damage costs related to CO_2 emissions (see, for example, Strand, 2007). This suggests that direct public support for increased renewable energy production is currently an expensive way to mitigate carbon emissions compared with an efficient carbon-pricing regime, although returns may be higher if future cost reductions from induced learning-by-doing are considered.

Domestic Policy Measures Affecting Emissions *(concluded)*

Brazil	National objective to increase the share of renewable energy sources to 10 percent by 2030 and expand availability of electricity to an additional 12 million citizens • Roughly 50 percent reduction in deforestation between 2004 and 2006 through improved satellite monitoring, land use controls, and sustainable logging incentives • Mandatory 22 percent blend of ethanol in gasoline and 2 percent mix of biosourced diesel (rising to 5 percent in 2013) • Subsidized lines of credit for biodiesel production; support for research into biodiesel and expansion of ethanol and sugar program to other products • 20-year feed-in tariffs for renewable electricity generators;[12] supplier obligation to invest 1 percent of net operational income in efficiency measures and research and development • Adoption of U.S. efficiency standards for light vehicles and EU standards for motorcycles and heavy vehicles • Investment in decentralized, renewable electricity as part of "Light for All" electrification program

[1]China Markets Group, Lawrence Berkeley Laboratories: http://china.lbl.gov/china_buildings-asl-standards.html.
[2]See Capoor and Ambrosi (2007).
[3]EU action against climate change: research and development to stimulate climate-friendly technologies.
[4]The Energy Performance of Buildings Directive is designed to realize an estimated cost-effective savings potential of about 22 percent of present consumption in buildings across the European Union by 2010. The European Commission is proposing to reduce the average emissions of CO_2 from new passenger cars in the European Union from about 160 grams a kilometer to 130 grams a kilometer in 2012.
[5]India, Planning Commission (2007).
[6]India, Ministry of New and Renewable Energy (2006).
[7]India, Ministry of Environment and Forests (2006), p. 25.
[8]India, Ministry of Environment and Forests and Ministry of Power Bureau of Energy Efficiency (2007), p. 7.
[9]Japan (2006).
[10]Nordqvist (2006), p. 6.
[11]"Outline of the Renewable Portfolio Standard (RPS) System." www.rps.go.jp/RPS/new-contents/english/outline.html.
[12]Brazil (2007), pp. 22, 27.

(by lowering other taxes) or equity (by compensating groups disadvantaged by the policy). However, under carbon taxes, the quantity of emission reductions is uncertain. Taxes also may be politically difficult to implement.

There are ways to reduce the disadvantages of cap-and-trade systems. Price volatility, for example, can be reduced by introducing safety valves that allow governments to sell some temporary permits if permit prices exceed some prespecified "trigger" levels, by allowing the depositing and borrowing of permits, or by creating a central-bank-type institution for overseeing permit markets. Such hybrid policies—combining elements of a carbon tax and a permit-trading system—could be superior to the respective single policy instruments (Pizer, 2002). Raising the trigger price of the safety valve over time would allow for the simultaneous targeting of emission prices, over the short run, and their quantity, over the long run.[21] See Box 4.6 for a further discussion of these and other issues that arise in the context of mitigation policies.[22]

Macroeconomic Effects of International Mitigation Policies

The importance of cross-border linkages is assessed by examining the macroeconomic effects of alternative mitigation policies using a dynamic intertemporal global general equilibrium model (the 2007 version of G-Cubed, developed by McKibbin and Wilcoxen, 1998). G-Cubed is well suited for evaluating the short-, medium-, and long-term effects of mitigation

[21]See Aldy and Stavins (2007) for a discussion of alternative mitigation policy proposals, including hybrid schemes proposed by Kopp, Morgenstern, and Pizer (1997) and McKibbin and Wilcoxen (1997, 2002b, 2002c).
[22]See also the October 2007 *World Economic Outlook*.

Box 4.6. Complexities in Designing Domestic Mitigation Policies

This box highlights some broader issues in the design of domestic emission-mitigation policies, beyond the basic choice between an emission tax and a cap-and-trade system (see Kopp and Pizer, 2007, for an in-depth discussion of design issues).

Building Flexibility into Emission-Control Policies

A major concern with rigid annual emission caps is the risk of volatility in emission prices that might be caused, for example, by changes in demand conditions or disruptions in energy markets. Severe volatility in allowance prices may deter investments in emission-saving technologies that have large upfront costs and could undermine political support for a cap-and-trade system. However, there are ways to partly address this problem.

One option is to include a safety-valve mechanism, under which permit prices are prevented from exceeding a certain ceiling price, with the regulator authorized to sell whatever additional allowances must be introduced into the market to prevent prices rising beyond this level (Pizer, 2002). Another option is to allow firms to borrow permits from the government during periods of high permit prices and to deposit such permits when there is downward price pressure, to help smooth out sharp price fluctuations. The European Union Emissions Trading Scheme (EU-ETS) now allows for permit banking (though not borrowing). A further option is government oversight of carbon markets through a new body, much like a central bank, which would intervene to sell or buy permits in response to unexpectedly high or low permit prices. Again, this type of oversight could help to stabilize the permit market while also providing greater confidence in the achievement of longer-run emission goals.

Yet some flexibility in permit prices actually may be beneficial, as this enables future knowledge about the likely impact of global warming to be reflected in real-time permit prices and abatement decisions. For example, when deciding whether there is a need for intervention, a "climate central bank" could take into account the factors driving changes in emission prices and allow permanent shocks to be reflected in prices. Even without the climate central bank, under a cap-and-trade regime that allowed depositing and borrowing of permits, if new evidence emerges that warming is occurring faster than projected, speculators would anticipate a tightening of the future emission cap, which would instantly shift up the trajectory of current and expected future permit prices (before any adjustment to the cap). In contrast, it may take some time to enact a legislative change in emission tax rates to reflect new scientific information, leaving emission control suboptimal during the period of policy stickiness.

Using Revenues to Keep Policy Costs Down

How the government uses the revenues from carbon taxes or cap-and-trade systems, to the extent that allowances are auctioned, can have a substantial effect on the overall costs of the policy. For example, if revenues are used to lower personal income taxes, this reduces the disincentive effects of these broader taxes on work effort and savings, offsetting the negative effect of higher energy prices on economic activity. Policies that do not exploit the revenue-recycling benefit are more costly, namely, cap-and-trade systems with free allowance allocation or emission taxes and cap-and-trade policies with auctioned allowances, where revenues are not used productively. For example, Parry, Williams, and Goulder (1999) estimate that the overall costs of moderately scaled emission permit systems with free allocation are more than double those for the equivalent, revenue-neutral carbon tax for the United States.

Compensating Low-Income Households and Energy-Intensive Firms

Fairness is a major issue for emission-mitigation policies because low-income households spend a relatively high share of their budgets on energy-intensive goods such as electricity, home

Note: The main author of this box is Ian Parry.

heating fuels, and gasoline, and are therefore more vulnerable to increases in the price of these goods. Cap-and-trade systems with free permit allocation provide no mechanism for addressing these concerns. But if allowances are auctioned, or emission taxes are implemented, fairness concerns may be addressed by recycling some of the revenue in ways that particularly benefit low-income households, such as reductions in payroll taxes or increases in income tax thresholds (Metcalf, 2007; and Dinan and Rogers, 2002). Some elderly or other nonworking households may require compensation through other means, such as targeted energy-assistance programs.

On the other hand, free allowance allocations can provide compensation for (politically influential) industries adversely affected by climate policy, which helps to reduce opposition from vested interests. However, according to Bovenberg and Goulder (2001), only a small fraction of allowances must be given away for free to provide such compensation, and so most allowances could still be auctioned. Ideally, any compensation would be progressively phased out over time. This would avoid practical difficulties in updating free allowance allocations as firms grow at different rates over time and would increase the potential fiscal dividend. In fact, after power companies reaped large windfall profits from the allowance giveaway in the initial phase of the EU-ETS, the plan is now to transition to 100 percent allowance auctions by 2020. Transitory compensation for affected industries also could be provided under an emission tax, for example, by applying the tax only to emissions in excess of some threshold level or by providing temporary corporate tax relief for energy-intensive firms downstream of the formal emission tax regime.

Advantages of an Upstream Program

Ideally, a carbon tax or emission trading system would be applied upstream in the fossil fuel supply chain (on petroleum refiners, coal producers, etc.), because this would encompass all possible sources of emissions when fuels are later combusted. Fuel producers would pay a tax, or be required to hold permits, in proportion to a fuel's carbon content, and therefore emission taxes or permit prices would be passed forward into fossil fuel prices and ultimately into the price of electricity and other energy-intensive products. This would provide incentives for emission-reducing behavior throughout the economy. Downstream trading programs, like the EU-ETS, currently cover electricity and large industrial emitters, which account for only about one-half of total CO_2 emissions (Kopp and Pizer, 2007). Therefore, they preclude many low-cost abatement opportunities, for example in the transportation sector. Upstream programs are also easier to administer. In the European Union or the United States, they would involve regulation of only about 2,000–3,000 entities, compared with 12,000 entities or more in a downstream program.

Incorporating All Sources of GHGs and Options for Sequestration

Insofar as possible, it is important to include non-CO_2 greenhouse gases (GHGs) into any emission-mitigation program. In the United States these gases currently account for about 20 percent of total GHGs when gases are expressed on an equivalent basis for warming potential over their atmospheric lifespan, whereas at the global level these gases account for about one-third of total GHGs (US CCSP, 2007). Some of these gases (such as vented methane from underground coal mines and fluorinated gases used as refrigerants and in air conditioners) are fairly straightforward to monitor and incorporate through permit-trading ratios or emission taxes, reflecting their relative global warming potential. Methane and nitrous oxides from landfills, manure management, and soil management might be incorporated into an emission-offset program. In that case, the onus would be on the individual entity to demonstrate valid emission reductions for crediting. However the remaining emission sources, which account for about a third of non-CO_2 GHGs in the United States, are especially

Box 4.6 *(concluded)*

difficult to monitor (for example, methane from ruminants).

Although still in the developmental stage, a potentially important means of reducing emissions from coal plants could be emission capture and storage underground (for example, in depleted oil reservoirs). Incentives for adopting this sequestration technology could be provided through emission offsets or tax credit provisions, although, according to Deutsch and Moniz (2007), the price of carbon would need to be higher than about $25 a ton to make the technology commercially viable. At least for the short term, facilities should be charged for any emission seepage from the underground sink. Because the incorporation and operation of carbon-capture technologies would be fairly easy to verify, emission sources in advanced economies might fund such investments in emerging economies to offset some of their own mitigation obligations.

Biological sequestration could also be a potentially cost-effective way to reduce emissions (Stavins and Richards, 2005). Ideally, farms that increased forestland coverage would be credited, and those that shifted from forests to agriculture would be penalized. For the United States, it would be feasible to incorporate forestry into a national emission-mitigation program, given that transitions between forest and agricultural land in the absence of any carbon policy are relatively small (Sedjo and Toman, 2001). Land use changes might be monitored through remote sensing from satellites or aircraft, with the carbon implications then assessed based on tree species, age in the growth cycle, and so on. Incorporating incentives for reduced deforestation in tropical regions into an international emission-offset program is more challenging, because there would need to be agreement on country baselines indicating forest coverage in the absence of policy. Moreover, major timber-producing regions would need to be covered by the program to lower the risk that reduced harvesting in one area was offset by additional harvesting elsewhere.

