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Moving Forward with Incorporating "Catastrophic" Climate Change into Policy Analysis

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Abstract

It has often been stated that current studies aimed at understanding the magnitude of optimal climate policy fail to adequately capture the potential for "catastrophic" impacts of climate change. While economic modeling exercises to date do provide evidence that potential climate catastrophes might significantly influence the optimal path of abatement, there is a need to move beyond experiments which are abstracted from important details of the climate problem in order to substantively inform the policy debate.

This paper provides a foundation for improving the economic modeling of potential large scale impacts of climate change in order to understand their influence on estimates of socially efficient climate policy. We begin by considering how the term "catastrophic impacts" has been used in the scientific literature to describe changes in the climate system and carefully review the characteristics of the events that have been discussed in this context. We contrast those findings with a review of the way in which the economic literature has modeled the potential economic and human welfare impacts of events of this nature. We find that the uniform way in which the economic literature has typically modeled such impacts along with the failure to understand differences in the end points and timescales examined by the natural science literature has resulted in the modeling of events that do not resemble those of concern. Based on this finding and our review of the scientific literature we provide a path forward for better incorporating these events into integrated assessment modeling, identifying areas where modeling could be improved even within current modeling frameworks and others where additional work is needed.

Keywords: Climate Change, Catastrophes, Integrated Assessment Model

JEL Codes: Q54, Q58

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1. Introduction

It is common within the academic and public discourse on climate change for the term catastrophe to be invoked when describing the possible outcomes of a changing climate and in justifying particular responses to the problem. In fact it has been suggested that the potential for "catastrophic impacts" as a result of climate change is the most important aspect of the problem for determining the optimal level of response (Pindyck and Wang 2012, Weitzman 2009). Pindyck (2012) goes so far as to argue that "the economic case for a stringent GHG abatement policy, if it is to be made at all, must be based on the possibility of a catastrophic outcome." Thus, it is perhaps not surprising that analyses of greenhouse gas mitigation benefits are often criticized for failing to adequately capture possible catastrophic impacts (e.g., Tol 2009, NAS 2010). Even the U.S. government in its primary work to value the benefits of greenhouse gas abatement notes a lack of accounting for catastrophic impacts as a major caveat that requires their analysis only be considered "provisional" (U.S. Interagency Working Group on Social Cost of Carbon, 2010). However, despite the seeming importance of such potential climate change related events there has been little progress in defensibly integrating catastrophic impacts into analyses considering the benefits of climate policy.

One obstacle that has impeded forward progress on this front is the inconsistent and sometimes nebulous way in which the expression "catastrophic impacts" has been used (Hulme, 2003). The term has been adopted as a catch-all phrase that refers to any climate induced impact that exhibits one or more of a number of characteristics: relatively sudden occurrence, irreversible transition to a new state after crossing a threshold, relatively large physical or economic impacts, or relatively low probability but extensive impacts. For this reason the types of impacts covered under the catastrophic moniker are numerous and heterogeneous. For example, the term climate catastrophe has been used to describe everything from dieback of Amazon rainforests over the coming decades to the potential massive release of methane emissions from the sea floor over the next thousand years (Lenton et al. 2008). Some even have argued for establishing an overall global threshold for climate change, below which we are deemed safe from violating "non-negotiable planetary preconditions… [and] avoid the risk of deleterious or even catastrophic environmental change at continental to global scales" (Rockstrom et al. 2009). The authors acknowledge that determining what is safe is a normative judgment, but link it to the notion that deleterious or catastrophic effects from climate change would occur when Earth systems are pushed out of the Holocene state (a period of relatively stability over the past 10,000 years) (Rockstrom et al. 2009). The ambition of an overall global warming threshold was formally endorsed in the 2009

Copenhagen Accord, in which more than two dozen key countries -- representing more than 80 percent of the world's global warming pollution – agreed to register non-binding national commitments to combat climate change:

> "To achieve the ultimate objective of the Convention to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change" (UNFCCC 2009).

In public discourse catastrophic impacts are often invoked as a seemingly monolithic occurrence[2], a tendency that is also often present in the economic analyses of optimal climate policy conditional on the potential for such events. By assuming uniformity across the multitude of characteristics over which these potential climate "catastrophes" may vary, the economic research on the subject has severely limited its ability to substantively inform policy discussions. In addition, many economic modeling efforts fall substantially short when it comes to incorporating scientific evidence regarding the causes, likelihood, and potential physical impacts of such climate change induced events. The former may arise from an absence of literature that summarizes the significant differences between potential large scale events resulting from climate change and what that means for incorporating them into economic analysis, while the latter appears to be the result of fundamental differences between disciplines as to what constitutes relatively rapid or large changes and the appropriate end points to measure in policy analysis. Both of these concerns have been observed by natural scientists (e.g., Hulme 2003), and calls are increasing across the scientific community for more research on welfare impacts, with better links to the scientific evidence on how physical processes are likely to unfold (e.g., Lenton 2011, Lenton and Ciscar 2012).

In this paper we seek to provide a foundation to help improve the economic modeling of potential large scale impacts of climate change within Earth systems in order to understand their influence on estimates of socially efficient climate policy. We begin by considering how the term "catastrophic impacts" has been used in the scientific literature to describe changes in the climate system and

[2] Examples of such statements include: "We have a window of only 10-15 years to take the steps we need to avoid crossing catastrophic tipping points" (Jan Peter Balkenende & Tony Blair, October 20, 2006), "Until now, leaders have focused on slowing warming to 2 degrees Celsius to prevent catastrophic changes associated with climate change" (MIT News, June 14, 2012), "Even if the ultimate result were an Earth that is still hospitable to mankind, the transition could be catastrophic" (The Economist, June 18, 2012).

carefully review the characteristics of the events that have been discussed in this context. We explore the potential economic and human welfare impacts of such events and contrast those findings with a review of the way in which the economic literature has modeled these events classified as possible climate catastrophes.[3] We find that the relatively uniform way in which the economic literature has typically modeled such impacts along with the failure to understand differences in the end points and timescales examined by the natural science literature have resulted in the modeling of events that do not resemble those of concern in reality. Based on this finding and our review of the scientific literature we suggest a path forward for better incorporating these events into integrated assessment modeling, identifying areas where modeling could be improved even within current IAM frameworks and others where additional work is needed.

2. Catastrophic Impacts from the Scientific Perspective

An often cited technical definition for the term catastrophe is "when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause" (NRC 2002). This characterization captures two of three salient aspects of the typical use of the term catastrophe in the scientific literature. First, the event occurs relatively quickly. Second, it causes a natural system to move to a new steady state. Catastrophes related to climate change have also been termed "surprises" in the scientific literature, which the IPCC (1996) defines as the rapid, non-linear response of a natural system to anthropogenic forcing.[4] This definition highlights a third important aspect of the term catastrophe: it could potentially result in a relatively large impact. In particular, the potential for relatively abrupt shifts in the states of natural systems are a cause for concern due to the "large and widespread consequences" that may result (IPCC 2007) and the possibility that they occur so rapidly that "human and other natural systems have difficulty adapting" (NRC 2002; Posner 2004).

[3] In this paper we focus on the economic study on specific large climate induced Earth system, outside of direct temperature response to anthropogenic emissions. Alternatively, there exists an economic literature that has focused on the policy implications of potentially large welfare impacts associated with a significantly stronger than expected climate response to anthropogenic emissions (e.g., Weitzman, 2011).

[4] The IPCC has also previously used the potentially confusing terminology of "large scale discontinuities" to describe such events. However, we note that the notion of a discontinuity in this case would arise from observing the time path of the system over a long time horizon, and does not refer to a mathematical discontinuity in the state transition dynamics of the system.

Threshold or tipping point behavior

Climate-change related events described in this manner are often associated with crossing a threshold, or "tipping point," in the Earth system. For instance, Perrings (2003) suggests that abrupt climate change due to a relatively small change in forcing is the result of triggering a sudden switch from one stable state to another. In this context Schneider (2003) also notes "anomalies can push the… system from one equilibrium to another." Schlesinger et al. (2007) defines a climate threshold as a point at which a relatively small perturbation in radiative forcing can result in a large, sudden change in the climate system. Kriegler et al (2009) defines a tipping point as one where a large-scale change or discontinuity in the Earth system will occur due to a small change in global mean temperature. Such an abrupt transition of an Earth system from one equilibrium state to another could easily be envisioned as a catastrophic change for that particular system.

Many natural systems exhibit this type of tipping or threshold behavior.[5] For instance, Sheffer et al. (2001) note that a shallow lake with rich vegetation could abruptly change from clear to turbid water (i.e. due to algae bloom) in reaction to increased nutrient loadings. When this occurs, vegetation dies off and the diversity of lake life declines. Alley et al. (2003) use the analogy of a canoe to describe this behavior: A paddler that leans over slightly in a canoe experiences only a small tilt, but if the paddler leans over a bit more the canoe may suddenly roll over, dumping the surprised paddler into the lake. What is common across these abrupt changes in state is that it typically consists of three basic components (NRC 2002): a trigger – in the case of the lake, added nutrients and in the case of the canoe, leaning over; an amplifier – the mechanism through which a small change in the lake or canoe causes a much larger result; and a source of persistence – fish reinforce the turbidity in the lake, while basic physics ensure it is more difficult to flip the canoe back over – making the new state stable and self – reinforcing.

We can similarly characterize many of the Earth systems affected by climate change using these three basic components of threshold or tipping point behavior: trigger, amplifier, and persistence. The National Academy of Science (NRC 2002; Alley et al. 2003) and the Intergovernmental Panel on Climate Change (IPCC 2007a) among many others have suggested that a rise in global mean temperature due to

[5] See Sheffer et al. (2001) for examples of other abrupt ecosystem shifts discussed in the literature. Holling (1973) and May (1977) are two early papers that discuss this phenomenon.

increases in the atmospheric concentration of greenhouse gases from the burning of fossil fuels, deforestation, and other land-use change could trigger changes within an Earth system. Feedback effects within these systems could amplify these changes (e.g., surface melting of an ice sheet can affect the speed of ice flow) leading to even larger impacts, such as the complete collapse of ice sheets, substantial dieback of the Amazon forest, or the thawing of permafrost, to name a few. Finally, the new state may exhibit persistence: the Earth system is described as eventually settling into a new but fundamentally different stable state that is irreversible (e.g. NRC 2002; IPCC 2007) or reversible only over very long time scales (Perrings 2003; Schneider 2003). Our analogy with other natural systems ends here, however. While a lake ecosystem or canoe has a defined and limited set of boundaries that constrains the problem, climate change affects the entire Earth through the coupled system containing the atmosphere, oceans, ice, and biological systems, which increases the analytical challenge associated with understanding the overall impacts of crossing of a given threshold within a particular system.

While much of the focus with regard to climate change has been on events that result from the crossing of a potential threshold in a natural system that leads to a new equilibrium (referred to as bifurcation), Lenton et al. (2008) argue that it is important to consider a broader set of tipping elements in the climate system. They define the term ‘‘tipping element’’ to describe "subsystems of the Earth system that are at least sub-continental in scale and can be switched—under certain circumstances—into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point—in forcing and a feature of the system—at which the future state of the system is qualitatively altered." This characterization would include the typical bifurcation point discussed above along with cases where the system may potentially bounce between states after the threshold is crossed. Therefore, the transition could be irreversible or a phase after which the system returns to its prior state. Lenton et al. (2008) stress that even though some transitions are reversible in principle, they are unlikely to be reversed in practice for many centuries because of the inertia in rising temperatures.

Time scales, geographic breadth, and climate end points

Scientific definitions of what can be considered a catastrophe also encompass a wide range of time scales, geographic breadth, and climate end points. Events within the scientific literature described as resulting in “rapid,” “sudden,” or “abrupt” state change include qualitative Earth system changes that can range in time scale from decades (e.g., NRC 2002; Clark et. al 2002; Alley et al. 2003; USCCSP 2008), to a few centuries (e.g., Shindell 2007), and sometimes even up to millennia (e.g., Lenton et al. 2008).

This variation exists because shifts in biological systems are often considered rapid in relation to the timescale of the previous stable state. For example, the transition in the Earth's biosphere from the last glacial into the present interglacial condition occurred over millennia but this is still less than 5% of the time that the previous state had lasted (Barnosky et al. 2012). The geographic scale of the event's impact may also be regional (e.g., Western Europe in the case of changes in the thermohaline circulation guiding ocean currents), continental (e.g., monsoon season change in Africa), or global (e.g., methane releases from thawing permafrost). Events that scientists classify as abrupt or sudden also vary in the affected physical end points (e.g., temperature, precipitation, storms), and the overall impact will depend on the interaction between all of these characteristics.

Choosing how to define a potentially catastrophic event given this variation has led to multiple methods of ad-hoc classification. Some authors have proposed using geographic scale as the metric. For instance, an event would qualify as a potential catastrophe when it occurs on a country or even continent-wide basis (e.g. NRC 2002; Clark et al. 2002; Lenton et al. 2008; USCCSP 2008). Posner (2004) proposes limiting the definition of a catastrophe to events that are truly global in scale: those that could end advanced civilization as we know it. Others have proposed that the time scale should also be used to classify potentially catastrophic events. Posner (2004) points out that "a span of a million years, let alone of a billion or a trillion, belongs to a timescale that cannot have real meaning for human beings living today." Lenton et al. (2008) proposes a short list of "policy relevant tipping points" based on two time scales: Earth system changes that may be triggered within this century – on the "political time horizon" – and those that would undergo a qualitative change within this millennium – within the "ethical time horizon."

Uncertainty

The scientific literature also has given notable thought to how the level of uncertainty surrounding a particular tipping point might influence its potential classification as a catastrophe. As noted by Alley et al. (2003), there is a high degree of uncertainty inherent in attempting to identify and quantify the causes of abrupt climate change, particularly near thresholds where the behavior of natural systems can become unpredictable. Therefore large error bounds exist around when a catastrophic event might be triggered, in addition to substantial uncertainty about how the transition would occur, and the ultimate impacts associated with them (e.g. Schlesinger et al. 2007; Keller et al. 2008). From a modeling perspective, it is difficult to capture processes that are deeply uncertain and where our understanding of that uncertainty exists with a low level of confidence. Perrings (2003) notes that the nature of the uncertainty will be inherently difficult to characterize in the case of climate change induced catastrophic events when both the full set of possible outcomes in addition to the probability distribution of the outcomes are largely unknown. However, some researchers have attempted to better classify and understand the uncertainties associated with these events (see Lenton et al. (2008), Lenton (2011) for summaries).

Another difficulty in assessing the uncertainty around tipping points is that many aspects of these events will be path dependent such that "the same forcing might produce different responses depending on the pathway followed by the system" (Schneider, 2003). For instance, Schlesinger et al. (2007) indicate that even a "slow, smooth forcing can induce abrupt, persistent changes in the climate system or a 'threshold' response." Shindell (2007) has noted that sudden climate change can occur due to either "rapid changes in the forcings or from the potential for feedbacks to be strong and perhaps nonlinear." Numerous authors note that the forcing that could trigger a large response in the climate system may not by itself be all that notable.[6]

Finally, it is worth noting that the nature of a surprise is that it is unanticipated (Schneider 2003). Schneider argues for differentiating between abrupt events that are imaginable or expected (or at least not unexpected) and those that are "true surprises" where the outcome is unknown. In the former case, even with all the inherent uncertainties discussed above, we may be able to bring modeling expertise to bear with regard to potential impacts. In the latter case, however, it may only be possible to "identify imaginable conditions for surprise" (Schneider 2003). Noting this important caveat we proceed to a discussion of how economists currently define and model catastrophes.

[6] These uncertainties affect the ability to model and predict Earth system behavior. Overpeck and Cole (2006) note that "the biggest obstacle to reliable abrupt climate change prediction is the limited state of our coupled atmosphere-ocean and ice sheet modeling capability….A major challenge to the scientific community is to build models that can simulate the observed record of past abrupt climate change in a realistic manner." Lenton (2009) points out that IPCC projections of climate change response do a relatively poor job of predicting abrupt or nonlinear effects of climate change because they: (1) focus on global mean quantities (i.e. regional-scale spatial variability is smoothed out); (2) use simple climate models such as MAGICC that are designed to capture some aspects of more complicated large-scale general circulation models (GCMs) but exclude their non-linear and stochastic aspects; and (3) often average GCM output over long time horizons and sometimes over a group of runs, which smoothes out short-term temporal variability.

