



Responding to Threats of Climate Change Mega-Catastrophes

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Responding to Threats of Climate Change Mega-Catastrophes

Faculty Research Working Paper Series

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Abstract

There is a low but uncertain probability that climate change could trigger “mega-catastrophes,” severe and at least partly irreversible adverse effects across broad regions. This paper first discusses the state of current knowledge and the defining characteristics of potential climate change mega-catastrophes. While some of these characteristics present difficulties for using standard rational choice methods to evaluate response options, there is still a need to balance the benefits and costs of different possible responses with appropriate attention to the uncertainties. To that end, we present a qualitative analysis of three options for mitigating the risk of climate mega-catastrophes—drastic abatement of greenhouse gas emissions, development and implementation of geoengineering, and large-scale ex ante adaptation—against the criteria of efficacy, cost, robustness, and flexibility. We discuss the composition of a sound portfolio of initial investments in reducing the risk of climate change mega-catastrophes.

Key Words: climate change, catastrophe, risk, decisionmaking under uncertainty

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Carolyn Kousky, Olga Rostapshova, Michael Toman, and Richard Zeckhauser*

1. Introduction

There is a very low probability that climate change could trigger a mega-catastrophe. As we use the term here, a mega-catastrophe is an event that is global in scale and has a high degree of irreversibility—at least on relevant human time scales. Mega-catastrophes would severely affect the well-being of much if not most of the world, though they are likely to affect poor countries more seriously on a proportional basis than richer countries.¹ We refer to the more localized and more reversible extreme events, including droughts, floods, and hurricanes, as “disasters” to distinguish them from the mega-catastrophes we consider here.

Catastrophes are of particular concern because, while an exact quantification is not possible, the most extreme adverse impacts from climate change (e.g., the worst 1 percent of scenarios) may account for a large portion of expected losses. Consequently, focusing primarily on more likely or anticipated (albeit serious) outcomes may miss much of the problem in terms of risks from climate change.²

We consider two types of mega-catastrophes. The first is caused by the climate’s crossing a threshold, triggering global impacts. Melting and collapse of ice sheets in the West Antarctic or Greenland leading to drastic sea level rise (several meters over time) is one example.

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¹ In terms of absolute numbers, losses are likely to be larger in richer nations. As a percentage of wealth and standard of living, however, losses in less-developed countries are likely to be higher since many have insufficient capacities even for measures that could reduce damages from non-catastrophic climate change.

² For many classes of disasters and catastrophes, the most extreme small percentage of the situations represents a significant proportion of the losses. We have witnessed this “fat tail” phenomenon recently with terrorist deaths and losses in a financial crisis. See Taleb (2007), Berger et al. (2008), and Kousky and Cooke (2009) for more on fat tails. Weitzman (2007) discusses how uncertainty can generate a fat-tailed climate change damage distribution.

A second type of potential mega-catastrophe could be created by “cascading consequences” of more localized climate change disasters that occur in relatively quick succession, with amplified effects becoming catastrophic, particularly if the disasters also occur in close spatial proximity.

From a policy perspective, the impacts of a mega-catastrophe must be viewed in terms of human impacts, not only impacts on the physical climate system. Thus, investment decisions in the near or medium term to mitigate the risks of potential catastrophes necessarily involve value judgments about what magnitude and speed of consequences are socially unacceptable. The anticipated consequences also need to be weighed against a variety of other risks society faces. In this paper, we do not analyze how much society should spend on reducing the risks of future mega-catastrophes relative to other threats. Instead, we provide a first-order analysis of a portfolio of response options, given that a decision has been made to reduce the risks.

Traditional responses to the risk of extreme events are of limited value in mitigating risks of a mega-catastrophe. The underlying changes in the climatic system could not be reversed over any time scale relevant for decisionmakers, limiting the efficacy of traditional recovery measures. Insurance markets will not function for these risks as they violate three key conditions of insurability: independent and identical losses, feasible premiums, and determinability of losses (Klein 2005). Impacts could be difficult to smooth over time, even for governments. There may be modest possibilities for risk-spreading between rich and poor nations, but when both rich and poor nations are severely affected, such risk-spreading will be significantly harder to elicit or sustain.

Response is further hindered by the fact that climate change mega-catastrophes are more often characterized by ignorance than by uncertainty. That is, not only do we not know the probability of a particular mega-catastrophe’s occurrence, we do not even know many of the possible outcomes. With this in mind, we suggest three categories of response options for mitigating a broad range of mega-catastrophe risks: (1) deep and very rapid cuts in global greenhouse gas (GHG) emissions, (2) development and subsequent application of geoengineering, and (3) global-scale adaptation targeted toward reducing the impact of a climate change mega-catastrophe should one occur.

Some authors have suggested that our ignorance of mega-catastrophes, coupled with the very low probability of such events and the possibility of extremely severe impacts, hampers the use of rational choice (RC)–based methods for analyzing response options. We believe systematic methods for weighing costs and benefits are especially crucial for helping to guide effective decisions in this context. The deep uncertainty does require, however, focused analysis

of the robustness and flexibility of options in addition to the anticipated benefits and costs. It also requires confronting the real possibility that for various reasons related to the nature of mega-catastrophes and how they are perceived, attitudes of the broader public about such events may not align with the results of a more systematic evaluation. This has implications both for the kinds of decisions that may receive public support and for the actions of decisionmakers to effectively convey the rationale for actions to be taken.

While investment in response options will shift over time with changes in circumstances, investments should be made at the outset in all three of the response options we suggest, with global efforts to coordinate them. One reason is that expenditures in any area will encounter diminishing returns. Thus, the costs of risk mitigation, for example, become more expensive for each incremental reduction in risk achieved through abatement. In addition, whether and to what extent the options will reduce the risk of climate change catastrophes are uncertain, and any risk-averse decisionmaker would thus want to diversify. The responses vary in their anticipated effectiveness in different states of the world. For example, if it turns out there are only moderate climate consequences, geoengineering may not be worth the risk, even if feasible. By contrast, if catastrophe appeared reasonably likely in the near future, geoengineering might be the only rapid response option. Since what state of the world will occur is unknown, a portfolio of options is preferred at the outset.

In the next section of the paper, we provide more detail on the types of mega-catastrophes that concern us here. In Section 3, we turn to the question of how our response to these risks should be analyzed. Building on the findings from this section, we turn in Section 4 to analyzing the three types of response options (dramatic abatement, geoengineering, and adaptation) against our four criteria (efficacy, cost, robustness, and flexibility). We offer recommendations on what should comprise an initial investment portfolio in response options. Concluding remarks are given in Section 5.

2. Background on Climate Change Catastrophes

2.1 Overview

As we are using the term, mega-catastrophes from climate change have the following basic characteristics:

- They would cause extremely severe impacts for a large number of people across broad geographic regions, if not the entire world. They are likely to affect people in developing

countries more severely than those in rich countries, as judged by percentage reduction in their standard of living.

- Their impacts would be extremely difficult to reverse over policy-relevant time frames.
- They are fairly to extremely unlikely, but it is highly probable that their risk grows as GHGs accumulate in the atmosphere.
- There is not only uncertainty about their likelihood of occurrence, but also “ignorance” about specific consequences (Zeckhauser 1991).

The type of climate change mega-catastrophe most extensively considered in the literature is that of the climate’s crossing a “systemic threshold” that causes the climate system to shift from one state to another (Schneider et al. 2007). This is often referred to as “abrupt” climate change.³ While a systemic threshold in the climate system might be crossed relatively quickly—perhaps over a period of a few years or decades—the consequences for both natural systems and human well-being may unfold much more slowly. This prospect for gradual onset (gradual from a human time frame, not a climatic or geologic one) may provide a window of time to adapt, although a timely signal of systemic change may be difficult to detect.⁴

The crossing of a climate threshold may not be the only mechanism through which climate change mega-catastrophes could arise. We also consider the possibility that a series of more localized disasters could trigger other disasters, and that this cascade of consequences could become severe enough to create a mega-catastrophe. This could include national security concerns, since a series of weather-related disasters could trigger political destabilization, mass migration, or violence. There is very little literature available for judging the possibility of

³ Alley et al. (2003) review several abrupt climate changes that have occurred in the past, ranging from regional to global disruptions.

⁴ It seems obvious to note that the ability to reduce uncertainty about the approach and onset of a critical global impact would have extraordinary value for planning the timing and scale of different interventions to mitigate the risk. Peters et al. (2004) and Lenton et al. (2008) describe the great difficulties encountered in modeling the nonlinear behavior of the natural systems. However, Dakos et al. (2008) and Keller and McInerney (2008) discuss how a reduction in observed fluctuations appears to have significant promise as an early indicator of an approaching tipping point. All of these sources strongly emphasize the need for more comprehensive measurement of the natural phenomena of interest across space and time. Keller et al. (2007) show that the value of information associated with earlier and more confident prediction of ocean circulation disruption could exceed the cost of the necessary ocean observation system by orders of magnitude.

cascading-consequences catastrophes, so our discussion of this potential mechanism is speculative.

