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Introduction

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The risks of unchecked global warming are now widely acknowledged: a rise in sea levels threatening the existence of some low-lying coastal communities; pressure on freshwater resources, making food production more difficult in some countries and possibly becoming a source of societal conflict; changing weather patterns providing favorable conditions for the spread of malaria. To make matters worse, the effects will be felt most in those parts of the world which are home to the poorest people who are least able to protect themselves and who bear the least responsibility for the build-up of greenhouse gases (GHGs). Concern has been great, but humanity has so far done very little that will actually prevent these outcomes. Carbon emissions have kept increasing, despite repeated promises of cuts.

As I wrote in *The Skeptical Environmentalist* (Lomborg 2001), man-made global warming exists. There is still meaningful and important work going on looking at the range of outcomes that we should expect but it is vital to emphasize the consensus on the most important scientific questions. We have long moved on from any mainstream disagreements about the science of climate change. The crucial, relevant conversation of today is about what to do about climate change – the economics of our response.

Finding a better response to global warming has become all the more important as the current political approach – seen at summits in Rio de Janeiro, Kyoto, and Copenhagen, has seemingly run aground. The failure of the Copenhagen Climate Summit in December 2009 was a great disappointment for the millions who had hoped for strong and meaningful action on global warming.

After Copenhagen, political leaders looked for sources of blame. China bore the brunt of western anger, while many declared that the UN negotiation process needed to be reformed.

It is more constructive to consider the range of policy responses that we have, and to identify what we can do in different areas. Economic research serves to underscore some of the hurdles before us – but it also highlights very promising avenues for exploration. It would be morally unconscionable to spend enormous sums of money making a minor difference to long-term global warming and human well-being if we could achieve a lot more impact on the climate – and leave future generations better off – with a smaller investment on smarter solutions.

The research presented in this volume was drafted by expert economists for the Copenhagen Consensus on Climate project, which utilizes a process that was first designed to prioritize global opportunities. The approach is simple, and is founded on the belief that basic principles of economics can be used to help any nation or organization to spend its money to achieve the most "good" possible.

In 2004 and 2008, the Center gathered research on ten key global challenges – from malnutrition to terrorism – and commissioned a panel of expert economists to rank the investments. The research from the Copenhagen Consensus 2004 and the Copenhagen Consensus 2008 is available in *Global Crises, Global Solutions* (Cambridge University Press, 1st edn., 2005, 2nd edn., 2009).

These projects attracted attention from all around the world. Denmark's government spent millions more on HIV/Aids projects, which topped the economists' "to do" list in 2004. Micronutrient programs in Africa and elsewhere received significant attention and greater resources after they topped the list in 2008.

The Copenhagen Consensus prioritization process has also been carried out with UN ambassadors from twenty-three nations including China, India and the USA, and for Caribbean and Latin

American problems. The research for the latter is available in *Latin American Development Priorities* (Cambridge University Press, 2009).

These projects showed that an informed ranking of solutions to the world's big problems is possible, and that cost-benefit analyses (CBAs) – much maligned by some – can lead to a clear and compassionate focus on the most effective ways to respond to the real problems of the world's most afflicted people.

Climate change is undoubtedly one of the chief concerns facing the world today. It has attracted top-level political concern and repeated efforts to form a global consensus on carbon cuts. But many questions have remained unaddressed and unanswered. Should politicians continue with plans to make carbon-cutting promises that, on past experience, are unlikely to be fulfilled? What could be achieved by planting more trees, cutting methane (CH_4), or reducing black soot emissions? Is it sensible to focus on a technological solution to warming? Or should we focus to adapt to a warmer world?

The research presented in this volume addresses these questions, along with how much each approach would cost and how much it would help in tackling climate change. Most importantly, the research presented together answers a fundamental question that we often overlook: not *if* we should do something about global warming, but rather *how best* to go about it. The starting point for every chapter is that global warming is a challenge that humanity must confront.