Difficulties in Preventing Emission Leakage

Some studies suggest that emission leakage, caused by footloose firms relocating to countries without carbon policies, may be significant, perhaps offsetting about 10 percent or more of the potential effects of abatement policies in developed countries (Gupta and others, 2007). However leakage is difficult to project in practice, as it depends on many factors (including, for example, how strictly abatement policies are enforced, whether potentially footloose firms receive any compensation for forgoing such opportunities, exchange rate risks, and political stability in countries without climate policies).

Preventing this international emission leakage is very tricky. Foreign suppliers from countries without climate policies might be required to pay fines, or purchase domestic permits, to cover the embodied carbon in products they sell domestically. Administratively, however, this would be very complex and contentious and may run afoul of international free-trade obligations. In the EU-ETS, firms are presently deterred from relocating outside the region through confiscation of their (free) allowance allocations. Conversely, so as not to deter new incoming investment, entering firms are granted free emission allowances. But these provisions also have perverse effects (Ellerman and Buchner, 2007). Allowance confiscation retards the exit of inefficient facilities, whereas new firm entry is excessive, given that firms do not pay for their new emission sources.

Complementing Mitigation Policies with Technology Incentives

There is general agreement that, in principle, carbon-abatement policies should be complemented with additional incentives to promote basic and applied clean technology research and development (R&D) at governmental and private institutions. Additional policies are justified on grounds of economic efficiency because of a second source of market failure (in addition to the carbon emission externality), which arises from the inability of innovators to fully appropriate the benefits to other firms of their new knowledge. However, available literature provides limited guidance on how R&D policies might be designed and implemented to complement emission-control policies. For example, it is unclear which is more efficient: subsidies for private R&D, strengthened patent rules, or technology prizes (Wright, 1983). It is also very difficult to project in advance how effective a given package of emission controls and technology incentives will be in bringing forth (as yet undeveloped) emission-saving technologies.

Finally, some analysts argue that, even after the successful development of new technologies or cleaner fuels, further incentives are needed to encourage their diffusion, such as vehicle fuel-economy regulations, energy-efficiency standards for household appliances, or clean fuel subsidies. Such policies would be warranted if there were additional market failures, such as an undervaluation by consumers of energy-efficiency improvements. However, there is little solid empirical evidence either way on the existence and magnitude of such market failures.

policies across countries. Detailed modeling of regions helps account for differences in countries' initial income levels and potential growth rates. Disaggregated production structures summarize the input-output relationships and sectoral cost structures. Forward-looking expectations underscore the importance of policy credibility for inducing changes in behavior.[23] Careful modeling of relative prices helps track the potential implications of rising energy costs for expenditure switching, factor substitution, terms of trade, and balance of payments adjustment. The latter reflects not only trade flows, but also international capital flows—a feature that has so far received little attention in most models used for climate policy analysis.

G-Cubed simulations are intended to illustrate the economic mechanisms at work following the introduction of mitigation policies and should not be taken as long-term macroeconomic forecasts or recommendations on specific emission targets or policies. G-Cubed focuses on modeling energy-related CO_2 emissions, which constitute the largest and the fastest-growing type of GHG emissions. The baseline used in this study broadly matches the stylized facts of the International Energy Agency's latest *World Energy Outlook* (IEA, 2007a). In particular, it assumes stronger growth in the demand for energy from emerging economies than most other studies do. For more details on G-Cubed and how it compares to other models used to analyze mitigation policies, see Appendix 4.1.

The eventual benefits of mitigation policies targeted to reducing emissions are not modeled in G-Cubed, but this is not a major drawback. That is because the focus is on the costs of mitigation policies during the three decades following their introduction, a period during which the benefits of mitigation policies are expected to be small.

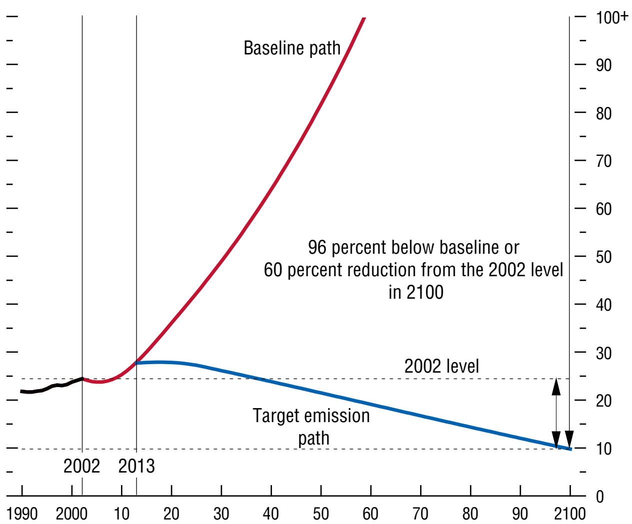
Simulation results in G-Cubed are largely driven by assumptions about countries' technologies, particularly their ability to substitute away from emission-intensive inputs. The shift to low-emission technologies is modeled through two channels—exogenous improvements in energy efficiency and endogenous substitution from carbon-intensive inputs such as fossil fuels into other raw materials, intermediate goods, capital, and labor, in response to changes in carbon prices. These technological changes can be interpreted as a shift to alternative sources of energy, such as biofuels, nuclear power, and renewables, and the introduction of carbon capture and storage technologies. Technology is assumed to be freely transferable across countries—if firms

[23]To be precise, expectations in G-Cubed are partially forward looking, because some households and firms are assumed to be myopic and to have recursive expectations. For more details, see Appendix 4.1.

Figure 4.9. Global Emission Targets and Paths, 1990–2100

(Gigatons of carbon dioxide)

The baseline path shows the projected level of global energy-based emissions under the assumption of a no-mitigation policy. The target emission path shows the level of global emissions from fossil fuels achieved in the policy simulation results, reaching a level that is 60 percent below the level of global emissions in 2002. The target level in 2100 is 96 percent below the projected level of the baseline in 2100.



Source: IMF staff estimates.

decide to move away from using fossil fuels and rely more on clean technologies, then they can obtain funding and know-how for such investment without any constraints, although they will face some adjustment costs. Country-specific results in G-Cubed depend to a large extent on assumptions about elasticities of substitution in production, consumption, and trade, which jointly determine the incremental costs at which individual economies can reduce their emissions (see Appendix 4.1).

The modeling exercise starts with an examination of the macroeconomic effects of a global mitigation policy that requires countries to agree on a common carbon price. Such a policy could be implemented through either a uniform global carbon tax or a hybrid policy under which countries commit to a common safety valve (with the price of additional permits tied to the rate of the carbon tax).[24] The effects of these policies are then compared to those of a global policy that requires countries to agree on an initial allocation of emission rights and international trade of these rights—a cap-and-trade system. Next, the study assesses the importance of international allocation rules for the magnitude and direction of international transfers and hence the compatibility of various incentives under a cap-and-trade system. In addition to these main policy experiments, the model is used to explore implications of policy coordination, country participation, technological improvements, and the robustness of mitigation policies to macroeconomic shocks. (Some caveats to the analysis are discussed hereafter.)

Global Carbon Tax and a Hybrid Policy

In this policy experiment, all economies introduce a common carbon price in 2013 and credibly commit to keeping it in place over

[24]The hybrid model considered in this chapter is the one proposed by McKibbin and Wilcoxen (1997, 2002c) with an initial allocation of long-term permits and then an annual issuance of permits to target a carbon price equivalent to the tax rate.

the long run, adjusting the rate as necessary to achieve the profile of global emissions depicted in Figure 4.9. Global emissions are assumed to follow a mildly hump-shaped path, peaking around 2018 and then gradually declining to 40 percent of the 2002 levels by 2100 (that is, a 60 percent reduction from the 2002 levels or a 96 percent reduction from the business-as-usual baseline that assumes no policy change).[25] The carbon price rises gradually over time, reaching $86 a ton by 2040 (an average annual rate of about $3 per ton of carbon).[26] This corresponds to a $0.21 increase in the price of a gallon of gasoline by 2040 and a $58 increase in the price of a short ton of bituminous coal. The price is imposed upstream in the fuel production chain, with revenues from carbon pricing used to fund government consumption and investment, and with the budget deficit and debt held constant (Appendix 4.1). Other energy pricing policies are assumed to remain intact.

The macroeconomic effects of the carbon tax and the hybrid system with a safety valve are equivalent in this experiment and are depicted in Figure 4.10. (Note, however, that carbon taxes and hybrid policies generally are not equiva-

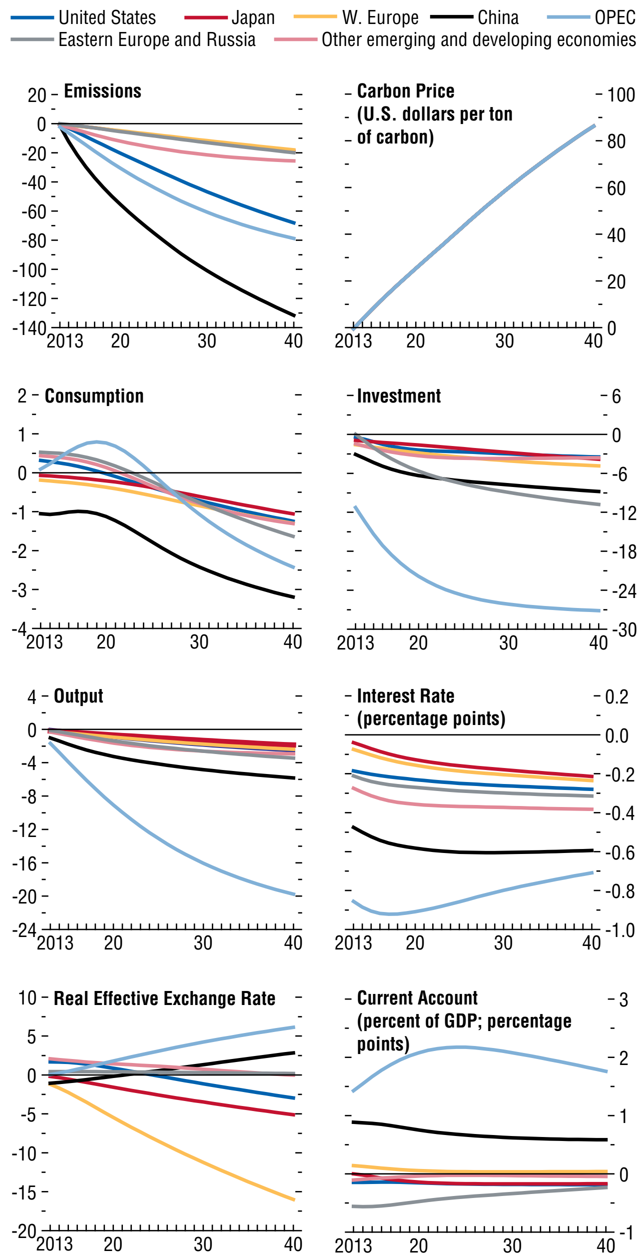
[25]The profile broadly matches the characteristics of the profiles shown as "Category III" in the Fourth Assessment Report of Working Group III of the IPCC (2007): peaking during 2010–30, and stabilizing CO_2–equivalent concentrations in the range of 535–590 parts per million (ppm) by volume by 2100. The scenario corresponds to a temperature increase of approximately 2.8°C –3.2°C by 2100.

