Incorporating ‘catastrophic’ climate change into policy analysis†

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Although existing economic research is informative with regard to the importance of including potential ‘catastrophic’ climate change impacts 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. This article provides an important starting point for a discussion of how to improve economic modelling of potential large-scale impacts of climate change. It considers how the term ‘abrupt climate change’ has been used in the scientific literature to describe changes in the climate system and carefully reviews the characteristics of the events that have been discussed in this context. The findings are compared to the way in which the economic literature has modelled potential economic and human welfare impacts of these ‘catastrophic’ events. In general, the economics literature is found to have modelled such impacts in a uniform way that fails to account for differences in relevant end points and time-scales. The result is policy recommendations based on events that do not resemble those of concern. Better treatment of these events in integrated assessment modelling would help ensure that future research efforts can serve as meaningful policy input.

Policy relevance
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. Existing economic modelling has provided evidence that, in general, potential climate catastrophes might significantly influence the optimal path of abatement. However, there is a need to move beyond experiments that are detached from important details of the climate problem to substantively inform the policy debate and improve analyses of GHG mitigation benefits (e.g. social cost of carbon estimates). This article identifies areas where modelling could be improved even within current frameworks and others where additional work is needed.

Keywords: climate change; integrated assessment; social costs; welfare impacts

1. Introduction
It is common within the academic and public discourse on climate change for the term ‘catastrophe’ to be invoked when describing possible outcomes of a changing climate and in justifying particular responses to the problem. It has been suggested that the potential for abrupt, large-scale ‘catastrophic impacts’ due to climate change is the most important aspect for determining the optimal level of response (Pindyck & Wang, 2012; Weitzman, 2009) and 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’ (Pindyck, 2012). Thus, it is perhaps not surprising that analyses of GHG mitigation benefits are often criticized for failing to adequately capture catastrophic impacts (e.g. National Academy of Sciences, 2010; Tol, 2009). However, despite the seeming importance of such potential climate change-related events, there has been little progress in defensibly integrating catastrophic impacts into analyses of the benefits of climate policy.

One obstacle that has impeded progress on this front is the inconsistent and sometimes nebulous way in which the expression ‘catastrophic impacts’ has been used (Hulme, 2003). The term often refers to any climate-induced impact that exhibits one or more characteristics: relatively sudden occurrence, irreversible transition to a new state after crossing a threshold, and relatively large physical or welfare impacts. In addition, some researchers consider catastrophic impacts to necessarily result from low-probability events. For this reason the types of impacts covered under the catastrophic label are often numerous and heterogeneous, 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 have even argued for establishing a global threshold for climate change, below which there is negligible risk of violating ‘planetary boundaries’ that ‘define the safe operating space for humanity’ … [and] avoid crossing threshold levels of key variables ‘with deleterious or potentially even disastrous consequences for humans’ scales’ (Rockstrom et al., 2009, p. 472).¹

In public discourse, catastrophic impacts are often invoked as a seemingly monolithic occurrence,² a tendency that is also often present in economic analyses of such events. By assuming uniformity, researchers have severely limited their ability to substantively inform policy discussions. This tendency may arise from an absence of literature that summarizes significant differences between potential large-scale climate events and what that means for incorporating them into economic analysis. In addition, many economic modelling efforts fall substantially short in incorporating scientific evidence regarding the causes, likelihood, and potential physical impacts of such climate change-induced events. While one expects a natural lag in the incorporation of new scientific findings into economic models, this shortcoming appears to stem more from fundamental differences between disciplines as to what constitutes relatively rapid or large changes (the scientific literature does not even use the term catastrophe, instead relying on the phrase ‘abrupt climate change’) 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 & Ciscar, 2013).

This article provides an important starting point for discussions of how to improve the economic modelling of potential large-scale impacts of climate change in order to understand how they influence assessments of socially efficient climate policy. Section 2 considers how the term ‘abrupt climate change’ has been used in the scientific literature to describe changes in the climate system. Section 3 then discusses how the economic literature has modelled these ‘catastrophic’ events.³ Based on this review of the economic and scientific literatures, Section 4 suggests a path forward for better incorporating these events into integrated assessment modelling, identifying ways in which the modelling could be improved even within current integrated assessment model (IAM) frameworks and where additional work is needed.
2. Catastrophic impacts from the scientific perspective

The scientific literature generally does not use the language of ‘catastrophe’ to the extent the term is used in the economics literature, policy discussions, and public discourse. Rather, natural scientists have focused on the definition and study of ‘abrupt climate change,’ and in the translation across disciplines an implicit mapping between the two terms has frequently occurred (i.e. abrupt climate change = catastrophe). An often cited definition of abrupt climate change 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’ (National Research Council [NRC], 2002, p. 14). This characterization captures two of three salient aspects of the typical use of the term in the scientific literature. First, the event occurs relatively quickly. Second, it causes a natural system to move to a new steady state. The scientific literature has also employed the term ‘surprise’, which the IPCC (1996) defines as the rapid, non-linear response of a natural system to anthropogenic forcing. This definition highlights a third important aspect of such an event: it could potentially result in a relatively large impact. In particular, the potential for relatively abrupt shifts in the states of natural systems ‘could be considered dangerous, because [they] would have major global consequences’ (IPCC, 2007a, p. 818) and the possibility that changes are so large or occur so rapidly that ‘human and other natural systems have difficulty adapting’ (NRC, 2002, p. 14; Posner, 2004).

2.1. Threshold or tipping point behaviour

Climate change-related events described in this manner are often associated with crossing a threshold in the Earth system, or ‘tipping point’, after which a relatively small perturbation in radiative forcing can result in a large, sudden change in the climate system (e.g. Kriegler, Hall, Held, Dawson, & Schellnhuber, 2009; Perrings, 2003; Schneider, 2003; Schlesinger et al., 2007). 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 behaviour (see Sheffer, Carpenter, Foley, Folkes, & Walker, 2001; Holling, 1973; May, 1977). For instance, Sheffer, Carpenter, Foley, Folkes, and Walker (2001) note that a shallow lake with rich vegetation could abruptly change from clear to turbid water in reaction to increased nutrient loadings. When this occurs, vegetation dies off and the diversity of lake life declines. Such a change in state typically consists of three basic components (NRC, 2002): a trigger (in the case of the lake, added nutrients), an amplifier (the mechanism through which a small change in the lake causes a much larger result), and a source of persistence (fish reinforce the turbidity in the lake, making the new state stable and self-reinforcing).

