

Climate Economics: The State of the Art



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Executive Summary

Climate science paints a bleak picture: The continued growth of greenhouse gas emissions is increasingly likely to cause irreversible and catastrophic effects. Urgent action is needed to prepare for the initial rounds of climatic change, which are already unstoppable. While the opportunity to avert all climate damage has now passed, well-designed mitigation and adaptation policies, if adopted quickly, could still greatly reduce the likelihood of the most tragic and far-reaching impacts of climate change.

Climate economics is the bridge between science and policy, translating scientific predictions about physical systems into projections about economic growth and human welfare that decision makers can most readily use. Regrettably, climate economics tends to lag behind climate science, especially in the slow-paced, peer-reviewed economics literature. The analyses rarely portray the most recent advances in climate science; instead, they often incorporate simplified representations of scientific knowledge that is out of date by several years, if not decades. Moreover, climate economics has often been hampered by its uncritical adoption of a traditional cost-benefit framework, minimizing or overlooking the deep theoretical problems posed by uncertainty, intergenerational impacts, and long-term technological change.

In late 2006, the Stern Review broke new ground by synthesizing the current knowledge in climate science and setting a new standard for good climate-economics analysis, using up-to-date inputs from climate science, introducing a near-zero rate of pure time preference (thus increasing the importance of future generations' welfare in today's climate decisions), and going beyond the costs and benefits of best-guess climate impacts to look at lower-probability catastrophic outcomes. Then, in 2007, the Intergovernmental Panel on Climate Change's Fourth Assessment Report (AR4) provided an authoritative and detailed update on the state of climate science.

Since 2007, both climate science and climate economics have advanced dramatically, partly in response to the well-publicized Stern Review. Scientific predictions have grown ever more ominous, with larger-scale impacts expected sooner than previously thought, along with growing evidence of near-term thresholds for irreversible catastrophes. The most likely outcomes are grave, even under scenarios of very ambitious emissions abatement. Limiting warming to 2°C, a widely embraced but challenging target, would still result in serious damages and require significant adaptation expenditures. In scenarios of future emissions without planned mitigation, the likely temperature increases would reach at least 4°C by the year 2100 and continue to increase thereafter.

As climate science has matured, it has revealed a slew of complex, nonlinear interactions in the physical system that make it difficult to describe a complete set of consequences with certainty. Under business-as-usual emissions scenarios, catastrophic climate outcomes are all too possible, and they become ever more likely as temperatures rise. A precautionary approach to limiting climate damages would require that emissions be reduced as quickly as possible and that efforts be made to accelerate the rate at which greenhouse gases are removed from the atmosphere. As this review demonstrates, such a precautionary approach is entirely consistent with the latest developments in both the science and the economics of climate change.

Continuing improvement in climate economics is important, above all, because such great credence is given to economic analysis in the public arena. The latest science shows that climate outcomes are intrinsically uncertain in detail but that catastrophic worst-case possibilities cannot be ruled out. It is not reasonable for an economic analysis of the same phenomenon to yield a single, definite, modest prediction of overall impacts. Rather, climate economics should have the same qualitative contours as climate science, with a range of irreducible economic uncertainty, including real risks of catastrophic losses. Our recommendations for aligning climate economics with climate science are as follows:

Climate-economics models should use an up-to-date representation of the climate system, including non-declining temperatures on a timescale of several centuries. Today's models of the physical climate system incorporate more interactions among systems and take account of irreducible uncertainty in future outcomes. The result is a more accurate and detailed range of likely temperatures, precipitation patterns, and rates of sea-level rise. Climate-economics models cannot match the overwhelming level of detail of the physical models. Instead, to achieve the state of the art in climate-economics, these models should approximate the range of potential outcomes in the latest scientific results.

Outcomes from climate change are uncertain, and climate-economics modeling results should reflect this uncertainty. Climate science projects a range of outcomes from bad to much worse; climate economics should do the same. Either by producing a range of results instead of a single best guess or by modeling multiple future states, climate-economics models should incorporate uncertainty. At a minimum, results should be presented based on the low end, middle, and high end of an up-to-date probability distribution for climate sensitivity.

Climate-economics models should incorporate up-to-date scientific findings on the expected physical and ecological impacts of climate change. To accurately model monetary damages as a function of temperature, economic models should incorporate recent scientific findings on sector-specific damages, regional variation in vulnerability and in baseline climate, human communities' reliance on ecological systems, and uncertainty in impact assessments, especially in the long run. Both low- and high-temperature damages must be subjected to serious, detailed economic evaluation. In particular, the common but entirely unsubstantiated practice of assuming that damages grow with the square of temperature should be discarded.

If damages cannot be accurately represented in welfare-optimization models, economists should instead use a standards-based approach. A precautionary, or standards-based, approach replaces welfare maximization with cost minimization, identifying the least-cost method of achieving a particular climate outcome – for example, keeping temperature increases below a threshold such as 2°C. This approach is consistent with the assumption that, beyond some threshold, even a small increase in temperature results in an unacceptably large increase in damages – an assumption that seems well-founded in science, and is ubiquitous in climate policy discussions.

All climate-economics analyses should be accompanied by an explanation of what discount rate was chosen and why. Regardless of model type and approach to discounting, climate-economics results should be presented together with an explicit statement of what discount rate was used and why. Where the case for using a particular discount rate is weak or ambiguous, presenting modeling results across a range of discount rates may improve policy relevance.

Policy relevance in climate economics depends on the ability to present impacts not just for the world as a whole but also by region or income group. It is simply not plausible that the welfare of the world's economically, culturally, and geographically diverse population can be well represented by the single "representative agent" of abstract economic theory. The diversity of climate effects around the world calls for at least the inclusion of multiple interest groups. At a minimum, climate-economics models should consider the concerns of poor and rich countries separately and should have the means to present results by region or other relevant grouping. In a similar vein, models that ignore or minimize interregional flows of funds for mitigation and adaptation should be explicit about the assumed institutional and political barriers to such flows.

Abatement costs should be modeled as both determining and determined by abatement investments. Abatement cost assumptions are key determinants of climate policy recommendations. Ideally, technological change should be modeled endogenously, taking into account learning and price reductions that grow with investments in a particular technology, rather than purely as a function of time. Our review of this literature also suggests that negative-cost abatement options (the fabled "low-hanging fruit"), while perhaps exaggerated at times, really do exist and should be taken seriously in economic analysis; that while the rebound effect (reducing the potential of energy-efficiency measures) also exists, backfire (a

rebound large enough to erase all energy-efficiency gains) is the economics equivalent of an urban legend; and that fossil fuel price assumptions are a significant determinant of the comparative affordability of different abatement measures.

In the end, analyzing climate change is not an academic exercise. The climate crisis is an existential threat to human society: It poses unprecedented challenges and demands extraordinary levels of cooperation, skill, and resource mobilization to craft and enact policies that will create a sustainable future. Getting climate economics right is not about publishing the cleverest article of the year but rather about helping solve the dilemma of the century. The tasks ahead are daunting, and failure, unfortunately, is quite possible. Better approaches to climate economics will allow economists to be part of the solution rather than part of the problem.

Chapter-by-chapter summary

Chapter I.0. Introduction: Climate science for economists

Economic analysis of climate change and climate policy requires a firm grounding in climate science. This rapidly evolving field is summarized every few years in assessment reports from the Intergovernmental Panel on Climate Change (IPCC). The latest of these, the *Fourth Assessment Report (AR4)*, appeared in 2007, reflecting peer-reviewed science through 2006. The next assessment (*AR5*) will appear in 2013-14. Part I of this report reviews the current state of climate science, emphasizing developments since *AR4* that are relevant to economic modeling.

Climate economics begins with predictions about the baseline or business-as-usual future of the world economy and its greenhouse gas emissions. Business-as-usual scenarios do not include plans for mitigation of emissions; they provide a baseline against which policy scenarios can be compared. The difference between climate impacts under business-as-usual and a policy scenario represents the extent of climate change that can be avoided by the proposed policy.

Our review of the recent (post-*AR4*) literature on the physical climate system identifies several important themes:

- Climate projections are now even more grave than represented in *AR4*: Emissions are at the highest end of the range projected; ice sheets, glaciers, ice caps, and sea ice are disappearing at an accelerated pace; and sea levels are rising more rapidly than expected.
- Critical tipping points for irreversible change are imminent and are difficult to predict with accuracy.
- Avoiding a 2°C increase in global temperatures above preindustrial levels – a commonly accepted benchmark for avoiding dangerous climate change – will require global emissions to be reduced to less than 20 percent of 2005 levels by 2050.
- The climate system is complex and nonlinear. Interactions and feedback loops abound, and newer work demonstrates that studies of isolated effects can lead to missteps, confusing a single action in a greater process with the complete, global result.
- “Overshooting” of global average temperatures is now thought to be irreversible on a timescale of centuries or millennia. Once a peak temperature is reached, it is unlikely to fall, even if atmospheric concentrations of greenhouse gases are reduced.
- Climate impacts will not be globally uniform. Regional heterogeneity is a strong theme in the new literature, shifting findings and research methods in every subfield of climate science.

Part I also reviews the scientific literature predicting the impact of climate change on natural and human systems. Of particular note in the post-*AR4* literature are impacts to forests, marine ecosystems, agriculture, coastal infrastructure, and human health. These climate impacts are the key inputs to assessments of the economic damages from climate change. In almost all cases, estimation of monetary damages lags far behind estimation of physical damages – there exists very little literature connecting the

physical impacts to their expected monetary costs. Instead, climate-economics models often employ generalized damage functions that assume simple, almost rule-of-thumb relationships between temperature and aggregate monetary losses (see Chapter II.1). This near-universal disconnect between the science and the economics of climate change is nothing less than astounding. Part I of this report is intended to help build the connection between these two complementary modes of inquiry about the nature and magnitude of the climate problem.

Chapter I.1. A complex truth: New developments in climate science

Climate economics has often lagged behind advances in science; many economic models have not yet incorporated the climate dynamics, risks, and impacts described in the IPCC's 2007 reports (*AR4*). Climate science, however, is not standing still; a number of important developments since *AR4* should be reflected in up-to-date economic modeling.

One recent discovery calls for a rethinking of mitigation scenarios: As emissions of greenhouse gases decline in the future, temperatures will not follow them downward. Instead, global average temperatures will remain at their peak level for centuries, if not millennia. Mechanisms such as gradual release of carbon dioxide from the oceans will block any decline in temperatures.

An active area of research concerns clouds and aerosols (airborne particulates). Clouds reflect sunlight away from the Earth; it is unclear whether warming increases or decreases cloud formation. Some aerosols reflect sunlight upward, and act as nuclei for cloud formation, slowing global warming. On the other hand, some aerosols have a net warming effect. Black carbon (soot) is thought to have a larger warming effect than any greenhouse gas except carbon dioxide.

Carbon-cycle feedbacks may have large and far-reaching effects. Rising temperatures – perhaps as little as 3°C of warming – could cause the release of enormous quantities of methane, now locked away in deep-sea sediments (methane hydrates) and in permafrost soil in the tundra and boreal forests. These releases could cause a much-accelerated, runaway greenhouse effect.

Climate sensitivity, the long-run temperature increase expected from a doubling of atmospheric CO₂ concentrations, is crucial to climate dynamics. Climate sensitivity estimates may be inescapably uncertain, implying a probability distribution with “fat tails” – i.e., with relatively large chances of extreme values. While 3°C is a best-guess estimate of climate sensitivity, there is growing discussion of worst-case possibilities of 6° – 7°C, or even higher. The risk of dangerously high climate sensitivity is central to economic theories of uncertainty (see Part II).

An intense debate about hurricanes (tropical cyclones) has reached an apparent consensus that warming will increase the intensity of storms, while disagreement continues over expected effects on the frequency of storms. South Asian monsoons are expected to become more intense and less predictable, with weak seasonal rainfall giving way to episodic, violent storms.

Recent research has projected rates of sea-level rise of 0.5 – 2.0m by 2100, a major change from *AR4*. These projections do not assume the collapse of the Greenland or West Antarctic ice sheet. Either of those events would eventually add many meters more, although the melting and sea-level rise would happen gradually, over a number of centuries.

Arctic sea ice is melting much faster than anticipated. Although this has only a small effect on sea-level rise, it replaces ice surfaces, which are very reflective, with open water, which is darker and absorbs more solar energy. Thus it leads to positive feedback, accelerating global warming.

Many climate risks involve tipping points, at which abrupt, perhaps irreversible transitions could occur. Recent studies suggest that loss of major ice sheets, the collapse of the Amazon rain forest, extinction of coral reefs, and large-scale release of methane from deep-sea deposits and tundra could occur at temperatures as low as 2° – 4°C of warming.

Chapter 1.2. Impacts on natural systems: Forests and fisheries

Climate change is not just a problem for photogenic species such as polar bears and coral reefs. Many species and ecosystems will be harmed by the early stages of climate change; impacts are expected to become widespread beyond 2°C, with critical aspects of ecosystem functioning beginning to collapse at 2.5°C. Tropical species, which normally experience little seasonal variation in temperature, may be the most affected.

Forests are affected in contradictory ways by climate change. On the positive side, they will benefit from carbon fertilization and from warmer temperatures and longer growing seasons at high latitudes and high altitudes. However, climate change means greater risk of forest fire, and damage by insects such as bark beetles. Fossil fuel combustion, the principal source of greenhouse gas emissions, leads to formation of ozone, which damages trees and offsets some of the benefits of carbon fertilization. In tropical forests, the combination of carbon fertilization and drought conditions may favor the growth of tree-strangling vines, potentially reducing the storage of carbon in those forests. Catastrophic collapse of tropical forests is a risk within this century; recent studies have estimated that the threshold temperature for irreversible dieback of the Amazon rain forest could be as low as 2°C, rather than the more commonly cited 3–4°C.

At the same time, the pace of climate change is affected by forests; stopping deforestation and promoting afforestation is frequently identified as a low-cost option for mitigation. Forest growth absorbs CO₂ from the atmosphere and increases evaporative cooling, lowering temperatures; on the other hand, forests have lower albedo (they are darker) than alternative land uses, so they absorb more solar radiation and reflect less, increasing temperatures. In the tropics the carbon absorption effect is stronger, so forest growth slows global warming. In boreal forests the albedo effect is stronger, and forest growth accelerates global warming. Temperate forests are intermediate, with indeterminate, probably small net effects. Thus attempts to combat climate change through forest sequestration must be concentrated on the tropics.

Fisheries, an important source of nutrition for many parts of the world, are affected both by ocean warming and by acidification (decrease in ocean pH). Warmer water temperatures are driving many fish species to lower depths and higher latitudes; the result will be a large increase in potential fisheries catch in subarctic areas, and a large decrease in the tropics. Species currently living near the poles, and in semi-enclosed seas, may become extinct. Among the species most sensitive to temperature are coral reefs, with widespread coral bleaching already associated with warming, and threats of more bleaching, and coral mortality, in the near future.

Absorption of CO₂ from the atmosphere lowers the pH of ocean water. This lowers the concentration of calcium carbonate, used by coral, mollusks, crustaceans and other species to form shells and skeletons. As carbonate concentrations drop, a tipping point could be reached by mid-century or earlier, at which it becomes much more difficult for calcifying species to form and maintain their shells.

In terms of catastrophic risk, acidification interacts with the temperature stress on coral reefs, potentially suggesting that some species are already headed for extinction; all coral may be unable to survive temperatures of 2.5°C or less. Arctic mammals are not far behind, with high risks of extinction expected before the world reaches 3°C.

Chapter I.3. Impacts on human systems: Agriculture, coastal zones, and human health

Human systems, as well as the natural environment, are likely to suffer serious damages from climate change, with major impacts expected on agriculture, coastal zones, and human health.

Studies of agriculture in the 1990s projected that the first few degrees of warming would bring significant net global benefits, due to carbon fertilization and longer growing seasons in colder regions. Newer research has lowered the projected benefits. Gains from carbon fertilization are smaller in more realistic outdoor experiments. Crops such as maize, sugar cane, sorghum, and millet do not benefit from carbon fertilization, and cassava yields are reduced at elevated CO₂ levels. Ground-level ozone, a result of fossil fuel combustion, lowers yields of many crops.

Recent research has illuminated temperature and precipitation effects on yields. For maize, soybeans, and cotton, there is a threshold temperature (29°C – 32°C) above which yields drop rapidly; the number of degree-days above the threshold is much more important than the average temperature. U.S. agricultural yields are projected to decrease sharply in this century, due to the threshold temperature effect. For California agriculture, access to irrigation is the key to yields; the principal climate threat there would be a decrease in the flow of water for irrigation. Other areas, such as India, also are at risk from interruption of precipitation or irrigation.

A recent global estimate suggests that warming will cause a 16 percent decrease in average yields without carbon fertilization, or 3 percent with carbon fertilization by the 2080s; this analysis does not include the threshold temperature effect. Nonetheless, it projects yield losses of more than 20 percent in many tropical regions, and more than 50 percent in parts of Africa.

Flooding threatens the nearly two-fifths of the world's population that lives in coastal zones. Understanding of sea-level rise is rapidly advancing, with geographically focused local studies identifying differential effects around the world; the continental United States, for example, is expected to face greater than average sea-level rise on both coasts. Areas most at risk include the large river deltas and coastal cities of Asia, the impoverished coastal regions of Africa, and small island nations that face extreme or even total inundation. Large-scale migration out of affected regions is a likely result, with unpredictable consequences. New modeling techniques allow analysis of storm surge effects in combination with sea-level rise. Five of the six most vulnerable big-city populations are located in India, China, and Vietnam; the ten cities with the most assets at risk are all in the United States, Japan, and the Netherlands.

Human health is threatened by climate change in several ways. Heat waves have caused widespread mortality and morbidity, notably in 2003 in Western Europe and in 2010 in Russia, but also in smaller events around the world. In the extreme, conditions that human physiology literally cannot survive without air conditioning become increasingly common beyond 7°C. Even a few degrees of warming affects labor productivity in tropical areas.

Mosquito-borne diseases such as malaria and dengue fever, now limited by temperature, will be able to extend their range as the world warms. Other air pollutants emitted from fossil fuel combustion cause a well-known range of health problems; reduction of these health impacts is an important co-benefit of emission reduction. Finally, changes in water availability, associated with spreading desertification, more variable monsoons, and predicted future decreases in glacier-fed river flow, are also harmful to health and sanitation.

Chapter II.0. The climate economics of Stern and his predecessors

Three fundamental features of climate change pose challenges to economic theory, requiring new approaches.

- *Uncertainty and irreversibility*: Climate science describes numerous high-stakes risks, some of which involve tipping points that could lead to abrupt and potentially irreversible transitions to

much worse outcomes. Probabilities of worst-case outcomes are uncertain, perhaps irreducibly so; learning by doing is not an option, since climate change will happen only once.

- *Deep time*: The earth's climate has enormous inertia; today's policy choices have effects that will be felt for centuries. This poses well-known, controversial problems for standard approaches to discounting. At the discount rates that are frequently used in cost-benefit analyses, economics seems to advise ignoring the welfare of future generations. The ongoing debate on these issues involves principles of both economics and ethics.
- *Global equity*: Emissions anywhere affect the climate everywhere; climate change is a global externality, and its solutions are global public goods. Yet there is extreme international inequality, both in climate impacts and in the resources required for mitigation and adaptation. Questions of equity and international negotiation, which have often been peripheral to economics, are central and inescapable in this case.

The best-known economic analyses of climate change before the *Stern Review* often seemed to minimize the problem: they adopted simple expected-value approaches to a limited range of uncertainties; they used discount rates high enough to effectively ignore far-future outcomes; and they said little about global equity.

Stern reached a very different conclusion, emphasizing the need for and the benefits of immediate large-scale action to reduce emissions. The analysis supporting this conclusion, however, made only modest changes to traditional approaches. Stern addressed uncertainty with the PAGE model, which includes a Monte Carlo analysis of a (relatively small) potential catastrophe; he embraced and eloquently restated the arguments for a low discount rate; and he emphasized the urgency of achieving a global agreement that is acceptable to all.

The *Stern Review* transformed the landscape of climate economics and broadened the international policy debate, demonstrating that rigorous economic analysis could recommend much more than incremental responses. It did not, however, represent the last word on any of the underlying theoretical and methodological issues. Rather, Stern opened the way for widespread innovation in climate economics. In the five years since the *Stern Review*, there has been a remarkable flourishing of new economic approaches, described in the following chapters.

Chapter II.1. Uncertainty in climate economics

The most important development in climate economics since the *Stern Review* is Martin Weitzman's "Dismal Theorem," a densely mathematical proof that, under plausible assumptions and standard models, the marginal benefit of emission reduction is infinite. The two crucial assumptions are that climate uncertainty is so great that there is a relatively high probability of extreme outcomes (that is, the probability distribution is fat-tailed), and that the loss of human welfare that could be caused by those extreme outcomes is limitless, as they approach the point of endangering the survival of the human race. Subsequent comments and re-examinations of the Dismal Theorem have shown that changes to either assumption can lead to a finite (though perhaps large) value of emission reductions. Both Dismal Theorem assumptions, however, seem quite plausible, while some of the proposed alternatives seem rather ad hoc.

Many analyses of climate uncertainty, including the Dismal Theorem, focus on the crucial but unknown climate sensitivity parameter (see Chapter I.1). Equally important, but less studied, is the uncertainty about the magnitude of economic damages that will occur as temperatures rise. Damage estimates in well-known economic models such as DICE, FUND, and PAGE rely on limited and dated empirical research, such as studies of agriculture from the early 1990s that projected large benefits from the first few degrees of warming (see Chapter I.3 for newer research on climate and agriculture). Another paper by Weitzman suggests an alternative approach, assuming much larger damages as temperatures rise above 3°C. Such alternatives imply a large increase in estimates of the "social cost of carbon" (i.e. the marginal damages from an additional ton of CO₂ emissions).

Several studies explore the effects of multiple uncertainties, often within the framework of the DICE model. A small-scale Monte Carlo analysis by Nordhaus compares economic and climate uncertainties, with the surprising result that higher temperatures are positively correlated with higher incomes; this occurs because the study assumes large variation in economic growth but small variation in climate outcomes. Other studies have generally found that inclusion of greater uncertainty in DICE leads to more active, precautionary policy recommendations.

A growing area of research addresses the treatment of risk aversion in climate economics. In the traditional framework, using the so-called “Ramsey equation,” increased risk aversion seems to imply a higher discount rate and smaller willingness to pay for mitigation. Newer work, by Newbold and Daigneault among others, shows that in the presence of sufficient uncertainty, greater risk aversion can increase willingness to pay for mitigation.

The paradoxes surrounding the Ramsey equation and the discount rate in climate economics are close analogues of the “equity premium puzzle” (in finance, optimal growth models fail to explain why long-run average returns are so high on stocks and so low on bonds). A fruitful new area of research involves application to climate economics of proposed solutions to the equity premium puzzle. For example, the Ramsey equation implies a close, and counterintuitive, connection between the intertemporal elasticity of substitution (which determines how we choose between present and future consumption) and risk aversion. Survey research confirms that these parameters are not, in fact, closely connected in practice. A leading response to the equity premium puzzle, Epstein-Zin utility, breaks the link between risk aversion and intertemporal substitution. Our own current research involves use of the Epstein-Zin utility function in climate economics models.

Chapter II.2. Public goods and public policy

Although climate policy choices are often analyzed in a private investment framework – as in the analogues to the equity premium puzzle in Chapter II.1, for instance – there are several reasons why this framework may not be adequate. Unlike most private investments, climate policy is intergenerational, with consequences far in the future. Public policy in general is different in scope, with options for collective response to risks that are not individually insurable. And public policy decisions are ideally democratic, weighting individual opinions equally regardless of wealth or spending, and allowing special consideration of the needs of lower-income or at-risk populations. Many new developments in climate economics reflect these broader concerns.

New approaches to discounting include: theoretical grounds for declining discount rates and explicit preferences for sustainability; the need for a differential discount rate for increasingly scarce environmental goods and services; recognition that uncertainty about future growth lowers the discount rate in the Ramsey equation; and a growing discussion of reasons why, even in a private investment framework, the appropriate discount rate might be at or below the risk-free rate of return (perhaps roughly comparable to the *Stern Review* discount rate in numerical value, though not in underlying logic).

Other approaches to intergenerational impacts include overlapping generations models, allowing separate treatment of costs, benefits, and preferences of successive generations. In addition, the relatively new technique of “real options” analysis, developed by analogy to financial options, calculates the value of climate policies that preserve options for future decision-makers.

A different decision framework focuses on avoiding catastrophic risks. Various referred to as “safe minimum standards,” “tolerable windows,” or “precaution,” it is loosely analogous to insurance. Non-economic policy proposals are often cast in these terms, as in the goal of avoiding 2°C of warming. Standards-based approaches lead to cost-effectiveness analysis of least-cost strategies for meeting the standard. They can be seen as a special case of cost-benefit analysis, in which the shadow price of benefits (or avoided damages) becomes infinite, or at least greater than the marginal cost of maximum feasible abatement. Standards-based approaches can also be based on alternative frameworks for

decision-making under extreme uncertainty, such as the “minimax regret” criterion, choosing the option that minimizes potential losses.

As a completely global public good (or public bad), climate change inevitably raises questions of international equity. Free-rider problems and debates over appropriate burden-sharing arrangements are endemic in negotiations. Climate economics models are typically silent on these questions, although there have been recent attempts to add equity weighting calculations onto existing models. A technical procedure used for solving complex models, “Negishi welfare weights,” contributes to the failure to address distributional issues; our own model, CRED, attempts to overcome this limitation, explicitly incorporating equity and development issues.

A wide range of burden-sharing proposals, embodying differing visions of equity, have been proposed in international negotiations, both to allocate the atmosphere’s scarce remaining capacity to absorb greenhouse gases and to distribute the costs of mitigation. Game theory models of climate negotiation have illuminated some possible patterns and pitfalls, although the outcomes depend on unresolved issues about how antagonistic or cooperative the climate policy “game” will turn out to be.

Chapter III.0. Scenarios for mitigation and adaptation

There are many proposed solutions to the global climate problem. Quick action on abatement can no longer spare us from all climate damages, but it could avoid the worst impacts and risks of climate catastrophe described in Part I. Regrettably, the problems described in Part II have complicated economic analysis and limited its value to the climate policy process, with some economic models still recommending very little short-run investment in mitigation.

The widely used, alternative “standards” or “cost-effectiveness” approach (see Chapter II.2) offers very different advice. When a standard is set for a maximum temperature increase or atmospheric concentration of greenhouse gases, numerous researchers agree that the resulting policy recommendation is for rapid, sustained abatement. In particular, the goal of keeping warming below 2°C (relative to pre-industrial levels) has become ubiquitous, with multiple studies finding that it requires immediate, large-scale reduction in emissions.

The goal of staying below 2°C of warming does not derive from economic optimization models. Rather, it is a widely accepted estimate of a threshold for avoiding the worst damages from climate change. Indeed, some advocacy organizations have called for even lower targets. Small island nations, among the most vulnerable to the first 2°C of temperature increase, have called for a threshold below 1.5°C of warming.

Meanwhile, even achieving the 2°C target is a tall order. The IPCC’s new scenario RCP 4.5, roughly corresponding to the old B1 (with the slowest-growing emissions among the old IPCC SRES scenarios), has, according to a recent U.K. government study, only a 4-percent chance of staying below 2°C. A new, lower IPCC scenario, RCP 3-PD, has about a 50 percent chance of keeping mean warming below 2°C. In that scenario, global emissions peak in 2015 and then plummet, with small net negative emissions (that is, sequestration exceeds emissions) by 2090. Our review of twenty scenarios that achieve similar results finds that all have similar, demanding requirements for rapid abatement: emissions peak in 2020 at the latest, and then fall rapidly. The higher and later the emissions peak, the more rapid the subsequent decline must be.

Few if any countries have made commitments consistent with these global reductions. The voluntary terms of the Copenhagen Accord, formalized in the Cancún Agreements, allow such high near-term emissions that drastic reductions will be required later to stay below 2°C; the same was true of the targets in the (failed) proposals for U.S. climate legislation in 2010. The world will either have to get much more serious about controlling emissions, or face temperature increases well above 2°C.

Chapter III.1. Technologies for mitigation

To achieve goals such as staying below 2°C of warming, an ambitious suite of new technologies will be required, some not yet created and others not yet commercialized.

Energy efficiency measures are among the lowest-cost options for emission reduction (the problem of “rebound” effects is discussed in Chapter III.2). Options for reducing CO₂ emissions from fossil fuel combustion are well-known, and are not reviewed here in detail. The gradual decarbonization of the electricity sector can rely on many low and no-carbon sources of power generation. It is likewise possible to reduce space and water heating emissions from commercial and residential buildings, using heat pumps, solar water heating, and other options. Emissions from transportation pose a greater challenge, requiring investment in public transit and a massive shift to non-petroleum vehicles, along with creation of the appropriate fueling infrastructure.

Other sources of emissions and opportunities for mitigation are not always included in climate economics models. After fossil fuel combustion, agriculture and land use changes represent the next-largest share of greenhouse gas emissions. Options for reducing agricultural methane and nitrous oxide emissions include changes in fertilizer use, tilling practices, and livestock feed. Carbon sequestration in soil is a complex and imperfectly understood part of the picture.

Carbon capture and sequestration (CCS) at power plants could become important, although it has yet to move beyond the stage of pilot projects. Several technologies for carbon capture exist, but have not yet been shown to be affordable and free of undesirable environmental impacts. Storage of the captured carbon requires a network of new pipelines, and large-scale, geologically stable disposal sites; leakage from those sites could cause numerous forms of damage. Nonetheless, CCS is crucial to many of the leading mitigation scenarios in current policy discussions.

Expanding forested areas and avoiding new deforestation are low-cost, feasible options for sequestering carbon. As noted in Chapter I.2, these efforts should be concentrated in tropical forests in order to have the desired effect on global warming. A number of practices might increase carbon sequestration in plants and in soils; biochar, forming charcoal from biomass and storing it in soil, is one widely discussed example, with moderately large potential.

Black carbon (soot) has recently been recognized as a major contributor to global warming, with many low-cost opportunities for reduction; it has complex interactions with other air pollutants, some of which contribute to cooling the earth.

Other options are farther from being practical, or in some cases, still quite speculative. Artificial capture of carbon dioxide from ambient air is one futuristic possibility. Ocean fertilization – seeding the oceans with iron, often thought to be a limiting factor in algae growth and hence in carbon absorption – has been tested, with disappointing results. Releasing sulfate aerosols into the atmosphere to reflect more incoming sunlight and cool the earth is a problematical idea. Once started, it would have to be repeated indefinitely; any interruption could lead to very rapid warming, with worse effects than the gradual warming it was designed to prevent.

Chapter III.2. Economics of mitigation

Estimates of the costs of mitigation differ by orders of magnitude, contributing to rival perspectives on the economic impact of climate policy. In the short run, mitigation costs depend on current technologies and prices; in the long run, the future evolution of technology becomes more and more important.

Many models have assumed that the rate of technical change is constant, independent of policy or experience. This has often been called the rate of “autonomous energy efficiency improvement.” Under this assumption, it becomes cheaper to wait as long as possible before investing in abatement. An alternative assumption is more realistic, but also more difficult to model: technological progress is endogenous, influenced by past experience. Learning curves, or “learning by doing” effects, are common

in empirical studies of specific technologies; costs per unit of production typically decline as the cumulative volume of production increases. Incorporation of learning curves into climate economics models is a relatively new area of research; not surprisingly, such models show greater returns to investment in new technologies. On the other hand, climate-related investments could crowd out investments in other industries, reducing the overall pace of technological change. Limited research on this possibility has not yet reached a clear conclusion.

One of the greatest gaps in the recent literature is the lack of attention to the price of oil and other fossil fuels. Mitigation measures frequently reduce consumption of fossil fuels, so their full cost impact, including benefits of avoided fossil fuel consumption, will go down when fuel prices go up, and vice versa. This is a hidden source of disagreement between economic analyses: higher projected oil prices imply lower net cost of mitigation. Climate policies can thus be a valuable hedge against uncertainty in oil markets.

A longstanding theoretical and empirical debate concerns the possibility of negative-cost abatement: is it possible to save money and energy at the same time? Studies from McKinsey & Company, among others, identify large negative-cost opportunities to reduce emissions. Standard economic theory, on the other hand, suggests that such opportunities are as rare as \$20 bills on the sidewalk – if they existed, someone would have already picked them up. A few older studies attempt to explain the market failures and barriers that might allow continued existence of negative-cost energy savings potential; there is little recent work on this important topic.

A recent controversy surrounds the “rebound effect,” which can reduce the net impact of energy efficiency measures. When improved efficiency reduces energy requirements and costs, households and businesses effectively become richer, and increase overall spending. This spending implies some increase in energy use, taking back some of the reductions achieved by efficiency. Contrarian arguments periodically claim that the rebound effect can amount to more than 100 percent of the original efficiency savings, an outcome dubbed “backfire” in one recent account. Empirical studies find no evidence of backfire, and suggest that rebound effects of 10 to 30 percent are common, with some larger and some smaller than that range. Even with rebound effects in this range, energy efficiency is often a very low-cost option for emission reduction.

Chapter III.3. Adaptation

Climate damages have already begun to occur. And even under rapid mitigation scenarios, damages will worsen in years to come, caused both by delayed effects of past emissions, and by the emissions expected in the near future. Adaptation, the process of reducing vulnerability to these damages and enhancing resilience toward changing climatic conditions, is now recognized as an essential component of climate policy.

It has proved difficult, however, to include adaptation in economic analyses. There is no single definition or measure of adaptation. The appropriate measures and technologies for adaptation are extremely localized, in contrast to mitigation technologies, which are often applicable across nations and latitudes. The expected costs of adaptation are contingent on the scenario of future mitigation; at the same time, the extent of adaptation affects climate damages, and therefore, the optimal level of mitigation. This interactive, endogenous system is extremely challenging to model. Omission of a region’s or sector’s damages or adaptation costs can distort calculation of optimal policies, but, as the *Stern Review* observed, a comprehensive catalogue of potential damages and adaptive measures is not feasible.

Another challenge is the substantial overlap between adaptation to climate change and measures that will enhance the quality of life under any scenario; many adaptation measures lead double lives as sensible steps toward economic development. As incomes rise, particularly in developing countries, the capital stock vulnerable to climate damage will grow larger, but investments in infrastructure, housing and energy are likely to become more robust to climate change. Recent literature focuses on the critical process of “climate-proofing” development.

A related issue is the impact of climate change on economic growth. Countries with higher average temperatures have, on average, lower GDP per capita. Temperature increases over the past 50 years have been associated with reduced growth in poorer countries, but uncorrelated with growth in richer countries. This suggests that damage functions and feedback between the climate and economic growth are misspecified in many economic models (see Chapter II.1).

Moreover, some proposed adaptation measures have substantial benefits regardless of future climate change. Economic models that omit such benefits will underestimate the optimal extent of adaptation investment.

A few attempts have been made to bring adaptation into climate economics models. A common finding is that the optimal policy is a mix of adaptation and mitigation, with a rapid start to mitigation, followed by adaptation investments. While important, adaptation should not be permitted to crowd out near-term mitigation.

Confirming the difficulty of defining and measuring adaptation, recent studies have estimated global costs for near-term adaptation measures at annual amounts ranging from \$4 billion to \$166 billion. Other studies have estimated adaptation costs for developing countries of \$80 billion to \$230 billion a year by 2030. A recent review of these estimates suggests that it is premature to draw a conclusion regarding even the order of magnitude of adaptation costs.

Introduction

Climate science paints a bleak picture: The continued growth of greenhouse gas emissions is increasingly likely to cause irreversible and catastrophic effects. Urgent action is needed to prepare for the initial rounds of climatic change, which are already unstoppable. While the opportunity to avert all climate damage has now passed, well-designed mitigation and adaptation policies, if adopted quickly, could still greatly reduce the likelihood of the most tragic and far-reaching impacts of climate change.

Climate economics is the bridge between science and policy, translating scientific predictions about physical systems into projections about economic growth and human welfare that decision makers can most readily use. Regrettably, climate economics tends to lag behind climate science, especially in the slow-paced, peer-reviewed economics literature. The analyses rarely portray the most recent advances in climate science; instead, they often incorporate simplified representations of scientific knowledge that is out of date by several years, if not decades. Moreover, climate economics has often been hampered by its uncritical adoption of a traditional cost-benefit framework, minimizing or overlooking the deep theoretical problems posed by uncertainty, intergenerational impacts, and long-term technological change.

In late 2006, the Stern Review broke new ground by synthesizing the current knowledge in climate science and setting a new standard for good climate-economics analysis, using up-to-date inputs from climate science, introducing a near-zero rate of pure time preference (thus increasing the importance of future generations' welfare in today's climate decisions), and going beyond the costs and benefits of best-guess climate impacts to look at lower-probability catastrophic outcomes. Then, in 2007, the Intergovernmental Panel on Climate Change's Fourth Assessment Report (AR4) provided an authoritative and detailed update on the state of climate science. Since these two landmark publications, many climate-economics models have taken Stern's work as a new benchmark. Others, however, still use outdated estimates of physical impacts, trivialize economic damages from climate change, and oversimplify the climate problem. As a result, these models – some of which have proven influential in the policy arena – continue to call for very gradual emissions mitigation.

Since 2007, both climate science and climate economics have advanced dramatically, partly in response to the well-publicized Stern Review. Scientific predictions have grown ever more ominous evidence of near-term thresholds for irreversible catastrophes. The most likely outcomes are grave, even under scenarios of very ambitious emissions abatement. Limiting warming to 2°C, a widely embraced but challenging target, would still result in serious damages and require significant adaptation expenditures. In scenarios of future emissions without planned mitigation, the likely temperature increases would reach at least 4°C by the year 2100 and continue to increase thereafter.

As climate science has matured, it has revealed a slew of complex, nonlinear interactions in the physical system that make it difficult to describe a complete set of consequences with certainty. Under business-as-usual emissions scenarios, catastrophic climate outcomes are all too possible, and they become ever more likely as temperatures rise. Even under emissions mitigation scenarios aimed at staying below 2°C, there is a chance of worse-than-expected outcomes, with temperatures rising by more than 4°C in this century. A precautionary approach to limiting climate damages would require that emissions be reduced as quickly as possible and that efforts be made to accelerate the rate at which greenhouse gases are removed from the atmosphere. As this review demonstrates, such a precautionary approach is entirely consistent with the latest developments in both the science and the economics of climate change.

Continuing improvement in climate economics is important, above all, because such great credence is given to economic analysis in the public arena. Quantitative analysis is often taken as proof of expertise. "Bottom line" conclusions from cost-benefit analyses are widely cited in policy debates – especially in the United States but in other countries as well. Traditional climate-economics analyses that are far behind the research frontier are thus used as arguments against the urgent warnings from climate science.

Climate economics must be aligned with climate science. The latest science shows that climate outcomes are intrinsically uncertain in detail but that catastrophic worst-case possibilities cannot be ruled out. It is not reasonable for an economic analysis of the same phenomenon to yield a single, definite, modest prediction of overall impacts. Rather, climate economics should have the same qualitative contours as climate science, with a range of irreducible economic uncertainty, including real risks of catastrophic losses.

Fortunately, as this review demonstrates, the latest developments in climate economics go well beyond this simple correspondence, presenting new insights into the unique theoretical and practical challenges posed by the problem of climate change.

