Garnaut Climate Change Review

Defining the impacts of climate change on catastrophic events

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1 Executive summary

Criteria for deciding whether a specific event or change is considered catastrophic include the immediate losses, the persistence of impacts, the potential for reversibility, and the potential for adaptation. In this report, catastrophic events are events that occur less frequently than two or three times per century with large-scale deleterious consequences that generally arise relatively quickly. Examples include one in 100-year flooding events, or very extreme weather events that cause hundreds or thousands of fatalities. Catastrophic events may also be linked to thresholds where nonlinear processes can cause parts of the earth system to shift from one major state to another. The existence of these thresholds may lead to large, widespread and irreversible (on human timescales) damage. Examples include the collapse of major ice sheets, or the widespread extinction of species.

The rareness of catastrophic events means that the usual method by which climate events are attributed to anthropogenic climate change cannot be used. Because of this, examining the possible catastrophic consequences of anthropogenic climate change requires more use of conceptual approaches. Naturally, this means that there is considerably less confidence in our ability to predict such catastrophic consequences or to provide detailed indications of when and where such catastrophes may arise.

Catastrophes are events for which societies have generally not adapted. Hence important strategies include understanding the sources of vulnerability and either reducing or removing the vulnerability or planning for effective emergency response and recovery. This places a stronger emphasis on the need to mitigate anthropogenic forcing to the degree possible to avoid the most dangerous and irreversible of catastrophes. Postponement of mitigation, in contrast, generally increases risks. The possibility of climate catastrophes is inherent to the evolving context of anthropogenic climate change, and needs to be explicitly taken into account in the evaluation of mitigation policies.

2 Introduction

The unique features of the climate change problem—the potential for irreversible change, high impact events with low probabilities, and the very long planning horizon—mean that the potential for catastrophe must be considered. However, the definition of a catastrophe is to some extent a value judgment (Schneider 2004). Hence, the IPCC[*] Fourth Assessment Report does not attempt a formal definition. The insurance industry, however, does adopt formal categorisations. For example, Munich Re assigns natural catastrophes to one of four categories for assessment purposes. These are classed as *severe* (more than 20 fatalities and more than US$50m in losses), *major* (more than 100 fatalities and US$200m losses), *devastating* (more than 500 fatalities and US$500m losses) and 'great disaster' (a United Nations defined event involving thousands of fatalities and severe economic effects.) Events with fewer losses than these are deemed to be extreme events.

The insurance industry definitions cannot account for catastrophes that have not occurred but could be envisioned (such as the collapse of the West Antarctic ice sheet*) or for catastrophes that cannot be insured against (such as species extinctions). Nevertheless, trends in defined catastrophes do provide some guidance for the evolving context. Munich Re's annual report notes that despite the general absence of extreme events in 2007, overall economic losses due to natural disasters in all categories reached US$75b, an increase of 50% over 2006 (US$50b). The loss figures were well short of the record in 2005 of US$220b, the year that Hurricane Katrina just missed New Orleans. But the *number* of defined catastrophes recorded in 2007 was 950, the highest figure since Munich Re began keeping systematic records in 1974.□□

The worst human catastrophes of 2007 occurred in developing countries. Storms, floods and landslides in Asia caused more than 11,000 deaths, with around 3,300 attributable to Cyclone Sidr alone, which struck Bangladesh in November. The most severe event in terms of insured losses occurred in Europe: Winter Storm Kyrill, which developed on 17 January 2007. With wind speeds far exceeding 100 km/hr, and peak gusts of over 200 km/hr, it wrought havoc across Europe as far as Poland, the Czech Republic and Austria. This one storm caused overall economic losses of US$10b (thus was classed as a devastating catastrophe), with insured losses of around US$5.8b. It was the second most expensive storm in Europe after Winter Storm Lothar (December 1999). A noticeable feature of Kyrill was that widespread areas of Europe experienced sustained high wind speeds.

In June 2007, Australia experienced weather severe enough, in terms of insured losses if not fatalities, that it ranked in the top ten largest natural catastrophes of 2007 (MRNatCatService 2007). Gale force winds and rising flood waters from the 8th to the 10th June on the New South Wales coast caused the deaths of nine people and the evacuation of six thousand. The interruption of the electricity supply to over 200,000 homes and businesses, the interruption of water and gas supplies, and sewerage system pump failures resulted in substantial public health threats. Insured losses were estimated at US$1.15b, with total losses around US$1.7b.