[26]By 2100, carbon prices are projected to rise to $168 a ton of carbon. These estimates are lower, for comparable experiments, than those obtained by Nordhaus (2007a) and US CCSP (2007), where carbon prices range from $300 to $6,000 in 2100. The difference stems mainly from the assumption of free capital flows in G-Cubed and a more flexible technological structure, both of which facilitate an efficient adaptation by firms and individuals to higher carbon prices. Further, G-Cubed models only CO_2 emissions from fossil fuels, which implies that smaller increases in carbon prices are needed to achieve a given reduction in emissions than in multigas models where emission reductions are specified in CO_2-equivalent terms. Comparisons with US CCSP (2007) are also complicated by the fact that the studies covered by that exercise targeted radiative forcings, not concentrations of CO_2-equivalent emissions.

Figure 4.10. Uniform Carbon Tax, 2013–40[1]

(Deviation from the baseline; percent unless otherwise stated)

Each region is assumed to introduce a carbon tax in 2013. The tax rate is common across regions and is calibrated to achieve a 60 percent reduction relative to the 2002 level in world (energy-based) carbon dioxide emissions by 2100. This corresponds to a 96 percent reduction in global emissions relative to the baseline at 2100. The emission profile is mildly hump shaped, allowing for some increases in the medium term, peaking in 2018.

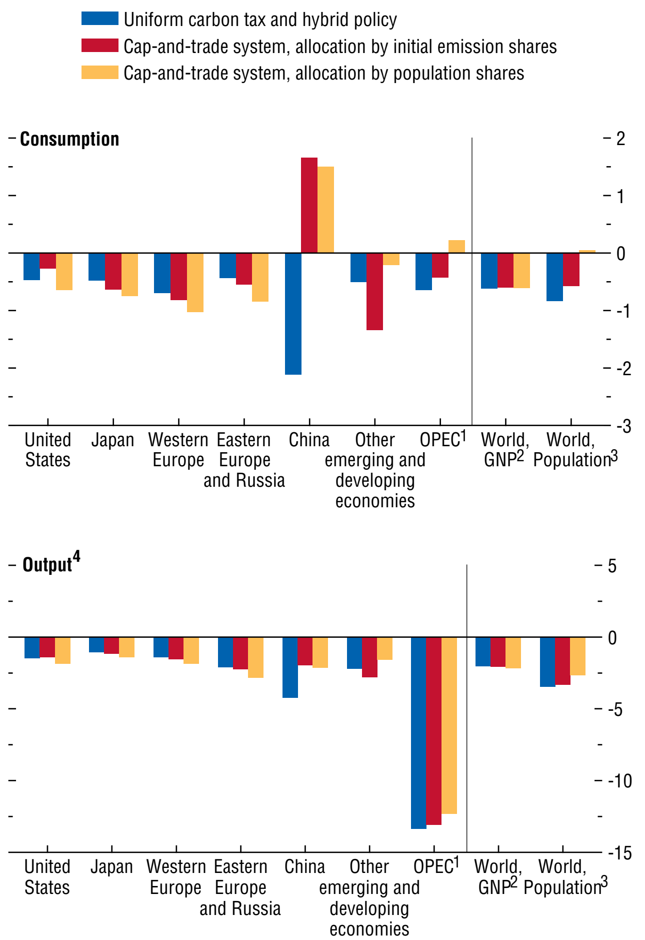


Source: IMF staff estimates.

[1]Output refers to gross national product. Interest rate refers to 10-year real interest rate. For real effective exchange rate, a positive value is an appreciation relative to the baseline.

Figure 4.11. Total Costs of Mitigation, 2013–40
(Deviation of the net present value from the baseline, percent)

This figure shows the costs of mitigation for the three policies shown in Figures 4.10, 4.12, and 4.14. The first panel shows the net present value of the difference between the path for real consumption in the policy experiment and the path for real consumption in the baseline, divided by the net present value of the path for real consumption in the baseline. The bottom panel shows the net present value of output (real gross national product) losses, defined in the same way as for consumption. The discount rate is constant over time and across regions at 2.2 percent, which is the difference between long-term world interest rates and trend GNP growth rates.



Source: IMF staff estimates.
[1]Organization of Petroleum Exporting Countries.
[2]Weighted by GNP shares in 2013.
[3]Weighted by population shares in 2013.
[4]Average prices of GNP and consumption can differ widely, owing to exchange rate movements. This implies that the rankings of GNP and consumption losses across countries are not necessarily the same.

lent.)[27] Firms change their technology, substituting away from carbon-intensive inputs and into capital (including noncarbon alternative technologies), materials, and labor. Households alter their consumption patterns, also substituting away from carbon-intensive goods. With higher carbon prices raising costs for firms, productivity and output fall. Aggregate investment falls because the average marginal product of capital is lower in each region, while consumption declines, following real incomes. Policy would be more effective to the extent that firms and households are forward looking and react immediately to the anticipated future prices. Although the levels of real activity fall permanently relative to the baseline, the shock has only a temporary effect on GNP growth rates: over time they return to baseline levels.[28]

Changes in national levels of GNP and consumption reflect countries' emission-reduction commitments and the costs of an incremental reduction in emissions. Each economy's marginal abatement costs (MACs) in G-Cubed depend on how intensely it uses carbon-based energy to produce goods for domestic consumption and for export, which in turn are driven by such factors as energy efficiency, factor endowments, and the production and export structure. China, Organization of Petroleum Exporting Countries (OPEC) members, and the United States have low MACs. MACs for eastern Europe and Russia and other emerging and developing economies are in the middle range, and MACs for Japan and western Europe are high. China is

[27]The hybrid policy is not equivalent to the carbon tax under conditions of uncertainty about abatement costs. In a scenario of slower-than-expected growth, the carbon price would fall under the hybrid policy and would remain constant under the tax. Hybrid policies may differ from carbon taxes in other respects as well, for example, in how emission reduction targets are achieved or how new information on damages from climate change is reflected in carbon prices. For a more detailed discussion of hybrid policies, see McKibbin and Wilcoxen (1997, 2002a) and Aldy and Stavins (2007).

[28]The study uses GNP as a measure of output. It is a better comparator of each region's fortunes under different mitigation policies, because, unlike GDP, it takes into account transfer payments.

Table 4.1. Losses in Real GNP, 2040
(Percent deviation from baseline)[1]

	Uniform Carbon Tax and Hybrid Policy	Cap-and-Trade Allocation by Initial Emission Shares	Cap-and-Trade Allocation by Population Shares
United States (130.1)	–2.1	–1.9	–2.6
Japan (80.0)	–1.5	–1.7	–2.1
Western Europe (109.9)	–2.0	–2.0	–2.5
Eastern Europe and Russia (131.8)	–2.8	–3.0	–3.9
China (404.5)	–4.8	–1.6	–2.1
Other emerging and developing economies (353.6)	–2.4	–3.3	–1.7
Organization of Petroleum Exporting Countries (196.0)	–16.2	–15.8	–14.6
World—GNP weighted (169.9)	–2.6	–2.6	–2.8
World—Population weighted (312.8)	–4.0	–3.9	–3.1

Source: IMF staff estimates.
[1]Numbers in parentheses denote the percent change in real GNP between 2007 and 2040 in the baseline.

least efficient in the use of energy, and it has by far the lowest MAC: it is producing nine times more emissions per unit of output than Japan, seven times more than western Europe, five times more than the United States, and three times more than eastern Europe and Russia and other emerging and developing economies (Appendix 4.1). The carbon intensity of the Chinese economy will be reduced as firms and households use energy more efficiently. The same is true for OPEC members and the United States, albeit to a lesser extent. In addition, because the burning of coal generates much higher emissions than the burning of other fossil fuels, rising carbon prices have a particularly strong effect in economies that use coal intensively—China and the United States—encouraging them to substitute alternative, lower-emission technologies. Given a uniform carbon price, economies reduce emissions up to the point at which their MACs are equalized. Economies with lower MACs undertake more emission reductions. China, in particular, reduces emissions by the most, followed by the United States and OPEC members.

Total abatement costs also vary across economies. The costs are highest for China, with the net present value of consumption declining by about 2 percent from the baseline levels by 2040 (Figure 4.11). For other economies, and for the world as a whole, the decline in the net present value of consumption is about 0.6 percent for the same period. When measured in terms of the bundle of goods produced, the costs are higher, with the net present value of world GNP declining by about 2 percent from the baseline by 2040 (see Figure 4.11). Yet this would still leave the world GNP 2.3 times higher in 2040 than in 2007 (Table 4.1).

Current accounts tend to improve over time in economies with lower MACs (for example, China and OPEC members) because reductions in investment outweigh reductions in savings. An exception to this pattern is the United States, where the current account worsens, because the marginal product of capital declines by less than in other countries, enabling the United States to absorb increased savings from China and OPEC members.[29] These capital inflows help support U.S. investment and consumption.

Changes in real exchange rates are driven by changes in production costs in the short run, whereas the adjustment path over time depends on real interest rate differentials. In western Europe, where energy efficiency is already relatively high, increases in carbon prices result in increases in average unit costs, hurting export competitiveness. The euro and other western European currencies depreciate as a result (the

[29]Owing to the larger size of its capital stock and smaller adjustment costs per unit of capital, the United States experiences fewer “bottleneck” problems with capital inflows.

euro by about 16 percent during 2013–40). By contrast, in China, the marginal costs of reducing emissions are low, and increases in carbon prices can be largely offset by improvements in energy efficiency. The resulting terms-of-trade improvement is reflected in an exchange rate appreciation.

MACs and emission reductions per dollar increase in carbon prices are similar to those obtained by Nordhaus (2007a) but lower than those in many other models (for example, US CCSP, 2007). This is true for three reasons. First, in contrast to models that assume technologies in which energy can be used only in fixed proportions with other inputs of production, G-Cubed allows for substitution between factors of production. Second, forward-looking expectations in G-Cubed make carbon price increases more effective in lowering emissions. The third factor driving down cost estimates is that G-Cubed explicitly models international capital flows, in contrast to most other models in the literature (Appendix 4.1). Free flow of capital implies that capital moves to economies with higher MACs, facilitating both the replacement of old capital stock and the transition to low-emission technology, and allowing the savings of economies with lower MACs to go where expected returns are higher.