Just as with any other problem we face, there are many possible remedies, and some of them are much better than others. Not just cheaper, but more effective, more efficient, and – crucially – more likely to actually happen.

This book presents some of the recommended responses to global warming by experts in each field. There is a range of fresh thinking and new approaches. In these pages, for example, you will find one of the first – and certainly the most comprehensive – CBA of climate engineering (CE) options.

For each topic in this book – whether it is CO_2 mitigation, adaptation, or technology transfer (TT) – you will find at least two responses. This is because we commissioned a secondary group of qualified economists to provide a critique on the assumptions made in each chapter, for every topic. The "Alternative Perspectives" papers provide another way of looking at the costs, benefits, and risks of a particular response to climate change, and highlight the areas where expert opinion diverges. Some of them also provide an alternative solution, complete with estimates on costs and benefits.

For the topic of Climate Engineering, J. Eric Bickel and Lee Lane (chapter 1) offer an assessment of the potential benefits and costs of such engineering, examining two families of technologies – solar radiation management (SRM) and air capture (AC). Among other findings, they conclude that large potential net benefits of SRM mean that there is strong evidence for researching this technology further in the short term.

Two authors offer different perspectives on CE. Roger A. Pielke, Jr. (Perspective paper 1.1) argues that Bickel and Lane's analysis of SRM is not grounded in a realistic set of assumptions about how the global earth system actually works. He agrees that there is justification for continued research into technologies of SRM, but finds that this judgment does not follow from a CBA. Pielke also summarizes an analysis of the potential role for AC technologies to play in the de-carbonization of the global economy, and argues that since the costs of AC are directly comparable with major global assessments of the costs of conventional mitigation policies, AC also deserves to receive further study.

Anne E. Smith (Perspective paper 1.2) overlays Bickel and Lane's work with a consideration of the potential unintended consequences from CE, and extends it by calculating the value of information (VOI) from research and development (R&D). She then goes further and takes a critical look at the theoretical assumptions underpinning the standard formula for VOI.

On carbon emission reductions, Richard S.J. Tol (chapter 2) examines the costs and benefits of cutting carbon under different scenarios, and finds that while a well-designed, gradual policy of carbon cuts could substantially reduce emissions at low cost to society, ill-designed policies, or policies that seek to do too much too soon, can be orders of magnitude more expensive. He notes that while the academic literature has focused on the former, "policy makers have opted for the latter." Tol specifically considers five policies for carbon dioxide emission reduction. His findings include the point that very stringent targets, such as the EU's target of keeping temperature rises under 2°C, may be very costly or even infeasible, while suboptimal policy design would substantially add to the costs of emission abatement.

Onno Kuik (Perspective paper 2.1) is in agreement with most of what is written by Tol on the state of the art of economic research into the impacts of climate change and climate change policies, but highlights a complementary approach based on a direct elicitation of preferences for climate change.

Roberto Roson (Perspective paper 2.2) notes that Tol's chapter is largely based on the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model and the results of a set of simulation exercises where a number of policy options are explored and assessed. Roson points out a series of limitations of this model. However, he concludes that when considering the simulation scenarios, "we could have got about the same findings with a different model."

Brent Sohngen (chapter 3) looks at forestry carbon sequestration and indicates that if society follows an "optimal" carbon abatement policy, as defined in Nordhaus (2009), forestry could accomplish roughly 30% of total abatement over the century, while if society places strict limits on emissions in order to meet a 2°C temperature increase limitation, then the component that forestry provides lowers overall abatement costs by as much as 50%. Sabine Fuss (Perspective paper 3.1) is in broad agreement with Sohngen's analysis of costs and benefits. She concludes, like Sohngen, that forest carbon will be needed as part of a strategy to mitigate climate change.