It is possible to similarly characterize many of the Earth systems affected by climate change using these three basic components of threshold or tipping point behaviour. A rise in global mean temperature due to increases in the atmospheric concentration of GHGs could trigger changes within a component of the Earth system (e.g. Alley et al., 2003; IPCC, 2007a; NRC, 2002). 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 (e.g. complete collapse of ice sheets, substantial dieback of the Amazon forest). Finally, the new state may exhibit persistence, whereby the Earth system eventually settles into a new but fundamentally different stable state that is irreversible (e.g. IPCC, 2007a, 2007b; NRC, 2002) or reversible only over very long timescales (Perrings, 2003; Schneider, 2003).
The analogy with other natural systems ends here, however. While a lake ecosystem 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 a given threshold within a particular system.

Although much of the focus with regard to climate change has been on events that result from the crossing of a threshold into a new stable equilibrium, Lenton et al. (2008) 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’ (Lenton et al., 2008, p. 1786). This characterization allows for cases where the system may potentially bounce between states after the threshold is crossed. However, 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.

2.2. Timescales, geographic breadth, and climate end points
Scientific definitions of catastrophe also encompass a wide range of timescales, geographic breadth, and climate end points. Events described in the scientific literature as resulting in ‘rapid’, ‘sudden’, or ‘abrupt’ Earth system changes can range in timescale from years (e.g. Alley et al., 2003; Clark, Piasias, Stocker, & Weaver, 2002; NRC, 2002; USCCSP, 2008) to a few centuries (e.g. Shindell, 2007), and sometimes even 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 still represents less than 5% of time spent in the previous state (Barnosky et al., 2012). The geographic scale of the event’s impact may be regional (e.g. Western Europe in the case of changes in the thermohaline circulation (THC) 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 that an event would qualify as a potential catastrophe when it occurs on a country- or even continent-wide basis (e.g. Clark et al., 2002; Lenton et al., 2008; NRC, 2002; USCCSP, 2008). Posner (2004) proposes limiting the definition of a catastrophe to events that could end civilization in its current form. Lenton et al. (2008) proposes a short list of ‘policy relevant tipping points’ based Earth system changes that may be triggered within this century and those that would undergo a qualitative change within this millennium.

2.3. Uncertainty
Given the high degree of uncertainty inherent in identifying and quantifying the potential causes of abrupt climate change, particularly near thresholds where the behaviour of natural systems can
become unpredictable (Alley et al., 2003), large error bounds exist around when a catastrophic event might be triggered, how the transition may occur, and what the ultimate impacts could be (e.g. Keller, Tol, Toth, & Yohe, 2008; Schlesinger et al., 2007). Perrings (2003) notes that the nature of the uncertainty will be inherently difficult to characterize when the full set of possible outcomes and the probability distributions of the outcomes are largely unknown. However, some researchers have attempted to better classify and understand the uncertainties associated with these events (see Lenton, 2011; Lenton et al., 2008).

Schneider (2003) argues for differentiating between abrupt events that are imaginable or expected and those that are ‘true surprises’ where the outcome is unknown. In the former case, even with all the inherent uncertainties discussed above, it may be possible to bring modelling expertise to bear with regard to potential impacts. In the latter case it may only be possible to ‘identify imaginable conditions for surprise’ (Schneider, 2003, p. 5). Noting this important caveat, the next section discusses how economists currently define and model catastrophes.

### 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, Williams (2009) defines abrupt climate change as fast enough – a decade or two – that adaptation is impossible even for the richest countries. Despite the importance of the timescale in economics, Hulme (2003) notes that this 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’ (p. 2003).

The economics literature has typically assumed much shorter timescales over which impacts will become fully realized. This disconnect is indicative of the more abstract way economists tend to use the term climate ‘catastrophe’. 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 timescale impacts will unfold is rarely evaluated. The disconnect may also stem from the practice of discounting, which defines society’s preference for allocating scarce resources across time. In the present context, discounting will place a practical limit on what is typically viewed as a catastrophic welfare loss. Economists typically measure economic damages associated with an increase in global mean temperature in terms of the change in societal welfare or foregone consumption equivalent in future years, discounted to the present. At positive discount rates, impacts thousands of years in the future are quantitatively negligible in present value terms.5

This section first examines the theoretical evidence to support the assertion that climate catastrophes may play an important role in understanding socially efficient abatement policy. Then it reviews how the economics field has chosen to model ‘catastrophes.’

#### 3.1. Economic theory of catastrophic events

The importance of including low-probability but potentially high-impact catastrophic events in an economic modelling 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 an uncertain threshold, at which time a discontinuity occurs and social welfare immediately falls to a subsistence consumption level. Within this setup she finds the potential for a catastrophe can lead to multiple market equilibria, suggesting such events could have strong policy implications.

Subsequent studies extend this theoretical framework to climate change, allowing for adaptation (Tsur & Zemel, 1996) or for the potential that a policy maker learns about expected damages over time (e.g. Baranzini, Chesney, & Morisset, 2003). These studies continue to find that, theoretically, the potential for catastrophic events induced by climate change could have significant policy implications in terms of the optimal abatement level. All of these theoretical studies maintain the assumption the catastrophe is unavoidable, and that crossing the threshold results in instantaneous and permanent economic damages of a fixed amount.

Climate change poses a unique problem for economic modelling in that mitigation requires large sunk costs in the near term with highly uncertain benefits occurring in the far future. Hendricks (1992) and Pindyck (2000) use 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. They find that the irreversible nature of abatement investments and uncertainty regarding their net social benefit imply that it may be optimal to delay mitigation to allow some uncertainty to be resolved. Baranzini et al. (2003) extend this concept to account for the possibility of a sudden exogenous 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. To understand the theoretical implications of failing to couple mitigation efforts and the potential for climate-induced catastrophes, Fisher and Narain (2003) extend Baranzini et al.’s (2003) real options framework and find that when the risk is assumed to be unavoidable (i.e. independent of abatement policies) the irreversible nature of investments in abatement leads 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 a function of emissions, its presence results in an increase in the theoretically optimal level of abatement (Castelnuovo, Moretto, & Vergalli, 2003).