The structure of this report: a preview

This report provides a synthesis of the current state of the art in climate economics (as of early 2011). It begins with key findings from climate science as they affect economic analyses, then turns to recent developments in economic theory, and concludes with the economics of mitigation and adaptation.

Part I, *Climate Science*, reviews the current science of the physical processes and impacts of climate change. It places special emphasis on findings qualitatively different from the 2007 IPCC report – and puts these findings in the context of their importance in climate-economic analysis. Part I begins by reviewing the latest forecasts for “business as usual” emission scenarios – assuming no purposeful greenhouse gas mitigation. We focus especially on the “Representative Concentration Pathways” that will be used as part of a set of central emissions scenarios in AR5, the next IPCC Assessment Report.

Chapter I.1, “A complex truth,” looks at areas in which there have been significant new findings since AR4, including the pace of emissions growth and temperature increases; the rate at which ice sheets, glaciers, ice caps, and sea ice are disappearing; current and future sea-level-rise rates; and “tipping points,” or thresholds for irreversible change to climate and ecological systems. We also look at climate interactions and feedback loops, and the growing body of literature on regional heterogeneity in climate impacts. We highlight a finding from our review of the science literature that is of particular importance to climate-economics modeling: New research demonstrates that “overshoot” scenarios, where temperatures reach a peak and then decline to a desired target, are not feasible.

Chapter I.2, “Climate Change Impacts on Natural Systems,” looks at new research on climate impacts to forests and fisheries, both of which are complex and not easily quantifiable. Climate change will have both negative and positive effects on forest growth, which, in turn, will have mixed effects on the climate. Recent studies suggest that tropical forest growth will slow warming, but boreal forest growth will accelerate it by reducing the albedo effect. New research also shows how great the ecosystem impacts of ocean warming and acidification will be, with the extinction of many coral species possible within this century. Marine species will also be moving toward the poles, reducing the fish catch in all but the highest latitudes.

Chapter I.3, “Climate Change Impacts on Human Systems,” begins with agriculture. New research on CO₂ fertilization and on the relationship between temperature and crop yields supports a much less optimistic outlook for global food production than was previously assumed. The chapter also looks at new models of sea-level rise, which predict much more serious impacts and permanent inundation of some coastal areas within this century, and important differences across regions. Projections of climate effects on human health and welfare have also become direr, with higher temperatures, precipitation changes, and more intense weather patterns taking a heavy toll.

Part II, *Climate Economics for the 21st Century*, details several transformative advances in the field. Climate change poses unique challenges to economic theory, requiring economists to delve into unfamiliar territory. Earlier analyses, some of which continue to influence public policy, often tried to apply traditional cost-benefit frameworks, leading to results that did not reflect the unique challenges of

the climate crisis. Newer economics research uses different analytical approaches, especially related to the economics of uncertainty, discounting, and equity.

Part II begins by looking at the treatment of uncertainty and discounting in climate economics before the Stern Review and at the innovations introduced by Stern. Previous economic models of climate change were typically framed as cost-benefit analyses, evaluating known or expected outcomes; in some cases, predictable, bounded variation was included via Monte Carlo analysis. Stern argued that economists must take the risk of catastrophic damages seriously, although he did not completely break with past modeling approaches. In discounting, the conventional wisdom implied that discount rates should be relatively high; Stern argued for a low discount rate, for ethical reasons, with a near-zero rate of pure time preference.

Chapter II.1, “Uncertainty,” takes an in-depth look at the economic implications of several dimensions of uncertainty in climate change. The probability distribution of potential outcomes is still an area of unsettled science; there are small but nontrivial probabilities of irreversible, catastrophic changes, with greater likelihood of these outcomes as temperatures rise. Long-term catastrophic risk is the subject of some of the most important recent developments in climate economics. We look at Weitzman’s argument about unbounded risk arising from irreducible uncertainty about the pace of climate change – and at the less widely discussed but also crucial uncertainty about the relationship between temperature increases and the magnitude of economic damages. We also review several studies that incorporate new approaches to uncertainty, concluding with new interpretations of risk aversion and parallels to similar topics in finance.

Chapter II.2, “Public Goods and Public Policy,” addresses the many reasons why climate policy choices should be made on a different basis from private investment decisions, including the intergenerational implications of climate policy, the “global public good” nature of the problem, and questions of equity within and between countries. These considerations have important implications for discounting and can lead to alternative decision-making criteria and policy frameworks. As an alternative to utility maximization, some economists have advocated a focus on avoiding the risks of possible climate catastrophes, an approach analogous to insurance against catastrophe. This approach starts by setting a threshold (e.g., a maximum temperature increase) necessary to avoid certain catastrophic damages (or keep their likelihood below a certain level) and then looks for the most cost-effective way to meet the standard.

The chapter ends by looking at different burden-sharing approaches that have been proposed to address equity issues in global climate negotiations and then evaluating the prospects for international climate negotiations, which some economists have analyzed in terms of game theory and strategic interaction.

Part III, *Mitigation and Adaptation*, examines the technologies and the economics of mitigation and adaptation. Drawing on the standards-based, or cost-effectiveness, approach described in Chapter II.2, it begins by exploring the latest research on climate thresholds, as well as the emissions scenarios consistent with a 50/50 or better chance of staying below the “2°C guardrail.” Even if the world acts promptly to reduce carbon emissions, temperatures are still expected to rise by another 0.1° to 0.6°C, and sea levels by another 0.1 to 0.3m, by 2100, with substantial impacts on vulnerable regions around the world.

Chapter III.1, “Technologies for Mitigation,” looks at recently proposed strategies for reducing emissions and even achieving negative net emissions by removing greenhouse gases from the atmosphere: from well-understood approaches such as improved energy efficiency, tree planting, and painting roofs and roadways white, to new ideas such as fertilizing the oceans so that they grow more carbon-sequestering algae, and larger-scale “geoengineering.” The chapter also looks at the technology choices made in specific mitigation scenarios developed by the International Energy Agency, McKinsey & Company, and several models’ low-emission scenarios.

Chapter III.2, “Economics of Mitigation,” reviews new approaches to mitigation in climate economics. Older models often overestimated the cost of mitigation, basing estimates on current costs of mitigation

technology, or assumed that costs would decrease automatically over time, requiring no investments in innovation now to reap productivity gains in the future. New models are exploring ways to endogenize technological change, including important effects for “learning by doing.” The chapter also looks at the impact of widely divergent assumptions about future oil prices, one of the leading determinants of abatement costs, and at controversies over the accuracy of negative abatement cost projections and over assumptions about the “rebound effect” in energy efficiency.

Chapter III.3, “Adaptation,” briefly reviews different approaches to adaptation, which vary considerably across regions. We examine the interconnections among adaptation, mitigation, and development and their implications for economic modeling. This chapter also reviews recent modeling exercises in this relatively new field and concludes with an overview of estimates of the costs of climate adaptation.

The *Conclusion* briefly summarizes and draws out the implications of the report.

Part I: Climate science for economists

Climate analysis requires both economics and science. Climate science is a rapidly evolving field, rich with new areas of research, important advances that refine our understanding of well-established facts, and an increasing reliance on interdisciplinary approaches to complex research questions. Every few years, this body of knowledge is pulled together, subjected to additional layers of peer review that require the agreement of many experts within a field, and published in Intergovernmental Panel on Climate Change (IPCC) Assessment Reports. The latest of these – the Fourth Assessment Report (AR4) – was released in 2007 (IPCC 2007), reflecting peer-reviewed literature through 2006. The next IPCC Assessment is expected in 2013-2014.

The process of predicting future economic impacts from climate change and deciding how best to react to those impacts begins with predictions about the baseline, or “business as usual,” future world economy and the greenhouse gas emissions that it is likely to release. Climate scientists build on these economic projections, combining them with records of past climatic changes and the most up-to-date knowledge about the climate system, to predict future atmospheric concentrations of greenhouse gases, temperature increases, and other climatic changes. These projections of our future climate system are used to estimate the type and magnitude of impacts expected in terms of physical and biological processes, such as changes to water availability, sea levels, or ecosystem viability. Economic modeling places monetary values both on measures that would reduce greenhouse gas emissions and avoid climate damages (the costs of mitigation) and on the physical damages that are avoided (the benefits of mitigation). Comparisons of climate costs and benefits are offered to policy makers as recommendations of the best actions to take.

Each step in this process – from baseline economic projections to climate policy recommendations – adds more uncertainty, which is a central theme of this report. Part I reviews the current state of the art in climate science as it relates to economic modeling. After a brief discussion of the latest forecasts for “business as usual” (no mitigation) emissions, we review the latest projections of the future climate and the expected impacts to natural and human systems. We summarize climate system projections and impacts both in terms of the most likely, “best guess” prediction, and less probable, but still possible, worst case (at times, catastrophic) predictions. Parts II and III discuss techniques for economic impact assessment, as well as the estimation of costs of mitigation and adaptation under conditions of uncertainty.

Business-as-usual emissions

Baseline, or business-as-usual, emission scenarios do not plan for greenhouse gas mitigation. These projections are sensitive to assumptions about population and economic growth, innovation and investment in energy technologies, and fuel supply and choice. Baseline emissions for future years vary widely. The most optimistic business-as-usual scenarios assume significant reductions in carbon per unit energy and in energy per dollar over time, together with slow population growth and slow economic development. These scenarios project atmospheric concentrations of CO₂ as low as 500-600 ppm in 2100 – up from 392 ppm CO₂ today.¹ Pessimistic business-as-usual scenarios project the growth of global emissions over time, with CO₂ concentrations reaching 900-1,100 ppm by 2100. It should be noted, however, that new research suggests that parameters commonly used to link concentrations to emissions may be mis-specified; the fraction of CO₂ emissions sequestered in land and ocean sinks may be shrinking in response to climate change, suggesting that atmospheric concentrations would be higher at every level of emissions (Le Quéré et al. 2009).

¹ Globally averaged marine surface monthly mean CO₂ concentration for April 2011, NOAA Earth System Research Laboratory (n.d.).

In this report, we will refer to a range of business-as-usual scenarios from 540 to 940 ppm in 2100; these endpoints are chosen to match two of the Representative Concentration Pathways, RCP 8.5 and RCP 4.5, that will be used as part of a set of central emissions scenarios in AR5, the next IPCC Assessment Report.²

- RCP 8.5 was developed using the MESSAGE model. This scenario reaches 540 ppm CO₂ in 2050 and 936 ppm CO₂ in 2100 (or 1,231 ppm CO₂-equivalent [CO₂-e]) in 2100, including measures of all climate “forcing” agents); by 2060, it exceeds 560 ppm CO₂, or double preindustrial concentrations – an important milestone related to the rate of temperature change, discussed in Chapter I.1. Emissions in RCP 8.5 are similar to those of the SRES A1FI scenario, used in previous IPCC Assessment Reports. CO₂ emissions grow from 37 Gt CO₂ in 2010 to 107 Gt CO₂ in 2100.
- RCP 4.5 was developed using the MiniCAM model. It reaches 487 ppm CO₂ in 2050 and 538 ppm CO₂ in 2100 (or 580 ppm CO₂-e in 2100); in this scenario, concentrations stabilize before exceeding 560 ppm CO₂. Emissions in RCP 4.5 are similar to those of SRES B1, with emissions peaking between 2040 and 2050 and falling to 16 Gt CO₂ in 2100 – a 43 percent decrease from 1990 emissions (a common benchmark). The RCP 4.5 scenario requires substantial use of carbon capture and storage technology (see Chapter III.2) and energy efficiency measures; coal use falls significantly, while biomass, natural gas, and nuclear energy grow in importance.³ Clearly, this scenario involves investments that have the effect of reducing emissions, but it does not necessarily involve *planned* mitigation with the purpose of reducing greenhouse gas emissions.

The table below compares the RCP concentration projections to those of SRES, as well as to business-as-usual projections from a recent Energy Modeling Forum (EMF) meta-analysis⁴ and International Energy Agency (IEA) Energy Technology Perspectives.⁵ RCP 8.5 falls in the upper half of EMF baseline scenarios, while RCP 4.5 is more optimistic than is any EMF projection. IEA projections extend only to 2050 and exceed those of RCP 8.5 for that year.

² RCP Database (IIASA 2009). The two scenarios are named for their radiative forcing pathways, which lead to 8.5 and 4.5 W/m² in 2100. Radiative forcing is discussed in Chapter I.1.

³ See also Clarke et al. (2007).

⁴ The EMF exercise compared ten integrated assessment models; see Energy Modeling Forum (2009).

⁵ International Energy Agency (2008).

Business-as-Usual Emissions Scenarios

Scenario	CO ₂ Concentration (ppm)		Year exceeding 560 ppm CO ₂
	2050	2100	
RCP 8.5	540	936	2060
RCP 6.0	478	670	2080
RCP 4.5	487	538	NA
RCP 3-PD	443	421	NA
SRES A1FI	561	964	2050
SRES A2	527	846	2060
SRES A1B	527	710	2060
SRES B2	476	616	2090
SRES A1T	499	579	2080
SRES B1	485	545	NA
EMF baseline: highest	571	1030	2050
EMF baseline: mean	522	782	2060
EMF baseline: lowest	499	612	2080
IEA 2008 baseline	550		

Sources: See text.

Climate projections and uncertainty

AR4 found unequivocal evidence of global warming and rising sea levels (Intergovernmental Panel on Climate Change 2007, Synthesis Report, Chapter 1.1) and reported a very high confidence that these changes are the result of anthropogenic greenhouse gas emissions (2.2). The report also found it likely (with a probability greater than 66 percent) that heat waves and severe precipitation events have become more frequent over the past 50 years (1.1). Even if further emissions were halted, great inertia in the climate system would mean that the earth was “locked in” to several centuries of warming and several millennia of sea-level rise (although at a far slower pace than would take place with additional emissions) (3.2.3). Continuing the current trend of emissions could lead to abrupt or irreversible changes to the climate system (3.4).

Although it lags behind the most current research, AR4 is the standard reference for the field. In 2009, the University of New South Wales Climate Change Research Centre (CCRC) published a comprehensive review of the literature released since the close-off for material included in AR4 (Allison et al. 2009).⁶ CCRC emphasizes several areas of research in which there have been significant new findings:

- Greenhouse gas emissions and global temperatures are following the highest scenarios (A1F1) considered in AR4. Recent CO₂ emissions have been growing three times faster than they were in the 1990s (p. 9).⁷
- The rate at which ice sheets, glaciers, ice caps, and sea ice are disappearing has accelerated (pp. 24-31).
- The current rate of sea-level rise was underestimated in AR4, as were projections of future sea-level rise (p. 37).

⁶ The U.K. government’s AVOID program has also released an update of climate science literature since AR4 with similar findings. See Warren et al. (2009).

⁷ The economic downturn led to a reduction in global emissions beginning in 2009. It is not clear how long the downturn, or the reduction in emissions, will last, but preliminary data from the IEA (2011) suggest that CO₂ emissions were greater in 2010 than in 2008.⁸ Changes in temperature relative to 1990 levels.

- Critical thresholds for irreversible change to climate and ecological systems are both imminent and difficult to predict with accuracy. There is a risk of crossing these tipping points before they are recognized (pp. 40-42).
- A two-out-of-three chance of avoiding a 2°C increase in global temperatures above preindustrial levels – the now-ubiquitous benchmark for avoiding dangerous climate change found in both the science and policy literatures (p. 50) – will require that by 2050, emissions be reduced by 80 to 100 percent from their 2005 levels, depending on the year in which emissions peak (p. 51).

In this report, Chapter I.1, “A complex truth,” focuses on several areas where advances since AR4 seem especially salient, and – within this focus – expands on the 2009 CCRC study by including literature published through early 2011. Of course, researchers in most areas of climate science have published significant literature over the past five years, but not all scientific findings – even when important for the development of the field – overturn previous results; many advance their field by making small improvements in accuracy or precision, confirming earlier findings, or ruling out counterfactuals. In our assessment, areas in which new findings represent a change to older research or an otherwise significant advance in our understanding of the climate system include albedo and reflection of solar radiation by clouds, aerosols and black carbon, and carbon-cycle feedbacks; sensitivity of temperature to the changes in the atmospheric concentration of greenhouse gases; frequency and intensity of severe weather; downscaling of precipitation forecasts; a complete makeover for AR4’s sea-level-rise projections; and the unforeseen pace of sea ice loss.

To CCRC’s assessment of the most important themes in contemporary climate science we add three more, discussed in detail in Chapter I.1:

1. The climate system is complex and nonlinear. Interactions and feedback loops abound, and newer work demonstrates that studies of isolated effects can lead to missteps, confusing a single action in a greater process with the complete, global result.
2. “Overshooting” of global average temperatures is now thought to be irreversible on a timescale of several millennia. Once a peak temperature is reached, it is unlikely to fall, even if atmospheric concentrations of greenhouse gases are reduced.
3. Climate impacts will not be globally uniform. Regional heterogeneity is a strong theme in the new literature, shifting findings and research methods in every subfield of climate science.

Climate impacts

While complex interactions can make specific regional outcomes difficult to predict, the latest climate science tells us that the likely effect of continued greenhouse gas emissions is a warmer climate with rising sea levels and more intense storms, and that there is a chance that business-as-usual emissions could lead to climatic changes that would result in a largely unrecognizable earth in the future. Economic analysis of climate change impacts takes as its starting point detailed scientific assessments of the effects of continued greenhouse gas emissions on human communities: How will climate change impact our sources of food and other materials? Will there be damages to buildings and infrastructure? How do emissions impact human health and water availability? Economists’ assignment of costs and benefits can be only as good as the scientific assessments upon which those assignments are based, and development of integrated assessment models must begin by synthesizing the scientific literature on impacts.

This literature, as it stood in 2006, was well represented in AR4 (IPCC 2007, Working Group II, Technical Summary, TS4.1), and many of these findings have been confirmed by more recent studies. With climate change resulting from business-as-usual (SRES A2) emissions:

- The number of people exposed to water stress will triple by 2050. Precipitation effects will vary regionally. In areas where precipitation is projected to increase, its variability will likely grow, as will the risk of floods. Many regions that are arid today will have less precipitation in the future, with the expected consequence of an increased demand for irrigation water.

- By 2100, many ecosystems will no longer be able to adapt naturally to climate change. The structure and functioning of both terrestrial and marine ecosystems will undergo substantial changes, and 20 to 30 percent of species will be at risk of extinction.
- Human health will be impacted by malnutrition, water stress, injury in extreme weather events, exposure to ground-level ozone, and increased incidence of certain diseases. Decreased mortality from cold exposure will be outweighed by increased mortality related to rising temperatures. Today, climate change is already increasing the incidence of disease and premature deaths.
- The communities at greatest risk of the worst climate-related damages are those that live in coastal lowlands, river deltas, or low-lying islands; rely on climate-sensitive resources; are in the midst of rapid urbanization; or have low-income populations.

The AR4 findings still represent the best knowledge regarding these impacts. Post-2007 studies refine these projections, but new research does not overturn or otherwise qualitatively change these findings. On the whole, the latest science confirms that the expected impacts of climate change are severe and takes important steps toward accurate and precise prediction of these impacts. There are several key research areas, however, where the newest studies offer findings that are qualitatively different from AR4. These impact areas are the focus of Chapters I.2 and I.3 of this report.

Chapter I.2, “Climate Change Impacts on Natural Systems,” focuses on new research regarding climate change impacts to forests and fisheries. Forests’ interaction with the changing climate system is complex; forests will experience both negative and positive effects from climate change, and the climate system will experience both increases and decreases to overall warming from forest growth. New research suggests that warming will be slowed by tropical forest growth and accelerated by boreal forest growth; temperate forest growth will have little effect. Other recent studies have clarified the ecosystem effects of ocean warming and decreased ocean pH. Coral reef ecosystems – important habitats and breeding grounds for many marine organisms – are expected to face widespread extinction of many species in the coming decades. The geographic distribution of marine species around the world will shift as sea-surface temperatures grow warmer, resulting in decreased fish catch everywhere but in the highest latitudes.

Chapter I.3, “Climate Change Impacts on Human Systems,” examines the latest research on climate change impacts to agriculture, coastal infrastructure, and human health. A better understanding of CO₂ fertilization – and of the relationship between temperature and agricultural productivity – calls into question older projections of increasing global food production with climate change. Newer, more accurate modeling of a full range of influences on sea-level rise now shows much more serious impacts, including some coastal communities facing permanent inundation in this century, even in scenarios with slower greenhouse gas emissions. Newer modeling also demonstrates important regional differences in the rate of sea-level rise. Higher temperatures and sea-levels, as well as new, less predictable and more intense weather patterns, will have costly impacts on the health of human communities around the world.

These climate impacts are the key inputs to assessments of the economic damages from climate change. In almost all cases, estimation of monetary damages lags far behind estimation of physical damages – there exists very little literature connecting the physical impacts to their expected monetary costs. Instead, climate-economics models employ generalized damage functions that assume a simple, often quadratic relationship between temperature and losses to global economics output in a rule-of-thumb effort to assign an order of magnitude to monetary losses (see Chapter II.1). This near-universal disconnect between the science and the economics of climate change is nothing less than astounding. Part I of this report is intended to help build the connection between these two complementary modes of inquiry about the nature and magnitude of the climate problem.

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Chapter I.1: A complex truth

Many areas of the science of our climate system are well understood: Increased concentrations of greenhouse gases in the atmosphere are amplifying the sun's ability to warm the earth, changing precipitation levels and other weather patterns, causing sea levels to rise, and decreasing pH levels in the oceans. A strong scientific foundation, however, does not always lead to precise forecasts of climate outcomes. While the larger relationship among greenhouse gas emissions, global temperatures, and sea levels is clear, policy makers' and economists' call for greater precision in modeling future climate impacts presents a challenge to the field. Climate dynamics are rarely simple or linear, and long temporal lags complicate both modeling efforts and popular perceptions of humans' role in causing – and stopping – climate change. In many regions around the world, the present-day effects of CO₂ and other greenhouse gas emissions are unobservable, and year-to-year variability in weather obscures longer-term climatic shifts. Feedback mechanisms, both physical and biological, are of great importance in the work of reducing uncertainty in climate projections.

Evidence has grown, in recent literature, of tipping points, or critical thresholds, for important components of the earth's physical and ecological systems. Once these thresholds have been passed, the effects on global systems will not be instantaneous but they will be world-changing and irreversible on a timescale of many centuries or millennia. A threshold of a 0.5 to 2°C global average temperature increase (with a range beginning well below the commonly cited but imprecise 2°C target for avoiding dangerous climate damages) will likely signal an end to Arctic summer sea ice and an eventual collapse of the Greenland Ice Sheet. At 3 to 4°C, the Amazon rainforest could begin a permanent dieback. At 3 to 5°C, West African monsoon circulation could be interrupted, the West Antarctic ice sheet could start a gradual collapse, and the Atlantic thermohaline circulation could be significantly disrupted. At 3 to 6°C, the El Niño-Southern Oscillation effects could become more severe.⁸ Many of these impacts will have important feedback effects on the climate system (Lenton et al. 2008).

It is also widely recognized that some level of climate change is now irreversible. Even if all greenhouse gas emissions were halted today, by 2100 global mean temperatures would rise by another 0.1 to 0.6°C (above year 2000 levels),⁹ and sea levels would rise by another 0.1 to 0.3m from the slow, implacable process of thermal ocean expansion, plus an uncertain additional amount up to 0.1m in this century, as land ice continues to melt in response to the global temperature increase that has already taken place (Wigley 2005).¹⁰

As emissions continue, further temperature increases are now thought, likewise, to be irreversible. Global average temperatures over the next millennia will be strongly determined by peak atmospheric CO₂ concentrations; that is, temperatures will plateau even as greenhouse gas concentrations fall (Solomon et al. 2009; Gillett et al. 2011; Matthews and Caldeira 2008).¹¹ Using a common but controversial “best guess” assumption about climate sensitivity (the relationship between concentration and temperature, discussed below), if concentrations peak at 450 ppm CO₂, temperature increase will plateau at about 0.9°C; for a 650 ppm peak, 1.8°C; for 850 ppm, 2.7°C; and for 1,200 ppm, 4.2°C.¹² This important new finding suggests that under emissions scenarios that involve “overshoot” (exceeding target concentrations

⁸ Changes in temperature relative to 1990 levels.

⁹ Using a range of climate sensitivities from 1.5 to 4.5°C.

¹⁰ Relative to 1990 sea level.

¹¹ According to Solomon et al. (2009) and Gillett et al. (2011), temperatures are expected to increase along with CO₂ concentrations but will remain constant (within $\pm 0.5^\circ\text{C}$) for the 2,000 years after CO₂ concentrations peak. Near-constant temperatures result from a near balance between 1) the decrease in radiative forcing due to shrinking CO₂ concentrations; and 2) gradually warming oceans, a process which will lessen their ability to remove heat from the atmosphere.

¹² See Solomon et al. (2009). Results assume a climate sensitivity of 3.2°C.

with the goal of soon dropping back to lower levels), the climate will “remember” the overshoot rather than the eventual target for centuries to come.¹³

Finally, since the publication of AR4 (2007), great strides have been made in improving climatic projections. A central, important theme in this new literature is the heterogeneity of regional impacts. Global average temperature change and sea-level rise are still good shorthand indicators for the overall sign and scale of the problem, but they do not reflect the regional magnitude of temperature and sea-level changes, nor do they comprise the full extent of expected climate change. Physical and biological feedback processes will translate global warming into regionally specific changes in precipitation, storm frequency, and/or intensity, as well as far-reaching changes to ecological systems.

The review presented here of key advances in climate systems science since 2007 underscores the essential role that the incorporation of uncertainty plays in research efforts throughout the field. This chapter describes several dynamic areas of research that are pushing climate science toward a more complex assessment of future impacts, with greater regional specificity and an enhanced appreciation of both global and regional interdependency of climate, atmosphere, ocean, terrestrial, and ecological systems. We discuss recent advances in the study of clouds, aerosols, and black carbon; carbon-cycle feedbacks; climate sensitivity; storm patterns; precipitation; sea-level rise; and sea ice. Finally, we summarize advances in climate system research in terms of both the most likely impacts of continued business-as-usual emissions and the catastrophes that are projected to occur with low but still important probabilities.

Clouds, aerosols, and black carbon

The impact of anthropogenic emissions on global temperatures is often discussed in terms of “radiative forcing” – the changes that greenhouse gases make to the global balance of energy, measured in incoming solar energy per unit of surface area as watts per square meter (W/m^2). On the whole, the relationship between greenhouse gases (CO_2 , methane, nitrous oxide, and a host of gases with smaller effects) and global average temperature increase is well established, but several ancillary effects introduce uncertainty, among them feedback from cloud albedo, reflectivity of aerosols and their role in cloud formation, and radiation absorbed by black carbon.¹⁴

Cloud albedo

Cloud cover reflects some solar radiation away from the earth’s atmosphere before radiative forcing can take place. Compared to many other surfaces, clouds have a relatively high albedo, defined as the fraction of incoming solar energy reflected back into space. The warmer temperatures that result from greenhouse gas emissions have two feedback effects on clouds: increasing albedo and hence reducing radiative forcing, and doing the opposite. Higher sea-surface temperatures result in more evaporation and more clouds, increasing the albedo effect as radiation reflects off the light-colored surface of clouds. At the same time, warmer temperatures can increase the likelihood of precipitation and cloud dissipation, revealing darker (low-albedo) land and water below and increasing the absorption of solar radiation.

Current models differ regarding the net impact of cloud feedbacks on radiative forcing. A recent review of the literature found that the general circulation models that best predict the seasonality of Arctic cloud cover over the last half-century project that rising greenhouse gas emissions and global temperatures will increase the region’s cloud cover (Vavrus et al. 2008). Another study using a different methodology, however, suggests the opposite effect: Rising temperatures will lead to reduced cloud cover (Clement et al. 2009). New research reveals the heterogeneity of cloud albedo impacts both regionally and seasonally,

¹³ For a more detailed review of current research on overshoot, see Warren et al. (2009), section A.9.

¹⁴ See NOAA Earth System Research Laboratory (2010) for a discussion of the radiative forcings of greenhouse gases and an index of these gases’ impacts on the global energy balance over time.

dynamics that will have important effects on the design of future studies (Balachandran and Rajeevan 2007; Vavrus et al. 2008; Clement et al. 2009).

Aerosols

Small particles in the atmosphere called aerosols (some of which result from the burning of fossil fuels and biomass) have two effects on radiative forcing: aerosols, like clouds, reflect solar radiation away from the earth's atmosphere. They also can act as "cloud condensation nuclei" that encourage the formation of clouds. Again, the newest studies show these effects to be highly regionalized, because local atmospheric pollution is an important predictor of cloud formation and precipitation (Sorooshian et al. 2009), and suggest flaws in previous research techniques that inaccurately model radiative forcing from partly cloudy conditions as the average of clear and overcast conditions (Charlson et al. 2007).¹⁵

Current anthropogenic radiative forcing is estimated at +1.6 (90 percent confidence interval: +0.6, -2.4) W/m² in AR4, including -0.5 ± 0.4 W/m² from the direct (that is, excluding cloud-formation) effects of aerosols (Intergovernmental Panel on Climate Change 2007, Working Group I, Chapter 2).¹⁶ A study by Myhre (2009) updates aerosols' direct effect to -0.3 ± 0.2 W/m², a decrease in their expected cooling that drives up overall radiative forcing to +1.8 W/m².

Black carbon

Aerosols' direct impacts on radiative forcing are composed of both negative and positive effects. Most atmospheric aerosols reflect solar energy, but a few, most importantly black carbon (soot), absorb it. Aerosols' direct effect of -0.50 ± 0.40 W/m², as reported by AR4, included $+0.20 \pm 0.15$ W/m² from atmospheric black carbon. In addition, total anthropogenic radiative forcing was estimated to include an additional $+0.10 \pm 0.10$ W/m² from surface soot-reducing snow and ice albedo (IPCC 2007, Working Group I, Chapter 2).

Ramanathan and Carmichael (2008) review updated estimates of atmospheric black carbon's impact on radiative forcing, presenting a new central value of +0.9 (-0.5, +0.3) W/m², more than half of total anthropogenic effects. With the exception of CO₂, black carbon has a larger radiative forcing than any greenhouse gas, aerosol, or albedo effect, although its presence in the atmosphere is measured in weeks as compared to decades or centuries for many greenhouse gases (Ramanathan and Carmichael 2008).¹⁷ The range of possible impacts from soot is wide, in part because of regionalized effects such as weather and the presence of other pollutants (Moffet and Prather 2009; Ramana et al. 2010), as well as the vertical distribution of black carbon in the atmosphere (Zarzycki and Bond 2010). Black carbon on Himalayan glaciers, for example, is accelerating the rate at which the glaciers melt, reducing long-run water availability (Xu et al. 2009).

Updated values for black carbon's snow albedo effect reduce AR4 estimates to +0.05 (90 percent confidence interval: +0.01, -0.12) W/m², with some variation related to the extent of boreal forest fires in a given year (Flanner et al. 2007). Some researchers trace black carbon on snow to fossil fuels burned in eastern North America and in Asia over time (McConnell et al. 2007). Others report that nine-tenths of

¹⁵ For reviews of the state of research on aerosols and climate change, see Rosenfeld et al. (2008) and Stevens and Feingold (2009).

¹⁶ Radiative forcing in 2005 relative to 1750.

¹⁷ Shindell and Faluvegi (2009) discuss advances in measuring the long-term impact of emissions and aerosols on radiative forcings, including interaction effects. For a critique of Ramanathan and Carmichael (2008), see Zarzycki and Bond (2010). Note that both CO₂ and black carbon can contribute more than half of anthropogenic radiative forcing, because there are also negative contributions, e.g., from other aerosols.

Arctic black carbon on snow results from combined natural and anthropogenic biomass burning (Hegg et al. 2009).¹⁸

Carbon-cycle feedbacks

Some of the least-understood feedback effects to the climate system may have large and far-reaching results. Among these are complex biological interactions among soil, vegetation, and climate systems. Warming temperatures will release greenhouse gases now locked away in frozen sediments below the oceans and in the permafrost soils of the tundra and boreal forest ecosystems. Forest systems sequester carbon, reducing atmospheric concentrations, but this storage is both sped up by carbon fertilization and disrupted by wildfires and forest dieback. Forest albedo is an additional countervailing force – carbon fertilization results in more carbon sequestration but also more dark surface areas that absorb more radiation; the net effect of forest feedbacks varies by latitude, as explained in Chapter I.2. A recent study reports that negative carbon-cycle feedback – the uptake of carbon by land and ocean – is four times greater than is positive feedback but far more uncertain (Gregory et al. 2009).

Oceanic sedimentary deposits

Deep-sea sediments hold between 1,600 and 2,000 Gt of carbon in methane hydrates, hundreds of times the annual mass of anthropogenic carbon released into the atmosphere each year (net emissions amount to 4.1 Gt C per year¹⁹). With 3°C of warming, 35 to 940 Gt C are expected to be slowly released from this reserve as methane, depending on the behavior of the gas bubbles as they pass through additional layers of sediment on their way to the surface. Models of 450 and 600 Gt C releases of methane hydrate deposits show an additional 0.4 and 0.5°C of warming, respectively (Archer et al. 2009). Shallow ocean deposits are particularly unstable; even a 1.0°C change in ocean temperature could trigger a significant release of deposits (Moridis and Reagan 2009).

Approximately 540 Gt of carbon lying under a layer of permafrost beneath the Arctic Ocean was thought, until recently, to be extremely stable. New research shows that Arctic submarine permafrost is currently venting methane hydrates and finds an abrupt release of as much as 50 Gt C highly possible – an amount twelve times greater than the current atmospheric concentrations of methane (Shakhova et al. 2008; Shakhova et al. 2010).

Methane released from soils

Still more carbon is stored in terrestrial soil, although the net effects of climate change on these deposits is uncertain. Climate change may facilitate removal of carbon from the atmosphere by some types of plants and sequestration in soil; conversely, decomposition of organic matter is accelerated by warming, thereby releasing greenhouse gases back into the air (Davidson and Janssens 2006; Khvorostyanov, Ciais, et al. 2008; Khvorostyanov, Krinner, et al. 2008). The northern permafrost region accounts for 16 percent of the world's soil area and contains 50 percent of the world's below-ground carbon (Tarnocai et al. 2009). In a recent paper, O'Donnell et al. (2010) discuss the complex interactions among temperature, precipitation, snow cover, and wildfire in determining the rate of release of carbon from frozen soils in the boreal region. Schuur et al. (2009) find that in the long run, thawing permafrost releases more carbon than plant growth absorbs, suggesting that this source may generate significant carbon emissions with climate change, perhaps as much as the current release of carbon from land-use changes (1.5 ± 0.5 Gt C per year).

Small temperature increases also have a much larger effect on CO₂ emissions from Arctic peatlands than previously thought. Under experimental conditions, annual CO₂ emissions accelerated by 50 to 60 percent

¹⁸ For a detailed synthesis of recent literature on black carbon and tropospheric ozone, see United Nations Environment Programme and World Meteorological Organization (2011).

¹⁹ Intergovernmental Panel on Climate Change (2007), Working Group I, Technical Summary.

with just 1°C of warming due to enhanced respiration of peat deposits – results that are consistent with annual emissions of 38-100 Mt of carbon (Dorrepaal et al. 2009). Nitrous oxide emissions from permafrost are an additional source of global warming potential that is still under study (Repo et al. 2009).

Studies also show that methane is released from wetlands with warming. Predictions for year 2100 methane emissions increase by 30 to 40 percent when feedback from warming is included in model assumptions (Eliseev et al. 2008; Volodin 2008).

Forest feedback effects

Positive and negative feedbacks of climate change on forests, and of forests on climate change, are discussed in detail in Chapter I.2. As explained there, increased CO₂ concentrations accelerate tree growth, especially in young trees, but the higher temperatures and changes in precipitation expected with climate change are expected to increase tree mortality in many regions as a result of more frequent wildfires, among other effects. In the Amazon, negative impacts from climate change are expected to dwarf positive effects; a recent study suggests that the threshold temperature for permanent loss of the Amazon forest may be as low as 2°C. Forests impact climate change via carbon sequestration, changes in the evaporative cooling caused by forests, and variations in their albedo (where clear cutting leads to higher albedo and afforestation leads to lower). Net forest feedback is expected to be negative (reducing warming) for tropical afforestation, neutral for temperate forests, and positive (increasing warming) for boreal forests.

Climate sensitivity

The influence of the basic “greenhouse effect,” together with the feedback effects of clouds, aerosols, and other factors (discussed later in this chapter), can be expressed in terms of the “climate sensitivity parameter,” defined as the equilibrium global average temperature increase caused by a doubling of the atmospheric concentration of CO₂. The climate sensitivity parameter plays a central role in the economic analysis of climate uncertainty, as seen in Chapter II.1.

An important recent paper shows that uncertainty about climate sensitivity is an unavoidable consequence of the nature of the climate system itself, suggesting that further research will not significantly narrow the distribution of climate sensitivity estimates (Roe and Baker 2007). The direct effect of greenhouse gases, with no feedback effects, would lead to climate sensitivity of about 1.2°C. Temperature increases, however, cause positive feedback, amplifying the direct effect. If a temperature increase of ΔT causes positive feedback of $f\Delta T$, where $0 < f < 1$, then the ultimate effect is the direct effect multiplied by $1/(1-f)$. As f approaches 1, small uncertainties in f translate into large uncertainties in $1/(1-f)$ and hence into climate sensitivity. A similar logic implies irreducible uncertainty in complex, positive-feedback systems in general; the earth’s climate may be the most important example (Roe 2009).²⁰ Climate sensitivity estimates may be inescapably uncertain, implying a probability distribution with “fat tails” – i.e., with relatively large chances of extreme values.

Since AR4, some studies have widened the distribution of climate sensitivity estimates, and almost all studies have pushed the estimated distribution to the right, toward higher climate sensitivities. AR4 gave a likely (two-thirds probability) range of climate sensitivity as 2.0 to 4.5°C, with a most likely value of 3.0°C (IPCC 2007, Working Group I, Chapter 10.2).²¹ Newer studies show a range (90 percent probability) of climate sensitivity of 1.5 to 6.2°C (Hegerl et al. 2006; Royer et al. 2007) and suggest that climate sensitivity may vary over time (Williams et al. 2008). One analysis of the paleoclimatic record

²⁰ For a technical critique of this analysis of feedbacks, see Zaliapin and Ghil (2010) and the original authors’ response (Roe and Baker 2011).

²¹ The IPCC ranks the likelihood of climate sensitivity falling within this range as “likely,” indicating a 17 to 83 percent confidence interval, and states that it is “very unlikely” (90 percent probability) that climate sensitivity would be below 1.5°C (see IPCC 2007, Working Group I, Box 10.2).

supports a long-run climate sensitivity of 6°C, doubling the most likely estimate presented in AR4. According to this study, slow climate feedbacks related to ice loss, changes in vegetation, and greenhouse gases released from soil and ocean sediments are not included in most general circulation models but could have important temperature effects on a timescale of centuries or less (Hansen et al. 2008). Other paleoclimatic research has found that the data support even higher estimates of long-run climate sensitivity, from 7.1 to 9.6°C (Pagani et al. 2009).²²

Our review of this literature suggests that at present there is no single distribution of climate sensitivities that can be identified as the new norm; climate sensitivity research is still in flux, and markedly different distributions are being employed by different researchers. Two recent analyses of the climate sensitivity distribution warrant special mention:

- The Murphy et al. (2004) distribution, with a median value of 3.5°C and a fifth to 95th percentile range of 2.4 to 5.4°C. This distribution does not incorporate the latest findings on the probability of very low and very high climate sensitivities, but it is the distribution used – in combination with uncertainty distributions for ocean vertical diffusivity and temperature/carbon-cycle feedback amplification – in Bernie’s (2010) analysis of the temperature implications of the AR5 RCP emission scenarios (see the introduction to Part I).
- Roe and Baker (2007) explore a range of recently published climate sensitivity distributions – including Murphy et al. (2004) – and offer a generalized function with two free parameters that can be chosen to provide a good fit to most recent distributions.²³ Roe and Baker incorporate evidence from newer studies of the climate sensitivity distribution, suggesting a greater probability of higher values.

