INCORPORATING CATASTROPHES INTO INTEGRATED ASSESSMENT: SCIENCE, IMPACTS, AND ADAPTATION

EVELYN L. WRIGHT and JON D. ERICKSON
[1]*U.S. Environmental Protection Agency, National Risk Management Research Laboratory,*
Mail Drop E-305-02, Research Triangle Park, NC 27711, U.S.A.
E-mail: evelynwright@mindspring.com
[2]*School of Natural Resources, 344 Aiken Center, University of Vermont, Burlington,*
VT 05405, U.S.A.
E-mail: jdericks@zoo.uvm.edu

Abstract. Incorporating potential catastrophic consequences into integrated assessment models of climate change has been a top priority of policymakers and modelers alike. We review the current state of scientific understanding regarding three frequently mentioned geophysical catastrophes, with a view toward their implications for integrated assessment modeling. This review finds inadequacies in widespread model assumptions regarding the nature of catastrophes themselves and climate change impacts more generally. The possibility of greatly postponed consequences from near- and medium-term actions suggests that standard discounting practices are inappropriate for the analysis of climate catastrophe. Careful consideration of paleoclimate and geophysical modeling evidence regarding the possibility of changes in ocean circulation suggests a reframing of the source of climate change damages in economic models, placing changes in climate predictability, rather than gradual changes in mean values, at the focus of economic damage assessments. The implications of decreases in predictability for the modeling of adaptation are further discussed.

1. Introduction

Integrated assessment (IA) modeling has been a primary tool used to estimate quantitatively the optimal level of greenhouse gas (GHG) mitigation. Many IA models seek to balance emissions reduction costs against avoided damage benefits to calculate optimal emissions trajectories and associated policy instruments such as carbon taxes. These have been denoted ‘policy optimization models’, distinct from more complex ‘policy evaluation models’ that produce a wider range of outputs that can be prioritized by the user (Kolstad, 1998). In general, IA policy optimization models consist of a simple climate model coupled – via production-dependent emissions, climate-change-induced damages, and emissions reduction cost functions – to an optimal growth model of the economy.

The conclusion emerging from these high-profile models is that economic efficiency considerations justify no more than very minor emissions reductions. Using his pioneering Dynamic Integrated model of Climate and the Economy (DICE), Nordhaus (1992, 1994b) found optimal near-term emissions reductions of 9% from a steadily rising unregulated baseline, gradually increasing to 15% by the end of the

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21st century. Peck and Teisberg (1992) found that the optimal emissions pathway in their Carbon Emissions Trajectory Assessment (CETA) model scarcely diverged from business as usual until the middle of this century, and then did so only if a nonlinear damage function was used. Similarly, Manne et al. (1995) found that only very small carbon taxes were justified on cost-benefit grounds in their Model for Evaluating Regional and Global Effects (MERGE) of GHG reduction policies.

These remarkably consistent results have been regarded by many economists (but by no means all; see, e.g., Bruckner et al., 1999; Chapman and Khanna, 2000) as a robust answer to the optimal mitigation level problem. In its Second Assessment Report, Working Group II of the IPCC (1996b) noted, 'A number of analysts have suggested that the results from these deterministic analyses provide a useful benchmark for near-term decision making'. More recently, IA modeler Charles Kolstad (1998) concluded, 'Considering the relatively short history of integrated assessment of climate, a surprising amount of knowledge has emerged. Probably the most striking result is that our current understanding of the damage of climate change does not justify more than modest emissions control'.

Despite these exuberant early assessments, it has been widely recognized that these models represent only a first, broad-brush pass at the problem of policy optimization. The recent IPCC Third Assessment Report (TAR) sought to cover a broader range of climate-related issues and decision analytical frameworks beyond the cost-benefit analysis of optimal mitigation levels, focusing particular attention on uncertainties and the need to incorporate them into decision analysis (IPCC, 2001b,c). One issue that consistently makes analysts' short lists for model improvement is the problem of how to include potential catastrophic consequences, or 'surprises' in the analysis (for example Azar, 1998; Kolstad, 1998; Toman, 1998). Several IA studies that have attempted to include catastrophic damages have found that they can indeed have a substantial impact on the optimal emissions path (Fankhauser, 1995; Gjerde et al., 1999; Roughgarden and Schneider, 1999).

However, these studies have modeled catastrophes as primarily economic events, reflected in the models' damage and/or utility functions and abstracted from the physical world. Modelers appear to be uncertain about how to incorporate presently available physical science into the IA framework. For example, in his call for better incorporation of catastrophes, Kolstad (1998) said, 'Currently there is little appreciation for what kinds of cataclysmic events might occur. Identifying such events is not in the domain of integrated assessment. After catastrophes have been characterized, IA can incorporate such extreme events in the models'.