3.2. Catastrophic events in IAMs

While the theoretical work on potential climate catastrophes provides strong motivation for incorporating such events into economic modelling, how best to reflect them within empirical modelling frameworks remains an open question. Quantitative analysis of climate change policy is often carried out with the aid of IAMs, which represent the complex interactions between natural Earth and human/economic systems. Those IAMs that consider ‘damages’ from climate change are designed to estimate the welfare loss in consumption-equivalent terms from impacts to both market goods (e.g. agriculture, energy) and non-market goods (e.g. biodiversity, human health). In general, these models exist in a simplified, highly aggregated form. For example, the Dynamic Integrated Model of Climate and the Economy (DICE) model represents the global welfare implications of climate change as a proportional loss of economic output that grows by the square of the average annual global temperature anomaly (Nordhaus, 2008; Nordhaus & Boyer, 2000). The Climate Framework for Uncertainty, Negotiation,
and Distribution (FUND) model (e.g. Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b) and the Global Change Assessment Model (GCAM) (Calvin et al., 2009) provide more detailed representations of natural and human/economic systems along with finer geographic and sectoral resolution, but the additional complexity brings significant computational burden to some types of uncertainty analysis. This section reviews how IAMs have been used to model types of events the scientific literature refers to as catastrophes (see Table 1 for a summary of studies).

Many IAM studies have modelled generic climate catastrophes, abstracted from the specifics of the natural science and economics of such events. Several early modelling attempts relied on the results of an expert elicitation to help parameterize the damage function in a way that accounted for the probability of a climate catastrophe (e.g. Gjerde, Grepperud, & Kverndokk, 1999; Nordhaus, 1994b; Nordhaus & Boyer, 2000). The survey asked a panel of 19 experts about the probability of losing 25% of global world product in each of three scenarios (3 °C mean global temperature anomaly in 2090, 6 °C in 2175, and 6 °C in 2090) (Nordhaus, 1994a). Yohe (1996) explicitly accounts for the possibility of low-probability, high-impact events by augmenting the original DICE model 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 gross domestic product (GDP) for an average global annual temperature anomaly of 2.5 °C compared to 1.6% at 3 °C). While the sophistication of these modelling efforts varies in some respects (e.g. Gjerde et al., 1999, implement regional impacts), the link between economic welfare and the potential high-impact natural event is often left vague and relatively undeveloped. Welfare impacts are still modelled as instantaneous and permanent in the event of a catastrophe.

A few articles improve on this generic approach by adjusting the model to account for differences in impacts across specific catastrophic events or allowing for welfare effects to phase in over time. Although more sophisticated, these are few in number and still not necessarily predicated on the existing scientific literature. Nicholls, Tol, and Vafeidis (2008), for example, advance 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, they model West Antarctic ice sheet (WAIS) melting occurring within as little as 100 years, which is inconsistent with the natural science community view that complete WAIS melting is not thought to be possible in less than 300 years (Lenton et al., 2008).7 Lemoine and Traeger (2012) consider how a variety of potential catastrophic events might affect optimal climate policy as well as the social cost of carbon (SCC). Unlike earlier studies, they differentiate between two types of climate tipping points. The first increases feedbacks that amplify the effect of emissions on temperature; it is said to be representative of rapid retreat of land ice sheets or climate-induced releases of methane deposits and is modelled with a doubling of the equilibrium climate sensitivity. The second increases the atmospheric lifetime of CO2; this is said to be representative of weakening of carbon sinks and is modelled as a decrease in the decay rate of atmospheric CO2. They use a modified version of the DICE model to consider both parametric uncertainty in the temperature threshold that will trigger a given catastrophe, and stochastic uncertainty in the temperature dynamics. Although this study uses the typical assumption that passing a given climate threshold results in an instantaneous and permanent shock to natural systems, it improves on the previous literature by not translating this to a direct shock to welfare. However, like Nicholls et al. (2008), the assumptions regarding the magnitude of the effects are ad hoc and not developed through rigorous scientific assessment. In addition, the modellers only consider one potential catastrophe at a time.
| Study                        | Model       | Catastrophic event analysed | Way catastrophe is represented                                      | Way damage function accounts for catastrophic impacts |
|-----------------------------|-------------|----------------------------|---------------------------------------------------------------------|------------------------------------------------------|
| **Nordhaus (1994b)**; Nordhaus and Boyer (2000) | DICE        | Generic catastrophe        | Based on expert elicitation                                         | Carbon emissions result in large damages – e.g. loss of 12.5% of GDP for an average global annual temperature anomaly of 2.5°C compared to 1.6% at 3°C. |
| 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°C compared to 1.6% at 3°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) | Carbon emissions result in large damages – e.g. loss of 12.5% of GDP for an average global annual temperature anomaly of 2.5°C compared to 1.6% at 3°C. |
| Keller et al. (2000)         | DICE augmented | THC shutdown             | Assume THC would collapse after passing an atmospheric carbon threshold, based on the work of Stocker and Schmittner (1997) | Ad hoc estimate for the welfare loss associated with a shutdown |
| 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 | Ad hoc estimate for the welfare loss associated with a shutdown |
| Link and Tol (2004)          | FUND augmented | THC shutdown             | Represent THC shutdown by adjusting regional temperature anomalies using Rahmstorf and Ganopolski (1999) | Ad hoc estimate for the welfare loss associated with a shutdown |

Continued
| Study                     | Model               | Catastrophic event analysed | Way catastrophe is represented                                                                 | Way damage function accounts for catastrophic impacts |
|--------------------------|---------------------|----------------------------|------------------------------------------------------------------------------------------------|-----------------------------------------------------|
| 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 |
|                          |                     |                            |                                                                                                  | • Probabilities chosen in a fairly ad hoc manner    |
|                          |                     |                            |                                                                                                  | • Permanent reduction in welfare, but it is not instantaneous |
|                          |                     |                            |                                                                                                  | • Transition period is considered uncertain, ranging from 20 to 200 years |
|                          |                     |                            |                                                                                                  | • Range of welfare impacts chosen fairly ad hoc; lower end of EU losses based on sea level rise damages in Anthoff et al. (2006); damages in other regions are based on their coastline length relative to that of the EU |
| 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    |