A climate change catastrophe may have causes or impacts that currently receive little attention. The history of the past 40 years is sobering with respect to our ability to identify catastrophe risks. In 1970, nuclear war would have been the leading contender for any world catastrophe, and few would have predicted the major looming threats of the current era, which include not just climate change, but also global pandemics and terrorism. If significant changes in climate do lead to a catastrophe, say a 1 percent likely extreme event, we may well be severely surprised.

2.2 Crossing Thresholds

The most widely discussed large-scale impact of climate change is global sea level rise. The Fourth Assessment Report (abbreviated AR4) of the Intergovernmental Panel on Climate Change (IPCC) reported an anticipated sea level rise of 0.2 to 0.3 meters by 2100, and potentially up to 0.6 meters, with relatively continuous impacts of climate change including expansion of ocean volumes from warming and melting of ice (Nicholls et al. 2007, Table 6.3).⁵ The melting and collapse of the West Antarctic or Greenland ice sheets would lead to sea level rise great enough to be a mega-catastrophe as we have defined it. Depending the amount and pace of increase in mean global temperature, which would in turn depend on a variety of socioeconomic and physical factors, there could be an irreversible partial loss of the West Antarctic ice sheet with anticipated sea level rise up to five meters, and an irreversible substantial loss of the Greenland ice sheet with anticipated sea level rise up to seven meters (Schneider et al. 2007, Table 19.1). However, sea level increases of this magnitude are anticipated to occur only over many centuries. The threat of catastrophic impacts from large sea level rise would reflect the large and continually increasing number of people living near coasts, as well as the infrastructure and other physical capital located there. It also would affect an increased area of vulnerability to severe weather events, and widespread damages to coastal ecosystems as well as drinking water supplies.⁶

⁵ Some more recent assessments suggest the potential is more on the order of one meter (for example, Rahmstorf 2007).

⁶ Small and Nicholls (2003) estimate that 1.2 billion people live within 100 kilometers of the shore. Dasgupta et al. (2007) find that a five-meter rise in sea level would have impacts on 245 million people in developing countries, although the impacts are quite heterogeneous across countries (see also Anthoff et al. 2006). Even with the sea level

A second category of mega-catastrophe risk involves weakening and other disruptions of ocean currents. This could potentially alter extreme events, enhance sea level rise, severely disrupt ocean ecosystems, and change precipitation patterns, with serious impacts on agriculture as well as other sectors (Schiermeier 2006; Vellinga and Wood 2008). These impacts also are seen anticipated to increase slowly, over many hundreds of years (Schneider et al. 2007).

Very large-scale ecosystem disruptions could occur sooner. There is the prospect of continued and expanded changes in vegetation, particularly irreversible conversion of forest to grassland, as well as increased desertification and acidification of the ocean (e.g., Scholze et al. 2006; Smith et al. 2009). Changes in ecosystems resulting from changes in temperature and rainfall incidence and increased climate variability have the potential to cause significant loss of biodiversity as well as impacts on food and forest products production. The IPCC estimates that with global mean temperatures increasing between 2°C and 3°C, 20 to 30 percent of species could be at risk of extinction by 2100 (Fischlin et al. 2007). For higher levels of warming, extinction rates could be 20 to 50 percent (Thomas et al. 2004). All of these effects would be exacerbated by a large and rapid warming that also set in motion other factors (such as more rapid melting of heat-reflecting snow cover, or release of liquefied methane from tundra and elsewhere) that cause a further acceleration in climate change.

2.3 Cascading Catastrophes

The global-scale catastrophes discussed in Section 2.2 have all been subjects of interdisciplinary research and as such are reviewed by the IPCC (Schneider et al. 2007). There has also been significant scientific research on the effect of climate change on more localized disasters, such as heat waves, flooding, droughts, and hurricanes. What has received significantly less attention is the possibility that a number of smaller disasters all occurring over a relatively short time period, especially in close proximity, could mutually reinforce each other in such a way that the resulting cascade of consequences becomes a global catastrophe.⁷

Some extreme events can have secondary consequences that generate substantial additional damage (Muir-Wood and Grossi 2008). Secondary consequences, in turn, can trigger

rise that may occur within this century, tens of millions of people in developing countries would be displaced. Estimates based on current population and national income understate the vulnerability by not accounting for future growth, and growth in the share of gross domestic product concentrated in coastal areas.

⁷ Posner (2005) refers to this situation as involving synergistic components of catastrophe.

tertiary consequences that further amplify the adverse consequences, and so on. The compounding or amplifying effects of individual adverse impacts would be the result of exceeding the resilience of a number of local socioeconomic systems concurrently. More frail components of socioeconomic systems, such as marginal subsistence agriculture, represent potential places of vulnerability. One example of this type of mega-catastrophe could arise if increased drought from climate change caused a series of local food shortages to occur in close proximity, leading to political instability, a breakdown of civil order, large-scale migration for survival, and regional conflicts that accompany such events.⁸ The economic and national security consequences that spill over to other countries could be catastrophic (CNA Corporation 2007).

Cascading-event catastrophes could occur much more rapidly than the slower-onset global impacts discussed in the previous subsection. It is possible that more comprehensive monitoring of disaster risks may facilitate the development of early warning indicators for cascading catastrophes. For example, if several years of historically unusual drought weakened agricultural systems in many vulnerable parts of the world, there would be a stronger basis for concern about cascading consequences than if agricultural failures were not occurring simultaneously. However, the time interval for action to avert the potential catastrophe could be short. Equally important is achieving a better understanding of potential socioeconomic tipping points and the synergies among them.

3. How Should we Analyze Climate Change Catastrophes?

The standard RC-based framework for societal-level decision analysis involves comparing aggregate expected costs and benefits of different alternatives and then selecting the one with the highest expected net benefits. In the climate change literature, RC analysis is performed by using integrated assessment models. These integrated climate–economy models compare the estimated costs of abatement with avoided damages from climate change to determine optimal policies. The standard RC framework is a simplified version of the traditional economic model for decisionmaking under uncertainty, expected utility theory, in which decisionmakers maximize the utility they receive from potential outcomes weighted by the probability the outcomes will occur.

⁸ Zhang et al. (2007) examined this possibility in the context of food disruptions resulting from the “little ice age” that occurred from 1400 through 1900. They found strong correlations among temperature, declines in agricultural yield, frequency of war, and population declines in Europe and China.

The mega-catastrophes discussed in this paper are very low-probability, high-consequence events. Some authors have raised concerns that in these situations, RC approaches, most specifically, cost–benefit analysis, may not be appropriate (e.g., van den Bergh 2004). We discuss three particularly relevant challenges to using standard RC models in considering climate change mega-catastrophes: (1) severe uncertainty to the point of ignorance, (2) difficulty in accurately estimating benefits and costs, and (3) people not behaving as expected utility maximizers.

It is also worth noting two other concerns with using RC approaches for climate change–related analysis: the choice of a discount rate is controversial, and RC analyses do not explicitly address distributional concerns. Both of these topics are well-covered in the literature and are not unique concerns for mega-catastrophes, so we do not explicitly discuss them here, except for two brief comments on the specific implications for mega-catastrophe analysis. On discounting, we note that if climate change policies reduce the likelihood of a mega-catastrophe, then the correlation of such investments with the rest of the economy may well be negative, implying a negative discount rate (Brekke and Johannson-Stenman 2008). When catastrophe risk will be faced by future generations, however, what is of greatest concern in choosing a discount rate is how current citizens feel about the welfare of future generations. To address concerns that certain regions or countries may have a much higher risk of facing particularly severe consequences from a mega-catastrophe, the global community would need to develop some form of transfer system to aid the most vulnerable. For reasons previously noted, however, the willingness of better-off countries to transfer resources with the onset of mega-catastrophe is questionable; and there is no way to ensure that resources set aside in the nearer term would be used for that purpose once a catastrophe strikes.

3.1 Severe Uncertainty

As stated earlier, with climate change mega-catastrophes, we are in a state of ignorance in which both probabilities and outcomes are unknown (Zeckhauser 1991). The traditional RC model does not work well here; without an established set of outcomes to assess, it is impossible to maximize net benefits. Labeling climate change catastrophes as a state of ignorance, however, may be too severe. Perhaps it is a situation of quasi-ignorance, since several potential catastrophes have been identified and researched, as discussed in Section 2. Even if there are others we cannot identify, analysis can begin with those we can identify, with allowance for some catchall hypothesis for the other cases. Instead of trying to identify specific outcomes, another approach that has been used is to simply posit a catastrophe risk that reduces global gross

domestic product (GDP) by some amount. In this case, the exact mechanism for the loss of GDP need not be specified, partially avoiding the difficulty in itemizing possible catastrophic outcomes.⁹

To use RC approaches in cases of uncertainty over probabilities, subjective assessments must be used. One way to do this is through expert judgment, as done by Nordhaus (1994). He asked a range of climate change scholars about the probability of global incomes falling by 25 percent or more under varying scenarios. For a doubling of CO₂ by the mid twenty-first century, the mean probability was 4.8 percent, and for a very rapid warming scenario the mean jumped to 17.5 percent. Means can mask considerable variation, however. For the rapid-warming scenario, the probability estimates among natural scientists ranged from 20 to 95 percent and for economists, the probabilities ranged from 0.3 to 9 percent. The disparities between the estimates of these two groups are startling and discomfoting.