This paper seeks to help bridge the gap between natural scientists and economic modelers by examining the implications for IA modeling of the current state of scientific understanding of the most widely discussed catastrophe scenarios. In the following section we examine the assumed profile of climate change impacts, both ordinary and catastrophic, that emerges from a review of the integrated assessment policy optimization literature. Section 3 offers a review of the scientific literature concerning three geophysical climate catastrophe scenarios and discusses the findings most significant for economic modelers. Due to the widespread interest in and potential importance of the possibility of changes in global-scale ocean circulation, special attention is devoted to making the history of hypotheses and evidence concerning this scenario accessible to nonspecialists. Section 4 examines the implications of this review for damage assessment and economic modeling, and Section 5 concludes.

2. Assumptions

Simplifying assumptions are necessary for any modeling exercise. In particular, for policy optimization models that seek to balance the costs and benefits of GHG mitigation, simplifying assumptions are necessary to represent the impact of GHGs on climate and translate these into an aggregate, monetized measure of damages to be compared against an aggregate mitigation cost. Clearly it would be infeasible to fully couple a general circulation model to an economy model, and impossible to model the impacts of climate change on every economic agent. However, it is important to ensure that assumptions support, rather than interfere with, an understanding of the underlying phenomena and do not systematically neglect significant features of the modeled systems. This section examines assumptions that have commonly been used to represent climate change impacts in cost-benefit policy optimization models.

2.1. THE TRANSLATED CLIMATE

While there have been numerous variations and sensitivity analyses, most IA policy optimization models have taken very similar approaches to modeling climate change impacts. In most cases, global mean temperature has been used as a single statistic to capture policy-relevant impacts. Temperature has universally been modeled as a well-behaved, gradually and monotonically increasing function of atmospheric GHG concentrations, with the coefficient of dependence frequently subject to stochastic treatment or other sensitivity analysis. With the exception of some of the catastrophe-oriented studies discussed in the next subsection, economic damages have, in turn, been represented by a continuous, monotonic function of mean temperature or, occasionally (e.g., Peck and Teisberg, 1994), of the rate of change of mean temperature.

This characterization amounts to the assumption that climate change will result in a simple sliding, or translation, of just one of the probability distributions describing climate. Changes to the shape of the temperature distribution, or its variability in space and time, are excluded, as are changes to distributions describing any other climate parameters.

This characterization appears to have arisen from the 1989 U.S. Environmental Protection Agency (EPA) impact assessment (Smith and Tirpak, 1989), from which the majority of policy optimization model damage functions have been derived. This pioneering study produced a primarily qualitative sector-by-sector evaluation of the impacts on the U.S. economy from a carbon dioxide (CO_2)-equivalent doubling. IA modelers have quantified and aggregated these impacts and constructed continuous damage functions that pass through this single point on a damage/concentration plot.

The most recent U.S. impact assessment (Mendelsohn and Neumann, 1999) retained the translated climate approach for the majority of sectors analyzed, examining CO_2 doubling scenarios involving geographically homogeneous changes in mean temperature and precipitation. Two sectors – timber and sea level rise – were assessed using 'translating' climate scenarios, characterized by smooth increases in temperature and precipitation, and sea level, respectively. Both the U.S. EPA and Mendelsohn assessments included separate analyses of the impacts of climate variability, primarily on the agricultural sector, but these were not integrated into the main body of the assessments. As the IPCC Working Group II concluded, 'Unfortunately, most of the vulnerability assessment literature still is focusing on a smooth transition from what is assumed to be an equilibrium climate toward another equilibrium climate (often $1 \times CO_2$ to $2 \times CO_2$). This means that most impact assessments still implicitly assume that climate change basically is a "well behaved" process' (IPCC, 2001b, p. 946).

IA modelers do recognize that, in the physical world, the impacts of climate change will be felt through events caused by changes in a number of climate variables, including precipitation, storminess, drought, and temperature extremes, along with changes in patterns of variability and the resulting effects on ecosystems. However, calls to incorporate these other climate dimensions into damage functions (e.g., Tol, 1995) appear to have gone largely unheeded, perhaps because of the great uncertainty surrounding these effects. The widespread reliance on global mean temperature as a 'sufficient statistic' (Nordhaus, 1994b) for the purposes of policy optimization modeling has contributed to an overly simplistic picture of a changed climate as 'the same, only warmer'.

2.2. CHARACTERIZING CATASTROPHE

The reliance on monotonic, deterministic temperature and damage trajectories has made it difficult to incorporate impacts not captured in the extrapolation from CO_2 doubling studies. Such impacts have been lumped under the catchall terms 'catastrophe' or 'surprises'. As these terms have been used, they include changes to the climate, atmospheric composition, or geophysical earth system that are sufficient to have significant global impacts. Events more limited in geographic scope – such as the displacement of communities through sea level rise – have not been included in these terms, although they may well be experienced as 'catastrophic' by those affected. The distributional issues raised by such possibilities represent another key area that IA policy optimization models have so far been ill equipped to address.

Examination of the many commentaries that have called for better incorporation of these events and some exploratory modeling exercises reveals several key assumptions about the nature of these events and their place in policy analysis.