The total costs of mitigation in G-Cubed are higher than in many other studies, but they are within the range of estimates reported in IPCC (2007).[30] The main reasons this analysis yields higher estimates is that it assumes relatively strong emission growth in the baseline (benchmarked in IEA, 2007a), and that G-Cubed uses conservative assumptions about the availability of so-called backstop technologies with zero emissions. In many other studies, GDP losses are substantially reduced or even eliminated by 2050 because innovation and the diffusion of backstop technologies and other low-emission technologies are assumed to proceed rapidly, at a faster pace than in G-Cubed (for example, US CCSP, 2007; Criqui and others, 2003; den Elzen and others, 2005; and Nakicenovic and Riahi, 2003).[31]

A Global Cap-and-Trade System

This experiment assumes that a permanent cap-and-trade policy is put in place in 2013. Emission rights for the world as a whole are assumed to follow the emission profile shown in Figure 4.9—by 2010 the world is allowed to emit only 40 percent of the 2002 emission levels. Individual economies receive emission rights for each year from 2013 onward. These rights are proportional to the economy's share of global emissions in 2012, following the profile depicted in Figure 4.9. Emission permits can be traded internationally, which establishes a common price.[32] Economies with higher MACs buy permits from economies with lower MACs, compensating them for undertaking more abatement than implied by their share of emissions. Hence, the actual emission paths of individual economies differ from their initial allocations of permits, whereas the world emission path is consistent with the targeted profile.

The macroeconomic effects of the global cap-and-trade system are similar to those of the global carbon tax and the hybrid policy with a safety valve, with differences reflecting the various mechanisms through which a common carbon price is established (Figure 4.12). Under the global tax, countries are assumed to agree on a common carbon price, whereas under the

[30]In this study, mitigation policies reduce world GDP by 3.8 percent by 2050 compared with the business-as-usual baseline. The range of estimates reported in IPCC (2007) is 0 to 4 percent.

[31]The carbon tax system considered in this study does not require international transfers: governments are assumed to agree on a common tax rate. In practice, however, the establishment of such a system may require side payments, which would alter macroeconomic outcomes. Border tax adjustments also may be used as a way to induce other countries to participate, albeit at the risk of a protectionist response.

[32]Emission permits are allocated to governments, which then sell them to the private sector. Firms are free to trade permits internationally. Governments spend revenues from permit auctioning on consumption and investment, keeping deficits unchanged.

global cap-and-trade system, a common carbon price is established through international trade in emission permits. For most economies, transfers are small and hence the macroeconomic effects are similar; for China (a recipient), other emerging and developing economies (payers), and OPEC members (recipients), transfers reach about 10 percent, –2 percent, and 1 percent of GDP, respectively, by 2040 (Figure 4.13). China receives the largest transfers because it is comparatively inefficient in the use of energy and can reduce emissions at much lower costs than other economies. Advanced economies, as well as other emerging and developing economies, buy emission rights from China because emission reductions are very costly for them. The above findings concerning the direction and magnitude of transfers are highly sensitive to marginal abatement costs assumed in G-Cubed for individual economies (see Appendix 4.1) as well as to the rule used for allocating permits across countries (see below).

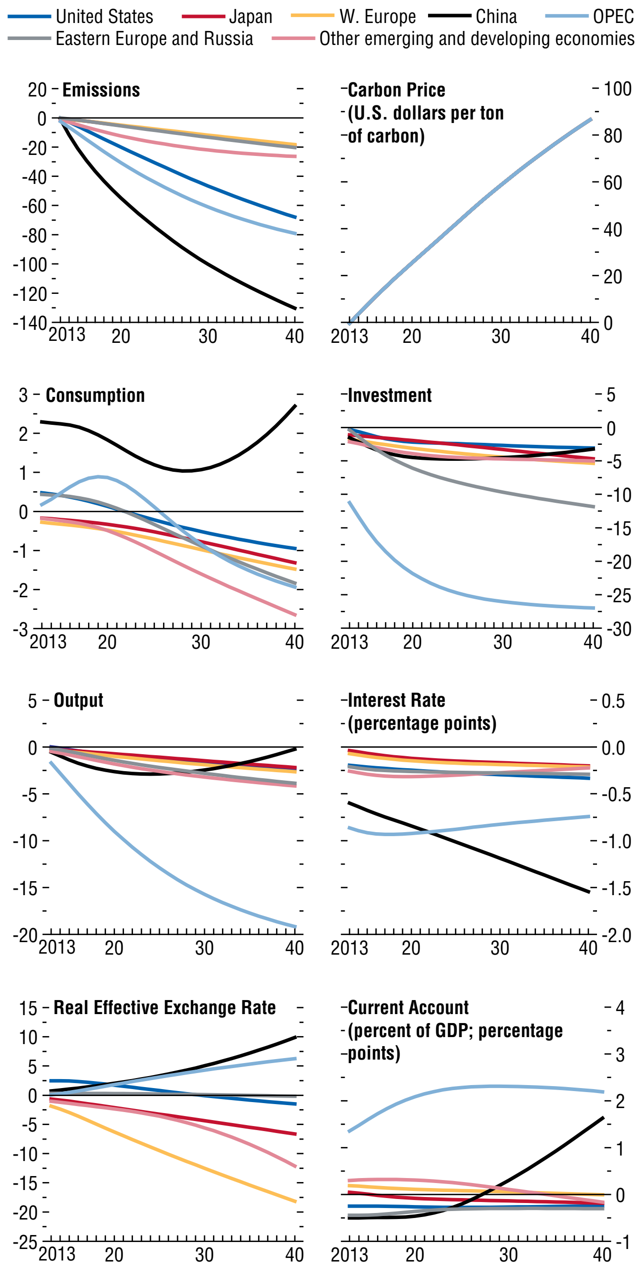
Differences in the macroeconomic effects of a global cap-and-trade system, a global carbon tax, and the hybrid with a safety valve are thus most vivid for China. China's consumption rises under a cap-and-trade system, but declines under a carbon tax and under the hybrid (see Figure 4.12). Under cap and trade, the current account remains broadly stable for the first 10 years (and gradually improves after that); there would be an immediate improvement under both a carbon tax and the hybrid (see Figure 4.10). International transfers also result in a larger real appreciation of the renminbi under cap and trade (10 percent by 2040 compared with 3 percent under a carbon tax and the hybrid).

Total (GNP-weighted) world abatement costs are similar under a cap-and-trade system, a carbon tax, and the hybrid policy, but the population-weighted costs are higher under cap and trade, because the increase in costs for other emerging and developing economies outweighs the decrease in costs for China. The costs for economies paying transfers (Europe, Japan, Russia, and other emerging and developing

Figure 4.12. Cap-and-Trade System, 2013–40[1]

(Deviation from the baseline; percent unless otherwise stated)

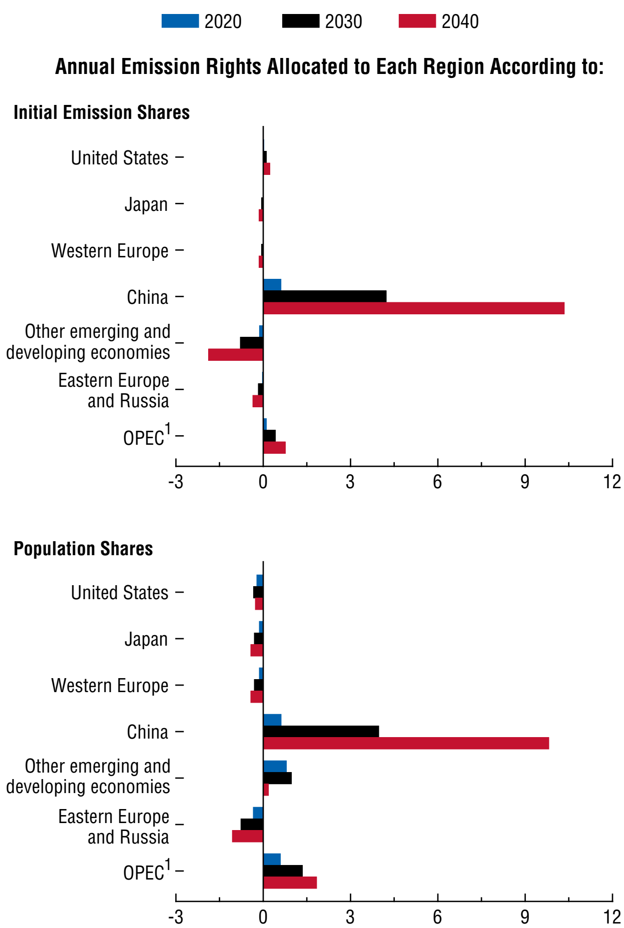
Each region is assumed to introduce a cap-and-trade system in 2013. Each region has to achieve a 60 percent reduction relative to the 2002 level in world (energy-based) carbon dioxide emissions by 2100, but is able to buy and sell emission permits to do so. This corresponds to a 96 percent reduction in global emissions relative to the baseline at 2100. Each region's emission target is mildly hump shaped, allowing for some increases in the medium term, peaking in 2018.



Source: IMF staff estimates.
[1]Output refers to gross national product. Interest rate refers to 10-year real interest rate. For real effective exchange rate, a positive value is an appreciation relative to the baseline.

Figure 4.13. International Transfers under the Cap-and-Trade System
(Percent of GDP)

This figure shows the net value of international transfer payments for emission rights. A positive value denotes a receipt of transfers—that is, the region is selling its emission rights. The top panel summarizes results for a cap-and-trade system under which emission rights are allocated proportionally to emissions in 2012 (see Figure 4.12 for details on this policy experiment). The bottom panel summarizes results for a cap-and-trade system under which emission rights are distributed based on the share of population in each year from 2013 onward (see Figure 4.14).



Source: IMF staff estimates.
[1]Organization of Petroleum Exporting Countries.

economies) rise under a cap-and-trade system compared with those under a carbon tax and the hybrid policy, while the costs decline for the economies receiving transfers (China, OPEC members, and the United States).

Although most studies predict that advanced economies—especially western Europe and Japan—would have to pay for emission permits, there is no consensus about international transfers for emerging market economies. Such countries have high growth potential, which implies high future demand for emission rights, but they also emit high levels of carbon per unit of output, which implies a lot of room for efficiency gains and hence the ability to sell emission rights. The latter effect dominates in den Elzen and others (2005) and Criqui and others (2003), which predict that China will sell permits. But Persson, Azar, and Lindgren (2006) project that China will develop so rapidly that it must buy permits. In Grassl and others (2003), China buys permits from other emerging market economies, because Africa, Latin America, and south Asia are assumed to have large innate potential for reduction in emissions through the increased use of solar power and biomass. By contrast, here, China is able to reduce emissions through improvements in the energy efficiency of households and firms, leaving it with a large surplus of emission rights that can be sold.

Alternative Allocations of Emission Permits

The pattern of international transfers and the macroeconomic effects of cap and trade are highly sensitive to how emission rights are allocated. Suppose each economy receives emission rights not according to its initial share of emissions, but according to its share of world population in each year from 2013 onward. For the same global emission target, OPEC members and other emerging and developing economies would receive more permits than under the rule based on the initial share of emissions. This would substantially change the pattern of international trade in permits and the macroeconomic effects, with other emerging and developing economies now selling permits and receiving transfers in the amount of about 1 percent of GDP during 2020–30 (see Figure 4.13). Transfers to OPEC members would also rise to about 2 percent of GDP in 2040, whereas those to China would remain broadly unchanged.