With different experts varying in their estimates of catastrophe probabilities and outcomes, whose estimates should we use? For example, should we use mean values across all experts or their models? We don't have an answer to this question, but it is one with which policymakers must grapple. Notwithstanding the difficulties, expert judgment is in many cases the best information currently available for judging the potential benefits of risk-mitigation actions.¹⁰

3.2 Uncertain Benefits and Costs

Estimates of the benefits and costs of climate change are highly uncertain—even for outcomes that are far from catastrophic. Estimates of costs are dependent on assumptions about technological change and technology adoption. For catastrophes, it is also uncertain how much

⁹ In considering catastrophic outcomes, Weitzman (2007) assumes a utility function that goes to negative infinity as a catastrophe is approached. For that reason, he rejects the standard cost–benefit framework. Alternative utility formulations would imply finite values of catastrophe costs, which lead to a quite different conclusion. Though the potential for catastrophe makes more aggressive action more desirable, it does not necessarily require monumental action. Summers and Zeckhauser (2008) argue that most individuals would not pay nearly all of their lifetime income to avoid a 1 in 1,000 chance of their death. This implies that death does not have an infinitely negative utility, an implication that surely holds true for catastrophic climate change as well.

¹⁰ A recent study (Lenton et al. 2008), based on a workshop and expert elicitation, tried to gauge how sensitive suspected tipping points were to mean temperature increase and the degree of uncertainty surrounding the underlying physical mechanisms; the conclusion was that several may well tip within the next century.

GHG abatement in the nearer term would be needed to sharply reduce the risk of a catastrophe. Estimates of benefits for reducing the risk of climate change catastrophes are even more uncertain. They depend first on how the current generation, making the relevant decisions, values reducing the risks confronted by future generations (and future ecosystems). Assessing this, in turn, presumably requires estimating potential future damages avoided, both direct (future destruction of capital, loss of life) and indirect (emotional suffering). Estimates of avoided damages also depend on the relative values of different future assets. For instance, if production of manufactured goods increases as a consequence of economic growth, but ecosystem services decline as the result of climate change, the relative price of the ecosystem services will increase, heightening damages to them from climate change (Stern and Persson 2008).

3.3 People Are Not Expected Utility Maximizers

There is a growing literature in behavioral economics and psychology that demonstrates that individuals do not make decisions according to the expected utility paradigm. Individuals are only boundedly rational (Simon 1955, 1957). That is, they do not have full information nor the time or ability to fully assess the consequences of decisions, so they adopt certain rules of thumb and mental shortcuts. These so-called heuristics and biases lead to choices that may depart from predictions of standard RC theory (Kahneman et al. 1982).

For instance, when probabilities are unknown and must be estimated, individuals have been found to assess an event as more likely when examples come to mind more easily. This phenomenon is known as the availability heuristic (Tversky and Kahneman 1973). Individuals also place an added value on certainty (Kahneman and Tversky 1979). That is, people prefer to reduce a small risk to zero more than they prefer reducing a larger risk by a greater amount. When contemplating a risk that engenders highly emotional responses, people can disregard probabilities altogether, treating all outcomes as equal, a phenomenon known as probability neglect (Sunstein 2002). Finally, when thinking about possible disasters, people tend to be overoptimistic, thinking negative outcomes are less likely to happen to them (Camerer and Kunreuther 1989).

This research has also found that context matters when individuals are making decisions. For instance, experiments have found evidence that people tend to “anchor” their preferences on an immediately available piece of information and fail to update their assessments adequately in the face of new information (Tversky and Kahneman 1974). People also disproportionately prefer to maintain the status quo in their choices, even if conditions or options change (Samuelson and Zeckhauser 1988). Errors of commission (trading away a number that wins) are

viewed as much worse than errors of omission (failing to trade for a winning number) (Zeckhauser and Viscusi 1990). This can lead politicians to tilt to the side of inaction. Individual choices are also strongly affected by the way that information is presented or worded. These are generally all referred to as framing effects (e.g., Tversky and Kahneman 1981; Keller et al. 2006).

Finally, numerous studies have documented that factors other than private income or wealth enter utility functions. For example, psychometric research has found that choices depend upon the extent to which a risk evokes feelings of dread (Slovic et al. 1982). Personal utility has also been shown to depend on perceptions of equity and fairness (Thaler 1988).

3.4 The Need for Rational Choice Approaches to Address Mega-Catastrophes

The challenges in Sections 3.1–3.3 raise serious questions about the application of standard RC methods for judging the costs and benefits of potential responses to mega-catastrophes. However, it is in cases like these that the discipline of investigating and weighing benefits and costs, broadly defined, can prove most useful. In particular, when there is reason to see various behavioral heuristics and biases as errors in perception or judgment, decisionmakers can be aided by the practice of this discipline. That said, some of the behavioral research findings do reflect salient personal evaluations of uncertainty that need to be considered. Individuals are willing to spend more to reduce dread risks, for example, than another risk with the same consequence that is less emotionally charged. For these types of heuristics, decisionmakers need to recognize that reducing anxiety is a tangible benefit.¹¹

We also agree with Posner (2005) that uncertainty over benefits and costs does not prevent the application of analytically weighing costs and benefits for evaluating and comparing options. He suggests a “tolerable windows” approach. By analyzing a range of scenarios and estimates, we can identify a level of effort on risk reduction at which the benefits clearly exceed the costs and a level at which costs clearly exceed benefits. We can then target policy to remain in this window. For climate change, a similar approach can be taken if one has some confidence in the evaluation of costs of different policies but great uncertainty about the potential benefits. In that case, one could investigate how large the potential benefits might have to be to make a case for the selection of one set of options over another in a portfolio. Similarly, if the benefits

¹¹ This is similar to the hoof clops of mounted police bringing peace of mind to the populace (Sunstein and Zeckhauser 2009).

are reasonably well understood conditional on a catastrophe's occurrence, but there is uncertainty about the probability of a catastrophe, then one can ask how large the probability would have to be to justify a particular portfolio of actions.¹²

Such analysis must include sensitivity analyses and other methods to incorporate both quantitative and qualitative estimates. The above analysis suggests that in order to account for the severe uncertainty surrounding climate change mega-catastrophes, the flexibility and robustness of the options must be considered as well as anticipated costs and benefits. All four of these metrics are considered in our analysis of policy options below.

4. Building a Portfolio of Ex Ante Response Options

4.1 Scope and Approach

In this section, we assess three types of possible ex ante responses to the threat of climate change mega-catastrophes:

1. dramatic global abatement to rapidly stabilize the concentration of GHGs in the atmosphere at a level low enough to significantly reduce the probability of a catastrophe,
2. development and deployment of controlled geoengineering to reduce the impacts of GHG accumulation on the climate system and thus on human well-being, and
3. various large-scale adaptation measures that would reduce the consequences of mega-catastrophes or short-circuit the cascading of more localized disasters.

We can expect some uncoordinated investments by individual nations, especially in adaptation but also in geoengineering, to be made out of self-interest. However, the use of these options to effectively reduce catastrophe risk on a global scale will require a larger and more coordinated global response. Substantial planning regarding when, how, and by whom they would be used will be needed.

¹² For a technical approach to tolerable windows modeling, see Bruckner et al. (2003). A “precautionary approach,” often advocated for dealing with climate change, is a particular case of this reasoning that emphasizes the potential risks of climate change in arguing for very rapid and aggressive interventions. With this strong emphasis on risk mitigation over the opportunity costs of taking action, this approach could lead to overly stringent response measures. See also Sunstein (2002).

We evaluate the three response options against the four metrics noted above:

1. potential efficacy in mitigating risk (benefits anticipated),
2. estimated costs of development and implementation,
3. robustness of outcomes from the response across unanticipated changes in risks that alter potential future scenarios, and
4. flexibility to adjust the pace or other specific characteristics of the policy.

Flexibility is related to robustness in the sense that a more flexible response could adjust more quickly to changes in the size and nature of risks anticipated. However, flexibility goes beyond this by including the capacity to alter the pace of implementation for other reasons (for example, adjustments to cost). In addition, flexibility has more than one dimension. One aspect is the technical and economic capacity to adjust a response upward or downward during implementation. Another is the degree to which, once undertaken, responses would be more or less costly to expand or reverse.

Section 4.2 discusses the three options and Sections 4.3–4.6 evaluates them against our four decision criteria. Section 4.7 then summarizes the findings and discusses the implications for initial investment levels, including a discussion of how investments will be influenced by the behavioral findings presented in Section 3. For reasons discussed below, a desirable portfolio will comprise some investment, including possible investment in research and development (R&D), in each of the three response options.