2.2.1. *As Low Probability, High Impact Events*

Catastrophic events have been consistently characterized as very unlikely, very high damage events (e.g., Azar, 1998; MacIver, 1998; Toman, 1998). Such a characterization also appears to be implicit in the use of the term 'surprise'. This characterization has been adopted by several IA policy optimization studies seeking to address the possibility of catastrophe. Large damages have been variously represented by highly nonlinear damage functions (Nordhaus, 1994b; Peck and Teisberg, 1992) and by a precipitous drop in utility levels (Gjerde et al., 1999). By far the most common representation has been through very long right-hand tails in damage probability distributions. Probability estimations were either constructed *ad hoc* (Chao, 1995; Fankhauser, 1994, 1995; Tol, 1995) or drawn from Nordhaus's (1994a) expert opinion poll (Gjerde et al., 1999; Roughgarden and Schneider, 1999; Nordhaus and Boyer, 2000).

Under such a characterization, the crucial determination for the policy analyst is the speed with which probability goes to zero as damages approach infinity. Because only the product of probability and damages appears in an expected value calculation, if the probability approaches zero sufficiently quickly, the high damage limit will contribute nothing to the calculation. The decision to include or exclude low probability, high damage events amounts to a judgment about how quickly probabilities fall off as damages increase. Many IA modelers appear to have indeed assumed that these probabilities are sufficiently low to allow these events to be neglected completely. However, the review of the scientific literature in Section 3 indicates that this characterization is more appropriate for some geophysical catastrophe scenarios than others. As Azar (1998) has pointed out, 'Such impacts are often omitted from CO_2 optimization models. Unfortunately, this tends to be forgotten when the results of these models are presented, and particular emission scenarios are presented as optimal even if one argument favoring emissions reductions never entered the analysis'.

2.2.2. *As Threshold Phenomena*

Catastrophic consequences have also been characterized as events that might be triggered once a 'safe' level of warming has been surpassed (Lempert et al., 1994; Nordhaus, 1998). A number of IA studies have attempted to include catastrophic impacts by specifying a threshold level of warming beyond which significant changes occur in the physical behavior of the climate system (Lempert et al., 1994) or the magnitude of the damage function (Nordhaus, 1994b; Peck and Teisberg, 1992). These studies have found that such thresholds have only a minor effect on optimal near-term emissions reductions. As Nordhaus explains, 'The reason for the modest controls in early periods is because of the high productivity of capital, which implies that investment to slow climate change should be postponed in favor of investment in conventional capital until the fateful threshold is relatively close'.

However, the ability to postpone investment in mitigation until the last possible moment clearly depends on knowledge of the precise degree of warming necessary to trigger the catastrophe. Assumptions about uncertainty therefore play a key role in the impact of threshold-type catastrophes on optimal emissions reductions. In the case of changes in global ocean circulation, this characterization may have been encouraged by a sensitivity analysis using a simplified atmosphere-ocean circulation model in which various combinations of the level and rate of change of atmospheric GHG concentrations were found to induce shutdown of the model ocean circulation (Stocker and Schmittner, 1997). The threshold behavior produced by this model was adopted wholesale by one IA study that constrained a modified DICE model to maintain the circulation (Keller et al., 2000). While Stocker and Schmittner's simple model displayed regular, repeatable threshold behavior, it is far from clear that the same will be true of the physical climate system.

2.2.3. *As a Readily Resolvable Uncertainty*

Models that treat the possibility of catastrophic change have frequently assumed that the relevant uncertainties will be satisfactorily resolved within the next 1 to 2 decades (e.g., Lempert et al., 1994; Manne, 1995). The distinction between a perfectly foreknown threshold for catastrophic change and an unknown one has a significant effect on the outcome of IA policy optimization studies. Building on the work of Cropper (1976), Gjerde et al. (1999) characterized catastrophic damages using a hazard function, so that the probability of catastrophe occurrence increases with increasing temperature, but a catastrophe is never deterministically foreknown. Using this characterization, they found that the possibility of catastrophe had a greater impact on optimal emissions reductions then the continuous, gradual damages that have been the subject of most IA policy optimization study. Other studies using a stochastic representation of damages that allowed for the possibility of catastrophic impacts found similar increases in optimal emissions control (Fankhauser, 1994, 1995; Roughgarden and Schneider, 1999).

3. Geophysical Catastrophes

While some analysts have pointed out that 'surprises' are by definition unexpected, and should therefore be taken to include classes of events currently undreamt of, most analysts seem to include in this category several possibilities that have been widely discussed in scientific and stakeholder communities, including: a 'runaway greenhouse' driven by positive methane feedbacks, rapid sea level rise from the melting of polar ice sheets, and changes in global-scale ocean circulation (IPCC, 2001b). This section reviews the current state of scientific understanding of these three possibilities and critically examines the usefulness and validity of the above economic modeling assumptions for analyzing these phenomena.