Climate sensitivity is the key link between greenhouse gas emissions and most climate damages. As of early 2011, CO₂ concentrations had reached 392 ppm,²⁴ up from 280 ppm in preindustrial times.²⁵ Business-as-usual emission scenarios vary greatly (as discussed in the introduction to Part I); the range of projected baseline CO₂ concentrations – with little or no planned mitigation – appears to be 540 to 940 ppm in 2100, using the AR5 RCP 8.5 and RCP 4.5 emission scenarios as benchmarks for the top and bottom of this range, respectively (see the introduction to Part I). (When a full suite of radiative forcing agents is included, these levels correspond to 1,230 and 580 ppm of CO₂-e in 2100.) The temperature increases caused by these concentrations depend on the unknown – and perhaps unknowable – level of climate sensitivity, several other less-studied and uncertain parameters (including ocean vertical diffusivity and temperature/carbon-cycle feedback amplification), and the time lag before temperatures approach the equilibrium level associated with changes in atmospheric CO₂.²⁶

According to Bernie (2010), the range of temperature increases consistent with this range of business-as-usual concentration projections is 2.3 to 7.1°C (from the 10th to the 90th percentile of combined probabilities across three uncertain parameters). At the 50th percentile of the uncertainty distribution, the mean temperature change across these two scenarios is 4.2°C. At the high end of business-as-usual emissions scenarios, there is a near-zero chance of staying below an increase of 3°C and a 6 percent chance of staying below 4°C; using the lowest baseline scenario, with a 43 percent decrease from 1990

²² See Warren et al. (2009), section A.8, for a discussion of several additional recent studies on climate sensitivity.

²³ The U.S. Interagency Working Group on Social Cost of Carbon (2010) uses a truncated version of the Roe and Baker distribution, asserting that this distribution updates the IPCC climate sensitivities with the most up-to-date information about the tails of the distribution. The Working Group calibrates and truncates the Roe and Baker distribution using three constraints derived from AR4: 1) setting the median equal to 3°C, 2) two-thirds probability of falling between 2.0°C and 4.5°C, and 3) zero probability of being less than 0°C or greater than 10°C.

²⁴ Globally averaged marine surface monthly mean CO₂ concentration for April 2011, NOAA Earth System Research Laboratory (n.d.).

²⁵ IPCC (2007), Working Group I, Technical Summary, p. 25.

²⁶ Equilibrium temperature lags several millennia behind peak concentration, but it takes just 25 to 50 years to reach about 60 percent of the temperature change associated with a given climate sensitivity although higher climate sensitivities are associated with longer time lags (Hansen et al. 2005; IPCC 2007, Working Group I, Chapter 10).

CO₂ emissions by 2100, there is a 4 percent chance of staying below an increase of 2°C, a 53 percent chance of staying below 3°C, and an 88 percent chance of staying below 4°C. And these temperatures, once reached, might not fall for millennia, even with dramatic decreases in CO₂ concentrations (Solomon et al. 2009; Gillett et al. 2011).

Storm patterns

Another ongoing debate in climate science regards the projected effects of greenhouse gas emissions on hurricanes (tropical cyclones). AR4 found it likely (with a two-thirds probability) that there would be an increase in the lifetime and intensity of hurricanes with climate change and that it's possible that their frequency would decrease (IPCC 2007, Working Group I, Technical Summary and Chapter 3.8).²⁷ Some studies find that hurricane frequency, too, will increase as sea-surface temperatures rise (Mann and Emanuel 2006; Knutson et al. 2008; Elsner et al. 2008; Wang and Lee 2009; Yu and Wang 2009; Mann et al. 2009). Others find that hurricane frequency may diminish or remain unchanged, even as hurricane wind speed becomes more intense (Wang and Lee 2008; Emanuel et al. 2008; Barsugli 2009).

A clear anthropogenic signal has been identified in the factors influencing changes in precipitation extremes (Min et al. 2008), but research continues on the causes of and regional variations in tropical cyclone formation in the Atlantic, Pacific, and Indian oceans. Some studies find sea-surface temperatures to be the best predictor of hurricane formation (Zhang and Delworth 2009), while others point to vertical shear from increased radiative forcing (Kim et al. 2009). The mechanisms causing increased hurricane intensity are also a source of some dispute. Climate-change-induced shifts in the location of hurricane formation may increase the length of storms tracks over the open ocean and allow more time for storms to absorb energy before striking land (Wu and Wang 2008).

Like hurricanes, South Asian monsoons are likely to increase in intensity with climate change. Monsoon weather has become less predictable over the past few decades (Mani et al. 2009; Turner and Slingo 2009); warmer sea-surface temperatures have been linked to the increased intensity and reduced predictability of the monsoon in the Indian Ocean near Australia (Taschetto et al. 2009). The departure of monsoons from their past pattern is expected to continue and to manifest in an abrupt transition from weak seasonal rainfall to episodic, sudden, violent storms as a result of a threshold effect in radiative forcing (Levermann et al. 2009). A thermal gradient caused by seasonal effects of black carbon – the “Asian brown cloud” – causes stronger precipitation, an additional source of changes to monsoon weather (Meehl et al. 2008; Wang et al. 2009).

Precipitation

New “downscaled” models couple global general circulation models together with regional climate models to produce climate projections at a finer geographic resolution. Refinements to regional downscaling techniques now make it possible to approximate future climate impacts on a smaller geographic scale. Since AR4, the trend in regional downscaling of global climate models has accelerated, especially with regard to hydrological cycles and interactions between human and natural systems. Climate forecasts at grosser scales of resolution are still more accurate; nonetheless, temperature and precipitation predictions are presented at ever-finer levels of resolution. This literature is extensive, and the review presented here is therefore illustrative rather than comprehensive.

Newer regionalized findings support and extend a more general finding of AR4: A key result supported by both observational data and modeling projections is that with climate change, wet regions will generally (but not universally) become wetter, and dry regions will become drier (John et al. 2009). The first regions expected to experience significant precipitation change in the next few decades are the

²⁷ According to AR4, models suggest “the possibility of a decrease in the number of relatively weak hurricanes, and increased numbers of intense hurricanes. However, the total number of tropical cyclones globally is projected to decrease” (IPCC 2007, Working Group I, Technical Summary, p. 74).

Arctic, the Mediterranean, and eastern Africa. Important changes to average annual precipitation will next appear in eastern and southern Asia and the Caribbean and toward the later decades of the 21st century in southern Africa, the western United States, the Amazon Basin, southern Australia, and Central America (Giorgi and Bi 2009). By the end of this century, hydrological effects, coupled with changes to vegetation albedo, are projected to increase the global area of “warm desert” by 34 percent from 1901 to 2099, mostly through expansion of the Sahara, Kalahari, Gobi, and Great Sandy deserts (Zeng and Yoon 2009).

With 2°C of warming, dry-season precipitation is expected to decrease by 20 percent in northern Africa, southern Europe, and western Australia, and by 10 percent in the southwestern United States and Mexico, eastern South America, and northern Africa by 2100 (Giorgi and Bi 2009).²⁸ In the Sahel area of Africa, the timing of critical rains will shift, shortening the growing season (Biasutti and Sobel 2009), and more extensive periods of drought may result as temperatures rise (Lu 2009).²⁹ In the Haihe River basin of northern China, projections call for less total rainfall but more extreme weather events (Chu et al. 2009). In the United States, there is a strong relationship between higher temperatures and lower precipitation levels, especially in the South (Portmann et al. 2009). Recent research on the United States highlights another key finding related to regional downscaling: Land-use changes – affecting vegetation and soil moisture, along with a concurrent release of aerosols – impact both precipitation levels and the incidence of extreme weather events (Portmann et al. 2009; Diffenbaugh 2009; Leung and Qian 2009).

Sea-level rise

For most areas of research, AR4 represented the best in scientific knowledge as of 2006, but sea-level-rise projections are an exception. The AR4 projections of 0.18 to 0.38m of sea-level rise in the 21st century under B1, the lowest-emission SRES scenario, and 0.26 to 0.59m under the highest-emission A1FI scenario are widely viewed as too conservative (Rahmstorf 2007; Overpeck and Weiss 2009; Allison, Bindoff et al. 2009).³⁰ In making these projections, IPCC chose to leave out feedback processes related to ice melt, citing uncertainty of values in the published literature – a decision that essentially negates the contribution of melting ice sheets to future sea-level rise. The net contribution of the polar ice sheets is near zero in AR4, with Greenland melting balanced out by greater snowfall in Antarctica (IPCC 2007, Working Group I, Chapter 10.6). The AR4 sea-level-rise projections are consistent with the assumption that the aggregate mass of ice sheets will not change as global temperatures grow warmer.

Research since the publication of AR4 indicates that the rate of sea-level rise over the past four decades has been faster than was formerly assumed and that an improved understanding of melting ice has an essential role in informing sea-level-rise projections. New, more refined estimates show that global average sea levels rose at a rate of 1.5 ± 0.4 mm per year from 1961 to 2003 (Domingues et al. 2008) as well as there being a greater contribution of melting land ice than in previous estimates.³¹ Four-fifths of current-day annual sea-level rise is a result of melting ice sheets and glaciers (Cazenave et al. 2009).³² In addition, a recent study reports that even with far more rapid reductions in greenhouse gas emissions than thought possible – including measures to remove CO₂ from the atmosphere – sea-level rise will still exceed 0.3m over the next century (Moore et al. 2010).³³ At current temperatures, glacial and small ice

²⁸ End-of-century (2081-2100) precipitation under A1B relative to 1981-2000.

²⁹ Lu (2009) notes that there is significant uncertainty regarding future Sahel drying, because it is influenced by 1) sea-surface temperature changes over all the world's oceans; and 2) the radiative effects of greenhouse gas forcing on increased land warming, which can lead to monsoon-like conditions.

³⁰ Sea-level rise is relative to 1990 levels. IPCC sea-level rise ranges reported as 5 to 95 percent of the spread of model results. For background on the SRES scenarios, see Nakicenovic et al. (2000).

³¹ Kemp et al. (2011) find instead that sea levels have risen at a rate of 2.1mm per year since the late 19th century, compared to 0.6mm per year in the proceeding four centuries.

³² Based on annual estimated sea-level rise from 2003 to 2008.

³³ Relative to 2000 sea level.

cap melt alone will result in 0.18m of sea-level rise over the next century, while a continuation of current warming trends will result in 0.37m from non-ice-sheet melting (Bahr et al. 2009).³⁴

Newer studies of future sea-level rise have included systemic feedback related to melting ice but only partially incorporate the latest revised empirical evidence. Of these, the best known is Rahmstorf's (2007) response to AR4, which projected 0.5 to 1.4m of sea-level rise by 2100 across all six SRES scenarios. Other models, each using slightly different techniques, report 0.54 to 0.89m (Horton et al. 2008), 0.72 to 1.60m (Grinsted et al. 2009), 0.75 to 1.90m (Vermeer and Rahmstorf 2009), and 0.6 to 1.6m (Jevrejeva et al. 2010).³⁵ U.K. government climate projections place an upper limit on global mean sea-level rise in the 21st century at 2.5m, based on the estimates of average rates of change during the last interglacial period (Jenkins et al. 2010; Rohling et al. 2008).

The latest empirical research highlights the unexpectedly fast pace of ice melt, including observations of ice sheets that are not only shrinking in expanse but also thinning (Pritchard et al. 2009; Velicogna 2009; Chen et al. 2009; Van Den Broeke et al. 2009). Another study demonstrates that – far from the gain in ice mass projected in AR4 – rapid ice loss on the Antarctic Peninsula is responsible for 28 percent of recent sea-level rise (Hock et al. 2009).³⁶ The Antarctic as a whole has warmed significantly over the past half-century (Steig et al. 2009), and paleoclimatic evidence indicates a clear relationship between Antarctic temperatures and global sea levels; prehistoric rates of sea-level rise are thought to have reached 50mm per year in some periods (Rohling et al. 2009). Uncertainty in the likelihood of collapse of the Greenland or Antarctic ice sheet is a key unknown in sea-level-rise modeling (Allison, Alley, et al. 2009).

The complete collapse of the West Antarctic Ice Sheet (WAIS) alone would add 3.26m to long-term global average sea levels, including up to 0.81m in the first century after collapse. A detailed study modeling the gravitational pull of the ice, together with improved topographical data, reveals regional variation in sea-level changes unrelated to local subsidence and uplift. Peak sea-level increases from WAIS melt are forecast to be approximately 4m and follow a latitudinal band around the earth centered at 40°N, which includes the United States' Pacific and Atlantic coasts, among many other densely populated regions (Bamber et al. 2009). Other studies support this finding: Due to a relaxation of the gravitational attraction of ocean waters toward the current locations of ice sheets, sea-level rise from WAIS collapse would be substantially higher in North America and the Indian Ocean and lower in South America and some parts of Europe and Asia. The highest values of sea-level rise from WAIS, more than 30 percent higher than the global average, are projected for the Pacific Coast of North America and the U.S. Atlantic seaboard (Mitrovica et al. 2009; Gomez et al. 2010; Han et al. 2010).

In addition, new evidence indicates that the climate models may overestimate the stability of the Atlantic Meridional Overturning Circulation (AMOC) (Hofmann and Rahmstorf 2009), although little agreement exists among experts regarding processes determining the strength of the AMOC (Zickfeld et al. 2007). The expected slowdown of the AMOC due to decreased salinity will likely cause additional regional variation in sea-level rise, particularly during the 22nd century. As lower salinity levels gradually disrupt the AMOC, higher-than-average sea-level rise is projected for the Atlantic Coast of North America (Körper et al. 2009).³⁷

Sea ice

The loss of sea ice due to warming is a critical positive feedback mechanism in climate dynamics; as light-colored, reflective ice is replaced by darker, radiation-absorbing waters, the surface albedo decreases, and radiative forcing is enhanced. AR4 predicted a decline in Arctic ice cover, and new

³⁴ Relative to average sea level from 1997 to 2006.

³⁵ For AR4, projections are relative to 1990 sea level; for Horton et al., projections are relative to average sea level from 2001 to 2005; for Grinsted et al., projections are relative to 2000 sea level (based on results of the "Moberg experiment"); for Vermeer et al. and Jevrejeva et al., projections are relative to 1990 sea level.

³⁶ "Recent" refers to sea-level rise from 1961 to 2004.

³⁷ For a more detailed review of current research on sea-level rise, see Warren et al. (2009), section A.5.

research shows that sea ice loss is advancing much more rapidly than expected. According to observational data from 1953-2006, annual summer sea ice coverage has fallen 7.8 percent each decade, a decline that is three times faster than what is projected by the AR4 models for this period. The current minimum annual ice coverage now corresponds to the extent projected for 30 years in the future (Stroeve et al. 2007). Seasonal ice (melting and reforming each year) now covers a larger share of the Arctic than does perennial ice, and the remaining sea ice grows thinner with each passing year (Kwok et al. 2009; Kwok and Rothrock 2009).

Summer sea ice extent has decreased by nearly 25 percent over the last quarter-century. If current trends in greenhouse gas emissions continue (modeling under the A1B scenario), projections show an ice-free Arctic by 2100 (Boé et al. 2009). The potential for an ice-albedo feedback effect (where albedo loss speeds ocean warming and, thus, more ice melts) is increased by climate change, paving the way for a year-round, ice-free Arctic. This threshold effect could be abrupt and irreversible (Eisenman and Wettlaufer 2008). Loss of sea ice is already adding to radiative forcing, reducing Arctic cloud cover (an additional decrease in albedo) and changing Arctic weather patterns (Seierstad and Bader 2008; Liu et al. 2009; Simmonds and Keay 2009; Deser et al. 2010).

Melting sea ice is also expected to raise sea levels. While melting ice chills ocean water, causing thermal contraction (and sea-level decline), it also freshens water, which reduces its density, causing sea levels to rise. The latter effect slightly outweighs the former, and a total loss of sea ice would cause a net addition of 3.5 to 5.2mm to current global average sea levels (see Table 1 in Jenkins and Holland 2007). Sea ice melt added 0.05mm to the current annual rate of sea-level rise from 1994 to 2004 (Shepherd et al. 2010).

Likely impacts and catastrophes

The most likely, best-guess effects of business-as-usual trends in greenhouse gas emissions are global averages of about 4.2°C of warming (averaged across the RCP 8.5 and RCP 4.5 scenarios) and 1.2m of sea-level rise by 2100, compared to 0.3°C and 0.15m by 2100 if all emissions were to come to a halt today. If global greenhouse gas emissions are not seriously curtailed in the near future, the best guess regarding our climate future shows the world far exceeding the 2°C of warming standard for avoiding climate damages in this century. The exact effects of exceeding 2°C are uncertain; among the possible effects are several thresholds for irreversible processes, including the collapse of the Greenland and West Antarctic ice sheets and the permanent loss of the Amazon rainforest (Lenton et al. 2008). As noted above, if we overshoot the concentration level that (together with the unknown climate sensitivity) will trigger 2°C of warming, temperatures are not expected to fall with concentrations; the temperature overshoot will last for millennia.

Of course, as discussed below in Chapter II.1, we rarely make important decisions based solely on the most likely effects of our actions. Instead, we include in our consideration unlikely but very serious consequences. Today's projections of climate change impacts include low-probability events that could, with some understatement, be described as world changing. If the high end of business-as-usual emissions scenarios comes to pass, there is about a one-in-10 chance of adding 7.1°C or more by 2100; even using the lowest emissions scenarios for little or no planned mitigation, there is a one-in-10 chance of exceeding 2.3°C. In addition, if ice sheets collapse sooner than expected, sea-level rise in this century could be higher than the 1.9m predicted in the highest estimate. At these rates of temperature change, still more irreversible thresholds would likely be crossed, including disruption of the Atlantic thermohaline circulation and disruption of important climate patterns like the El Niño-Southern Oscillation.

In understanding the potential for catastrophe, two overarching characteristics of the climate system are of particular note and have been confirmed again and again in recent research. First, the climate system is not linear. Greenhouse gas emissions increase radiative forcing, which increases temperatures, but these emissions also set off a host of feedback effects that are difficult to quantify and in many cases are expected to accelerate warming and other climate damages: changes in cloud cover and aerosols, including black carbon; precipitation's effect on vegetative albedo; warmer oceans; and various carbon-

cycle effects. The uncertainty that these feedback effects imply for climate sensitivity is thought to be irreducible. This finding highlights the importance of climate-economics models investigating – and reporting results across – a range of different climate sensitivities, including values from the low-probability, high-sensitivity (i.e., high-damages) right tail of the distribution.

The second key characteristic is regional diversity in climate impacts. This diversity is the cause of an important share of the uncertainty in net climate system feedbacks and the level of climate sensitivity. It also has important implications for our understanding of what climate change and climate damages will mean to communities around the world. Important new findings in this area include a wealth of temperature and precipitation change predictions from downscaled general circulation models, as well as expected geographic disparities in sea-level rise. As the geographic coverage of regionalized climate projections becomes more complete, more specificity in damage function parameters may be expected in integrated assessment models that include regional disaggregation.

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Chapter I.2. Climate change impacts on natural systems

The impacts of climate change are often popularized in terms of photogenic species such as coral and polar bears. The expected effects on natural systems, however, extend well beyond the best-known images. If business-as-usual emissions continue, the most likely late-21st-century temperature increase is 4.2°C (with a one-in-10 chance of exceeding 7.1°C; see Chapter I.1). With 2 to 3°C warming, AR4 projected that 20 to 30 percent of plant and animal species are likely to be at high risk of extinction and that substantial changes in the structure and functioning of terrestrial and aquatic ecosystems are very likely. With 1.7°C warming, all coral reefs will be bleached, and by 2.5°C they will be extinct; at 2.8°C there is high risk of extinction for polar bears and other Arctic mammals. At 4°C of warming, AR4 projects major extinctions around the world (Intergovernmental Panel on Climate Change 2007, Working Group II, Chapter 4).

Evidence of the impacts of anthropogenic climate change on ecosystems is compiled in a wide-ranging review article that identifies all significant, temperature-related changes in physical and biological systems reported in peer-reviewed literature, in cases where 20 or more years of temperature data are available (Rosenzweig et al. 2008). The review encompasses a massive European database of more than 28,000 biological indicators and more than 1,000 other biological and physical indicators worldwide. More than 90 percent of the biological indicators and more than 95 percent of the physical indicators are consistent with the response expected from anthropogenic climate change; the pattern of results is very unlikely to be caused by natural variability in climate. An evaluation of possible publication bias, using the extensive European data, shows that a similar conclusion is reached when the larger number of data series showing no temperature-related changes is included.

Another review article analyzes 71 studies that identify a specific temperature or CO₂ concentration for the onset of climate impacts on species or ecosystems and summarizes their findings on a consistent scale, relative to preindustrial global average temperature (Warren et al. 2010). Some ecosystem thresholds are reached as low as 1.7°C above preindustrial temperatures. Beyond 2°C, projections of ecosystem impacts become widespread; critical aspects of ecosystem functioning begin to collapse at 2.5°C.

Climate change threatens to overwhelm the resilience of many ecosystems, because changes in temperature, precipitation, atmospheric CO₂ concentrations, ocean acidification, and other conditions move beyond the ranges to which many species can adapt. Although often studied at the individual species level, the response to climate change also affects ecosystem interactions. Species that currently interact may respond to warming and other climatic conditions at differential rates, disrupting the timing of food requirements and availability, the synchronization of pollinators and flowering plants, and other interdependencies. Likewise, complex ecological communities may experience different changes in geographical range, moving to higher altitudes or latitudes at differential rates. In either case, the result is the disruption of existing ecosystems (Walther 2010).

Global warming may do the most harm to natural systems in tropical regions, even though temperature changes there will be smaller than the global average: Tropical species normally experience little seasonal variation in temperature, so they may not be resilient to small changes, and in many cases they are already close to their optimal temperatures (Deutsch et al. 2008; Tewksbury et al. 2008). By 2100, 75 percent of current tropical forest regions will be too hot for closed-canopy forest, which could lead temperature-sensitive species to seek refuge in areas that still provide their historical temperature ranges. The nearest such cool refuges, however, will be more than 1,000 km away for more than 20 percent of the tropical mammals with small ranges (Wright et al. 2009).

Post-AR4 research has extended the understanding of climate impacts, providing greater detail in many areas. Here we focus on two kinds of natural systems in which new research provides a qualitative change from that presented in AR4: forestry and fisheries. In forestry, contributions of afforestation and deforestation to climate change can now be differentiated by tropical, temperate, and boreal forests. In

fisheries, a serious decline in the viability of coral reefs and the far-reaching ecosystems that rely on these reefs may already be inevitable, and these impacts are expected earlier in the century than previously thought.

Both forests and marine ecosystems are of great economic importance both directly and indirectly. The economic role of natural systems in general may be less obvious but is also of paramount importance. The diverse range of economic benefits produced by ecosystems and biodiversity is documented in the recent reports of the United Nations-sponsored TEEB (The Economics of Ecosystems and Biodiversity) project.³⁸ While noting the difficulty of monetizing the “priceless” benefits of natural ecosystems, TEEB presents numerous arguments and methods for valuing ecosystem services. One summary estimate of the costs of climate policy inaction suggests that the ongoing loss of biodiversity in land ecosystems already has a global welfare cost equal to \$68 billion per year and that these welfare losses will grow rapidly over time.³⁹ Taking the order of magnitude of this estimate together with the importance of both market and subsistence forestry and fisheries activities, it seems clear that natural systems are an important component of a comprehensive climate-economics analysis.

Forestry

Vast amounts of carbon are stored in forests, both in vegetation and in the soil. Changes in this carbon reservoir are of great importance for climate dynamics. Moreover, forests have other important interactions with the earth’s climate. There is a complex cyclical pattern of feedbacks: Climate change affects forests, and forests affect climate change, and there are positive and negative effects in both directions. Recent research has clarified many of the individual effects, but the net result varies regionally and, for many areas, remains uncertain.

Positive effects of climate change on forests

Plants grow by photosynthesis, a process that absorbs CO₂ from the atmosphere. For many plants, including trees, the availability of CO₂ is the limiting factor on their growth, so an increase in atmospheric CO₂ will cause acceleration of plant growth and of the resulting removal of carbon from the atmosphere. This process, known as “carbon fertilization,” is discussed further in the review of agricultural research in Chapter I.3. Other positive effects of climate change on forests include increased temperatures and longer growing seasons at high latitudes or high elevations.

There is empirical evidence of benefits to forests from carbon fertilization. Free-Air CO₂ Enrichment (FACE) experiments, which allow plants to be grown outdoors simulating conditions in nature, show an average 23 percent increase in net primary production (i.e., growth in biomass) at 550 ppm CO₂ (compared to today’s 392 ppm⁴⁰) in young forest stands but little or no impact in older forest stands (Norby et al. 2005; Kirilenko and Sedjo 2007; Lenihan et al. 2008). A study of temperate forests finds faster-than-expected growth over the past two decades and offers six possible explanations, three of which – increased temperatures, longer growing seasons, and carbon fertilization – are consequences of climate change (McMahon et al. 2010). Modeling of forest growth in California projects that climate change will increase the size of pine trees and the yields of managed pine forests, with greater growth in warmer and wetter climate scenarios (Battles et al. 2009). Global estimates project worldwide increases in timber output due to climate change over the next 50 years (Seppälä et al. 2009).

Forest carbon sequestration, particularly in tropical countries, is often identified as one of the lowest-cost options for reducing net global emissions. Carbon accumulation in forests slows down as trees mature,

³⁸ The Economics of Ecosystems and Biodiversity [TEEB] (n.d.), <http://www.teebweb.org>.

³⁹ TEEB (2008), p. 35; Bakkes et al. 2008. Welfare cost of €50 billion (in 2007 currency) converted to dollars at 1.36 dollars per euro.

⁴⁰ Globally averaged marine surface monthly mean CO₂ concentration for April 2011, NOAA Earth System Research Laboratory (n.d.).

but recent research finds that old-growth forests, particularly in the tropics, continue to absorb significant amounts of additional carbon over time (Luyssaert et al. 2008; Phillips et al. 2008; Lewis et al. 2009).

Recent research models the joint dynamics of the carbon and nitrogen cycles; this reduces but does not eliminate the projected effect of carbon fertilization (Zaehle et al. 2010; Thornton et al. 2009). Both carbon and nitrogen are essential for plant growth; the lack of available nitrogen could cause a large decrease in the long-term effect of carbon fertilization, particularly in boreal and temperate forests. Modeling the nitrogen cycle also reveals a smaller, opposing effect of climate change: As temperatures rise, accelerated decomposition of dead biomass makes more nitrogen available, easing the nitrogen constraint on plant growth. The first effect is much larger, so the net effect of the nitrogen cycle is to decrease forest carbon sequestration: By 2100, under the A2 emissions scenario, the atmospheric concentration of CO₂ is projected to be 48 ppm higher in an integrated carbon-nitrogen model than in a climate model that ignores nitrogen dynamics (Zaehle et al. 2010).

Negative effects of climate change on forests

There are a number of effects of climate change that threaten the growth or, in the extreme, the survival of forests.

AR4 found a likely increased risk of forest fire associated with a decrease in summer precipitation (IPCC 2007, Working Group II). New research refines this global assessment, pointing to regionally heterogeneous impacts. While there is a potential for widespread impacts of climate change on wildfire, regional downscaling reveals both increases and decreases to wildfire incidence. Under a business-as-usual emissions scenario (A2), in the next few decades many areas around the world that do not currently experience wildfires will be at an increased risk of suffering these events, including parts of the U.S. Southwest; much of the European and Siberian northern latitudes; a large part of Western China; and some areas of Asia, Africa, and South America. At the same time, the risk of wildfire will decrease in central Canada, southeastern Brazil, northeastern China, and southeastern Siberia (Krawchuk et al. 2009).

In northern forests, wildfire has an important influence on net changes in carbon storage. By 2100, wildfire-related carbon emissions from North America's boreal forests are projected to increase by 2.5 to 4.4 times, depending on climate change scenario and assumptions regarding CO₂ fertilization; boreal wildfires release 13 to 26 percent of the carbon stored aboveground in the forest and 5 to 38 percent of the ground layer of carbon storage (Balshi et al. 2009).⁴¹ Wildfires also form charcoal, which sequesters carbon when stored in soil, a countervailing effect. Boreal soils store 1 Gt of carbon as a result of past forest fires, an amount equal to 1 percent of carbon stored in plants in boreal forests (Ohlson et al. 2009).

In the United States, the connection between climate and forest fires is becoming increasingly clear. A study of 20th-century forest fires in the northern Rockies found that the peak fire years were those with warm springs; low spring snowpack; and warm, dry summers (Morgan et al. 2008). A study of large forest fires throughout the western United States from 1970 to 2000 found an abrupt increase in the mid-1980s, closely correlated with increases in spring and summer temperatures and a shift toward earlier spring snowmelt (Westerling et al. 2006).

There is also evidence that more trees are dying as the climate changes. A study of unmanaged forests in the western United States found that "background" (non-catastrophic) mortality rates had increased almost everywhere, across different elevations, tree sizes, species, and past fire histories (van Mantgem et al. 2009). The study found a correlation of tree mortality with regional warming and water deficits. Tree mortality is difficult to analyze because the precise influence of temperature on mortality appears to be mediated by species-specific traits; thus, predictions for different forest areas will depend on their mix of tree species (Adams et al. 2009). The mechanisms linking climate change to tree death are not simple and can include increased vulnerability to disease; increased survival of pests such as bark beetles; decreased

⁴¹ Relative to 1990 carbon emissions.

moisture availability leading to desiccation; and physiological temperature stress that induces mortality and/or makes other species more competitive, forcing out the weaker species (Kliejunas et al. 2009).

Tropospheric (low-level) ozone, a pollutant that results from fossil fuel combustion, inhibits forest growth. Although ozone is not a consequence of climate change, it is a byproduct of the principal source of greenhouse gas emissions. High ozone levels are associated with insect-related disturbances, worsen the negative effects of frost, and affect leaf gas exchange, offsetting some of the forest productivity gains from CO₂ fertilization (Boisvenue and Running 2006).

Insects, especially the mountain pine beetle and other bark beetles, kill trees across millions of acres in the western United States each year. Rising temperatures increase their survival rates, accelerate their life cycle development, facilitate their range expansion, and reduce their hosts' capacity to resist attack. At lower elevations, it is possible but not certain that the area favorable for mountain pine beetles will shrink; at higher elevations, bark beetles will continue to expand their range (Bentz 2008).

A number of climate-related threats are specific to tropical forests. Woody vines, or lianas, respond to carbon fertilization, perhaps more rapidly than do trees; lianas also fare better than do trees under drought conditions (Swaine and Grace 2007). The growth of lianas can strangle and kill large trees, leading to a net decrease in forest biomass (Warren et al. 2010). In this way, rising CO₂ concentrations, combined with droughts, could lead to carbon fertilization of the "wrong" plants and an overall decrease in forest carbon sequestration.

Researchers have also identified the potential for catastrophic collapse in tropical forests, resulting from deforestation and climate-related changes in temperature and precipitation. The best-studied example, the Amazon rainforest, may be approaching a threshold beyond which an irreversible dieback will be set in motion.

Over the past few decades, deforestation associated with land-use conversion has dramatically reduced the size of the Amazon forest; this forest loss is altering the hydrological cycle, reducing precipitation, and causing still more forest loss (Brovkin et al. 2009). Studies suggest that only large-scale intervention to control deforestation and wildfire can prevent the Amazon from passing a tipping point for its demise and that the dieback could occur during the 21st century (Malhi et al. 2008; Malhi et al. 2009). Recent research suggests that the threshold for eventual Amazon dieback could be less than 2°C (Jones et al. 2009), as compared to the more commonly cited 3 to 4°C (Lenton et al. 2008).

Even if greenhouse gas levels were eventually reduced and temperatures stabilized, the Amazon – like many other biological systems – would be locked into a particular path by considerable inertia in its response to climatic change (Jones et al. 2009). Carbon lost from Amazon vegetation and soil has the potential to cause significant climate feedback effects; a 2005 Amazon drought has been estimated to have caused the loss of 1.6 Gt C in that single year (Phillips et al. 2009).

Effects of forests on climate change

While climate change has multiple positive and negative effects on forests, there are complex effects of forests on climate change; the net impact differs by region (Bonan 2008). Positive effects of forests that reduce the impact of climate change include sequestration of carbon, which lowers atmospheric CO₂ concentrations; and evaporative cooling, which lowers temperatures. On the other hand, forests have lower albedo (they are darker and therefore absorb more solar radiation) than do alternative land uses, which tends to increase radiative forcing and raise temperatures.

In tropical forests, which contain most of the world's forest carbon, the sequestration and evaporative cooling effects are strong, while the decrease in albedo is only moderate, leading to a net reduction in warming. At the other extreme, in boreal forests, the sequestration and evaporative cooling effects are weaker, while the change in albedo – when forests replace snow- or ice-covered surfaces – is large; it is

possible, therefore, that boreal forests make a positive net contribution to warming. Temperate forests are intermediate in all these dimensions, with an uncertain net effect on climate change (Bonan 2008).

The possibility that boreal forest growth intensifies climate change is surprising to many readers but is extensively discussed in the research literature. One study found that boreal forest fires have a long-term net cooling effect, because the increase in surface albedo over the many years before the trees grow back outweighs the loss of carbon storage and the effect of emissions from the fires themselves (Randerson et al. 2006). Simulation of large-scale deforestation in a detailed climate model found an increase in long-run equilibrium temperature from tropical deforestation, roughly no change from temperate deforestation, and a decrease in equilibrium temperature from boreal deforestation (Bala et al. 2007).

Forests provide many important ecological and economic services in addition to climate stabilization; thus, the surprising findings described here do not justify advocacy of boreal deforestation or indifference to temperate deforestation. When viewed as a strategy for climate mitigation, however, afforestation and prevention of further deforestation should be focused specifically on tropical forests.

Fisheries

Global fisheries are both an important economic sector and a key source of nutrition. Climate change is expected to have profound effects on marine ecosystems, driving many species of coral to extinction, decreasing crustacean and mollusk populations, and causing large-scale disturbances to the distribution of numerous commercial fish species. Changes to ocean pH, driven by high concentrations of CO₂, are expected to cause some of the first serious, irreversible ecosystem damages due to anthropogenic greenhouse gas emissions. There is considerable evidence that a tipping point triggering widespread coral extinction has already been passed. Here we discuss two main pathways for climatic disruption of marine biological systems: ocean warming and ocean acidification.

Ocean warming

As the earth's atmosphere warms, so will the ocean waters nearest to the surface, where most marine flora and fauna live. Ocean warming will shift the distribution of many ocean species poleward, including fish species of utmost importance to commercial fisheries. These shifts will vary regionally and by species, depending on complex factors of reproductive biology, shifts elsewhere in the food chain, and the physical oceanography of currents. A model of global shifts in fish production under climate change (using the A1B scenario) projects a large-scale redistribution of potential fisheries catch by 2055; on average, catch potential would increase by 30 to 70 percent in northern subarctic areas and decrease by up to 40 percent in the tropics. Norway, Greenland, Alaska, and Siberia would see the greatest gains to potential marine catch, while Indonesia, the U.S. lower 48 states, Chile, and China would see the greatest losses (Cheung et al. 2010).

Biodiversity is likely to be very sensitive to climatic changes, especially in the high northern and southern latitudes. Species everywhere are vulnerable to temperature change. Polar marine species tend to have especially narrow bands of temperature tolerance; tropical species often exist at the top end of their thermal tolerance already. Many species in the subpolar regions, the tropics, and semi-enclosed seas may become locally extinct, even as new species rapidly invade the Arctic and Southern oceans (Cheung et al. 2009). Regional studies indicate that distributional shifts due to climate change are species specific. Among the diadromous⁴² fish of Europe, North Africa, and the Middle East, for example, the distribution of some species (including shad, herring, and several other commercially important fish) is expected to contract while others expand (Lassalle and Rochard 2009).

New research suggests that “fish recruitment,” or growth in a fish population, is the key mechanism driving climate-change-related shifts in the distribution of oceanic species. Distributions shift as more

⁴² Diadromous fish spend part of their life cycle in marine waters and part in fresh water; salmon are a well-known example.

larvae survive (or fail to survive) under the new climatic conditions (Rijnsdorp et al. 2009). On the northeast U.S. continental shelf, the distribution of fish species has already shifted with climate change over the past 40 years. Temperatures have become too warm for cod and other larvae at the southern end of their New England range, causing a northward shift (Nye et al. 2009).

Reef-forming coral are among the organisms most sensitive to ocean warming, and many marine species rely on reefs as a source of food or as shelter for nursery grounds. Coral depend on a symbiotic relationship with photosynthetic protozoa for their source of food. This symbiosis is extremely sensitive to temperature: Slight increases in temperature cause the coral to release or expel the algae, triggering the phenomenon known as “coral bleaching.” While it is possible for coral to survive bleaching by recruiting new protozoa, this reversal occurs only when the original stressor to the symbiotic relationship is removed. Where the stressor is a continual, gradual increase to ocean temperatures, the most likely outcome is coral mortality, with local and sometimes global extinction of species.

One-third of all coral species are already at risk of extinction as a result of bleaching and disease caused by ocean warming in recent years. Caribbean coral appears to face the greatest and most immediate threat, although coral around the world are at risk (Carpenter et al. 2008). A report from the Global Coral Reef Monitoring Network and the Reef and Rainforest Research Centre (Wilkinson and Souter 2008) documents recent impacts to Caribbean coral reefs and finds that 2005 had the warmest sea-surface temperatures on record and the highest rates of coral bleaching and mortality ever recorded.

Ocean acidification⁴³

Greenhouse gas emissions have a second important impact on ocean ecosystems: Marine waters are absorbing CO₂ at a higher rate, causing ocean pH to fall. At lower pH levels, concentrations of calcium carbonate decrease, and as a result, calcifying organisms such as coral, mollusks, and crustaceans may have difficulty forming their shells and skeletons, causing populations to decline. Most of the surface ocean is currently supersaturated with both aragonite and calcite, the two major forms of calcium carbonate. Different calcifying species use one or the other. Supersaturation makes it easy for calcium carbonate shells and skeletons to form and helps maintain their integrity after formation. As calcium carbonate concentrations fall, however, the oceans approach the point at which they become undersaturated and hence potentially corrosive; in undersaturated water, calcium carbonate tends to dissolve out of unprotected shells into the water. Some species can maintain shell stability at low pH and low saturation but at great metabolic cost (Turley et al. 2010).