4.2 Response Options

4.2.1 Dramatic Abatement

Dramatically and rapidly abating GHG emissions would lower the risks of climate change catastrophes, although determining the relationship between emissions levels and catastrophe probabilities is difficult. The results of the IPCC AR4 suggest a growing level of risk to human well-being as warming goes from 2.5°C to 4.5°C or higher above preindustrial levels.¹³ The IPCC report indicates that limiting temperature increases to around 2.5°C would require stabilization of GHG concentrations near 450 parts per million by volume (ppmv) (Fisher et al.

¹³ See Yohe et al. (2007, Table 20.8). Others suggest we may face “dangerous” climate change with as little as a 1°C warming (Hansen 2005).

2007). This can be compared to projections of almost 700 ppmv in 2100 under business as usual (Nordhaus 2008) and associated temperature increases in excess of 5°C (Yohe et al. 2007). To achieve a target of 450 ppmv, GHG emissions would have to be reduced quickly and dramatically—global emissions would have to start to fall before 2015 and be reduced to less than 50 percent of current emissions by 2050 (Fisher et al. 2007). Even stabilization at 550 ppmv, which could lead to warming between 2.8°C and 3.2°C, would require global emissions to peak in less than two decades and return to year 2000 emissions by 2040 (Fisher et al. 2007).

A few studies have attempted to estimate temperature and/or emissions levels that would prevent some of the specific catastrophes discussed in Section 2. O’Neil and Oppenheimer (2002) estimate that limiting temperature increases to 2°C above 1990 temperatures could conceivably guard against collapse of the West Antarctic ice sheet, while limiting increases to 3°C over the next 100 years may prevent collapse of thermohaline circulation in the Atlantic. Thus, both might be prevented if concentrations were stabilized at 450 ppmv. Other studies suggest a higher level of concentrations before substantial weakening of thermohaline circulation in the Atlantic (Keller et al. 2000). The IPCC Fourth Assessment Report estimates several meters of sea level rise for warming between 2°C and 5°C above 1980–1999 levels as well as weakening of the meridional overturning circulation (Yohe et al. 2007). All estimates are dependent on assumed values of key parameters, particularly climate sensitivity and rate of emissions (Zickfeld and Bruckner 2003) and are thus very uncertain.

More intensive abatement may be needed to prevent a cascading catastrophe. For instance, even with only 2°C of warming relative to the late twentieth century, 1–2 billion additional people could face increased water stress in the twenty-first century (Kundzewicz et al. 2007). The comparable range for a 1°C warming is 0.4–1.7 billion people. Findings also vary regionally and demonstrate some large jumps in vulnerability with greater warming (Yohe et al. 2007). Conditions could thus be favorable for cascading catastrophes related to water scarcity and conflict for warming less than 2°C—though we stress again the lack of knowledge available about sufficient conditions for cascading.

4.2.2 Geoengineering

The term “geoengineering” is defined as intentional large-scale manipulation of the Earth’s environment in order to combat the effects of changes in atmospheric chemistry

(National Academy of Sciences 1992; Keith 2000). Current proposals for using geoengineering to lower the climatic impacts of GHG accumulation fall into two categories.¹⁴ The first is technologies to reduce the amount of solar energy the planet absorbs. The most commonly discussed option involves seeding the upper atmosphere with particulate matter—sulfates—to reflect sunlight (Crutzen 2006). This is a method that would be relatively easy to test in stages and to deploy, and that could be stopped if desired. On the downside, it could exacerbate acid rain and other pollution problems, and its longer-term side effects remain unknown. Other approaches include increasing the reflectivity of the earth (e.g., painting rooftops white), changing cloud cover, and even putting mirrors in space.

The second category of geoengineering approaches concerns the removal of CO₂ from the atmosphere. Machines that function like artificial trees could be built to trap air, isolate the CO₂, and then store it underground or cycle it into biomass production. The main environmental concern is the safety and permanence of the CO₂ storage. Another possibility is to fertilize the ocean to increase algae growth and through that, CO₂ absorption. This could, however, have disastrous side effects on oceanic ecosystems. Finally, there is early discussion of nanobots that could “eat” carbon dioxide in the atmosphere.

Geoengineering technologies are still being explored. If developed and successfully tested for safety, efficacy, and affordability so that it could be deployed in the nearer term, geoengineering could be used as a complement to GHG abatement. However, this would require stringent maintenance of energy-reflecting geoengineering applications in order to avoid a catastrophic “backsliding.” Geoengineering is more typically considered in the context of efforts to mitigate global-scale impacts of climate change, including threats of catastrophes. If we became confident there would be enough lead time to deploy effective geoengineering if necessary, it could function as a contingency option should a climate change catastrophe appear likely, or in an effort to arrest the consequences of a catastrophe as it materializes (including a catastrophe from a cascading sequence of more localized disasters).

Any application of geoengineering should be based on confidence that benefits in stemming impacts from climate change were not outweighed by potentially large side effects. Effective use of geoengineering would require international implementation since without coordination, as for any international public good, its usage would be inefficiently low and there

¹⁴ For a more comprehensive analysis of geoengineering approaches, see MacCracken (2009).

would be no mechanism to address side effects, especially those that could fall disproportionately on certain countries from more unilateral application.¹⁵

While there is uncertainty about how effective geoengineering would be as a more localized shield, countries facing an imminent disaster will have strong incentives to make unilateral use of geoengineering to the extent that it could be effective and affordable. They will thus have incentives to develop a capacity for deploying lower-cost geoengineering, in particular sulfate seeding of the upper atmosphere, even if its safety is not yet established. If such localized use of geoengineering imposes costs on others, these costs will not be internalized, a situation that could lead to excessive or risky geoengineering being undertaken. Such a situation could also lead to international conflict concerning whether and to what extent the use of geoengineering is the cause of negative climate impacts (Schneider 1996). For these reasons, global governance of geoengineering is particularly important but tricky (Barrett 2008).

4.2.3 Global-Scale Adaptation to Reduce Potential Impacts of Catastrophes

The IPCC has defined adaptation measures as “actual adjustments, or changes in decision environments, which might ultimately enhance resilience or reduce vulnerability to observed or expected changes in climate” (Adger et al. 2007). The bulk of the adaptation literature has focused on responses at a national, sub national, or sectoral level either to gradual effects of climate change or to more localized disasters. Adaptation options have previously been divided into reactive adaptations, which are undertaken in response to changes as they occur, and anticipatory adaptations, which are taken in advance of impacts (Smith 1997).¹⁶ In this section, we consider the potential for anticipatory adaptation that could reduce the potential damages of mega-catastrophes.

The more severe the losses, the more valuable even a modest reduction in their potential magnitude. By way of analogy, consider the pandemic flu of 1918 that killed somewhere between 20 and over 40 million people worldwide, with one estimate at 50 million (Niall et al. 2002), assuredly a catastrophe. Say that additional public health adaptation measures would have had the potential to cut deaths by “only” 10 percent. That still would have been an amazing

¹⁵ The possible unilateral use of geoengineering is illustrated by efforts undertaken by China to ease drought conditions (McDonald 2009).

¹⁶ Another important distinction in the adaptation literature is between autonomous adaptation, undertaken by individual actors on their own behalf, and adaptation measures initiated by the public sector or international bodies. It is the latter that is of concern here, given the nature of the events we are considering.

accomplishment, one worth bearing significant costs to attain. As discussed in Section 3, the field of behavioral decision science tells us that individuals do not easily distinguish between, for example, 95 million and 100 million deaths, or between a climate-change catastrophe that cut the world standard of living by 20 percent or 18 percent. But if we reframe the accomplishments as saving 5 million lives, or boosting the standard of living by 2 percent, which is what these hypothetical adaptations would do, the massive benefits are apparent. Thus, in the face of potential catastrophe, even adaptations that only partly control the problem make a significant contribution.

Examples of anticipatory adaptation measures that could reduce vulnerability are illustrated in a study of potential responses to a collapse of the WAIS that would trigger five meters of sea level rise (Tol et al. 2006). That analysis identified several adaptation options, including raising dikes or other flood protection infrastructure, abandoning low-lying areas, and reshaping urban areas to be akin to Venice. In another study that included interviews and a policy exercise on the impact of a WAIS collapse on the Thames Estuary (including London), three adaptation options were considered: increasing structural protection, complete relocation outside of London, and letting some areas of the city be flooded while protecting others (Lonsdale et al. 2008). This research suggests that both structural protective works and anticipatory relocation are potential adaptation options.¹⁷

To adapt to major ecosystem disruption, anticipatory set-asides of large land tracts in developed and developing countries could be undertaken for protection of natural ecosystems. The set-asides could be used to address problems of both biodiversity loss and changes in vegetation.¹⁸ Where to locate such lands, how much it would cost, and how effective it would be are still unanswered questions.