3.1. RUNAWAY GREENHOUSE

It has been estimated that anywhere from several hundred to several thousand times the amount of methane presently in the atmosphere is trapped in sea sediments within the lattice of frozen water molecules. These materials are known variously as clathrates, methane hydrates, or gas hydrates. It is perhaps the sheer size of this reservoir that has given rise to concerns about a runaway positive feedback loop in which anthropogenic warming destabilizes some of these materials, enhancing warming and leading to further destabilization. There are also clathrates within permafrost, at depths of 200 m and more below the surface. These are not expected to be significantly affected by climate change, at least for several centuries, because of the tremendous amount of time needed to melt the layer above them (Kvenvolden, 1999).

The most thorough recent analysis has concluded that, for anthropogenic warming of up to 6 °C, clathrate feedbacks might lead to at most a further 25% increase in warming (Harvey and Huang, 1995). This result hinges on the authors' estimate that 98% of sea sediment clathrates would require an *in situ* warming of greater than 4 °C (corresponding to a significantly greater surface warming) before becoming destabilized. It has also been suggested that much of any methane released would be oxidized to CO_2 and dissolve in the ocean before reaching the surface (Kvenvolden, 1999). Whether this occurs appears to depend on the rates and processes of methane release.

Given this state of scientific knowledge, a *runaway* clathrate-climate feedback can be regarded as a very low probability, high consequence event under the range of warming currently predicted to occur this century (IPCC, 2001a). A significant change in the scientific understanding of the size of this reservoir and/or the conditions for its destabilization would be necessary to change this conclusion. However, the possibility that warming at the upper end of this range could be significantly enhanced by clathrate destabilization should be included in IA models, and possible system behavior beyond 6 °C warming remains unexplored.

3.2. RAPID SEA LEVEL RISE

Concern about rapid sea level rise from ice sheet melting centers primarily on the West Antarctic ice sheet (WAIS). The grounded portion of the WAIS contains 3.8 million km^3 of ice, enough to raise global sea levels by 4–7 m (IPCC, 2001b; Revelle, 1983). Unlike the ice sheets covering east Antarctica and Greenland, the WAIS rests primarily on land below sea level. Surrounding the grounded ice sheet are a number of floating ice shelves, which are trapped by rocks at their edges and fed by ice streams flowing seaward from the ice sheet's center.

This configuration was once thought to be inherently unstable (Weertman, 1974). The floating ice shelves, wedged up against rocks, were believed to 'buttress' the ice sheet. As these melted, the ice sheet was expected to flow outward, lifting and thinning until, when the ice shelves had completely disappeared, most of the ice sheet would be floating. Mercer (1978) suggested that a CO_2 doubling might be enough to initiate this process, which would then proceed rapidly, resulting in full collapse within perhaps a century.

Two developments in the understanding of ice sheet dynamics have made this hyperinstability scenario appear far less likely. First, improved observation and modeling of the flow of the ice streams suggest that these help to stabilize the ice sheet by allowing different parts of it to continually readjust to local changes. Although these dynamics are still poorly understood, most observers no longer consider a sudden, widespread collapse due to hydrostatic instability likely (Bentley, 1997; Oppenheimer, 1998). Second, it is now recognized that, even in the case of hydrostatic instability, there are limits to the rate at which grounded ice can be discharged into the sea. As icebergs calve from the sheet, ocean currents would need to clear them from ice stream outlets in order for upstream ice to continue to flow. These considerations have led to revised WAIS disintegration time estimates of 400–2400 years (Oppenheimer, 1998). Vaughan and Spouge (2002) report the results of a recent Delphi exercise involving 12 experts, which concluded that there was no greater than a 5% probability of rapid sea level rise from WAIS disintegration over the next 200 years, with considerable uncertainty in this estimate.

Although collapse of the WAIS within the usual time horizon of IA models now appears to be a very low probability event, this does not mean that consideration of the WAIS can be excluded from integrated assessment. It remains a possibility (of unknown, rather than low probability) that this century's warming could trigger 4–6 m of sea level rise several centuries from now. The possibility of such deterministic, but greatly postponed, consequences sheds critical light on the problems associated with intergenerational discounting. With any significant positive discount rate, the catastrophic consequences of such significant flooding would be valued at a minuscule amount today. Consideration of this possibility supports recent suggestions that discount rates ought to decline as the time horizon increases (Heal, 1997). This issue is discussed further in Section 4.

3.3. OCEAN CIRCULATION CHANGE

Recently, much of the concern and analysis regarding geophysical climate catastrophes has focused on the possibility of shutdown or disruption of global-scale ocean circulation (e.g., IPCC, 2001b; Nordhaus and Boyer, 2000; Keller et al., 2000). This *thermohaline* circulation (THC) is one of the key elements of the climate system. Its horizontal components are responsible for nearly half of total equatorto-pole heat transport, while its vertical components carry heat, nutrients, and gases, including CO_2, to the ocean depths (IPCC, 1996a,b).