3. How Economists Define and Model Climate Catastrophes

There are several differences in the way potential climate catastrophes are characterized and discussed in economics compared to the scientific literature. An economic catastrophe is often defined with regard to how rapidly it will occur relative to the time required for mankind to adapt to this new state of the world. For instance, the NRC (2002) defines abrupt climate change from a societal perspective as "having sufficient impacts to make adaptation difficult." Likewise, Williams (2009) defines rapid climate change as fast enough – a decade or two – that adaptation is impossible even for the richest countries. Despite the importance of the time scale in economics Hulme (2003) notes that this area is a major source of confusion and miscommunication between the scientific and policy communities as the term "abrupt as used by the paleoclimate community has different meanings to abrupt as used in more popular discourse." In turn the economics literature has typically assumed time scales over which impacts will become fully realized that are often much shorter than the broader, more inclusive definition of "rapid" or "abrupt" used by the scientific community. This disconnect is indicative of the way economists tend to use the notion of a climate induced catastrophe more loosely, rarely applying the same degree of precision as found in the scientific literature. How the treatment within economic studies lines up with the scientific community's evaluation of which tipping points are likely to occur, when, and on what time scale impacts will unfold is rarely evaluated. The disconnect may also in part stem from the practice of discounting in economic models, which puts a practical limit on what is typically viewed as catastrophic in economic terms. Economists typically measure economic damages associated with an increase in global mean temperature in terms of the change in societal welfare or foregone consumption in future years, discounted to the present. At positive discount rates, impacts thousands of years in the future are quantitatively negligible when expressed in present value terms.

Other differences in the treatment of climate change induced events may stem from the role of discounting in economic models, which places a practical limit on which events would be viewed as catastrophic in economic terms. With a positive discount rate, the present value of social welfare losses due to climate change will be negligibly affected by events occurring far in the future (e.g., in thousands of years).

In this section we first examine the theoretical evidence to support the assertion that climate catastrophes may play an important role in understanding socially efficient abatement policy. Then we review how the economics field has chosen to model the types of events the scientific literature refers to as "catastrophes."

Economic Theory of Catastrophic Events

The importance of including low probability but potentially high impact catastrophic events in an economic modeling framework was initially informed by the theoretical work of Cropper (1976). She considers the generic case of a stock pollutant whose buildup reduces social welfare in a continuous fashion up to the point where the stock crosses a threshold, at which time a discontinuity occurs and social welfare immediately falls to the level associated with subsistence consumption. While the level of the threshold is uncertain the decision maker has an informed prior. Within this setup she finds that the potential for a catastrophic event can cause the presence of multiple market equilibria, suggesting the potential existence of such events has strong policy implications.

Tsur and Zemel (1996) were among the first to translate this theoretical framework to the case of climate change, with the stock pollutant representing atmospheric carbon, which through its impact on Earth systems could potentially lead to a catastrophic event. As in Cropper (1976), if the stock pollutant crosses an uncertain threshold the stream of economic damages associated with the pollutant are instantaneously and permanently increased by a fixed amount. Tsur and Zemel (1996) extend this basic framework to allow for adaptation where resources may be diverted from consumption towards mitigating the impacts of the catastrophic event. Even with the potential for adaptation they find that, in theory, the potential for catastrophic events induced by climate change could have significant policy implications for the optimal level of abatement.

Climate change poses a unique problem for economic modeling in that mitigation requires large sunk costs in the near term with highly uncertain benefits occurring in the far future. Given this situation reducing the uncertainty associated with the payoff for mitigation may have tremendous value to the policy makers. Therefore, Hendricks (1992) and Pindyck (2000), among others, have used a real options framework to examine the characteristics of optimal climate policy given the potential for a policy maker to learn about the expected damages over time. Assuming that the net benefits of pollution abatement are uncertain but well represented by continuous stochastic differential equations, they develop the basic result that the irreversible nature of abatement investments implies delaying mitigation may be optimal. This is directly derived from the assumption that uncertainty regarding the impact of climate change will be, at least, partially resolved over time. Baranzini et al. (2003) extend this concept to account for the possibility of a climate related catastrophe and find that the potential for a large scale event could theoretically offset the irreversible capital effect, negating the benefits of delaying action. This result is derived from the assumption that the arrival of a climate catastrophe is well modeled by a negative Poisson jump process with an exogenous arrival rate. This assumption describes a catastrophe that occurs instantaneously and whose likelihood of occurring is independent of any abatement policy adopted.

Clearly a notable concern with the work of Baranzini et al. (2003) is the assumption of unavoidable catastrophes. As noted by Pindyck (2007), "the possibility of a catastrophe will likely increase the expected benefit from any amount of abatement." To understand the theoretical implications of failing to couple mitigation efforts and the potential for a climate induced catastrophes, Fisher and Narain (2003) extend this real options framework. They assume that "the world comes to an end after [a] catastrophe has occurred," or in other words, utility is instantaneously and permanently reduced to zero in a fashion similar to Cropper (1976). When this risk is assumed to be unavoidable (i.e., independent of abatement policies) they find the irreversible nature of investments in abatement will lead to less abatement, a result also found by Kolstad (1996). This is because when the risk of the catastrophe is purely exogenous it effectively acts as an increase to the discount rate. However, when the probability of a climate catastrophe occurring is allowed to be a function of emissions its presence results in an increase in the theoretically optimal level of abatement.

Economists have also considered the role for publically subsidized research in abatement technology in the face of such potential events. Castelnuovo et al. (2003) use a regional model that includes endogenous technical change to examine the role of catastrophes in optimal investment patterns. They take a similar approach to Fisher and Narain (2003) and Bosello and Moretto (1999) such that if a climate induced catastrophe occurs it would instantaneously bring about "the end of the world" as represented by a permanent reduction of utility to zero. Their results suggest that the potential for such an event increases the value of abatement capital and therefore the optimal level of research and development investment. Based on the public good nature of the product they suggest that there may exist a role for policy to incentivize such spending.

Catastrophic Events in Integrated Assessment Models

While the theoretical work on potential climate catastrophes and optimal policy provides strong motivation for incorporating the possibility of such events into economic modeling, how best to reflect them within empirical modeling frameworks remains an open question. Quantitative analysis of climate change policy is often carried out with the aid of integrated assessment models (IAMs) that allow for a potential bi-directional coupling of natural Earth and economic systems. Due to the complex nature of these systems they are often represented in a simplified, highly aggregated form in order to keep the model tractable from the perspective of both utilization and parameterization. For example, William Nordhaus' Dynamic Integrated Model of Climate and the Economy (DICE) model represents the global implications of climate change as a proportional loss of economic output that grows by the square of the average annual global temperature anomaly (Nordhaus and Boyer 2000, Nordhaus 2008). More complex integrated models such as the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (e.g., Tol 2002a, Tol 2002b, Anthoff et al. 2009, Tol 2009) and the Global Change Assessment Model (GCAM) (Calvin et al., 2009) provide more detailed representations of natural and economic systems along with finer geographic and sectoral resolution, but the additional complexity brings significant and potentially prohibitive computational burden to some types of uncertainty analysis. In this section we review how IAMs have been used to date to model the types of events the scientific literature refers to as "catastrophes" (see Table 1 for a summary of studies).

Nordhaus (1994b) made one of the first attempts to incorporate the potential of catastrophic events due to climate change into quantitative economic modeling of optimal carbon policy. This work used the results of an expert elicitation to help parameterize the damage function of the DICE model in a way that accounted for the probability of a climate catastrophe. The survey asked a panel of 19 experts about the probability distribution of climate change induced damages for a series of three scenarios (3 ^{o}C mean global temperature anomaly in 2090, 6 ^{o}C in 2175, and 6 ^{o}C in 2090) (Nordhaus 1994a). One question specifically asked about the probability of losing 25% of global world product in each of the three scenarios receiving a median response of 0.5%, 3.0%, and 5.0% for the three scenarios, respectively. In later versions of the DICE model this probability of catastrophic consequences was explicitly brought into the calibration of the damage function to proxy for the expected value of climate change impacts (Nordhaus and Boyer 2000).[7] Yohe (1996) expanded on this line of research by explicitly considering the possibility of low probability high impact events within an IAM when analyzing optimal carbon policy. In this work an augmented version of the DICE model is run with a discrete (two state) probability distribution that allows for the small probability of a world in which carbon emissions result in large damages (e.g., a loss of 12.5% of GDP for an average global annual temperature anomaly of 2.5 ^{o}C compared to 1.6% at 3 ^{o}C).

[7] While Nordhaus and Boyer (2000) state they are calibrating their model to the survey results of Nordhaus (1994b) the values reported in this later work to be from the survey do not match those reported in the original discussion of the survey results.

The choice to model climate catastrophes in a generic manner, abstracted from the specifics of the natural science and economics of such events, has continued well beyond these initial studies. A typical example of this trend is the work by Gjerde et al. (1999). While the sophistication of the modeling effort has improved from earlier analyses in some aspects (e.g., implementation of regional impacts), the link between economic welfare and the potential high impact natural event is left vague and relatively undeveloped. To analyze the optimal GHG emissions path in the presence of uncertain but potentially catastrophic events, they use a regionalized IAM in which a social planner maximizes an additively separable intertemporal welfare function that is negatively affected by climate change. In an approach that doesn't differ substantially from that of Cropper (1976), Gjerde et al. (1999) incorporate the possibility of climate induced catastrophe through a piecewise utility function where household well being is instantaneously and forever reduced by a fixed amount in the event of a catastrophe, where the probability of such an event occurring is calibrated to the expert elicitation of Nordhaus (1994a).[8]

A few papers improve on this generic approach by either adjusting the model to account for differences in impacts across specific catastrophic events or to allow for the welfare effects to phase in over time. However, while more sophisticated, these papers are few in number and still are not necessarily predicated on the existing scientific literature. Nicholls et al (2008), for example, advance the estimation of welfare impacts due to West Antarctic ice sheet (WAIS) disintegration using the FUND model. They extend the typical paradigm by allowing for a basic version of endogenous adaptation through protection measures as a function of the rate of sea level rise. However, the abstract WAIS melting scenarios considered in this study, within as little as 100 years, appear inconsistent with the timescales considered relevant for WAIS by the natural science community where a WAIS collapse has not been simulated to occur in less than 1,000 years (Lenton and Ciscar 2012). See appendix for additional discussion.

Lemoine and Traeger (2012) consider how a variety of potential catastrophic events might affect optimal climate policy as well as the marginal social cost of carbon (SCC).[9] Unlike prior studies, the authors model the potential for two types of climate tipping points. The first increases feedbacks that amplify the effect of emissions on temperature, and is said to be representative of rapid retreat of land ice

[8] Interesting to note is that given their setup, the inclusion of a large instantaneous impact from catastrophic events (permanent reduction of GDP by 25%) lowers the optimal emissions path such that the probability of a catastrophe by 2090 is only reduced from 4.8% in the business as usual case to 4.0% in the policy case.
[9] The social cost of carbon represents the discounted present value of the welfare losses associated with the release of an additional metric ton of CO_2 into the atmosphere in a given year.

sheets or climate induced releases of methane deposits. The second increases the atmospheric lifetime of CO2, which is said to be representative of weakening of carbon sinks. They use a modified version of the DICE model which allows them to consider both parametric uncertainty in the temperature threshold that will trigger a given catastrophe, and stochastic uncertainty in the temperature dynamics. The impact of each possible catastrophe is modeled differently such that a doubling of the equilibrium climate sensitivity is used to represent large climate feedbacks from a rapid retreat of land ice sheets or releases of methane deposits a decrease in the modeled decay rate of atmospheric CO_2 represents a weakening of carbon sinks. While this study represents one of the most sophisticated modeling exercises used to examine the policy implications of potential catastrophic events to date, it still uses the traditional assumption that passing a given climate threshold results in an instantaneous and permanent shock to the system. The study improves on the previous literature by not forcing all modeled catastrophes as a direct shock to welfare, but, like Nicholls et al. (2008), follows the traditional approach in which the assumptions regarding the magnitude of the effects are ad-hoc and not developed through a rigorous scientific assessment. In addition the modelers only consider one potential catastrophe at a time and assume that the trigger is reached around 2040 (it is modeled with uncertainty so this is the central point of the distribution) under the no policy reference case, independent of which of the four potential catastrophes is being considered.

Cai et al. (2012) take a similar approach to Lemoine and Traeger (2012) and use a stochastic version of the DICE model to consider the impact of potential tipping points on optimal carbon policy. As with much of the previous work they assume that in the event of crossing a tipping point there will be an instantaneous and permanent economic shock, specifically they model the outcome as a permanent upward shift in the damage function. The occurrence of a catastrophic event is assumed to be uncertain and is modeled as a jump process where the hazard rate is a function of the current temperature anomaly and is calibrated using the expert elicitation results in Zickfeld et al. (2007) and Kriegler et al. (2009). However, the economic impact of a catastrophic event (i.e., the shift in the damage function) is chosen ad-hoc to range from an additional 2.5% to 10% of GDP.[10] Like previous work in the area they find that the optimal climate policy may be substantially influenced to the potential for catastrophic events, and add to the state of literature by showing that the result is sensitive to the way in which risk aversion is captured within the modeling framework.

[10] Therefore as modeled it is possible to have a world with a global and annual mean temperature anomaly of 2.5 ^{o}C suffer climate damages of 1.8% of GDP and then the next instant face damages of 4.3%-11.8% of GDP if an event occurs.

One of the few examples where a potential climate catastrophe has not been modeled as an instantaneous shock is the work of Hope (2011), which uses the PAGE09 integrated assessment model.[11] PAGE09 models a generic potential climate catastrophe, where the probability of such an event occurring is zero until a given threshold is reached after which point the probability begins to rise. If a climate catastrophe is triggered, there is a permanent reduction in welfare. However, unlike prior versions of the model, it is not instantaneous and instead there is a transition period over which the welfare impact is phased in. Since the model only incorporates a single generic potential climate catastrophe the transition period is considered uncertain with a range of 20 to 200 years. The probability that an event occurs and the range of welfare impacts considered are both chosen in a fairly ad-hoc manner. The lower end of the range for potential welfare losses in the European Union are based on potential sea level rise damages studied in Anthoff et al. (2006), however no justification is provided for the upper end of the range. Furthermore, potential damages in other regions are primarily based on the length of their coastline relative to that of the European Union.

While most studies have chosen to model a generic event, when a specific event is considered the most popular one has been the potential for a shutdown of the Atlantic thermohaline circulation (THC). Link and Tol (2011) use the FUND IAM not to directly examine the policy implications of a potential shutdown of the THC, but to estimate the welfare impacts if such an event does occur. They use experiments conducted with an atmospheric and ocean general circulation model (GCM) to determine the impact that a shutdown of the THC would have on regional temperature anomalies and feed this information into a nationalized version of the FUND model.[12] This setup produces estimates of the additional welfare loss that would be experienced in the event of a shutdown of the THC, assuming the impact of the shutdown begins in 2070 and increases linearly until its full effect is reached in 2100 (see the Appendix for more detail).

Ceronsky et al. (2011) consider a similar experiment, but consider the policy implications more directly by examining the effect on the SCC. Specifically, they use an updated version of the FUND model to look

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[11] The PAGE (Policy Analysis of the Greenhouse Effect) model was developed by Chris Hope in 1991 for use by European decision-makers in assessing the marginal impact of carbon emissions. In the previous version of the PAGE model, PAGE2002, a generic potential climate catastrophe was modeled as an instantaneous and permanent reduction in welfare, where the probability of such an event occurring was zero until a given threshold was reached after which point the probability would begin to rise (Hope 2006).