This is one of a pair of papers prepared for the Garnaut review. The other focuses on extreme weather and climate events, which are rare by definition. The focus in this paper is on events that are even less frequent and even more damaging than is the case with extreme events. In many cases discussed here, the event would be a 'one off' event—something that would never be likely to be repeated within a human generation or two. On the other hand, many of the extreme weather events classed as catastrophes by the insurance industry would be typically expected to occur a few times in a decade. In climate change research, such events are considered to be extreme events, but not catastrophes.

Thus, a heatwave would have deleterious consequences but would not normally be considered to be 'catastrophic' because such heatwaves occur almost every year. Similarly, a heavy rainfall would usually be considered an extreme (and is therefore discussed in the companion paper) but generally be unlikely to be considered a 'catastrophe' unless permanent inundation or record inundation of a large, heavily populated region such as a river delta resulted. On the other hand, there are events

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[*] see Glossary for this and other terms marked with an asterisk

which are so substantial and irreversible (on human timescales) that they may only be classed as catastrophes, such as ice sheet collapse, coral reef destruction, and loss of unique cultures and species. This complexity means that the assessment presented here will inevitably include some value judgments—where possible we have made these judgments apparent.

What is a catastrophic event?

Criteria for deciding whether a specific event or change is considered catastrophic include the immediate losses, the persistence of impacts, the potential for reversibility, and the potential for adaptation. In most cases, we will consider that catastrophic events are more rare than extreme weather and climate events (e.g. less frequent than two or three times per century) with large-scale deleterious consequences that generally arise relatively quickly. Examples include one in 100 year flooding events, or weather events that cause hundreds or thousands of fatalities. As such, it is a more stringent definition than that adopted by the insurance industry.

Catastrophic events may also be linked to thresholds* where nonlinear processes can cause parts of the earth system to shift from one major state to another. The existence of these thresholds may lead to large, widespread and irreversible (on human timescales) consequences that may be considered catastrophic, even if these consequences do not occur suddenly. Examples include ice sheet disintegration leading to large sea-level rises or important species extinctions.

3 Observed record of natural catastrophes

The problems of data, definition and interpretation described in the companion paper on extremes apply with even more force in the case of catastrophic events. However, once again we may turn to the insurance industry to obtain some sense of the changes that have occurred over time (Table 1). It has been argued in some contexts that increases in losses from catastrophes are associated primarily with increases in vulnerability (e.g. Downton and Pielke 2005). However, it is apparent from the Munich Re records that the number of events has also increased. In the case of heatwaves it is clear that the intensity has increased (see companion paper on extremes). Hence, it is possible to argue that an increase in weather and climate related catastrophes, and indeed an increased risk of irreversible catastrophes, would be expected when the climate is subject to anthropogenic* forcing. However, the rareness of catastrophic events means that the usual method by which climate events are attributed to anthropogenic climate change, through detection of a change and then using a climate model to demonstrate that such an event was consistent only with anthropogenic factors, cannot be applied. Further, such an approach cannot be applied to events:

- that have yet to occur, or
- are so rare that no useful record of their previous occurrence can be prepared, or
- that have occurred only under very different climate situations than have been experienced in modern times.

Table 1 Natural catastrophes in 2007 and comparison with previous years, from NatCatService, Geo Risks Research, Munich Re

			Original values (US$ billion)		
Year	Number of events	Fatalities	Total losses	Insured losses	Major events
1994	680	13,000	89	21	Earthquake, Northridge
1995	615	20,800	172	16	Earthquake, Kobe; floods, North Korea
...					
2000	890	10,300	38	9.6	Floods, UK; Typhoon Saomai
2001	720	25,000	40	12	Tropical storm Allison; hailstorm, USA
2002	700	11,000	60	14	Floods, Europe
2003	700	109,000	65	16	Heatwave, Europe; earthquake, Bam/Iran
2004	650	235,000	150	47	Hurricanes, Atlantic; typhoons, Japan; tsunami
2005	670	101,000	220	99	Hurricanes, Atlantic; earthquake, Pakistan
2006	850	20,000	50	15	Earthquake, Yogyakarta/Indonesia
2007	950	15,000	75	30	Winter storm Kyrill; floods, UK

Because of this, examining the possible catastrophic consequences of anthropogenic climate change requires less reliance on climate models and formal climate change detection and projection, and more use of conceptual approaches. Naturally, this means that there is considerably less confidence in our ability to predict such catastrophic consequences, and to provide detailed indications of when and where such catastrophes may arise.