Robert E. Baron, W. David Montgomery, and Sugandha D. Tuladhar point out in chapter 4 that a significant share of current net warming is attributable to black carbon. Black carbon is essentially the soot produced through diesel emissions, and – in developing countries – people burning organic matter to cook food and stay warm. It can be eliminated with cleaner fuels and new cooking technologies. Sooty pollution from indoor fires claims several million lives each year so reducing black carbon would also be a life-saver. Black carbon can be controlled in developing countries through the implementation of cleaner fuels, new cooking technologies, and changing crop management practices. The authors present potential ways to implement these policies, and provide cost-benefit (C/B) estimates that indicate that spending around $359 million could slash around 19% of black carbon emissions. Milind Kandlikar, Conor C.O. Reynolds, and Andrew P. Grieshop (Perspective paper 4.1) argue that it is important to recognize that black carbon reductions are not a substitute for reductions in emissions of carbon dioxide (CO_2), but that the two approaches must be applied together.

Claudia Kemfert and Wolf-Peter Schill (chapter 5) look at ways to mitigate CH_4, a major anthropogenic greenhouse gas (GHG), second only to CO_2 in its impact on climate change. They recommend an economically efficient global CH_4 mitigation portfolio for 2020 that includes the sectors of livestock and manure, rice management, solid waste, coal mine CH_4, and natural gas.

David Anthoff (Perspective paper 5.1) argues that joint methane (CH_4) and CO_2 emission mitigation is an optimal policy mix and leads to the highest net benefits, suggesting that an "either-or" approach between CO_2 or CH_4 emission mitigation forgoes at least some joint benefits. Daniel J.A. Johansson and Fredrik Hedenus (Perspective paper 5.2) note that the technical measures available to reduce emissions from livestock, the most important single sector emitting CH_4, are small. The combination of being a non-point emission source and having few technical abatement measures implies that output-based policies may be appropriate for reducing these emissions.

Francesco Bosello, Carlo Carraro, and Enrica De Cian (chapter 6) carry out an integrated analysis of both optimal carbon mitigation and adaptation at the global and regional level, and show that, compared to mitigation which reduces mainly future damages, adaptation is more rapidly effective for contrasting future and present damages. In particular, in a high-damage world (but without climate catastrophes), adaptation becomes the preferred strategy and this is reflected in an increasing BCR. They note that most adaptation expenditures need to be carried out in developing countries, but that the size of the required resources is likely to be well beyond their absorptive capacity. Therefore, international cooperation is necessary to successfully transfer resources and adaptation technology to developing countries.

Samuel Fankhauser (Perspective paper 6.1) argues that adaptation is now unavoidable, because there are no realistic mitigation policies that restrict warming to a level that does not require substantial adaptation. He notes that it is made more difficult by uncertainty about the exact nature of the expected change, which puts a premium on adaptations that yield early benefits or increase the flexibility of systems to react to unexpected change. Frank Jotzo (chapter 6.2) notes that economic analysis of adaptation is subject to the same complications and limitations that beset quantitative economic analysis of climate change mitigation. There is a long road ahead in improving the tools for economic modeling of adaptation, and the mitigation–adaptation nexus, and in the meantime the crucial question for policy makers is whether and where specific adaptation actions are beneficial, what new policies are needed to support adaptive action, and what existing policies need to be changed or scrapped.

Isabel Galiana and Christopher Green (chapter 7) examine a technology-led approach to climate policy. They write that the rationales for this approach include the huge energy technology challenge to stabilizing climate; the lack of readiness or scalability of current carbon emission-free energy technologies; the energy-intensive nature of growth in populous developing countries, especially in Asia; the economic and political limitations of a carbon pricing-led policy; and the large economic cost of "brute force" mitigation policies.

Valentina Bosetti (Perspective paper 7.1) finds that combining R&D and climate policies might lead to efficiency gains and help contain climate policy costs. Bosetti also specifically focuses on analyzing the costs and benefits of research and development in CO_2 capture and storage (CCS). This allows the continued use of fossil fuels while reducing the CO_2 emissions produced and may therefore be hugely helpful, especially in countries like China and India, that heavily rely on coal for the generation of electricity. Although uncertainties are present when dealing with R&D investments, Bosetti finds that a program aiming at decreasing capturing costs or increasing the CO_2 capture rate is shown to pass the cost-benefit (C/B) test, if a climate policy is in place.