Lower ocean pH levels and undersaturation of calcium carbonate have the potential to affect a wide range of commercially important species: Mussel, oyster, giant scallop, clam, crab, sea urchin, dogfish, and sea bass populations are all projected to decline in health and/or numbers with higher concentrations of CO₂ in ocean waters. One study finds that 30 percent of U.S. commercial fishing revenues come from mollusks, 19 percent from crustaceans, and another 50 percent from predators that consume calcifiers (or consume the predators of calcifiers). Only 1 percent of revenues is not influenced by changes in ocean pH (Fabry et al. 2008; Cooley and Doney 2009). There is also evidence that elevated ocean CO₂ levels may disrupt some coral-reef-dwelling fish larvae’s sense of smell and, therefore, their ability to navigate and to select appropriate areas for settlement (Munday et al. 2009).

AR4 reported that anthropogenic CO₂ emissions have already caused ocean surface pH to fall by 0.1 (equivalent to a 30 percent increase in hydrogen ion concentrations) and that a further decrease in pH of 0.3-0.4 is predicted for 2100. This was projected to be particularly harmful to cold-water coral ecosystems and to the numerous calcifying species in the Arctic and Southern oceans (IPCC 2007, Working Group II, Chapter 4). IPCC scenarios imply that by 2050, global mean surface pH is likely to be lower than at any time in the last 24 million years (Turley et al. 2010). Detailed modeling of ocean chemistry projects an accelerated timeline for declining concentrations of calcium carbonate. Undersaturation of aragonite,

⁴³ Technically, ocean pH is lowered but not turned acidic by projected increases in the concentration of CO₂.

which is used by most mollusks and corals, could take place as early as 2020-2030 in the Arctic Ocean and 2050-2060 in the Southern Ocean (Feely et al. 2009).

Research on impacts of acidification on marine life has also expanded, with complex results that differ by species. One study subjected 18 calcifying species to high levels of atmospheric CO₂, inducing low levels of calcium carbonate in water. In 10 of the 18 species, calcification slowed down as CO₂ concentrations rose; in six species, there was net dissolution (loss of calcium carbonate) at the highest level of CO₂. In seven species, however, there was an increase in calcification at intermediate and/or high levels of CO₂, perhaps reflecting differences in their ability to regulate pH and protect their shells (Ries et al. 2009). Two recent meta-analyses of the effects of acidification on marine organisms reach opposite conclusions, one suggesting that the likely damages have been exaggerated (Hendriks et al. 2010) and the other projecting serious damages to many species (Kroeker et al. 2010). Both agree that calcification is expected to decline on average and that impacts on individual species will differ widely.

Coral reefs have been extensively studied, leading to ominous projections of decline. From 1990 through 2005, calcification rates fell by 14 percent among *Porites* coral in the Great Barrier Reef, a phenomenon that researchers refer to as “severe and sudden”; in 400 years of calcification records, there are no similar anomalies. These results indicate that a tipping point for coral mortality may already have been passed in the late 20th century (De’ath et al. 2009). Other studies support this finding and suggest that coral reefs worldwide are already committed to irreversible decline. If atmospheric CO₂ concentrations were to reach 450 ppm (from today’s 392 ppm), rapid coral mortality would follow, along with widespread ecosystem effects (Veron et al. 2009).

Likely impacts and catastrophes

Given business-as-usual emissions, the most likely climate outcomes are around 4.2°C of warming (with a one-in-10 chance of temperatures falling below 2.3°C in the most optimistic business-as-usual scenario and exceeding 7.1°C in the most pessimistic) and 1.2m of sea-level rise by 2100 (see Chapter I.1). Even if greenhouse gas emissions ceased today, with 0.5°C of inevitable warming still to come, the least resilient ecosystems would experience some impacts – indeed, the most vulnerable ecosystems already are feeling the effects of climate change.

If emissions are not greatly reduced from current trends, the expected impacts to vulnerable natural systems are likely to be devastating. By the end of this century, there would be extinctions of vulnerable plants and animals worldwide. For some species, these extinctions are likely to happen much sooner. For many coral species, the stresses of changing temperatures and pH levels may have already been too great; the tipping point for some species’ extinction may already have been passed, and the threshold for extinction of all coral ecosystems may be as low as 2.5°C. For the Amazon rainforest ecosystem, the threshold for an irreversible dieback may be as low as 2.0°C, and high risk of the extinction of many Arctic mammals is expected at 2.8°C.

For these especially vulnerable natural systems, the impacts projected for business-as-usual emissions and the mean climate sensitivity are enormous. At higher climate sensitivities, extinctions and other catastrophic ecosystem effects would be more widespread and would occur at an early date.

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Chapter I.3 Climate change impacts on human systems

As temperatures and sea levels rise and precipitation patterns change, human systems are expected to suffer damages. Like forestry and fisheries, described in Chapter I.2, agriculture, coastal settlements, and human health are expected to experience the most direct impacts from climate change. In the coolest regions, agriculture output may show modest gains from the first few degrees of climate change, but in most temperate and almost all tropical regions, changes to temperature and precipitation are expected to lower yields in the coming century. Low-lying coastal settlements are extremely vulnerable to rising sea levels, from both permanent inundation and greater storm damage. Human health is affected not just by high temperatures but also by climate-induced changes in disease vectors and by decreasing water availability, which is expected to have the biggest impact on already-dry regions.

Agriculture

Climate impacts on agriculture have been studied for at least 20 years and are central to many economic assessments of climate change. At first glance, the emphasis on this small economic sector might seem surprising; agriculture represents 1.2 percent of GDP in the United States, 1.6 percent in the European Union, and 2.9 percent for the world as a whole. In the least developed countries, however, agriculture makes up nearly one-quarter of GDP – a value that still ignores all subsistence agriculture grown and consumed by the same family.⁴⁴ Regardless of its contribution to individual countries' GDP, food is an absolute necessity of life; in economic terms, this is reflected in a very low price elasticity of demand.⁴⁵ The low price elasticity, in turn, implies that the consumer surplus from food production is very large.⁴⁶ Thus, agriculture looms much larger in welfare terms if industries are measured by their contribution to consumer surplus rather than to GDP.

Research in the 1990s often projected net global benefits in agriculture from the early stages of climate change. Such projections were based primarily on the expected effects of carbon fertilization and on longer growing seasons as temperatures rise in cold northern areas. As recently as 2001, the first National Assessment from the U.S. Global Change Research Program estimated that climate change would on balance be beneficial to U.S. agriculture through the 2090s, causing yield increases, many of them quite large, for most crops (Reilly et al. 2001).

AR4 found that 1 to 3°C warming in mid-to-high-latitude regions would result in small crop yield increases but that 1 to 2°C warming would reduce yields in low-latitude regions (Intergovernmental Panel on Climate Change 2007, Working Group II, Chapter 5). Newer work based on older agricultural research continues, nonetheless, to appear. For example, the FUND integrated assessment model, one of the three used to develop the U.S. government's 2009 estimate of the social cost of carbon, projects net benefits to the world from the first 3°C of warming (Interagency Working Group on Social Cost of Carbon 2010). A recent disaggregated analysis of climate damages in FUND finds that the model's net global benefit comes almost entirely from agriculture, an area where FUND's calculations are benchmarked to studies from the mid-1990s (Ackerman and Munitz 2011).

Recent research has raised new questions that suggest a more complex relationship between climate and agriculture. In a number of cases, this has led to still-lower estimates of the agricultural benefits of warming. It seems clear that new approaches are needed to modeling climate impacts on agriculture; there is not yet an adequate summary analysis that incorporates the latest findings. Three major areas of

⁴⁴ Agricultural value added as a share of GDP for 2008 (World Bank Open Data, <http://data.worldbank.org/>).

⁴⁵ That is, food purchases are almost unchanged when there are small increases to food prices.

⁴⁶ Consumer surplus is the benefit that consumers receive from purchasing goods at prices lower than the maximum they would be willing to pay. The more inelastic the demand, the greater the consumer surplus. For instance, consumers are willing to pay far more than the market price for essentials such as food but less for luxuries.

research on climate and agriculture are discussed here: carbon fertilization, temperature and precipitation impacts on crop yields, and climate impacts on farm revenues and farmland values.

Carbon fertilization

Plants grow by photosynthesis, a process that absorbs CO₂ from the air and converts it into organic compounds such as sugars. If the limiting factor in this process is the amount of CO₂ available to the plant, then an increase in the atmospheric concentration of CO₂ could act as a fertilizer, providing additional nutrients and allowing faster growth. Almost all plants use one of two styles of photosynthesis.⁴⁷ In C₃ plants, which include the great majority of food crops and other plants, growth is limited by the availability of CO₂, so that carbon fertilization may be important. In contrast, C₄ plants have evolved a different photosynthetic pathway that uses atmospheric CO₂ more efficiently. C₄ plants, which include maize (corn), sugarcane, sorghum, and millet (as well as switchgrass, a potential ethanol feedstock) do not benefit from increased CO₂ concentrations except in drought conditions (Leakey 2009).

Initial experimental studies conducted in greenhouses or other enclosures found substantial carbon fertilization effects. The 2001 U.S. National Assessment summarized the experimental evidence available at that time as implying yield gains of 30 percent in C₃ crops and 7 percent in C₄ crops from a doubling of CO₂ concentrations (Reilly et al. 2001). More recently, Free-Air CO₂ Enrichment (FACE) experiments have allowed crops to be grown in outdoor environments with a greater resemblance to the actual conditions of production. According to a widely cited summary, the effects of CO₂ on yields for major grain crops are roughly 50 percent lower in FACE experiments than in enclosure studies (Long et al. 2004).⁴⁸ Another literature review reaches similar conclusions, offering “six important lessons from FACE,” of which the sixth is that “the [CO₂] ‘fertilization’ effect in FACE studies on crop plants is less than expected” (Leakey 2009).

According to a recent summary, FACE experiments imply that an increase in atmospheric CO₂ from 385 ppm (roughly current conditions⁴⁹) to 550 ppm would increase yields of the leading C₃ crops, wheat, soybeans, and rice, by 13 percent and would have no effect on yields of maize (corn) and sorghum, the leading C₄ grains (Ainsworth and McGrath 2010). Cline (2007) uses a similar estimate; because C₄ crops represent about one-fourth of world agricultural output, he projects a weighted average of 9 percent increase in global yields from 550 ppm.

While research on carbon fertilization has advanced in recent years, there are at least three unanswered questions in this area that are important for economic analysis. First, there is little information about the effects of very high CO₂ concentrations; many studies have examined yields at 550 ppm, and few have gone above 700 ppm. Long-term projections of business-as-usual emissions scenarios, however, can reach even higher concentrations. Does CO₂ fertilization continue to raise yields indefinitely, or does it reach an upper bound?

Second, most studies to date have focused on the highest-value crops, primarily the leading grains and cotton; other crops may have different responses to CO₂. In at least one case, the response may be negative: Cassava (manioc), a dietary staple for 750 million people in developing countries, shows sharply reduced yields at elevated CO₂ levels, with tuber mass reduced by an order of magnitude when CO₂ concentrations rise from 360 ppm to 710 ppm (Gleadow et al. 2009; Ghini et al. 2011).

Third, carbon fertilization may interact with other environmental influences. Fossil fuel combustion, the principal source of atmospheric CO₂, also produces tropospheric (ground-level) ozone, which reduces

⁴⁷ A third photosynthetic pathway exists in some plants subject to extreme water stress, such as cacti and succulents; it is not important in agriculture.

⁴⁸ This article has been criticized by Tubiello et al. (2007); the original authors respond in Ainsworth et al. (2008).

⁴⁹ The atmospheric CO₂ concentration was 392 ppm in April 2011 (globally averaged marine surface monthly mean CO₂ concentration), per NOAA Earth System Research Laboratory (n.d.). The experimental data refer to recent years in which concentrations were slightly lower.

yields of many plants (Ainsworth and McGrath 2010). The net effect of carbon fertilization plus increased ozone is uncertain, but it is very likely to be less than the experimental estimates for carbon fertilization alone.

Temperature, precipitation, and yields

Many studies examine the effects of temperature and precipitation on crop yields in order to project the expected results of climate scenarios. Some of these studies omit the effects of carbon fertilization, because CO₂ concentrations were roughly constant throughout the time span of the underlying data (typically the late 20th century). New research suggests that uncertainties related to temperature are more important to overall climate change uncertainty than are those related to precipitation (Lobell and Burke 2008).

In cases where adaptation is possible, including a shift in farm locations toward colder areas, the net impacts of 21st-century climate change may be modest. A study of China's rice, wheat, and maize production (Xiong et al. 2007), together with a more detailed analysis of the country's rice production (Xiong et al. 2009), finds that by the 2080s, yields will decrease without carbon fertilization but will increase if carbon fertilization is taken into account. Rice production, now concentrated in the hotter, southern regions of China, is expected to migrate northward; as such, the development and adoption of heat-resistant cultivars are important to the prospects for grain yields. Slower climate change (the B2 rather than A2 scenario) will lead to greater food production in China.

Not every country has the option of shifting agriculture to colder regions. A study of wheat production in Australia projected that carbon fertilization would offset yield losses due to temperature and precipitation changes through 2050 but by 2070 yields would fall by 6 percent, even with carbon fertilization (Wang et al. 2009).

In other cases, precipitation is the limiting factor. A study of rain-fed wheat cultivation in India found that yields in the years of lowest rainfall are 33 percent of the baseline (based on moderate rainfall years); a high level of irrigation is required to prevent major losses in the driest years (Pathak and Wassmann 2008). Thus, the most immediate climate risk to wheat in India may be a reduction in rainfall.

Most crops have an optimum temperature, with lower yields when it is either colder or hotter. The simplest and most widely used model of this effect assumes that yields are a quadratic function of temperature. The quadratic model, however, imposes symmetry around the optimum: One degree too hot and one degree too cold are modeled as having the same effect on yields. A detailed study of temperature effects on corn, soybeans, and cotton in the United States finds strongly asymmetric patterns: Yields increase slowly as the temperature rises to the optimum and drop rapidly at higher temperatures (Schlenker and Roberts 2009). The study estimates the optimum temperatures to be 29°C for corn, 30°C for soybeans, and 32°C for cotton. For corn, replacing 24 hours of the growing season at 29°C with 24 hours at 40°C causes an estimated 7 percent decline in yields. The relationship between temperature and yields is quite similar in the coolest and warmest parts of the country, suggesting that there has been little or no adaptation to long-standing temperature differences. Assuming no change in growing regions, average yields (without carbon fertilization) are projected to decrease by 30 to 46 percent under slow (B1) warming or 63 to 82 percent under fast (A1FI) warming by the end of this century.

A study of five leading food crops in sub-Saharan Africa found strong relationships of yields to temperatures. By mid-century, under the A1B climate scenario, yields are projected to drop by 17 to 22 percent for maize, sorghum, millet, and groundnuts (peanuts) and by 8 percent for cassava. These estimates exclude carbon fertilization, but maize, sorghum, and millet are C₄ crops, while cassava has a negative response to increased CO₂, as noted above (Schlenker and Lobell 2010). Negative impacts are expected for a number of crops in developing countries by 2030. Among the most vulnerable are millet, groundnut, and rapeseed in South Asia; sorghum in the Sahel; and maize in Southern Africa (Lobell et al. 2008).

There are many studies of climate change and California agriculture. These studies have often reached ambiguous conclusions – as long as water for irrigation is assumed to remain abundant. One study projects an increase in California farm profits due to climate change, with gains for some crops and losses for others, assuming that current policies and the availability of irrigation are unchanged (Costello, Deschênes, et al. 2009). Perennial crops such as fruits and nuts are of great importance in California; individual crops differ widely in the impacts of climate on yields (Lobell et al. 2007). Among six leading California perennial crops, climate change through 2050 is projected to decrease yields in four cases and to cause no significant change in the other two – again, assuming that irrigation remains unchanged (Lobell et al. 2006). In a study of the projected loss of winter chilling conditions in California, Germany, and Oman, fruit and nut trees showed large decreases in yield due to climate change (Luedeling et al. 2011).

The principal climate risk to California agriculture appears to be the possibility of shortfalls in irrigation. According to one recent study, climate change is increasing irrigation requirements, because crops need more water at warmer temperatures. This makes the already-serious, long-term regional water supply problems even harder to solve (Ackerman and Stanton 2011). A study of climate and California agriculture that focuses on the growing scarcity of water projects a drop in irrigated acreage and a shift toward higher-value, less-water-intensive crops (Howitt et al. 2009). An analysis of potential water scarcity in California due to climate change estimates that there will be substantial costs in dry years, in the form of both higher water prices and supply shortfalls, to Central Valley agriculture (Hanemann et al. 2006).

Aggregate impacts of climate on agriculture

A comprehensive assessment of climate impacts on U.S. agriculture, from the U.S. Climate Change Science Program, projects the effects on major crops of the next 30 years of climate change – interpreted as the combination of a 1.2°C temperature increase and an increase in atmospheric CO₂ from 380 to 440 ppm (Hatfield et al. 2008). It concludes that the benefits of CO₂ fertilization and the damages from rising temperatures will roughly offset each other in that time frame, resulting in only small changes in yields. Specifically, it projects yield gains (percentage changes in parentheses after each crop) in soybeans (+9.9 Midwest, +3.9 South), cotton (+3.5), and peanuts (+1.3); roughly no change in wheat (+0.1); and yield losses in dry beans (-2.5), maize (-3.0), rice (-5.6), and sorghum (-8.4). It anticipates that the outlook beyond 30 years will be less favorable, because adverse temperature effects will worsen while CO₂ fertilization benefits will diminish. The study also comments on the relative lack of research on climate impacts on livestock, which accounts for about half the value of U.S. agricultural output. And it notes that CO₂ fertilization appears to promote greater growth in weeds than in cash crops and that the widely used herbicide glyphosate (Roundup) is less effective against weeds at higher CO₂ concentrations. Climate effects on weeds are not included in the study's estimates of changes in crop yields (or in most research on yields).

As an alternative to studies of individual crops, some economists have tried to estimate the aggregate impacts of climate change on agriculture as a whole. One common approach, hedonic, or “Ricardian,” analysis takes the value of farmland as an indicator of agricultural productivity and correlates it with climate variables. The name is inspired by David Ricardo’s argument that the value of agricultural land depended on its fertility. Here, as with carbon fertilization, the conclusions of studies in the 1990s were more optimistic than is newer research about the benefits of near-term warming.⁵⁰

In a worldwide assessment of global warming and agriculture, William Cline projects that by the 2080s, a business-as-usual climate scenario (A2) would reduce world agricultural output by 16 percent without carbon fertilization or by 3 percent with carbon fertilization effects (Cline 2007).⁵¹ Cline finds that the losses from climate change will be disproportionately concentrated in developing countries; for the

⁵⁰ For reviews of earlier studies in this area, see Cline (2007) and Schlenker et al. (2005).

⁵¹ Cline’s (2007) results are the average of six A2 scenarios, with a mean climate sensitivity of 3.3°C.

United States, he projects an agricultural output loss of 6 percent without carbon fertilization or a gain of 8 percent with carbon fertilization.

Two major studies of U.S. agriculture have reached somewhat different conclusions. Deschênes and Greenstone (2007) analyze county-level farm profits per acre⁵² as a function of temperature, precipitation, and soil quality. Their model assumes quadratic relationships with temperature and precipitation. They estimate that by the end of the century, climate change will cause a 4 percent increase in agricultural profits nationwide, with considerable diversity among states; California suffers a 15 percent loss in farm profits in this model. A subsequent study of California, however, uses a similar model to project climate-related increases in farm profits for the state, with faster climate change (A2 versus B1) causing larger profits (Costello, Deschênes, et al. 2009).

Schlenker et al. (2006) analyze farmland values per acre for agricultural counties east of the 100th meridian.⁵³ They include similar explanatory variables and distinguish between two measures of temperature: growing season degree days⁵⁴ in the range of 8° to 32°C (a range in which warmth is beneficial to many crops) and growing season degree days above 34°C (temperatures that are harmful to almost all crops). By the end of the century, assuming no change in growing locations, Schlenker et al. project average decreases in farmland value due to climate change ranging from 27 percent under the B1 climate scenario to 69 percent under the A1FI scenario. All the climate variables are significant, but more than 90 percent of the losses in every scenario are attributable to the increase in degree days above 34°C. A subsequent study of agriculture in California, the most important agricultural area west of the 100th meridian, found no significant correlation of farmland values and temperature or precipitation but a strong relationship with irrigation water per acre (Schlenker et al. 2007).

The differences between the studies of U.S. agriculture could reflect simply the differences in specification; there is no measure of extreme temperatures in the Deschênes and Greenstone (2007) analysis that corresponds to the all-important variable, degree days above 34°C, in the Schlenker et al. study. In addition, the latter research group has circulated a technical critique of the Deschênes and Greenstone analysis, alleging that there are significant gaps and errors in its data set and analytical problems in its use of the data (Fisher et al. 2010). According to one of the authors of the critique, it has been accepted for publication in the *American Economic Review*, and the reply by Deschênes and Greenstone acknowledges the errors.⁵⁵

The current understanding of agriculture

The rapid expansion of research on climate and agriculture has challenged earlier conclusions and broadened our knowledge of many specific aspects of the problem. It has not yet coalesced into a streamlined new synthesis. Based on the research now available, it appears that there is a moderate carbon fertilization benefit to most C₃ plants, with the caveats noted above. The relationship of yield to temperature, at least for several leading crops, is markedly asymmetrical, with a gradual increase below the optimum temperature but rapid decline above that threshold. In some parts of the world, risks of

⁵² Defined as the difference between market revenues and costs of production, as reported in the U.S. Census of Agriculture at five-year intervals.

⁵³ The 100thth meridian is a north-south line that forms the eastern edge of the Texas Panhandle and roughly bisects the Dakotas. It is traditionally taken as an approximation of the precipitation threshold for rain-fed agriculture: Most of the area east of the 100th meridian has at least 20 inches of rain per year and does not rely on irrigation, while most of the area west of the line, excluding the Northwest coast, has less than 20 inches of rain and must rely on irrigation.

⁵⁴ Degree days are often used to measure seasonal totals of heat or cold. Relative to the 8°C baseline for beneficial warmth used in this study, a day with an average temperature of 12°C would represent four degree days. The study adds up such calculations for every day in the growing season to measure beneficial heating. Harmful, excessive heating was calculated by adding up similar calculations relative to a 34°C baseline for every day when temperatures exceeded that baseline.

⁵⁵ Personal communication, Michael Hanemann, July 2011.

change in the supply of water, either from precipitation or irrigation, may be the most important effect of climate on agriculture. In other farming areas, the anticipated increase in extremely hot days rather than the change in average temperature may be the dominant climate effect.

For an analysis of global impacts, Cline (2007) appears to be the newest and best available. Note, however, that Cline's estimate for the United States is much more optimistic than is the more-detailed Schlenker et al. (2006) study of climate impacts on U.S. agriculture and does not include a measure of extremely hot days. For the 2080s in a business-as-usual emissions scenario, Cline projects a 3 percent net global loss of production due to climate change when carbon fertilization is included, with many northern countries seeing net gains. Net losses are expected for most developing countries and even with carbon fertilization benefits included, Cline projects yield losses greater than 20 percent for 29 countries and regions, primarily in Africa, Latin America, and South Asia; the expected losses are greater than 50 percent in some parts of Africa.⁵⁶

In tropical areas, even small temperature increases are expected to cause a decline in yields for many crops; these impacts could be observable on a regional scale by the 2030s. Even 2 to 3°C of warming in this century would result in devastating losses to agricultural yields in many developing countries. In many temperate areas, new research continues to roll back earlier claims of increased agricultural yields from climate change. The latest research shows very modest net global gains from business-as-usual emissions throughout this century, but these net increases include net losses from many crops and regions.

Coastal flooding

With nearly two-fifths of the world population living in coastal zones, flooding from sea-level rise and storm surges has the potential to prompt large-scale migration of human populations, together with political instability, and could cause devastating losses of homes, businesses, infrastructure, and coastal shallow-water ecosystems. Recent studies of sea-level-rise impacts improve on older projections by including the best current estimates of the contribution from melting ice sheets (which were left out of AR4's estimates – see Chapter I.1) by taking into account more information about regional variation in the rate of sea-level rise and by modeling the combined effects of sea-level rise and storm surge instead of taking each effect in isolation.

Sea-level rise

The combined effects of sea-level rise and storm surges pose a significant risk to coastal populations everywhere. As of 1995 (the latest year for which complete data are available), 39 percent of the world's population lived within 100 kilometers (60 miles) of the coast, with some of the most densely populated coastal areas in East and Southeast Asia, Europe, and the East Coast of the United States.⁵⁷ Sea-level rise varies significantly by region. Between 1992 and 2009, the rate of sea-level rise (including local subsidence and uplift) ranged from +20mm per year in parts of Southeast Asia, Oceania, and northern Australia to -20mm per year in the Caspian Sea and in isolated parts of the Arctic and Antarctic. Most areas saw sea levels rise at a rate of 2 to 5mm per year. No standard source for projected sea-level rise currently exists (as discussed in Chapter I.1), but a review of recent estimates by Nicholls and Cazenave (2010) gives a range of 0.3 to 1.8m by 2100 across all SRES emissions scenarios.

Nicholls and Cazenave also review recent literature on populations vulnerable to climate-change-induced sea-level rise and report three areas of particular risk. First, the deltas of South, Southeast, and East Asia have large, rapidly growing large coastal populations living at very low elevations. Second, Africa's coastal areas often have very low-income populations with high growth rates; Egypt and Mozambique are especially at risk. Finally, small island states in the Pacific and Indian oceans and the Caribbean face the

⁵⁶ See Cline (2007), Table 5.8 and p.72.

⁵⁷ World Resources Institute (2000).

worst risks, including the submergence of some low-lying islands such as the Maldives or Tuvalu during the 21st century.

In the United States, coastal counties accounted for 29 percent of the 2008 population and contained five of the 10 most populous cities. Nearly half of the U.S. coastal population (by this definition) lives on the Atlantic Coast – including 15 percent each in New York and Florida, another 15 percent on the Gulf Coast, and 29 percent in California.⁵⁸ Sea-level-rise projections for the U.S. Atlantic and Pacific coasts are considerably higher than are global mean changes.

A study of the U.S. coastline from Virginia to Massachusetts using mean global sea-level rise of 0.38m (under the B2 climate scenario) and 0.45m (under A2) by 2100 resulted in an increase in modeled sea levels up to 0.74m, depending on local rates of sea-level rise (which vary with gravitational changes from lost polar ice, as well as salinity effects on the stability of the Atlantic Meridional Overturning Circulation; see Chapter I.1) and subsidence. The largest increases to sea level were projected for Maryland, New Jersey, and Virginia. By far the most populous areas likely to be inundated by 2100 are in New York and New Jersey (Wu et al. 2008). For New York City, the effect of the expected change in ocean salinity on circulation alone has been projected to reach 0.15 to 0.21m by 2100 – an additional source of sea-level rise not included in global mean projections (Yin et al. 2009). On the Gulf Coast, the combined effect of sedimentation lost due to upstream dam construction and climate-change-induced sea-level rise may result in widespread inundation of the Mississippi Delta (Blum and Roberts 2009; Heberger et al. 2009).

Storm surge

In the past, studies of coastal damages from climate change have often focused on a single mechanism, either permanent inundation from sea-level rise or storm-surge flooding from hurricanes and other major storms. The real impact of climate change on coastal regions, however, can be understood only as the confluence of these two effects. Some newer economic analyses of coastal climate damages look at both kinds of flooding: permanent inundation and *additional* storm-surge inundation starting from these new average sea levels.

Several recent studies combine the DINAS-COAST database of coastal social, economic, and ecological attributes with the Dynamic Interactive Vulnerability Assessment (DIVA) modeling tool and include both permanent and storm-surge inundation in their climate change scenarios (Vafeidis et al. 2008). Using DIVA, Nicholls et al. (2008) rank port cities by their vulnerability to flooding in the absence of adaptation. Assuming 0.5m of flooding, along with some city-specific assumptions about anthropogenic subsidence, the 10 most vulnerable cities with current populations greater than 1 million are Mumbai, Guangzhou, Shanghai, Miami, Ho Chi Minh City, Kolkata, Greater New York, Osaka-Kobe, Alexandria, and New Orleans. In terms of exposed assets, the most vulnerable cities are Miami, Greater New York, New Orleans, Osaka-Kobe, Tokyo, Amsterdam, Rotterdam, Nagoya, Tampa-St. Petersburg, and Virginia Beach. All these cities are located in just three countries: the United States, Japan, and the Netherlands. Dasgupta et al. (2009) use DIVA to model how storm-surge impacts intensify in developing countries with a 1-meter rise in sea levels. The 10 countries at greatest risk in terms of the share of coastal population affected are the Bahamas, Kuwait, Djibouti, United Arab Emirates, Belize, Yemen, Togo, Puerto Rico, El Salvador, and Mozambique.

Countless other studies use detailed Global Information System elevation data, local tide, subsidence and uplift observations, and regionalized sea-level-rise projections to fine-tune economic analyses to the best possible current information. For example, one study projects that 1.4m of sea-level rise would put half a million Californians at risk of storm-surge flooding, many of them in low-income communities. This same study also emphasizes that many areas of the California coast are not directly vulnerable to flooding (because of their steep topography) but are still extremely susceptible to erosion (Heberger et al. 2009).

⁵⁸ Wilson and Fischetti (2010).

Local studies offer the greatest accuracy but are generally very small in scope, covering a single island, inlet, or coastal region. A study by Stanton et al. (2010) applies the techniques used in local sea-level-rise studies to the full length of the Canadian coastline. Combining detailed elevation and sea-level-rise data with national census data, the study finds that the combined effects of permanent and storm-surge flooding will have the greatest economic impacts on British Columbia. Throughout Canada's coastal regions, low-income and racial/ethnic minority populations face elevated vulnerability to climate-change-related flooding.

Human health

Likely impacts on human health from climate change documented in AR4 include increased incidence of malnutrition; increased incidence of disease, injury, and death from heat waves, floods, storms, fires, and droughts; and changes in the range of some infectious diseases, including malaria (IPCC 2007, Working Group II, Chapter 8).⁵⁹ More recent research suggests that 88 percent of the current disease burden from climate change falls on children, compared to the overall pediatric burden of disease – 5 percent in high-income countries and 31 percent in developing countries (Sheffield and Landrigan 2011; Tillett 2011; Bernstein and Myers 2011). One study of the change in incidence of diarrheal diseases under a business-as-usual emissions scenario projected a 22 to 29 percent increase by the late 21st century (Kolstad and Johansson 2010).

Temperature is by far the best-studied link between climate and human health.⁶⁰ While most experts expect negative health effects from rising temperatures, this opinion is not quite unanimous. One recent study projects that 1°C of warming will save more than 800,000 lives a year by 2050. This appears to be based on a series of errors that led to mistaken projections of large reductions in cold-related deaths and much smaller increases in heat-related deaths.⁶¹ In the opinion of most other analysts, global warming will be harmful to human health. The real culprit in heat-induced mortality, however, is not gradual warming but rather the greater incidence of life-threatening heat waves.

Heat waves have caused widespread mortality and morbidity, notably in 2003 in Western Europe and in 2010 in Russia, but also in smaller events around the world. The latest research on temperature stress in humans shows that heat waves associated with a 7°C increase in mean global temperatures could make some regions uninhabitable without air conditioning. At an 11 to 12°C increase, regions containing a majority of the human population (as currently distributed) would be rendered uninhabitable. These regions would reach, at least once a year, combinations of temperature and humidity that human beings cannot survive (Sherwood and Huber 2010). Weitzman (2010) has argued on this basis that 12°C warming would essentially destroy the world economy. Even with just a few degrees of warming, labor productivity would be affected in many tropical areas (Kjellstrom et al. 2009).

Greenhouse gas mitigation not only is expected to keep temperature increases to a minimum but also holds great potential for providing ancillary benefits in relation to human health. Combustion of fossil fuels and biomass results in the release of particulates, ground-level ozone, and other pollutants, thereby greatly reducing air quality. Climate-change-induced wildfires have similar effects, and the increasing incidence of asthma and other diseases triggered by airborne allergens is also thought by some researchers to be related to climate change. Emission mitigation would have the beneficial side effect of improving air quality (Haines et al. 2010; Markandya et al. 2009; Tagaris et al. 2009).⁶²

⁵⁹ Gamble et al. (2008) and Costello, Abbas et al. (2009) come to a very similar set of conclusions for the United States.

⁶⁰ AR4 (IPCC 2007 Working Group II, Chapter 8) summarizes these findings through 2007. More recent research includes Jackson et al. (2010); Knowlton et al. (2009); and Ostro et al. (2009).

⁶¹ The original study is Bosello et al. (2006). For a critique, see Ackerman and Stanton (2008). For the original authors' response, see Bosello et al. (2008).

⁶² Kinney (2008) and Bell et al. (2008) both review the literature on ancillary benefits from greenhouse gas mitigation through 2007.

New research that incorporates effects on air quality into general circulation models shows increased ozone and particulate levels, especially in urban areas (Jacob and Winner 2009). Fuel choice is a key predictor of future air pollution levels. A study comparing the life-cycle emissions of biofuels to those of gasoline found health impacts to be higher for corn ethanol, lower for cellulosic ethanols, and especially low for ethanols derived from diverse prairie vegetation (Hill et al. 2009). Research from the United Kingdom points to complex effects on air quality from fuel choices that may limit the near-term ancillary benefits of mitigation in practice. Since 2001, U.K. policies to reduce greenhouse gas emissions have been associated with an increase in the market share of diesel cars, and diesel fuel releases pollutants that have more dangerous health effects than those of gasoline (Mazzi and Dowlatabadi 2007).

Undesirable organisms will also be affected by climate change. There is an ongoing debate about the relationship between climate change and malaria: On the one hand, transmission of malaria is optimized at temperatures of 28 to 32°C but is blocked by temperatures below 16°C, implying that warming will increase vulnerability in many areas. On the other hand, there are many other factors that have an equal or greater influence on the spread of malaria, creating uncertainty about the future outlook for the disease (Chaves and Koenraadt 2010). Dengue fever is transmitted by a particular mosquito whose range is limited by adult and larval cold tolerance, and warming will allow the mosquito, and hence the disease, to expand into areas currently too cold for it (Kearney et al. 2009).

A final area of concern human health is water availability. Regional downscaling of climate models suggests that in most cases, wet regions will become wetter and dry regions dryer with climate change, posing a grave problem for areas that are already water stressed. The Sahara, Kalahari, Gobi, and Great Sandy deserts are expected to expand, and 10 to 20 percent decreases in precipitation are projected for already-dry areas around the world (see Chapter I.1). Arid regions facing reduced precipitation risk water shortages unless they can make up the difference from groundwater (a finite source and, therefore, a short-term solution), energy-intensive ocean desalination, and conservation and efficiency measures.

Recent advances in modeling water availability, due in part to improved projections of the rate of melting glaciers and other land ice (see Chapter I.1), suggest that precipitation changes can only partially predict water stress suffered by human communities. Since AR4, global systems for tracking glaciers have become more complete and more accurate (Cogley 2010), and effects on glaciers can now be represented in regional climate models (Kotlarski et al. 2009). As climate change progresses, water availability will decrease in river systems fed by glacier meltwater, including large parts of Southeastern Europe and Central and Eastern Asia. In a few areas, high dependence on glacial meltwater coincides with high population density. The regions that rely on the Aral Sea, Indus River, and Ganges River stand out in their water supply vulnerability (Kaser et al. 2010).

Likely impacts and catastrophes

With continued business-as-usual emissions, the most likely end-of-the-century temperature increase is 4.2°C (with a one-in-10 chance of temperatures falling below 2.3°C in the most optimistic business-as-usual scenario and exceeding 7.1°C in the most pessimistic). At this rate of change in temperatures, agricultural productivity will decline in South Asia and Africa by the 2030s. Without adaptation, by late in the century average global agricultural yields will have fallen by 6 percent, with much larger losses in most of the developing world. In some parts of Africa, more than half of the current agricultural output would be lost to climate change by the 2080s.

Another most likely result of business-as-usual emissions is 1.2m of sea-level rise by 2100. Low-lying small islands, coastal and delta populations are especially vulnerable to rising sea levels. Without adaptation, serious flooding damage could occur before mid-century. Studies using one-half or less of the most likely 2100 sea-level rise predict large-scale damages. With the likely changes in temperature and sea levels will come an increase in disease, injury, and death associated with heat waves; changes to the range of disease vectors; and reduced access to clean water. Children, especially, will be vulnerable to negative health effects from climate change.

In catastrophic scenarios of climate change, with temperatures and sea levels rising much faster than the most likely rates, the likely impacts on human systems described here would occur closer to mid-century.

Climate-economics models commonly include estimates of damages in terms of GDP losses – losses to economic output from the forestry, fisheries, agriculture, and tourism sectors – and also sometimes include damages to coastal infrastructure or a decrease in labor productivity. Climate damages may, however, include losses that cannot easily be measured in monetary terms: permanent inundation of entire communities and even entire nations; irreversible harm to ecosystems, including the permanent loss of biodiversity; or lives lost to climate-induced disease or injury. Economic models of damages to human systems cannot truly represent these catastrophic losses, and in any case, this is an area where economic analysis currently lags far behind scientific research. Attempts to suggest the magnitude of impacts to human society in the “damage functions” of economic models are discussed in Chapter II.1.

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Part II: Climate economics for the 21st century

Recent scientific research has deepened and transformed our knowledge of climate change. As seen in Part I, the earth's climate is a complex, nonlinear system with dynamics that cannot be predicted in detail – including, among other hazards, the possibility of thresholds at which abrupt, irreversible transitions could occur. A range of feedback effects intensify the warming caused by rising concentrations of greenhouse gases, leading to a rapid, though perhaps irreducibly uncertain, pace of climate change. There is also a growing understanding of the numerous harmful impacts that are expected before the end of this century, even at the most likely rate of climate change, and of the additional catastrophic outcomes that could result – with lower but nontrivial probability – if climate change proceeds more rapidly.

These results of climate science have important implications for economic theory. Analyses and models that project modest-sized, precisely known climate impacts, although still seen in the economics literature, now seem quaint and dated. They are based, at best, on hopes and guesses that might have been reasonable to entertain in the 1990s or earlier, before the nature and magnitude of the problem became so painfully clear. New developments in climate science require corresponding new developments in climate economics.

In the most general terms, there should be a qualitative match between the economics of climate change and the pattern of scientific findings on which it rests. Scientific projections of climate outcomes are uncertain, with the range of possibilities including extremely damaging impacts; therefore, the corresponding economic projections should consist of ranges of possibilities, including economic results that reflect the seriousness of worst-case climate outcomes.

There are three fundamental features of climate change that pose unique challenges to economic theory, requiring extensions of economic analysis into unfamiliar territory. In brief, they involve the extent of uncertainty, the spans of time involved, and the global nature of the problem and its solutions. Each of these issues arises, often in a more limited form, in other areas of economics; an extreme form of each of these issues is central to climate economics, potentially requiring new and different approaches.

Moreover, as explained later in this chapter, one of the traditional frameworks for climate economics conflates all three issues, leading to paradoxical implications that are only beginning to be resolved in recent economics research.

High-stakes uncertainty

Any analysis involving future outcomes is subject to some uncertainty. The accumulated effect of small unknowns naturally grows over time, with the result that uncertainty is normally greater at a longer horizon. A standard practice in economic theory is to calculate the expected value, or certainty equivalent, of future outcomes over the range of possibilities, but this is of limited help in cases where the future probability distribution is unknown. In the terminology introduced long ago by Frank Knight (1921), expected values can be calculated for risks with known probabilities but not for uncertainties with unknown probability.⁶³ The dilemmas of decision making under Knightian uncertainty arise in multiple policy arenas, including, among others, toxic chemical hazards (Ackerman 2008), nuclear reactor safety, and nuclear waste management, as well as the threat of terrorism and, perhaps, systemic financial crises (for a thoughtful recent review, see Farber 2011).