Adaptation measures to address cascading-event catastrophes are more difficult to identify. There is already a large literature on disaster risk reduction and disaster management at the level of individual countries or regions that can be used to address the increased risk of

¹⁷ Relocation as an adaptation is already being undertaken in some small island nations where sea level rise will almost surely create a localized disaster. The president of the Maldives has proposed setting aside tourism revenue in a national fund so that the country can purchase land in countries with higher ground for relocation of the entire population when the time comes (Henley 2008). The president of Kiribati is trying to relocate young citizens now to New Zealand and Australia to prevent the need for mass migration in the future (Russell 2009).

¹⁸ None of these approaches addresses the stress on ocean ecosystems from significant climate change, such as increased acidification (Section 2 above).

climate change–induced disasters. The additional challenge in addressing cascading-event catastrophes is putting in place “circuit breakers” that prevent the secondary and tertiary effects of individual disasters, which might otherwise cause a more global-scale catastrophe to develop.¹⁹ Since the likelihood and impact of potential synergies that cause disasters to cascade into catastrophes are not yet known, it is difficult to be specific about how these kinds of circuit breakers would need to operate. One example of a circuit breaker adaptation might include extremely large stockpiles of basic food, water, and shelter that could be dispatched quickly if a series of smaller disasters threatened to slide into a larger-scale catastrophe. Development of contingency plans would be a critical complement to any other preparedness measures for effective circuit breakers.

4.3 Anticipated Efficacy and Benefits of Response Options

All three types of response options pass basic tests of efficacy. For dramatic abatement, we judge from the analysis in the latest IPCC report that going rapidly to a 550-ppmv concentration limit would reduce the risk of a gradual-onset global catastrophe by an appreciable percentage, though perhaps not by a very high percentage. Stabilization at 450 ppmv is more likely to be effective at significantly reducing climate change catastrophe risks. Mitigating the risks of cascading-event catastrophes may require even larger reductions in GHG concentrations; this could be the case if the socioeconomic tipping points underlying the cascading-event catastrophes occurred with smaller degrees of climate change than the large-scale environmental tipping points.

The efficacy of global-scale application of geoengineering needs to be considered separately for several cases. It could be quite effective for mitigating the risks of a threshold-crossing type of catastrophe, assuming there is technical success in developing reliable geoengineering methods with limited side effects. Based on current knowledge, these conditions are not satisfied; verifying or refuting them will occur only after additional R&D. It also would be necessary to deploy geoengineering at a large enough scale to be effective, with international agreement to govern and coordinate its use. Otherwise, the net effectiveness of the approach is

¹⁹ A smaller-scale example of this comes from Hurricane Katrina. Catastrophe models had predicted—before Katrina—that even with a major hurricane, there would not be significant flooding in the city because levees would remain intact and, importantly, the city’s pumping system would be operating. The storm took out power, however, which prevented the pumps from working, and even if they had been operable, the forced evacuation meant that no one was available to operate the systems (RMS 2005).

highly uncertain. For sunlight-reflecting technologies, including particles injected into the atmosphere, sustained use is also crucial, since stopping reflection could result in a “rebound” that would accelerate the rate of climate change.

The effectiveness of geoengineering in stopping a cascade of consequences is more difficult to gauge, even assuming technical success as described above. Geoengineering could be both highly effective and politically manageable if it could be applied quickly and locally, with limited and manageable impacts on neighbors. On the other hand, difficulties in undertaking targeted applications, or in limiting unintended or unanticipated side effects, could cause serious problems.

The potential efficacy of adaptation options for large-scale catastrophes is high. Relocating individuals and rebuilding structures out of harm’s way would be very effective, assuming threatened areas are identified. Large increases in protected natural areas to mitigate some of the stresses on natural ecosystems also could be effective, though this would depend on the size and connectivity of the areas and the particular threats being addressed—issues about which we still have limited understanding. Adaptation options to short-circuit cascading events could be effective, but even the best-informed and prepared response capacities could be undercut by surprise—especially since locations of potential cascading catastrophes will likely remain quite uncertain. It is important to stress, though, that even if the efficacy of an adaptation (or another measure) is uncertain or anticipated to be only partial, it still may be worth undertaking.

4.4 Anticipated Costs of the Response Options

The costs of the response options will vary, although all will be high. Achieving dramatic and rapid reductions in global GHG emissions will likely be very costly, in the absence of major breakthroughs in low-carbon energy technology or carbon sequestration. Assumptions matter crucially. As a rough guide to the costs, the IPCC estimates that at stabilization between 445–535 ppmv CO₂-equivalent, GDP in 2050 is no more than 5.5 percent below baseline (this is well above current GDP given the effect of continued economic growth). The authors also note there has been little analysis of achieving this stringent target compared to others (Fisher et al. 2007). The IPCC figures also reflect ideal conditions for policy implementation. With less than fully cost-effective implementation, as must be expected, whether from delayed participation by developing countries or the use of some cost-ineffective mitigation policy mechanisms, the total cost would be much larger. For example, DICE runs suggest that with only 50 percent of

countries participating, abatement costs for the same goal would increase by 250 percent relative to full global participation (Nordhaus 2008).

The cost of geoengineering remains highly uncertain. One estimate of particulate seeding puts the cost at \$25–\$50 billion per year (Crutzen 2006). While this is a large number in absolute terms, it is a very small fraction of anticipated world GDP. However, anticipated negative side effects also are a critical part of the cost analysis. Negative side effects of scattering particulates in the atmosphere could include alteration of the hydrologic cycle and acidification of the ocean due to continued buildup of carbon dioxide. These developments in turn could have severe economic consequences that should be a part of the cost analysis. In addition, the costs of geoengineering R&D and deployment are a matter of speculation. Research and pilot-scale experiments would be needed not only to establish an adequate capacity to control large-scale geoengineering and to gather even rough estimates of cost, but also to identify and then find ways to ameliorate side effects. Given the complexity of the natural systems with which the world would be experimenting, it is possible research could not fully put to rest concerns about side effects.²⁰

The costs of adaptation measures are sure to vary widely and will be difficult to assess a priori in many cases. Adaptation options involving very large land set-asides in the relatively near future for massive relocation of people would have quite high opportunity costs (including a significant amount of social dislocation). Large set-asides for protected areas also could be costly. More gradual set-asides and relocation would presumably be cheaper—especially compared to abandoning threatened areas and relocating people extremely rapidly later, when a threat appears more imminent and critical. Stricter land-use regulations across the world in coastal and other areas projected to be severely affected by climate change would be an important and relatively less expensive way to hold down adaptation costs later.²¹ However, given population growth rates in coastal areas across the world, predominantly due to immigration, even this option meets with political resistance. Costs for circuit-breaker responses to cascading catastrophes are even more difficult to gauge, though estimates for disaster

²⁰ See also McCracken (2009) for a discussion of a range of different possible geoengineering approaches and the uncertainties surrounding them at present.

²¹ Some initial efforts along these lines are being undertaken. For instance, the New Jersey Coastal Blue Acres Program is a land acquisition program run by the New Jersey Department of Environmental Protection. The department purchases vulnerable coastal lands damaged or prone to damage by storms.

preparedness would be a point of departure (and the adaptation measures would provide some co-benefits in that respect). Our rough judgment is that the costs would be moderate, not huge.

4.5 Robustness of the Response Options

Dramatic abatement is the most robust response option (in the sense we are using the term). The potential impacts of catastrophes—indeed all negative impacts of climate change—depend strongly on accumulating emissions, so reducing these emissions would reduce risks across a range of future scenarios.

Coordinated international use of geoengineering could be almost as robust as dramatic GHG abatement, since it likewise attacks the root of the climate catastrophe risk: the amount and impact of increased radiative forcing. In principle, it might accomplish this goal more quickly than dramatic abatement if risks unexpectedly were seen to be much larger. However, these conclusions depend on a coordinated and timely use of geoengineering that is reasonably safe as well as effective. Otherwise, it could exacerbate other risks for reasons presented above, and in that sense, robustness would be lost. Abatement does not carry this risk.

Adaptation may not be robust. Previous authors have pointed out that we can maladapt; that is, we can be worse off from the adaptation than had we done nothing (e.g., Scheraga and Grambsch 1998). Here, we consider a slightly different concept, which we term brittle adaptation. These are adaptation measures that provide benefits under the circumstances for which they were designed, but not if impacts are significantly different. It has been observed in the United States, for example, that regulations and protection programs designed for more modest-scale disasters can become at best ineffective and at worst counterproductive when addressing larger-scale events (Moss et al. 2009). Levees have been found to create a feeling of safety, leading to increased development behind them (Tobin 1995). When they are overwhelmed or fail they can cause more damage than had they not been built initially.

In our context, structural protection measures like levees could be brittle—in a particularly severe event they would fail to provide benefits, and they may even cause more damage. A similar effect could occur with relocation if population and investment were concentrated at the edge of the “cleared zone.” Relocation programs could be brittle in a different way as well—for example, we might discover that increased risks of disease from climate change are a more urgent threat than sea level rise, and these disease risks might even be exacerbated during relocation. Programs to sharply limit in-migration, and the creation of large protected areas for preserving critical natural capital and habitat, would be more robust since

they would provide benefits in a range of states of the world as well as environmental co-benefits.