Gregory Nemet (Perspective paper 7.2) agrees with Galiana and Green regarding the magnitude of the technological revolution required to address climate change, and the inability of on-the-shelf technologies to adequately fulfill the required technological change. Among other points, Nemet notes that a carbon price signal is insufficient to induce the technology development investments required to limit global temperature increase, and that the technology-led policy will shift the bulk of technological decision making from the private sector to the public sector.

Zili Yang (chapter 8) looks at technology transfer (TT): the process of sharing skills, knowledge, and technological breakthroughs among governments and other institutions to ensure that scientific and technological developments are accessible to a wider range of users. He finds that such transfers are an effective and necessary component when dealing with climate change, because international cooperation on both GHG mitigation and adaptation must involve transfer of technologies or dissemination of knowledge. David Popp (Perspective paper 8.1) critiques Yang's estimate of the potential of TT as a climate policy option, noting that Yang focuses on the direct gains from developed country financing of abatement in developing countries. Popp points out that there is an important secondary gain from TT – the potential for knowledge spillovers. He assesses the potential role that spillovers might play, and offers an assessment of the overall potential of international TT as a policy solution.

I believe that all of this research, in itself, provides a valuable contribution to and overview of today's discussions on global warming policy. But it is vital that we test and debate the experts' recommendations, and identify the most attractive possibilities for policy makers to further explore. That is why the Copenhagen Consensus process goes beyond just gathering new research.

As in the Copenhagen Consensus 2004 and 2008 projects, an Expert Panel of economists – including three Nobel laureates – examined all of the research presented here. The five-strong Expert Panel for the Copenhagen Consensus on Climate engaged with all of the chapter and Perspective paper authors and came to their own conclusions about the merits of each suggested solution.

The Expert Panel discussed and debated all of the possibilities raised in the research, in sessions designed to promote free debate. They weighed up each solution that you will find in this book, and compared it to the other options. The Expert Panel was tasked with answering the question:

> If the global community wants to spend up to, say, $250 billion per year over the next 10 years to diminish the adverse effects of climate changes, and to do most good for the world, which solutions would yield the greatest net benefits?

Later in the book, you will find their answers to that question, along with their individual explanations of how it was reached. They focused largely on estimates of costs and benefits, which is a transparent and practical way to show whether or not spending is worthwhile.

I invite you to read the research and the Expert Panel's findings, and form your own view on the best – and worst – ways we can respond to global warming. It is certainly time that we focused more on the solutions to this challenge.

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PART I

The Solutions

CHAPTER 1

Climate Engineering

J. ERIC BICKEL AND LEE LANE*

Considering Climate Engineering as a Response to Climate Change

Climate Change and Benefit-Cost Analysis

The task of this chapter is to answer a question that has been posed as part of the Copenhagen Consensus exploration of climate policy. That question is:

> If the global community wants to spend up to, say, $250 billion per year over the next 10 years to diminish the adverse effects of climate changes, and to do most good for the world, which solutions would yield the greatest net benefits?

To address this question, we agreed to summarize the existing literature regarding the costs and benefits of geoengineering (GE), supplement these estimates where needed and feasible, and to provide benefit-cost ratios (BCRs) for at least two GE alternatives. Based on this analysis, the current chapter argues that some portion (0.3%) of the hypothetical $250 billion a year should be devoted to the task of researching and developing two GE areas: solar radiation management (SRM) and air capture (AC). As the reader will see, we argue that more emphasis should be placed on SRM but that AC merits some research support.