[12] The study of Link and Tol (2011) provides three extensions to their earlier study (Link and Tol, 2004) in that they move from a regional to national scale for modeling welfare impacts of climate change, use a more sophisticated atmospheric and ocean GCM to determine the temperature impact of a THC shutdown, and no longer assume that such impacts will be felt instantaneously.

at the effect of a potential weakening of the THC and large scale methane releases from the deep ocean on the SCC, assuming we know one of these events will occur with certainty. Similar to an earlier study by Link and Tol (2004), they represent the impact of a THC shutdown by adjusting regional temperature anomalies using the results of Ranhmstorf and Ganopolski (1999). To test the impact of a potential large scale methane release from the deep ocean they assume that starting instantaneously in 2050 methane emissions will increase by a fixed amount. Both the time of the instantaneous shift in emissions and the level of the shift are based on the judgment of the researchers, and sensitivity analysis is only conducted around the level of the shift.

Keller et al. (2000) estimate the costs associated with preventing a shutdown of the THC. They determine a threshold level of atmospheric carbon, based on the work of Schmittner and Stocker (1999), beyond which the THC would collapse. They then run the DICE model subject to the constraint that this event cannot occur. In a post processing step Keller et al. (2000) compare the additional cost associated with meeting this constraint to an ad-hoc estimate for the welfare loss associated with a shutdown of the THC in order to assess the social optimality of preventing this potential climate catastrophe. While the welfare impacts of the catastrophe are not endogenous to the model the additional benefit-cost analysis is conducted under the implicit assumption that after passing the threshold, social welfare will be instantaneously and permanently reduced.

Mastrandrea and Schneider (2001) address one of the primary caveats of Keller et al. (2000) by allowing the welfare impacts of changes in the overturning of the northern Atlantic Ocean to be endogenous therefore allowing them to estimate the optimal carbon policy given the presence of this potential catastrophe. Like Keller et al. (2000), Mastrandrea and Schneider (2001) start with the DICE model but expand on the previous analysis by allowing the THC shutdown threshold to be a function of both the carbon stock and the rate at which the stock is increasing. This addition is said to account for the possibility that rapid increases in the carbon stock could overwhelm the ocean's ability to dilute surface water through mixing with the lower ocean. Furthermore, Mastrandrea and Schneider (2001) allow for the possibility of a partial shutdown of the THC that feeds back into the damage estimates within the DICE model. In their study the uncertainty is not over the location of the threshold associated with the natural event but with the social welfare losses that would result from such an event, such that a full shutdown of the THC could result in an additional loss of between 1% and 25% of global GDP above the baseline climate damages. While this work provides a representation of the Earth system change that is more firmly rooted in the scientific literature, the welfare impacts of the potential event are set forth in an ad-hoc manner. The range of welfare impacts is not based on the results of a damage assessment and no judgement is made about the likelihood of any of the cases studied.

In commenting on the social and policy implications of potential climate catastrophes, Hulme (2003) noted that there were no estimates for the social welfare loss associated with such events that are grounded in "substantive environmental, economic, or social research." While Hulme (2003) was particularly focused on the example of a THC shutdown, our review suggests that most economic studies looking at the policy implications of potential climate catastrophes have failed to define the welfare losses from such events in a rigorous fashion. However, a few new studies have sought to move forward by developing welfare loses in response to occurrence of a climate induced catastrophe using bottom-up analyses (e.g., Link and Tol 2011, Ceronsky et al. 2011). The economic literature has also typically fallen short when it comes to incorporating the latest natural science on potential climate catastrophes. Lenton and Ciscar (2012) note that there is currently a "huge gulf between natural scientists' understanding of climate tipping points and economists' representations of climate catastrophes in integrated assessment models." Such a criticism appears warranted given that the most commonly applied description of a climate catastrophe is an event which occurs instantaneously as a result of crossing a given threshold, after which part of the system (typically welfare) is permanently altered by a fixed quantity. Therefore while the economic modeling exercises to date provides evidence that potential climate catastrophes might significantly influence the optimal path of abatement, they do not provide results sufficiently grounded in natural and economic science to meaningfully inform the policy debate.

4. Moving Forward

Within the economics literature climate induced catastrophes have been modeled by most researchers as equivalent to a large, permanent, and instantaneous impact on social welfare once a critical Earth system threshold is crossed. While the common failure to rigorously calibrate these exercises is of particular concern, even more startling is the fact that such a specification bears little resemblance to the potential climate catastrophes discussed within the scientific literature. There has been some progress recently in improving the estimation of welfare losses from potential climate catastrophes (e.g. Ceronsky et al. 2011; Link and Tol 2011), but these efforts have focused on the potential weakening of the THC, an event that is considered less likely to occur than many other large scale earth system changes (Kriegler et al. 2009). To help lay the foundation for improving the economic modeling of potential climate catastrophes for use in policy analysis, this section briefly describes what is known about often discussed potential Earth system changes that fall within the definition of climate catastrophe as used by the scientific literature. Based on this review we offer thoughts on potential near term modeling improvements that would allow for enhanced quantitative analyses of climate catastrophes in the economics literature.

Our review of potential large scale Earth system disruptions and their associated physical impacts is intended to provide a summary of what information is available for modelers. We consider what the scientific literature has written about issues that are particularly relevant to economic analysis in terms of being able to both better model these impacts and prioritize which ones may initially command more attention. Such relevant characteristics include which events are considered more or less likely to occur, whether there exists more or less scientific consensus on how and when physical impacts will unfold, and which physical end points have probabilistic projections defined. This summary is written from the perspective an economist and is not intended to be an assessment of the scientific merits of particular studies. It is intended to help modelers identify potential climate catastrophes that can be better incorporated into IAMs now, and where additional research and modeling work is needed for others. It is worth emphasizing at the onset that there is still a great deal of uncertainty even for events that are viewed as having a higher probability of occurrence. Though there may be a paucity of data in many cases, this section highlights that there appears to be enough information available to significantly improve the way in which climate catastrophes are represented in economic analyses.

Overview of Potential Climate "Catastrophes"

The starting point for our review is a set of 15 often discussed large-scale Earth system changes that may be induced as a result of climate change (see Table 2). Many of these have been characterized in the scientific literature as exhibiting "tipping point" behavior in that once a critical threshold is crossed for some control parameter, the system will be qualitatively altered and often cannot go back to its original equilibrium.[13] While the details of our review are provided in the Appendix, Table 2 offers a brief description of each potential "catastrophe" and two key characteristics: the level of global warming

[13] The set of potential events in Table 2 is not meant to be exhaustive, but representative. See Lenton and Ciscar (2012) for a discussion of some additional large scale events that might occur as a result of climate change, including the North Atlantic sub-polar gyre and aridification of southwest North America. Also note that in this paper we do not attempt to offer our own definition of "climate catastrophe" or "tipping points". Rather our goal is to review the evidence on large scale Earth system changes as a first step to improving how well they are captured in IAMs.

needed to trigger the event and the timescale over which the transition to a new state is expected to occur. Even this small amount of information highlights the considerable variation across potential climate catastrophes. First, some changes are primarily a direct result of increasing temperatures (e.g., ice sheet melt), while others hinge on changes in precipitation patterns, ocean temperature gradients, and/or a complex combination of mechanisms (e.g., changes in ENSO, West African monsoon). Second, based on Lenton et al.'s (2008) assessment of the amount of warming needed to pass potential critical thresholds (measured relative to 1980-1999 temperatures), it is possible that some thresholds may have already been crossed (e.g., loss of Arctic summer sea ice). However, it also appears that in a majority of the cases a significant level of additional warming would be required to trigger an irreversible shift in the equilibrium of these systems (though within the expected level warming over the next couple centuries given business as usual emissions). Third, there appears to be considerable variation in the estimated timescales over which physical impacts are expected to unfold, where the full impact may not be realized for decades, centuries, or even millennium. In quite a few cases, even if a critical threshold is transgressed, the effects – and particularly their full impact – are a long way off. This information also reinforces the observation that these potential events are poorly represented in most IAMs when they are modeled as a low probability of an instantaneous change in global welfare.

Finally, it is important to note that the events listed in Table 2 are not necessarily independent of each other, such that the occurrence of one can increase the risk of others being realized. For example, changes in the frequency or magnitude of the El Nino Southern Oscillation (ENSO) will likely affect precipitation patterns in South America and thus influence the probability of massive dieback of the Amazon rainforest. Similarly, a collapse of the West Antarctic Ice Sheet (WAIS) is expected to encourage thawing of permafrost and in turn additional melting of the Greenland Ice Sheet (GIS). The full set of feedbacks between these fifteen Earth systems is too complex to summarize in the Table, but Lenton and Ciscar (2012) provide an overview of many of the critical linkages identified to date. It is also possible for a combination of changes to cause a planetary shift to occur even if no single boundary or tipping point is transgressed (Barnosky et al. 2012). It is for this reason that Lenton and Ciscar (2012) call on IAM modelers to consider all tipping points together instead of in isolation. While it may not be possible to adequately include all tipping points initially, nor desirable to postpone analysis until this is possible, it at least suggests that after analysts study one potential catastrophe they do not remove it from the model before proceeding to the next potential event.

Potential for Near Term Modeling Improvements

Given the wide variation in the types of potential climate catastrophes, an important question is which of these possible events are the most decisive and/or feasible to better represent in IAMs? The categorizations or rankings provided in scientific review articles may appear to provide an easy starting point to prioritizing research efforts. Table 3 considers a few such notable categorization efforts. Lenton et al. (2008) suggested their own new categorization such that "policy relevant tipping points," are those Earth system changes that may be triggered within this century – on the "political time horizon" – compared to those that would undergo a qualitative change within this millennium, which they denote as the "ethical time horizon." It is important to note that this definition of a political time horizon is based on the crossing of a threshold and not necessarily the time frame under which the impacts would become realized. Lenton's (2011) assessment of relative likelihoods and impacts are based on a five-point scale: low, low-medium, medium, medium-high and high. His likelihood rankings are based on his reviews of the literature and expert elicitation (Kriegler et al 2009). Impacts are based on limited research (Lenton et al. 2009) and subjective judgment, and are rated relative to the one system (THC) with multiple impacts studies. Impacts are considered on the full 'ethical time horizon' of 1,000 years, assuming minimal discounting of impacts on future generations. Allison et al. (2009) provide a categorization of potential climate catastrophes that are "of greatest concern" meaning those that are "the nearest (least avoidable) and those that have the largest negative impacts." This assessment is also based primarily on Kriegler et al. (2009) and other existing reviews (e.g., Lenton et al. 2008, Lenton 2009).

Although these categorization efforts are potentially helpful as a first cut, care should be taken in using them to prioritize IAM efforts because they may not match up with what is most relevant to modeling of economic consequences that meaningfully inform policy analysis today. For example potential events that require a significant amount of warming, have multi-century transition times, and a low likelihood of occurring are less likely to produce rapid, significant near-term economic damages than ones that have low temperature thresholds, short transition times, and are less uncertain. Also, a focus on tipping points should not come at the expense of improved representation of large-scale Earth system changes that, although not expected to exhibit tipping point behavior, are likely to have gradual, sometimes large physical impacts with relatively high probability.

In Tables 4 and 5 we begin to take a closer look at each event to help prioritize which potential climate catastrophes are most appropriate and feasible to analyze initially in economic models. We consider details such as the types of physical endpoints that would be impacted, the degree of scientific consensus around even the basic characteristics of how these impacts will likely unfold, the shape of the transition dynamics, and data availability. This summary is based on a careful review of the scientific literature, the details of which are in the Appendix.

First, Table 4 assesses which of these potential Earth system changes are expected to produce significant physical impacts in the near term (e.g., in this century) and summarizes the availability of scientific projections of key physical endpoints relevant to each event. This information is important for understanding which events are more or less likely to produce economic damages within the next century – thus making them more relevant to incorporate into present day policy analysis. This is not to say that economic research on the more uncertain or distant potential climate catastrophes is unimportant, but rather to highlight the areas where improved modeling of the physical and economic impacts is more feasible in the near term and at the same time are likely to have the greatest implications for current policy analysis.

We find that regardless of the degree of certainty about the existence of a tipping point and location of critical threshold for each of these events, important large-scale changes in many of these Earth systems are expected within this century even under moderate warming scenarios. Changes in some systems are already occurring and projections are becoming available for a number of physical endpoints that may allow for improved climate and natural system modeling of these events even within current IAM frameworks (e.g., permafrost thaw). The degree of consensus about how the physical impacts are expected to unfold varies greatly across the potential climate catastrophes. Our review shows that of the 15 identified potential climate catastrophes, there is relatively more scientific consensus regarding the impacts of about half of them. By consensus we mean a general understanding of how Earth systems will respond (e.g., which physical endpoints will be affected and the direction of impact on these endpoints) rather than scientific agreement on the detailed modeling and projections of physical impacts. For example, in several cases the scientific uncertainty is primarily with regard to the magnitude and rate of change (e.g., sea level rise from ice sheet melt). For other events there is still considerable debate not only on the magnitude and timing of the Earth system change but even on the direction of change. For example, although many of the mechanisms and physical feedbacks that control the characteristics of the El Nino Southern Oscillation (ENSO) are expected to be affected by rising GHG emissions, recent assessments find models are highly inconsistent with respect to their projections of change in ENSO amplitude, frequency, and variability. Some models show an increase in the amplitude of ENSO variability in the future, others show a decrease, and some show no statistically significant changes. Similarly, the debate over the vulnerability of the Atlantic Thermohaline Circulation (THC) is still far from settled. Some studies consider a weakening of the THC to be much more likely to occur than a complete shutdown, with the rate of warming being a critical factor, and even among models predicting an anthropogenic weakening of the THC, the impacts are not expected to be imminent. (See the Appendix for more discussion of both the ENSO and THC literature.)

The first step to improved representation of these potential events in IAMs is improved representation of the key physical endpoints through which economic consequences are most likely to be experienced. Table 5 summarizes our assessment of these key endpoints, as grouped into four general categories: temperature, sea level, precipitation, and extreme events. We have also added an “other” category which, for many events, captures whether the economic consequences will be a result of ecosystem impacts (e.g., vegetation/forest cover impact, species loss), but can also include other changes (e.g., opening of trade routes from sea-ice loss, direct health impacts from ozone hole). Shaded cells indicate physical endpoints that have received the most attention by scientists – either because they are expected to be the largest/most significant sources of economic damage associated with the catastrophic event or because more is known to date about how the physical impacts will evolve.

Our assessment is highly simplified as many details and complex interactions between events are not captured in this table,[14] yet it provides a useful starting point for improved reduced form representation of some potential climate catastrophes in IAMs. For example, it highlights for modelers the appropriate physical endpoint(s) through which the potential catastrophic events should be incorporated into the IAM framework. Though depending on the IAMs completeness in terms of linking physical to economic endpoints, the modeler may be required to develop mappings of how these physical changes relate to economic damages. In a similar vein, Table 5 also highlights the need for more explicit representation of certain physical endpoints in IAMs. The current generation of reduced form IAMs each take a somewhat different approach to damage functions, but in all cases the majority of damages are based on changes in global and annual mean temperature and sea level rise. However, for many of the potential climate induced catastrophes additional physical endpoints, poorly correlated with changes in global temperature, such as precipitation and those associated with extreme weather events are critical for capturing their impacts. One needs to be careful in recognizing that incorporating these additional

[14] Lenton and Ciscar (2012) summarize some physical impacts not included in Table 5, such as impacts on atmospheric and ocean circulation, and interactions between events.

physical systems is only part of the task, as changes must then be translated into welfare impacts, which remains a challenging issue.

Ideally, modelers would have access to studies that provide information on the path of changes in the physical endpoints listed in Table 5 and any other relevant Earth system impacts over time, the distribution around that path, and the correlation with climate variables/other tipping points/large scale feedbacks for each of the potential climate catastrophes. With such data modelers would be able to credibly represent the impacts that these potential climate catastrophes will have on natural system endpoints and begin to map them more explicitly to economic damages.[15] Our review suggests that the scientific literature is far from being able to provide all of this information but, as was shown in Table 4, in some cases it appears a richer set of data already exists that could readily be incorporated into IAM modeling efforts.