Continued
| Study                          | Model                        | Catastrophic event analysed                                                                 | Way catastrophe is represented                                                                 | Way damage function accounts for catastrophic impacts                                                                 |
|-------------------------------|-----------------------------|---------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| 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: • Increases effect of emissions on temperature (e.g. rapid retreat of land ice sheets, releases from CH₄ deposits) • Increases atmospheric lifetime of CO₂ (e.g. weakening of carbon sinks) | • Tipping point 1 represented by increasing climate sensitivity from 3 °C to 4 °C, 5 °C, or 6 °C | Does not force modelled 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 GCM 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                                                                               | • Assume event would occur with certainty                                                      | Temperature changes fed into FUND damage function to determine welfare loss                                                |
|                               |                             | • Large-scale CH₄ release from deep ocean                                                    | • Represent THC shutdown with regional temperature anomalies from Rahmstorf and 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 |                                                                                                                              |
Cai, Judd, and Lontzek (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. Like previous work, they find that the optimal climate policy may be substantially influenced by the potential for catastrophic events, but again the magnitude and triggering of the events’ effects are quantitatively ad hoc. However, they provide significant contributions to the literature by also including macroeconomic uncertainty and showing that the result is sensitive to the way risk aversion is characterized in the model. The common approach to preference specification in the literature combines society’s preference for trading off consumption over time and their aversion to risk. As a result, consideration of higher rates of risk aversion thought to be more realistic implies a higher discount rate thought to be unrealistic. Cai et al. (2012) allow for a more robust description of preferences that allows for the separation of these parameters and show that the optimal climate policy when considering the potential for catastrophes is sensitive to higher rates of risk aversion.

One of the few examples where a potential climate catastrophe is not modelled as an instantaneous shock is Hope (2011). That research used the PAGE09 integrated assessment model. 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 the probability begins to rise. If a climate catastrophe is triggered, there is a permanent reduction in welfare, but its impact is phased in over time. The transition period is uncertain, ranging from 20 to 200 years. The probability that an event occurs and the range of welfare impacts are fairly ad hoc. The lower end of the range for welfare losses in the EU from a potential climate catastrophe are based only on potential sea-level rise damages in Anthoff, Nicholls, Tol, and Vafeidis (2006), but no justification is provided for the upper end of the range. Furthermore, potential damages incurred by other regions due to the climate catastrophe are based on scaling the welfare loss in the EU by the length of the region’s coastline relative to the that of the EU. The model also includes non-catastrophe-related market and non-market damages from an increasing global temperature anomaly along with damage from sea-level rise. These three damage categories are also calibrated for the EU and then scaled to other regions based on the length of their coastline relative to that of the EU.

While most studies model a generic event, there are several cases where a specific event has been modelled, most commonly the potential shutdown of the Atlantic THC. Link and Tol (2011) use existing results from an atmospheric and ocean general circulation model (GCM) to determine the impact that a THC shutdown would have on regional temperature anomalies and feed this information into a nationalized version of the FUND model to estimate welfare loss, assuming the impact of the shutdown begins in 2070 and increases linearly until its full effect is reached in 2100. The FUND model provides a bottom-up analysis of the damages by modelling the impact of climate change on individual sectors (e.g. energy, agriculture, human health) and then aggregating across the sectors.

Ceronsky, Anthoff, Hepburn, and Tol (2011) consider a similar experiment using an updated version of the FUND model to look at the effect of a potential THC weakening and large-scale methane releases from the deep ocean, assuming one of these events will occur with certainty. Following Link and Tol (2004), they represent the impact of a THC shutdown by adjusting regional temperature anomalies using the results of Rahmstorf and Ganopolski (1999). The methane release is modelled as an instantaneous fixed increase in methane emissions starting in 2050, and the impact is then estimated through the effect that the additional emissions have on temperature and also sea-level rise.
(through the temperature). Both the time and level of the shift in emissions are based on the judgement of the researchers, and sensitivity analysis is only conducted around the level of the shift.

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

Like Keller et al. (2000), Mastrandrea and Schneider (2001) start with the DICE model but expand on the previous analysis by modelling the THC shutdown threshold as a function of the carbon stock and the rate at which the stock is increasing (i.e. making it endogenous). This addition is made 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. They also allow a partial shutdown of the THC to feed back into the damage estimates. Uncertainty is not over the location of the threshold associated with the natural event but with the social welfare losses that would result (i.e. a full THC shutdown could result in an additional loss between 1% and 25% of global GDP above baseline climate damages). This representation of the Earth system change is more firmly rooted in the scientific literature, but the range of welfare impacts is not based on the results of a damage assessment and no judgment is made about the likelihood of any of the cases studied.

Lenton and Ciscar (2013) note that there is a ‘huge gulf between natural scientists’ understanding of climate tipping points and economists’ representations of climate catastrophes in integrated assessment models’ (p. 585). Such a criticism appears warranted given that the most commonly applied description of a climate catastrophe is an event that 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. Likewise, Hulme (2003) noted that estimates of social welfare loss associated with potentially catastrophic climate events are not grounded in ‘substantive environmental, economic, or social research’ (p. 2011). While Hulme (2003) was particularly focused on the example of a THC shutdown, this review suggests that most economic studies have failed to represent natural system physical impacts and associated welfare losses from such events in a rigorous fashion. A few newer studies have developed bottom-up analyses to estimate welfare losses of a climate induced catastrophe (e.g. Ceronsky et al., 2011; Link & 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).

4. Moving forward

This section helps to lay the foundation for improving the economic modelling of potential climate catastrophes. Section 4.1 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 (for a detailed review see the supplemental appendix in the online version of this article at http://dx.doi.org/10.1080/14693062.2014.864947). The focus is on aspects of the physical science that are
particularly relevant to modelling the economic impacts of each event. The assessment also prioritizes areas that may initially command more attention based on the likelihood that an event will occur, the degree of scientific consensus on how and when physical impacts will unfold, and the availability of probabilistic projections for physical end points. Note, however, that this summary is written from the perspective an economist and is not intended to be an assessment of the scientific merits of particular studies.

Based on this review, Section 4.2 offers thoughts on potential near-term modelling improvements that would allow for enhanced quantitative analyses of climate catastrophes in the economics literature. It is intended to help modellers identify events that can be better incorporated into IAMs now, and where additional research and modelling 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. However, while there is a paucity of data in many cases, there appears to be enough information available to significantly improve the way in which climate catastrophes are currently represented in economic analyses.