The reader should not interpret our focus on climate engineering (CE) as implying that other responses to climate change are unneeded. The proper mix and relative priority of various responses to climate change is in the purview of the expert panel, to which our chapter is one input. One might also note that, with but one exception, every scenario considered in this chapter is accompanied by greenhouse gas (GHG) control measures.

The US Environmental Protection Agency (EPA) describes GE as "the intentional modification of Earth's environment to promote habitability" (EPA 2009). Many experts prefer the term "climate engineering" (CE) as more accurately describing the most widely discussed current concepts of modifying climate to curtail the harmful effects of global warming, and we will adopt this term.

Following the Copenhagen Consensus project framework, this chapter applies benefit-cost analysis (BCA) to gain insight into the net economic benefits that society might achieve by deploying CE. A finding that net benefits may be large, but are uncertain, suggests that society should devote some current resources to researching and developing this capacity. Some people object to BCA, and to CE, on what they regard as ethical grounds. Ethical conjectures are notoriously resistant to empirical falsification, and this chapter will not attempt to join this debate. Instead, we adopt the viewpoint that climate-change policies, including the possible use of CE, should be designed to maximize the welfare of human beings over time. "Welfare," in this context, includes the consumption of both market and non-market goods, such as environmental services (Nordhaus 2008).

Other objections to BCA rest on more purely pragmatic grounds. BCA is often difficult to apply because either costs or benefits may be difficult, or maybe even impossible, to quantify with confidence. Analysts may be tempted to overlook or to assume away some of these hard-to-quantify factors in hopes of keeping the analysis tractable. To choose an example that this chapter will address, BCA often ignores transaction costs, and a whole

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school of economics has grown up around the task of correcting the mistakes to which this simplification can sometimes lead (North 1990). Transaction costs are, indeed, hard to quantify. The existing climate policy literature has made no attempt in this direction, and this chapter will offer only a qualitative discussion of some salient points about the main issues. It suggests, however, that the transaction costs associated with SRM may be smaller than those that apply to some other climate strategies.

Likewise, we do not attempt to perform a probabilistic BCA, though one is clearly needed. We take this approach for two reasons. First, an important aspect of the Copenhagen Consensus project framework is ensuring a consistency among the chapters, which is harder to maintain in a probabilistic setting. Second, the state of knowledge about both the benefits of CE and its costs is primitive. Even base-case estimates for many important benefit and cost parameters are unknown. Thus, where the existing literature contains quantitative estimates, this chapter will select what we regard as the best available, with the caution that today's estimates are very much subject to change. Where possibly important factors have not been quantified, this analysis will point to their nature and discuss their potential significance.

In sum, we adopt what we hope readers will regard as a pragmatic approach to BCA. As one economist has observed, "everyone who urges a change in policy (or resists one) is at least implicitly comparing costs with benefits" (Cooper 2000). Making the basis of this comparison more explicit seems, on principle, likely to facilitate a more reasoned discourse.

The Budget Constraint and the Assumption of "Sensible" Policies

At this point, the Copenhagen Consensus budget constraint does not play much of a role in the issues raised by CE. Currently, CE is a concept deserving, we believe, R&D. It is not ready for deployment. How much money should go into the concept's exploration depends in part on the results of the initial research. However, the rudimentary state of knowledge about the concept suggests that an investment of perhaps 0.3% ($750 million per year) of the global total proposed by the Copenhagen Consensus guidelines might be an appropriate average yearly expenditure for the first decade. As R&D progresses, and assuming that results were favorable, spending would increase from tens of millions of dollars in the early years to the low billions of dollars. Extended large-scale field tests might be needed for perhaps an additional five years. Thus, spending in the first decade would not approach the budget constraint, although deployment could involve costs in the tens to hundreds of billions.

The chapter focuses on a BCA of deploying CE beginning in 2025. That choice rests on the proposition that the very large net benefits found in this analysis of CE make a convincing case for incurring upfront costs to research, to develop, and to demonstrate the concept. The chapter, in this regard, does assume that future policies will be "sensible," in that it assumes that R&D of a concept promising large net benefits would lead, at some point, to an effort to realize those benefits in practice.