4 Catastrophic events likely to be affected by climate change

Despite these problems, a number of low probability but high consequence events have been considered as possible outcomes of anthropogenic climate change (e.g., in the IPCC Working Group II contribution to the Fourth Assessment Report; IPCC 2007). The following list of possible catastrophic consequences of anthropogenic climate change is derived largely from the most recent IPCC assessment. We have categorised them into different classes.

4.1 Irreversible on human time scales

Elimination of polar ice sheets

Climate models suggest that the Greenland ice sheet loses mass more rapidly as temperature increases than the ice sheet gains due to increased snowfall. The estimated point at which this process starts to lead to net ice loss varies widely between models, from a warming (globally averaged) of anywhere between 1.9 and 4.6°C. The corresponding climate is comparable to that inferred for the last interglacial period*. This period, around 125,000 years ago, was one where palaeoclimatic* information suggests a sea level rise of 4 to 6 m. A complete elimination of the Greenland ice sheet (termed deglaciation) would result in a contribution to sea level rise of about 7 m, and could be irreversible.

Dynamical processes related to ice flow—which are not included in current models but are suggested by recent observations—could increase the vulnerability of the ice sheets to warming, and hence increase the rapidity of sea level rise. Understanding of these processes is limited and there is no consensus on their magnitude.

Current global model studies project that the Antarctic ice sheets are likely to remain too cold for widespread surface melting, and the ice sheets will probably gain mass due to increased snowfall. However, deglaciation of some parts of Antarctica could occur if dynamical ice discharge becomes more prevalent. An example of the rapid changes that are possible was the collapse of the 10,000 year old, 3200 km^2 Larsen B ice shelf over a 35 day period in 2002.

Coastal inundation

As a direct result of thermal expansion of the oceans, melting of glaciers and potential collapse of major ice sheets, coastal zones are projected to be exposed to increasing risks of erosion and inundation. The increasing concentration of settlement, commerce and industry in coastal areas will exacerbate the impact. Globally, by the 2080s, many millions more people than today are projected to experience floods every year due to sea level rise. The numbers affected will be largest in the densely-populated and low-lying megadeltas of Asia and Africa while small islands are especially vulnerable. In the short term, however, the influence of storm surges associated with extreme weather events is likely to force adaptation and retreat. Australia's coastal zone is of particular concern due to the strong concentration of high value infrastructure along the coast: in 2001, 85% of Australians lived within 50 kilometres of the coastline of Australia and the proportion was growing.

Destruction of coral reefs through ocean acidification and thermal bleaching

The uptake of anthropogenically released carbon dioxide since 1750 has led to the ocean becoming more acidic, with an average decrease in pH of 0.1 units. This process is known as acidification. Climate model projections suggest a reduction in average global surface ocean pH of between 0.14 and 0.35 units over the 21st century. While the effects of observed ocean acidification on the marine biosphere are as yet undocumented, the progressive acidification of oceans is expected to have negative impacts on marine shell-forming organisms, such as crustaceans, molluscs and corals. This is because, as ocean pH falls, so does the concentration of the carbonate ion, and when carbonate becomes under-saturated, structures made of calcium carbonate are vulnerable to dissolution. Research has already found that corals, coccolithophore algae, foraminifera, shellfish and pteropods experience reduced calcification or enhanced dissolution when exposed to elevated carbon dioxide (e.g. Gattuso et al. 1998; Riebesell et al. 2007; Gazeau et al. 2007).

In addition, corals are vulnerable to thermal stress (Hoegh-Guldberg et al. 2007). Increases in sea surface temperature of between 1 and 3ºC are projected to result in more frequent coral bleaching events and widespread mortality, unless there is acclimatisation by corals. A warming of 2ºC above 1990 levels will result in bleaching of warm-water coral reefs globally. Wind, exposure at low tide, and extreme weather can contribute to coral bleaching. Once bleaching begins, corals tend to continue to bleach even if the stressor is removed. If the coral system survives, it often requires weeks to months for the remaining symbiont population to reach a normal density.