For example, in the case of permafrost thaw numerous studies have projected change in active layer depth and extent of permafrost area for the 21st century (and beyond), and forecasts of the magnitude of the accompanying carbon feedback are also becoming available (Schaefer et al. 2011). The thawing of permafrost was not ranked highly in the scientific reviews included in Table 3 due to its lack of a specific tipping point. However, this is an event that is expected to occur (and may already be occurring) in this century, for which there is relatively more scientific consensus regarding its impacts, and the primary endpoints are already captured within most current IAMs. Therefore permafrost climate feedbacks seem to be an ideal candidate for inclusion into the current modeling frameworks. While multiple economic studies have mentioned the thawing of permafrost as a possible source of catastrophic or abrupt climate change, the most "advanced" study to model this type of event (Lemoine and Traeger, 2012) considers it to be a fixed, instantaneous and permanent doubling of the equilibrium climate sensitivity. Our review indicates that a more explicit representation of the additional carbon flux from thawing permafrost and associated damages from the resulting additional warming is possible, based on available projections from Schaefer et al. (2011) or similar studies. The currently available reduced form IAMs have the capacity to incorporate the magnitude and rate of this carbon feedback effect, and are already designed to account for the welfare impacts of additional releases of carbon emissions. While more research and modeling is needed to incorporate other damage categories (e.g., valuation of

[15] In order to assess the welfare implications of non-marginal policies with the use of IAMs inclusive of potential climate change induced catastrophes, the endogeneity of these physical endpoint changes to anthropogenic emissions would have to be established within the models.

ecosystem impacts from permafrost thaw), an initial study correctly capturing the timing and quantitative welfare impacts is currently feasible.

In the case of a potential Amazon dieback there also exists a richer set of data on physical impacts that could be incorporated into IAM efforts. For example, relevant physical endpoints for which 21st century projections are available include: change in tree cover, vegetation and soil carbon, precipitation, amplified regional warming (e.g. Cox et al. 2000, 2004). Rammig et al. (2010) go so far as to estimate probability density functions for change in vegetation carbon storage (kg C m-2) by Amazonian region for 2070 –2100 vs. 1970–2000 using the variation in GCM rainfall projections and sensitivity to CO2 fertilization. Although it would require more work than permafrost thaw, some basic incorporation of this latest scientific research into IAM modeling of Amazon dieback seems feasible.

In some cases, the scientific literature may at least provide plausible bounds on the size or speed of impacts. For example, the latest research suggest a reasonable range for total sea level rise from all sources to be about 0.5-2 meters by 2100, with a lower likelihood assigned to the upper end of this range (Nicholls et al. 2011), and zero probability of sea level rise exceeding 2m by 2100 (with at most about 50-60cm coming from either ice sheet) (Pfeffer et al. 2008). Since in most IAMs some structure already exists to measure welfare impacts to changes in sea level rise, better modeling of the dynamics of sea level alone, as is already done in some newly released IAMs (e.g., Nordhaus 2010), will help to improve representation of catastrophic ice sheet loss. Simplified representation of some impacts of melting summer sea ice may also be possible. The complete loss of summer sea ice in the Arctic is one of the most widely expected Earth system changes examined in this paper, yet, to our knowledge, none of the IAMs currently model the damages associated with feedback effects of this loss. It appears the results of studies examining the regional temperature and weather pattern impacts of sea ice loss (see Appendix) could be brought to bear on the economic damages resulting directly from temperature (and perhaps precipitation) changes. Models of the economic impacts associated with improved accessibility of Arctic harbors (e.g., for resource extraction, shipping) could also begin to be developed based on existing projections of sea ice extent.

As mentioned previously, for several potential climate catastrophes the primary Earth system end points that are expected to be impacted are not typically modeled within the current generation of IAMs. Therefore, even if these potential events are judged to be of great concern in scientific reviews such as those included in Table 3, improved modeling of the physical and economic impacts may be less feasible in the near term as it will require improved representations of other Earth system changes, which could be a relatively difficult process in some cases. For example, most IAMs used to estimate the welfare impacts of climate change are not currently designed to directly assess the effects of changes in precipitation or intra-annual weather variability. Therefore in the case of potential changes to the ENSO, there may be a need to better incorporate additional Earth system endpoints and their associated welfare connections into the model before the potential climate catastrophe can be adequately represented. Similarly, modeling of a weakening/collapse of the West African Monsoon (WAM)/greening of the Sahel would also require additions to the currently available models.

Finally, those Earth system changes that are not likely to manifest until very far out in time may be of lower priority than others because they are outside the scope of what economic models typically focus on (pre-2300?). For example, a massive release of methane from sea floors would lead to significant amplified global warming effects. However, the timescale of the forcing needed for this to occur is assessed to be over 1000 years off because it will take that long for the sediment to warm to the point of reaching the hydrate deposits.

We suggest caution even in the cases where the models currently represent the affected Earth system endpoints and their welfare implications. Most of the existing models predicate welfare impacts on the level of the change in Earth system endpoints, and do not explicitly account for the rate at which those changes occur. In general, the more gradual the shift, the more likely it can be captured within the existing framework of even a very reduced form IAM. However, the more quickly the event is expected to speed up another change (i.e., rapid increase in the rate of temperature growth or sea level rise) the more important it will be for the model to incorporate how vulnerability and adaptation possibilities can be affected by the rate of change. This is a widely acknowledged limitation of the current suite of models available as they exhibit very limited, if any, opportunity for endogenous adaptation. In the case of potential climate catastrophes one must be concerned not just with the presence of endogenous adaption, but the whether realistic “time-to-build” constraints are implemented.[16]

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[16] Another note of caution is that the current suite of models may be limited in modeling the implications of irreversible tipping points. It has been shown generically in the economics literature that the irreversibility associated with crossing the threshold may have implications for the value of GHG mitigation policies (e.g., Fisher and Narain (2003), Pindyck (2000)), but the techniques for computing the implications of irreversibility may currently be computationally infeasible when working with more detailed IAMs that have been modified to more accurately represent the effects of large scale Earth system changes. Simpler models commonly used to explore the importance of irreversibility may be need to be calibrated to more detailed IAMs that more accurately represent potentially catastrophic climate changes in order to develop an understanding of the magnitude, timing,

5. Closing Thoughts

A common question regarding integrated assessment models used to assess the benefits of GHG mitigation policies is how well they capture the potential for "catastrophic" events induced by climate change. While this question has in part been motivated by earlier economic research on the potential policy importance of a generic and abstract event that occurs with a low probability, a careful review of the scientific and economic literature suggests there is an error in translation when modelers incorporate the climate "catastrophe" work of natural scientists into IAMs. In the scientific literature emphasis has been placed on the Earth systems that are associated with tipping points. This focus appears justified given that a relatively abrupt, irreversible (at least on relevant time scales) move from one equilibrium to a distinctly different equilibrium by definition represents a large scale change for that system itself. Through interactions between natural systems such changes could also represent large scale changes for the Earth system as a whole. In the context of the economics literature and the benefit-cost analysis of GHG mitigation policies, the question becomes one of the economic impacts of these Earth system changes. Thus far, the majority of efforts to understand the benefits of GHG mitigation when there exists a possibility of large scale Earth system changes have grouped all possible changes into a single "catastrophic" damage category that has a low probability of being realized. Motivated by modeling convenience and scientific descriptions of such changes as being relatively abrupt, the economics literature has commonly assumed that in the event this catastrophe is triggered there will be an instantaneous and permanent reduction in global welfare. In short, the economics community has loosely interpreted scientifically 'abrupt climate change' to mean 'instantaneous change in welfare.'

While the economic research efforts to date are informative with regard to the potential importance of including such large scale events in the analysis of GHG mitigation benefits, the generic and abstract form of the "catastrophe" implemented has led to a lack of specific policy implications. One reason for this is the lack of attention to policy relevant timescales. For scientific audiences, timescales of relevance are defined by the speed of an Earth system shift relative to the timescale of the previous stable state, so something as long as 100 or even 1,000 years could be considered abrupt. For an economic analysis such time scales are not likely to be considered policy relevant or well represented by an instantaneous regime shift. The shape of the transition during the policy relevant time horizon therefore becomes

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and likelihood of the effects. This would allow the community to develop estimates of the impacts of irreversibility accounting for the uncertainty of such changes and the sunk costs of mitigation policies to determine their joint effect.

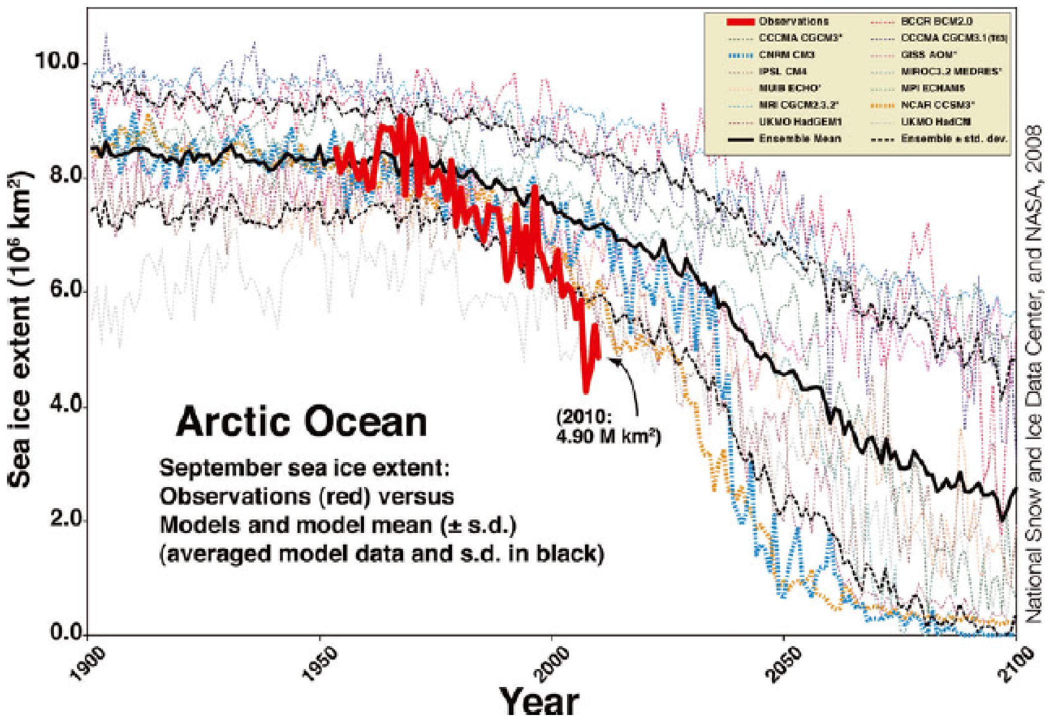
particularly relevant to understanding the policy implications of potential large scale Earth system changes due to climate change. Second, there is often no explicit representation of the geographic extent over which these impacts may be experienced. Such detail is important to understand how Earth system changes will interact with the differing vulnerability and adaptation possibilities across regions. The third, and perhaps clearest, issue at hand is that the economics literature has often modeled the economic impact due to a large scale Earth system change in a relatively ad hoc manner. There have been relatively few endeavors to determine what the expected economic impacts would be given the relevant changes in particular Earth system endpoints. Some economics research has chosen to carefully examine the details of particular Earth system changes (e.g., Link and Tol's (2011) study of THC shutdown) and have started to account for how these changes interact with adaptation measures (e.g., Nicholls et al.'s (2008) study of WAIS disintegration). However, these studies are in the minority and only provide a picture of the damages associated with one possible event at a time.

As researchers make strides to more explicitly and accurately represent Earth system changes and feedback effects that have until now often been grouped together in a catch all "catastrophic impact" category, a closer look at the scientific literature can help modelers understand which ones could more readily be modeled given the current state of IAMs and in other cases what improvements to modeling frameworks would be required to include additional large scale Earth system changes. It is also important to keep in mind that the underlying goal of this line of research is to better understand the benefits of GHG mitigation policies given the possibility of large scale economic consequences over the next few centuries due to climate change. Therefore, we recommend that effort be applied to develop modeling improvements not only in the way IAMs characterize Earth systems and the possibility of large scale changes that may or may not be have an associated tipping point, but also in the way they characterize uncertainty over the availability of adaptation or interaction between sectors that could lead to potential large scale economic consequences. The existence of a threshold in a natural system is neither a necessary nor sufficient condition for an event to have potentially important global or large regional impacts within this century. It is unclear without further research that carefully models the natural and economic systems and their interactions, whether the most policy relevant Earth system changes are those associated with tipping points that may be crossed this century or are those associated with more gradual but significant feedback effects that also are currently not represented in IAMs used for policy analysis.

Appendix: Review of evidence on fifteen potential climate "catastrophes"

Loss of Arctic Summer Sea Ice. It is widely accepted that the Arctic region will warm considerably due to climate change. One of the most immediate consequences of higher atmospheric temperatures and numerous feedback effects (e.g., reduced Arctic summer snowfall) is the melting of summer sea ice in the Arctic Ocean, which then through feedback pathways plays a central role in the region's temperature amplification (Screen and Simmonds 2012). The complete loss of summer sea ice in the Arctic is one of the most likely Earth system changes listed in Table 2 (Lenton et al. 2008, Lenton 2011). Observations using satellite data show a loss in the extent of permanent summer sea ice over past decades. The IPCC (2007) reported decreases of 7.4 [5.0 to 9.8] % per decade since 1978, and more recent observations suggest the decline has been even faster, at a rate of greater than 11% per decade (Kattsov et al. 2010), with the area of summer sea ice now about one third smaller than the average over 1979 to 2000 (AMAP 2011) and typically 40% smaller in recent years than in the 1980s (Stroeve et al 2012). Numerous studies project this trend will continue with recent estimates predicting nearly sea ice free Arctic summers by as early as the 2030s (e.g., Wang and Overland 2009, AMAP 2011, Zhang 2010). Many global circulation models forecast this to be a non linear transition (Lindsey and Zhang 2005), but others show a more linear loss and there is little consensus that a common critical threshold of warming can be identified for this change (Holland 2006, Lenton et al. 2008, Kerr 2009). Lenton et al.'s (2008) overall assessment is that the critical global mean temperature change needed to trigger the sea ice disintegration is about 0.5–2°C global warming and suggest a rapid transition time of about 10 years to an ice free state. Wang and Overland (2009), Zhang (2010), and Kattsov et al. (2010), among others explore the uncertainties in the magnitude and timing of sea ice loss, variation in projections (due to both within-model contributions from natural variability and between-model differences), and why projections are still smaller than recent observations. Figure 1 shows the Arctic September sea-ice extent from observations and projections from 13 models included in the Coupled Model Intercomparison Project (CMIP3) (Meehl et al. 2007), and a multi-model ensemble. Using six models under IPCC emission scenarios A1b and A2, Wang and Overland (2009) find the median time to transition from the current sea ice extent (4.6 M km2 in recent years) to ice free summers (less than 1.0 M km2) is 30 years (2037) with the overall mean at 32 years, and quartiles at 21 and 41 years. The record low sea ice observed in September, 2012 (3.41 M km2 (or 1.32 M mi2))[17] is leading some scientists to contend that even these projections may be overly optimistic.[18]

Figure A1. September Sea Ice Extent, Observations and Projections*



*This figure is taken from Kattsov et al. (2010). It displays observed Arctic September sea-ice extent (thick red line) and 13 CMIP3 models, together with the multi-model ensemble mean (solid black line) and one standard deviation range of model estimates (dotted black line). Models with more than one ensemble member are indicated with an asterisk. Note that these are September means, not yearly minima.

The primary physical impacts of an ice free Arctic Ocean include amplified warming (Screen and Simmonds 2010), large scale wind and weather pattern changes over the Northern hemisphere (NOAA), and ecosystem changes (e.g., threatened marine mammals (Kovacs et al. 2010) – esp. polar bears, walruses, potential increases in biological productivity (NASA 2003). Less summer sea ice will increase the amount of solar heat absorbed into the upper ocean which will then be released back to the atmosphere, increasing atmospheric temperatures. Some climate modeling studies find these temperature impacts will be more limited to the Arctic itself. For example, Deser et al. (2010) find the impact of future Arctic sea ice loss on air temperature and precipitation are greatest in November–

[17] National Snow and Ice Data Center, September 19, 2012, Press Release: Arctic sea ice reaches lowest extent for the year and the satellite record. http://nsidc.org/news/press/2012_seaiceminimum.html .
[18] http://in.reuters.com/article/2012/08/30/climate-arctic-idINL6E8JTH2620120830 .