The primary driver of this system is generally believed to be the formation of *deep water* – water that has become cool, salty, and hence dense enough to sink from the ocean's surface layers to its depths – in a small number of narrowly specified areas in the northern North Atlantic (Bigg, 1996). The heat and salt gradients that drive the circulation appear to be maintained, at least in part, by the circulation itself (Warren, 1983). It has been widely suggested that these interconnecting feedback loops may also make the system vulnerable to disruption and to shifts between multiple stable states.

Although Stommel had showed in 1961 that a simple box ocean model of this system had multiple stable states, interest in multiple stable states within the physical ocean blossomed only in the mid 1980s as a possible explanation for the Younger Dryas – a severe, centuries-scale cold snap that interrupted the warming that terminated the last ice age (Anderson, 1997). Broecker and his colleagues (1985, 1988, 1989, 1990) proposed that a sudden increase in freshwater input to the North Atlantic reduced surface water density sufficiently to block deep water formation, halting the circulation and greatly reducing heat flows to the region. The early version of this hypothesis invoked a sudden incursion of meltwater from the Laurentide ice sheet. However, coral reef-based reconstructions of sea level rise during deglaciation failed to support the proposed time profile of this meltwater pulse (Fairbanks, 1989). When evidence of additional oscillations throughout the glacial period were found in Greenland ice cores (Dansgaard et al., 1982, 1989), Broecker et al. (1990) modified their hypothesis, proposing that the North Atlantic and surrounding glacial ice sheets acted as an oscillator, alternately halting the circulation through meltwater-induced freshening and restarting it through excess salt buildup.

A wide variety of modeling studies have since found multiple stable states vulnerable to freshwater perturbation in thermohaline systems. Model results in freshwater perturbation experiments have included a near shutdown of circulation, followed by oscillating recovery (Manabe and Stouffer, 1995, 2000), shifts in the site of deep water formation (Rahmstorf, 1994), and a complex set of hysteresis behavior, bifurcations, and multiple equilibria (Rahmstorf, 1995). Because of these results, most practitioners now conclude that the thermohaline circulation is sensitive to freshwater perturbations and can occupy multiple stable states (Higgins et al., 2001; IPCC, 2001a; Stocker and Marchal, 2000).

Observational evidence has produced a more complex and uncertain picture of circulation behavior through cold/warm period transitions than the freshwater-triggered on/off switch proposed by Broecker et al. Sea sediment core studies using a variety of proxies – including nutrient levels, microorganism remains, radionuclide concentrations, and grain size measurements (Lehman and Keigwin, 1992; McCave et al., 1995; Muscheler et al., 2000; Veum et al., 1992) – suggest an alternation between a weaker and shallower THC during cold periods and a deeper, more vigorous circulation capable of transporting more heat during warm periods (Zahn, 1992). Although this pattern has not been observed at all sites examined (Sarnthein et al., 1994), most researchers now accept a picture of a shallow and weaker vs. deep and strong oscillation in THC behavior (Anderson, 1997).

Many questions remain about the chain of causation linking ocean circulation change and abrupt climate change. First, the well-documented abrupt-onset cold event that occurred early in the present interglacial (Alley et al., 1997) suggests that extensive northern hemisphere ice sheets are not necessary to trigger abrupt change. Second, oscillations apparently corresponding to those seen in North Atlantic climate records have now been observed around the globe: in ice cores from Bolivia and Peru (Thompson et al., 1998), glacier movement patterns in Chile and New Zealand (Lowell et al., 1995), drought records from sub-Saharan Africa (Street-Perrott and Perrott, 1990), lake sediments from California (Benson et al., 1997), and sea sediment cores from the western tropical Atlantic (Hughen et al., 1996), the eastern Pacific, and the Arabian Sea (Boyle, 2000). The apparent global interconnections suggested by these observations have been variously used to support the hypothesis that THC circulation changes caused global climate disruption and to argue that some other mechanism must link these globally dispersed effects (Cane, 1998; Pierrehumbert, 2000; Lowell et al., 1995). The dating in most of these records is not sufficiently precise to reveal the exact order of these events or shed much light on their causes.

Although the role of ocean circulation changes in past climate change cannot be confidently determined at this time, there are two important lessons that economists and policy analysts can take away from this research. First, past climate change, whatever its complex network of causation, was characterized by abrupt transitions between alternative patterns of ocean and atmospheric circulation (Alley, 2000; National Research Council, 2001). Greenland ice core records of the Younger Dryas suggest a 7 °C warming in South Greenland over the course of 50 years, with a change from a dry, cold, stormy climate to a mild, humid, calm one in less than 20 years (Dansgaard et al., 1989). Abrupt changes in concentrations of continental-source and sea salt ions within the cores imply a reorganization of northern hemisphere atmospheric circulation on a scale of 10 to 20 years (Mayewski et al., 1993). Switches between alternative climate states also appear to be accompanied by greatly increased climate variability. Taylor et al. (1993) found that each transition between century-scale cold and warm periods was marked by rapid alternation between dusty and dust-free conditions. As many as four such ‘flickers’, each lasting 5–20 years, accompany each transition, suggesting extremely abrupt, repeated changes in northern hemisphere weather patterns. This picture of climate change is very different from the gentle translation of mean temperature envisioned in IA policy optimization models.