4.1. Overview of potential climate ‘catastrophes’

The starting point for this review is 15 often-discussed large-scale Earth system changes that may be induced as a result of climate change. Many of these have been characterized in the scientific literature as exhibiting ‘tipping point’ behaviour. Table 2 offers a brief description of each potential ‘catastrophe,’ the level of global warming needed to trigger the event, and the timescale over which the transition to a new state is expected to occur. Considerable variation in these characteristics is observed. 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 the El Nino Southern Oscillation (ENSO) and the West African monsoon). Second, based on Lenton et al. ‘s (2008) assessment of the amount of warming needed to pass potential critical thresholds, it is possible that some thresholds may have already been crossed (e.g. loss of Arctic summer sea ice). However, in a majority of the cases significant additional warming over the present day would be required to trigger an irreversible shift in the equilibrium of these systems (although less than the warming expected over the next couple of centuries with no additional policies). Third, there is considerable variation in the timescales over which physical impacts are expected to unfold, where the full impact may not be realized for decades, centuries, or even millennia. 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 events are poorly represented when modelled as a low probability of an instantaneous change in global welfare.

Finally, the events listed in Table 2 are not necessarily independent of each other, so the occurrence of one can increase the risk of others being realized. For example, changes in the frequency or magnitude of the ENSO will probably affect precipitation patterns in South America and thus influence the probability of massive dieback of the Amazon rainforest. Similarly, a collapse of the WAIS is expected to encourage thawing of low-lying permafrost by flooding it, and in turn additional melting of the Greenland Ice Sheet (GIS). It is for this reason that Lenton and Ciscar (2013) call on IAM modellers to consider all tipping points together instead of in isolation. While it may not be possible to adequately include all
| Potential 'catastrophe' | Description/cause | Trigger level of global warming $^b$ | Transition timescale to new state $^c$ |
|-------------------------|-------------------|-------------------------------------|------------------------------------------|
| 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 year |
| 2 Collapse of GIS | Higher atmospheric temperatures and numerous feedback effects can commit to a retreat and complete melting of the ice sheet | + 1–2 °C | >300 year |
| 3 Collapse of 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 the 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 year |
| 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 behaviour | + 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 year |

$^a$Lenton et al. (2008)

$^b$Change in global surface average temperature

$^c$Timescale of transition to new state
| Potential ‘catastrophe’ | Description/cause | Trigger level of global warming | Transition timescale to new state |
|-------------------------|-------------------|-------------------------------|---------------------------------|
| 7 Weakening/shutdown of Atlantic THC | The THC, an ocean water circulation pattern responsible for a large fraction of northward heat transport of the Atlantic Ocean, may weaken or shut down 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. | $+3–5 \, ^\circ\text{C}$ | $\sim100 \, \text{years}$ |
| 8 Collapse of West African monsoon (WAM)/greening of the Sahel | The 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. | $+3–5 \, ^\circ\text{C}$ | $\sim10 \, \text{years}$ |
| 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 CO$_2$ and temperatures, together with brown haze, affect the thermal contrast between land and sea needed to build up a monsoon, and 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$^a$ | $\sim1 \, \text{year}$ |
| 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. | $-^{f}$ | $\sim100 \, \text{years}$ |
| 11 Permafrost thaw$^d$ | Rising temperatures can cause vast thawing of permafrost (carbon-rich ground that is at or below 0 $^\circ\text{C}$ for at least two consecutive years), leading to significant amplified warming effects. | $-$ | $<100 \, \text{years}$ |
| 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$^g$ | Continued |
| Potential 'catastrophe' | Description/cause                                                                                                                                                                                                                                                                                                                                 | Lenton et al. (2008)\textsuperscript{a} |
|-------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------|
| 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  
>1000 years  |
| 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 years  |
| 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 year |

Notes:
\textsuperscript{a}The columns do not necessarily incorporate all the most recent studies on each event. For example, more recent research suggests the threshold beyond which the GIS retreats onto land may have already been transgressed (Lenton & Ciscar, 2013). In addition, some studies specify thresholds with different endpoints; e.g., WAIS collapse may be triggered when the surrounding ocean warms by around 5 °C (Pollard & DeConto, 2009). Amazon dieback threshold may be transgressed once deforestation exceeds about 40% of the entire Amazon basin (Davidson et al., 2012; Nobre & Borma, 2009). See the literature review in the Supplemental Appendix for more details.
\textsuperscript{b}The amount of warming needed to pass potential critical thresholds (measured relative to 1980–1999 temperatures).
\textsuperscript{c}Represents the time from when a critical threshold is transgressed.
\textsuperscript{d}This entry pertains to overall prospects of permafrost thaw. Recent research suggests permafrost thaw in the Yedoma region of Siberia may exhibit tipping point behaviour. See Supplemental Appendix for more discussion.
\textsuperscript{e}Subcontinental scale critical threshold could not be meaningfully related to temperature.
\textsuperscript{f}Critical threshold could not be identified at subcontinental scale.
\textsuperscript{g}Either the trigger level of warming is not established or global warming is not the only or dominant forcing.
tipping points initially, nor desirable to postpone analysis until this is possible, it at least suggests that analysts not treat the potential catastrophes included in their models as independent.

4.2. Potential for near-term modelling improvements
Given the wide variation in types of potential climate catastrophes, an important question is which of these possible events are the most feasible to better represent in IAMs? Categorizations or rankings provided in scientific review articles provide a starting point to prioritize research efforts (Table 3). Lenton et al. (2008) suggested that ‘policy relevant tipping points’ are Earth system changes that may be triggered within this century – on the ‘political time horizon’ – while those that would undergo a qualitative change within this millennium are relevant on an ‘ethical time horizon’ (p. 1787). Note that these definitions are based on the crossing of a threshold and not necessarily the timeframe under which the impacts would be realized. Based on available research, expert elicitation, and subjective judgement, Lenton (2011) develops a five-point scale (low, low–medium, medium, medium–high, and high) of relative likelihoods and impacts. Impacts are rated relative to the one system (THC) with multiple impacts studies and are considered on the full ‘ethical time horizon’ of 1000 years, assuming minimal discounting of impacts on future generations. Allison et al. (2009) categorizes potential climate catastrophes as ‘of greatest concern’ when they are ‘the nearest (least avoidable) and ... have the largest negative impacts’ (p. 41). Both assessments are based primarily on Kriegler et al. (2009) and other existing reviews (e.g. Lenton, 2009; Lenton et al., 2008).