December over Siberia and northern Canada, with late 21st century (2080-99) values ~7°C and ~0.16 mm per day higher, respectively, than in the late 20th century (1980-99). Others show impacts on weather and storm tracks over wider areas (Serreze and Barry 2011). For example, the higher temperatures can elevate pressure surfaces over the North Pole into early winter and may impact large scale wind patterns, potentially allowing cold air to move southward and produce unusually cold winters in the eastern U.S. and eastern Asia, and cooler than usual weather in late winter from Europe to the Far East (Honda et al. 2009, Strey et al 2009, Francis et al. 2009, Budikova 2009, Petoukhov and Semenov 2010).

One of the economic impacts associated with these changes is improved accessibility of Arctic harbors. This could reduce the costs of exploitation of oil, natural gas, and minerals in the Arctic, and potentially open new transport routes between Europe and East Asia. The USGS estimates that substantial off shore reserves of oil and natural gas are yet to be discovered in the Arctic.[19] With less sea ice, more of these reserves may become accessible, although studies caution against being too optimistic about the ease of navigation in the Canadian Northwest passage due to hazardous conditions induced by the sea ice loss (e.g., Wilson et al. 2004, Stewart et al. 2007). The harsh environmental conditions, along with other economic and political challenges, environmental stewardship and regulatory permitting will likely affect timelines for exploration and production of Arctic resources, and make oil and natural gas projects in the Arctic more expensive that similar projects in warmer areas for some time to come.[20]

The physical changes outlined above suggest other, perhaps nearer term, economic impacts could include Northward expansion of commercial fishing[21], energy demand impacts in parts of the Northern hemisphere, increased coastal erosion from wind/waves/storms, non-use values for ecosystem changes, and damages associated with amplified warming. Tol (2009) expects the positive impacts associated

[19] USGS estimates that 90 billion barrels of oil, 1,669 trillion cubic feet of natural gas, and 44 billion barrels of natural gas liquids may remain to be found in the Arctic, of which approximately 84 percent is expected to occur in offshore areas See http://pubs.usgs.gov/fs/2008/3049/fs2008-3049.pdf.

[20] Development of reserves is more challenging and costly in these regions due to factors such as: the need for equipment that can withstand frigid temperatures, additional site preparation costs to keep equipment and structures stable on poor soils for onshore projects, greater difficulty of existing technology to handle offshore oil spills in Arctic waters with ice flows, long supply lines and limited transportation access to manufacturing centers, higher wages to retain workers in isolated areas, etc. One study of onshore oil and gas projects in Arctic Alaska found them to cost 50 to 100 percent more than similar projects undertaken in Texas. See http://www.eia.gov/oog/info/twip/twiparch/111221/twipprint.html, http://www.eia.gov/todayinenergy/detail.cfm?id=4650.

[21] However, management of new fisheries will not be trivial. The United States closed nearly the entire U.S. Arctic Ocean in December 2009 to any commercial fishing.

with less sea ice to be small, but we are not aware of any study that has estimated the magnitude of economic impacts from sea ice loss over any particular time frame.

Collapse of Ice Sheets. Melting of the Greenland Ice Sheet (GIS) and West Antarctic Ice Sheet (WAIS) are also ranked relatively high among the list in Table 2 in their likelihood of occurring as a result of climate change. Lenton (2011), for example, considers them to be medium and medium-high on a 5 category scale and the integrity of both ice sheets are widely thought to be subject to tipping points. That is, most ice-sheet models exhibit multiple stable states and nonlinear transitions from one to another. The threshold for GIS collapse is generally thought to be accessible this century. IPCC (2007) put the threshold at +1.9–4.6°C global warming (above preindustrial); Gregory et al. (2004) and Huybrechts and De Wolde (1999) find the threshold to be around 3°C of regional warming. More recent assessments suggest a closer and narrower range above present is possible because of the speed of recent changes (e.g., +1-2°C global warming (Lenton et al. 2008)), and we may have already transgressed a threshold beyond which the ice sheet retreats on to land (Lenton and Ciscar 2012), leading to about 1 m of global sea-level rise (Ridley et al., 2009). The level of warming needed to trigger full WAIS collapse is generally thought to be further off than for the GIS. Lenton et al (2008) assessed the WAIS threshold to be about +3-5°C global warming (above preindustrial); this is consistent with historical evidence of repeated WAIS collapse under this level of warming (Naish et al., 2009). Others specify the threshold in terms of ocean temperature – e.g., when surrounding ocean warms by around 5°C (Pollard and DeConto, 2009).

The primary physical impacts of the melting of either the GIS and/or WAIS are large increases in sea level and amplified warming. Estimates of the total sea level rise from the complete melting of the GIS and WAIS are as high as 2-7 meters and 3-5 meters, respectively, but this full impact for either ice sheet is not expected to be realized for at least 300 years after the threshold is past (Lenton et al. 2008). In the very long run there is a significant probability of total sea level rise greater than 10 m (Lenton and Ciscar 2012), but projections for this century are much more modest. The IPCC (2007) estimated total climate change induced global sea level rise to be in the range of +0.4-0.7m in 2100 from pre-industrial times, with most of the increase due to thermal expansion rather than ice sheet loss. More recent assessments suggest a somewhat wider range is possible. NAS (2011) estimates global sea level rise in 2100 to be in the range of 0.5 – 1 m, with GIS and WAIS melting contributing up to 0.285m (under the IPCC A1B emissions scenario, or +2.3-4.3°C warming, assuming a doubling in ice discharge for the Greenland outlet glaciers, and the Amundsen Coast Basin in Antarctica). The rest would come from melting of glaciers and ice caps (0.37±0.02 m), and thermal expansion (0.23±0.09 m). Nicholls et al. (2011) contend a pragmatic range for overall global sea level rise from all sources is 0.5-2m by 2100 (relative to 1980-99). The low end of this range is based on AR4 projections and that observed sea level rise is closer to the high end of SRES scenarios (Rahmstorf et al. 2007; Pielke 2008). The high end of Nicholls et al.'s range is based on post-AR4 studies (summarized in Table 2 of Nicholls et al. 2011). Finally, although they do not assign specific probabilities, the authors suggest the upper part of the 0.5 - 2m range is unlikely to be realized. It should also be noted that there remains a large spread in deviations of regional sea-level rise from global mean value (Pardaens et al. 2010); gravitational adjustment will make sea level rise smallest nearest the ice sheet that is being lost and greatest on the opposite side of the planet (Mitrovica et al. 2009; Mitrovica et al. 2001).

Among the post-AR4 studies, Pfeffer et al. (2008) avoid model simulations and instead estimate the maximum contribution of ice sheet collapse to global sea-level rise as constrained only by the maximum ice speed possible and the width of ice discharge outlets. Using this type of physical constraint analysis they conclude that global sea-level rise in excess of 2 meters is "physically untenable" by 2100, and find Greenland contributes a maximum of 50 cm to this rise. Other studies find Greenland's contribution to be much smaller. For example, Lenton and Ciscar (2012) note that one state-of-the-art study estimates only 4.5 cm sea-level rise from Greenland ice dynamics (Price et al. 2011). Moon et al. (2012) also find estimates consistent with Price et al. They attribute this finding to slower glacier acceleration (based on wide sampling of actual 2000 to 2010 changes) than Pfeffer et al.(2008). Melt water from Greenland could have a small effect of weakening the Atlantic thermohaline circulation (Driesschaert et al. 2007; Jungclaus et al. 2006). See Lenton and Ciscar (2012) for discussion of other longer run atmospheric and ocean circulation impacts of losing the ice sheet.

Antarctica's maximum contribution to global sea level rise has been estimated at around 60 cm this century (Pfeffer et al. 2008), but Levermann et al. (2012) contend it could be higher because Pfeffer's assumptions are less suited for Antarctica - i.e., discharge is potentially quicker than Greenland due to outlet glaciers being less constrained by topography. Lenton and Ciscar (2012) discuss other impacts resulting from WAIS melt – e.g., encouraging retreat of the GIS, flooding of extensive regions of permafrost in the Arctic, releasing methane and carbon dioxide.

The main economic impacts from sea level rise stem from damages associated with dryland and wetland loss and infrastructure loss, or the adaptation and relocation costs associated with avoiding these losses. Of the Earth system changes listed in Table2, sea level rise has received the most explicit representation in integrated assessment models to date, and in at least one model, DICE2010, the contribution of melting of the GIS and WAIS can be examined separately.[22] Modeling of the resulting economic damages is generally less detailed. DICE2010's loss function includes a simple quadratic function of sea level rise. PAGE09 models damages from sea level rise as increasing less than linearly with the sea level based on the assumption that low-lying shore line regions suffer higher damages than inland regions.

The FUND model explicitly includes damages associated with the inundation of dry land due to sea level rise. The amount of land lost within a region is dependent upon the proportion of the coastline being protected by adequate sea walls and the amount of sea level rise. Nicholls et al (2008) adjust FUND 2.8n to allow for nonlinear impacts from extreme sea level rise to estimate impact of collapse of WAIS. This study advances the modeling of the welfare impacts of WAIS disintegration in that it includes the rate of SLR and its interactions with adaptation measures. However, the review above indicates the abstract WAIS melting scenarios considered by Nicholls et al.'s scenarios (e.g., an additional 5-m rise in 100 years (by 2130)) are inconsistent with the timescales considered relevant for WAIS by the natural science communities. Lenton and Ciscar (2012) also highlight the disconnect with the latest science on WAIS melt. For example, they note that 1) the fastest WAIS collapse yet simulated by models takes around 1000 years (Pollard and DeConto, 2009), 2) the fraction of the WAIS vulnerable to abrupt collapse is equivalent to around 3.3 m rather than 5 m of sea-level rise (Bamber et al., 2009), and 3) the sea-level rise would not be globally uniform, but rather would be higher along U.S. eastern seaboard (Mitrovica et al., 2009).

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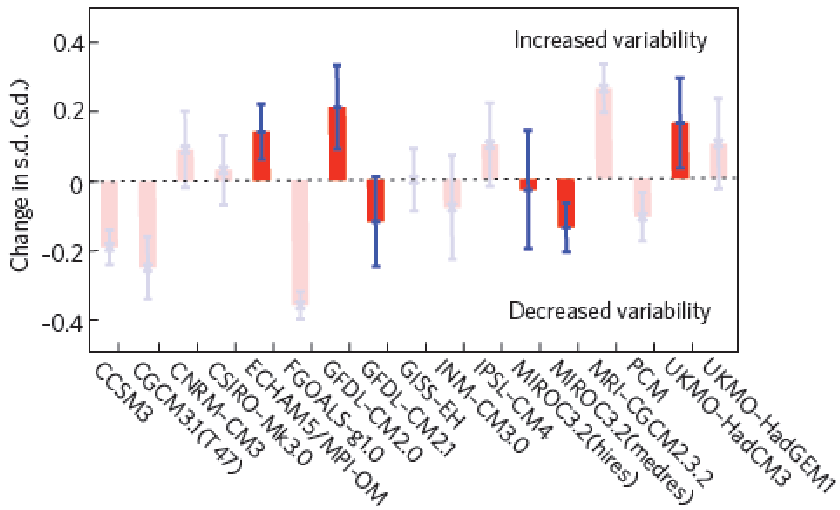
[22] In DICE2010, the average global sea level anomaly is modeled as the sum of four terms that represent contributions from: 1) thermal expansion of the oceans, 2) melting of glaciers and small ice caps, 3) melting of the Greenland ice sheet, and 4) melting of the Antarctic ice sheet. The parameters governing these four components are calibrated to match consensus results from the IPCC's Fourth Assessment Report. The rise in sea level from thermal expansion in each time period (decade) is 2 percent of the difference between the sea level in the previous period and the long run equilibrium sea level, which is 0.5 meters per degree Celsius (°C) above the average global temperature in 1900. The rise in sea level from the melting of glaciers and small ice caps occurs at a rate of 0.008 meters per decade per °C above the average global temperature in 1900.
The contribution to sea level rise from melting of the Greenland ice sheet is more complex. The equilibrium contribution to SLR is 0 meters for temperature anomalies less than 1 oC and increases linearly from 0 meters to a maximum of 7.3 meters for temperature anomalies between 1 °C and 3.5 °C. The contribution to SLR in each period is proportional to the difference between the previous period's sea level anomaly and the equilibrium sea level anomaly, where the constant of proportionality is a quadratic function of the temperature anomaly in the current period.
The contribution to SLR from the melting of the Antarctic ice sheet is -0.001 meters per decade when the temperature anomaly is below 3 °C and increases linearly to a maximum rate of 0.025 meters per decade at a temperature anomaly of 6 °C.

Increase in amplitude and/or variability of ENSO. The El Nino/La Nina Southern Oscillation (ENSO) is a periodic climate pattern characterized by variations in the temperature of the surface water of the tropical eastern Pacific Ocean—warming (El Niño) or cooling (La Niña)—and air surface pressure in the tropical western Pacific (the Southern Oscillation). The ocean warming and pressure variations are generally coupled so that the warm oceanic phase, El Niño, accompanies high air surface pressure in the western Pacific, while the cold phase, La Niña, accompanies low air surface pressure in the western Pacific. Many of the mechanisms and physical feedbacks that control the characteristics of ENSO are expected to be affected by rising GHG emissions. For example, expected mean changes over the tropical Pacific include: a weakening of tropical easterly trade winds, faster warming in surface ocean temperatures near the equator, shoaling (deepening) of the equatorial thermocline (the thin layer of water that marks the rapid temperature transition between the wind-mixed upper ocean and deeper layers), and steeper temperature gradients across the thermocline. Because the impacts of these changes on the amplifying and damping processes could partly cancel each other out, most recent studies conclude that it is not clear at this stage what the net ENSO response to climate change will be and is thus highly uncertain. Although the first global circulation model studies showed a shift to more persistent or frequent El Nino-like conditions, subsequent model intercomparisons and more recent assessments find models are highly inconsistent with respect to their projections of change in ENSO amplitude, frequency, and variability (see e.g., Guilyardi et al. 2009, Collins et al. 2010, Latif and Keenlyside 2009). As summarized in Figure A2, some models show an increase in the amplitude of ENSO variability in the future, others show a decrease, and some show no statistically significant changes (Collins et al. 2010).

Figure A2. Projected Changes in the Amplitude of ENSO Variability*



* Figure taken directly from Collins et al. (2010), and show the projections from the various models included in the Coupled Model Intercomparison Project (CMIP3) (Meehl et al. 2007). The measure is derived from the interannual standard deviation of a mean sea-level-pressure index, which is related to the strength of the Southern Oscillation variations. Positive changes indicate an ENSO strengthening, and negative changes indicate a weakening. Statistical significance is assessed by the size of the blue bars, and the bold bars are those judged to have the best simulation of present-day ENSO characteristics and feedbacks.

The uncertainty in model predictions does not mean that strong changes will not happen and transient ENSO responses are possible as well. For example, since the surface ocean changes faster than the deep ocean, initial surface warming could lead to increased ENSO activity although in a longer run equilibrium state, after GHG concentrations stabilize, ENSO may be more stable (Latif and Keenlyside 2009). Yeh et al. (2009) find an increase in the occurrence of a different type of El Nino event (termed the Central Pacific El Nino) under global warming, and expect this could lead to more effective forcing of drought over India and Australia. Furthermore, Lenton et al. (2008) argue that ENSO impacts, even if smooth and gradual, may exhibit tipping point behavior, with the transition time to a new state being on the order of 100 years. While Lenton et al. (2008) consider there to be a significant probability of a future increase in ENSO amplitude that is accessible this century (+3-6 in global mean temperature, although the existence and location of any threshold is particularly uncertain), in his most recent assessment Lenton (2011) gives it a low likelihood of occurring relative to other climate tipping points.