The second major lesson from this research is that significant changes in ocean and/or atmospheric circulation cannot be regarded as an unlikely consequence of anthropogenic warming. Warming in the North Atlantic region is expected to reduce surface water density directly through thermal expansion and indirectly through increased precipitation and meltwater runoff (IPCC, 2001a). With extended anthropogenic warming, these effects may be sufficient to disrupt deep water formation. Virtually every modeling study that has investigated this possibility has found a change in global climate patterns that goes beyond the translated climate assumed in IA studies. Results range from a shutdown of one or both sites of deep water formation (Manabe and Stouffer, 1993, 1994; Wood et al., 1999), to a stabilization of circulation by a significant temperature and precipitation anomaly in the central eastern tropical Pacific, similar to an ongoing El Niño event (Latif et al., 2000). The extent and duration of deep water formation changes have been found to be sensitive to the model's hydrological sensitivity (Rahmstorf and Ganopolski, 1999) and the rate of atmospheric GHG concentration increase (Stocker and Schmittner, 1997). Recent evidence from sea sediment cores suggests that deep water formation did not occur in the Labrador Sea during the last interglacial, which at about 2 °C warmer than present may provide an appropriate analogue for expected medium-term anthropogenic warming (Hillaire–Marcel et al., 2001).

4. Implications for Climate Economics

Examination of these three climate catastrophe scenarios reveals varying degrees of fit with the assumed catastrophe profiles discussed in Section 2. A runaway clathrate feedback scenario can appropriately be viewed as a very low probability/high consequence event, a classic 'surprise' that we would expect to take place only if current scientific understanding were seriously in error. Rapid sea level rise from a collapse of the WAIS, while also appropriately viewed as low probability in the near term, may well become likely in the very long-term (4–6 centuries) even when forced with only this century's warming. The low probability/high consequence profile is even more inappropriate for changes in ocean circulation, which must be regarded as a likely outcome of sustained anthropogenic warming. These latter two catastrophe scenarios raise additional questions and problems for climate economics in three areas: discounting, damage assessment, and adaptation.

4.1. DISCOUNTING

The choice of discount rate is one of the most controversial issues in climate policy analysis. Many policy optimization studies have found that small changes in the discount rate can lead to large changes in optimal policy (e.g., Gjerde et al., 1999; Mastrandrea and Schneider, 2001). In the economic growth model formulation used in IA policy optimization models, the real discount rate is given by the formula $r = \rho + ag$, where ρ is the pure rate of time preference, a is the absolute value of the elasticity of the marginal utility of consumption, and g is the rate of growth of consumption. Many authors have suggested that, on ethical grounds, ρ or even r should be low or zero for problems of such a long time horizon as climate change. Others have insisted that the choice of discount rate is an empirical matter that must be based on observations of actual rates of return in order for investments in climate change mitigation to be treated consistently with other investments (IPCC, 1996c; Lind and Schuler, 1998). The possibility of greatly postponed, high damage consequences arising from near- and medium-term activities – for example, in the case of disintegration of the WAIS – throws these issues into sharp relief.

Explaining the empirical school of thought, Nordhaus argues that 'it is essential that the discount be based on *actual* behavior and returns on assets rather than on a *hypothetical* view of how societies should behave or an idealized philosophy about treatment of future generations' (Nordhaus, 1994b, p. 125, original italics). But observed rates of return reflect expectations of economic growth and return on investments over a relatively short time horizon, generally within the current generation or the immediate succeeding one, rather than judgments about potential catastrophes over a horizon of several centuries. It is far from clear therefore that these observations are applicable to the case of catastrophic climate change. Indeed, because the time frame of climate change and climate catastrophe is so much longer than that of market behavior, people's philosophical beliefs about the treatment of future generations may be one of the few appropriate sources of empirical evidence available. Paul Portney's (1998) suggestion of a 'referendum' or contingent valuation exercise on climate change might help to provide more applicable data.

Returning to the optimal growth formula, the possibility of catastrophic consequences raises another argument for low discount rates. In most IA policy optimization formulations, g is taken to be positive, although frequently declining, throughout the model horizon. The possibility of a climate catastrophe sufficient to significantly decrease consumption – as has been assumed in several IA catastrophe analyses (Chao, 1995; Gjerde et al., 1999; Mastrandrea and Schneider, 2001) – suggests that future values of g may at some point turn zero or negative, leading to a low or negative discount rate. As Weitzman (1998) has shown, under uncertainty about the far-distant-future discount rate, low values of the discount rate have the greatest impact on the expected difference between present values of benefits and costs, implying that the lowest possible (nonnegative) rate should be used to discount the far distant future.