Although these categorization efforts are useful as a first cut, care should be taken in using them to prioritize IAM modelling efforts. Potential events that require significant warming, have multi-century transition times, and a low likelihood of occurring are less likely to produce rapid, significant near-term economic damages than those 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 behaviour (e.g. permafrost thaw), are likely to have gradual, sometimes large physical impacts with relatively high probability.

A closer look at each event (Tables 4 and 5) helps to prioritize which events are the most appropriate and feasible to analyse initially in economic models. Details such as the types of physical endpoint that would be impacted, the degree of scientific consensus around how these impacts will likely unfold, transition dynamics, and data availability are considered.

Regardless of the degree of certainty about the existence of a tipping point and the location of the critical threshold for each of these events, important large-scale changes in many Earth systems are expected within this century (Table 4). Changes in some systems are already occurring and projections are becoming available for a number of physical endpoints that may allow for improved modelling of these events 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. This review shows that, of the 15 identified potential climate catastrophes, there is considerable scientific consensus regarding the impacts of about half of them. 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 ENSO are expected to be affected by rising GHG emissions, recent assessments find models are highly
inconsistent with respect to their projections of changes in ENSO amplitude, frequency, and variability. Similarly, the debate over the vulnerability of the Atlantic 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

**TABLE 3** Recent ranking or categorization of potential climate ‘catastrophes’

| Potential ‘catastrophe’ | ‘Policy relevant’ tipping point | Tipping points ‘of greatest concern’ | Relative likelihood of occurring | Relative impact |
|-------------------------|---------------------------------|-------------------------------------|---------------------------------|-----------------|
| 1 Melting of Arctic summer sea-ice | X                               | High                               | Low                             |
| 2 Collapse of GIS        | X                               | X                                  | Medium–high                     | Medium–high     |
| 3 Collapse of WAIS       | X                               | X                                  | Medium                          | High            |
| 4 Change in amplitude/variability of ENSO | X | X | Low | Medium–high |
| 5 Dieback of Amazon rainforest | X | X | Medium | Medium |
| 6 Dieback of boreal forest | X | X | Low | Medium–low |
| 7 Weakening/shutdown of Atlantic THC | X | X | Low | Medium |
| 8 Collapse of WAM/greening of the Sahel | X | X | Medium–low | High |
| 9 Collapse/volatiele ISM | X | X | Not considered | Not considered |
| 10 Retreat of tundra     | Not considered                  | Not considered                     | Not considered                  | Not considered |
| 11 Permafrost thawb      | Not considered                  | Not considered                     | Not considered                  | Not considered |
| 12 Weakening/shutdown of AABW formation | Not considered | Not considered | Not considered | Not considered |
| 13 Massive release of marine methane hydrates | Not considered | Not considered | Not considered | Not considered |
| 14 Ocean anoxia          | Not considered                  | Not considered                     | Not considered                  | Not considered |
| 15 Climate-induced Arctic ozone hole | Not considered | Not considered | Not considered | Not considered |

Notes:

a. The assessments provided in each column are taken from independent studies. Lenton et al. (2008) defines ‘policy relevant’ tipping points as those Earth system changes that may be triggered within this century and would undergo a qualitative change within this millennium. 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’ (p. 41). Lenton’s (2011) assessment of relative likelihoods and impacts is made 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, Footitt, & Dlugolecki, 2009) and subjective judgement, and are specified relative to the one system (THC) with multiple impacts studies. Impacts are considered on the full ethical time horizon of 1000 years, assuming minimal discounting of impacts on future generations. Lenton (2011) also notes that most impacts would be high if placed on an absolute scale, compared with other climate eventualities.

b. This entry pertains to overall prospects of permafrost thaw. Recent research suggests permafrost thaw in the Yedoma region of Siberia may exhibit tipping point behaviour. See Supplemental Appendix for further discussion.
TABLE 4 Scope for near-term IAM modelling improvements?

| Potential ‘catastrophe’                                      | Likelihood of significant physical impacts occurring this century<sup>a</sup> | Scientific consensus in how physical impacts will unfold<sup>b</sup> | Physical endpoints for which (at least 21st century) projections are available<sup>c</sup> |
|--------------------------------------------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| 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 GIS                                           | Medium–high                                                                 | More                                                                | Sea-level rise                                                                            |
| 3 Collapse of 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; probability density functions for change in vegetation carbon storage (kgC m<sup>–2</sup>) by region |
| 6 Dieback of boreal forest                                  | Medium                                                                      | More                                                                | Regional change in temperature, precipitation, sea-level from hypothetical instantaneous hosing experiment<sup>d</sup> |
| 7 Weakening/shutdown of Atlantic THC                        | Medium–low                                                                  | Less                                                                |                                                                                             |
| 8 Collapse of WAM/ greening of the Sahel                    | Medium–low                                                                  | Less                                                                |                                                                                             |
| 9 Collapse/volatile 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 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?                                                               |                                                                                             |

Notes:

<sup>a</sup>This does not necessarily mean a tipping point is transgressed this century. This ranking is based on the review of the literature provided in the Supplemental Appendix.

<sup>b</sup>Consensus refers to a general understanding of how Earth systems will respond (e.g. which physical endpoints will be affected and the direction of the impact on these endpoints) rather than scientific agreement on the detailed modelling and projections of physical impacts. This assessment is based on the review of the literature provided in the Supplemental Appendix.

<sup>c</sup>The literature reviewed in the Supplemental Appendix provides more information on each of these projections. See, e.g., Stroeve et al. (2012) and Deser, Tomas, Alexander, and Lawrence (2010) for Arctic sea ice projections; Nicholls et al. (2011) for sea-level rise; Collins et al. (2010) for ENSO; Cox et al. (2000) and Rammig et al. (2010) for Amazon dieback; Vellinga and Wood (2002, 2008) and Schaefer et al. (2011) for permafrost thaw, among others.

<sup>d</sup>A ‘hosing’ experiment refers to a modeling exercise in which extra fresh water is added into some location in the ocean.
warming being a critical factor, and even among models predicting an anthropogenic weakening of the THC, the impacts are not expected to be imminent.