Transfers to other emerging and developing economies would improve their consumption outcomes, but would lead to real exchange rate appreciation and a phenomenon akin to Dutch disease (Figure 4.14). Agriculture and services sectors in other emerging and developing economies would experience a larger contraction than under the emission-based cap-and-trade system. Appreciation would persist during several decades following the introduction of the population-based cap and trade.

Nonetheless, when measured in GNP-weighted terms, world abatement costs would be similar under a population-based cap and trade, under an emission-based cap-and-trade system, and under a uniform global carbon tax, reflecting similar outcomes in terms of increased energy efficiency. In population-weighted terms, world costs decline owing to consumption benefits now accruing to other emerging and developing economies and OPEC members (see Figure 4.11).

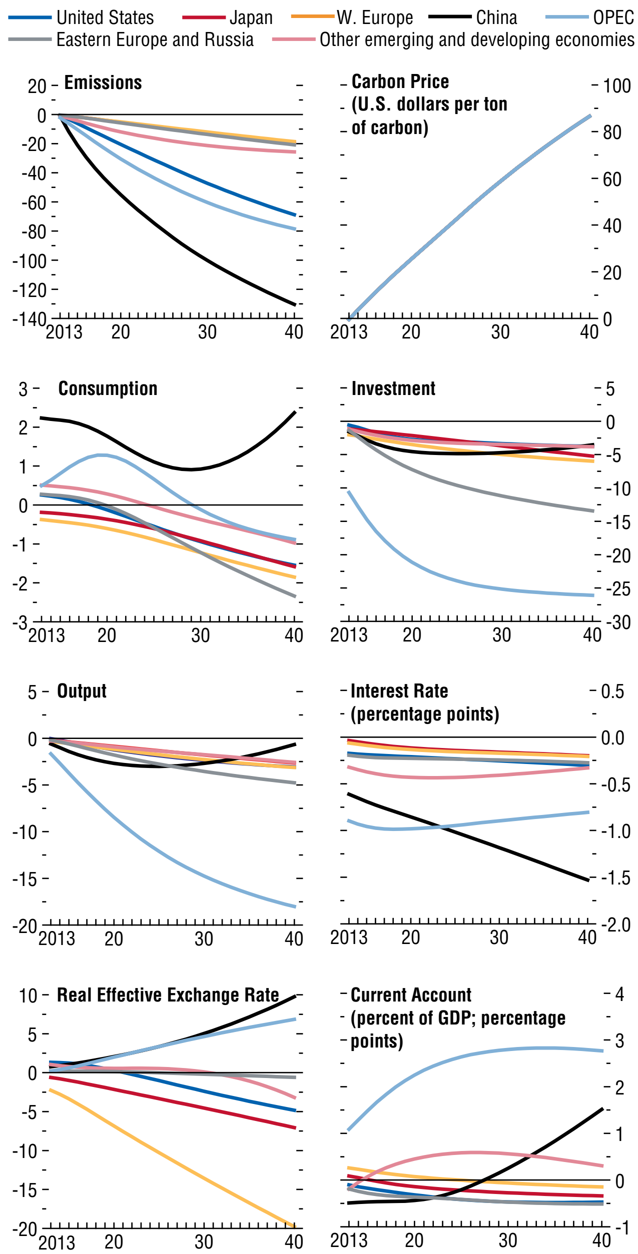
Other Findings

Nonharmonized mitigation policies—for example, under which each economy independently chooses its own path for carbon prices in order to achieve a 60 percent reduction from 2002 emission levels by 2100—would be more costly than harmonized policies because they do not provide for an efficient allocation of abatement across the world (Nordhaus, 2007a). Under G-Cubed simulations, total costs at least double for other emerging and developing economies, eastern and western Europe, Russia, and Japan, compared with the costs of the uniform global carbon tax. Although China, OPEC, and the United States would have lower costs than under a uniform carbon tax, the total global costs of uncoordinated policies are still 50 percent higher than those of harmonized policies. Countries with higher MACs would

Figure 4.14. Cap-and-Trade System for All Regions Based on Share of World Population, 2013–40[1]

(Deviation from the baseline; percent unless otherwise stated)

Beginning in 2013, there is a cap-and-trade system for all regions to gradually achieve 60 percent reductions in total world (energy-based) carbon dioxide emissions relative to the 2002 level by 2100, allowing for some increases in the medium term, peaking in 2018. This corresponds to a 96 percent reduction in global emissions relative to the baseline at 2100. Emission rights are allocated by share of global population in each year from 2013 onward.



Source: IMF staff estimates.

[1]Output refers to gross national product. Interest rate refers to 10-year real interest rate. For real effective exchange rate, a positive value is an appreciation relative to the baseline.

be particularly adversely affected by the lack of policy coordination, because these countries would no longer be able to relocate abatement to other destinations. This policy experiment suggests that an international policy architecture based on country-specific carbon prices would be less efficient than an architecture establishing a common world carbon price.

An international agreement that does not include emerging and developing economies will be ineffective in stemming climate change. If only Annex I economies[33] (Australia, Canada, eastern and western Europe, Japan, New Zealand, Russia, and the United States) were to assume the full burden of reducing world emissions by 40 percent from 2002 levels by 2100, their emissions would need to be 12½ times lower than in the baseline. This is because they would need to offset the large contribution of non-Annex I countries (China and other emerging and developing economies) to the growth of world emissions. This would represent an unrealistically high cost to Annex I economies. Alternatively, if only Annex I economies decided to reduce their total emissions by 60 percent by 2100, global emissions would be 7½ times higher than in 2002, resulting in greater warming.

The carbon tax and the hybrid policy with a safety valve provide more flexibility for firms and households to respond to fluctuations in abatement costs stemming, for example, from changes in the rate of economic growth. During periods of cyclically high demand and expanding production, cap and trade may become too restrictive, requiring firms to abate to the same extent despite higher abatement costs. When one region experiences unexpectedly higher growth, this would drive up the price of carbon permits for all countries, with the result that those countries that were previously net beneficiaries of transfer payments might find themselves having to pay (McKibbin and Wilcoxen, 2004). If carbon prices are volatile, variations in growth may put a stress on a global cap-and-trade agreement. This is not the case under the carbon tax or the hybrid policy.[34]

This policy experiment also illustrates that mitigation policies may have important implications for the way macroeconomic shocks are transmitted across countries. For example, under a price-setting policy, unanticipated growth spills over positively to other countries, although this implies that the world misses its emission targets. By contrast, under the global cap-and-trade system, the world global emission target can be achieved, but higher economic growth in one large economy may have negative repercussions across other countries by driving up permit prices.

Energy-efficiency improvements are unlikely to eliminate the need for carbon prices, but they would reduce their level (Nordhaus, 2007a). Even assuming that energy efficiency exogenously improves at a pace that is twice as high as in the baseline, carbon prices would still need to rise to achieve the same reduction in emissions (the carbon price would need to reach $76 by 2040, instead of $86, as in the original policy experiments with the global price-based policies). This points to the potential benefits of complementing carbon pricing with well-designed incentives for innovation and the broad diffusion of clean technologies (see Box 4.6).

Less-stringent emission targets—aiming to stabilize GHG concentrations at about 650 ppm in CO_2e terms, rather than 550 ppm, by 2100—would be less costly to achieve, but the difference in costs would not be dramatic. Analysis of an alternative mitigation scenario, under which emissions were only 40 percent below 2002 levels by 2100 and were allowed to continue to grow for longer before declining,[35] shows that

[33]Annex I of the Kyoto Protocol lists the assigned emission targets over the commitment period 2008–12. This does not necessarily mean that the emission targets have been agreed to or met.

[34]The hybrid has a number of advantages under uncertainty, such as directly addressing the problem of time consistency that arises under the cap-and-trade system and carbon-tax approaches.

[35]Matching the "Category IV" scenarios in IPCC (2007) and corresponding to 590–710 ppm in CO_2e terms.

the patterns of macroeconomic responses under carbon taxes, hybrid policies, and cap-and-trade systems remain largely unchanged. However, under the less-stringent scenario, carbon prices would rise more slowly, to $165 by 2100, implying slightly lower consumption and GNP losses (of about 0.5 percent and 1.7 percent in net present value, respectively).

Caveats

Several caveats need to be underlined. The most important is that it is difficult to say anything precise about the state of the world economy and individual country economies in 2040, let alone 2100, especially if there are large and fundamental changes in the price of energy. Many innovations in technology could occur that would change the outlook dramatically over several decades, and these innovations could diffuse at different rates across countries. Results are most sensitive to assumptions about economic growth, autonomous energy-efficiency improvements, and marginal abatement costs—small changes in these assumptions can have a big impact on results in G-Cubed. The direction and magnitude of macroeconomic effects for individual countries, including financial transfers, are particularly sensitive to assumptions about elasticities of substitution in production, consumption, and trade. Using only current technologies, many firms may be unable to react to market demand to the extent estimated in this analysis; yet by basing many of the estimates of the price responsiveness of households and firms on historical experience through econometric estimation, the model attempts to reflect plausible outcomes in technological change. Although G-Cubed does not model when backstop technologies would emerge, it assumes that changes in carbon prices can induce large substitutions away from fossil fuels. Many other models have more rigid technological structures or assume that capital and technology do not flow freely across countries, even over the long run. At the same time, by focusing only on energy-related CO_2 emissions, G-Cubed does not take into account cheap abatement opportunities that may exist in other areas, for example, by reducing deforestation.

Conclusions

Climate change is a powerful global trend that, along with trade and financial integration, is likely to have profound effects on economies and markets in coming decades. As temperatures and sea levels rise and precipitation patterns change, the global pattern of comparative advantage will shift in tandem. This will prompt structural changes within economies, at the domestic as well as at the global level. There will be shifts in international trade, in capital and migration flows, and in the prices of commodities, other goods and services, and assets.

The macroeconomic effects of climate change will unfold unevenly across time and space. Poor countries will be hit earlier and harder, owing to their geography, heavier reliance on agriculture, and more limited capacity to adapt. Their health and water systems may come under stress from more frequent natural disasters, coasts may be flooded, and populations may migrate. Rich countries may be affected by spillovers from climate change in poor countries, and they would also face severe direct damage if the tail risks of climate catastrophes were to materialize.

The ability of domestic macroeconomic policies to help public and private sectors cope with climate-related risks will be increasingly tested over time. Sound macroeconomic policies and innovative financial and development strategies will be needed to help countries successfully adapt to climate change. Countries with higher incomes, stronger fiscal positions, more developed financial markets, and greater structural policy flexibility will be better positioned to adapt to the adverse consequences of climate change. Countries that are increasingly subject to risks from weather volatility and extreme weather events will need to devise strategies for managing such risks, including the appropriate use of self-insurance through budgetary management, the building of reserves, and the use of weather derivatives, catastrophe bonds, and other forms of disaster insurance. Global cooperation in transferring knowledge about the financial management of weather-related risks would help poor countries better adapt to climate change.