However, the analysis also considers some policies that are not sensible – or perhaps one should say that it looks at some policies that do not appear to be optimal within the framework of a somewhat blinkered BCA. The paper considers how these options might affect the performance of CE, and looks briefly at how CE might affect the results of a few badly structured GHG control regimes. Some consideration of non-optimal policies can offer useful insights about how CE might function in the real world in which policy choices are rarely optimal (North 1990).

Description of Human-Induced Climate Change

Greenhouse gases (GHGs) in the Earth's atmosphere cause the planet's surface to be about 30°C warmer than would otherwise be the case (Stocker 2003). These gases allow the passage of short-wave radiation (sunlight), but absorb long-wave radiation (heat) and radiate a fraction of it back to the Earth's surface (Trenberth *et al*. 2009). This fact has been well established for a very long time.

It is equally clear that human activities can add to the GHG stocks in the Earth's atmosphere. The burning of fossil fuels, deforestation, and agriculture and animal husbandry are all practices that have this effect (IPCC 2007). All else being equal, although all else may not be equal, higher GHG concentrations will raise global mean temperatures (IPCC 2007).

The policy implications of this relationship, though, remain far from clear. Hard-to-predict demographic and economic trends will influence future emissions. Technological change is also a powerful driver of emissions, and its future direction and pace are still more unclear than are those of population and output. How well or poorly will societies adapt to climate change? The answer remains in doubt, but it will greatly affect the size of the costs and benefits that societies will experience.

The state of climate science compounds the uncertainties (IPCC 2007). How an increment of GHG will impact future temperature remains the subject of lively dispute. Man-made GHG emissions may interact in poorly understood ways with clouds, eco-systems, ocean currents, chemical cycles, and myriad other factors. These interactions may produce non-linear effects. Some feedback loops may amplify the warming impetus of larger GHG stocks. Some may dampen it. Science understands some of the interactions well, but many remain murky.

Even more doubts shadow predictions of what to expect from whatever warming does occur. Some experts believe that the climate system includes "tipping points" at which temperature, or other factors, may generate rapid and potentially very destructive changes. Where these tipping points may lie, how many (or few) of them there may be, whether they are near or far in time from the present, what happens if they are crossed – all these questions are unanswered.

The trajectory of GHG emissions also depends on future policy choices by many nation-states, and how their policies evolve. On this score, the historical record is clear:

> The year 2008 marks the 20th anniversary of the first meeting of the IPCC, the international body established by the UN to solve the problem of warming. The "progress" to date has been almost purely rhetorical. Currently, according to the US Energy Information Agency, global emissions of CO_2 [carbon dioxide], the most important greenhouse gas, were over a third higher than they had been in 1988. The IPCC reports that the rise in atmospheric concentrations has accelerated through the last several decades. (Lane and Montgomery 2008)

In fact, global CO_2 emissions grew four times more quickly between 2000 and 2007 than they did between 1990 and 1999 (Global Carbon Project 2008).

Thus, twenty years of protracted diplomatic talk and laborious scientific study have so far failed to move the needle on emission rates. During this period, GHG output has fallen in some countries, but, where such declines have occurred, "underlying changes in economic structure may have played a bigger role than climate policy" (Lane and Montgomery 2008). For example, most Kyoto Protocol signatories are failing to reduce emissions, much less meet their targets (UNFCCC 2009). The reductions that were achieved were heavily concentrated in Central and Eastern Europe (CEE), whose economies contracted and were restructured after the fall of the Soviet Union (UNFCCC 2008). The overall trend remains clear, and the prospects daunting.

Three Aspects of GHG Emissions that Cause Concern

GHG emissions may actually cause three quite distinct kinds of problems. They differ in the likelihood of their occurrence, their probable timing, and the incidence of their costs and benefits.