The impacts of changes in ENSO include, but are not limited to, increased regional rainfall, drought, monsoons, and other natural disasters. In El Nino years, countries on the western side of South America, like Peru and Chile, experience unusually heavy rainfall, while on the other side of the Pacific, parts of

Australia and Indonesia suffer from severe drought (Latif and Keenlyside 2009, Easterling et al. 2000). Increased drought in Southeast Asia from an increase in ENSO climate variability (Lenton et al. 2008) could also have an impact on India's monsoon season (Kumar et al. 2006). Impacts of changes in ENSO variability would not be limited to countries adjacent to the Pacific, however. In North America, El Nino phases tend to produce much more rain in Southern California, higher number of frost days in Florida, and lower hurricane activity in the North Atlantic (Latif and Keenlyside 2009). Several studies have also investigated the potential role that changes in ENSO patterns play in the salinity of the Atlantic and hence the stability of the THC (e.g., Latif et al. 2000, Thorpe et al. 2001, Mignot and Frankignoul 2005). Finally, studies that have examined the ecological impacts of El Nino have found evolutionary impacts on finch beak size in the Galapagos (Boag and Grant 1984), changes in marine biotic systems (Roemmich and McGowan 1995, Sagarin et al 1999), and associations with widespread coral bleaching events following intense El Nino periods (Coffroth et al 1990, Glynn 1990).

The economic implications of potential changes in ENSO variability or amplitude would likely include agricultural and health impacts and hurricane related damages (death, injury, property damage) in many regions. However, given underlying uncertainty with regard to physical impacts described above, we would expect there is also substantial uncertainty with regard to the timing and magnitude of the economic impacts. Increases in crop losses from unusually heavy rain or drought and storm damages may be due not only to increased strength or frequency of natural disasters but also due to diminished forecasting ability which can impair preparedness plans. Many studies have examined the damages of various extreme weather events on agriculture, including several that estimate the value of farmers adapting to ENSO event information (e.g., Solow et al. 1998, Chen and McCarl 2000) or the economic damages to U.S. agriculture from ENSO events (e.g., Adams et al. 1999). However, the only study we have found that estimates the economic consequences of shifts in ENSO frequency or strength is by Chen et al. (2001). Chen et al. (2001) use a stochastic model (which simulates production, acreage allocation and consumption based on a stationary joint probability distribution of yields for 10 crops in 63 U.S. and 28 world regions from 1972 to 1993) to estimate annual damages to agriculture from two changes in ENSO patterns as predicted by Timmermann et al. (1999) – i.e., a 40% increase in ENSO frequency and a 10% increase in intensity (the frequency of the stronger El Niño and La Niña events). Their analysis also indicates farmers would be able to mitigate some damages if ENSO forecasts were available to help them anticipate events and alter planting decisions to smooth out the impacts of ENSO phases. See Meza et al. (2008) for a recent survey of published evidence about the economic value of seasonal climate forecasts for agriculture.

Studies have identified relationships between ENSO and numerous health impacts – e.g., the incidence of malaria in South America, rift valley fever in east Africa, dengue fever in Thailand, hantavirus pulmonary syndrome in the southwestern U.S., childhood diarrhoeal disease in Peru and cholera in Bangladesh. However, overall the regions expected to be the most vulnerable to health risks from a potential increase in amplitude of ENSO variability are areas around the Pacific and Indian oceans (Patz et al. 2005). Finally, there are several studies that examine the economic impacts of intensification of hurricanes and cyclones due to global warming (e.g., Nordhaus 2010, Narita et al. 2009, Narita et al 2010, and for earlier estimates, Pielke et al. 2001). These generally model damages as a function of wind speed and storm frequency,[23] but none to our knowledge have made a specific link to changes in ENSO variability or amplitude.

Dieback of Forests: Amazon Rainforest and Boreal Forest.

Amazon Rainforest. Climate change induced dieback of the Amazon rainforest is generally thought to be due to widespread reductions in precipitation and lengthening of the dry season, primarily due to more persistent El Nino conditions (Cox et al. 2000, Cox et al. 2004, Betts et al. 2004).[24] Regional surface warming caused by substantial forest loss, along with land use change and increased fire frequency amplified by forest fragmentation, will likely make it difficult for the forest to reestablish, thus the system is thought to subject to a tipping point (Lenton et al. 2008) Land-use change alone could potentially bring forest cover to a critical threshold. Lenton et al. (2008) assess the global mean temperature change corresponding to a critical value of control to be about 3-4°C global warming (consistent with Betts et al. 2004, White et al. 1999) and suggest a medium transition time of about 50 years to a new state. Jones et al. (2009) find the forest will be committed to a significant degree of dieback before any is even observed and show longer timescales of gradual, rather than sudden, forest

[23] For example, Narita et al. (2009) develop a separate climate impact module in FUND (FUND version 3.4) to estimate damages from tropical cyclones. In this module, damages are assumed to be proportional to the third power of wind speed (consistent with Emanuel 2005), and wind speed is assumed to increase by 4% per degree Celsius warming of tropical sea surface temperature (per the consensus statement by the World Meteorological Organization (WMO 2006)). Nordhaus (2010) finds a much higher value (namely 9) for the parameter representing the relationship between damages and maximum wind speed based on his statistical analysis of U.S hurricane impacts.

[24] Changes in the gradient of the Atlantic sea surface temperatures between the Northern and Southern hemispheres are also thought to play a role (Harris et al. 2008).

loss as temperatures exceed about 3°C global warming. Others specify the threshold in terms of the extent of forest loss – e.g., a tipping point may be transgressed once deforestation exceeds about 40% of the entire Amazon basin (Davidson et al. 2012, Nobre and Borma 2009). Lenton (2011) assigns a "medium" likelihood of massive Amazon dieback and its impacts relative to other climate tipping points, but as with other events, scientists are generally a long way from providing precise estimates of the probability of this tipping point occurring (Cox et al. 2004).

Although the location of a tipping point for the entire Amazon basin is likely to continue to be difficult to define for some time to come, some large-scale changes have already been observed in parts of the Amazon basin, such as lengthening of the dry season (Butt et al. 2011, Knox et al. 2011) and increases in wet season river discharge in some ecologically and agriculturally important areas (Costa et al. 2003, Coe et al. 2011). Most studies predict these trends will continue and result in some dieback, but the intensity and even the direction of the change are uncertain due to the differences in rainfall projections as well as uncertainty of long-term CO2 fertilization effects. Generally, models predicting greater reductions in precipitation forecast larger amounts of dieback (Cook and Vizy 2008) while global climate models (Li et al. 2006) projecting smaller reductions (or increases) of precipitation do not produce dieback (Schaphoff et al. 2006). Using the Hadley Centre global climate model, Cox et al. (2000) find that CO2 fertilization helps to maintain the rainforest cover through about 2050, but the warming and drying eventually lead to abrupt reductions in the forest fraction (e.g., 78% loss in vegetation carbon and a 72% loss in soil carbon by the 2090s). The threshold for abrupt reductions is highly uncertain and the rate and extent of loss is model dependent. However, Cox et al. (2000, 2004) find Amazon dieback to dominate global vegetation carbon loss projections once climate effects are incorporated into the carbon cycle.

Huntingford et al. (2008) explore uncertainties in Cox et al. (2000) predictions of Amazon dieback and find that the predicted 21st century loss of Amazonian rainforest is robust across a wide range of global climate sensitivities, as well as with more sophisticated modeling of photosynthetic behavior coupled with soil moisture stress and the introduction of a dynamic vegetation model. However, others point out that the threshold for abrupt reductions is highly uncertain and the rate and extent of forest loss is model dependent. Willis and Bhagwat (2009) caution that improved characterization of topography or "microclimatic buffering" and full acclimation capacity of plants and animals can seriously alter model predictions. Lapola et al. (2009) developed a new vegetation model for tropical South America and found that when the CO2 fertilization effects are considered, they overwhelm the impacts arising from temperature. In this case, rather than the large-scale dieback predicted by Huntingford et al. (2008), tropical rainforest biomes remain the same or substituted by wetter and more productive biomes. However, for 2 of the 14 models, this result was dependent on the dry season not extending beyond 4 months; if it does, then the tropical biome becomes savanna. Malhi et al. (2009) found rainfall regime of E. Amazonia is likely to shift over the 21st century in a direction that favors more seasonal forests rather than savanna, and that rainforest-favoring climate remaining will likely remain in W. Amazonia (although the drier northern and southern margins may not), with 10% possibility of shifting from a generally aseasonal moisture regime to a seasonally dry regime.

Rammig et al. (2010) develop formal characterization of uncertainty around rainfall projections and estimate probability density functions for a change in vegetation carbon storage (kg C m-2) by Amazon region for 2070 –2100 vs 1970–2000 on the basis of rainfall projections from 24 GCMs (under IPCC A1b warming scenario) that are weighted by climate model performance for current conditions. They also perform sensitivity analysis over the strength of the CO2 fertilization effect. They find biomass vulnerability to vary across regions, with the CO2 fertilization being a key source of uncertainty. As summarized in Table A1, under weak CO2 fertilization (i.e., no additional CO2 fertilization effects compared with current conditions), Eastern and Northwestern Amazonia are likely to see small biomass loss, Southern Amazonia will experience the largest biomass changes, and Northeastern and Southern Brazil are less vulnerable to further drying. The probability of simulated forest dieback due to decreased rainfall is greatly reduced when a strong CO_2 fertilization response is added to the model (Rammig et al 2010),

Table A1. Projected probability of biomass loss in five regions of South America*

	Probability of any biomass loss (%)		Probability of biomass loss of25% or more	
	CLIM only	CLIM+ CO2	CLIM only	CLIM+ CO2
Eastern Amazonia	86.40	0.15	15.70	0.00
Northwestern Amazonia	85.90	0.00	1.10	0.00
Southern Amazonia	100.00	0.00	61.30	0.00
Northeastern Brazil	47.30	0.00	1.00	0.00
Southern Brazil	27.03	0.00	0.90	0.00

* Table taken from Rammig et al. (2010). Biomass loss is expressed by a reduction in the vegetation carbon storage or 'biomass' (in kg C m^{-2}). The CLIM+CO2 case assumes standard CO2 fertilization effects in addition to climate change, including a reduced transpiration rate and higher amount of photosynthesis; the CLIM only case assumes no additional CO2 fertilization effects compared with current conditions.

In addition to the loss of the forest cover itself, key physical impacts of Amazon rainforest dieback include biodiversity impacts and additional reductions in precipitation (~20-30%, Zeng et al. 1996). Dieback could also have an amplifying effect to climate change (Kleidon and Heimann 2000) with the forest eventually becoming a CO_2 source, which could ultimately release up to ~100 Gt C (Allison et al. 2009). See Davidson et al. (2012) for thorough review of major factors and linkages affecting the transition of the Amazon from a carbon sink to a carbon source.

Boreal Forest. The Boreal Forest is an immense span of forests, lakes, wetlands, rivers, and tundra covering approximately 6.5 million square miles in northern regions of Russia, Scandinavia, Canada and Alaska. The region has a biologically rich and largely unspoiled ecosystem; it is home to wide variety of tree species and wildlife, and billions of birds breed there each spring. Cold temperatures prevent plant remains from decomposing and allow the region to remain an important global carbon sink. The area is projected to be vulnerable to rising temperatures and other impacts of climate change, with increased water stress and increased peak summer heat stress leading the trees to be more vulnerable to pests, disease, mortality, and fires, along with decreased reproduction rates.

The forest could experience extensive dieback (Lucht et al. 2006, Joos et al 2001), and be replaced by open woodlands or grasslands (Hogg and Schwarz 1997) that support increased fire frequency, amplify summer warming, and potentially produce a strong positive feedback. Studies have already reported widespread pest induced tree mortality (such as the Canadian mountain pine beetle invasion (Kurz et al. 2008a)) and an overall decline in boreal forest area due to increasing heat stress (Lucht et al. 2006, Joos et al 2001). Lenton et al. (2008) suggest a threshold for large-scale dieback of 3-5°C global warming, but limitations in existing models and physiological understanding make this highly uncertain. Kurz et al. (2008b) find that Canada's forests have already turned from a carbon sink to a carbon source. Others, however, argue that in contrast to the amplifying effect of Amazon dieback, a diminishing global climate feedback effect could accompany boreal forest dieback (Allison et al 2009). Dieback would release CO_2 but this would be outweighed by cooling if more of the snow cover was exposed (Betts 2000). Finally, since tree growth in this region is generally more limited by temperature than precipitation, studies generally find that at lower levels of warming, climate change will tend to increase boreal forest growth (e.g., Garcia-Lopez and Allue 2012, Aaheim et al. 2011) and lead to a northward expansion of the forest rather than dieback (e.g., Jones et al. 2009, Cramer et al. 2001, Scholze et al. 2006). Overall, Lenton (2011) assigns a low likelihood of transgressing a tipping point for boreal forest dieback relative to other large-scale Earth system changes and assess medium-low impacts relative to other climate tipping points. In our review, we did not find any projections of the rate and extent of dieback over 21st century, or associated amplified warming, similar to projections for the Amazon.

Global integrated models so far find an overall positive impact of climate change up to a certain level of global temperature increase, at least in boreal forests (Aaheim et al. 2011, Sohngen et al. 2010). This stems primarily from the CO2 fertilization effect – e.g., Tol (2002) assumes a significant productivity gain in boreal forests in FUND. To our knowledge, existing models of climate impacts of forests and forest management have not been applied to the examination of economic consequences of large-scale dieback of either the Amazon rainforest or boreal forests. However, forests are represented to varying degrees in global, regional, and national studies of climate change impacts and forest management. See Aaheim et al. (2011) for a thorough review of economic and ecological models that address impacts and adaptation to climate in the forest sector. Sohngen et al.'s (2010) general overview of potential climate change impacts on the forest sector in the short, medium, and long run highlights the need for fuller integration of ecological and economic models (which tend to work on different time and geographic scales, and neglect to take into account adaptation in examining ecological impacts) to better understand how forest ecosystems and markets may be affected by climate change. That said, existing IAMs may be further developed to improve representation of potential dieback and associated damages at higher temperatures. And the importance of certain modeling improvements may vary by region. For example, since boreal regions are less managed and touched by human influence (Sohngen et al. 2010), detailed modeling of adaptation responses, timber market impacts, and interactions with agriculture may play a smaller role at least in the nearer term. Better modeling of changes in precipitation patterns (e.g., climate impacts on ENSO) may also be less important than in tropical rainforests.

Weakening/Shutdown of Ocean Circulations.

Atlantic Thermohaline Circulation (THC). The THC is an ocean water circulation pattern responsible for a large fraction of northward heat transport of the Atlantic Ocean. The response of the THC to climate change is generally thought to hinge on factors affecting the water density and pressure gradients at high latitudes, especially the addition of freshwater into the North Atlantic from higher precipitation and ice melt and the warming of surface waters from higher atmospheric temperatures. The IPCC (2007) argued that an abrupt transition of the THC is ''very unlikely'' (probability less than 10%) to occur before 2100 and that any transition is likely to take a century or more. However, the IPCC projection did not reflect the impact of freshwater runoff from GIS melt. Subsequent simulations suggested that a THC tipping point is accessible this century (Mikolajewicz et al 2007); expert elicitation suggested a 50% probability of passing a threshold for THC collapse at 4°C global warming (Kriegler et al 2009). Some studies consider a weakening of the THC resulting from these changes to be much more likely to occur than a complete shutdown (e.g., Stouffer et al. 2006, Zickfeld et al. 2007), although the rate of warming is a critical factor (Schmittner and Stocker 1999, Naevdal and Oppenheimer 2007). For example, the THC may be sustained under a 5°C temperature increase occurring over 500 years, but a complete collapse could occur if the same increase occurred over 100 years (Naevdal and Oppenheimer 2007). Lenton and Ciscar's (2012) review suggests the debate over the vulnerability of the THC is still far from settled.

Even among models predicting an anthropogenic weakening of the THC, the impacts are not expected to be imminent (Latif et al. 2006, Zhang et al. 2011). It is expected that the THC will remain within the range of natural variability during the next several decades (Latif et al. 2006). Lenton et al. (2008) assess the global mean temperature change corresponding to a critical value of control to be about 3–5°C global warming and suggest a gradual transition time of about 100 years to a new state.