4.2. DAMAGE ASSESSMENT

The recognition that changes in ocean and/or atmospheric circulation are a likely, rather than unlikely, consequence of anthropogenic warming implies that this possibility must be fully incorporated into damage and policy assessments, rather than treated as an add-on that is unlikely to alter policy recommendations. Recent attempts to include simple models of ocean circulation dynamics and associated damages into policy optimization models represent one approach to this problem. Mastrandrea and Schneider (2001) integrated a simple ocean circulation model into a version of DICE enhanced to include parameterized damages from ocean circulation change. They found that inclusion of these damages substantially increased optimal carbon taxes and emission control rates. Interestingly, only when the model was run with a discount rate below a certain threshold were optimal carbon taxes sufficiently high to prevent THC collapse.

As the authors readily admit, in order for this approach to be truly informative, a better understanding of the consequences of ocean circulation change and the economic impacts of these consequences will need to be developed. Impacts on North Atlantic fisheries, on Northwestern European agriculture, human health, and amenity, and on ocean uptake of CO_2 are among those frequently mentioned (Keller et al., 2000). However, model- and paleoclimate reconstruction-derived understanding of the consequences of ocean circulation change is still insufficient to guide a sector-by-sector damage assessment. Although many authors have suggested that a THC shutdown could lead to as much as a 10 °C cooling in northwestern Europe, in analogy with the Younger Dryas cold snap, it remains unclear how much *net* cooling this region would suffer. The northern latitudes would likely have experienced several degrees of warming by that time, making the Younger Dryas, with its relatively cool onset conditions, a poor analogy. In addition, the emerging global profile of THC-associated climate oscillations and the possibility of climate ‘flickering’ suggests that a focus solely on North Atlantic cooling and carbon pumping may miss significant impacts in other regions.

Recognizing these difficulties, Keller et al. (2000) pursue the inverse approach. They subject DICE to the additional constraint that the THC must be maintained and estimate the magnitude of THC shutdown damages that would be needed to make such a constraint efficient in a cost-benefit sense. The value they obtain is surprisingly low: roughly 0.86% of gross world product, assuming a climate sensitivity of 3.5 °C and a pure rate of social time preference of 3%. Further development of this approach may provide a helpful guide in the difficult task of assessing ocean circulation change-related damages.

However, consideration of two additional aspects of the standard catastrophe profile – threshold and uncertainty – reveals a more serious difficulty for attempts to integrate ocean circulation dynamics into standard policy optimization models. Like other IA policy optimization models, Mastrandrea and Schneider’s and Keller et al.’s enhanced DICE models are characterized by perfect foresight, with changes in ocean circulation occurring at a time completely determined by the time profile of emissions, climate sensitivity, and other model parameters. In the physical climate system, perfect knowledge about the location of such thresholds and the impacts of surpassing them is unlikely to be obtained. Even when scientific uncertainty about the drivers of abrupt climate change is resolved, another *inherent* uncertainty will remain due to the sensitive dependence on initial conditions that arises in complex, nonlinear systems. Indeed, many of the models that have been used to study the circulation themselves show sensitive dependence on initial conditions. In one such model, random perturbations of the wind field, intended to represent different weather realizations within the same climate, led to collapse times that varied by 250 years in response to identical freshwater forcing (Marotzke, 2000).

Instead, recognition that abrupt changes between alternative stable modes of ocean and/or atmospheric circulation are a predominant mode of climate change, and that the conditions that would trigger such a change may well remain impossible to specify, suggests that the deterministic behavior of modeled impacts in IA studies fails to capture a significant source of climate change damages: those arising from the loss of climate predictability. The ability to form reliable expectations about upcoming climate is presently an unvalued asset, precisely because no one has ever considered losing it. However, it is predictability that allows much of an industrial economy to be insulated from weather-related impacts, through appropriate infrastructure and well-calculated hedges against risks. An insurance company may be able to diversify risk in the face of a known probability distribution for hurricanes, and a farmer may be able to adjust crop varieties and techniques to respond to known changes in weather conditions. However, both may have difficulty making these same adjustments when confronted by an unknown shift in the relevant distributions (Reilly, 1998).

Including damages from lost predictability will not be as simple as adding an additional damage parameter to an otherwise unchanged policy optimization model. Deterministic, perfect foresight characterizations of predictability loss are clearly nonsensical. Instead, it appears that an estimation of damages from lost predictability must be made outside the IA framework and parameterized as a stochastic source of damages. One approach would be to attempt to gauge the value of climate predictability in the present economy, perhaps by adapting the ‘natural climate experiment’ method of Mendelsohn and Neumann (1999) to compare regions of high and low predictability, or by estimating the value of present efforts to collect and interpret information on weather statistics. It may also be possible to regard damages from recent weather events as failures of current predictability, since climate predictability is presently far from perfect. Further development of stochastic methods to represent catastrophic change will be needed to integrate such damages into IA models. The inherent uncertainty involved in characterizing abrupt climate change and predictability loss may also further encourage efforts to explore decision analysis frameworks that move beyond cost-benefit analysis and focus on discovering cost effective, tolerable, and/or robust policies, rather than seeking to prescribe optimal ones (IPCC, 2001c).