The first step to an 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

### TABLE 5 Primary physical impacts leading to economic consequences of climate ‘catastrophes’

| Potential ‘catastrophe’                      | Changes in temperature | From additional GHG feedback | Sea-level rise | Changes in precipitation | Shifts in frequency/magnitude of extreme weather events\(^b\) | Other – e.g. impacts on ecosystems/species/biodiversity? |
|---------------------------------------------|-------------------------|-------------------------------|----------------|--------------------------|-------------------------------------------------------------|----------------------------------------------------------|
| 1 Melting of Arctic summer sea-ice          | X (hemispheric)         | X (CO\(_2\) and CH\(_4\))   |                | X                        | X                                                           | X                                                        |
| 2 Collapse of GIS                           | X (local)               | X (CO\(_2\) and CH\(_4\))   | X (global)     | X                        |                                                             | X                                                        |
| 3 Collapse of WAIS                          | X (local)               | X (CO\(_2\) and CH\(_4\))   | X (global)     | X                        |                                                             | X                                                        |
| 4 Change in amplitude/variability of ENSO   | X (regional)            | X (CO\(_2\))                 |                | X                        | X                                                           | X                                                        |
| 5 Dieback of Amazon rainforest              | X (regional)            | X (CO\(_2\))                 |                | X                        | X                                                           | X                                                        |
| 6 Dieback of boreal forest                  | X (local)               | X (CO\(_2\))                 |                | X                        |                                                             | X                                                        |
| 7 Weakening/shutdown of Atlantic THC         | X (hemispheric)         | X (CO\(_2\))                 |                | X                        |                                                             | X                                                        |
| 8 Collapse of WAM/greening of the Sahel     | X (regional)            |                               |                | X                        |                                                             | X                                                        |
| 9 Collapse/volatile ISM                     | X (local summer)        |                               |                | X                        |                                                             | X                                                        |
| 10 Retreat of tundra                        | X (regional?)           |                               |                | X                        |                                                             | X                                                        |
| 11 Permafrost thaw                          | X (regional?)           |                               |                | X                        |                                                             | X                                                        |
| 12 Weakening/shutdown of AABW formation     | X                       |                               |                | ?                        |                                                             | ?                                                        |
| 13 Massive release of marine methane hydrates| ?                       | X (CH\(_4\))                 |                | ?                        |                                                             | ?                                                        |
| 14 Ocean anoxia                             | ?                       |                               |                | ?                        |                                                             | ?                                                        |
| 15 Climate-induced Arctic ozone hole        | X (regional)            |                               |                | X                        |                                                             | X                                                        |

**Notes:**

\(^a\)This assessment is based on Lenton and Ciscar (2013) and a review of the scientific literature (see Supplemental 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 catastrophes’ or because more is known to date about how these physical endpoints will evolve.

\(^b\)For example, drought, floods, fire, hurricanes, other storms.
experienced. Table 5 summarizes the assessment of these key endpoints, grouped into five general categories: temperature, sea-level, precipitation, extreme events, and other. For many events, the ‘other’ category captures whether the economic consequences will result from ecosystem impacts (e.g. vegetation/forest cover impact, species loss), but can also include changes such as opening of trade routes from sea-ice loss or direct health impacts from the 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.

This assessment is highly simplified – many details and complex interactions between events are not captured in Table 5 – yet it provides a useful starting point for an improved reduced form representation of some potential climate catastrophes in IAMs. For example, it highlights the physical endpoint(s) through which each event should be incorporated into the IAM framework and the need for more explicit representation of many of these endpoints in IAMs. Current reduced-form IAMs each take a somewhat different approach to damage functions, but in general the damages are based on changes in global and annual mean temperature and sea-level rise. Over half the events considered in the table are expected to influence global temperature at least indirectly, but nearly all have direct temperature impacts at a regional or local scale as well. A first step to a better representation of these direct temperature impacts is to adapt current IAM frameworks to adequately accommodate regional variation in temperature changes. In addition, about half of the events considered in the table are expected to impact the frequency and/or magnitude of extreme weather events, and over half are expected to impact precipitation patterns; these changes are poorly correlated with changes in temperature (as is currently assumed in the model) yet are critical for capturing their impacts. Incorporating these physical endpoints into IAMs is only part of the task, however, as changes must then be translated into welfare impacts, which remains a challenging issue.

Ideally, modellers would have access to studies that provide information on the path of changes in the physical endpoints for 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 potential climate catastrophe. With such data, modellers would be able to credibly represent the impacts on natural system endpoints and begin to map them more explicitly to economic damages. This review suggests that the scientific literature is far from being able to provide all of this information, but, in some cases, a richer set of data already exists that could readily be incorporated into IAM modelling efforts.

For example, for the case of permafrost thaw, studies have projected the 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, Zhang, Bruhwiler, & Barrett, 2011). The thawing of permafrost was not ranked highly in the scientific reviews (Table 3) due to its lack of a specific tipping point. However, this is an event that is expected to occur (and is already 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. While economic studies have mentioned the thawing of permafrost as a possible source of catastrophic or abrupt climate change, the study to most specifically consider this type of event (Lemoine & Traeger, 2012) models it as a fixed, instantaneous and permanent doubling of the equilibrium climate sensitivity. This 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.
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 modelling is needed to incorporate other damage categories (e.g. valuation of ecosystem impacts from permafrost thaw), 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, Betts, Jones, Spall, & Totterdell 2000; Cox et al., 2004). Rammig et al. (2010) even estimate probability density functions for changes in vegetation carbon storage by Amazonian region for 2070–2100 using variation in GCM rainfall projections and sensitivity to CO₂ fertilization. Although requiring more work than permafrost thaw, some basic incorporation of this latest scientific research into IAM modelling 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 m by 2100, with a lower likelihood assigned to the upper end of this range (Nicholls et al., 2011). Because, in most IAMs, some structure already exists to measure welfare impacts to changes in sea-level rise, better modelling of the dynamics of sea-level alone (e.g. Nordhaus, 2010a, 2010b), 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, yet none of the IAMs included in this review currently models the damages associated with feedback effects of this loss. Results of studies examining the regional temperature and weather pattern impacts (including, e.g., the effects on extreme weather events in mid-latitudes) of sea ice loss could be used to understand the economic damages resulting directly from these changes. Models of the economic impacts associated with improved accessibility of Arctic harbours (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 endpoints that are expected to be impacted are not typically modelled within the current generation of IAMs. Therefore, even if these potential events are judged to be of great concern in scientific reviews (Table 3), improved modelling of the physical and welfare impacts may be less feasible in the near term. For example, most IAMs are not currently designed to directly assess the welfare impacts of changes in precipitation or intra-annual weather variability. Thus, 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.