Dealing with climate change also poses enormous multilateral policy challenges. These range from fostering synergies in adaptation and protecting the natural environment to preserving energy security and managing the risks of protectionism. Yet the main task is to address the causes and impacts of climate change by significantly reducing emissions of GHGs over the next several decades, and to do this at the lowest possible cost. This requires joint action by advanced, emerging market, and developing economies.

This chapter concludes that climate change can be addressed without imposing heavy damages either on the global economy or on individual countries. For climate policies to be successful, their potentially adverse economic consequences—slower growth, higher inflation, loss of competitiveness—must be addressed, either through carefully designed climate policies or through supportive macroeconomic and financial policies. Measures to limit the adverse economic effects would strengthen the incentives for a broad range of countries to fully participate in mitigation efforts and would help unleash the potential economic and financial benefits of the transition to a more climate-friendly global economy.

- Carbon-pricing policies need to be long term and credible. They must establish a time horizon for steadily rising carbon prices that people and businesses consider believable. Increases in world carbon prices need not be large—say a $0.01 initial increase in the price of a gallon of gasoline that rises by $0.02 every three years. Such gradual increases, if started early, would allow the cost of adjustment to be spread over a longer period of time. The total cost to the global economy of such policies could be moderate for policies introduced in 2013 that aim to stabilize CO_2e concentrations at 550 ppm by 2100—entailing only a 0.6 percent reduction in the net present value of world consumption by 2040. Even with this loss, world GNP would still be 2.3 times higher in 2040 than in 2007.
- Carbon-pricing policies should induce all groups of economies—advanced, emerging, and developing—to start pricing their emissions. Any policy framework that does not include emerging and developing economies (particularly, large and fast-growing economies such as Brazil, China, India, and Russia) in some way (for example, with a lag or with initially less-stringent targets) would be extremely costly and would be politically untenable. That is because during the next 50 years, 70 percent of emissions are projected to come from these and other emerging and developing economies. Some countries may need to strengthen their institutional capacity, however, to implement carbon pricing.
- Carbon-pricing policies should strive to establish a common world price for emissions. This would ensure that emission reduction occurs where it is least costly to do so. Emerging and developing economies, in particular, will likely be able to reduce emissions much more cheaply than advanced economies. For example, if China and India have access to technologies similar to those available in Europe and Japan, they could cut emissions dramatically by improving their intensity of energy use and by reducing their reliance on coal. The difference in costs can be significant—for the world as a whole, costs would be 50 percent lower if carbon prices were the same across countries. Countries would either need to agree to harmonize the rate of a carbon tax, coordinate trigger prices for the safety valve under a hybrid policy, or allow international trading of emission permits under a cap-and-trade system.
- Carbon-pricing policies should be sufficiently flexible to accommodate cyclical economic fluctuations. During periods of high demand, for example, it would be more costly for firms to reduce their emissions, and the opposite would be true when demand is low. Abatement costs would be lower if firms could vary

their emissions over the business cycle. That would allow a given average level of emission reductions to be achieved over the medium term. In contrast to carbon taxes and hybrid policies, a cap-and-trade system could prove restrictive in periods of higher growth owing to increased demand and prices for emission permits, unless it incorporates elements that help control price volatility.

- The costs of mitigation should be distributed equitably across countries. Some mitigation policies—for example, a uniform tax, a cap-and-trade system under which permits are allocated based on countries' current shares of emissions, or a hybrid policy combining elements of the two—would impose high costs on some emerging and developing economies. Substantial cross-border transfers may be needed to encourage them to participate and to help them deal with the negative impact. The direction and magnitude of transfers under cap and trade generally depend on the incremental costs of reducing emissions in individual countries (which in turn are a function of countries' domestic technological capabilities and access to foreign technology) as well as on the specific design features of mitigation policies (for example, rules for allocating emission permits, the timing of countries' entry into the climate agreement, supplementary conditions, and the like). If policies were designed so that transfers flow from advanced economies to emerging and developing economies, this would reduce the costs of carbon-pricing policies for the latter two groups, encouraging them to participate. Using border tax adjustments as a way to induce countries to join could elicit a protectionist response that would detract from mitigation efforts.

In addition, countries may need to complement carbon pricing with appropriate macroeconomic and financial policies. For example, under a global cap-and-trade system, transfers from economies that buy permits to economies that sell them could be potentially large—for example, several percentage points of GDP. Such transfers may cause real exchange rates in the recipient countries to appreciate considerably, making some sectors of their economies less competitive—Dutch disease. Such macroeconomic effects can be reduced if countries save a portion of these inflows, continue to improve their business environments, and, depending on their exchange rate regimes, allow appreciation to take place at least partly through the nominal exchange rate rather than through inflation.

This chapter also points to the supporting role of international capital movements and technology transfer in dealing with climate change. Capital and technology flows can reduce the costs of mitigation by helping allocate abatement to the least costly destinations, while making abatement easier through the use of modern technology. Initiatives by major advanced economies to subsidize the transfer of clean technologies to emerging and developing economies can complement a global commitment to contain carbon emissions through a broadly accepted global carbon-pricing framework. While unlikely to eliminate the need for carbon pricing, well-designed incentives for innovation and the diffusion of clean technologies can help reduce the costs of addressing climate change.

Climate change is a complex global problem that does not lend itself to easy policy solutions. This chapter does not pretend to provide a solution. Its focus has been narrow—on the cross-country macroeconomic dimensions of climate change. Yet its conclusion has broad relevance for ongoing policy debates: climate change can be addressed with minimum damage to the economy, if policy solutions follow some basic principles.

Appendix 4.1. The G-Cubed Model, Baseline Assumptions, and Other Models in the Climate Change Literature

The main author of this appendix is Alasdair Scott.

This appendix outlines the key features of the model used to produce the analysis in Chapter 4, the baseline scenario and its underlying assumptions, the factors affecting the differences in marginal abatement costs (MACs) across countries, and comparisons with some other models that have been prominently used in the literature on climate change mitigation.

The G-Cubed Model

G-Cubed (see McKibbin and Wilcoxen, 1998) is a dynamic general equilibrium model of the global economy. The world is divided into multiple regions linked by international trade and capital flows, with each region divided into multiple production sectors. Decisions about saving, investment, and asset pricing are modeled by assuming that forward-looking households and firms aim to maximize, respectively, consumption utility and profits, but are subject to cash flow constraints, while backward-looking households and firms follow simple rules of thumb.[36] Outputs of different sectors are linked to emissions of carbon dioxide using data for the emission intensity and the energy efficiency of each sector.

Some of the key features of G-Cubed relevant for this study include the following:

- disaggregation of the real sector into an input-output structure to allow for production and trade of multiple goods and services within and across economies, facilitating the examination of how changes in energy prices are transmitted within and across economies;
- "stock-flow" accounting for capital stock and financial assets and enforcement of cash flow and budget constraints;
- integration of real and financial markets, including the modeling of international capital flows along with trade balances; and
- modeling of fiscal and monetary policies.

The 2007 version of G-Cubed used in this study splits the world into the following nine economies:[37]

- United States;
- Japan;
- Western Europe (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and United Kingdom);
- Australia;
- Canada and New Zealand;
- Eastern Europe and Russia (Albania, Bulgaria, Czech Republic, Hungary, Poland, Romania, and Russia);
- China;
- other emerging and developing economies (Argentina, Brazil, Cambodia, Chile, Egypt, Hong Kong SAR, India, People's Democratic Republic of Korea, Republic of Korea, Lao PDR, Malaysia, Mexico, Morocco, Myanmar, Nepal, Pakistan, Philippines, Singapore, South Africa, Sri Lanka, Thailand, Turkey, and Vietnam);
- OPEC economies (Algeria, Indonesia, Islamic Republic of Iran, Iraq, Kuwait, Libya, Niger, Oman, Qatar, Saudi Arabia, and United Arab Emirates).

The six economies covering Australia, Canada and New Zealand, western Europe, eastern Europe and Russia, Japan, and the United States are broadly equivalent to the definition of Annex I under the Kyoto Protocol (United Nations, 1998).

The production structure of each region is the same, with the following 12 production sectors:

- energy sectors: electric utilities, gas utilities, petroleum refining, coal mining, crude oil and gas extraction; and

[36]Thirty percent of households are forward looking and 70 percent follow rules of thumb. Expectations play a key role in the effectiveness of carbon prices at reducing emissions, because forward-looking households will factor all future carbon price increases into their current decisions. Hence, for the same carbon price profile, a larger share of forward-looking households would imply earlier reductions in emissions.

[37]Country coverage is constrained by data limitations. Hence, the definition of the "world" may differ from that in other studies, and this may need to be taken into consideration when comparing policy scenarios.

- nonenergy sectors: mining; agriculture, fishing, and hunting; forestry and wood products; durable goods manufacturing; nondurable goods manufacturing; transportation; and services.

The structure of each region is identical but varies in the values of parameters describing shares, weights, and elasticities. Each region consists of several economic agents: households, a consolidated government, the financial sector, and the production sectors listed above. Each firm makes decisions about capital investment and the use of labor, intermediate materials, and energy so as to maximize the value of the firm, given available technology and the prices the firm faces for inputs and outputs. Labor supply is assumed to meet labor demand from firms in the short run—in the long run, it is constrained by population levels—and workers are fully mobile across sectors (they receive the same real wage). By contrast, it takes time to shift and install capital. Each household receives labor and dividend income from firms and (net) transfer income from the government. Given its period-by-period budget constraints and the prices of goods relative to income and other goods, each household makes decisions about total consumption expenditure and the way that expenditure is allocated across a basket of energy and nonenergy goods.

The government administers monetary and fiscal policy. It faces a binding period-by-period fiscal constraint, balancing revenues with expenditures. Each region has the same fiscal rule: given targets for tax rates, transfers, deficits, and expenditures on wages, extra revenues—such as from carbon taxes or sales of emission permits—are used to fund government consumption and investment. To the extent that a rise in carbon prices reduces private demand, this rule will have a small offsetting effect on aggregate demand. The main conclusions in this study are broadly robust to using alternative fiscal rules.[38] There are nominal rigidities for prices and wages. Governments in the model can use nominal interest rates to achieve targets for inflation, money growth, nominal GDP growth, or exchange rates, or for a mixture of these.

An important aspect of the model is the way in which sectors and economies are linked by trade in goods and services, current transfers, and capital flows. All goods are potentially tradable, but the degree to which they are traded depends on how much they are used as inputs of production in other countries and on their relative prices, which depend in turn on their elasticities of substitution in production and consumption. Relative prices, such as terms of trade and real exchange rates, adjust to clear the worldwide market for goods and services. In addition, capital is assumed to flow freely across borders in search of the highest rate of return. Current flows include transfers from permit trades under a cap-and-trade system, in addition to investment returns on foreign assets.