⁶³ Knight's terminology, although well-known in economics (see Runde 1998 for a contemporary discussion) is not universally accepted or applied. The field of risk assessment sometimes uses the terms "known uncertainty" and "unknown uncertainty," which roughly correspond to Knight's risk and uncertainty (Daneshkhah 2004). Informal usage, including portions of the text of this report, often uses risk and uncertainty as synonyms. For instance, the common expression "catastrophic risk" does not always imply knowledge of probabilities.

Climate change involves uncertainty on many levels. In the near term, climate change appears to be associated with increased hazards from extreme weather events. Individual extreme events are not predictable on any but the shortest timescale; the global weather system exhibits very complex dynamics that defy long-run prediction. Indeed, a path-breaking early analysis of chaotic dynamics and sensitive dependence on initial conditions emerged from a simple weather model (Lorenz 1963; Gleick 1987). The probability distribution of extreme events is, in part, an area of still-unsettled science but may well be worsening as the world warms (see, e.g., the ongoing debates over hurricane frequency and intensity in Chapter I.1). The uncertainty surrounding extreme events is a central concern in the economics of adaptation (see Chapter III.3).

In the longer run, much of the science described in Part I implies that there are nonzero probabilities of irreversible changes that would threaten the prosperity or even survival of human society in its present form. While still reasonably improbable under today's conditions, these dangers will become ever less unlikely as the temperature rises. There may even be tipping points at which fairly abrupt transitions to worse outcomes will occur (Lenton et al. 2008). Learning about the risks of tipping points by trial and error is not an option, because climate change is an experiment that we can only do once. The stakes could not be higher, forcing us to consider disastrous risks and to question how unlikely is unlikely enough. In contrast to most other policy problems that involve decision making under uncertainty, the worst-case outcomes from climate change appear to be unbounded, involving arbitrarily large threats to our common future. Long-term catastrophic risk is the subject of some of the most important recent developments in climate economics, discussed in Chapter II.1.

Deep time

Comparisons of costs and benefits at different points in time are common in economics; most investments involve consequences that stretch multiple years into the future. In the case of climate change, however, the standard methodology for intertemporal calculations, or the discounting of future values, has resulted in extensive, unresolved controversy. Discount rates used in other areas are often so high that, if applied to climate policy, they imply that the well-being of future generations and the most serious long-term consequences of climate change can be ignored.

The logic of the elementary textbook argument for discounting is unimpeachable once its numerous assumptions are granted. Suppose that an investor is evaluating a private investment that yields a known monetary benefit at a future date within the investor's lifetime and imposes no externalities on anyone else. Assume that future market outcomes, including incomes and rates of return on capital, are known with certainty. Then the future benefit should be discounted at the market rate of return. If the market rate of return is a constant r , and a benefit X occurs T years from now, then its present value is either $X(1+r)^{-T}$ or Xe^{-rT} , depending on whether time is treated as a discrete (annual) or a continuous variable.

Many of the assumptions in this story about discounting are clearly inapplicable to climate economics. Hence the discounting debate can be reframed around two related questions: Which assumptions have to be changed in order to apply discounting to climate change? And how does that affect the discount rate or the discounting process? Each of the three major issues in climate economics addressed in this review has implications for the discounting debate.

Uncertainty pervades the calculations of climate costs and benefits, affecting, among other things, future incomes, market rates of return, and climate outcomes. Much of the discussion of uncertainty in Chapter II.1 has a direct effect on the appropriate discount rate. Some aspects of uncertainty imply that a low and/or declining discount rate should be used. This involves still-unsettled questions at the frontiers of economic research.

The global externalities associated with greenhouse gas emissions, and the view of climate policies as global public goods (discussed below), raise questions about the appropriateness of the private investment framework for decision making. That framework is implicit in the elementary argument for discounting. Here, too, there is ongoing, unresolved debate, often presented in terms of political economy and ethics rather than formal economic theory.

The vast time span of climate processes also affects the discounting framework, requiring it to be applied to events far beyond a single lifetime. Climate science makes it clear that causation stretches across centuries. A significant fraction of CO₂ emissions remains in the atmosphere for more than a century, continuing to warm the earth and change the climate throughout that period of time. As atmospheric temperatures rise, the oceans take centuries to catch up; the thermal expansion of oceans causes sea-level rise, which will continue for centuries after atmospheric temperatures are stabilized. Major ice sheets melt (and hence contribute to sea-level rise) over a multi-century time frame. Even if a tipping point were to occur at which, for instance, complete loss of the Greenland Ice Sheet became inevitable, it would take centuries to finish melting.

As a result, costs and benefits of the same climate policy will typically be spread across multiple centuries. This changes one of the important, usually implicit assumptions in the simple story about discounting: It is impossible for a single individual to experience both the costs and benefits of today's actions. Instead, current costs must be weighed against benefits to be experienced, in significant part, by future people whose lifetimes will not overlap with those of us who are alive today. Is discounting applicable to intergenerational decisions? If so, what discount rate should be used? If not, what other methods should be used for intergenerational decision making?

The problem of decision making across “deep time” arises in other contexts, perhaps most dramatically in the case of nuclear waste. Some of the byproducts of nuclear reactors and nuclear weapons production will remain hazardous for hundreds of thousands of years, raising unique challenges for protection of and communication with our far-future descendants (see, e.g., Benford 1999).

Climate change occurs on a timescale that is modest compared to the many millennia of nuclear waste hazards – but immense compared to almost everything else, and outside the boundaries of familiar methodologies such as single-lifetime discounting. This question is explored further in Chapter II.2.

It's a small world

Externalities and public goods are familiar features of economics; free-rider problems and other conflicts over the provision and financing of public goods are endemic. In political economy terms, all public policies are debated and adopted in the context of an unequal world where costs, benefits, incomes, and opportunities are often distributed unfairly. Yet in most cases, externalities and remedies can be addressed at a local, national, or regional level, setting aside the formidable problems of international inequality and the lack of effective global governance.

Climate change is the ultimate global externality. Greenhouse gases emitted anywhere contribute to global warming everywhere. Sea-level rise on all islands and coastal regions is a function of the total volume of water in the world's oceans. Climate solutions are equally universal, requiring virtually complete global cooperation in emission reduction and other policies. Other global externalities have arisen in the past; the frequently cited example of stratospheric ozone depletion provides a success story for international negotiation. The Montreal Protocol for elimination of ozone-depleting substances, however, involved costs that are smaller by orders of magnitude than the likely costs of climate mitigation, as well as technological changes in only a few industries. Climate change appears to be unique in the magnitude of costs and the extent of technological transformation required for a solution. (The expected costs and technology implications of climate policies are discussed in Part III.)

While the global nature of climate change means that we are all in the same boat, some of us have much nicer cabins than others. There are important inequalities in climate impacts, historical responsibility, and ability to pay for both adaptation and mitigation. Climate damages are expected to vary greatly by location, with tropical, coastal, and arid regions likely to be hardest hit; these are disproportionately lower-income parts of the world. In terms of responsibility, the long-term persistence of greenhouse gases in the atmosphere means that global warming today is driven by emissions over the past century or more; those historical emissions are in large part the result of the economic growth of high-income countries. In terms of ability to pay, climate costs will be felt everywhere, but the need for adaptation funding will be greatest in the hardest-hit, disproportionately low-income countries, and the need for mitigation funding will be most urgent in rapidly industrializing, emerging economies with low-to-medium per capita incomes.

In this small and interdependent world, a climate solution must be accepted as fair by both rich and poor nations in order to succeed. This challenging requirement has been widely discussed in the context of international negotiations but has received less attention in the economics literature. It is explored further in Chapter II.2.

Stern and his predecessors

The remainder of this chapter reviews the treatment of two of these fundamental issues, uncertainty and discounting, in climate economics before and in the Stern Review (Stern 2006). (The somewhat-separate and more limited literature on global equity issues in climate economics is presented in Chapter II.2.) The chapter then closes with a comparison to the economics of financial markets, which has become important in the recent discussion of climate economics. Chapter II.1 examines the analysis of uncertainty since the Stern Review, and Chapter II.2 turns to developments in discounting and equity – both between generations and within the world today.

Uncertainty before Stern

In the era before the Stern Review, economic models of climate change were typically framed as cost-benefit analyses, evaluating known or expected outcomes. In some cases, predictable, bounded variation was included via Monte Carlo analysis, as in studies by Richard Tol (for example, Tol 2002) using the FUND model. On the approach to uncertainty in early studies, see Watkiss and Downing 2008. Two well-known models, DICE and PAGE, took another step: Each included, in a limited fashion, the potential for abrupt, “catastrophic” losses. These losses initially have low or zero probability but become less improbable as temperatures rise.

In DICE, the magnitude of a potential catastrophe was initially based on a survey of expert opinion in the early 1990s (discussed most fully in Roughgarden and Schneider 1999); minor adjustments have been made since then (Nordhaus 2008). Uncertainty is represented by assigning a small, temperature-dependent probability to the average of expert guesses about the magnitude of catastrophe. The certainty-equivalent value (i.e., the product of probability and magnitude) is then included in the DICE damage function. Thus, DICE assigns a value to its interpretation of uncertainty but then treats the expected value as if it were a certain cost of climate change.

PAGE, from its earliest versions through PAGE2002 (the version used by the Stern Review), has calibrated its damage estimates to other studies and models such as DICE (Hope 2006). PAGE includes a potential catastrophe, with its most likely magnitude comparable to the DICE estimate of catastrophe. In PAGE, however, three key parameters – the temperature threshold for catastrophe, the (temperature-dependent) probability of occurrence once that threshold is reached, and the magnitude of catastrophe – are all Monte Carlo variables. While producing average results similar to DICE, PAGE is also able to generate probability distributions, showing extremes such as 95th percentile outcomes, as well as mean outcomes.

Uncertainty in the Stern Review

The Stern Review called for a broad reframing of the economics of climate change. Regarding uncertainty, its starting point was the scientific analyses of potential tipping points, with serious threats of large-scale, irreversible harms from just a few degrees of warming. In later writing as well, Stern has continued to argue that economists need to take such dangers seriously (Stern 2008).

The quantitative calculations in the Stern Review, however, did not represent a complete break with past modeling. The Stern Review used the PAGE2002 model with only limited changes in its inputs and parameters; the assumptions about catastrophes, calibrated to DICE and other earlier studies, remained unchanged. Thus, it could be argued that the narrative of the Stern Review implied a need for upward revision in the estimates of both the magnitude and likelihood of catastrophe (Ackerman et al. 2009) – a perspective that is influencing a forthcoming revision of the PAGE model⁶⁴ – but the Stern Review’s economic calculations only partially reflect Stern’s prescription for change in climate economics. Nonetheless, the PAGE2002 model results used in the Stern Review projected larger climate damages than did many other economic analyses, in part because the Stern Review’s low discount rate raised the present value of catastrophes, which are more likely to occur in the later years of the multi-century simulations.

Some critics argue that the Stern Review overstates the risk, and therefore the certainty-equivalent value, of future damages. In their view, Stern’s damage calculations are biased upward both by the use of damage estimates based on assumptions about risk that are incompatible with the Stern Review’s own model and by the assumption that uncertainty is not reduced by learning about the climate system over time (Tol and Yohe 2006). Other critics make the opposite argument, maintaining that the Stern Review underplays the degree of uncertainty in climate science, making excessively confident predictions of severe climate impacts (Carter et al. 2006; Byatt et al. 2006).

The Stern Review team’s response is that, if anything, the Stern Review understates uncertainty and damages; it uses damage estimates based on “best guess” calculations (thus ignoring known sources of uncertainty), and it deliberately includes only modest feedback effects. While future learning about the climate system is possible, this may not diminish uncertainty (e.g., see the discussion of climate sensitivity in Chapter I.1). It does not support delayed action, which could be an additional source of risk (Dietz, Hope et al. 2007; Dietz, Anderson et al. 2007).

Discounting before Stern

The early discussion of discounting and intertemporal equity in climate economics was framed by a chapter of the IPCC’s Second Assessment Report written by six prominent economists, including Kenneth Arrow and Joseph Stiglitz (Arrow et al. 1996). They introduced the basic distinction between “prescriptive” and “descriptive” approaches to discounting, as well as summarized leading arguments for and against each approach.⁶⁵

The prescriptive approach, according to Arrow et al. (1996), assumes that discounting of future costs and benefits is an ethical issue; the appropriate discount rate, therefore, should be deduced from first principles, focusing on the utility of consumption today versus consumption tomorrow. The foundation of this approach, credited to Ramsey (1928), is an argument demonstrating that along an optimal growth path, the discount rate for consumption equals the productivity of capital. Later mathematical analysis led to the formalization of this principle in what is often referred to as the “Ramsey equation.” In the *Stern Review*’s (2006) notation:

$$(1) \rho = \delta + \eta g$$

⁶⁴ Personal communication regarding PAGE09, Chris Hope, November 2010.

⁶⁵ For additional views from the early stages of the discussion, see Portney and Weyant (1999), a widely cited collection of essays.

Here, ρ is the discount rate applied to consumption, or to goods and services in general; δ is the rate of pure time preference, i.e., the discount rate that would apply if all generations had equal resources (or equivalently, it is the discount rate for utility); η is the elasticity of the marginal utility of consumption (discussed later in this chapter); and g is the growth rate of per capita consumption.

The descriptive approach, on the other hand, assumes that discounting should be based on the choices that people actually make about present versus future consumption. That is, the discount rate should be inferred from current rates of return on financial assets. In this view, setting the discount rate below market interest rates would allow investments in mitigation to crowd out more valuable, higher-return investments in other activities, thus reducing the overall resources available for future generations.

Another valuable background source is the massive literature review by Frederick et al. (2002). It surveys the rich complexity of economic thinking about time and discounting, both before and after the brief paper by Samuelson (1937) that introduced the idea of a constant discount rate. Frederick et al. (2002) examine numerous arguments for hyperbolic or declining discount rates, including evidence drawn from experimental or behavioral economics. They do not, however, include the important analysis of Weitzman (1998), which demonstrates that under a descriptive approach to discounting, uncertainty about future interest rates can imply a steadily declining “certainty equivalent” discount rate. (Weitzman returns to this issue, reformulating his analysis to account for additional risks and complexities, in Weitzman 2010; his basic conclusion is qualitatively unchanged.)

Discounting in the Stern Review

The Stern Review provides an extensive discussion of the ethical issues involved in discounting, advocating a prescriptive approach with a near-zero value for δ , the rate of pure time preference. All people of current or future generations are of equal moral standing and deserve equal treatment, according to the Stern Review. A larger rate of pure time preference would inappropriately devalue future people who are not yet here to speak for themselves. Similar arguments date back at least to Ramsey and have been made by many economists and philosophers; no attempt will be made to review that earlier literature here.

At the same time, a value of exactly zero for pure time preference is problematic for economic theory. With an unbounded time horizon, it would imply that the present value of future utility is infinite and that the welfare of the current generation could be ignored as a vanishingly small part of the intergenerational whole. Stern’s solution is to include a small probability that human society will not survive some unspecified cataclysm, arbitrarily set at 0.1 percent per year. This becomes the rate of pure time preference: Because we are only 99.9 percent sure that anyone will be around next year, the certainty-equivalent present value of next year’s well-being is 0.999 as great as this year’s. There is a strong feeling of *deus ex machina* (or perhaps *diabolus ex machina*) about this solution, but it results in a low discount rate without setting the pure time preference literally to zero.

Stern was not the first economist to advocate low discount rates. Cline (1992) proposed a similarly low discount rate, including the pure time preference of zero, and reached conclusions similar to Stern’s about the economic justification for immediate, large-scale mitigation efforts. The high profile of the Stern Review, however, led to renewed debate on the issue. Many critiques, such as Nordhaus (2007), Tol and Yohe (2006), and Yohe (2006), identified the low discount rate – much lower than rates conventionally used by economists or policy makers – as the principal weakness of the Stern Review. Some noted that Stern’s near-zero rate of pure time preference, if used by individuals, would imply much higher savings rates than are actually observed (Arrow 2007; Weitzman 2007), so that if discount rates are to be consistent with actual savings behavior, the rate of pure time preference should be higher. In this context, Stern’s very low rate of pure time preference has been described as paternalistic (Weitzman 2007; Nordhaus 2007), imposing its own ethical judgment over the revealed preferences of most individuals. Debate continues on these issues, with Baum (2009), for example, defending Stern against the charges of

paternalism. It seems safe to conclude that no resolution has been reached, or is in sight, to the fundamental disagreement over the rate of pure time preference.

The Ramsey equation: An unsolved puzzle?

The rate of pure time preference is not the only locus of controversy concerning the discount rate. As seen in equation (1), the discount rate also includes a term involving η , the elasticity of marginal utility. Additional, perhaps more esoteric controversy surrounds the choice of η . Both Cline and Stern assumed relatively low values of η (1.5 and 1.0, respectively), contributing to their low discount rates. Other economists have argued that η should be higher, which implies a higher discount rate (as long as per capita consumption is rising, so that $g > 0$ in equation (1)).

It is common to assume a utility function that exhibits constant relative risk aversion (CRRA), of the form

$$(2) \quad u(c) = \frac{c^{1-\eta}-1}{1-\eta}$$

Here c is per capita consumption and η is the coefficient of relative risk aversion. (When $\eta = 1$, equation (2) is replaced by $u(c) = \ln c$.) The CRRA utility function is mathematically convenient but is not based on empirical evidence about consumer behavior. Even in theoretical terms, CRRA utility is problematic: Although it is useful under a specific set of conventional assumptions about growth and uncertainty, its useful properties are not robust under small changes in these assumptions (Geweke 2001). Indeed, there are problems with the entire analysis of risk aversion in terms of utility maximization with a concave utility function such as CRRA. In general, this approach cannot provide an explanation of risk aversion that applies consistently across risks of widely differing magnitudes (Rabin 2000; Rabin and Thaler 2001).

Despite these problems, the CRRA utility function is almost an industry standard in climate-economics models. When it is used in combination with the Ramsey equation, the same parameter η simultaneously measures risk aversion, “inequality aversion” within the current generation, and inequality aversion over time toward future generations (Atkinson et al. 2009). A larger value of η implies greater risk aversion in equation (2) and hence greater inequality aversion in the present, i.e., more egalitarian standards. It also implies a higher discount rate in equation (1), diminishing the importance attached to future generations. This paradox is highlighted in the response to the Stern Review from Dasgupta (2007), who accepts Stern’s low rate of pure time preference but still maintains that Stern’s overall discount rate is too low, because a higher value of η is required for equity in public policy decisions today. In this formulation, fairness to the poor in this generation seems to require paying less attention to future generations.

Similar problems have arisen in the economics of finance, which uses some of the same analytical apparatus. It has been known for some time that models based on the CRRA utility function cannot easily explain the “equity premium puzzle,” i.e., the relatively high level of the return on equity and the low level of the risk-free rate (Mehra and Prescott 1985). Using a standard growth model, Mehra and Prescott found that values of η less than 10 were not consistent with either a high enough return on equity or a low enough risk-free rate to match the historical data. Despite decades of analysis, there is no universally accepted resolution to the equity premium puzzle (DeLong and Magin 2009).

There are, however, many analyses and rival proposed explanations. Several innovative ideas in climate economics, described in the next chapter, arise as analogs to the equity premium puzzle literature in finance.

New ideas in climate economics

Part II reviews the new and ongoing developments that are transforming climate economics. Traditional cost-benefit frameworks are not appropriate to the challenges of modeling our uncertain, multigenerational, and uniquely global climate crisis. Chapter II.1, “Uncertainty,” looks at the latest research incorporating uncertain climate and economic forecasts into integrated assessment models. The

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likelihood of irreversible, catastrophic damage is small but nontrivial and irreducible uncertainties in the physical system raise the possibility of unbounded risks and the question of how to model such risks.

Chapter II.2, “Public goods and public policy,” addresses new innovations in modeling costs and damages over long timescales and disparate populations. Climate change is a global public goods problem that raises modeling challenges unique in the literature of economic analysis. Equity both within and between countries complicates assumptions about the discount rate and calls into question the best way to aggregate the well-being of an economically diverse world population in order to make fair policy decisions.

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Chapter II.1 Uncertainty

A core message of the science of climate change, as described in Part I, is that climate outcomes are uncertain – and the range of possibilities includes very serious threats to human society and existing natural ecosystems. The Stern Review (Stern 2006) took a step forward in recognizing the significance of this deep uncertainty and calling for its incorporation into economics, as described in the introduction to Part II. Since Stern, there has been extensive exploration of the economics of climate uncertainty, which is the subject of this chapter. It has been an area of important advances, although more remains to be done.

Uncertainty about the climate sensitivity parameter – the temperature increase resulting from a doubling of the atmospheric concentration of CO₂ – has been widely discussed and is the basis for Weitzman’s “Dismal theorem,” the subject of the first section of this chapter. The second section discusses uncertainty in climate damages, the response of the economy to temperature increases, and other changes in the climate. Although equally significant, this has received far less attention to date and is a priority area for additional research. A third section briefly reviews several studies that have incorporated several varieties of uncertainty. The final section examines new work on interpretations of risk aversion and the parallels to similar topics in finance.

The line separating this chapter from the following one is inevitably somewhat blurred. Many issues relating to discounting and intergenerational analysis, decision-making standards, and global equity – subjects covered in Chapter II.2 – have implications for uncertainty. Conversely, the discussion of uncertainty in this chapter affects discounting and other topics in the next chapter. The two should be read as a linked pair, treating the range of recent innovations in climate economics.

Climate sensitivity and the dismal theorem

In a widely cited assessment of the Stern Review, Weitzman (2007a) said that Stern was “right for the wrong reason.” According to Weitzman, Stern was right to highlight the urgency of the climate problem but wrong to base that conclusion on a very low discount rate rather than on the fundamental problem of uncertainty. Weitzman’s analysis of uncertainty has reshaped climate economics; it is the most important contribution to the field since the Stern Review.

The so-called dismal theorem (Weitzman 2009) is a densely mathematical demonstration that, under plausible assumptions and standard models, the marginal benefit of a reduction in greenhouse gas emissions is literally infinite. The two crucial assumptions leading to this result are 1), the structure of the earth’s climate is so uncertain that our best estimates inevitably have a fat-tailed⁶⁶ probability distribution, and 2) the disutility of extreme outcomes is unbounded as they approach the limits of human survival.

Regarding the first assumption, the climate sensitivity parameter is a crucial determinant of the impacts of climate change: Higher values for this parameter imply higher temperatures and a greater likelihood of the catastrophic outcomes discussed in Part I. Yet the climate sensitivity parameter remains uncertain (see Chapter I.1). Large-scale experiments to determine its value are obviously impossible; knowledge of climate sensitivity gained through indirect inference is limited, and the uncertainty may be inherently irreducible (Roe and Baker 2007). Weitzman argues more generally that in a complex, changing system such as the climate, older information may become obsolete at the same time that new information arrives, imposing an upper limit on the amount of empirical knowledge that we can acquire. Therefore,

⁶⁶ In a “fat-tailed” probability distribution, the probability of extreme outcomes approaches zero more slowly than does an exponential function; examples include the Student’s t-, Pareto, and other power law distributions. A “thin tailed” distribution approaches zero more rapidly than does an exponential function; the normal distribution is thin-tailed.

we are forced to rely on a limited amount of data, implying that our best estimates follow a fat-tailed probability distribution with a fairly large probability of dangerously high climate sensitivity.

The second assumption involves climate damages, which are addressed in more detail in the next section. The proof of the dismal theorem depends only on the limit approached by climate damages in extreme cases. It assumes that at sufficiently high levels of climate sensitivity, climate change would be severe enough to destroy much or all of economic output, driving per capita consumption down to subsistence levels or below. The resulting welfare loss, in standard economic models, rises without limit as consumption falls toward the threshold for human survival.⁶⁷ These disastrous scenarios cannot be ruled out or even ruled sufficiently improbable due to the fat-tailed probability distribution for climate sensitivity.

When outcomes are uncertain, economic analysis relies on expected values, which are probability-weighted averages (or integrals) across all scenarios. The fat-tailed probability distribution means that the disastrous scenarios in the tail of the curve, which have extremely bad outcomes, are only moderately improbable. Therefore, their contribution to the weighted average is huge; they dominate the expected value of climate change mitigation. Infinite values, as in the dismal theorem, result when these extremes are so large that the expected value, calculated as the sum of an infinite series, or an integral, fails to converge.

Responses to the dismal theorem

The discussion prompted by the dismal theorem has transformed the economic understanding of climate uncertainty and has shifted attention away from expected or most likely impacts toward catastrophic risks. There have been numerous criticisms and disagreements with Weitzman's formulation of the problem; many of these comments can be interpreted as proposing alternative theoretical frameworks for analyzing catastrophic risk.

Nordhaus (2009) challenges both of the assumptions of the dismal theorem. In his view, the unbounded, fat-tailed distribution of possible outcomes conflicts with the possibility that scientific knowledge and principles might place an upper bound on climate sensitivity and damages, while the second assumption, unbounded negative utility as consumption approaches zero, unrealistically implies unlimited willingness to pay to avoid even very small risks to human survival. Nordhaus then explores conditions that lead his DICE model to predict a "catastrophic" outcome, which he defines as world consumption per capita falling 50 percent below the current level. He concludes that three factors must all be present to drive consumption below this threshold: high climate sensitivity, high damages (i.e., a damage function steeper than DICE assumes), and the absence of any mitigation policy.⁶⁸

Pindyck (2010) accepts the dismal theorem's first assumption, the fat-tailed distribution of possible climate outcomes, implying significant risks of extreme impacts, but he rejects the second assumption, marginal utility becoming infinite as consumption drops toward zero, on much the same grounds as Nordhaus. Once a limit, even a very high one, is placed on marginal utility, Pindyck then demonstrates that the fat-tailed distribution of climate outcomes is important but not necessarily decisive. Willingness to pay for abatement can be greater in a model with a thin-tailed distribution of outcomes, depending on the choice of other parameters.

Costello et al. (2010) pursue the opposite strategy, exploring the effects of changing the first assumption, i.e., imposing upper limits on climate sensitivity. Using a fat-tailed distribution for climate sensitivity and

⁶⁷ This feature is often attributed to the "constant relative risk aversion" (CRRA) utility function, but the same problem would arise with any function that assigns an infinite disutility to the extinction of the human race. CRRA utility is proportional to a negative power of per capita consumption or to the logarithm of per capita consumption, either of which tends toward negative infinity as per capita consumption goes to zero.

⁶⁸ DICE does not model adaptation, so adaptation policy options are not discussed. Climate damages that cause catastrophic drops in consumption, however, are likely to be too severe to handle with adaptation.

a very simplified model, they reproduce the dismal theorem result when climate sensitivity is unbounded, with willingness to pay to avoid climate change approaching 100 percent of GDP. When a high upper limit is placed on climate sensitivity – they experiment with limits from 20 to 50°C – then the paradoxical result disappears, and willingness to pay to avoid climate change drops below 10 percent of GDP in most of their scenarios.⁶⁹

Yohe and Tol (2007) acknowledge the logic of the dismal theorem and discuss its implications. As they point out, Tol also found that the marginal utility of emission reduction could become infinitely large in a FUND model scenario when lack of precipitation drove future incomes to subsistence levels in one region of the world (Tol 2003). There are several responses to this problem in Tol (2003), Yohe and Tol (2007), and other works by these authors.

One response from Yohe and Tol is that many potential climate catastrophes can be averted or moderated by a stringent policy of emission reduction. So an analysis showing that climate change threatens to cause economic collapse and infinite marginal utility could be answered by active policy intervention, which might eliminate catastrophic risk and the accompanying infinite values. Another response, seemingly inconsistent with the first one, is that the same risks and infinite values might be present in both the base case and policy scenario but not in the difference between them. If that is the case, then cost-benefit analysis could still be applied to the difference between the two scenarios, which is all that is needed for policy analysis. Moreover, Yohe and Tol suggest that economic trade-offs between competing priorities simply must be evaluated, regardless of the presence or absence of infinities in the analysis. They conclude that the dismal theorem is of limited applicability to real-world problems.

Weitzman replies

In a recent paper, Weitzman responds to comments on the dismal theorem (Weitzman 2010a). He begins with a challenge to standard cost-benefit analyses, reminiscent of Stern's approach: How could economic analysis of climate change be *unaffected* by deep uncertainty about extreme events? We are headed for atmospheric greenhouse gas concentrations more than twice as high as at any time in the last 800,000 years. The projected temperature that will result from this is extremely sensitive to the (unknown) shape of the probability distribution assumed for climate sensitivity, and the projected economic impact of climate change depends on arbitrary choices about the (unknown) shape of the damage function.

Weitzman maintains that the two pillars of the dismal theorem are sound: Our best estimate of the probability distribution of climate outcomes must be fat-tailed, because we have so little data about analogous past events, and the disutility of extreme outcomes must be unbounded, "because global stakeholders cannot short the planet as a hedge against catastrophic climate change" (Weitzman 2010a, p.15). To avoid infinite values, the probability distribution can be thinned or truncated, and a cap can be put on utility. The results of the analysis, however, will be sensitive to the details of the procedure used to remove the infinite results. "Non-robustness to subjective assumptions about catastrophic outcomes is an inconvenient truth to be lived with. ... The moral of the dismal theorem is that, under extreme tail uncertainty, seemingly casual decisions about functional forms, parameter values, and tail fatness can dominate" the economic analysis of climate change (Weitzman 2010a, p.16).

Modeling climate damages

The climate sensitivity parameter is not the only uncertain factor that plays a central role in climate economics. Climate sensitivity measures the global average temperature and the pace of climate change, in general, that results from a given concentration of greenhouse gases in the atmosphere. Additional uncertainty surrounds the economic damages that result from a given temperature, or other physical measures of climate change such as sea-level rise. Such damages are often represented in integrated assessment models by a "damage function" expressing economic losses as a function of temperature.

⁶⁹ Note that these high values for climate sensitivity are upper limits on the probability distribution, not averages.

While uncertainty about climate sensitivity is starting to be incorporated into economic analysis, uncertainty in damage functions remains a relatively unexplored frontier. For example, the U.S. government's Interagency Working Group met in 2009 to estimate the "social cost of carbon" (the marginal economic damages per ton of CO₂ emissions) for use in cost-benefit analysis of regulations. It performed a careful Monte Carlo analysis of uncertainty in climate sensitivity but accepted without question the default assumptions about damages in its three selected models: DICE, PAGE, and FUND (Interagency Working Group on Social Cost of Carbon 2010).

An examination of those three models shows that current economic modeling of climate damages is not remotely consistent with the recent research on impacts described in Part I; this is an area where significant additional research effort is clearly needed. While two of the models include Monte Carlo analysis of damages and other features, their damage estimates and underlying damage probability distributions are based on very limited and dated research. They do not represent the current best guesses or current scientific understanding of uncertainty about climate damages.

The FUND model performs a detailed, disaggregated calculation of 15 categories of costs and benefits, with an extensive Monte Carlo analysis of uncertainty.⁷⁰ Yet it projects net economic benefits to the world from the first several degrees of warming and produces estimates of the social cost of carbon (the value of damages) that are consistently lower than those produced by many other models. An analysis of FUND's damage calculations finds that they include large net benefits in agriculture, balanced against modest expected costs in other areas. The largest cost of global warming for some time to come, according to FUND, will be the increased cost of air conditioning. FUND's agriculture calculations are calibrated to research published in 1992-96, a time when the prevailing estimates of carbon fertilization were much higher than they are today, and the negative effects of temperature increases on crop yields were not yet well understood. Moreover, the agriculture calculations in FUND 3.5 and earlier versions contain a mathematical error that could cause division by zero for a relatively likely value of one of the Monte Carlo variables (Ackerman and Munitz 2011).

DICE relies on a single, aggregated damage function calibrated to estimates of losses at 2.5°C and assumes a simple quadratic relationship between temperature and climate losses.⁷¹ The net output ratio R , or output net of climate damages, expressed as a fraction of the output that would have been produced in the absence of climate change, can be written as:

$$(3) \quad R = \frac{1}{1+(T/18.8)^2}$$

Here T is the global average temperature increase in °C above the level of the year 1900.

It is calibrated to estimates of six categories of climate impacts at 2.5°C of warming that sum to a loss of less than 2 percent of world output (Nordhaus and Boyer 2000; Nordhaus 2008). One of the categories is unique to DICE: the estimated monetary value of the subjective benefit of warmer weather, based on a survey of U.S. attitudes toward outdoor recreation at varying temperatures (but applied worldwide). In DICE-1999, the subjective benefit of warmer weather outweighed all damages at low temperatures, leading to a net benefit from the early stages of warming (Ackerman and Finlayson 2006); in DICE-2007, net damages are constrained to be positive at all stages, but the subjective benefit of warming is still included, lowering net global damages at 2.5°C. In a review and critique of the DICE estimates as applied to the United States, Michael Hanemann develops alternative estimates for damages at 2.5°C, which are,

⁷⁰ This account is based on FUND version 3.5 and its technical documentation (<http://www.fund-model.org/FundDocTechnicalVersion3.5.pdf>), dated May 2010, the latest available documentation as of mid-2011. A modified form of FUND 3.5 was used in the U.S. Interagency Working Group analysis discussed in the text.

⁷¹ This account is based on DICE-2007, the latest complete version available as of mid-2011 (<http://nordhaus.econ.yale.edu/DICE2007.htm>). At that time, DICE-2009 was available only in an incomplete and undocumented "beta" version that did not yet include the major announced innovation of a separate sea-level-rise module.

in total, almost exactly four times the DICE default value (Hanemann 2008). The Hanemann recalculation, extrapolating to the world as a whole, can likewise be written as:

$$(4) R = \frac{1}{1+(T/9.1)^2}$$

The PAGE model, from its outset through PAGE2002, has calibrated its damage estimates to other models such as DICE. Thus, it is not surprising that its estimates of the social cost of carbon have often resembled those from DICE. PAGE calculates three categories of damages: market impacts, nonmarket (non-catastrophic) impacts, and catastrophic losses. The major innovation in early PAGE damage calculations was the treatment of catastrophic risk, as described in the introduction to Part II. PAGE09, the next version of PAGE, includes a separate treatment of sea-level rise; preliminary results and description show that PAGE09 includes much higher estimates of climate damages and may represent a departure from past modeling practice in this area.⁷²

One approach to modeling uncertainty in damages would involve a long march through the many categories of disaggregated damages – for example, revising each of FUND's 15 categories based on the latest research. Another approach is to modify a simple damage function, such as the one used in DICE, to reflect catastrophic risks at high temperatures. Pursuing the latter approach, Weitzman (2010b) suggests a damage function that matches the DICE model's estimates for low temperatures but rises rapidly above it at higher temperatures. Weitzman assumes, as a round-number representation of catastrophe, that 50 percent of world output would be lost to climate damages at 6°C of warming and 99 percent at 12°C. To motivate the latter estimate, effectively assuming that the world economy would be destroyed by 12°C of warming, Weitzman cites the finding, discussed in Chapter I.3, that at 12°C, large parts of the world would, at least once a year, exceed the temperatures that human physiology can survive (Sherwood and Huber 2010).

Neither the original DICE nor the Hanemann 2.5°C estimate provides a basis for projecting damages at much higher temperatures.⁷³ It has become conventional to extrapolate the same quadratic relationship to higher temperatures, but there is no economic or scientific basis for that convention. The extrapolation implies that damages grow at a leisurely pace, especially in the DICE version. From equations (3) and (4), it is apparent that half of the world output is not lost to climate damages until temperature increases reach 18.8°C, according to DICE, or 9.1°C, according to the Hanemann variant.

To reach his catastrophic estimates for 6°C and 12°C while keeping the DICE low-temperature damages unchanged, Weitzman suggests adding an additional temperature-related term, yielding roughly (with numerical estimates rounded):⁷⁴

$$(5) R = \frac{1}{1+(T/20.2)^2 + (T/6.08)^{6.76}}$$

For the Hanemann low-temperature estimate, the comparable form is:

$$(6) R = \frac{1}{1+(T/9.2)^2 + (T/6.47)^{7.41}}$$

⁷² Under the SRES A1B emissions scenario, the PAGE09 mean estimate of the social cost of carbon is \$95 per ton of CO₂, compared to \$30 in PAGE2002 (Hope and Watkiss 2010). More complete descriptions of PAGE09 were still under review for publication in mid-2011.

⁷³ Nordhaus presents some numerical estimates of damages at 6°C, suggesting they are between 8 percent and 11 percent of output (Nordhaus 2007). These estimates are not well documented and do not appear to be used in the calibration of DICE.

⁷⁴ Equations (5) and (6) are estimated by minimizing the sum of squared differences from the DICE or Hanemann damage estimate at 2.5°C and Weitzman's estimates at 6°C and 12°C. See Ackerman and Stanton (2011) for more discussion.

When the temperature increase is well below 6°C, the last term in the denominator of (5) or (6) is very small and can be ignored. On the other hand, as the temperature climbs above 6°C, the last term grows very rapidly; it is more than 100 times as large at 12°C as at 6°C.

It is essentially impossible to distinguish between equations (3) and (5) or between equations (4) and (6) on the basis of low-temperature empirical evidence. Yet they have very different implications. The first leads to the gradual “climate policy ramp” discussed by Nordhaus (2008), while the second, as Weitzman (2010b) demonstrates, can lead to more substantial, vigorous initiatives to reduce emissions, even at a discount rate as high as 6 percent.

In a recent analysis and critique of the U.S. Interagency Working Group’s estimates of the social cost of carbon, Ackerman and Stanton (2011) find that a switch from damage function (3) to (5), holding all other assumptions constant, multiplies the social cost of carbon by a factor of three to four (depending on the other assumptions). The switch from (4) to (6) has a smaller but still sizable impact, multiplying the social cost of carbon by about 1.5. Thus, uncertainty about whether damages become catastrophic by 12°C of warming, as assumed in the Weitzman point estimates used to derive (5) and (6), has a massive effect on estimates of the social cost of carbon or monetary value of damages.

Damage functions such as (3) or (4), assuming that temperatures can increase by 18°C (or even 9°C) before damages reach half of global output, are difficult to reconcile with the results of scientific climate impact assessments. Quadratic damage functions are an arbitrary convention, not based on anything in the science reviewed in Part I of this report. Moreover, the estimate that 2.5°C of warming causes losses of less than 2 percent seems incompatible with the discussion of serious climate impacts that are expected at that temperature or even lower. A range of uncertainty that includes a much steeper damage function, as in (5) or (6), brings the possibility of catastrophic damages into the realm of modeling results. This does not, of course, say anything about the probability of such catastrophic outcomes but rather introduces a broader range of uncertainty into the otherwise-spuriously precise and often surprisingly low monetary estimates of climate damages.

Combined effects of multiple uncertainties

A number of recent studies have attempted to combine multiple dimensions of uncertainty, such as climate sensitivity and the shape of the damage function. The first study described here appears to challenge the conventional wisdom that faster warming will be worse for the economy.