For circuit-breaker adaptations, contingency plans that allow for rapid changes in the type and volume of assistance provided to individual disaster locations would be the most robust option. One example comes from combating the 2003 heat wave disaster in France. Lagadec (2004) found that responding to the heat wave required many organizations apart from traditional emergency responders, such as nursing homes, to enter “crisis” mode. Because many were unaccustomed to doing so, the response was ineffectual.²² To be effective, contingency plans must have material backing for a range of responses—from food aid to public safety.

4.6 Flexibility of the Response Options

Dramatic reduction of emissions is not flexible. Once a commitment to rapid decarbonization is made, it will be costly to ramp up the target for mitigation even further due to the volume of newly sunk investment. The goal could subsequently be relaxed, but that also would involve economic costs from reconfiguring the energy system as well as political opposition to “stranding” prior low-carbon investments. And if companies knew there was a likelihood of such reversal on target emissions levels, they would be less likely to invest in reductions in the first place.

In one respect, geoengineering is relatively flexible. Rates of application of geoengineering methods such as ocean fertilization or rates of particulate seeding could be scaled up or down relatively easily. However, geoengineering technologies involving reflection of energy cannot be stopped once GHGs have accumulated without risk of abrupt and severe climate change. This implies much stronger limits in the downward flexibility of reflective geoengineering than would be the case with massive GHG abatement. Thus, unless or until uncertainty about side effects can be reduced very significantly, the lack of downward flexibility could be a serious impediment to its use.

Structural adaption would be fairly inflexible. Adaptation involving acquisition of large areas of land to hold for future relocation or ecosystem protection may not be upwardly flexible, but could be more downwardly flexible. There is an option value associated with acquiring more

²² In a region in France that had excess mortality of 171 percent during the crisis, a nursing home that had developed broader risk reduction measures across its range of activities performed much better (Poumadère et al. 2005).

land than is expected to be needed in order to protect against widespread mega-catastrophe as opposed to localized disaster, a value that should be weighed against the cost of such acquisition in light of the perceived probability of catastrophe. However, it likely would be difficult to adjust the pace of actual relocation, and once people were relocated, it would be costly to return them to their former locations if less relocation were found to be sufficient. The circuit-breaker measures would be very flexible; they can be scaled down relatively inexpensively, and for the most part they can be scaled up relatively quickly if at least some minimum level of response capacity is maintained.

4.7 Constructing a Portfolio

A sound *ex ante* policy for addressing the threat of climate change mega-catastrophes will be a portfolio comprised of at least some investment in each of the three response options. A portfolio of responses will be desirable for three reasons. First, there are diminishing marginal returns to expenditures on each of the three options. That is, a marginal increase in reducing the risk of a catastrophe utilizing one of the options becomes increasingly expensive as we do more. Given diminishing returns, for any budget, greater risk reduction can be achieved by allocating some of the budget to all three options.²³ Second, we are uncertain about whether and to what degree each of the three options will actually reduce the risk of a catastrophe. An option may fail to be effective for a variety of reasons: because we have misunderstood the climate system, the technology fails, unforeseen consequences reduce its effectiveness, or because of political impediments. Due to this uncertainty over potential benefits from each option, diversification across all three policies will be preferred by a risk-averse decisionmaker. Finally, a portfolio with some investment in each option will be preferred since the future state of the world is unknown and the three strategies have different strengths of performance across states. For instance, if a particular catastrophe is determined to arise relatively quickly with little to no warning, then dramatic mitigation would be preferred to geoengineering, for which there might be little deployment time.

Investment in an option also includes R&D. There are large option values associated with expanded and accelerated R&D and pilot deployment of low-carbon technologies and geoengineering in the near term. Public-good problems will likely arise in obtaining globally

²³ We exclude the corner-solution case, in which some option is so unattractive that zero should be spent on it before the whole budget is spent on the other two.

optimal R&D investments given inevitable spillovers, and government assistance to help finance start-up efforts will be needed. Similarly, there is a very high option value associated with improved information on the nature of the risks to guide anticipatory adaptation decisions.

The results of the preceding analysis of responses are summarized in Table 1. Massive abatement is highly effective and the most robust option. Depending on what low-carbon technologies are used to achieve reductions in emissions, negative side effects will be minimal (one potential exception being the extent to which wider deployment of nuclear power brings with it other risks). Abatement is, however, not flexible. How costly it is will depend on how rapidly low-carbon energy technologies advance. It will be very costly with today's suite of technologies and those that can be realistically anticipated in the nearer term, but successful initial investments will stimulate further technical advance through learning-by-doing. Drastic GHG abatement will be very difficult to achieve globally, for the well-discussed political economy reasons, at least without a major decline in the cost of low-carbon energy and carbon sequestration. This nearly certain difficulty in adequately abating global emissions is one of the reasons to invest in the other two options as well.

With more research into making geoengineering effective and safe, it could be preferable to drastic abatement and very desirable as a complement to more gradual abatement. Without assurances of efficacy and safety, however, abatement will be preferable. Global cooperation to sustain adequate geoengineering and curb harmful unilateral applications also could prove difficult to maintain. While these features of geoengineering argue strongly against a commitment to its near-term deployment, research on geoengineering is an essential part of an initial portfolio for catastrophe risk mitigation. If research yields favorable results, geoengineering could prove to be an important breakthrough for dealing with climate change. Even if research can only partly resolve concerns about side effects, however, geoengineering may still be an unappealing but necessary safety valve should international mitigation efforts prove insufficient or a climate catastrophe becomes imminent. Research could also discover side effects that are too great to make geoengineering worthwhile, allowing policymakers to focus resources elsewhere.

Table 1: Summary of Response Options

	Abatement	Geoengineering*	Adaptation
Efficacy	Stabilization at 450 ppmv likely effective in reducing risk of crossing thresholds; stabilization at 550 ppmv somewhat less effective Less effective for mitigating cascading catastrophes	Effectiveness dependent on developing reliable and safe methods with limited side effects, but high in that case Could be more effective for more localized applications to mitigate cascading catastrophes, if adequately controllable	Efficacy varies by adaptation strategy, but large land set-asides and gradual relocation likely effective Improved contingency planning could have large benefits for addressing cascading catastrophes
Cost	Potentially very costly, depending on state of technology; option value associated with near-term R&D to lower cost	Potential for modest direct costs, but negative side effects could be large and R&D costs for safe and effective system remain uncertain	Costs of contingency planning will be small; other adaptations likely to have high opportunity costs; regulation limiting development in at-risk areas now will reduce cost of later responses
Robustness	Highly robust	Highly robust under good conditions; risk of lost robustness if misapplied or if other risks are aggravated	Structural measures need not be robust; relocation and contingency planning will be more so
Flexibility	Not flexible	Flexibility in rate of use, but bigger concern is lack of downward flexibility once applied (climate “rebound”)	Circuit-breaker measures are flexible, others only modestly so

*Comments here apply primarily to use of sulfate particles for solar reflection.

Circuit-breaker adaptation options appear affordable, robust, flexible, and at least partly effective, suggesting initial investments to strengthen the availability of such options are strongly warranted. Because there is a positive externality associated with each country’s adoption of circuit-breaker adaptations, some under provision is to be expected. For global catastrophes, more drastic adaptation measures, such as relocation of populations and structural measures, would be very costly and fairly nonrobust. They would also require international coordination and aid to developing countries. It is thus not possible to make a case for such measures until more is known about the nature of the potential catastrophe risks, including their timing, and until more is known about the potential efficacy of the other two options. Changes in land-use regulation and initial acquisitions of set-aside lands should be part of an initial portfolio of relatively low-cost adaptation responses.

The arguments above, combined with our previous review of what is known about catastrophe risks, lead us to conclude that none of the three types of response options should be immediately undertaken full-bore. What should be immediately and aggressively undertaken is,

first, a major increase in the kind of research and applied technology development highlighted in our comments about option values. Deep cuts in global GHG emissions will be very difficult to accomplish for both economic and political reasons without significant progress in low-cost energy options, improved land-use practices, and carbon sequestration. It is difficult to see geoengineering going anywhere, except perhaps as a last-ditch measure, without major efforts to better understand its capacities and risks in actual use. Most of all, it is virtually impossible to imagine concerted worldwide efforts to relocate vulnerable populations and protect natural habitats until the need is more clearly established for such stringent measures.

The other opportunity to be exploited more intensively in the near term is mitigation and adaptation with significant co-benefits—lower energy costs, less conventional pollution, improved livelihoods, and greater resilience to current shocks in the system. This statement is made so often that it seriously risks becoming a bromide. Yet it continues to be repeated in part because progress on this front is so limited. This curious lack of progress points to the need for a much better understanding of the behavioral and institutional constraints that must lie behind our failure to pursue seemingly obvious self-interested actions.