Many studies have focused primarily on the problems a collapse of the THC may pose to countries bordering the North Atlantic. Northwest Europe could experience substantial cooling (although underlying global warming trend still tends to dominate) (Gregory et al. 2005), reduced rainfall (Vellinga and Wood 2002), and additional increase in sea level of approximately 25-50 cm (Levermann et al. 2005; Vellinga and Wood 2008). Ecosystem impacts from a weakening/shutdown of the THC, however, are not expected to be confined to the North Atlantic, due to changes not only in temperature but also in precipitation patterns (Higgins and Vellinga 2004). The Northern Hemisphere is likely to experience reduced rainfall while a shutdown induced shift of the Intertropical Convergence Zone could lead to pronounced precipitation increases over South America and Africa.

Efforts to model the economic impacts of a THC shutdown or weakening include one analysis using an extension of the DICE model (Mastrandrea and Schneider 2001), and a few using variations of the FUND model (e.g., Link and Tol 2011). As discussed in Section 3, Mastrandrea and Schneider (2001) model the THC related damages as a series of hypothetical nonlinear enhancements to the DICE damage function where they assume damages range from 1-25% of global GDP for a complete shutdown and 0.5-12.5% loss in GDP from a weakening. Link and Tol (2011)'s analysis is somewhat more connected to the scientific literature on the THC in that the authors base the average temperature change expected from THC changes on Vellinga and Wood (2002). They use the FUND model to monetize damages in 2100 from temperature changes expected under a scenario in which a shutdown occurs with certainty and the temperature transition between the two states of the THC occurs linearly over a 30 year period (2070-2100).[25] Although this is a more rapid shutdown than expected in many models, it is consistent with paleo-data (Lenton and Ciscar 2012). Consistent with other studies using the FUND model, the key economic sectors affected are water resources and energy consumption, as well as cardiovascular and respiratory diseases among health impacts. Overall, the authors find that a complete THC shutdown has a relatively small negative effect on global welfare (-0.1% of global GDP in 2100), but impacts vary considerable across regions and some countries may be severely affected. National results are likely to be biased to some unknown degree, however, due to the omission of several impact categories, such as impacts on fisheries, tourism, precipitation, sea level rise, the distribution of extreme events in the North Atlantic, and the probability of transgressing monsoon tipping points in other regions. Lenton and Ciscar (2012) note that many of these omitted impacts are likely to be much more significant than those experienced from temperature changes alone.

Antarctic Bottom Water (AABW) formation. The stability of the Antarctic Bottom Water formation is another aspect of the great ocean conveyer belt that may be affected by climate change. Similar to the mechanism affecting the THC, freshening of the water in the Southern Ocean (SO) could cause the AABW to weaken (Seidov et al. 2005) or collapse (Bi et al. 2001), causing a cooling around Antarctica. Lenton et al. (2008) do not consider the AABW to be subject to a tipping point since more assessment is needed to establish the robustness of collapse and to assess the threshold at which it may occur. Recent research stresses the importance of the state of the AMOC (present state active mode vs. an off state) when analyzing the impact of a freshwater input in the Southern Ocean (Swingedouw et al. 2009). However, study of this potential climate "catastrophe" is still in its infancy. No studies have attempted to incorporate a possible weakening or shutdown of the AABW in assessing the economic consequences of climate change.

Collapse and/or Increased Volatility of Major Monsoon Seasons.

Collapse of West African monsoon (WAM)/Greening of the Sahel. The Sahel is an approximately 1000 km wide semi-arid belt across Northern Africa, bordered by the Sahara to the north and less arid

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[25] Link and Tol (2011) is an extension of Ceronsky et al. (2005) and Link and Tol (2004) with more detailed spatial resolution.

savanna regions to the South, that is irrigated by the West African monsoon (WAM) summer rains. There is little to no consensus in 21st century precipitation change projections for West Africa (Cook and Vizy 2006; Douville et al. 2006; Christensen et al. 2007; Giannini et al. 2008; Druyan 2011). However, since the WAM circulation is affected by sea surface temperatures, any changes in the Atlantic THC could also have implications for the WAM, and thus the Sahel region. According to one of the three IPCC (2007) models that produces a realistic present climate for the Sahel, it is thought that a weakening of the THC could contribute to warming in the Gulf of Guinea (Cook and Vizy 2006), disrupting the seasonal onset of the WAM (Chang et al. 2008) and its subsequent movement northward into the Sahel (Hagos and Cook 2007). In other words, there would be a southward shift in the WAM, which would further dry the Sahel (Chang et al. 2008, Lenton and Ciscar 2012). However, among the other two realistic IPCC models, one projects a wetter and greener Sahel (Cook and Vizy 2006; Patricola and Cook 2008), even if the WAM collapses, and the other find no significant change in precipitation (Lenton and Ciscar 2012). Lenton et al. (2008) assess that the global mean temperature change corresponding to a critical value of control for WAM collapse and greening of the Sahel to be about 3–5°C global warming and suggest a rapid transition time of about 10 years to a greener Sahel.

There are relatively few studies offering projections of the physical and economic impacts of changes to the WAM and the Sahel region. The greening of the Sahel could increase the carrying capacity of the region, with grasslands expanding into up to 45% of the Sahara, at a rate of up to 10% of Saharan area per decade (Claussen et al 2003). Shrub vegetation is also thought to increase due to increased water use efficiency under higher atmospheric CO_2 (Lucht et al 2006). While these impacts seem to be primarily regional, a diminishing feedback on global climate change could also result as the greening would absorb CO_2 and probably increase regional cloud cover (Allison et al. 2009). Given the significant uncertainty about the direction of physical impacts, there has been little study or speculation about the potential economic consequences of changes in the WAM, but a greener Sahel region is likely to include some positive impacts to agricultural productivity.

Collapse/Volatile Indian Summer Monsoon (ISM). The Indian Summer Monsoon refers to the rainy season that supplies the Indian sub-continent with about 80% of its annual rainfall. It is difficult to isolate the effect of climate change on the ISM, or to identify potential tipping point behavior beyond a critical threshold of warming, because the stability of the monsoon is thought to be likely already disrupted by brown haze, or soot, that acts to cool the land surface (Ramanathan et al. 2005, Meehl et al. 2008, Allison et al. 2009). Cooler land temperatures reduce the thermal contrast between land and sea that is required to build up a monsoon, although increasing CO2 may counteract this effect to some degree. The result may be increased volatility - where chaotic switches from active to weak monsoons could occur from one year to the next (Lenton et al. 2008)-, more complex changes in the strength and location of monsoons (Lenton and Ciscar 2012), or a potential collapse (Levermann et al 2009, Zickfield et al 2005). In a recent review, Turner and Annamalai (2012) find that models show generally wetter conditions over South Asia in the future, but model uncertainty remains high, especially regarding interseasonal variability. Another player in interannual variations in monsoon rainfall is the ENSO. Historically, above- (below-) average Indian monsoon rainfall has been generally associated with the cold (warm) phase of the ENSO, although this relationship has become markedly less clear since the 1980s (Kumar et al. 1999). Ramanathan et al. (2005) find the brown haze forcing could lead to a doubling of drought frequency within a decade.

In a country home to over a billion people and where 60% of agricultural production is rainfed, even small changes in monsoon patterns can have large economic impacts for India. There may also be tradeoffs or complementaries between impacts of brown haze aerosol emissions and greenhouse gases that need to be taken into account. Both have been found to have contributed to reduced rice harvests in India during the past two decades (Auffhammer et al. 2006). Since society can better plan and adapt to mean interannual changes than increased variability or changes on shorter timescales, a better understanding of the regional variation on subseasonal timescales will be key to assessing the most serious consequences of changes in monsoon patterns on affected populations (Turner and Annamalai 2012). Even with a robust monsoon, changes in the intensity of extreme events and the duration of drought spells could have devastating consequences. Several studies have found a decrease in the frequency of moderate-to-heavy rainfall events over most parts of India (e.g., Dash et al. 2009; Guhathakurtha et al. 2010) and a significant rise in the frequency and duration of monsoon breaks over India during recent decades (see Ramesh Kumar et al. 2009, Turner and Hannachi 2010). However an increase in frequency of extreme rainfall events (10 cm/day) has also been observed in some regions (Goswami et al. 2006; Guhathakurtha et al. 2011). Turner and Slingo (2009) find an intensification of both active and break events, although no change to the duration or likelihood of monsoon breaks.

Retreat of Tundra and Permafrost Thaw.

Tundra generally refers to a biome where the tree growth is hindered by low temperatures and short growing seasons. The soils in these regions, especially in the Arctic tundra, is mainly permafrost, or permanently frozen ground.[26] Global warming impacts on the tundra (and other permafrost regions) are of significant concern because they could lead to potentially large amplified warming feedback effects. First, rising temperatures could allow the northern boundary of the boreal forest to encroach on the tundra areas (specifically when regions exceed 1000 growing degree days above zero), leading to amplified warming as the trees obscure the snow. Second, the permafrost could thaw. Thawing of permafrost is of significant concern because this frozen soil holds vast amounts of carbon (e.g., 60 to 190 Pg of carbon frozen in arctic tundra soils alone and 20–60% of global soil carbon stores thought to be in soils of boreal forests and northward (Hobbie et al. 2000); ~1466 Gt C in permafrost (Tarnocai et al. 2009).[27] As the ground thaws, the carbon may be activated leading to enhanced methane and/or carbon dioxide emissions.

There is evidence to suggest both of these feedback effects are occurring. Summer warming trends are increasing shrub growth in the tundra (Chapin et al. 2005) and greening of the boreal forest (Lucht et al. 2002). Permafrost temperatures have risen by up to 2 °C, particularly in colder areas. The depth of soil above the permafrost that seasonally thaws each year has increased in Scandinavia, Arctic Russia west of the Urals, and inland Alaska. The southern limit of the permafrost retreated northward by 30 to 80 km in Russia between 1970 and 2005, and by 130 km during the past 50 years in Quebec (ACIA 2004). Emission increases accompanying permafrost thaw have also been reported – e.g., a 22–66% increase in methane emissions in Sweden (Christensen et al., 2004), a 10- fold increase in carbon dioxide in a boreal forest (Goulden et al., 1998).

Lenton et al. (2008) does not consider either the retreat of tundra or permafrost thaw to be climate tipping points since they do not exhibit nonlinear or threshold behavior. Models suggest the transition from tundra to boreal forest will be a continuous process (Schaphoff et al 2006, Lucht et al 2006, Joos et al 2001) and future projections of permafrost thaw, although substantial, are quasi-linear and cannot convincingly demonstrate threshold behavior (Stendal and Christensen 2002, Lawrence and Slater 2005). However, global circulation models are just beginning to represent simple permafrost dynamics, so the debate over the degradation rate, the stability of deeper permafrost, and magnitude of feedback effects continues (e.g., Lawrence and Slater 2005,Delisle 2007,Burn and Nelson 2006, Froese et al. 2008, Zimov 2009). Projections vary considerably on the exact amount of permafrost thaw under

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[26] Technical definition of permafrost is ground that is at or below 0C for at least two consecutive years.

[27] Abrupt reductions in Arctic summer sea ice extent also help to increase rapid warming on land and subsequent permafrost degradation (Lawrence et al. 2008b).

various climate scenarios, but models agree that the extent of permafrost will decrease and the active layer[28] will deepen (e.g., Lawrence et al. 2008a). See Table A2 for a comparison of 2100 projections across studies and IPCC scenarios (IPCC 2007).

Table A2. Published projections of permafrost degradation in 2100*

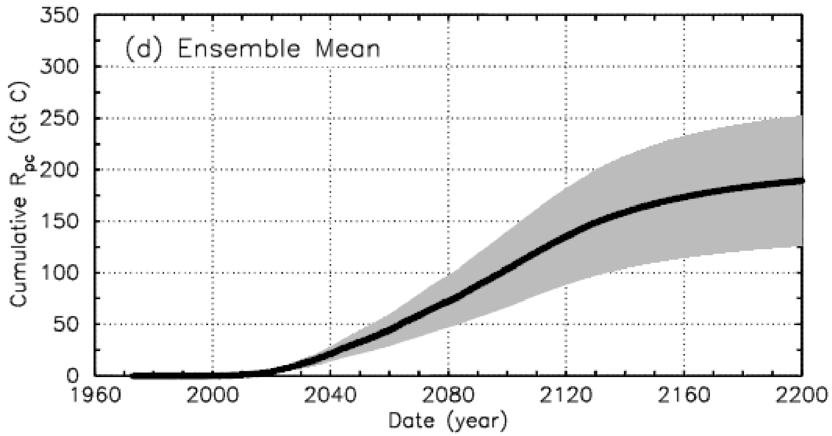
Study	Scenario(s)	Domain	Decrease in permafrost area (%)	Increase in active layer depth (ALT) (cm)
Marchenko et al. (2008)	A1B	Alaska	7.0**	162***
Zhang et al. (2008a)	B2, A2	Canada	16-20**	30-70
Zhang et al. (2008b)	B2, A2	Canada	21-24	30-80
Euskirchen et al. (2006)	A1B	Northern Hemisphere	27**	-
Saito et al. (2007)	A1B	Northern Hemisphere	40-57	50-300
Lawrence and Slater (2005)	A2, B1	Northern Hemisphere	60-90	50-300
Eliseev et al. (2009)	B1, A1B, A2	Northern Hemisphere	65-80**	100-200
Lawrence and Slater (2010)	A1B	Northern Hemisphere	73-88	-
Lawrence et al. (2008a)	A1B	Northern Hemisphere	80-85	50-300
Schaefer et al. (2011)	A1B	Alaska	22-61	69-105
Schaefer et al. (2011)	A1B	Canada	22-36	55-90
Schaefer et al. (2011)	A1B	Northern Hemisphere	20-39	56-92

*Adapted from Table 5 in Schaefer et al. (2011). **Calculated by Schaefer et al. (2011) from numbers or tables in text. ***Calculated by Schaefer et al. (2011) from estimated trends.

Some forecasts of the magnitude of the accompanying carbon feedback are also available. For example, Schaefer et al (2011) forecast a cumulative permafrost carbon flux to the atmosphere of 190 ± 64 Gt C by 2200. See Figure A3. They find that 46% of this release occurs after 2100, even though 80-90% of the thawing occurs before 2100.

Figure A3. Projected cumulative carbon flux from permafrost degradation*

[28] The active layer is the soil over the permafrost that freezes and thaws annually.



*Mean (± 1 standard deviation) projected cumulative permafrost carbon flux (Rpc) from degradation under various warming rates based on the A1B IPCC scenario. Figure taken directly from Schaefer et al. (2011).

Some economic studies mention the thawing of permafrost as a possible source of catastrophic or abrupt climate change but the permafrost climate feedback is not represented in current IAMs commonly used for policy analysis. A recent study by Lemoine and Traeger (2012) comes closest to trying to model an impact specific to permafrost thaw and incorporates it as a fixed, instantaneous and permanent doubling of climate sensitivity. Given the review above, it seems possible to at least rudimentarily represent the additional carbon flux from thawing permafrost and associated damages from additional warming in existing reduced form IAMs. More research and modeling is needed to incorporate other damage categories – e.g., valuation of ecosystem impacts from permafrost thaw.

Other.

Massive release of marine methane hydrates. Similar to the frozen soils of the tundra, areas under the sea floor store vast amounts of carbon. Between 500 and 10,000 GtC are thought to be stored under the marine continental shelf and slope sediment in the form methane hydrates, a crystalline structure of methane gas and water molecules (Brook et al. 2008). The concern is that as the oceans and eventually the sediment layer warms under anthropogenic forcing, a massive release of the methane could be triggered from these sea floors. Such a release would lead to significant amplified global warming effects, since once methane release events begin, each one adds to the warning thus promoting additional releases (Lenton et al. 2008). The timescale of the forcing needed for this to occur is assessed to be over 1,000 years into the future because it will take that long for the sediment to warm to the point of reaching the hydrate deposits (Lenton et al. 2008, Archer and Buffet 2005).