The Great Barrier Reef along the northeast coast of Australia suffered two mass coral bleaching events in the summers of 1998 and 2002, and also in the southern reaches of the reef in 2006. While most reef areas recovered with relatively low levels of coral death, some locations suffered severe damage, with up to 90% of corals killed.

Ecosystem extinctions

The resilience of many ecosystems is likely to be exceeded this century by an unprecedented combination of

- changes in temperature and rainfall, including the occurrence of drought
- extreme weather events such as flooding and tropical cyclones
- concomitant changes in other systems, such as increasing parasite ranges and ocean acidification
- other drivers associated with human activities, such as land-use change, pollution, fragmentation of natural systems, and over-exploitation of resources.

Approximately 20–30% of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperatures exceed 1.5–2.5ºC. The Great Barrier Reef is only one example of Australia’s unique ecosystems that are at risk. A temperature rise of between 2 and 3ºC has led to scientific findings that include:

- 41 of 42 species of fauna examined from major Victorian bioclimatic regions are predicted to reduce their range, with at least 1 of those species predicted to go extinct (Brereton et al. 1995)
- 92% of butterfly species’ core habitat is predicted to decrease significantly (Beaumont and Hughes 2002)
- a 98% decrease in Bowerbird habitat in the tropical highlands, with likely extinction of the bird itself (Hilbert et al. 2004)
- a loss of 80% of the freshwater wetlands in Kakadu, given an assumed 30 cm sea level rise (Hare 2003).

Loss of unique cultures

There is very high confidence that human settlements in polar regions and Pacific Islands are already being adversely affected by climate change (Lynch and Brunner 2007; Barnett 2005). In the future, climate change is very likely to result in further disruption to traditional cultures and potential the loss of whole communities. Shifts in ecosystems are very likely to alter traditional use of natural resources, and in consequence, foundations of culture. Warming of freshwater sources poses risks to the health of people utilising those sources because of transmission of disease. Economic stresses imposed by climate policies have the potential to contribute to social dislocation.

Small island nations like Tuvalu, island communities such as the Torres Strait, and low lying coastal states such as Bangladesh are likely to experience large impacts due to the combination of higher exposure to sea level rise and storm surge and limited ability to adapt (Huq et al. 1999). Subsistence activities and commercial agriculture in these regions are likely to be adversely affected by climate change, as a result of storm inundation, seawater intrusion into freshwater lenses, soil salinisation, decline in freshwater supply and deterioration of water quality. The long-term sustainability of societies of small islands poses special challenges due to the limited size, exposure to natural hazards, limited adaptive capacity and high costs relative to GDP.

Indigenous communities in remote areas of Australia can be characterised by inadequate infrastructure, health services and employment. The resulting social and economic disadvantage reduces coping ability and may restrict these communities' resilience to climate hazards (Ellemor 2005.) Many of these communities strongly connect the health of their country to their cultural well-being (Jackson 2005). Hence, the manifestations of climate change in these regions are likely to have significant impacts on the social and cultural cohesion of these communities.

Destabilisation of permafrost and marine methane sediments

Warming can destabilise permafrost* and marine sediments of methane gas hydrates*. Changes in soil seasonal freeze-thaw processes have a strong influence on spatial patterns, seasonal to interannual variability, and long-term trends in terrestrial carbon budgets and surface-atmosphere trace gas exchange, both directly through biophysical controls on photosynthesis and respiration and indirectly through controls on soil nutrient availability. Thawing of ice-rich permafrost can lead to subsidence of the ground surface as masses of ground ice melt and to the formation of uneven topography know as thermokarst, generating dramatic changes in ecosystems, landscape and infrastructure performance (Nelson et al. 2001). Further, observations indicate substantial increases in methane directly released from northern peatlands that are experiencing permafrost thaw (e.g. Wickland et al. 2006).