Nordhaus (2008) examines both climate and economic uncertainties, concluding that the economic factors are more important. He presents a small-scale Monte Carlo analysis with 100 iterations, in which he allows eight parameters in DICE to vary. He finds that temperature change over this century is positively correlated with consumption per capita at the end of the century. This occurs because he allows relatively large variation in economic growth (driven by his assumptions about potential variation in productivity growth and population) but relatively small variation in climate impacts (driven by his assumptions about climate sensitivity, the shape of the damage function, and the discount rate). High-growth scenarios have greater output and hence greater emissions, leading to warmer temperatures; in DICE, the resulting climate impacts reduce but do not reverse the benefits of economic growth, such as higher per capita consumption.

Another study focuses on two key uncertainties in DICE: the climate sensitivity parameter and the shape of the damage function (Ackerman et al. 2010). Under DICE-07 default assumptions, the optimal policy involves very gradual abatement, taking 200 years to reach complete abatement of carbon emissions, and despite moderate climate losses, per capita consumption grows throughout the simulation period. This endorsement of gradualism is robust under relatively large changes in either climate sensitivity or the shape of the damage function but not both together. Variation in both dimensions at once produces scenarios in DICE in which business-as-usual emissions would cause large economic losses and sharp drops in per capita consumption. The optimal policy becomes one of very rapid elimination of carbon emissions.

Others have objected that the uncertainty should be incorporated in the inner workings of a model rather than repeatedly drawing parameters from a probability distribution and running a deterministic model such as DICE for the chosen parameters (the methodology used in the two studies just described, among others). A DICE-like model, redesigned to address this criticism, shows that failing to accurately account for risk can lead to substantial underestimation of the benefits of greenhouse gas abatement (Gerst et al. 2010). Using seven Monte Carlo variables, including a probability distribution for climate sensitivity derived from Roe and Baker (2007), the study contrasts rapid and gradual abatement scenarios, reflecting policies recommended by Stern and Nordhaus, respectively. The Stern scenario reduces the probability of climate catastrophe to near zero and is the preferable scenario under most assumptions. The Nordhaus scenario is preferable only if the discount rate is very high *and* uncertainties in the climate system, economic damages, and the carbon cycle are ignored.

Risk aversion revisited

A final area of recent research on uncertainty leads to a deeper understanding of risk aversion and addresses problems related to the Ramsey equation and the limitations of the constant relative risk aversion (CRRA) utility function, raised in the introduction to Part II. One important result offers a resolution to the paradoxically conflicting meanings of η in the Ramsey equation – that is, the problem that greater risk aversion or inequality aversion today (larger η) seems to imply a higher discount rate and thus less concern for future outcomes. Other research explores alternative interpretations of risk aversion and, in some cases, alternative utility functions paralleling approaches to the equity premium puzzle in finance.

Newbold and Daigneault (2009) conduct a series of numerical simulation experiments using both a very simplified climate-economics model and a modified version of DICE to study the effects of uncertainty about climate sensitivity. In many but not all scenarios, they find a large, positive risk premium – defined as the difference between willingness to pay for emission reduction in a model with uncertain climate sensitivity and willingness to pay in a deterministic version of the same model, using best guesses for uncertain parameters. Their estimates span the range from a small negative risk premium, matching the Nordhaus result described in the previous section (i.e., higher temperatures are correlated with higher consumption), to willingness to pay approaching 100 percent of global output, matching the dismal theorem. Their estimates are sensitively dependent on assumptions about extreme conditions, such as climate losses at 10°C of warming or the level of subsistence consumption. Newbold and Daigneault confirm Weitzman’s findings, both on the possibility of unbounded benefits from emission reduction and on the sensitivity of model results to subtle, often-untestable assumptions about uncertain relationships.

This result demonstrates that under conditions of uncertainty, increases in η can lead to greater willingness to pay for climate mitigation. If uncertainty is severe enough, the increase in risk aversion resulting from a higher value of η may outweigh the effect on time preference per se. Weitzman (2010b) suggests that this situation (higher η decreases the discount rate) is the norm, driven by the “fear factor” of risk aversion to potentially catastrophic shocks.

As noted in the introduction to Part II, the problems of interpretation of the Ramsey equation, limitations of CRRA utility, and multiple meanings of η also play central roles in the economics of financial markets, particularly in the analyses of the equity premium puzzle. The extensive research on the equity premium puzzle has produced a range of rival explanations (DeLong and Magin 2009), of which at least three have potential analogs in climate economics. One group of theories proposes that the perceived risk of extreme losses is greater than is suggested by recent experience; a second group proposes a more complex, multidimensional interpretation of utility; and a third group relies on findings from behavioral economics to explain the puzzle.

In the first group, emphasizing anticipation of extreme events, Weitzman’s dismal theorem resembles, and is in part derived from, his earlier analysis of financial markets (Weitzman 2007b). Markets, not unlike the climate, have complex, changing structures in which old information becomes obsolete over

time. This implies that investors can have only a limited amount of knowledge of the current structure of the market, so their best estimates of market returns follow a fat-tailed probability distribution with relatively high risks of extreme outcomes. Weitzman's work along these lines appears to be more influential in climate economics than in finance: The hypothesis that future risks of extreme events are outside the range of past experience is clearly consistent with climate science, but it is less obvious in finance, where there is a long history of abrupt market downturns and crashes.

Taking a different approach to extreme risk in finance, Barro, among others, argues that the 20th-century history of major economic slumps is sufficient to explain extreme risk aversion and large equity premiums in financial markets around the world (Barro 2006). This is more controversial than it might seem at first glance: Because virtually all the major downturns that drive Barro's result occurred in the first half of the 20th century, this approach assumes that investors have very long memories. A recent climate-economics analysis using a modified version of DICE with a Barro-type calibration of risk aversion (implying $\eta = 6.7$) and a variant on the Ramsey equation concludes that standard models greatly underestimate the true willingness to pay for climate mitigation and that whenever $\eta > 3$, aggressive mitigation is desirable (Gerst et al. 2011). This echoes the Newbold and Daigneault (2009) result that higher values of η often lead to greater willingness to pay for mitigation.

A second group of theories calls for a more sophisticated approach to utility, separating the multiple roles played by η . The limited empirical research on this subject suggests that people do not apply a single standard to risk, inequality, and time preference – all of which are represented by η in the Ramsey equation. A survey of more than 3,000 respondents (an international, nonrandom “convenience sample” recruited over the Internet) asked questions designed to elicit preferences toward risk, inequality today, and inequality over time (Atkinson et al. 2009). The results show clear differences among all three, with median values of η falling between 3 and 5 for risk aversion, between 2 and 3 for inequality today, and above 8 for inequality over time. Correlations among individuals' responses to the three questions were weak. For additional experimental evidence on the distinction between preferences toward time and risk, see Coble and Lusk (2010). Older empirical estimates of η typically did not distinguish among these different roles. For example, an analysis of attitudes toward inequality revealed by the progressive income tax structures of OECD countries estimated an average of $\eta = 1.4$ (Evans 2005).

A more complex utility function is needed to allow explicit separation of attitudes toward risk and time, representing each with its own parameter. This approach has been developed and applied in the equity premium puzzle literature in finance; the best-known example is by Epstein and Zin (1989). It offers a theoretically elegant solution to the dilemmas of the multiple roles of η – at the cost of much-increased mathematical complexity and computational burden. The explicit treatment of risk makes each period's utility depend on expectations about the next period, leading to a recursive, or non-time-separable, utility function.

The use of such utility functions has been suggested in the empirical studies of risk and time preference. Atkinson et al. (2009) closes with a suggestion that Epstein-Zin preferences should be considered, while Coble and Lusk (2010) frame their analysis in terms of the Kreps-Porteus model, a precursor of Epstein and Zin. To date, there has been little application of this new class of utility functions in climate economics; one of the few examples is Ha-Doung and Treich (2004), using a simplified climate model to demonstrate that the separation of risk aversion and time preference makes the optimal carbon tax much more sensitive to risk aversion. For other exploratory discussions, see Aase (2011) and Jensen and Traeger (2011). Our own work in progress involves application of Epstein-Zin utility to integrated assessment models of climate economics.

Behavioral economics approaches to the equity premium puzzle have received less attention in climate economics. However, Brekke and Johansson-Stenman (2008) discuss behavioral approaches to both finance and climate economics, concluding that the appropriate discount rate should be close to the risk-free rate (i.e., the rate of return on government bonds) – an idea that is discussed, on other grounds, in Chapter II.2.

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Chapter II.2: Public goods and public policy

Climate change poses unique economic problems by raising new, fundamental issues both about uncertainty and about public goods and public policy. New economic analysis primarily concerned with uncertainty is covered in Chapter II.1, while analyses primarily concerned with public goods and public policy issues are addressed in this chapter. The separation, however, is not a clean or unambiguous one, and the two chapters should be read together.

There are a number of reasons why climate policy choices might be made on a different basis from private investment decisions:

- Climate policy is intergenerational, involving actions now with major consequences far in the future. It is not clear that present value calculations and cost-benefit analysis have the same meaning when extended across a span of multiple generations. This gives rise to the dilemmas of discounting and to alternative approaches to modeling intergenerational impacts.
- Public policy in general is different in scope from private market choices. For instance, society as a whole can afford to provide insurance that the private sector cannot against risks such as unemployment compensation and flood relief. The uncertain risks of catastrophe have inspired exploration of precautionary or insurance-like approaches to climate policy, reflected in alternative decision-making criteria.
- Public policy decisions are ideally made on a democratic basis, weighting all individuals' opinions equally; private market outcomes weight individual preferences in proportion to wealth. Public policy may incorporate equity concerns, choosing on ethical grounds to weight impacts and burdens on lower-income groups more heavily. Due to the global nature of the problem, contested questions of international equity are central to the search for an adequate climate solution.

There are four major sections in this chapter: new approaches to discounting, other analyses of intergenerational impacts, alternative decision-making criteria, and the complex issues surrounding global equity.

New approaches to discounting

Discounting permeates the economics of climate change. Much of the discussion of uncertainty in Chapter II.1, especially the new approaches to risk aversion and the interpretation of η in the Ramsey equation, has a direct effect on discount rates and procedures. This section presents four additional topics related to discounting: incorporation of a preference for long-term sustainability, the effects of environmental scarcity, the extension of the Ramsey equation to include precautionary savings, and the choice of interest rates to use under the descriptive approach to discounting.

When applied to intergenerational problems, simple approaches to discounting are fundamentally flawed. At any significantly positive, constant discount rate, the far future doesn't matter. The logic of discounting – essential to cost-benefit analyses conducted over shorter time frames – collides with the common conviction that climate change and long-run sustainability must matter. One response is to assume that people place some value on long-term sustainability and current consumption. This is argued informally in a widely cited paper by Summers and Zeckhauser (2008) and formally in a mathematical model by Chichilnisky (2009), building on her earlier work in “axiomatizing sustainability.” In both cases, the result is that the discount rate declines gradually to zero over time.

This is not the only argument for declining discount rates. The behavioral economics evidence reviewed by Frederick et al. (2002) suggests that people reveal a preference for declining discount rates in their market behavior. An analysis of uncertainty about future interest rates by Weitzman (1998) demonstrates that the discount rate should gradually decline over time, from the expected value of future rates toward

the lowest possible future rates. The valuation of long-term sustainability, as proposed by Summers and Zeckhauser and by Chichilnisky, is a third independent argument for declining discount rates.

A second innovation involves the assumption of environmental scarcity. The growth model underlying the Ramsey equation assumes a single, undifferentiated output or equivalently perfect substitution among outputs. There is a long-standing debate in ecological economics about the degree of substitutability between marketed goods and environmental services; it is far from clear, in reality or in theory, that perfect substitution is the right assumption. If the two sectors are not close substitutes, and one is subject to absolute scarcity (i.e., no additional “natural environment” can be produced), the long-run price trends for the two sectors will diverge.

A two-sector model in which the output of ordinary goods can grow without limit but the supply of environmental services is constant or decreasing has striking implications for discounting (Hoel and Sterner 2007; Sterner and Persson 2008). Assuming that consumers obtain utility from both sectors and that there is limited substitution between them, economic growth leads to a steady increase in the relative price of environmental services. Even with a high discount rate, the change in relative prices can outpace the effect of discounting so that the present value of future environmental services is rising rather than falling with time – implying that the optimal climate policy is a rapid reduction in carbon emissions. This model successfully formalizes an intuition often expressed by non-economists, namely that something seems wrong with applying the same discount rate to financial and environmental assets.

The third “new” approach to discounting is not, strictly speaking, an innovation; it is reasonably well known but routinely ignored. Examination of the theoretical derivation of the Ramsey equation shows that the usual form, as presented in the introduction to Part II, is only an approximation, valid when the parameters and the consumption growth rate are small (Ackerman et al. 2009; Dasgupta 2008). Even under that assumption, it is derived only for a single optimal growth path, assuming a known rate of growth of consumption. If the future rate of growth is uncertain, with an expected variance of σ^2 , the Ramsey equation becomes

$$(7) \quad \rho = \delta + \eta g - \frac{1}{2} \eta^2 \sigma^2$$

The final term, which is always negative, can be interpreted as representing a precautionary savings motive. That motive becomes stronger as uncertainty (σ^2) increases; a lower discount rate implies greater concern for the future and hence a higher optimal savings rate. It also becomes stronger as risk aversion (η) increases, consistent with the everyday understanding of precaution. Indeed, this expanded form of the Ramsey equation shows one reason why it is possible that increases in η may lower the discount rate, as discussed in the last section of Chapter II.1.⁷⁵ Simple applications of the Ramsey equation, however, rarely include the final, precautionary term. As a result, they overstate the appropriate discount rate under conditions of uncertainty about economic growth.

Descriptive discounting and the risk-free rate

A final point about discounting is also well-established in theory but frequently overlooked in practice. Under the descriptive approach to discounting, the appropriate discount rate depends on the risk profile of the asset being discounted. The risk profile of investment in climate protection could lead to the use of a very low discount rate.

Due to the declining marginal utility of additional consumption, the same monetary return on an investment yields more utility when incomes are low and less utility when incomes are high. In order to obtain equal utility from a range of investments, investors demand higher rates of return on assets that do best when incomes are high, such as equities. Risk-reducing assets – ones that do best when incomes are low, such as insurance – can pay lower rates of return; the rate of return on an insurance policy is typically negative. Government bonds are intermediate between these extremes, with almost no risk and

⁷⁵ Differentiation of equation (7) shows that the discount rate is a decreasing function of η whenever $g < \eta\sigma^2$.

the same low but positive rate of return whether incomes are high or low. (That is, the covariance of returns with personal income or per capita consumption is positive for equities, roughly zero for government bonds, and negative for insurance.)

To express the present value of the return on any asset in terms of utility, it should be discounted at its own rate of return: a high, positive rate for equities, positive but near zero for risk-free assets such as government bonds, and negative for insurance. Which of these does investment in climate protection most closely resemble?

Many analysts have used a rate of return on equity or on assets of average risk, assuming that investments in mitigation are competing with, and comparable to, ordinary investments in other sectors. Others, such as Howarth (2003), have argued that mitigation is at least risk neutral if not risk reducing and should be discounted at the rate of return on risk-free assets such as government bonds. The risk-free rate or lower is appropriate for discounting mitigation costs under the widely but not universally accepted conclusion that mitigation reduces overall economic risk.⁷⁶ If anything, it appears that insufficient attention has been paid to the possibility that mitigation is risk reducing and therefore should be discounted at less than the risk-free rate. For additional analysis of circumstances under which the risk-free rate might be the appropriate discount rate, see Howarth (2009) and Brekke and Johansson-Stenman (2008), cited in Chapter II.1.

Intergenerational impacts

Discounting is not the only approach to the analysis of intergenerational impacts. A leading alternative involves the use of overlapping generations (OLG) models. The standard framework of integrated assessment, shared by Stern, Nordhaus, and others, evaluates all present and future costs and benefits from the standpoint of the current generation – assuming either infinitely lived agents or a dictatorship of the present generation over its descendants. In contrast, OLG models allow separate treatment of the costs, benefits, and preferences of successive generations.

Proposed some time ago as a framework for modeling long-term sustainability (Howarth and Norgaard 1992), OLG models are an active area of research in recent climate economics. Such models can highlight the importance of abatement cost assumptions in determining the burden on successive generations and can estimate the point in time at which climate mitigation becomes a net benefit (Gerlagh 2007). Another OLG model finds that the allocation of scarcity rents, such as the value of emissions permits, can determine the net present value of a climate policy; the same policy could have a negative bottom line (net costs to society) with grandfathered emission rights versus net benefits with per capita rights (Leach 2009). A formal OLG model with hyperbolic (declining) discount rates within each generation and extensive game-theoretic analysis reaches policy conclusions broadly compatible with the Stern Review (Karp and Tsur 2011).

One remarkable suggestion is that there is less of an intergenerational conflict than is commonly believed: In the presence of a large, unpriced externality, business as usual (i.e., no new mitigation efforts) is a distinctly suboptimal scenario. An optimal mitigation policy creates large welfare gains, allowing both current and future generations to be better off (Rezai et al. 2011). Elaborating on this perspective, Karp and Rezai (2010) create an OLG model in which a carbon tax benefits the current older generation by increasing the scarcity and hence the value of that generation's capital assets, and benefits future generations by improving environmental quality. The current younger generation, which receives lower

⁷⁶ The common assumption is that the scenarios where mitigation has its greatest value, i.e., cases where temperatures and climate impacts are growing most rapidly, are ones where the economy is weakest, due to climate damages. In that case, the returns on mitigation are negatively correlated with overall market returns, justifying the use of a discount rate below the risk-free rate. The surprising finding by Nordhaus (2008) of a positive correlation between economic growth and temperature, cited in Chapter II.1, would contradict this conclusion, suggesting that returns on mitigation are positively correlated with overall market returns. The Nordhaus finding, however, appears to be an outlier, reflecting the fact that his analysis encompasses a wide range of assumed economic uncertainty but only a narrow range of climate uncertainty.

labor income due to the carbon tax, can be compensated by the current older generation, making everyone better off.

Another framework that addresses intergenerational issues is the relatively new technique of “real options” analysis applied to climate policy by Anda et al. (2009). In addition to the costs and benefits of a policy, real-options analysis calculates the value of maintaining the flexibility to achieve a desirable future goal, such as a low atmospheric concentration of greenhouse gases. Real-options analysis is developed by analogy to financial options, which guarantee to the buyer the right to purchase an asset at a future date. Under the assumption of great uncertainty, a mitigation policy that has substantial net costs – that is, its costs exceed its benefits, as conventionally defined – might have a real option value greater than its net costs: The policy could be valuable if it preserves the opportunity for decision makers a generation from now to change course and aim for lower-than-planned greenhouse gas concentration targets. Such a policy would be rejected by cost-benefit analysis but approved by real-options analysis.

Standards-based decision making

As an alternative to utility maximization, some economists have advocated a focus on avoiding the risks of possible climate catastrophes (e.g., Yohe and Tol 2007). This approach is not entirely new and has gone by various names, such as “safe minimum standards,” “tolerable windows,” and “precaution.” It is often described as analogous to insurance against catastrophe, both in popular writing (e.g., Ackerman 2009) and formal research (e.g., Weitzman 2010).

The insurance analogy is literally appropriate up to a point: As business enterprises that exist to manage risks, private insurers are increasingly addressing climate concerns and can play an essential role in promoting adaptation and improving disaster resilience (Mills 2009). There are limits, however, to private insurance. The increasing but unpredictable likelihood of extreme events may reduce the insurability of important risks related to natural disasters (Mills 2007). Public policy is essential to address the full range of climate risks.

Precautionary or insurance-like approaches to climate policy begin with a predetermined objective that is deemed necessary to avoid thresholds that could trigger catastrophic damages – or more precisely and modestly, to reduce risks of catastrophic damages to a very low level. The objective can be defined in terms of avoidance of specific discontinuities, such as the collapse of the Atlantic thermohaline circulation (Bahn et al. 2011) or the Western Antarctic Ice Sheet (Guillerminet and Tol 2008). It can also be defined in terms of an upper limit on allowable temperature increases (den Elzen et al. 2010) or an upper limit on atmospheric concentrations of greenhouse gases (Vaughan et al. 2009; Bosetti et al. 2009).

Standards-based analyses frequently find that an immediate, ambitious mitigation effort is needed either in general (den Elzen et al. 2010; Vaughan et al. 2009) or under stringent stabilization targets (Bosetti et al. 2009), or under an assumption of high climate sensitivity (Bahn et al. 2011).⁷⁷ With a predetermined standard in place, the economic problem becomes one of cost-effectiveness analysis, seeking to determine the least-cost strategy for meeting the standard. This is different from and more tractable than cost-benefit analysis. In a cost-effectiveness analysis, only the costs of mitigation need to be calculated, because the standard replaces the more problematic calculation of benefits (i.e., avoided damages).

In a broader sense, however, the cost-effectiveness analysis of meeting a standard can be seen as a special case of cost-benefit analysis in which the shadow price of the benefits (or the value of the avoided damages) has become infinite or at least larger than the cost of maximum feasible abatement. A literally infinite value is not necessary; the same practical result will follow if damages become very large very quickly, implying that the marginal damage curve becomes nearly vertical. Under these circumstances, welfare optimization can lead to the same result as precautionary, standards-based policy making.

⁷⁷ For a review of the recent literature of climate economics models, including those models classified under “cost minimization,” see Stanton et al. (2009). For an expanded discussion of cost-effectiveness modeling in climate economics see Stanton and Ackerman (2009).

Weitzman's dismal theorem, concluding that greenhouse gas mitigation could have literally infinite value (see Chapter II.1) is difficult to interpret, let alone incorporate into cost-benefit analysis. An infinite value implies the implausible conclusion that willingness to pay to avert climate change should approach 100 percent of GDP. Weitzman himself, in the dismal theorem article, suggests the alternative of assigning a large but finite value to the survival of humanity, akin to the "value of a statistical life" that is often used in cost-benefit analyses. This would eliminate the infinite value while still obtaining a large numerical result (Weitzman 2009). There is, however, little rigorous basis for such limits. In nontechnical terms, how could the extinction of the human race be said to represent only a finite loss of utility for the human subjects of the theory? Does this mean that there is some imaginable package of goods and services that is more valuable than the survival of the human race?

In a sense, estimates of infinite damages are irrelevant, as many authors have suggested. After all, the ability to pay for climate mitigation is finite, constrained by income. Indeed, for policy purposes, there is an even lower limit to relevant damage estimates. Once climate damages exceed the marginal cost of the maximum feasible scenario for emission reduction, it no longer matters how high the damages are: The policy recommendation will be the same, endorsing maximum feasible abatement. Our analysis of uncertainty in climate damages, described in Chapter II.1, finds worst-case estimates that are far above the marginal cost of a maximum feasible abatement scenario. While these estimates are clearly not infinite, they may be close enough to infinity for all practical purposes.

There is limited literature on decision making under extreme uncertainty, when the decision maker knows the set of all possible outcomes but not the probabilities of individual outcomes within that set (for a nontechnical introduction to this literature in the context of policy toward toxic chemical risks, see Ackerman 2008, Chapter 4). Under reasonable assumptions, such as risk aversion, the best decision under extreme uncertainty is based primarily or entirely on information about the worst-case outcome – just as suggested by the precautionary principle. For a recent discussion and proposal along these lines, see Farber (2011).

One rule for decisions under extreme uncertainty that has appeared in the recent climate literature is the minimax regret criterion. Assume that, facing an uncertain state of the world, you choose a course of action, and then the true state of the world becomes known. The "regret" associated with your choice is the difference between the utility under that choice and the greatest utility attainable from another choice for the same state of the world. The "maximum regret" for your choice is the greatest regret you would experience under any state of the world; it is the worst case for the choice you made. The minimax regret criterion picks the choice that has the smallest maximum regret; it is the choice for which the worst case looks least bad.

Using an integrated assessment model with a broad range of inputs and scenarios, Hof et al. (2010) find that the minimax regret criterion recommends more stringent mitigation than does a conventional cost-benefit analysis if either a low discount rate or the combination of high climate sensitivity and high damages is assumed. In the absence of these assumptions, the difference between the minimax regret criterion and cost-benefit analysis is much smaller.

Using the FUND model, Anthoff and Tol (2010a) compare cost-benefit analysis and minimax regret (along with other decision criteria). Using a 1 percent rate of pure time preference and a rate of risk aversion (η) of 1, the carbon tax that maximizes expected welfare (the cost-benefit criterion) is \$33 per ton of CO₂ in 2010. Varying interpretations of the minimax regret rule recommend carbon taxes of \$27 to \$46 per ton of CO₂ for the same year.

Global equity implications

Climate change is a completely global public good (or public bad). It is caused by worldwide emissions and can be controlled only by worldwide cooperation to reduce or eliminate those emissions. At the same time, the significant costs of climate protection must be borne by a very unequal world economy. Free-rider problems and debates over the appropriate formulas for burden-sharing will be endemic.

Economics famously has much more to say about efficiency than about equity, but it would be a mistake to conclude that economists have been silent on the distributional issues surrounding climate policy. Here we review three areas of recent research and discussion: approaches to equity and redistribution in climate-economics models, equity-based proposals for international negotiations, and game-theoretic analyses of the prospects for international agreement.

Equity and redistribution in integrated assessment models

At any one point in time, costs and benefits are typically expressed, compared, and aggregated in monetary terms. For private market decisions, it is difficult to imagine the use of any other standard. Public policy, however, could be based on a different, equity-based standard. The fundamental principle of declining marginal utility implies that the same amount of money yields more utility to lower-income individuals.⁷⁸ Thus, equitable distribution of policy costs, if measured in utility, should place a smaller burden on low-income groups than would equitable distribution measured in money.

Attempting to implement this principle, several articles explore “equity weighting,” a hybrid technique that modifies cost-benefit calculations to give greater weight to costs borne by lower-income regions. Hope (2008) argues that costs in each region should be multiplied by

$$\left(\frac{\text{world income per capita}}{\text{regional income per capita}} \right)^{\eta}$$

Because η , among its other roles, is the elasticity of marginal utility with respect to consumption, multiplication by this factor effectively converts climate costs from measurement in monetary terms to utility. Equal utility impacts rather than equal dollar impacts are given the same value wherever they occur. Using PAGE, Hope models greater equity weighting by increasing η and finds that it decreases the social cost of carbon: The increase in η increases the discount rate (using the simple form of the Ramsey equation, as seen in the introduction to Part II), which reduces the present value of future impacts.

A number of other studies of equity weighting use the FUND model. Anthoff, Hepburn and Tol (2009) experiment with several formulas for equity weighting, ranging from an approach that makes almost no difference to the social cost of carbon, to one that leads to very large increases under some scenarios. Anthoff, Tol and Yohe (2009) explore the interactions of pure time preference (η), uncertainty, and equity weighting, finding: “As there are a number of crucial but uncertain parameters, it is no surprise that one can obtain almost any estimate of the social cost of carbon.” Equity weighting appears to generally increase the social cost of carbon in this analysis.

Anthoff and Tol (2010b) explore not only equity weights but also weights representing four different policies that might be followed by a national decision maker: sovereignty (ignoring all impacts abroad); altruism (taking into account all impacts abroad, regardless of source); good neighbor (taking account of the country’s own impacts abroad); and compensation (payment is required for all of the country’s international impacts). While equity weights roughly double the optimal carbon tax in this analysis, two of the national policies, good neighbor and compensation, cause even larger increases in the optimal carbon tax in high-income countries.

Another perspective suggests that a tilt toward equity should be a natural consequence of the assumption of diminishing marginal utility in climate-economics models. National, regional, or global utility is typically calculated as individual utility (at the mean per capita consumption level) multiplied by population. Under this approach, equalization of incomes between regions will always increase total utility.

This is reminiscent of early 20th-century economic theory, which assumed that utility was measurable and comparable between individuals and that income must have a higher marginal utility for the poor. Leading economists of the day such as Marshall and Pigou knew that this created a presumption in favor

⁷⁸ The question of interpersonal comparison of utility is addressed below.

of progressive redistribution. That school of thought was overturned by Robbins and others in the “ordinalist revolution” of the 1930s (Cooter and Rappoport 1984). The ordinalist view, which has dominated economic theory since that time, maintains that while each individual experiences diminishing marginal utility, it is impossible to compare one person’s utility to another; utility is an ordinal rather than a cardinal magnitude.

Regardless of its theoretical merits, however, ordinalism offers little help in quantitative modeling of optimal decisions and social welfare. Perhaps solely for mathematical convenience, climate-economics modeling has rolled back the ordinalist revolution and reinstated cardinal utility and interpersonal comparisons. Why doesn’t this create “equity weighting” by default?

There are two answers, one institutional and one technical. In institutional terms, significant transfers of resources from rich to poor nations are not common in reality; most models accordingly exclude this possibility without comment. In technical terms, regionally disaggregated models often use a procedure known as “Negishi welfare weighting” (see Stanton 2010 for a critique of this method). Negishi introduced a method for the calculation of an equilibrium point in a general equilibrium model (Negishi 1972). It applies weights to each individual’s utility, such that maximization of the weighted sum of utilities leads to the same outcome as a competitive market equilibrium. The Negishi weights are inversely proportional to marginal utility, so that Negishi-weighted marginal utility is equal for all. The Negishi solution thus counters the tendency toward income equalization that is built into the utility function; it maximizes a sum to which everyone’s (weighted) utility contributes equally at the margin, implying that there are no welfare gains available from redistribution.

A new integrated assessment model, Climate and Regional Economics of Development (CRED), is designed to remove both the institutional and the technical obstacles to redistribution (Ackerman et al. 2011). CRED allows global income redistribution and evaluates its contribution to climate protection and to welfare maximization. When there are no constraints on redistribution, the optimal scenario involves massive transfers of resources from high-income countries in order to fund investment in mitigation and in economic development in low-income countries. This scenario has greater global welfare *and* better climate outcomes than any others in the model. Even when redistribution is constrained to much lower levels, it still makes an important, often-decisive contribution to climate stabilization and raises overall welfare.

Global equity and international negotiations

A separate discourse about global equity has emerged in the process of international climate negotiations. International climate policy proposals focus on identifying each nation’s responsibility for mitigating domestic emissions and on industrialized countries’ unilateral responsibility to pay for emissions and adaptation measures in less-developed countries. While economics has much to say about the efficiency of emission reduction mechanisms and the likely distribution of their burden, it cannot solve the normative dilemmas posed in international negotiations: What determines a country’s responsibility for global emissions reductions? Should rights to fill the limited atmospheric sink for greenhouse gases be allocated on a cumulative, historical basis or start with a fresh slate today? Should these rights be considered on an equal per capita basis, and if so, how should population growth be treated? Do some countries have an obligation to pay for mitigation efforts outside of their own borders? Does this international obligation extend to adaptation measures that aim to limit exposure to climate damages?

This set of issues – often referred to as “burden sharing” – is at the heart of international climate negotiations. To cite one important dimension of the problem, the share of developed countries in global emissions is markedly larger over a longer time frame. An analysis by the World Resources Institute found that in 2000, the United States accounted for 21 percent of global greenhouse gas emissions and the EU-25 for another 14 percent. However, from 1990 through 2002, the U.S. share was 24 percent and the EU-25 share 17 percent. Over a much longer time span, from 1850 through 2002, U.S. emissions were 29 percent and the EU-25 countries’ emissions 27 percent. Japan, having industrialized much more recently,

was responsible for 4 to 5 percent of world emissions over any of these time frames (Baumert et al. 2005). As such, U.S. and EU (but not Japanese) obligations depend on the time period over which emissions are measured.

There is a growing literature on burden-sharing strategies that sets out general principles and specific plans for two sticky normative problems: how much each country should be permitted to emit and how much each country should pay for mitigation and adaptation efforts abroad.⁷⁹ Most proposals assume that each country is expected to pay for its own emissions abatement (an exception is noted below), although the sale of unused emissions rights to other countries is generally allowed. Proposals that have been raised in international negotiations or that exemplify alternative approaches to equity include:

- “Equal Per Capita Emissions Rights” would set a limit on global emissions and award emissions rights on an equal per capita basis. A country’s allocation would be the sum of its residents’ emissions rights. The global emissions target would be reduced over time, and national allocations would fall along with it (Agarwal and Narain 1991; Narain and Riddle 2007).
- The closely related “Indian Proposal” would allocate emissions rights differently in industrialized and developing countries. Less-developed countries would have per capita emission rights equal to current industrialized countries’ average per capita emissions. In this way, developing countries’ economic growth would not be hindered by mitigation efforts; indeed, these countries would have no obligation to abate unless industrialized countries were abating as well. As high-income nations abated emissions, emission rights in low-income nations would shrink (Singh 2008).⁸⁰
- “Individual Targets” is another variation on equal per capita rights. It uses the income distribution of each country to estimate how its greenhouse gas emissions are distributed among individuals. It then sets a consistent worldwide cap on individual emissions and derives the corresponding national emissions caps. No reductions are required for citizens of any nation whose emissions are equal to or lower than the target. The strategy aims to prevent high-emission individuals in low-emission countries from free riding by using the unclaimed rights of their poorer neighbors (Chakravarty et al. 2009).
- Another well-known proposal is “Contraction and Convergence,” which creates a transition toward equal per capita rights. The global target for per capita emissions shrinks steadily toward a sustainable level. Countries with per capita emissions above the global target have their emissions allocation reduced over time; countries below the global target receive gradual increases in their allocations. Using this strategy, global emissions would contract while per capita emissions among countries would converge (Global Commons Institute 2010).⁸¹
- “Greenhouse Development Rights” sets global mitigation targets and distributes the costs of meeting those targets on the basis of nations’ capacities to pay for mitigation and adaptation and their responsibility for past and current emissions (e.g., cumulative emissions since 1990). These criteria are defined with respect to an income threshold. Only individuals with incomes above this threshold have a responsibility to help pay for global mitigation efforts, and a country’s responsibility is the sum of its residents’ responsibilities (Baer et al. 2007). Prominent Chinese economists have proposed a variant on this approach, “Revised Greenhouse Development Rights,” which bases responsibility for the problem on cumulative emissions back to 1850 and places a greater obligation on industrialized countries to pay for emissions reductions (Fan et al. 2008).

⁷⁹ See also Stanton and Ackerman (2009).

⁸⁰ This plan was first proposed by Indian Prime Minister Manmohan Singh at the 2007 G8 meeting in Germany and then discussed in greater detail in his release of India’s National Action Plan on Climate Change in June 2008.

⁸¹ For an additional proposal closely resembling contraction and convergence, see Gao (2007).

Game theory and the prospects for agreement

The lengthy and frustrating process of international negotiation is far from guaranteed to be a success. A number of economists have analyzed the prospects for agreement in terms of game theory and strategic interaction. Barrett (2003) offers useful background in this area, combined with a historical treatment of negotiations. Wood (2011) provides an extensive review of the implications of game theory for climate policy. He concludes that mechanisms can be designed to promote cooperation, such as binding commitments to abatement conditional on actions taken by others. Milinski et al. (2008) introduce a collective-risk social dilemma in a controlled experiment designed to simulate the climate problem. People in a group are each given a sum of money from which they have to make individual contributions to a common investment. They can keep any leftover money if they collectively reach the investment target but not if they fail. Only half of the groups succeed; the investigators see a need for additional effort to convince people that they are at risk of grave individual loss.

Some investigations strike a more optimistic note. Rübbelke (2011) proposes that rich countries' funding of adaptation in developing countries, although not directly on the path to controlling emissions, may nonetheless improve the prospects of success in international negotiations by increasing the perception of fairness. Saul and Seidel (2011) analyze leadership in a game-theoretic model of cooperation, finding that increased leadership contributes to international cooperation. Testing this model against data on annual climate negotiations since 1995, they find that the extent to which the EU has exerted leadership is positively correlated with the progress achieved in the negotiations. DeCanio and Fremstad (2011) provide a comprehensive review of game-theoretic models for climate negotiation, emphasizing that the prisoner's dilemma is not necessarily the relevant framework, multiple approaches to solutions (e.g., maximin versus Nash equilibrium) are possible, and slight changes in preferences can dramatically change the prospects for agreement. In another study modeling the positions and interests of major countries in potential climate negotiations, DeCanio (2009) argues that the primary division is not between north and south but between those regions with large fossil fuel reserves, notably Russia and the Middle East versus all others. DeCanio suggests that the decision by the United States about whether to ally with fossil fuel producers or with other developing countries will be crucial to the prospects for negotiation.

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Part III: Mitigation and adaptation

The global climate problem is not without solutions. A small amount of climate change is now locked in, but the serious impacts and potential catastrophes described in Part I are still avoidable if quick action is taken on emissions abatement. At the same time, sensible adaptive preparations could offer protection from impacts caused by past (and unavoidable near-term future) emissions. Regrettably, there is a set of problems (described in Part II) that complicates economic analysis – and therefore policy decisions – related to climate change in ways that few, if any, other economic or environmental concerns have prepared us for: The magnitude of climate impacts is uncertain but potentially enormous, solutions require one generation to act to benefit a later generation, and success in international cooperation appears to be inextricably linked to controversial issues of equity among countries and among income groups.

Newer economic research does a better job of accounting for these gnarly issues in its policy recommendations, but many existing economic models are behind the times, and new improvements to uncertainty analysis are still in active development throughout the field. Even more problematically, economic estimation of the value of climate damages is not based on anything like the complete contemporary understanding of damages presented in Part I; the best-known, most widely used climate-economics models rely on simple rule-of-thumb damage functions with little – and dated – empirical foundation. As a result, some economic models are still recommending very little short-run investment in climate mitigation.

The alternative “standards” or “cost-effectiveness” modeling approach (see Chapter II.2) offers very different advice. When a standard is set for a maximum temperature increase or concentration level beyond which expected losses are considered to be unacceptable, the resulting policy recommendations are consistent across studies released by different researchers: There is a need for rapid, sustained abatement. Described in detail below, a simple summary would be that to keep global temperatures from rising more than 2°C above preindustrial levels, global greenhouse gas emissions need to peak almost immediately and fall rapidly thereafter. The higher and later that emissions peak, the faster and deeper the decline must be. Emissions peak no later than 2020 in every recent mitigation scenario that offers at least a 50/50 chance of staying below 2°C (or meets a similar criterion related to atmospheric concentrations).

The 2°C guardrail

The goal of staying below 2°C of warming has become ubiquitous in climate policy discussion. It does not derive from economic analysis, and it is not necessarily the policy recommended by economic optimization models. Rather, it emerges from the standard-setting approach to climate policy; it represents a widely accepted estimate of a threshold for avoiding the worst damages from climate change. Citing AR3 (Intergovernmental Panel on Climate Change 2001) and Smith et al.’s (2009) update to its risk analysis, the Synthesis Report of the 2009 Copenhagen Climate Congress (Richardson et al. 2009) states:

While there is not yet a global consensus on what levels of climate change might be defined to be “dangerous,” considerable support has developed for containing the rise in global temperature to a maximum of 2°C above pre-industrial levels. This is often referred to as “the 2°C guardrail.” IPCC as well as more recent scientific research indicate that even with temperature rises less than 2°C impacts can be significant, although some societies could cope with some of these impacts through pro-active adaptation strategies. Beyond 2°C, the possibilities for the adaptation of society and ecosystems rapidly decline with an increasing risk of social disruption through health impacts, water shortages and food insecurity.

Some advocacy organizations call for still-deeper emissions cuts, either aiming to stay well below the 2°C guardrail under standard assumptions or anticipating stabilization targets that are consistent with 2°C warming at higher climate sensitivity values – an important finding in research released since AR4 (see

Chapter I.1). The Alliance of Small Island States – representing some of the populations most vulnerable to the first 2°C of temperature increase – supports a threshold “well below” 1.5°C above preindustrial levels, noting that its members are “profoundly disappointed by the lack of apparent ambition within the international climate change negotiations to protect [small island developing states] and other particularly vulnerable countries, their peoples, culture, land and ecosystems from the impacts of climate change” (Alliance of Small Island States 2009).

