

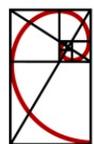
Climate Economics: The State of the Art



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November 2011

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Cover art: LEFT – Flooding in Addison County, VT, after Tropical Storm Irene / Flickr-Bryan Alexander; RIGHT – Lake Houston, in Humble, TX, amid the 2011 drought / Flickr-dasroofless.

Acknowledgments:

Thanks to Alejandro Reuss and Aaron Strong for research and literature reviews, to Donna Au, Jeffrey Cegan, and Ellen Fitzgerald for fact-checking, and to Marion Davis for copy-editing. Thanks also to the peer reviewers of this report, William Cline, Steve DeCanio, Richard Howarth, Robert Litterman, and Rachel Warren.

Thanks above all to World Wildlife Fund for inspiration and financial support. At WWF, Pablo Gutman and David Reed made it all possible, launched this report, and saw it through to completion. All statements made in this report are the views and conclusions of the authors alone; this document does not represent the opinions or positions of WWF or any of its staff.

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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advances in climate science; instead, they often incorporate simplified representations of scientific knowledge that is out of date by several years, if not decades.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

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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 I.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.