Finally, Earth system changes that are not likely to manifest until very far out in time may be of lower priority than others in the context of an economic model that discounts future impacts. 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.

Caution is suggested even in cases where 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 existing IAM frameworks. 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 are affected by the rate of change. This is a widely acknowledged limitation of the current suite of models 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 with whether realistic ‘time-to-build’ constraints are implemented.

5. Conclusions

A careful review of the scientific and economic literature suggests there is an error in translation when modellers 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 move from one equilibrium to another represents a large-scale change for that system itself and, in some cases, for the Earth system as a whole. In the context of modelling the benefits and costs of GHG mitigation policies, the question becomes one of the welfare impacts of these Earth system changes. Thus far, the majority of efforts to understand the benefits of GHG mitigation when there is a possibility of one or more large-scale Earth system changes have treated these changes monolithically, as a single ‘catastrophic’ damage category that has a low probability of being realized. Motivated by modelling convenience and scientific descriptions of such changes as relatively abrupt, the economics literature has commonly assumed that when a catastrophe is triggered, it will be instantaneous and result in a permanent reduction in global welfare. In short, the economics community has interpreted scientifically ‘abrupt climate change’ to mean ‘instantaneous change in welfare.’

While economic research is informative with regard to the potential importance of including 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 1000 years could be considered abrupt. For an economic analysis such timescales are not likely to be considered policy-relevant or well represented by an instantaneous regime shift. Second, there is often no explicit representation of the geographic extent over which these impacts may be experienced. Such detail is important to understand the differing vulnerability and adaptation possibilities across regions. The third, and perhaps clearest, issue at hand is that there have been relatively few endeavours in the economics literature to determine what the expected welfare impacts would be given the relevant changes in particular Earth system endpoints. Some researchers have carefully examined the details of particular Earth system changes (e.g. Link and Tol’s (2011) study of THC shutdown) and 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 move to more explicitly and accurately represent Earth system changes and feedback effects, a closer look at the scientific literature can help them understand which could be more readily modelled given the current state of IAMs, and what modelling improvements are required to include additional large-scale Earth system changes. The underlying goal of this line of research is to better understand the benefits of GHG mitigation policies. The economics literature has not yet provided enough insight regarding the magnitude of the expected welfare effects of potential climate catastrophes to speculate on how estimates of the social cost of carbon used in policy analysis might be affected by improved representation of potential climate catastrophes. To move forward, it is recommended that effort be applied to improve not only the way IAMs characterize Earth systems and the possibility of large-scale changes that may or may not have an associated tipping point, but also the way they characterize uncertainty over the availability of adaptation or interaction between sectors, which could lead to potential large-scale economic consequences. With such an effort there may also be a need to expand the way in which preferences are represented in the models in order to more adequately capture society’s aversion to risk. 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 welfare impacts in the near to medium term. It is unclear without further research whether the most policy-relevant Earth system changes are those associated with tipping points that may be crossed in this century or with more gradual but significant feedback effects that are currently not represented in the IAMs used for policy analysis.

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Notes

1. The ambition of a global threshold was endorsed in the 2009 Copenhagen Accord, in which two dozen key countries agreed to ‘prevent dangerous anthropogenic interference with the climate system’ by limiting global temperature increases to below 2 °C (UNFCCC, 2009).
2. For example: ‘We have a window of only 10–15 years to take the steps we need to avoid crossing catastrophic tipping points’ (Jan Balkenende & Tony Blair, 20 October 2006) and ‘Even if the ultimate result were an Earth that is still hospitable to mankind, the transition could be catastrophic’ (The Economist, June 18, 2012).
3. This article focuses on the economic study of specific large Earth system changes, outside of direct temperature response to anthropogenic emissions. For information on the potentially large welfare impacts associated with a significantly stronger than expected climate response to anthropogenic emissions, see Weitzman (2011).
4. The Intergovernmental Panel on Climate Change (IPCC) has also used the potentially confusing terminology of ‘large scale discontinuities’ to describe such events. However, the notion of a discontinuity in this case arises from observing the time path of the system over a long time horizon, and often does not refer to a mathematical discontinuity in equilibrium solutions of the system.
5. Estimating society’s preference for trading off costs and benefits across time, particularly for intergenerational contexts, is an active area of discussion and research. Cropper (2013) provides a detailed discussion of the issue.
6. Real options analysis refers to a dynamic programming framework for modelling optimal policies that involves a non-trivial sunk cost under uncertain net benefits. Traditionally, the framework has considered problems with stochastic uncertainty whereby the decision maker learns passively over time about the state of nature. For more information on real options analysis, see Dixit and Pindyck (1994).

7. Other studies suggest WAIS collapse would take much longer (e.g. Pollard & DeConto, 2009), but there are still uncertainties and challenges in modelling or measuring ice-sheet dynamics (see e.g. Cooke, 2013; Little, Urbana, & Oppenheimer, 2013; Moore, Grinsted, Zwinger, & Jevrejeva, 2013, for some of the most recent reviews and assessments).

8. The SCC represents the discounted present value of the welfare losses from an additional ton of CO₂ emitted into the atmosphere in a given year.

9. In the previous version of the Policy Analysis of the Greenhouse Effect model, PAGE2002, a generic potential climate catastrophe was modelled as an instantaneous, permanent reduction in welfare, where the probability of occurrence was zero until a given threshold was reached, after which the probability would begin to rise (Hope 2006).

10. Table 2 is not meant to be exhaustive. See Lenton and Ciscar (2013) for a discussion of additional potential large-scale climate change-induced events as well as an overview of many critical linkages across Earth systems.

11. Consensus refers to 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 projections of physical impacts. For example, in the case of sea-level rise from ice-sheet melt, the scientific uncertainty is primarily with regard to the magnitude and rate of change.

12. To assess the welfare implications of non-marginal policies inclusive of potential climate catastrophes, the endogeneity of these physical endpoint changes to anthropogenic emissions needs to be established within the IAMs.

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