Model studies suggest that today's seafloor methane inventory would be diminished by 85% with a warming of bottom water temperatures by 3°C (Buffett and Archer, 2004). Based on this inventory, an anthropogenic release of 2,000 Gt of carbon to the atmosphere could cause an additional release of methane from gas hydrates of a similar magnitude (<2,000 Gt of methane) over a period of 1000 years. (For reference, 165 Gt of carbon was added to the atmosphere between 1750 and 1994.) Thus, gas hydrate decomposition represents an important positive methane feedback to be considered in global warming scenarios on longer time scales. This process has been proposed to explain the rapid warming that occurred during the Palaeocene/Eocene thermal maximum*.

Changes in the North Atlantic meridional overturning circulation

The sensitivity of the North Atlantic meridional overturning circulation to anthropogenic forcing is regarded as a key vulnerability due to the potential for sizeable and abrupt impacts. Potential impacts associated with changes in this circulation include reduced warming or even cooling of northern high latitude areas near Greenland and northwest Europe, an increased warming of southern hemisphere high latitudes, and tropical drying. These changes would lead to impacts on marine ecosystems productivity, terrestrial vegetation, the uptake of carbon dioxide by the oceans, oceanic oxygen concentrations, and shifts in fisheries. Analogues from palaeoclimate and model simulations show that the meridional overturning circulation can react abruptly and irreversibly once a certain forcing threshold is crossed. Overall, there is high confidence in predictions of a meridional overturning circulation slowdown during the 21st century, but considerably less confidence in the scale of response, and no reliable estimates of the likelihood of an irreversible change. However, it is known that the response of the meridional overturning circulation increases with the extent and rate of anthropogenic forcing, and hence the risk of an irreversible change increases with increasing emissions.

4.2 High impact

Tropical cyclones

The power of a tropical cyclone storm is proportional to the cube of the wind speed. Consequently, the impacts of these storms are highly nonlinear and one big storm may have much greater impacts on the environment and climate system than several smaller storms. Hence, the category of storm is important in determining the potential for catastrophic impacts. Webster et al. (2005, 2006) found a large increase in the frequency and proportion of hurricanes reaching categories 4 and 5 globally since 1970 even as the total number of cyclones decreased slightly in most basins. The largest increase was in the North Pacific, Indian and Southwest Pacific Oceans. While some authors have questioned this finding, subsequent analysis suggests that it is robust (Trenberth et al. 2008). At this stage, for the Australian region, no clear picture emerges on observed changes, but a number of model-based studies do suggest an increase in tropical cyclone intensity in the future (Walsh et al. 2004). It should also be noted that fluctuations in the El Niño – Southern Oscillation (ENSO) have a strong impact on patterns of tropical cyclone occurrence in the region, and therefore uncertainty with respect to future ENSO behaviour contributes to uncertainty with respect to tropical cyclone behaviour

Flood events

Available research suggests a significant future increase in heavy rainfall events in many regions, including some regions in which the mean rainfall is projected to decrease. In addition, an increase in storms in coastal regions and associated storm surge inundation is likely in some locations. It is likely that up to 20% of the world population will live in areas where river flood potential will increase in the 21st century. The resulting increased flood risk poses challenges to communities, physical infrastructure and water quality. The most likely source of catastrophic impacts from flooding are situations in which flood is combined with a precursor condition such as bushfire affected ground (Tryhorn et al. 2008) or sea level increase (Abbs 2004). As noted in the companion paper on extremes, the ability of climate models to make predictions of these hydrological events remains quite limited. Hence, the risk of catastrophic events is unquantifiable at this time.

Deterioration of water supply quality

Increased temperatures and saltwater intrusion will affect the physical, chemical and biological properties of freshwater lakes and rivers, with predominantly adverse impacts on many individual freshwater species, community composition and water quality. For example, there is a 50% chance by 2020 of the average salinity of the lower Murray River exceeding the threshold set for desirable drinking and irrigation water (MDBMC, 1999). There are few detailed studies of the impacts of climate change on the range of factors that affect water quality, including runoff quantity and quality, salt interception and revegetation policies (Hennessy et al. 2007). However, there is good evidence that toxic algal blooms are likely to become more frequent and to last longer due to climate change, posing a threat to the health of humans, livestock and wildlife. Saltwater intrusion as a result of sea-level rise and decreases in river flows is likely to alter species composition in freshwater habitats. Again, the potential for these effects to have catastrophic consequences cannot be quantified.