Determining particular initial investment levels in such a portfolio of response options will require policymakers to make subjective judgments regarding each of our three evaluation criteria: how effective different investments may be to reduce climate change catastrophe risks to an acceptable level under different assumptions about those risks; the potential costs of developing different options; and the degree of potential negative side effects. Experts currently disagree about the answers to these questions. For example, proponents of geoengineering believe the costs will be low and the efficacy high, whereas proponents of drastic mitigation believe once we start investing in low-carbon technologies, costs will fall and efficacy will be high. While there will be a potentially wide distribution of expert assessments with respect to these factors, decisionmakers should form their judgments by taking into account the whole range of expert judgments rather than being risk averse by putting more emphasis on the negative possibilities. A structured approach based on a range of expert judgments likely will be preferable to having decisionmakers make uninformed ad hoc subjective assessments or being swayed by those who are most vocal in expressing their views.

Initial levels of investment also will need to be adjusted over time in response to learning about these many uncertainties. Investments will also change, in some cases more problematically, due to behavioral propensities in the face of experience. For example, if the risks of geoengineering become “available” (as in the availability heuristic discussed in Section 3) through a field experiment gone wrong, investment levels in geoengineering may plummet

much more than they should. Similarly, because errors of omission are preferred to errors of commission, there will be reluctance to invest in geoengineering if there is a “salient” risk of negative consequences, even if the anticipated net benefits otherwise are seen to be strongly positive. But if not investing is a larger risk, due for example to a sharp increase in the threat of a climate change catastrophe, this reluctance will need to be confronted.

5. Concluding Remarks

Dealing with catastrophic climate change is an effort in reducing probabilities. There are obviously no guaranteed results, even if we plan carefully. Two major challenges will be (1) to choose sensible policies despite an array of behavioral propensities that afflict us when we confront risks characterized by great uncertainties and low probabilities and (2) to secure effective international cooperation on expenditures to provide the public good of reducing climate change catastrophe risk.

Despite these challenges, we stress that perfection should not be the enemy of improvement. Even in the most optimistic scenario for action, a positive probability of catastrophe will remain. Citizens and policymakers will have to actively try to overcome the common bias toward undervaluing risk reductions if they do not eliminate the threat. Reducing the risk by a fraction of its value could be hugely beneficial in expected value terms.

As scholars have remarked about international cooperation on climate change, sometimes it is most important to take a first step than to take the optimal first step. We thus recommend the implementation of an initial investment portfolio for addressing this risk, with the full understanding that it will need to be adjusted over time. Given the many uncertainties, initial investments in each area—particularly research that strengthens our ability to more effectively use various options—should pay large dividends.

References

- Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit and K. Takahashi. 2007. Assessment of Adaptation Practices, Options, Constraints and Capacity. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson. Cambridge, UK: Cambridge University Press, 717–743.
- Alley, R.B., J. Marotzke, W.D. Nordhaus, J.T. Overpeck, D.M. Peteet, R.A. Pielke Jr., R.T. Pierrehumbert, P.B. Rhines, T.F. Stocker, L.D. Talley, and J.M. Wallace. 2003. Abrupt Climate Change. *Science* 229: 2005–2010.
- Anthoff, D., R.J. Nicholls, R.S.J. Tol and A.T. Vafeidis. 2006. Global and Regional Exposure to Large Rises in Sea Level: A Sensitivity Analysis. Working Paper 96. Norwich, UK: Tyndall Centre for Climate Change Research, University of East Anglia.
- Barrett, S. 2008. The Incredible Economics of Geoengineering. *Journal of Environmental and Resource Economics* 39(1): 45–54.
- Berger, A., C. Kousky, and R. Zeckhauser. 2008. Obstacles to Clear Thinking about Natural Disasters: Five Lessons for Policy. In *House and Home: Disasters, Cities, Public Policy*, edited by J.M. Quigley and L.A. Rosenthal. Berkeley, CA: Berkeley Public Policy Press.
- Brekke, K.A., and O. Johansson-Stenman. 2008. The Behavioural Economics of Climate Change. *Oxford Review of Economic Policy* 24(2): 280–297.
- Bruckner, T., G. Petschel-Held, M. Leimbach, and F.L. Toth. 2003. Methodological Aspects of the Tolerable Windows Approach. *Climatic Change* 56(1–2): 73–88.
- Camerer, C.F., and H. Kunreuther. 1989. Decision Processes for Low Probability Events: Policy Implications. *Journal of Policy Analysis and Management* 8(4): 565–592.
- CNA Corporation. 2007. *National Security and the Threat of Climate Change*. Alexandria, VA: The CNA Corporation.
- Crutzen, P.J. 2006. Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma? *Climatic Change* 77: 211–219.

- Dakos, V., M. Scheffer, E.H. van Nes, V. Brovkin, V. Petoukhov, and H. Held. 2008. Slowing Down As an Early Warning Signal for Abrupt Climate Change. *Proceedings of the National Academy of Sciences* 105: 14308–14312.
- Dasgupta, S., B. Laplante, C. Meisner, D. Wheeler, and J. Yan. 2007. The Impact of Sea Level Rise on Developing Countries: A Comparative Analysis. Policy Research Working Paper 4136. Washington, DC: The World Bank.
- Fischlin, A., G.F. Midgley, J.T. Price, R. Leemans, B. Gopal, C. Turley, M.D.A. Rounsevell, O.P. Dube, J. Tarazona, and A.A. Velichko. 2007. Ecosystems, Their Properties, Goods, and Services. In *Climate Change 2007: Impacts, Adaptation and Vulnerability; Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson. Cambridge, UK: Cambridge University Press, 211–272.
- Fisher, B.S., N. Nakicenovic, K. Alfsen, J. Corfee Morlot, F. de la Chesnaye, J.-C. Hourcade, K. Jiang, M. Kainuma, E.L. Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S. Rose, D. van Vuuren, and R. Warren. 2007. Issues Related to Mitigation in the Long-Term Context. In *Climate Change 2007: Mitigation; Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson. Cambridge, UK: Cambridge University Press.
- Hansen, J. 2005. A Slippery Slope: How Much Global Warming Constitutes "Dangerous Anthropogenic Interference"? *Climatic Change* 68: 269–279.
- Henley, J. 2008. The Last Days of Paradise. *The Guardian UK*, November 11. <http://www.zimbio.com/The+Guardian+UK/articles/815/The+last+days+of+paradise> (accessed October 23, 2009).
- Kahneman, D., P. Slovic, and A. Tversky (eds.) 1982. *Judgment under Uncertainty: Heuristics and Biases*. Cambridge, UK: Cambridge University Press.
- Kahneman, D., and A. Tversky. 1979. Prospect Theory: An Analysis of Decision Under Risk. *Econometrica* 47(2): 263–292.
- Davidson, R. Swart, and J. Pan. Cambridge, UK: Cambridge University Press.
- Keith, D.W. 2000. Geoengineering the Climate: History and Prospect. *Annual Review of Energy and the Environment* 25: 245–284.

- Keller, C., M. Siegrist, and H. Gutscher. 2006. The Role of the Affect and Availability Heuristics in Risk Communication. *Risk Analysis* 26(3): 631–639.
- Keller, K., C. Deutsch, M.G. Hall, and D.F. Bradford. 2007. Early Detection of Changes in the North Atlantic Meridional Overturning Circulation: Implications for the Design of Ocean Observation Systems. *Journal of Climate* 20: 145–157.
- Keller, K., and D. McInerney. 2008. The Dynamics of Learning about a Climate Threshold. *Climate Dynamics* 30: 321–332.
- Keller, K., K. Tan, F.M.M. Morel, and D.F. Bradford. 2000. Preserving the Ocean Circulation: Implications for Policy. *Climatic Change* 47: 17–43.
- Klein, R.W. 2005. *A Regulator's Introduction to the Insurance Industry*. Kansas City, MO: National Association of Insurance Commissioners.
- Kousky, C., and R. Cooke. 2009. Climate Change and Risk Management: Challenges for Insurance, Adaptation, and Loss Estimation. RFF Discussion paper 09-03-REV. Washington, DC: Resources for the Future.
- Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen, and I.A. Shiklomanov. 2007. Freshwater Resources and Their Management. In *Climate Change 2007: Impacts, Adaptation and Vulnerability; Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson. Cambridge, UK: Cambridge University Press, 173–210.
- Lagadec, P. 2004. Understanding the French 2003 Heat Wave Experience: Beyond the Heat, A Multi-Layered Challenge. *Journal of Contingencies and Crisis Management* 12(4): 160–169.
- Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber. 2008. Tipping Elements in the Earth's Climate System. *Proceedings of the National Academy of Sciences* 105: 1786–1793.
- Lonsdale, K.G., T.E. Downing, R.J. Nicholls, D. Parker, A.T. Vafeidis, R. Dawson, and J. Hall. 2008. Plausible Responses to the Threat of Rapid Sea-Level Rise in the Thames Estuary. *Climatic Change* 91: 145–169.