The German Advisory Council on Global Change (WGBU) (2009, p.14), which appears to have coined the term “2°C guardrail,” asserts that this target has been acknowledged by 133 nations representing four-fifths of the world population and three-quarters of current greenhouse gas emissions, that many nations have adopted climate policies with the express purpose of limiting temperature increases to 2°C, and that climate scientists broadly support this goal.⁸² The WGBU report goes on to invoke Article 3 of the United Nations Framework Convention on Climate Change (United Nations 1992):

The Parties should take precautionary measures to anticipate, prevent, or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost.

WGBU suggests that signatories to the UNFCCC – now ratified by 165 nations – have agreed to approach decision making with regard to climate change from a precautionary, standards-based perspective (WGBU 2009, p. 22) and explores mitigation scenarios consistent with a 67 to 75 percent probability of keeping temperature increases below 2°C (pp. 25-34). These scenarios, together with other recent mitigation scenarios, are described in more detail in the next section.

Standards-based mitigation scenarios

According to a recent U.K. government study, the range of business-as-usual emissions scenarios described in Part I (from AR5 scenarios RCP 8.5 to RCP 4.5, corresponding roughly to the range from the IPCC’s earlier A1FI to B1 scenarios) results in a 0 to 4 percent chance of keeping global mean temperature increases below 2°C and a 0 to 53 percent chance of staying below 3°C (Bernie 2010). In other words, even RCP 4.5 – corresponding to B1, the slowest-growing of the old IPCC scenarios – offers virtually no chance of staying below 2°C. Two important measures of the pace of mitigation are the timing and the level of the peak in emissions. For comparison, global emissions were 34 Gt CO₂ (44 Gt CO₂-e) in 2005.⁸³ In the more optimistic RCP 4.5 scenario, emissions peak at 42 Gt CO₂ around 2035; in the more pessimistic RCP 8.5 scenario, emissions reach 106 Gt CO₂ by 2100 and are still rising.⁸⁴ Although RCP 4.5 would be a great improvement over RCP 8.5, even more needs to be done to meet standards such as a reasonable chance of staying below 2°C. Several studies have demonstrated how demanding that goal turns out to be.

The lowest AR5 Representative Concentration Pathway (RCP 3-PD) has about a 50 percent chance of keeping mean warming below 2°C, and rapid abatement is required to achieve that result. In this scenario, emissions peak at 38 Gt CO₂ around 2015, and there are small net negative emissions (that is, sequestration is greater than emissions) by 2090.⁸⁵ In the most ambitious mitigation scenarios, of which RCP 3-PD is an example, success in keeping temperatures low depends on the timing and the shape of the future emissions peak and on the trajectory after the peak. The table below presents a synopsis of 20

⁸² See also Allison et al. (2009) and Ackerman et al. (2009, 2010).

⁸³ Climate Analysis Indicator Tool (World Resources Institute n.d.), <http://cait.wri.org>.

⁸⁴ RCP Database, version 2.0 (International Institute for Applied Systems Analysis 2009).

⁸⁵ RCP 3-PD has a 48 percent chance of staying below 2°C and a 92 percent chance of staying below 3°C (Bernie 2010). See International Institute for Applied Systems Analysis (2009) for RCP emissions data.

mitigation scenarios that either have at least a 50/50 chance of staying below 2°C or have low target concentrations, on the order of 350 to 450 ppm CO₂.

All 20 mitigation scenarios share several characteristics. Emissions peak in 2020, at the latest, and do not exceed 46 Gt CO₂ or 55 Gt CO₂-e. Emissions then fall rapidly, at rates of 2 to 10 percent each year. The higher and later that emissions peak, the more rapid the subsequent decline.⁸⁶ The scenarios have another similarity not represented in the circumscribed data in this table: The higher and later that emissions peak, the more necessary it becomes to drive annual emissions down to zero or even to net negative levels toward the end of this century. Most of the listed scenarios either do not report data for years later than 2050 or show temperatures that continue to climb after 2100 (for some models, the probabilities shown are the chance of staying below 2°C through 2100). Lowe et al. (2009) suggest that there would be very little reduction in temperature in the century after peak warming was reached. Other studies suggest that peak temperatures will not decline for several hundred years (see Chapter I.1).

At present, there is no international accord aimed at a global emissions peak in the next five or 10 years followed by steep annual reductions. Few – if any – countries have made internal commitments consistent with these global reductions. For comparison, the voluntary terms of the Copenhagen Accord – formalized in the Cancún Agreements – would allow global emissions to exceed 50 Gt CO₂-e in 2020, an increase of 1 percent per year over 2005 levels (United Nations Environment Programme 2010; Bernie 2010).⁸⁷ Recent (failed) proposals for U.S. climate legislation called for annual emission reduction of about 1 percent each year through 2020, 2 percent through 2030, and 6 percent thereafter (Stanton and Ackerman 2010).

⁸⁶ The Ackerman et al. (2009) 2200 scenario, which has both an early peak and a rapid decline thereafter, was designed to stabilize at 350 ppm CO₂ by 2200 without requiring negative net emissions.

⁸⁷ Kartha and Erickson (2011) review four pledge analyses, including UNEP (2010) and two that contain pledges made since the Cancún Agreements, and find that developing countries have, collectively, pledged more emissions reductions than did Annex I nations, and the two combined fall well short of any 2°C pathway.

Scenarios of Business-as-Usual and Mitigation Emissions and Temperatures

	Peak emissions Year	Level (Gt)	Annual rate of decrease after emissions peak	Cumulative 2010-2050 (Gt CO ₂)	2100 Concentration (CO ₂ / CO ₂ -e)	Chance of staying below:		
						2°C	3°C	4°C
Business-as-usual range:								
RCP 4.5	2035	42 CO ₂	2.0%		538 / 581	0.04	0.53	0.88
RCP 8.5	no peak	106 CO ₂ (in 2100)	NA		936 / 1231	0.00	0.00	0.06
Mitigation scenarios:								
Ackerman et al. 2200	2010	39 CO ₂	9.8%		370 / NA			
PIK Comparison	2015	31 CO ₂	4.3%		400 / NA			
Hansen et al.:								
IPCC reserves	2005	46 CO ₂	9.8%		350 / NA			
EIA reserves	2005	46 CO ₂	4.5%		400 / NA			
Lowe et al.	2015		3.0%			0.55		
RCP 3-PD	2015	38 CO ₂	5.4%		421 / 427	0.48	0.92	0.99
WGBU:								
Option 1				600		0.75		
Option 2a	2011	32 CO ₂	3.7%	750		0.67		
Option 2b	2015	34 CO ₂	5.3%			0.67		
Option 2c	2020	37 CO ₂	9.0%			0.67		
IEA:								
BLUE Map	2015	30 CO ₂	2.2%		445 in 2050 / NA			
450 Policy Scenario	2020	47 CO ₂ -e	1.9%		450 / 520	0.50		
Gohar and Lowe:								
A1B_2016:4% zero	2016	55 CO ₂ -e	3.0%		NA / 461	0.57	0.92	0.99
A1B_2016:5% zero	2016	55 CO ₂ -e	4.0%		NA / 447	0.63	0.95	0.99
A1B_2016:9% zero	2016	55 CO ₂ -e	9.0%		NA / 426	0.74	0.96	1.00
A1FI_2016:3%	2016	50 CO ₂ -e	3.0%		NA / 488	0.48	0.92	0.99
A1FI_2016:5%	2016	50 CO ₂ -e	5.0%		NA / 471	0.56	0.95	0.99
B2_2016:3%	2016	44 CO ₂ -e	3.0%		NA / 515	0.55	0.95	1.00
B2_2016:5%	2016	44 CO ₂ -e	5.0%		NA / 460	0.62	0.97	1.00
McKinsey 400 ppm	2015	46 CO ₂ -e	3.1%-6.5%		NA / 480 in 2065	.70-.85		

Sources: RCP emissions and concentration data: International Institute for Applied Systems Analysis (2009). RCP temperature implications: Bernie (2010); Ackerman et al. (2009). PIK: Edenhofer et al. (2010); Kitous et al. (2010); Magne et al. (2010); Leimbach et al. (2010); Barker and Scricciu (2010); van Vuuren et al. (2010); Hansen et al. (2008); Lowe et al. (2009); WGBU (2009); International Energy Agency (2008, 2010); Gohar and Lowe (2009); McKinsey & Company (2009).

Climate action agenda

No one action can solve the climate problem. Steep and immediate emissions reductions will require policy measures on many fronts, including international agreements, market incentives, government regulations, and investment in technical innovation. Part III explores the key elements necessary to portray climate policy options in economic analysis: the technology and economics of both mitigation and adaptation.

Chapter III.1, “Technologies for Mitigation,” looks at strategies for reducing annual emissions and even achieving negative net emissions by removing greenhouse gases from the atmosphere. The technologies reviewed run the gamut from well-understood energy efficiency, fuel switching, and tree planting to nascent climate engineering proposals such as painting roofs and roadways white, and fertilizing the oceans so that they grow more carbon-sequestering algae. This chapter also profiles the technology choices made in the more sector and fuel-specific of the low-temperature mitigation policies above – the International Energy Agency’s BLUE Map, McKinsey’s 400 ppm CO₂-e concentration trajectory, and the

range of technology proposals in the Potsdam Institute for Climate Change Research (PIK) comparison project.

Chapter III.2, “Economics of Mitigation,” reviews new developments in portraying mitigation in climate economics. Technology prices that remain static or decrease steadily with time are a poor representation of the real-world effects of learning and innovation; newer models are exploring ways to endogenize technological change. Widely divergent assumptions about oil prices, found in recent climate policy assessments, can be one of the strongest determinants of abatement costs. Controversy continues about the accuracy of negative abatement cost projections and assumptions regarding the energy-efficiency rebound effect. The latest literature on both topics is discussed in the context of climate-economics modeling.

Even if rapid mitigation succeeds, temperatures are still expected to rise by another 0.1 to 0.6°C and sea levels by another 0.1 to 0.3m by 2100 (see Chapter I.1). These unavoidable future changes, added to the warming and other changes that have already occurred, will pose ongoing challenges of adaptation for vulnerable regions around the world.

Chapter III.3, “Adaptation,” touches briefly on adaptation technologies – which are largely dissimilar across regions – and then reviews the literature regarding this relatively new area of economic modeling: the costs of climate adaptation and its interactions with mitigation efforts and economic development.

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Chapter III.1: Technologies for mitigation

The standards-based climate-economics models targeted at keeping global mean temperatures below 2°C share a common policy prescription: immediate, rapid reductions in greenhouse gas emissions. There is much less agreement, however, regarding the best method of achieving these reductions. Each mitigation scenario makes a unique set of choices regarding not only in what countries reductions should be made and who should pay for them (as described in Chapter II.2), but also in the optimal mix of technologies to bring about these changes. Reduction in fossil fuel combustion is at the heart of every mitigation scenario, but in order to maintain low temperatures and minimize climate damages, more far-reaching, innovative abatement measures will also be required.

Either in place of the deepest near-term cuts in fossil fuel use (in less ambitious plans) or along with these cuts (in more ambitious plans), alternative mitigation strategies such as afforestation and carbon capture and sequestration are a key ingredient. A subset of mitigation methods is often classified as “geoengineering” or “climate engineering” – purposeful attempts to intervene in the climate system, with the goal of reducing radiative forcing and forestalling temperature increases (Shepherd et al. 2009). These proposed methods have received some attention in the economics literature and in policy circles but to date lack commercial applications or even large-scale demonstrations.⁸⁸

Still, future technological innovation will no doubt include methods either not yet imagined or ill regarded today. Here we discuss three categories of mitigation options, some currently feasible and some the topics of current research and future aspirations: reducing emissions (including both CO₂ and non-CO₂ greenhouse gases, as well as point-source carbon capture and sequestration); removing greenhouse gases from the atmosphere (afforestation and reforestation, enhanced sequestration, air capture, and ocean fertilization); and directly reducing radiative forcings (black carbon reduction and solar radiation management). We do not attempt comprehensive coverage of the widely discussed options for reduction of fossil fuel emissions but instead concentrate on newer and less familiar options that are of potential importance for future mitigation policies. The chapter concludes with a brief overview of the mix of technologies employed in some of the more detailed low-temperature mitigation scenarios shown in the introduction to Part III.

Reducing emissions

Slowing the emission of CO₂ and non-CO₂ greenhouse gases is an essential first step in every mitigation strategy. In many of the low-temperature mitigation scenarios, annual emissions are very nearly eliminated by the late 21st century.

Carbon dioxide

CO₂ emission reduction strategies focus on energy-efficiency improvements and fuel switching for electricity generation, transportation, buildings, and industry. The International Energy Agency’s BLUE Map scenario (International Energy Agency 2008) calls for sustained global energy-efficiency gains of 1.7 percent per year, with end-use efficiency alone accounting for 36 percent of 2050 emissions reductions (compared to business-as-usual projections). Many energy-efficiency measures are thought to be low or negative cost, although efficiency gains may be accompanied by smaller “rebound” efficiency losses. Both negative-cost abatement measures and energy-efficiency rebound effects are discussed in Chapter III.2.

Mitigation scenarios call for the gradual decarbonization of the power-generation sector, with the remaining fossil fuel and biomass generators using carbon capture and sequestration technology (discussed below). A variety of low and no-carbon generation options – renewable fuels (such as hydro-,

⁸⁸ For additional discussions of uncertainty regarding geoengineering methods, see Blackstock and Long (2010) and Blackstock et al. (2009).

solar, wind, and geothermal power) together with nuclear energy and some switching to less carbon-intensive fossil fuels (from coal to natural gas, for example) – will be needed to reach these goals, especially as demand for electricity increases around the world (IEA 2008). According to McKinsey & Company (2009), low-carbon power generation has the potential to supply 70 percent of global electricity by 2030.

Transportation emissions can be reduced by behavioral changes, public investment in mass transit, and fuel-efficiency improvements, but fuel switching poses more of a technological challenge. Today the vast majority of vehicles are powered by petroleum; mass production of electric and hydrogen vehicles is impeded by their need for a very different fueling infrastructure – electric outlets and battery-charging stations in the place of gas stations. Electric-powered vehicles, including plug-in hybrids and those using hydrogen fuel cells, also will necessitate the generation of additional electricity. IEA's BLUE Map scenario requires a significant share of electric-, hydrogen-, and biofuel-powered light-duty vehicles, while its emissions reductions from other forms of transit – trucks, buses, rail, air, and water – focus primarily on efficiency gains (Köhler et al. 2010; IEA 2008).

While commercial and residential buildings contribute a relatively small share of total CO₂ emissions, switching to less carbon-intensive fuels for space and water heating is still crucial to mitigation strategies that limit temperature increases to 2°C. Heat pumps, solar water heating, biofuels, and lower-intensity fossil fuels such as natural gas are all potential tactics. The IEA emphasizes the importance of transitioning from “traditional” biomass technologies, still used widely around the world, to cleaner “modern” biomass technologies, in particular, dimethyl ether biogas, which is nontoxic and can be produced from a variety of feedstocks (IEA 2008). Industrial processes contributed 22 percent of 2005 global emissions, and that share is expected to grow over the next decades. In the McKinsey & Company (2009) 400 ppm CO₂-e stabilization scenario, reductions to industrial emissions account for 16 percent of total mitigation.

Non-CO₂ greenhouse gases

Several non-CO₂ gases make important contributions to radiative forcing (see Chapter I.1). Where anthropogenic increases to CO₂ have added 1.66 W/m² to the global energy balance, other long-lived gases jointly add slightly less than 1 W/m² (methane, 0.48 W/m²; nitrous oxide, 0.16 W/m²; and all halocarbons combined, 0.34 W/m²), and ozone adds another net 0.30 W/m² (-0.05 W/m² for stratospheric ozone and 0.35 W/m² for tropospheric).⁸⁹ Eliminating all emissions of these gases would be equivalent to a 77 percent decrease in CO₂ emissions. While the bulk of CO₂ emissions come from energy production, most non-CO₂ greenhouse gases do not. Most methane and nitrous oxide emissions result from land-use changes, agriculture, and waste management, and most halocarbons result from industrial processes (Weyant et al. 2006).

Agriculture and land-use changes contribute about 30 percent of all emissions (measured in CO₂ equivalents), the second largest share of anthropogenic greenhouse gases after CO₂ (Intergovernmental Panel on Climate Change 2007, Working Group III Technical Summary; Weyant et al. 2006). Methods proposed for reducing agricultural methane and nitrous oxide emissions include changes to the rate or type of fertilizer applied, tilling practices, and feed for livestock (Beach et al. 2008). There are, however, many constraints to implementation, both technical and economic. Carbon sequestration in soil is complex: The rate of sequestration declines as soil and ecosystem carbon storage capacity reaches a maximum; its contribution to global mitigation is difficult to measure due to questions of additionality,⁹⁰

⁸⁹ With 90-percent confidence intervals: CO₂, 1.66 ± 0.17 W/m²; methane, 0.48 ± 0.05 W/m²; nitrous oxide, 0.16 ± 0.02 W/m²; stratospheric ozone, -0.05 ± 0.02 W/m²; and tropospheric ozone, 0.35 (0.25-0.65) W/m². See IPCC (2007), Working Group I, Chapter 2.

⁹⁰ Additionality in greenhouse gas mitigation refers to the net impact of any measure. A new mitigation initiative may crowd out existing actions, or it may merely formalize actions that are already taking place without increasing total abatement. For a discussion of additionality in relation to the Kyoto Protocol's Clean Development Mechanism, see Schneider (2009).

and some related feedback processes are still not well understood. It may also be the case that carbon sequestration practices in one location tend to push cheaper high-carbon-emitting agricultural practices to other areas rather than eliminating them (Smith et al. 2007).

Carbon capture and sequestration

Anthropogenic CO₂ can be captured before its release into the atmosphere and then sequestered by direct injection into underground storage – a process referred to as carbon capture and sequestration (CCS).⁹¹ Several CCS pilot projects are currently in operation, but technical and political hurdles still exist to widespread implementation (Haszeldine 2009). Both the capture and storage phases of CCS face remaining challenges. Carbon capture must be comprehensive (all or nearly all carbon emissions captured from a source) but not too energy intensive. Several potentially viable carbon capture technologies exist, but challenges lie in scaling these methods up while keeping costs and energy use low, and limiting further environmental burdens from process by-products and pollutants (Liu and Gallagher 2009; Kanniche et al. 2010).

Post-combustion capture – using, for example, amine scrubbing – requires large facilities for the treatment of enormous volumes of gas (Rochelle 2009). Alternatively, fossil fuels can be combusted in near-pure-oxygen environments in a process referred to as “oxy-combustion” or “oxyfuels.” This method requires lower temperatures for combustion, allowing CO₂ to be captured in its liquid form, and obviates the need for chemical solvents such as amine. To date, only a few small pilot projects are using oxyfuels. In a third method, pre-combustion gasification of fossil fuels forms carbon monoxide, which is converted to CO₂ and captured, and hydrogen, which is used as a clean fuel (the sole by-product of hydrogen combustion is water). High costs of retrofitting plants for pre-combustion gasification have derailed some pilot projects (Hart and Gnanendran 2009; Olajire 2010; Kanniche et al. 2010). No method is a clear winner, though there may be a trend toward using pre-combustion for newly built plants and post-combustion for retrofits (Haszeldine 2009).

Carbon storage presents additional challenges. After CO₂ has been captured, it must be transported to a suitable location and stored. CO₂ could be transported by fossil-fuel-powered vehicles, but the volumes are significant, and the attendant transportation emissions could be large. The alternative is construction of a new network of CO₂ pipelines, moving the gas from power plants to appropriate disposal sites, such as oil and gas fields under either dry land or ocean. The investment necessary to create such an infrastructure would be substantial (Haszeldine 2009).

Another concern is the potential for CO₂ injected into subsurface geological formations to leak back in the atmosphere. Leakage would not only risk increased atmospheric concentrations of CO₂, but if released in bursts of concentrated CO₂, it would also threaten human health (Fogarty and McCally 2010). Leakage from subsea CO₂ injection could result in considerable ocean acidification and oxygen depletion (Shaffer 2010). On a global scale, substantial space is available for this kind of storage, but careful site selection is essential (Orr 2009).

These obstacles notwithstanding, CCS is expected to be a major source of emissions reduction in many of the mitigation scenarios discussed in the introduction to Part III. The PIK comparison of the MERGE, REMIND, POLES, TIMER, and E3MG models includes 29 to 36 percent of generation from fossil fuel and biomass technologies using CCS by 2050 (Edenhofer, Knopf, Leimbach, et al. 2010). IEA’s BLUE Map (2010a) assumes that in 2050, carbon capture applies to 55 percent of power-generation emissions, 21 percent of industry emissions, and 24 percent of transportation emissions, noting that there is also “an urgent need to accelerate the demonstration of CCS in the power sector and to develop comprehensive regulatory approaches to enable its large-scale commercial deployment” (p.11). An analysis of

⁹¹ For a detailed discussion of CCS technologies, see the Sept. 25, 2009, special issue of *Science* magazine, titled “Carbon Capture and Sequestration” (see Smith et al. 2009 for an introduction to the special issue).

deployment strategies projected commercial rollout of CCS between 2015 and 2020 and global rollout between 2020 to 2025 (Gibbins and Chalmers 2008).⁹²

Removing greenhouse gases from the atmosphere

The higher and later that emissions peak, the lower and more quickly they will have to fall to keep warming below 2°C. Many low-temperature mitigation scenarios include measures to increase the rate of CO₂ sequestered on land and in oceans. In some scenarios, sequestration is so large in scale that net emissions become negative later in this century.

Afforestation and reforestation

Expanding forested areas and avoiding new deforestation are essential components of many rapid mitigation scenarios. Estimates of the technical potential for near-term reforestation are estimated to range from 186 to 1023 g C/m² per year, depending on the type of forest (Alexandrov et al. 2002, p. 302). AR4 considered both economic feasibility and technical potential in presenting a range of 1 to 14 Gt CO₂ sequestration from afforestation each year (IPCC 2007, Working Group III Technical Summary). To put these numbers in context, terrestrial systems in 2005 absorbed 3.3 Gt CO₂ per year, while the net addition to atmospheric concentrations from all sources and sinks was 15.0 Gt CO₂ per year (IPCC 2007, Working Group I Technical Summary).

A recent IPCC technical paper reports the results of two new studies of afforestation's potential for mitigation. One finds 12.5 Gt CO₂ of feasible potential emission reductions by 2030 – 12.4 Gt in less-developed countries – at average prices lower than \$2 per ton. The second uses a bottom-up methodology to identify 2.0 Gt CO₂ of mitigation potential in 2020 at \$15 per ton (United Nations Framework Convention on Climate Change, 2008). Stern's *Blueprint for a Safer Planet* (2009) calls for spending \$15 billion per year to combat deforestation in tropical countries, sequestering 3.0 Gt CO₂ per year at \$5 per ton, and Hansen et al.'s (2008) 350 ppm CO₂ trajectory requires sequestration of 6.5 Gt CO₂ per year by 2030 from a combination of afforestation and biochar (charcoal formed from biomass and stored in soil). As discussed in Chapter I.2, newer research demonstrates that afforestation and reforestation efforts should take place in tropical countries to have the best effect on lower atmospheric concentrations. Adding to forested areas in temperate zones has a neutral net effect on radiative forcing, while in boreal forests the net effect is an increase in warming.

Enhanced sequestration

There may also be some scope for purposefully enhancing the biological and geological processes that remove carbon dioxide from the atmosphere, with the object of increasing net carbon storage. Plants rely on photosynthesis, the process of converting CO₂ into glucose, as their source of energy. Sugar from photosynthesis builds plant matter, or biomass, which may be burned or may undergo aerobic decomposition by bacteria and fungi, releasing CO₂ back into the atmosphere. To the extent that plant matter is placed in longer-term storage, as wood in trees or in organic material that enters into soils without decomposition, CO₂ is effectively removed from atmospheric stores. Enhanced sequestration initiatives increase the share of biomass carbon that is stored in trees and soil, often through land-use decisions. For example, the United Nations Reducing Emissions from Deforestation and Forest Degradation (REDD) program is attempting to create a financial incentive for carbon sequestration in forests and a system for their long-term sustainable management (UN-REDD Programme n.d.).

Carbon sequestration in agricultural soils can be enhanced by the carefully calibrated application of nitrogen fertilizers and tillage of biomass (Lu et al. 2009). The full life-cycle impacts of these practices, however, warrant careful consideration: The greenhouse gases released during the production and

⁹² See also Florin and Fennell (2010).

distribution of fertilizer have been estimated to surpass the carbon sequestered in agricultural soils using enhancement methods (Schlesinger 2010).

One of the most discussed methods for enhanced sequestration is biochar. Charcoal, a form of black carbon, can be mixed into soils, increasing their carbon storage. A higher share of charcoal in the composition of soil also slows the rate at which soil emits CO₂, a feedback mechanism that may be mis-specified in general circulation models (Lehmann et al. 2008). Stable long-term storage of black carbon in soil depends on the action of microorganisms and on limiting human disturbance such as tilling, fire, and land-use changes (Czimczik and Masiello 2007).

Worldwide, of the 222 Gt CO₂ converted by photosynthesis each year, an estimated 10 percent is potentially available for biochar, including crop and forestry residue and animal waste. Conversion of this 22 Gt CO₂ to charcoal could offset the combustion of fossil fuels generating 6.6 Gt of emissions and sequester an additional 11.0 Gt as biochar. Combined, these effects would exceed net addition to atmospheric concentrations from all sources and sinks (annually, 15.0 Gt CO₂, or 26.4 Gt in fossil fuel and cement emissions, less 11.4 Gt of net oceanic and terrestrial contributions⁹³). The systemic effects of such a large-scale effort at biochar are not well understood; climate feedback mechanisms and biological effects on soil biota require substantial additional study (Amonette et al. 2007). In comparisons of different uses of biomass, biochar outperformed biofuels except where these fuels displaced coal-fired electricity generation (Fowles 2007; Gaunt and Lehmann 2008). A full life-cycle assessment of biochar concluded that transportation distances are an important obstacle to the economic viability of any large-scale biochar scheme (Roberts et al. 2010).

Air capture

Air capture is a variant of carbon capture and sequestration in which CO₂ is harvested directly from ambient air (Keith 2009). While it would, in some ways, be far simpler to capture the more concentrated CO₂ that is an effluent from power plants and many industrial processes, air capture may hold some advantages. It could be used to remove emissions from mobile and other small-scale sources, and if conducted on a large enough scale it could – like afforestation – affect a net removal of CO₂ already present in the atmosphere. Some studies have gone so far as to suggest that a viable air capture strategy reduces the need for short-run precautionary mitigation (Keith et al. 2005). While air capture is generally thought to be prohibitively expensive, some studies have disagreed, suggesting that the unit cost of air capture would be similar to that of other mitigation methods (Pielke Jr. 2009).

Ocean fertilization

Certain areas of ocean may be “iron limited,” implying that iron fertilization could lead to blooms of diatoms (a type of algae), effectively sequestering carbon when plant material from these blooms sinks to the deep ocean. Iron enrichment experiments on a scale of 25 to 225 km² have been conducted in the equatorial Pacific, subarctic Pacific, and Southern oceans. Unfortunately, these experiments show strong responses in diatom blooming but very little carbon removed to the deep ocean (Strong et al. 2009).⁹⁴ Initial results from the 300 km² LOHAFEX study conducted in 2009 suggest that carbon in algae becomes remineralized, returning to surface waters (National Institute of Oceanography 2009). Two natural experiments in iron fertilization (one from upwelling along islands in the Southern Ocean, the other due to a volcanic eruption in the Aleutian Islands) also showed algae blooms but little or no carbon sequestration (Tilmes et al. 2008; Pollard et al. 2009). In 2008, the London Convention on Marine Pollution and the UN Convention on Biological Diversity placed an effective moratorium on further ocean iron fertilization experiments, with the exception of small-scale legitimate scientific research projects. As of 2010, these experiments must be assessed and approved by the London Convention (International Maritime Organization 2010).

⁹³ IPCC (2007), Working Group I, Chapter 7.3.

⁹⁴ See also Harvey (2008).

Reducing radiative forcing

Several additional mitigation technologies aim to enhance albedo, directly decreasing radiative forcing. Keeping the earth cool by increasing albedo would not necessarily preserve current precipitation patterns nor would it keep ocean CO₂ concentration from rising.

Black carbon reduction

Black carbon (soot) absorbs solar radiation in the atmosphere and decreases surface albedo (impeding reflection and allowing further radiation to be absorbed), especially when deposited on ice and snow (for further discussion, see Chapter I.1). Black carbon has a greater effect on radiative forcing than does any other single anthropogenic influence other than CO₂, and as such, cleaning up this pollutant has enormous potential for climate change mitigation. Post-combustion capture (filtration) and storage are far more straightforward for black carbon than for CO₂. Burned biomass, heavy fuel oils, and coal are the primary sources of black carbon. Fuel switching and filtration could greatly limit these emissions, reducing a major source of warming (Ramanathan and Carmichael 2008; Wallack and Ramanathan 2009).

Black carbon's contribution to radiative forcing is determined by the source of the emissions. Black carbon from fossil fuels is twice as powerful a warming agent as black carbon from biomass. Moreover, emissions of black carbon are often combined with sulfates and organic aerosols, resulting in negative forcings: that is, they reflect solar radiation and reduce warming. Calculations of the impact of black carbon reduction initiatives, therefore, need to include the net effects of decreased positive forcings from CO₂ and black carbon and decreased negative forcings from other aerosols. Mitigation strategies for black carbon may be more effective if they start by reducing emissions from fuels with high black-carbon-to-sulfate ratios (Ramana et al. 2010).⁹⁵

Solar radiation management

Solar radiation management describes a diverse set of proposals for reducing warming by reflecting sunlight away from the earth's atmosphere. Methods range from giant sunshades in space to land-use modifications aimed at increasing surface albedo. Painting roofs and roads white (or using light-colored materials to construct them) has the potential to transform the albedo effect of developed areas from heat sink to heat reflector. Levinson and Akbari (2009) report that painting 80 percent of U.S. commercial rooftops white would result in an annual cooling energy savings of 10.4 TWh, increased heating energy use of 133 million therms (equivalent to about 4 TWh), net energy cost savings of \$735 million, and CO₂ reductions of 6.2 million metric tons. Another study estimates that a 10 percent global increase in urban albedo would increase outgoing radiation by 0.5 W/m² while slightly reducing mean surface temperatures (Menon et al. 2010). Increasing the solar reflectance of urban roofs and pavement would also lessen heat island effects and improve outdoor air quality (Akbari et al. 2009).

Other solar radiation management proposals include the problematical idea of increasing the concentration of aerosols such as sulfates in the atmosphere (Lenton and Vaughan 2009). Releasing sulfate aerosols into the stratosphere could mimic the global cooling effects of volcanic eruptions, although it would have no effect on ancillary negative impacts of high atmospheric CO₂ concentration, such as ocean acidification. Offsetting a 760 ppm concentration of CO₂ (twice today's levels of CO₂) would require the release of 1.5-3.0 Mt of sulfur every year, depending on the size of the particles and their stability over time. Larger aerosol particles (like those from volcanic eruptions) are less effective at reflecting radiation than are smaller ones (Rasch et al. 2008). For this strategy to be effective, stratospheric sulfate injections would have to continue for thousands of years due to millennial persistence of CO₂ in the atmosphere. If stratospheric aerosol levels are not maintained, there is potential for rapid warming of up to 5°C within several decades, which would be more damaging than would gradual warming of the same amount (Brovkin et al. 2008). Stratospheric sulfate injections may also

⁹⁵ See also United Nations Environment Programme and World Meteorological Organization (2011).

disrupt the Asian and African summer monsoons, jeopardizing food supplies for billions of people (Robock et al. 2008). Other potential feedback effects from stratospheric sulfates include a reduction in global precipitation and increased rates of polar ozone depletion (Bala et al. 2008; Tilmes et al. 2008).

Mitigation scenarios in climate-economics models

All the mitigation scenarios discussed in the introduction to Part III draw from the same palette of technologies, but each one chooses a different mix of emission reductions and accelerated sequestration; none include direct reductions to radiative forcing.

IEA's BLUE Map scenario relies on a portfolio of fuel switching, carbon sequestration, and efficiency measures. By 2050, emissions are 48 Gt CO₂ lower than business-as-usual projections. Thirty-six percent of this reduction comes from end-use fuel and electricity efficiency improvements, 21 percent from renewable electricity generation sources, 19 percent from CCS power generation and industrial production, 11 percent from end-use fuel switching, 7 percent from power-generation efficiency and fuel switching, and 6 percent from nuclear. Abatement costs range from \$200 to \$500 per ton of CO₂ in 2050, depending on the degree of optimism regarding technological innovation. In IEA's more stringent "450 Scenario," global oil production peaks around 2020, and the deepest emissions cuts (relative to baseline growth) take place in the United States, the European Union, Japan, China, and India. By 2035, the nuclear sector's share of power generation doubles, renewables account for 45 percent of global generation, half of all coal-fired plants are fitted with carbon capture and sequestration, and 70 percent of all car sales are of hybrid or electric models (IEA 2008; IEA 2010b).⁹⁶

In McKinsey's 450 ppm CO₂-e scenario, 70 percent of all abatement potential comes from developing countries, including 22 percent from China alone. Projected 2030 emissions fall from 70 Gt CO₂-e in the baseline to 38 Gt CO₂-e. This mitigation strategy includes 22 percent from transport, buildings, and waste; 21 percent from afforestation, reforestation, and changes to agricultural management; 17 percent from industrial emissions (including energy-efficiency measures); 11 percent from renewable electricity generation; 7 percent from CCS; 6 percent from other power sector measures; and 5 percent from nuclear. Abatement costs range from \$90 to \$150 per ton of CO₂ in 2030. In the McKinsey 400 ppm CO₂-e scenario, behavior changes and additional, higher-cost technical measures reduce emissions by another 9 Gt CO₂-e (McKinsey & Company 2009).

An inter-model comparison project run by researchers at the PIK in Germany compared scenarios from five models that stabilize carbon dioxide concentrations at 400 ppm by 2100: MERGE, REMIND, POLES, TIMER, and E3MG. Across models, mitigation shares range from 29 to 50 percent for fossil fuels and biomass without CCS, 29 to 36 percent for fossil fuels and biomass with CCS, 4 to 53 percent for renewables, and 11 to 21 percent for nuclear. Abatement costs in these scenarios range from \$75 to \$275 per ton in 2030 and \$150 to \$500 per ton of CO₂ in 2050, with a central value of \$260 per ton (Edenhofer, Knopf, Barker, et al. 2010; Kitous et al. 2010; Magne et al. 2010; Leimbach et al. 2010; Barker and Scricciu 2010; van Vuuren et al. 2010).

⁹⁶ Note that these projections were made and published before Japan's 2011 nuclear disaster. Newer projections may well downgrade the importance of nuclear power's contribution to total future energy production.

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Chapter III.2: Economics of mitigation

Estimates of the cost of mitigation differ by orders of magnitude and are of great significance in the public debate about climate policy. The Stern Review projects that most climate damages could be avoided and the climate stabilized at an annual cost of about 1 percent of world output. On the other hand, Lomborg (2010) argues that the cost of staying under 2°C of warming could be 12.9 percent of world output in 2100. In recent U.S. debates, the extreme positions regarding action or inaction to confront climate change have been based on extreme estimates of costs: Business lobbies opposed to climate policy have relied on consultant studies showing ruinous costs from even small initiatives, while environmental groups have developed their own studies showing little or no net cost from ambitious “win-win” solutions (for a look at the range of perspectives, see Ackerman et al. 2009; Ackerman et al. 2010).

In the short run, the costs of climate policy depend on empirical information about current technologies and prices. As the time frame of the analysis lengthens toward a century or more, and because it must to encompass the climate crisis, the anticipated future evolution of technology becomes more and more important. What will the energy technologies of the 22nd century look like, and what will they cost? This seems like a subject for science fiction rather than economic analysis. Yet even fiction has failed to foreshadow the future of technology in decades past. A half-century ago, most science fiction still imagined that computers would keep getting bigger and bigger as they became more powerful. Economists face a similar challenge today: Gazing deep into our climate models, how accurately can we imagine the future of, for instance, photovoltaic cells?

The Stern Review (Stern 2006) sidestepped many of the difficult issues about costs, relying instead on the fact that two separate methodologies, a consensus of published model estimates and a new study of energy technology costs, both implied costs of roughly 1 percent of world output to meet the Stern Review’s emission reduction targets. Yet for ongoing analysis exploring other scenarios, a deeper look at mitigation costs is needed – both in the areas where recent research has been active and in other areas that deserve more attention.

This chapter explores four issues in the economics of mitigation. First, endogeneity in technological change and learning effects is an area of active research: Does technological progress just happen, or can we influence its pace and direction? Second, one of the greatest uncertainties in the global economy, the future price of oil, has an inescapable influence on climate policy costs. Given the importance of the topic, far too little has been said about oil prices and climate costs. Third, bottom-up empirical studies repeatedly identify opportunities to reduce emissions at zero or negative net costs, a possibility that seems to be ruled out by economic theory. This is an area where data development has run ahead of economic analysis. Finally, rebound losses that shrink energy-efficiency gains are sometimes touted as being greater than the savings themselves. Recent research finds these losses to be no greater than 50 percent of savings, and usually much less. For many sectors, the rebound effects are trivial.

Endogenous technical change and learning effects

Many models have adopted a simple ad hoc solution to the “science-fiction problem” of predicting future technologies: Assume a constant annual rate of technical change. In energy models, this has often been called the rate of autonomous energy-efficiency improvement (AEEI), where change is “autonomous” in the sense of occurring independently of policy or experience. The DICE model, for example, assumes that the cost of achieving any given level of emission reduction is a fraction of GDP. That fraction decreases at a fixed rate over time (Nordhaus 2008). This assumption makes it cheaper to wait to reduce emissions,

contributing to the gradual “climate policy ramp” recommendation that emerges from Nordhaus’ analyses with DICE.⁹⁷

An alternative assumption is more realistic but also more difficult to model. To quote one of the Stern Review team’s responses to critics, “[T]echnical progress does not appear exogenously with the ‘passage of time’ ... but endogenously with investment in R&D, demonstration and deployment” (Dietz et al. 2007, p. 236). The Stern Review surveyed cost estimates from many existing models, and also developed its own estimates of the likely evolution of costs of a range of energy technologies over the next several decades. Both the average of model estimates and the Stern Review’s own technology cost estimates assumed that climate policy would lead to moderate cost reductions over time (Stern 2008; Dietz et al. 2007).

Learning curves, or “learning by doing” effects, have been studied since the 1930s. Many new technologies experience gradual reductions in unit costs over a period of time as the cumulative volume of production increases.⁹⁸ Unfortunately, it is difficult to tell how rapid the reductions will be and how long they will continue. For an attempt at predicting learning curves for energy technologies, see Alberth (2008).⁹⁹ The best available learning curves clearly outperform a simple time trend, but the data remain noisy.