Ocean anoxia. Different mass extinctions of marine ecosystems have been linked to warming, ocean acidification, and ocean anoxia – i.e., a complete depletion of oxygen below the surface levels. Of these, ocean anoxia is most often discussed to potentially exhibit tipping point behavior under anthropogenic forcing (Lenton et al. 2008). Ocean anoxic events occur when the ocean is completely deleted of oxygen, causing mass extinctions. Anoxia is exacerbated by sustained phosphorus input to the ocean (e.g., from human agricultural fertilizer application), and higher temperatures are expected to further accelerate weathering processes which release phosphorus. Lenton et al. (2008) assess the long response time of deep ocean phosphorus means that deep ocean anoxia will not occur for at least 1,000 years, but the potential for nearer term widespread coastal anoxia requires further study.

Climate-induced Arctic ozone hole. It is thought that a climate change-induced ozone hole could form, especially over Europe (Austin et al 2003, Shindell et al 1998), as higher temperatures cool the stratosphere that supports formation of ice clouds, which in turn provide a catalyst for stratospheric ozone destruction (Lenton et al. 2008). Lenton et al. (2008) assess that the time needed for a qualitative change to occur may be quite short (less than 1 yr), but there has been little study of the extent to which global warming could trigger such an event, and the magnitude of the physical impacts.

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Table 1. Integrated Assessment Model Studies of Potential Climate "Catastrophes"

Study	Model	Catastrophic event analyzed	Way catastrophe is represented	Way damage function accounts for catastrophic impacts
Nordhaus (1994b); Nordhaus and Boyer (2000)	DICE	Generic catastrophe		Based on expert elicitation
Yohe (1996)	DICE augmented	Generic catastrophe	discrete (two state) probability distribution that allows for the small probability of catastrophe	Carbon emissions result in large damages – e.g., loss of 12.5% of GDP for an average global annual temperature anomaly of 2.5 ^{o}C compared to 1.6% at 3 ^{o}C.
Gjerde et al. (1999)	regionalized IAM in which a social planner maximizes an additively separable intertemporal welfare function	Generic catastrophe	probability of event occurring is calibrated to the expert elicitation of Nordhaus (1994a)	piecewise utility function where welfare loss is instantaneous and permanent by a fixed amount if event occurs
Keller et al. (2000)	DICE augmented	THC shutdown	Assume THC would collapse after passing atmospheric carbon, based on the work of Stocker and Schmittner (1997)	• ad-hoc estimate for the welfare loss associated with a shutdown • implicit assumption that after the threshold, welfare loss will be instantaneous, permanent
Mastrandrea and Schneider (2001)	DICE augmented	THC weakening or shutdown	allow THC shutdown threshold to be a function of both the carbon stock and the rate at which the stock is increasing.	• allow welfare impacts of THC changes to be endogenous • shutdown results in 1% - 25% global GDP loss above baseline. • no judgement is made about the likelihood of cases studied
Link and Tol (2004)	FUND augmented	THC shutdown	represent THC shutdown by adjusting regional temperature anomalies using Ranhmstorf and Ganopolski (1999).	Temperature changes fed into FUND damage function to determine welfare loss.
Nicholls et al. (2008)	FUND augmented	WAIS collapse	• ad-hoc melting scenarios, ranging from 0.5 to 5 m sea level rise by 2130	• Temperature changes fed into FUND damage function to determine welfare loss • Damages are a function of rate of sea level rise and its interactions with adaptation measures

Hope (2011)	PAGE 2009	Generic catastrophe	• probability of event occurring is zero until a given threshold is reached after which the probability begins to rise • probabilities chosen in a fairly ad-hoc manner	• permanent reduction in welfare, but it's not instantaneous. • transition period is considered uncertain, ranging 20-200 yrs • range of welfare impacts chosen fairly ad-hoc. Lower end of EU losses based on SLR damages in Anthoff et al. (2006). Damages in other regions are based on their coastline length relative to EU.
Lemoine and Traeger (2012)	DICE modified to consider parametric uncertainty in the temperature threshold and stochastic uncertainty in the temperature dynamics	two types of tipping points: • 1) increases effect of emissions on temp (e.g., rapid retreat of land ice sheets, releases from CH4 deposits); • 2) increases atmospheric lifetime of CO2 (e.g., weakening of carbon sinks)	• Tipping point 1 represented by increasing climate sensitivity from 3 deg to 4, 5, or 6. • Tipping point 2 represented by reducing CO2 decay rate, i.e., decreasing the transfer of CO2 out of the atmosphere by 25%, 50%, or 75%. • assume 2040 trigger (central point of the distribution) under no policy • passing threshold results in instantaneous permanent shock	Does not force modeled catastrophes as a direct shock to welfare, but assumptions regarding the magnitude of the effects are ad-hoc
Link and Tol (2011)	FUND augmented	THC shutdown	• temperature anomalies from shutdown based on OAGCM experiments • impact of the shutdown phased in linearly 2070-2100	Temperature changes fed into FUND damage function to determine welfare loss.
Ceronsky et al (2011)	FUND augmented	• THC weakening • large scale CH4 release from deep ocean	• assume event would occur with certainty • represent THC shutdown with regional temperature anomalies from Ranhmstorf & Ganopolski (1999). • Represent CH4 release with instantaneous fixed increase in CH4 emissions in 2050. Timing, level of the shift based on judgement. Sensitivity analysis around level	Temperature changes fed into FUND damage function to determine welfare loss.

Table 2. Description and Key Characteristics of Potential Climate "Catastrophes"

Potential "Catastrophe"		Description/Cause	Lenton et al. (2008)	
			Trigger level of global warming	Transition timescale to new state
1	Melting of Arctic summer sea-ice	Higher atmospheric temperatures and numerous feedback effects (e.g., reduced Arctic summer snowfall) cause the Arctic sea-ice to melt completely by late summer.	+0.5-2 C	~10 yr
2	Collapse of Greenland ice sheet (GIS)	Higher atmospheric temperatures and numerous feedback effects can commit to a retreat and complete melting of the ice sheet.	+1-2 C	>300 yr
3	Collapse of West Antarctic ice sheet (WAIS)	Higher atmospheric temperatures and numerous feedback effects can commit to a retreat and complete melting of the ice sheet.	+3-5 C	>300 yr
4	Change in amplitude/frequency/variability of ENSO	Many of the mechanisms and physical feedbacks that control the characteristics of ENSO are expected to be affected by rising GHG emissions – e.g., a weakening of tropical Pacific easterly trade winds, changes in surface ocean temperatures and ocean temperature gradients near the equator. Strong transient ENSO responses and shifts to new ENSO state are possible, but models are inconsistent in magnitude and direction of change.	+3-6 C	~100 yr
5	Dieback of Amazon rainforest	Climate change induced dieback of the Amazon rainforest is generally thought to be due to widespread reductions in precipitation and lengthening of the dry season, primarily due to more persistent El Nino conditions. However, land use change may also play a significant role in tipping point behavior.	+3-4 C	~50 yr
6	Dieback of Boreal forest	Boreal forests (contained in northern regions of Russia, Scandinavia, Canada and Alaska) are projected to be vulnerable to rising temperatures and other impacts of climate change, with increased water stress and increased peak summer heat stress leading the trees to be more vulnerable to pests, disease, mortality, and fires, along with decreased reproduction rates.	+3-5 C	~50 yr
7	Weakening/Shutdown of Atlantic Thermohaline Circulation (THC)	The THC, an ocean water circulation pattern responsible for a large fraction of northward heat transport of the Atlantic Ocean, may weaken or shutdown due to changes in water density and pressure gradients at high latitudes, especially the addition of freshwater into the North Atlantic from higher precipitation and ice melt and the warming of surface waters from higher atmospheric temperatures.	+3-5 C	~100 yr

8	Collapse of West African monsoon (WAM) /Greening of the Sahel	The West African monsoon (WAM) summer rains are affected by sea surface temperatures, so any changes in the Atlantic THC could also have implications for the WAM, and thus the Sahel region. A weakening of the THC could cause a shift in the WAM, with ramifications for precipitation in the Sahel, but there is significant uncertainty about the direction of physical impacts,	+3-5 C	~10 yr
9	Collapse/Volatile Indian Summer Monsoon (ISM)	The ISM refers to the rainy season that supplies the Indian sub-continent with about 80% of its annual rainfall. Increasing CO2 and temperatures, together with brown haze, affect the thermal contrast between land and sea needed to build up a monsoon. The result may be increased, chaotic volatility in monsoon strength, location, or even a potential collapse. Changes in ENSO may also affect ISM volatility.	N/A	~1 yr
10	Retreat of Tundra	Rising temperatures could allow the northern boundary of the boreal forest to encroach on tundra (a biome where the tree growth is hindered by low temperatures and short growing seasons), leading to amplified warming as the trees obscure the snow.	-	~100 yr
11	Permafrost thaw in Siberia	Rising temperatures can cause vast thawing of permafrost (carbon rich ground that is at or below 0C for at least two consecutive years), leading to significant amplified warming effects.	-	<100 yr
12	Weakening/Shutdown of Antarctic Bottom Water (AABW) formation	Similar to the THC, the AABW may weaken or even collapse due to freshening of the water in the Southern Ocean.	unclear*	
13	Massive release of marine methane hydrates	Rising ocean temperatures (and eventually sediment layer temperatures) could trigger a massive release of methane from sea floors, leading to significant amplified warming effects.	unclear	>1,000 yr
14	Ocean anoxia	Ocean anoxia occurs when the ocean is completely deleted of oxygen, causing mass extinctions. Anoxia is exacerbated by sustained phosphorus input to the ocean (e.g., from human agricultural fertilizer application), and higher temperatures are expected to further accelerate weathering processes which release phosphorus.	unclear	~10,000 yr
15	climate-induced Arctic ozone hole	A climate change-induced ozone hole could form as higher temperatures cool the stratosphere that supports formation of ice clouds, which in turn provide a catalyst for stratospheric ozone destruction.	unclear	<1 yr

*Either the trigger level of warming is not established or global warming is not the only or the dominant forcing.

Table 3. Recent Ranking or Categorization of Potential Climate "Catastrophes"

	Potential "Catastrophe"	**"Policy Relevant" Tipping Point** (Lenton et al. 2008)	**Tipping Points "Of Greatest Concern"** (Allison et al. 2009)*	**Relative likelihood of occurring** (Lenton et al. 2011)**	**Relative impact** (Lenton et al. 2011)**
1	Melting of Arctic summer sea-ice		X	High	Low
2	Collapse of Greenland ice sheet (GIS)	X	X	Med-High	Med-High
3	Collapse of West Antarctic ice sheet (WAIS)	X	X	Med	High
4	Change in amplitude/variability of ENSO		X	Low	Med-High
5	Dieback of Amazon rainforest	X	X	Med	Med
6	Dieback of Boreal forest		X	Low	Med-Low
7	Weakening/Shutdown of Atlantic Thermohaline Circulation (THC)		X	Low	Med
8	Collapse of West African monsoon (WAM) /Greening of the Sahel	X	X	Med-Low	High
9	Collapse/Volatile Indian Summer Monsoon (ISM)	X	X	(not considered)	(not considered)
10	Retreat of Tundra			(not considered)	(not considered)
11	Permafrost thaw in Siberia			(not considered)	(not considered)
12	Weakening/Shutdown of Antarctic Bottom Water (AABW) formation			(not considered)	(not considered)
13	Massive release of marine methane hydrates			(not considered)	(not considered)
14	Ocean anoxia			(not considered)	(not considered)
15	climate-induced Arctic ozone hole			(not considered)	(not considered)

*Allison et al. (2009) define tipping points of "greatest concern" as those that are "the nearest (least avoidable) and those that have the largest negative impacts."

** Lenton's (2011) assessment of relative likelihoods and impacts are assessed on a five-point scale: low, low-medium, medium, medium-high and high. His likelihood rankings are based on his reviews of the literature and expert elicitation (Kriegler et al 2009). Impacts are based on limited research (Lenton et al. 2009) and subjective judgment, and are relative to the one system (THC) with multiple impacts studies. Impacts are considered on the full 'ethical time horizon' of 1,000 years, assuming minimal discounting of impacts on future generations.

Table 4. Scope for Near Term IAM Modeling Improvements?

	Potential "Catastrophe"	Likelihood of significant physical impacts occurring this century*	Scientific consensus in how physical impacts will unfold?**	Physical endpoints for which (at least 21st C) projections are available
1	Melting of Arctic summer sea-ice	High, changes already observed	More	September sea ice extent, regional winter temperature and precipitation impacts
2	Collapse of Greenland ice sheet (GIS)	Medium-High	More	Sea level rise
3	Collapse of West Antarctic ice sheet (WAIS)	Medium-High	More	Sea level rise
4	Change in amplitude and/or variability of ENSO	Medium	Less	change in ENSO amplitude, frequency, and variability ??
5	Dieback of Amazon rainforest	Medium-High	Less	Change in tree cover, vegetation and soil carbon, precipitation, amplified regional warming; pdfs for change in vegetation carbon storage (kg C m-2) by region
6	Dieback of Boreal forest	Medium	More	
7	Weakening/Shutdown of Atlantic Thermohaline Circulation (THC)	Medium-Low	Less	Regional change in temperature, precipitation, sea level from hypothetical instantaneous hosing experiment
8	Collapse of West African monsoon (WAM) /Greening of the Sahel	Medium-Low	Less	
9	Collapse/Volatile Indian Summer Monsoon (ISM)	High, changes already observed	Less?	
10	Retreat of Tundra	High, changes already observed	More	
11	Permafrost thaw	High, changes already observed	More	Change in active layer depth and extent of permafrost area, accompanying atmospheric carbon flux
12	Weakening/Shutdown of Antarctic Bottom Water (AABW) formation	Needs more study	Less	
13	Massive release of marine methane hydrates	Low	More?	
14	Ocean anoxia	Low in deep ocean. Coastal areas need more study	More?	
15	climate-induced Arctic ozone hole	Needs more study	More?	

*This does not necessarily mean a tipping point is transgressed this century.

**By consensus we mean a general understanding of how earth systems will respond (e.g., which physical endpoints will be affected and the direction of impact on these endpoints) rather than scientific agreement on the detailed modeling and projections of physical impacts.

Table 5. Primary Physical Impacts Leading to Economic Consequences of Climate "Catastrophes"*

Potential "Catastrophe"		Changes in Temperature		Sea Level Rise	Changes in Precipitation	Shifts in frequency/magnitude of extreme weather events**	Other – e.g., impacts on ecosystems/species/bidiversity?
		Direct	From additional GHG feedback				
1	Melting of Arctic summer sea-ice	X (hemispheric)	X (CO2 & CH4)		X	X	X
2	Collapse of Greenland ice sheet (GIS)	X (local)	X (CO2 & CH4)	X (global)	X		
3	Collapse of West Antarctic ice sheet (WAIS)	X (local)	X (CO2 & CH4)	X (global)	X		
4	Change in amplitude/variability of ENSO	X (regional)	X (CO2)	X (regional)	X	X	X
5	Dieback of Amazon rainforest	X (regional)	X (CO2)		X	X	X
6	Dieback of Boreal forest	X (local)	X (CO2)		X?	X	X
7	Weakening/Shutdown of Atlantic Thermohaline Circulation (THC)	X (hemispheric)	X (CO2)	X (regional)	X	X	X
8	Collapse of West African monsoon (WAM) /Greening of the Sahel	X (regional)			X	X	X
9	Collapse/Volatile Indian Summer Monsoon (ISM)	X (local summer)			X	X	
10	Retreat of Tundra	X (regional?)					X
11	Permafrost thaw in	X (regional?)	X				X

	Siberia						
12	Weakening/Shutdown of Antarctic Bottom Water (AABW) formation	X	?	?	?	?	?
13	Massive release of marine methane hydrates		X (CH4)				X?
14	Ocean anoxia	?					X
15	climate-induced Arctic ozone hole	X (regional)					X

* This assessment is based on Lenton and Ciscar (forthcoming) and our review of scientific literature (see Appendix). An "X" indicates the physical impact is expected as a result of the "climate catastrophe" occurring. For some columns, additional information is provided in parentheses about the expected extent of the impact. Shaded boxes indicate physical impacts that have received the most attention by scientists – either because they are expected to be the largest/most significant sources of economic damage associated with the "climate catastrophe" s or because more is known to date about how these physical endpoints will evolve.

**e.g., drought, floods, fire, hurricanes, other storms.