Baseline Assumptions

The baseline—which is sometimes referred to in other studies as the reference path or business-as-usual (BAU) scenario—is a set of paths, for variables such as GDP and emissions, that is generated by the model and does not include any shocks other than those implicit in assumptions about population and productivity growth and does not include any policy interventions other than those implicit in fiscal and monetary rules. The main assumptions that drive the baseline are those that affect underlying trend growth (here, population and productivity growth), policy assumptions (such as tax rates and spending levels), emission-related assumptions (such as any improvements in energy efficiency), and the structure of the economies

[38]For example, the most efficient use of carbon revenues would be to reduce distortionary taxes on capital. Equity considerations might argue for a reduction in income tax rates for those with lower incomes, as carbon taxes are regressive. Alternatively, carbon revenues could be used to fund research in clean technologies or to pay down debt.

Table 4.2. Baseline Growth Assumptions
(Percent change)

	United States	Japan	Western Europe	Eastern Europe and Russia	China	Other Developing and Emerging Economies	Organization of Petroleum Exporting Countries
Population	0.71	–0.54	0.03	–0.57	0.08	1.29	1.18
	0.18	–0.56	–0.07	–0.53	–0.23	0.20	0.27
Nonenergy sector productivity	1.55	0.52	0.62	1.55	6.78	2.61	0.72
	1.56	1.49	1.50	1.57	1.58	1.71	1.26
Energy sector productivity	0.10	0.06	0.14	0.29	0.94	0.31	0.03
	0.10	0.09	0.11	0.16	0.20	0.21	0.03

Source: IMF staff calculations.
Note: The first row for each category shows the annual average percent change during 2003–30; the second row shows the percent growth rate in 2100.

(as represented by parameters for elasticities and shares).[39]

Table 4.2 summarizes the growth assumptions used in the baseline. Although all regions gradually converge to common trend growth, note that there are substantial differences in the short run (and across sectors within each economy).[40]

[39]Parameter assumptions affect the baseline, including values for the intertemporal elasticity of consumption substitution and the household discount rate. A rise in the discount rate would increase the market rate of interest that households use to evaluate permanent income, but such a change would leave the ordinal comparisons of policies unchanged. This is in contrast to studies that attempt to calculate welfare losses and gains in a full cost-benefit analysis of mitigation policies. See, for example, the *Stern Review* (Stern, 2007) and discussion, such as Nordhaus (2007a).

[40]Some have argued that climate models using GDP measures based on market exchange rates (MER) rather than purchasing power parities (PPP) understate the size of emerging and developing economies and therefore, by assuming convergence, overestimate GDP and emission growth (see, for example, Castles and Henderson, 2003). This point is hotly debated. IPCC (2007) argues that the resulting bias is small compared with other sources of uncertainty. A practical limitation to adopting PPP measures for climate change studies is that PPP-consistent production accounts would be required for the modeling of energy sectors and energy inputs into other sectors, and such accounts are not available. Furthermore, even if they were, comparisons across time would be problematic because PPP-consistent accounts would impose constant weights or relative prices for different goods. For this reason, Nordhaus (2007c) argues that “superlative” PPP accounts are required that would combine PPP exchange rates with actual market prices over time for each country. In this study, relative growth rates are calibrated using PPP-based national income comparisons, but projections for economies’ expenditure, income, production, and balance-of-payments variables are made on an MER basis.

For example, data from population projections produced by the United Nations (2006) indicate that other emerging and developing economies will experience substantial population growth over the next quarter century, whereas the populations of Japan, eastern Europe, and Russia will shrink. Similarly, although productivity growth in nonenergy sectors in the developed world is assumed to be modest, there are substantial productivity gains in emerging and developing economies. All other things equal, emission levels reflect activity levels, implying a rising share of emissions produced by developing economies.

Productivity in nonenergy sectors is assumed to exceed the ability to improve the efficiency of producing energy from all sources in each region at all times—this implies that carbon-based energy becomes relatively more expensive over time. Raising energy sector productivity—particularly among OPEC members—would result in higher economic growth and higher emissions in the baseline.

G-Cubed does not explicitly model renewable and low-carbon-emission technologies. But it assumes that there is a constant, albeit modest, improvement in the efficiency with which energy is used by households and firms (sometimes referred to as autonomous energy efficiency improvement) of 0.5 percent each year. This can be thought of as representing advances in clean technologies, which further encourage lower emission intensity—emissions per unit of output—over time. In addition, substitution from

Table 4.3. Carbon-Based Emission Coefficients
(Metric tons of carbon emissions per unit of real GDP in U.S. dollars)

	United States	Japan	Western Europe	Eastern Europe and Russia	China	Other Developing and Emerging Economies	Organization of Petroleum Exporting Countries
Coal	20.88	7.67	7.68	5.48	76.09	15.08	13.62
Crude oil	7.89	2.56	1.75	1.50	7.14	4.90	9.77

Sources: Global Trade Analysis Project database; and IMF staff calculations.

carbon-based energy toward capital as a factor of production can be seen as a type of technological progress toward clean technologies. This plays an important role in reactions to policies and contrasts with some models that model energy sectors and technologies in more detail but implicitly assume that energy and capital must be used in fixed proportions.

In the short run, monetary policy assumptions have an effect on the baseline as regions converge to their trend growth paths. Western Europe, Japan, the United States, Canada, Australia, and New Zealand are assumed to have fully flexible exchange rates, and other regions are assumed to have managed exchange rate regimes. Monetary policy is summarized by an augmented Taylor-type monetary reaction function; in managed exchange rate regimes, a relatively large weight is put on changes in the nominal exchange rate, as well as on output gaps and inflation. Tax rates, transfers, and deficits (the last as a share of GDP) are assumed to stay constant.

In addition to assumptions about economic growth and policy, assumptions made about the structures of the economies—in particular, how intensively and flexibly they use energy, as summarized by share parameters and elasticities—play an important role in determining the baseline paths. One important subset describes the emissions produced from the use of coal or crude oil in each economy to produce a unit of output, which is illustrated by the coefficients in Table 4.3. These parameters are backed out from the model-consistent data to match observed activity levels with measured carbon emissions. China is the most coal intensive, followed by the United States, other emerging and developing economies, and OPEC economies. OPEC economies are the most oil intensive, per unit of output, followed by the United States, China, and other emerging and developing economies.

Elasticities of substitution—the ease with which firms and households can alter the composition of the factors of production they use and the goods they consume—also affect the baseline. Firms have the ability, to some degree, to change the proportions of energy they use to produce a given unit of output by substituting toward capital, labor, and materials. They also can alter the mix of fossil fuels used to produce energy. Production elasticities have otherwise been estimated, where possible, and have been calibrated to match typical values (averaging around 0.5) from other studies. Trade elasticities are about 0.9, except for energy goods, which are more substitutable (2.0).[41] Higher elasticities imply that economies respond more to relative price movements; they also imply that baseline activity grows faster because they allow economies to reduce their reliance on energy earlier than otherwise.

Together, these assumptions generate the baseline scenario summarized in Table 4.4. Most economic growth over the baseline is coming from non-Annex I regions. Although most

[41]The values of these elasticities are standard. But the so-called constant elasticity production functions and consumption bundles used here are vulnerable to the criticism that, in reality, firms and households cannot always substitute away from carbon-based energy (even at a very high price). For example, reducing fossil fuel use by just one more unit might actually imply that completely new technologies—such as renewables, hydro power, or nuclear energy—would have to be installed. This implies that there are nonlinearities that are not addressed in this analysis.

Table 4.4. Summary of the Baseline Scenario

GDP Growth Rates (Annual percent change)		2010	2020	2030	2040
United States		2.60	2.64	2.51	2.40
Japan		2.05	1.70	1.70	1.67
Eastern Europe		1.81	2.78	2.37	2.24
Western Europe		1.89	2.39	2.26	2.19
Annex I economies		2.18	2.46	2.32	2.23
China		10.19	5.04	3.50	2.70
Other developing and emerging economies		4.54	5.39	4.33	3.82
OPEC economies		2.31	3.97	3.39	3.14
Non-Annex I economies		5.19	5.20	4.10	3.58
World		2.83	3.21	2.88	2.71
Emission levels ($GtCO_2$)	2002	2010	2020	2030	2040
United States	5.8	6.2	7.5	9.1	11.0
Japan	1.2	1.4	1.6	1.8	2.1
Eastern Europe	3.1	3.0	3.5	4.1	5.4
Western Europe	3.5	3.7	4.1	4.7	5.4
Annex I economies	14.5	15.1	17.8	21.2	25.0
China	3.3	3.8	8.2	12.3	16.6
Other developing and emerging economies	5.0	5.0	8.2	12.8	18.8
OPEC economies	1.7	1.5	1.9	2.7	3.6
Non-Annex I economies	10.0	10.2	18.2	27.8	39.9
World	24.4	25.3	36.1	48.9	64.0
Emission shares (percent)	2002	2010	2020	2030	2040
United States	23.5	24.3	20.7	18.6	17.2
Japan	4.9	5.5	4.4	3.8	3.3
Eastern Europe	12.7	11.8	9.8	8.4	7.5
Western Europe	14.2	14.5	11.4	9.7	8.4
Annex I economies	59.3	59.7	49.4	43.3	39.1
China	13.5	14.9	22.7	25.2	26.0
Other developing and emerging economies	20.4	19.6	22.6	26.1	29.3
OPEC economies	6.8	5.8	5.3	5.5	5.6
Non-Annex I economies	40.7	40.3	50.6	56.7	60.9

Source: IMF staff calculations.
Note: OPEC = Organization of Petroleum Exporting Countries; $GtCO_2$ = gigatons of carbon dioxide.

emissions are currently produced by Annex I regions, this growth—together with the assumptions about emission intensity—implies that most emissions are produced by non-Annex I regions within the next 30 years.

The levels of emissions from fossil fuels are higher than the median of the levels in the studies published after the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios in 2001, but are within the 75th percentile (Figure 4.15).[42] The baseline used in this study has slightly higher growth rates than is typical in most other studies, but the main reason for higher emission levels in later periods in this study is higher emission intensity, because no explicit assumptions are made about the adoption of zero-emission technologies.[43]

The Determinants of Marginal Abatement Costs

A key determinant of the distribution of the burden of adjustment to policies in the simulations are the MACs, which allow for a compari-

[42]See IPCC (2007).

[43]For example, the baseline emission path up to 2050 is very similar to that of the IGSM model from the Massachusetts Institute of Technology Joint Program used in US CCSP (2007). This model has a broadly similar structure to G-Cubed, and similar assumptions are made about population and productivity growth. But baseline emission growth in this study continues strongly after 2050, whereas emission growth from IGSM in US CCSP (2007) falls off considerably even in the absence of any policy intervention.

Table 4.5. Emission Intensities in the Baseline
(Emissions of CO_2 from fossil fuels as a proportion of real GDP)

	2002	2010	2020	2030	2040
United States	0.55	0.51	0.47	0.45	0.43
Japan	0.30	0.28	0.28	0.27	0.26
Eastern Europe	0.85	0.77	0.69	0.63	0.58
Western Europe	0.37	0.35	0.31	0.29	0.26
Annex I economies	0.51	0.47	0.43	0.40	0.38
China	3.11	2.48	2.69	2.72	2.72
Other developing and emerging economies	0.87	0.75	0.71	0.70	0.69
OPEC economies	1.82	1.50	1.36	1.34	1.31
Non-Annex I economies	1.29	1.12	1.14	1.12	1.08
World	0.67	0.61	0.63	0.63	0.63

Source: IMF staff calculations.
Note: OPEC = Organization of Petroleum Exporting Countries.