Kemfert and Truong (2007) review past studies of learning effects in energy technologies and test their importance in WIAGEM. They distinguish between endogenous technical change (unit costs go down as cumulative production goes up) and induced technical change (targeted climate policies such as research and development reduce new technology costs). With endogenous technical change included in the baseline, the addition of induced technical change reduces the costs of meeting stringent CO₂ targets by about 20 percent by 2100. In a study using the E3MG model, Barker et al. (2008) find that inducing technological change with a high carbon price is insufficient to reaching a 50 percent decrease in CO₂ emissions by 2050. To achieve this reduction, they model targeted investments in low-greenhouse-gas technologies using part of the revenues collected from auction or tax revenues.

In another detailed study, Kypreos (2007) uses MERGE to model many individual energy technology costs, including separate treatment of endogenous and induced technical change. Every doubling of cumulative production is assumed to reduce unit costs by 20 percent. In addition, every doubling of the accumulated stock of knowledge lowers the cost of new technologies by 15 percent. The stock of knowledge is increased by research and development spending but depreciates over time. These assumptions lower the cost of meeting a 450 ppm CO₂ target by almost 50 percent by 2100, compared to a baseline without learning. A similar finding is reached with a different model in Gerlagh (2008). Studies of specific technologies show similar results; for example, Ek and Söderholm (2010) look at learning curves and public investments in European wind power, finding a decline in both costs and government expenses.

Others have analyzed the effects of induced technological change on the optimal time path of mitigation. In several studies, the possibility of reducing costs through learning leads to an early surge in investment, accelerating mitigation. Greaker and Pade (2009) find high carbon taxes in the near future may be justified in order to spur investment in research and development if there are positive knowledge spillovers. Hart (2008) concludes that, with induced technological change and positive knowledge spillovers, the optimal carbon tax may be higher than the Pigouvian tax in order to stimulate investment in emissions reduction. Rout et al. (2010) conclude that early subsidization of “climate friendly” technologies may help make them cost-competitive more quickly and is more effective than is

⁹⁷ For a discussion of the sources of technological change and their representation in existing models, see Clarke et al. (2008).

⁹⁸ While most commonly applied to cost estimates of energy supply technologies, learning curves are equally applicable to energy demand technologies (Weiss et al. 2010).

⁹⁹ Gillingham et al. (2008) discuss some of the problematic empirical evidence underlying the current modeling of endogenous technical change.

subsidization at later stages. Fischer and Newell (2007) find that such positive knowledge spillovers have a discernible effect on the relative cost of alternative climate policy instruments.

Climate R&D investments may also have an opportunity cost: They may “crowd out” other R&D investments, dampening overall gains from induced technological change. Popp and Newell (2009) find only limited and sector-specific evidence for crowding out from investments in energy R&D. Gillingham et al. (2008) explore tensions between modeling spillover and modeling crowding out across a broad selection of climate-economics models.

A more complex pattern is described by Alberth and Hope (2007). Using the PAGE model, they find that with learning, the optimal pace of mitigation is slightly slower in the near future, because investment is initially focused on learning about new technologies, but then substantially faster in later years as the new technologies are applied. They discuss the political difficulties of mobilizing the resources required in this scenario for exploration of unproven new technologies and the risks of failure of those technologies. A more gradual learning process may be the more prudent course.

Some studies have identified contradictory influences on timing of mitigation. Ingham et al. (2007) argue that the possibility of learning leads to delays in anticipation of obtaining better information, while the risks of irreversibility of damages result in earlier mitigation. Improved adaptation possibilities may ease the irreversibility constraint and thus delay mitigation. The study finds the combined effects of such factors to be ambiguous but small. Lange and Treich (2008) explore the effect of learning on the optimal mitigation path, finding that it is ambiguous and depends on the details of model specification.

The effect of learning may also depend on the manner in which economic policy is modeled. Using a modified version of DICE, Webster et al. (2008) find that the possibility of future learning has little effect in a conventional cost-benefit framework but is potentially more important in a standards-based cost-effectiveness framework, where a fixed target must be met. Lee et al. (2010) examine the impact of high regulatory standards, or “technology forcing,” on automobile makers in the United States and find that regulation played an important role in leading to innovations and determining the subsequent direction of technological change.

Other aspects of learning in climate science and economics can have unexpected results. Oppenheimer et al. (2008) note that incorrect learning may lead away from the right answers (“negative learning”) arguing that this has happened at times in climate science when models are mis-specified. Negative learning can occur even when Bayesian analysis is correctly applied. Oppenheimer et al. (2008) illustrate the costs of negative learning in a modified version of DICE.

Oil prices and climate policy costs

One of the greatest gaps in the recent literature is the lack of attention to the role of oil prices, and fossil fuel prices in general, in determining the cost of emission reduction. As the McKinsey abatement cost studies (discussed in the next section) make clear, a typical emission reduction measure consists of a capital expenditure that reduces fossil fuel consumption over its lifetime. The capital costs are almost independent of fossil fuel prices; the market value of the fuel savings is, of course, determined by fuel prices. Thus, the net cost of most emission reduction technologies should be negatively correlated with fuel prices.

Fossil fuel price assumptions play an important though little-noticed part in recent political debates over climate policy. The extreme views of climate policy cost, cited above, are based in part on clashing fossil fuel price projections. Those who view climate policy as prohibitively expensive assume that fossil fuel prices will be low. In contrast, detailed studies from environmental groups finding net benefits from emission reduction often rest on oil price projections of \$100 per barrel or more (see the discussions in Ackerman et al. 2009, Ackerman et al. 2010). While there are other differences between these two camps, their fossil fuel price assumptions alone would ensure substantially different evaluations of climate policy costs.

A handful of studies have examined the connections between climate policy and oil prices. Rozenberg et al. (2010) show that climate policies are a valuable hedge against uncertainties in oil markets. In their words, “climate policies are less costly when oil is scarce because, in addition to their benefits in terms of avoided climate impacts, they bring important co-benefits in terms of resilience to oil scarcity” (p. 666). Higher oil prices lead to some reduction in fossil fuel consumption and carbon emissions, but Vielle and Viguier (2007) argue that higher oil prices are no substitute for sensible climate policies. Oil price increases are both less efficient and less equitable than is a climate policy designed to reduce emissions. And because alternative energy producers will be among the beneficiaries of carbon reduction policies, it is not surprising to find that higher oil prices increase the stock prices of alternative energy companies (Henriques and Sadorsky 2008).

In simpler analyses and cost estimates, fossil fuel prices will inevitably be treated as exogenous. This understandable simplification leads, however, to the problem faced by the dueling political advocates: Your fossil fuel price assumptions go a long way toward determining your results. An adequate, comprehensive analysis of climate economics should make fossil fuel consumption and prices endogenous. Mitigation strategies reduce the long-run demand for conventional fuels and should have long-run effects on prices.

Modeling fossil fuel prices is a daunting challenge. It involves enormous uncertainties about the extent of reserves, the availability and environmental impacts of “dirty” supplies such as oil shale and sands, oligopoly behavior in a complex geopolitical context, and the potential for substitution of alternative fuels. Nonetheless, it is an essential part of the puzzle, required for a complete economic analysis of the costs and benefits of climate policy. This is an area where more research is essential.

Negative-cost abatement: Does it exist?

Disaggregated, bottom-up studies of the potential for energy savings and emission reduction routinely find substantial opportunities with negative net costs – that is, cases where energy savings quickly outweigh the initial costs. Such negative-cost abatement opportunities present a challenge to economic theory, reflected in the old saying about \$20 bills on the sidewalk. If energy savings are available at a net economic benefit, why hasn’t someone already found it profitable to invest in them?

The debate about negative-cost savings is an old one, and there is relatively little new academic research in this area. The important innovation is in the realm of data, in the comprehensive empirical studies from McKinsey & Company, an international consulting firm, developing marginal abatement cost curves for the world and for major countries and regions (e.g., McKinsey & Company 2009 for the world; Creyts et al. 2007 for the United States). The McKinsey studies find large savings available at negative cost, implying very low estimates of average abatement costs. They are widely cited and are now treated as an established data source in many contexts.

The older research literature in this area offers several possible explanations for the “efficiency paradox,” or the “efficiency gap” (between the cost-minimizing level of investment in energy efficiency and the actual level). Market failures and barriers may discourage investment in low-cost efficiency measures; examples include misplaced incentives, unpriced costs and benefits, incomplete information, capital market barriers, and incomplete markets for efficiency (Brown 2001). Consumer reluctance to invest in efficiency measures could reflect extremely high discount rates for such purchases, possibly due to uncertainty and incomplete information. Households may avoid investments in efficiency unless payback times are very rapid. Business investment in energy efficiency may be shaped by organizational and institutional factors that, in practice, cause systematic deviations from profit-maximizing behavior (DeCanio 1998).

In another theory that implies the existence of \$20 bills on the sidewalk, the Porter hypothesis (Porter and van der Linde 1995) asserts that carefully designed regulation can create a competitive advantage and increase profits for regulated firms – controversially implying that the firms were not maximizing profits prior to the regulation. Bréchet and Jouvet (2009) review the Porter hypothesis literature and provide a

microeconomic rationale for no-regret abatement options. Regulation may lead a firm to invest in learning about additional production techniques, and while initially costly, the learning process can lead to the discovery of profitable long-run production possibilities.

Little has been written about the McKinsey marginal abatement cost curves in academic research. In the CRED climate-economics model (discussed in Chapter II.2), the McKinsey curves are used as the basis for the model's estimate of abatement costs, with one major modification (Ackerman and Bueno 2011). McKinsey's negative-cost abatement measures are arbitrarily assumed to have a small but positive cost, while the McKinsey data on positive-cost abatement measures are used to estimate CRED's abatement cost curves. A comparison of the CRED calculations to abatement cost curves from MIT's EPPA model shows that the two models make broadly similar estimates.

In a recent paper estimating global abatement costs, Cline (2010) compares CRED's McKinsey-based estimates, the comparable cost estimates from a new version of RICE (a regionally disaggregated version of DICE), and a synthesis of estimates from several models in the Energy Modeling Forum (EMF). The three estimates are strikingly different, with RICE in the middle; the CRED cost estimates are lower, often one-third of those of RICE, while the original EMF estimates are far above RICE by up to an order of magnitude (Cline also suggests a modification that lowers the EMF estimates). The lack of consensus shows that, even apart from the issue of negative-cost abatements, there are serious disagreements and issues to be resolved about the costs of climate protection.

Rebound effects: Do they reverse efficiency gains?

An important ongoing controversy in energy and climate economics is the existence of a "rebound effect," where energy-efficiency gains are reduced by other related market effects. This rebound is thought to come from a combination of sources: savings from energy efficiency (an effective increase in disposal income) may be spent on other goods, which in turn require energy to produce; or supply-side energy-efficiency measures may lower the unit cost of energy – either because less energy is needed to provide each unit of energy service or because the highest unit-cost generation facilities are never brought online – driving up the quantity demanded. Steinhurst and Sabodash (2011) identify three possible forms of the rebound effect:

- Negative rebound: Energy savings are higher than expected.
- Typical rebound: Energy savings are less than expected.
- Backfire, or the "Jevons paradox": Energy savings are negative (that is, overall energy use increases as a consequence of an energy-efficiency measure).

While much has been written about the dangers of energy-efficiency backfire, most actual rebound effects result in losses but are not large enough to erase savings, in part because energy is only a small share of total purchases and because savings from energy efficiency are correspondingly small (Steinhurst and Sabodash 2011). Warnings about backfire date back to William Stanley Jevons' book *The Coal Question* (1865) and surface periodically as contrarian arguments against otherwise-desirable efficiency measures. Recent examples of this genre include Sorrell (2009), Herring and Sorrell (2009), and Jenkins et al. (2011). Hard evidence for rebound effects approaching or exceeding 100 percent, however, is rare. Jenkins et al. (2011) largely suggest that it is important to consider the possibility that rebound might reach 100 percent. Empirical research, on the other hand, finds distinctly smaller rebound effects. A recent review of this literature shows rebound losses of 10-30 percent for residential space heating, 0-50 percent for residential space cooling, <10-40 percent for residential water heating, 5-12 percent for residential lighting, 0 percent for residential appliances, 10-30 percent for automobiles, 0-2 percent for commercial lighting, and 0-20 percent for commercial process uses (Ehrhardt-Martinez and Laitner 2010).¹⁰⁰

¹⁰⁰ See also Sorrell (2007).

In a historical analysis of lighting, Tsao et al. (2010) demonstrate that the development of new technologies has generated considerable growth in the consumption of energy but that these large rebounds have not resulted in backfire. Historically, savings from energy-efficiency measures have been positive when GDP and population growth are taken into account. Goldstein et al. (2011) show that, despite a broad mandate for energy efficiency starting in the 1970s, California's energy consumption per capita has remained steady while the rest of the United States' energy consumption per capita has grown by more than half.

Using the E3MG climate-economics model, Barker et al. (2009) model the potential rebound effects resulting from climate policy. They distinguish among direct, indirect, and economy-wide rebound effects, and they estimate direct rebound effects, resulting from the use of more energy-efficiency devices, to reduce savings globally by about 10 percent. With indirect (lower unit energy costs increase the quantity of energy demanded) and economy-wide (lower energy prices deflate the overall price level) effects included, overall reductions to savings are estimated as 31 percent in 2020 and 52 percent in 2030. Ehrhardt-Martinez and Laitner (2010) estimate the direct rebound effect to be a 10 to 30 percent loss of energy-efficiency savings and the total effect to be a 40 percent loss.

Druckman et al. (2011) estimate the potential rebound effect of U.K. households' greenhouse gas abatement actions at 34 percent but find that if savings are targeted toward spending on goods and services with low greenhouse gas intensities, the losses can be reduced to 12 percent. Using evidence from a computable general equilibrium of the Chinese economy, Liang et al. (2009) identify smaller rebound effects for policies that combine a carbon tax with subsidies to primary energy producers as compared to producer subsidies alone.

In short, empirical research on the rebound effect shows that it is real but modest in size. Estimates of 10 to 30 percent seem common, with some larger and some smaller. Actual evidence of backfire, or rebound effects of 100 percent or more, appears to be nonexistent. Perhaps most promising is the possibility that well-designed policies could reduce the extent of rebound, thus maximizing gains from energy efficiency. Even when careful calculation of losses due to rebound are included, energy efficiency remains a very low-cost option for reducing emissions.

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Chapter III.3: Adaptation

Past greenhouse gas emissions have already altered the earth's climate, "locking in" some amount of additional change to temperatures, sea levels, and precipitation patterns that can no longer be avoided (see Chapter I.1). The ambitious mitigation scenarios described in the introduction to Part III that limit global mean warming to 2°C still allow for significant future emissions and damages (see Chapters I.2 and I.3). The large and diverse set of measures aimed at reducing vulnerability to these damages and enhancing resilience with regard to changing climatic conditions is collectively referred to as adaptation. AR4 reviewed the limited state of the adaptation literature as of 2007, explaining:

Adaptation occurs in physical, ecological, and human systems. It involves changes in social and environmental processes, perceptions of climate risk, practices and functions to reduce potential damages or to realize new opportunities. ... In practice, adaptations tend to be on-going processes, reflecting many factors or stresses, rather than discrete measures to address climate change specifically (IPCC 2007, Working Group II, Chapter 17.4).

While adaptation investments have great potential to lessen near-term climate damages, the economics of estimating adaptation costs is complicated by interrelations among adaptation, mitigation, and economic development. For many developing countries, the "additionality" of adaptation aid – over and above current development funding – is a central issue (Fankhauser and Burton 2011; Smith et al. 2011). For others, especially small island states, the question of whether the international community will provide compensation for irreversible losses is a key issue (Grenada 2011; Barnett and Dessai 2002). Still others, in particular those with extensive fossil fuel resources, call for a definition of "adaptation" that is broad enough to include economic losses due to emissions mitigation efforts (Kingdom of Saudi Arabia 2011; Barnett and Dessai 2002).

Fair treatment of developing countries is of the utmost importance to a successful outcome from current climate policy negotiations. Adaptation investments, including funding from rich countries for adaptation in poor countries, will be an essential component of a comprehensive international climate policy. Nonetheless, near-term adaptation investment choices have little impact when modeling optimal mitigation scenarios, and climate-economics models that incorporate explicit adaptation decisions have concluded that rapid emissions abatement should take precedence in the next few decades. In this chapter, we briefly sketch out the wide range of adaptation technologies and then focus on the very serious challenges that exist to the inclusion of adaptation investment in climate-economics models.

Adaptation technology

The technology of adaptation varies from setting to setting and includes a broad swath of building, infrastructure, and energy technologies, as well as numerous public health and even poverty reduction measures. The inclusive definition of "adaptation" – reducing vulnerability and enhancing resilience – makes for a very big tent, with room for almost any investment in economic development to also be classified as adaptation. A lexicon of types of adaptation may serve as an illustration (IPCC 2007, Working Group II, Chapter 17; Smith 1997; Margulis et al. 2008; de Bruin et al. 2009):

- *Reactive adaptation* occurs after and in response to climate change; *anticipatory adaptation* precedes and prepares for climate change. Reactive measures may preclude unnecessary precautionary investments but can also lead to short-term, high-cost solutions; reactive adaptation would also fail to avert irreversible damage. Anticipatory adaptation also includes investments in innovation to develop new adaptive measures.
- *Planned adaptation* is the result of public policy decisions; *autonomous adaptation* is the result of actions by households, businesses, and communities. Both planned and autonomous adaptation can be either reactive or anticipatory.

- *Induced adaptation* refers to unplanned adjustments to new climatic conditions, including transition costs and transition time. In economic models, *implicit adaptation* is built into the climate damage function, so the damage function actually models residual damages after the assumed optimal adaptation. *Explicit adaptation* is modeled separately from climate damages.
- *Nonoptimal adaptation* is inefficient or poorly suited to actual circumstances; *maladaptation*, which may be a response to climate change or to climate policies, increases vulnerability or reduces resilience to new climatic conditions.
- *Hard adaptation measures* offer an “engineering” response using built infrastructure; *soft adaptation measures* include early warning systems, community preparedness programs, zoning, and water price adjustments. The terms *hard adaptation measure* and *soft adaptation measure* are also used to distinguish between built infrastructure (such as dikes and seawalls) and measures that enhance natural systems (such as rehabilitating sand dunes, salt marshes, and barrier islands).

Most of these types of adaptation have potential relevance to many of the areas of climate impacts discussed in Chapters I.2 and I.3. In AR4, disparate examples of damages that could be ameliorated by adaptation include sea-level rise, saltwater intrusion into aquifers, storm surges, permafrost melt, change in ice cover, loss of snow, glacier melt, extreme temperatures, droughts, and floods (IPCC 2007, Working Group II, Chapter 17). The economic sectors most likely to be impacted are agriculture, forestry, fishing, and tourism. Infrastructure will be affected in a wide range of climates and settings, especially indoor climate control, roads and railways, and coastal property. In addition, to the extent that energy demands will increase with climate change, new investments in energy infrastructure may be viewed as adaptation.

Unlike mitigation technologies, which are often applicable across nations and latitudes, adaptation technologies are extremely localized. The types of expected damages are different in each locality, as are the solutions considered most technically sound and culturally appropriate.

Adaptation and mitigation

Any estimation of the costs of adaptation is necessarily contingent on a scenario of future mitigation. Temperature and other climatic changes will depend on the amount and pace of emissions abatement together with climate sensitivity (see Chapter I.1), and potential damages will depend on these climate outcomes. In optimizing models that compare costs and benefits of climate policy, damages are equal to abatement costs at the margin. Thus, in any optimal scenario, marginal abatement cost equals the value of marginal averted damages (i.e., the social cost of carbon). Adaptation investments, in turn, affect the social cost of carbon (or marginal damages) and, therefore, the optimal level of mitigation. The endogeneity of adaptation and mitigation is extremely challenging to model (Warren 2011). The optimal mix of adaptation, mitigation, and investment in innovation will vary by time and scenario (Agrawala et al. 2010; Anda et al. 2009).

Model results are very sensitive to choice of damage function (as discussed in Chapter II.1) and the local or regional distribution of damages (Agrawala et al. 2010). Unit adaptation costs also vary by region, economic sector, and time period. For accurate modeling, each of these factors should be considered in determining the exposure of assets and costs of climate proofing (Agrawala and Fankhauser 2008). The omission of a region’s or sector’s damages or adaptation costs has the potential to distort optimal mitigation recommendations, but a comprehensive catalog of all potential damages and adaptive measures is not feasible (Stern 2006). Modeling the stock (investment) and flow (operations and maintenance) of adaptation is an additional complication (Callaway 2004).

The greatest challenge for integrated assessment modeling, both with and without explicit adaptation, is the uncertainty inherent in the climate and economics systems (see Chapter II.1). The magnitude, type, and timing of impacts are highly uncertain, as are the costs of new technology (see Chapter III.2) and the effectiveness of anticipatory adaptation measures (Wilby and Dessai 2010). The interdependence of adaptation, mitigation, and technical innovation compounds uncertainties in each of these areas (Anda et al. 2009; Smith 1997). Uncertainty regarding future climate outcomes can have the effect of limiting

adaptation measures to short-run adjustments or increasing the risks of nonoptimal adaptation or maladaptation (Callaway 2004).

Adaptation and economic development

Another challenge for incorporating adaptation into climate-economics models is the substantial overlap between measures that enhance resilience to climate changes and measures that will enhance the quality of life regardless of climate change. Many adaptation measures lead double lives as sensible improvements for economic development (Anda et al. 2009; Fankhauser and Schmidt-Traub 2011). Two specific concerns are of particular importance to climate-economics modeling.

First, baseline GDP and population assumptions are important to delineating adaptation investments (what is and what isn't adaptation), even in no-adaptation scenarios. If real GDP per capita is expected to grow over time, especially in developing countries, then today's levels of public infrastructure, quality of housing, and energy-generation and delivery systems are likely a poor proxy for future levels. With higher incomes, the capital stock vulnerable to climate damage will be larger, but it is also likely that new investments built by a richer population will be more robust to climate change. Development substantially increases the potential damages from climate change, and the recent literature regarding adaptation finance highlights issues of "climate proofing" development (Fankhauser and Schmidt-Traub 2011; Smith et al. 2011).

A related issue is the uncertain impact of climate change on GDP growth. Overall, the economics literature suggests an inverse relationship between temperature and income: Countries with higher average temperatures have lower GDP per capita (Dell et al. 2009), and temperature increases over the past 50 years have been associated with reduced economic growth in poorer countries but have had little effect on economic growth in richer countries (Dell et al. 2008). Other studies have reported that higher temperatures are a risk factor with an adverse effect on global economic growth (Bansal and Ochoa 2010). In most climate-economics models, however, higher temperatures occur in low or slow mitigation scenarios with high GDP growth; lower temperatures occur only when a share of GDP is diverted from standard investment into abatement investment. The existence of an inverse relationship between temperature and GDP growth suggests, again, that damages functions used in integrated assessment models (IAMs) are very likely mis-specified (as discussed in Chapter II.1), particularly at lower levels of temperature change.

Second, even after baseline GDP per capita growth is accounted for, some proposed climate change adaptation measures will still overlap with more general improvements for economic development. Improving sanitation and water delivery, and making protection from disease vectors such as those for malaria universally available, would save millions of lives every year, regardless of future climate change. Flood protection, high-tech irrigation systems, and energy-efficiency measures would lower costs even if only the lowest climate change damages came to pass. Without these measures, lower-income populations, especially in developing countries, would be still more vulnerable to climate change. In modeling adaptation investments, IAMs need to account for benefits to society that increase welfare above and beyond negating a potential loss due to climate change.

New developments in economic modeling of adaptation

Several research groups are actively engaged in bringing adaptation investment choices into climate-economics models. De Bruin et al. (2009) modify the DICE and RICE climate-economics models to incorporate explicit adaptation decisions, and they examine interactions between adaptation and mitigation as well as the distribution of adaptation costs across regions. The authors construct regional adaptation cost curves where the costs and benefits (damages reductions) of adaptation are restricted to

occur only in the same period. The most efficient policy for reducing climate damages is found to be a mix of adaptation and mitigation investments.¹⁰¹

Agrawala et al. (2010) extend de Bruin et al.'s AD-DICE and AD-RICE models and also present modifications to the WITCH model. For all three IAMs, the representation of adaptation has been improved to include both flows of adaptation costs and benefits over time and the stock of climate-adaptation-related capital. The authors' AD-WITCH model allows for anticipatory investments in adaptation capacity, as well as reactive actions designed to reduce same-period climate damages. The study finds that adaptation measures can be a cost-effective policy choice, with benefit-to-cost ratios of 1.8 in AD-DICE and 2.0 in AD-WITCH. In AD-RICE and AD-WITCH, South Asia and sub-Saharan Africa had the highest adaptation costs, while the United States, Japan, and China had the lowest.

Bosello (2010) adds planned adaptation to the FEEM-RICE model. This study finds that a combination of adaptation, mitigation, and technology innovation investments is necessary to keep climate damages small, and suggests that the best intertemporal allocation of investment funds would involve rapid anticipatory mitigation measures, together with adaptation investments, to counteract residual damages in later decades. Other studies reach a similar conclusion: Adaptation investments should not be permitted to crowd out near-term mitigation investments (Carraro et al. 2010; World Bank and United Nations 2010). Rapid emissions reductions are the top priority for immediate climate policy spending.

Recent estimates of optimal global adaptation costs

Several recent studies have attempted to estimate the costs of near-term adaptation measures. Agrawala et al. (2008) reviewed an array of sectoral, national, and global multi-sectoral estimates and found substantial variations. In the latter category, the World Bank projected \$9 billion to \$41 billion in annual costs to developing countries; the Stern Report \$4 billion to \$37 billion, an Oxfam paper at least \$50 billion, and a United Nations Development Programme study \$86 billion to \$109 billion (by 2015). Agrawala also reviewed United Nations Framework Convention on Climate Change (UNFCCC) estimates, which put annual global adaptation costs at \$44 billion to \$166 billion per year, including \$28 billion to \$67 billion for developing countries. Of the global total, \$8 billion to \$130 billion would be required for infrastructure investments, \$14 billion for agriculture, \$11 billion each for water systems and coastal zones, and \$5 billion for human health.¹⁰²

Based on this review, Agrawala et al. (2008) find that the multi-sectoral estimates face “serious limitations,” most notably due to their sensitivity to assumptions about two parameters for which there is little reliable information: the share of assets and financial flows exposed to climate risk, and the incremental cost of “climate proofing” those assets. They also raise concerns about the lack of direct attribution to specific adaptation activities, the lack of consideration of the benefits of adaptation investments, and issues of double counting and scaling up to global levels. Thus, they conclude, “the ‘consensus’ on global adaptation costs, even in order of magnitude terms, may be premature” and not useful for decision making (p. 14).

Parry et al. (2009) evaluate the UNFCCC adaptation cost estimates and find that the UNFCCC underestimated costs in included sectors by a factor of two to three and omitted other important adaptation costs, including health costs in high-income countries and ecosystems protection. By 2030, they estimate that annual costs to developing countries will be \$134 billion to \$230 billion. A recent World Bank study (2010) estimated \$80 billion to \$90 billion in 2030 adaptation costs for developing countries, including \$29 billion each in coastal zones and infrastructure.

¹⁰¹ See also de Bruin et al. (2007).

¹⁰² See Agrawala et al. (2008), Table 2.6 for a summary. The studies reviewed are World Bank (2006); Stern (2006); Oxfam International (2007); United Nations Development Programme (2007); and United Nations Framework Convention on Climate Change (2007).

A recent analysis of adaptation and development costs by Smith et al. (2011) finds that a large share of estimated adaptation costs coincides with development expenditures and that an important share of current development expenditures goes to climate-sensitive projects. The analysis concludes that coordination of adaptation and development investments could make both funding streams more effective.

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Conclusion

In the years since AR4 and the Stern Report, climate science has made great leaps in understanding the likely pace and extent of climate impacts. The uncertainties inherent in predicting climate change are now better understood and better represented in forecasts. In order to be relevant and useful in policy making, climate economics must catch up with climate science. Our review of the latest literature brings to light the most critical improvements needed to assure that climate-economics models are based on the best possible scientific knowledge. In our judgment, the following elements are essential to a state-of-the-art, policy-relevant climate-economics analysis:

Climate-economics models should use an up-to-date representation of the climate system, including non-declining temperatures on a timescale of several centuries.

The latest general circulation models (GCMs) draw on the best new knowledge in climate science to produce a more detailed – and more complicated – representation of the planet’s physical systems. The climate is not a simple, predictable system. Increases in atmospheric concentrations of CO₂ do not have a simple, predictable effect on future temperatures. The number of factors affecting the future climate is immense. Predictions are complicated by many feedback effects. Today’s GCMs incorporate more interactions among systems and take account of irreducible uncertainty in future outcomes. The result is a more accurate and detailed range of likely temperatures, precipitation patterns, and rates of sea-level rise.

The integrated assessment models (IAMs) of climate economics cannot match the overwhelming level of detail needed to make GCMs effective. Instead, IAMs use simplified representations of the climate system that are designed to approximate GCM results, given the same emission inputs and baseline climate. Of course, calibrating IAMs to the GCMs of five or 10 years ago is not sufficient to policy-relevant climate-economics analysis. To achieve the state of the art in climate-economics modeling, IAMs should emulate the state of the art in climate science by approximating the latest suite of GCM results.

One new scientific finding critically important to policy results is the relationship between peak greenhouse gas concentrations and temperatures. After reaching their high point, temperatures are unlikely to decline for the next several hundred years. This means that “overshoot” scenarios are no longer viable options for policy analysis. While it is possible to exceed target concentrations and then gradually reduce atmospheric levels to a lower stabilization trajectory, this course of action will not have the previously anticipated effect of quickly reducing global temperatures. Climate-economics analyses should model non-declining temperatures to avoid producing infeasible policy recommendations.

Outcomes from climate change are uncertain, and climate-economics modeling results should reflect this uncertainty.

Climate science projects a range of outcomes from bad to much worse; climate economics should do the same. Economic growth and the carbon intensity of future technology are not known, nor are, therefore, future emissions. The relationships among greenhouse gases, radiative forcing, and temperature change are thought to be irreducibly uncertain – a problem that raises possibilities of unbounded risks, posing a fundamental challenge to climate economics. The pace of sea-level rise will depend, in part, on the timing of irreversible and potentially abrupt threshold events, such as large ice sheets breaking apart or shifts in ocean circulation, with important implications for damage estimates. Forecasts of precipitation levels and storm frequency and intensity depend on the assumptions made about emissions, climate sensitivity, and ocean circulation, as well as inherently unpredictable weather patterns.

New approaches to risk aversion that raise the possibility of improved modeling frameworks are a promising area in recent climate-economics research. The intriguing parallels to new developments in finance suggest that this could be part of a broader rethinking of the economics of markets, risk, and uncertainty. Short of such paradigm-changing innovations, however, there is much that can be done to improve the treatment of uncertainty in existing models.

Either by drawing from an assumed distribution of parameter values – producing a range of results instead of a single best guess – or by using the more complicated approach of modeling multiple future states of climate outcomes within the IAM structure, climate-economics models should incorporate uncertainty. At a minimum, results should be presented for values corresponding to the low end (e.g., first to 10th percentiles), median, and high end (e.g., 90th to 99th percentiles) of an up-to-date climate sensitivity probability distribution. Alternatively, models can use a climate-sensitivity distribution to estimate the probability of exceeding set temperature-increase thresholds, such as 2°C, 3°C, and 4°C.

Climate-economics models should incorporate up-to-date scientific findings on the expected physical and ecological impacts of climate change.

Many economic models arrive at a policy recommendation by evaluating trade-offs among abatement investments, other investments, and current consumption in order to find the spending mix that maximizes global utility. In these welfare-optimization models, utility is extremely sensitive to assumptions made about the relationship between emissions and climate damages: If damages are assumed to be only trivially increasing as emissions rise, these models recommend little or no spending on mitigation.

At present, the functions representing damages in many of the best-known welfare-optimization models appear to have no basis whatsoever in the current scientific literature on climate impacts. This fundamental disconnect between physical impact analysis and economic impact analysis undermines welfare-optimization models' relevance to climate policy.

To accurately model monetary damages as a function of temperature, IAMs should incorporate recent scientific findings on sector-specific damages, regional variation in vulnerability and in baseline climate, human communities' reliance on ecological systems, and uncertainty in impact assessments, especially in the long run. Both low- and high-temperature damages must be subjected to serious, detailed economic evaluation. In particular, the common but entirely unsubstantiated practice of assuming that damages grow with the square of temperature should be discarded.

Methods for modeling adaptation investment choices within IAMs are still under development. Endogeneity between adaptation and mitigation and the overlap between adaptation and economic development present significant analytical challenges. In the absence of a clear, widely adopted method for incorporating adaptation as a separate investment choice, IAM damage functions often represent climate impacts after an arbitrary, assumed level of adaptation. Policy recommendations will be strongly dependent on this assumed adaptation level, and it is therefore imperative that climate-economics model results be presented with an explicit explanation of the degree of adaptation that they assume.

If damages cannot be accurately represented in welfare-optimization models, economists should instead use a standards-based approach.

Accurate modeling of the relationship among emissions, temperatures, and damages is a daunting task. The data requirements for such an endeavor are overwhelming, and no simple function can represent sector- and region-specific damages. The uncertainties, large enough to make modeling difficult at low temperatures, are imponderable at high temperatures. If damages cannot be modeled in a way that reflects current scientific knowledge, welfare-optimizing models cannot offer good policy advice. Fortunately, there is another approach that obviates the need to model damages in IAMs: the widely used standards-based, or precautionary, approach.

A standards-based approach to climate-economics analysis replaces welfare maximization with cost minimization, identifying the least-cost method of achieving a particular climate outcome – for example, keeping temperature increases below a threshold such as 2°C. Although they are derived from different theoretical frameworks, the welfare-optimization and cost-effectiveness approaches are functionally equivalent when the damage function used for utility maximization reflects a near-vertical relationship between temperatures and damages. This implies that, beyond some threshold, even a small increase in temperature results in an unacceptably large increase in damages.

The assumption of a near-vertical damage function at some point not far beyond the 2°C threshold is, an assumption that seems well-founded in science, and is ubiquitous in climate policy discussions. It also fits a broadly accepted normative standpoint: Temperature increases above this level would create too great a possibility of catastrophic damages for the most vulnerable in our own generation and for future generations and should therefore be avoided even if the necessary precautionary actions are costly. Standards-based models take the near-vertical temperature-damage relationship as a given and focus on trade-offs regarding where and when to use particular abatement technologies in order to find the mix that minimizes global costs.

All climate-economics analyses should be accompanied by an explanation of what discount rate was chosen and why.

Climate change results from a form of pollution that has global and long-lasting effects, as well as appropriate responses, will also be global and long lasting in nature. Climate change is a public problem that requires public policy solutions. The distinction between public and private decision making is important in the choice of a discount rate, both in utility modeling in welfare-optimizing IAMs and in the evaluation of abatement costs in standards-based models. When decisions involve multiple generations, as well as populations within the current generation that cannot plausibly be said to share common objectives with regard to climate policy, the discount rate is an ethical construct with no empirical basis.

Welfare-optimizing IAMs' utility functions include parameters quantifying the importance of equity, both within and across generations, to model results. The public nature of the climate problem and its long time frame – decisions made today will have potentially enormous impacts on the well-being of future generations – point to the appropriateness of a low discount rate and/or other approaches to intergenerational equity. In standards-based (cost-effectiveness) models, the focus on nearer-term abatement investments makes discounting choices less crucial and makes a market-based discount rate more appropriate. Even for cost-effectiveness models, however, it may be important to analyze decisions extending beyond the current generation. For this reason, a discount rate that declines over time may lead to a better depiction of far-future investment decisions than would a simple market-based rate.

Regardless of model type and approach to discounting, climate-economics results should be presented together with an explicit statement of what discount rate was used and why. Where the case for using a particular discount rate is weak or ambiguous, presenting modeling results across a range of discount rates may improve policy relevance.

Policy relevance in climate economics depends on the ability to present impacts not just for the world as a whole but also by region or income group.

It is simply not plausible that the welfare of the world's economically, culturally, and geographically diverse population can be well represented by the single "representative agent" of abstract economic theory. Despite the global-public-goods aspect of the problem, economic and physical vulnerability, baseline climate, and expected climate damages all vary by region, as do energy infrastructure, abatement options, and technical costs. Under any climate policy, some members of the current generation will benefit from averted damages, improved access to more reliable energy sources, or jobs in green industry. Others will suffer net losses due to higher taxes, energy costs, or carbon charges, or from residual damages that occur despite mitigation and adaptation investments.

The diversity of climate effects around the world calls for at least the inclusion of multiple interests within a single objective function or for multiple objective functions across geographic regions. At a minimum, both welfare-optimizing and standards-based climate-economics models should consider the concerns of poor and rich countries separately and should have the means to present results by region or other relevant grouping.

In a similar vein, climate-economics models that act as if the distribution of income is immutable (using Negishi weighting) should be explicit regarding limitations they have placed on interregional transfers or

investments. Assumptions regarding the global distribution of income – and opportunities (or lack thereof) for changing it – are of paramount importance to international climate policy negotiations.

Abatement costs should be modeled as both determining and determined by abatement investments.

With an appropriate temperature-damage relationship, or a standards-based approach, the question of *what* to do about climate change has a clear answer: Stop increases to global emissions as soon as possible, with rapid and sustained annual decreases thereafter. The question of *how* to reduce annual net emissions cost effectively, however, still requires substantial exploration. This is an area where climate economics can make an important contribution to the decisions made in international climate policy negotiations and in domestic policy decisions around the world.

For all types of climate-economics analysis, abatement cost assumptions are key determinants of policy recommendations. Ideally, IAMs should model technological change endogenously, taking into account learning and price reductions that grow with investments in a particular technology. Abatement costs should not be modeled as purely a function of time or as a deadweight cost to society; research and development investment in emissions mitigation has clear benefits in improving future technological innovation, lowering energy costs, and providing jobs and income.

Modeling abatement choices and costs is complicated not only by endogeneity with respect to investment decisions but also by several ongoing controversies in the field of climate economics. Our review of this literature suggests, on the one hand, that negative-cost abatement options (the fabled “low-hanging fruit”), while perhaps exaggerated at times, really do exist and should be taken seriously in economic analysis. On the other hand, while the rebound effect (reducing the potential of energy-efficiency measures) also exists, backfire (a rebound large enough to erase energy-efficiency gains) is the economics equivalent of an urban legend.

Finally, abatement cost estimates include another critical assumption that should be made explicit when presenting modeling results: Fossil fuel price assumptions are a significant determinant of the comparative affordability of different abatement measures. A complete analysis of climate economics would make these prices endogenous, but this would require a level of complexity beyond the scope of most modeling efforts (and would, in any case, introduce new uncertainties). As with other assumptions in climate-economics models, assumptions about future fossil fuel prices should be presented explicitly, along with an explanation of the choices made. Where these choices seem especially arbitrary, the policy relevance of model recommendations would be improved by presenting results across a range of possible future fossil fuel prices.

In the end, analyzing climate change is not an academic exercise. The climate crisis is an existential threat to human society: It poses unprecedented challenges and demands extraordinary levels of cooperation, skill, and resource mobilization to craft and enact policies that will create a sustainable future. Getting climate economics right is not about publishing the cleverest article of the year but rather about helping solve the dilemma of the century. The tasks ahead are daunting, and failure, unfortunately, is quite possible. Better approaches to climate economics will allow economists to be part of the solution rather than part of the problem.