Deterioration of regional food supplies

Nationally, median crop yields are likely to decrease, dominated by reductions in the south-west and south-east, with modest increases in the north. Hennessy et al. (2007) reports substantial risk to the industry as maximum potential increases in crop value are limited but maximum potential losses are large but adaptation through changing planting dates and varieties is likely to be highly effective. As a result, the local impacts are not likely to be catastrophic. In contrast, by 2020, in some countries in Africa, yields from rain-fed agriculture could be reduced by up to 50%. Agricultural production, including access to food, in many African countries are projected to be severely compromised. This would further adversely affect food security and exacerbate malnutrition, and have implications for Australia in terms of national security and the global economy.

Environmentally-induced migration and conflict

Stresses such as increased drought, water shortages, and riverine and coastal flooding will affect many local and regional populations. This will lead in some cases to relocation within or between countries, exacerbating conflicts and imposing migration pressures.

Changes in the modes of climate variability

Natural variability of the climate system, in particular on seasonal and longer time scales, predominantly occurs with preferred spatial patterns and time scales, through the dynamical characteristics of the atmospheric circulation and through interactions with the land and ocean surfaces. Such patterns are often called regimes, modes or teleconnections. Examples are the North Atlantic Oscillation (NAO), the El Niño-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM). Changes in these modes of climate variability in response to anthropogenic forcing can lead to important impacts because these modes dominate annual-to-decadal variability, and adaptation to this variability remains challenging in many regions. For example, some studies suggest that anthropogenic forcings would affect ENSO variability. Current ENSO projections are marked by many uncertainties, including the potential for an abrupt and/or irreversible response, the direction of the shift, and the level of warming when triggered. In Australia, shifts in the ENSO regime would affect agriculture, water supply, flooding, droughts, wildfires, tropical cyclones, and fisheries.

5 Opportunities to adapt to the catastrophic consequences of climate change

Adaptation potential is greater the more the system is under human management and control. Major geophysical changes leave little room for human managed adaptation. There is somewhat greater capacity for management of biological systems but it is still very limited. Ecosystems are likely to be impacted at a much faster rate than geophysical systems without a commensurately larger adaptive capacity for such impacts. It seems likely therefore that the greatest impacts in the near to medium term will occur in biological systems, many of which we presently reply on.

In the case of human social systems, adaptive capacity at the technical level increases dramatically. However, the understanding of impacts, adaptive capacity, and the costs of adaptation is weaker in human systems than in biological systems, and the uncertainties high. This is especially the case for synergistic or cross-cutting impacts. For example, when considered in isolation, the potential for agricultural adaptation may appear to be good. When related impacts in water regimes, droughts and floods, pest infestations and plant diseases, human health, the reliability of infrastructure, poor governance and other non-climate related stresses are taken into account, the picture is less clear.

Economic development is an important component of adaptation, but on its own, will not insulate the world's population from disease and injury due to climate change. Critically important will be the manner in which economic growth occurs, the distribution of the benefits of growth, and factors that directly shape the health of populations, such as education, health care, and public health infrastructure.

The forcing of the climate by human activities is likely to have the consequence of pushing the earth system from one equilibrium state to another, with abrupt change as a possible consequence. The harder and faster the system is perturbed, the higher the likelihood of such surprises—a conclusion that has significant bearing on the assessment of the potential benefits of the timing and stringency of greenhouse gas abatement measures. Action to mitigate climate change and reduce greenhouse gas emissions is the most reliable path to reduce the risk associated with potential catastrophic impacts of climate change. Postponement of such actions, in contrast, generally increases risks. Given the current climate change commitment and the range of projections for future climate change, some key impacts (e.g., deglaciation of major ice sheets) are unlikely to be avoided. The probability of initiating some large-scale events is very likely to continue to increase as long as greenhouse gas concentrations and temperature continue to increase.

6 Strategy and policy implications

The possibility of climate catastrophes is inherent to the evolving context of anthropogenic climate change, and needs to be explicitly taken into account in the evaluation of mitigation policies. As noted, the likelihood of climate catastrophes increases the desirability of implementing strong mitigation policies. Barazini et al. (2003) show that with catastrophic losses of US$100b per year, which is in the range of recent global losses, the probability of implementing a 5% abatement policy in the next 10 years is between 72% and 100%, depending on the discount rate. In the absence of these catastrophes, with a discount rate of 1.5%, this probability was 16% only. Clearly, additional analytical and empirical work is required in this area.