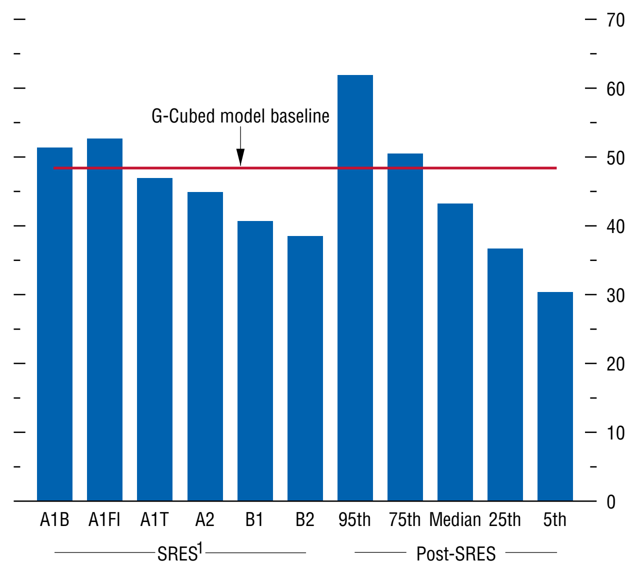
son of the ease for each economy of changing the intensity with which it uses carbon fuels. MACs are significantly affected by the values for elasticities of substitution. In the baseline, for a given sector, these values are common across regions.[44] MACs are significantly affected by the values for the shares of fossil fuels used by firms and households. Economies that are highly intensive users of energy have more potential for substitution toward other factors (which can be thought of, implicitly, as implementation of clean technologies). Economies that use more coal relative to oil will respond more to an increase in carbon prices, as coal has a higher proportion of carbon. These share parameters are determined by the data. They have a large impact on emission intensity, measured as emissions divided by GDP (Table 4.5).

Even though emission intensities decline over the baseline, reflecting gradual improvements in efficiency, non-Annex I regions are consistently much more intensive in their use of energy than Annex I regions. All else being equal, this implies that the most efficient return on investments in mitigation will come from the non-Annex I regions.

The net effects of substitution elasticities and shares on marginal abatement costs can be seen in Table 4.6, which calculates percentage emis-

[44]This reflects the paucity of data for many of these regions and is one of the major sources of parameter uncertainty in mitigation cost studies.

Figure 4.15. Global Emissions from Energy Only, 2030
(Gigatons of carbon dioxide)



Sources: IPCC (2007); and IMF staff estimates.
[1]IPCC's *Special Report on Emissions Scenarios* (SRES).

Table 4.6. Emission Reductions and Consumption Losses Following a Standardized Carbon Price Shock
(Percent deviations from baseline path)

	United States	Japan	Western Europe	Eastern Europe and Russia	China	Other Developing and Emerging Economies	Organization of Petroleum Exporting Countries
Emission reduction	8.00	2.10	2.30	2.40	15.00	3.00	9.00
Rank	7.00	1.00	2.00	3.00	9.00	4.00	8.00
Consumption loss	0.22	0.12	0.19	0.33	0.50	0.25	2.00
Rank	3.00	1.00	2.00	5.00	8.00	4.00	9.00

Source: IMF staff calculations.
Note: Reduction in emissions and consumption losses measured at 2040, following a permanent unanticipated increase of $10 a ton of carbon beginning in 2013 for each region, leaving all other regions' carbon prices unchanged.

sion reductions and consumption losses from the baseline following a standardized carbon price increase of $10 per ton of carbon.

The table shows that Japan achieves the lowest emission reduction of all economies when it raises carbon prices by the same amount. It has the highest MAC, which implies that it will reduce emissions less than all other regions when faced with a common carbon price, or will find it advantageous to buy emission rights under a cap-and-trade system. On the other hand, China can achieve approximately seven times the emission reduction as Japan for the same cost.[45]

For the world economy, G-Cubed has the same or lower abatement costs compared with other models. The main reason is that it explicitly models capital flows, which makes it easier for economies to install new capital and shift away from carbon-based energy in production.[46]

Comparisons with Other Models

The range of issues implied by climate change economics is reflected in the wide range of models, each of which emphasizes different aspects of the problem. In general, all these models aim to bring climate change analysis into a macroeconomic framework. But they differ substantially in the complexity with which they model the macroeconomy, climate, and technologies.

To illustrate the range of differences, Table 4.7 summarizes features of some prominent models in the climate change literature:[47]

- PAGE, maintained by Chris Hope and Cambridge University and used for the *Stern Review* simulations (Plambeck, Hope, and Anderson, 1997);
- DICE, maintained by William Nordhaus at Yale and used in Nordhaus (2007b);
- EPPA/IGSM, maintained by a team at the Massachusetts Institute of Technology (Paltsev and others, 2005);
- MERGE, maintained by a team at Stanford University (Manne, Mendelsohn, and Richels, 1995); and
- MiniCAM, maintained by a team at Pacific Northwest National Laboratories (Brenkert and others, 2003).

All of these models can claim some comparative advantage, usually because of more elaborate modeling of a particular sector or mechanism. Some of the main differences include the following:

- whether behavior is optimizing and/or forward looking (which can affect the effectiveness of carbon price increases);

[45]In the experiment where a uniform carbon tax is imposed on all countries, this ratio increases to nearly 9:1, which illustrates the importance of reductions in export demand.

[46]The model is solved using linearization methods commonly applied to dynamic macroeconomic models. Linearization implies that responses of endogenous variables are proportional to the shock—a doubling of an increase in carbon taxes produces twice the reduction in emissions, for example. In practice, it may be that there are important nonlinearities in making the transition from old to new energy technologies.

[47]The latter three were used in US CCSP (2007).

Table 4.7. Comparison of Climate Policy Models

	G-Cubed	PAGE	DICE	EPPA/IGSM	MERGE	MiniCAM
Disaggregation	9 regions 5 energy sectors	8 regions Energy sectors not modeled	1 region (world) 2 energy sectors	16 regions 8 energy sectors	9 regions 9 energy sectors	14 regions 9 energy sectors
Expectations	Forward looking	Recursive	Forward looking	Recursive	Forward looking	Recursive
Dynamics and frequency	Annual frequency with intertemporal friction	1- to 50-year steps	10-year steps	5-year steps; vintage capital	10-year steps; putty-clay technologies	15-year steps; vintage capital
Factors used in production	Capital, labor, energy, materials	Not modeled	Capital, labor	Capital, labor, energy, materials	Capital, labor, energy	Energy, land
Equilibrium linkages	Full stock-flow constraints	Limited stock-flow constraints	Full stock-flow constraints	Full stock-flow constraints	Full stock-flow constraints	Limited stock-flow constraints
International linkages	Trade in differentiated goods and services, plus capital flows	Not modeled	Not modeled	Trade in all goods, differentiated by region	Trade in all goods, differentiated by region	Trade in energy and agricultural goods
Emissions and climate	Single gas (CO_2); no feedback from climate	Multiple gases; no feedback from climate	Single gas (CO_2e)[1]; feedback from carbon cycle	Multiple gases; feedback from atmospheric and oceanic climate	Multiple gases; feedback from oceanic climate	Multiple gases; feedback from land and climate models
Technology and energy-efficiency improvements	Both exogenous	Both exogenous	Feedback from climate onto productivity, exogenous AEEI[2]	Exogenous	Exogenous	Exogenous

Note: In models with “vintage” capital, the effective capital stock depends not just on the total cumulative investment over time (net of depreciation), but on the time at which investments were made. Production will therefore depend on the age profile of the capital stock. A closely related concept is “putty clay” technologies, in which investment—putty—is fungible, but once set as capital—clay—it is not.
[1]Carbon dioxide equivalent.
[2]Autonomous energy efficiency improvement.

- whether relative prices are articulated or not (which is important for modeling expenditure switching, factor substitution, external balances, and trade);
- whether there are endogenous monetary and fiscal policy reactions (in particular, the way carbon price revenues are recycled is potentially very important); whether there is stock-flow consistency (which is important to ensure that policies are not able to deliver “free lunches”); and
- whether there is an endogenous feedback mechanism via a carbon cycle model (important for modeling the medium- and long-term implications of policies).

For example, the PAGE model has a relatively simple structure and is designed more as a “meta-model” to quickly incorporate assumptions from other studies about climate change and to be simulated quickly and easily, facilitating the analysis of uncertainty. But it lacks some features that are important for this study, such as forward-looking expectations, modeling of fiscal policy, and trade and capital linkages. The DICE model is designed to show how agents might respond to endogenous productivity effects from feedback of climate change and some mitigation policies; it simplifies analysis by looking at the world in aggregate using a Ramsey growth model, hence missing regional and sectoral detail. EPPA/IGSM is a large, integrated assessment model that mates a dynamic computable general equilibrium model of many regions and sectors with an elaborate climate change model, but with some loss of tractability. Even then it omits some features, such as forward-looking expectations and international capital flows.[48] MiniCAM is also an integrated assessment model, with detailed modeling of

[48]None of the models described here explicitly model international capital flows. However, free flow of capital is implicit in the DICE model, as it models the world economy as a single sector.

energy, agricultural systems, and land use, but it is not intended for general equilibrium analysis; in particular, only energy and agricultural goods are traded. By contrast, G-Cubed models emissions but not the consequences for GHG concentrations and climate change, and is not suitable for a full cost-benefit analysis of mitigation policies. But G-Cubed includes extensive detail on relative prices and policy linkages for regions and sectors, which is the focus of this study.

A key difference in models used to assess emission policies is the assumptions made about technology. Some models—for example, PAGE—do not make any explicit technology assumptions. Of those that do, there are two main types. In the first, firms have discrete choices of specific technology assumptions (such as nuclear, coal-based, and so on), each requiring inputs to be used in fixed proportions (an example is the MERGE model). In the second, smooth production functions are used and are sometimes nested (see, for example, EPPA/IGSM and G-Cubed). Fixed-proportion models imply that firms must pass cost-benefit thresholds before switching to a new technology, whereas models with smooth production functions allow continual adjustment. In this study, substitution possibilities are very important for determining the costs of emission reductions. Whether the nonlinearities implied by fixed-proportion technologies will be important *in the aggregate* for the reaction to emission policies is an important issue to be resolved.[49]

It is therefore important to realize that models place different emphases on these assumptions of economic behavior, as well as different—though perfectly reasonable—assumptions about population and productivity growth, emission intensity, and clean technologies, as well as about nonclimate policies. Therefore, the models can produce very different scenarios for emissions and for the costs of reducing them. Hence we should put more emphasis on the qualitative mechanisms at work than any quantitative predictions.

[49]For more comment and comparisons, see Weyant (2004) and references therein.

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