- MacCracken, M.C. 2009. Beyond Mitigation: Potential Options for Counter-Balancing the Climatic and Environmental Consequences of the Rising Concentrations of Greenhouse Gases. Policy Research Working Paper 4938. Washington, DC: The World Bank.
- McDonald, J. 2009. China Fights Drought with Chemical Cloud-Seeding. *USA Today*, Feb 8.
- Moss, M., C. Schellhamer, and D.A. Berman. 2009. The Stafford Act and Priorities for Reform. *Journal of Homeland Security and Emergency Management* 6(1): article 13.
- Muir-Wood, R., and P. Grossi. 2008. The Catastrophe Modeling Response to Hurricane Katrina. In *Climate Extremes and Society*, edited by H.F. Diaz and R J. Murnane. Cambridge, UK: Cambridge University Press.
- National Academy of Sciences. 1992. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base*. Washington, DC: National Academy Press.
- Niall, P.A., S. Johnson, and J. Mueller. 2002. Updating the Accounts: Global Mortality of the 1918–1920 “Spanish” Influenza Pandemic. *Bulletin of the History of Medicine* 76: 105–115.
- Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. Hay, R.F. McLean, S. Ragoonaden and C.D. Woodroffe. 2007. Coastal systems and Low-lying Areas. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson. Cambridge, UK: Cambridge University Press, 315-356.
- Nordhaus, W. 2008. *A Question of Balance: Weighing the Options on Global Warming Policies*. New Haven, CT: Yale University Press.
- Nordhaus, W.D. 1994. Expert Opinion on Climatic Change. *American Scientist* 82(1): 45–52.
- O’Neill, B.C., and M. Oppenheimer. 2002. Dangerous Climate Impacts and the Kyoto Protocol. *Science* 296(5575): 1971–1972.
- Peters, D.P.C., R.A. Pielke Sr., B.T. Bestelmeyer, C.D. Allen, S. Munson-McGee, and K.M. Havstad. 2004. Cross-Scale Interactions, Nonlinearities, and Forecasting Catastrophic Events. *Proceedings of the National Academy of Sciences* 101: 15130–15135.
- Posner, R.A. 2005. *Catastrophe: Risk and Response*. New York: Oxford University Press.
- Poumadère, M., C. Mays, S. Le Mer, and R. Blong. 2005. The 2003 Heat Wave in France: Dangerous Climate Change Here and Now. *Risk Analysis* 25(6): 1483–1494.

- Rahmstorf, S. 2007. "A Semi-Empirical Approach to Projecting Future Sea-Level Rise." *Science* 315(5810): 368-370.
- RMS (2005). Hurricane Katrina: Profile of a Super Cat: Lessons and Implications for Catastrophe Risk Management. Newark, California: Risk Management Solutions.
- Russell, C. 2009. First Wave. *Science News* 175(5): 25-29.
- Samuelson, W., and R. Zeckhauser. 1988. Status Quo Bias in Decision Making. *Journal of Risk and Uncertainty* 1: 7–59.
- Scheraga, J.D., and A.E. Grambsch. 1998. Risks, Opportunities, and Adaptation to Climate Change. *Climate Research* 10: 85–95.
- Schiermeier, Q. 2006. Climate Change: A Sea Change. *Nature* 439(7074): 256–260.
- Schneider, S.H. 1996. Geoengineering: Could—Or Should—We Do It? *Climatic Change* 33: 291–302.
- Schneider, S.H., S. Semenov, A. Patwardhan, I. Burton, C.H.D. Magadza, M. Oppenheimer, A. B. Pittock, A. Rahman, J.B. Smith, A. Suarez, and F. Yamin. 2007. Assessing Key Vulnerabilities and the Risk from Climate Change. In *Climate Change 2007: Impacts, Adaptation and Vulnerability; Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson. Cambridge, UK: Cambridge University Press.
- Scholze, M., W. Knorr, N.W. Arnell, and I.C. Prentice. 2006. A Climate-Change Risk Analysis for World Ecosystems. *Proceedings of the National Academy of Sciences* 103: 13116–13120.
- Simon, H.A. 1957. *Models of Man*. New York: John Wiley & Sons, Inc.
- . 1955. A Behavioral Model of Rational Choice. *The Quarterly Journal of Economics* 69: 99–118.
- Slovic, P., B. Fischhoff, and S. Lichtenstein. 1982. Why Study Risk Perception? *Risk Analysis* 2(2): 83–93.
- Small, C., and R.J. Nicholls. 2003. A Global Analysis of Human Settlement in Coastal Zones. *Journal of Coastal Research* 19(3): 584–599.
- Smith, J. B. 1997. Setting Priorities for Adapting to Climate Change. *Global Environmental Change* 7(3): 251-265.

- Smith, J.B., S.H. Schneider, M. Oppenheimer, G.W. Yohe, W. Hare, M.D. Mastrandrea, A. Patwardhan, I. Burton, J. Corfee Morlot, C.H.D. Magadza, F. Hans-Martin, A.B. Pittock, A. Rahman, A. Suarez, and J.-P. van Ypersele. 2009. Assessing Dangerous Climate Change through an Update of the Intergovernmental Panel on Climate Change (IPCC) "Reasons for Concern." *Proceedings of the National Academy of Sciences* 106: 4133–4137.
- Stern, T., and U.M. Persson. 2008. An Even Stern Review: Introducing Relative Prices into the Discounting Debate. *Review of Environmental Economics and Policy* 2(1): 61–76.
- Summers, L., and R. Zeckhauser. 2008. Policymaking for Posterity. *Journal of Risk and Uncertainty* 37(2): 115–140.
- Sunstein, C.R. 2002. Probability Neglect: Emotions, Worst Cases, and Law. *The Yale Law Journal* 112(1): 61–107.
- Sunstein, C.R., and R. Zeckhauser. 2009. Overreaction to Fearsome Risks. John F. Kennedy School of Government Faculty Research Working Paper No. RWP08-079. Cambridge, MA: Harvard University.
- Taleb, N.N. 2007. *The Black Swan: The Impact of the Highly Improbable*. New York: Random House.
- Thaler, R.H. 1988. Anomalies: The Ultimatum Game. *Journal of Economic Perspectives* 2(4): 195–206.
- Thomas, C.D., A. Cameron, R.E. Green, M. Bakkenes, L.J. Beaumont, Y.C. Collingham, B.F.N. Erasmus, M.F. de Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A.S. van Jaarsveld, G.F. Midgley, L. Miles, M.A. Ortega-Huerta, A. Townsend Peterson, O.L. Phillips, and S.E. Williams. 2004. Extinction Risk from Climate Change. *Nature* 427(6970): 145–148.
- Tobin, G.A. 1995. The Levee Love Affair: A Stormy Relationship. *Water Resources Bulletin* 31(3): 359–367.
- Tol, R.S.J., M. Bohn, T.E. Downing, M.-L. Guillerminet, E. Hitznyik, R. Kaspersen, K. Lonsdale, C. Mays, R.J. Nicholls, A.A. Olsthoorn, G. Pfeifle, M. Poumadere, F.L. Toth, A. Vafeidis, P.E. van der Werff, and I.H. Yetkiner. 2006. Adaptation to Five Metres of Sea Level Rise. *Journal of Risk Research* 9(5): 467–482.

- Tversky, A., and D. Kahneman. 1973. Availability: A Heuristic for Judging Frequency and Probability. *Cognitive Psychology* 5: 207–232.
- Tversky, A., and D. Kahneman. 1974. Judgment under Uncertainty: Heuristics and Biases. *Science* 185(4157): 1124–1131.
- Tversky, A., and D. Kahneman. 1981. The Framing of Decisions and the Psychology of Choice. *Science* 211: 453–458.
- van den Bergh, J.C.J.M. 2004. Optimal Climate Policy Is a Utopia: From Quantitative to Qualitative Cost–Benefit Analysis. *Ecological Economics* 48: 385–393.
- Vellinga, M., and R.A. Wood. 2008. Impacts of Thermohaline Circulation Shutdown in the Twenty-first Century. *Climatic Change* 91: 43–63.
- Weitzman, M.L. 2007. A Review of the Stern Review on the Economics of Climate Change. *Journal of Economic Literature* 45: 703–724.
- Yohe, G.W., R.D. Lasco, Q.K. Ahmad, N.W. Arnell, S.J. Cohen, C. Hope, A.C. Janetos, and R.T. Perez. 2007. Perspectives on Climate Change and Sustainability. In *Climate Change 2007: Impacts, Adaptation and Vulnerability; Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson. Cambridge, UK: Cambridge University Press.
- Zeckhauser, R.J. 1991. The Strategy of Choice. In *Strategy and Choice*, edited by R.J. Zeckhauser. Cambridge, MA: Massachusetts Institute of Technology, 1–24.
- Zeckhauser, R.J., and W.K. Viscusi. 1990. Risk within Reason. *Science* 248(4955): 559–564.
- Zhang, D.D., P. Brecke, H.F. Lee, Y.-Q. He, and J. Zhang. 2007. Global Climate Change, War, and Population Decline in Recent Human History. *Proceedings of the National Academy of Sciences* 104: 19214–19219.
- Zickfeld, K., and T. Bruckner. 2003. Reducing the Risk of Abrupt Climate Change: Emissions Corridors Preserving the Atlantic Thermohaline Circulation. *Integrated Assessment* 4(2): 106–115.