4.3. ADAPTATION

Perhaps the most significant impact of decreased predictability is the potential to seriously hamper adaptation efforts, which have been advocated as a strategy to avoid costly mitigation (Kane and Shogren, 2000; Yohe and Toth, 2000). While early approaches to modeling damages and adaptation were widely criticized for failing to take investors' ability to form expectations into account, recent approaches have replaced this so-called 'stupid farmer' assumption with a 'clairvoyant farmer' characterization (Schneider et al., 2000). In agricultural sector studies finding 10 to 80% damage reductions from adaptation, model investors were allowed perfect information about upcoming weather conditions (Crosson, 1993; Kaiser et al., 1993a,b). Similarly, Mendelsohn and Neumann's (1999) natural climate experiment approach, which attempts to quantify future climate change impacts on one geographic region by examining (well-adapted) economic behavior in a present-day, warmer region, relies on the assumption that climate change will result in no change in predictability. The impact of denying potential adapters foresight can be significant. In detailed site-level analyses of the potential for adaptation to gradual (and hence predictable) sea level rise, Yohe and colleagues (1998, 1999) found that when sea level rise is sufficient to force abandonment of structures, lack of foresight increases costs by up to 40%.

Changes in predictability may impact adaptation through two distinct effects. The first is a learning effect, which arises because expectations can be based only on past observations. When climate changes, previous experience is no longer a reliable guide to future system behavior, and some time must pass to allow a new base of observations to accumulate. These must be sufficient to allow economic agents to determine that whatever deleterious weather- and/or climate-related events they experience represent a true trend and not simply noise. Investigating this problem using a Bayesian learning framework and a simple translating climate scenario, Kelly and Kolstad (1999) found that it would take several decades to resolve uncertainty about the rate at which mean temperature was changing in response to changes in atmospheric GHG concentration.

A second effect arises whenever there are increases in variability, such as could be caused by a shift to a 'flickering regime' similar to those seen in Greenland ice cores. An increased spread of possible values around the mean implies that any individual prediction is less likely to be on the mark, hampering the calculations necessary for well-targeted investment and increasing the degree of risk to be diversified. For example, Fisher and Rubio (1997) found that increases in hydrological variability lead to an increase in the optimal size of water supply infrastructure, so that a wider variety of potential circumstances can be accommodated. Modeling the adaptation decision of an individual investor using an option value framework indicates that increased variability leads to postponed adaptation and increased preadaptation damages (Wright, 2000). Unlike predictability decreases resulting from the learning effect, those arising from increased variability do not decay with time. Instead, they represent an enduring degradation of the information available to climate-sensitive economic agents. These two effects will also intersect, with increased variability meaning that more observations will be necessary to establish a reliable understanding of changed climate distributions. Diminished predictability will clearly impact adaptation in different sectors to different extents. Sectors that are sensitive to variability on a daily-to-yearly scale (e.g., agriculture, water resources) are likely to be more greatly impacted than sectors in which impacts depend on conditions over longer time frames and/or averaged over large spatial scales. Determining these impacts will require a far more careful and detailed approach to the assessment of adaptation potential that clearly identifies what assumptions about predictability are made at which time scales (Reilly and Schimmelpfennig, 2000). Models of adaptation that do not include impacts from predictability change will overestimate the damage reductions to be gained through adaptation and lead to underestimates of climate change damages.

5. Conclusions

Our review of the current state of the science regarding three potential geophysical climate change catastrophes has found that significant changes in the characterization of both catastrophes themselves and climate change impacts more generally are in order for integrated assessment modeling. The possibility of very long-term changes in ice sheets resulting from near-term warming suggests that present discounting practices are inadequate for the aggregation of effects over very long time scales. Instead of a surprising catastrophe, the possibility of changes in ocean circulation may perhaps be better regarded as belonging to a continuum of poorly understood effects at a variety of geographical scales that encompasses changes in the local distribution of storms, droughts, and extreme temperature events; changes in regional scale oscillations, such as El Niño and the North Atlantic Oscillation; and changes in global scale oceanic and atmospheric circulation patterns. Some of these effects may be inherently abrupt and unpredictable, indicating that a significant source of climate change damages has yet to be evaluated. Damages from the loss of predictability and the consequent hampering of adaptation may well exceed those from the translated climate studies that have contributed to the consensus on mitigation arising from the previous generation of IA studies.

Biophysical catastrophes – such as greenhouse gas and climate feedbacks involving terrestrial and ocean biota, biodiversity loss, and local ecosystem change – have not been examined in this work. We think it likely that the themes of poorly understood long-term consequences and compromised predictability would also emerge from an examination of these possibilities, along with, no doubt, additional surprises.

As climatologists move away from a gradualist understanding of climate change (Overpeck and Webb, 2000), so too must climate economists. The assumption, so well expressed by Nordhaus (1994b) that, ‘humans live, move, and die faster than climatic impacts are likely to be noticed’, is untenable for the analysis of sustained anthropogenic warming. Incorporation of the possibility of inherently unpredictable, irregular ‘jumps’ (IPCC, 2001b) presents an important challenge for the next generation of IA models.

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