Gradual climate change

Gradual warming is likely to unfold over long periods of time, but its pace may vary from decade to decade. The process is likely to bring both benefits and costs. Benefits will include some higher crop yields from longer growing seasons and CO_2 fertilization. Mortality from cold will be likely to fall, as will heating costs. At the same time, gradual warming will impose costs. Some crop yields will fall, sea levels will rise, some storms may grow in intensity, more intense heatwaves will occasion health problems and raise cooling costs, and in some cases the range of tropical diseases may widen. While societies will adapt, as they have to prior climate changes, adaptation will often not be free. Many poorer societies currently lack the human and physical capital required to make the needed changes. Some valuable unmanaged eco-systems may also fall short on adaptive capacity.

Geographically, the incidence of costs and benefits will vary. Benefits are likely to be concentrated in higher latitudes, whereas most costs are likely to appear in climates that were warmer to begin with. Over time, though, even in regions with initially cooler temperatures, costs will climb relative to benefits. Nonetheless, in the midst of these changes – some positive, some negative – much of the industrial sector is likely to be unaffected. The pace of economic growth is generally expected to outrun that of gradual climate change (Schelling 2002). Thus, if climate changes gradually, the harm that it could occasion would take place in the context of a growing global economy.

Rapid climate change

Rapid high-impact climate change might occur relatively swiftly and could produce very large social costs. The timing and probability of such change are speculative. However, the risk cannot be ruled out. One current worry is that man-made warming could trigger large-scale methane (CH_4) release from the Arctic and sub-Arctic tundra (Corell *et al*. 2008). CH_4, itself, is a powerful GHG. Hence, man-made warming might unleash a self-reinforcing process. This warming might, in turn, accelerate the melting of the Greenland and Antarctic ice sheets. The latter would hasten the rise in sea levels, possibly doing serious economic harm to coastal cities. Other speculation has focused on major shifts in the pattern of ocean currents. Such a shift might reorganize the distribution of temperatures and precipitation.

Compared to gradual climate change, rapid change scenarios promise little upside (Barrett 2007a). The mere fact that a change happens rapidly is likely to raise the costs of adapting to it, and rapid change is often assumed to be quite destructive, even though its probability is low and highly uncertain (Weitzman 2007).

Ocean acidification

Finally, the ocean becomes more acidic as it absorbs CO_2 from the atmosphere (Royal Society 2005). Some studies suggest that, over time, this process could disrupt marine eco-systems and perhaps cause economic harm (Royal Society 2005). This risk, whatever its severity, is not strictly speaking climate change, but it is another aspect of CO_2 discharges.

Acidification and warming are likely to interact. Acidification is believed to weaken the ability of coral reefs to recover from bouts of bleaching caused by warm ocean temperatures (Kleypas *et al*. 2006). Corals are productive and economically valuable, and acidification might also harm other species near the base of the ocean food chain. The severity of the problem is poorly understood at the moment, but is causing concern among some scientists.

The uncertain state of knowledge about acidification greatly complicates the task of formulating an efficient policy response to it. At least some analysis suggests that even the most severe GHG controls might fail to halt the destruction of most coral reefs. The CO_2 already in the atmosphere could cause enough acidification to destroy all (or most) of the existing reefs (Cao and Caldeira 2008). Conversely, novel GE technologies beyond the scope of this chapter might be able to reverse acidification, at least in some areas (Rau *et al*. 2007). At this point, then, acidification appears to be a potentially important matter, but its relevance to CE remains doubtful. SRM does not address ocean acidification, and, accordingly, our BCA gives SRM *no* credit for doing anything about it.

Time Scales

CO_2, once in the atmosphere, will remain there for a century or more. Attempts to abate GHG emissions are also subject to lengthy time lags. Major technological changes often take a long time to mature, and new technology is often slow to diffuse globally (Edgerton 2007). Electrification of the global economy has been in train for over one hundred years, and is still incomplete. The spread of electrification was spurred forward by the large net benefits that accrued to those investing in it.