7 Recommendations for future research on catastrophic events

A significant category of key vulnerabilities is associated with large-scale, irreversible and systemic changes in geophysical systems. Large-scale changes such as changes in the West Antarctic and Greenland ice sheets could lead to significant impacts, particularly due to long term large sea-level rise. Therefore, to obtain improved estimates of impacts from both 21st century and long-term sea level rise, new modelling approaches incorporating a better understanding of dynamical processes in ice sheets are urgently needed. Furthermore, central to nearly all the assessments of key vulnerabilities is the need to improve knowledge of climate sensitivity—that is, developing an understanding of how large a response to forcing is possible in the climate system, and what the risk of such an extreme response may be.

Another important area for research is understanding societal and ecological vulnerabilities, and particularly the ways in which vulnerability is constructed. In the developed world there is an important role for research into urban planning and the built environment. In the developing world these constructed vulnerabilities are generally associated with resource constraints, and hence research into development mechanisms is required.

As noted earlier, it is important to understand and internalise the losses from both extreme events and catastrophic events as the climate changes. This remains a largely open question with many approaches to be explored.

Finally, there is important research to be conducted in emergency planning, management of response, and recovery. This includes important cultural considerations associated with communicating warnings and response advice, governance issues associated with responsibility and jurisdiction, and research into the organisation and the geographic scale of covering risk, and the roles of private and public insurance.

8 Conclusions

A wide variety of low probability, high consequence and sometimes relatively rapid events may arise from anthropogenic climate change. It is difficult to envisage how societies might adapt to reduce the deleterious consequences of such events. Tsunamis, volcanoes, earthquakes, major hurricanes are amongst the events that have in the past severely affected societies and are likely to occur in the current and future climate. The resource requirements of many human societies have led to a constructed vulnerability (e.g., population centres on coastlines and in river valleys) that have in the past (and still today) enhanced the risk presented by such catastrophes. But these are events for which societies have generally not adapted—they are events that are so catastrophic that the key lies in (1) understanding the sources of vulnerability and where possible removing ourselves from harm's way and (2) planning for effective emergency response and recovery. It is only through these approaches that it will be possible to adapt to reduce the consequences of any changes in catastrophes induced by anthropogenic climate change. This places a stronger emphasis on the need to mitigate anthropogenic forcing to the degree possible to avoid the most dangerous and irreversible of catastrophes. Such mitigation would not, of course, remove all the possibility of a catastrophic climate-related event, but would reduce the possibility of such catastrophes arising from our own actions.

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10 Glossary

anthropogenic: In the context of climate change, the term anthropogenic means caused by human activities.

ice sheet: A mass of land ice that is sufficiently deep to cover most of the underlying bedrock topography, so that its shape is mainly determined by the flow of the ice. There are only three large ice sheets in the modern world, one on Greenland and two on Antarctica, the East and West Antarctic Ice Sheets, divided by the Transantarctic Mountains. During glacial periods there were others.

interglacial period: The warm period between ice ages. The previous interglacial, dated approximately from 129 to 116 thousand years ago, is referred to as the Last Interglacial.

IPCC: In 1988, the United States and allied governments requested that WMO and UNEP establish an organisation that became the Intergovernmental Panel on Climate Change. The formal mandate of the IPCC was to assess available scientific information on climate change, assess the environmental and socio-economic impacts of climate change, and formulate response strategies.

methane gas hydrate: a special type of gas hydrate in which a lattice of water molecules encloses molecules of trapped methane gas. Scientists believe that compounds on the sea bed have trapped large amounts of methane in these configurations.

Paleocene-Eocene Thermal Maximum: In an event marking the start of the Eocene, the planet heated up in one of the most rapid and extreme global warming events recorded in geologic history.

palaeoclimate: Climate during periods prior to the development of measuring instruments, including historic and geologic time, for which only proxy climate records are available.

permafrost: Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years.

threshold: A point or level at which new properties emerge in a physical, ecological, economic or other system, invalidating predictions based on mathematical relationships that apply at lower levels.