ASSESSING THE RISKS OF A FUTURE RAPID LARGE SEA LEVEL RISE: A REVIEW

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Abstract

Our aim is to make an appropriate characterization and interpretation of the risk problem of rapid large sea level rise that reflects the very large uncertainty in present day knowledge concerning this possibility, and that will be useful in informing discussion about risk management approaches. We consider mainly the potential collapse of the West Antarctic ice sheet as the source of such a sea level rise. Our review, characterization and interpretation of the risk makes us conclude that the risk of a rapid large sea level rise is characterized by potentially catastrophic consequences and high epistemic uncertainty; effective risk management must involve highly adaptive management regimes, vulnerability reduction, and prompt development of capabilities for precautionary reduction of climate change forcings.

Keywords: sea level rise; West Antarctic ice sheet; climate change; adaptive management; epistemic uncertainty; risk management arenas; vulnerability.

1. Introduction

In 1982, Roger Revelle, in an early assessment of the potential effects of a climate-induced sea-level rise, graphically sketched the potential impacts: “The oceans would flood all existing port facilities and other low-lying coastal structures, extensive sections of heavily farmed and densely populated river deltas of the world, major portions of the states of Florida and Louisiana, and large areas of many of the world cities" (Revelle, 1982). Since that time an extensive literature has evolved aimed at delineating the risks of a large sea-level rise, particularly the potential probabilities of such an event, the rate at which it might occur, and the types and magnitudes of associated uncertainties. Despite this extensive scientific effort, the nature of the risk entailed in a major future sea-level rise continues to be elusive and subject to conflicting expert opinion. The most prominent possibility for a large and relatively abrupt rise in sea level under consideration at present is the potential collapse of the West Antarctic ice sheet (WAIS) and this is the focus of our review. The IPCC (Intergovernmental Panel on Climate Change) in its Second Assessment Report concluded: "Our ignorance of the specific circumstances under which West Antarctica might collapse limits the ability to quantify the risk of such an event occurring, either in total or in part, in the next 100 to 1,000 years" (Warrick et al., 1996). A recent study by the U.S. National Research Council of Abrupt Climate Change also notes that: "large, abrupt and widespread climate changes with major impacts have occurred repeatedly in the past, when the earth system was forced across thresholds. Although abrupt climate change can occur for many reasons, it is conceivable that human forcing of climate change is increasing the probability of large, abrupt events" (Alley et al., 2003).

Quantitative estimates of either the likelihood of West Antarctic ice sheet collapse over a given time period or the magnitude of the consequences of such a collapse are not possible at present. There is also little chance that credible estimates will be available for a considerable time. There is, however, a considerable amount of scientific information that requires interpretation, and there are many public policy and management issues that deserve attention. Accordingly, some sort of risk analysis, even an analysis lacking the specificity one normally expects in a risk assessment, is needed. We might use a more general name, "risk interpretation" for such a less specific review of the state of scientific knowledge. Such an interpretation would include an analysis of what is known about the "threat" or "threats"; including the state of knowledge about both potential consequences and likelihoods of such consequences. It would also include an evaluation of management opportunities for addressing the threats. Of particular importance would be a discussion of the nature of the uncertainties about consequences, likelihoods, and opportunities for mitigation. The discussion would include a qualitative discussion of plausibility and would evaluate the extent to which quantitative probabilities can be assessed. A key element of the interpretation would be an assessment of the opportunities and likelihood of acquiring new or improved information and identifying any signals germane to management initiatives, together with a determination of the capabilities required to acquire such information or define such signals. In what follows, we begin such a risk interpretation. In doing so, we have a particular interest in a worst case situation, that is, the occurrence of a rapid sea level rise of five to ten metres over the next several centuries. We proceed thematically as follows: (Section 2) the threat: sea level rise; (Section 3) potential collapse of the West Antarctic ice sheet; (Section 4) abrupt climate change; (Section 4) vulnerabilities and impacts; (Section 5) what kind of risk problem is this?; (Section 6) implications for risk management.

2. The threat: sea-level rise

A number of phenomena contribute to future sea-level rise, including the thermal expansion of the oceans, a loss of mass of glaciers and ice caps, a loss of mass of the Greenland and Antarctic ice sheets due to recent and projected climate change and ongoing adjustment to past climate change, and runoff from a thawing of permafrost and deposition of sediment on the ocean floor (Church et al., 2001 p. 682). On the basis of these contributions the IPCC has estimated an average global sea-level rise of 0.09 -0.88m with a central value of 0.48m, for a range of Atmosphere-Ocean General Circulation Models (AOGCMs) and emission scenarios (from the IPCC Special Report on Emission Scenarios), in the period 1990-2100 (Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin and Woodworth, 2001 p. 671). It is important to note that this IPCC average and uncertainty range do not take into account possibilities of dynamical ice movement in Antarctica (Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin and Woodworth, 2001 p. 683). We return to this factor below, but initially wish to point to the difference between global average sea level rise and what may occur at a local scale.

There is considerable variability associated with location, implying that relative sea level changes[1] may be considerably larger or smaller than the global average sea level rise. A number of factors contribute to this geographical variability. Some relate to the behaviour of the land next to the sea. Relative sea level changes is influenced for instance by tectonic land movements. Tectonic land movements include rapid displacements associated with earthquake events and slow movements such as mantle convection and sediment transport. Shorelines can retreat or advance in response to vertical land movements. Coastal subsidence in river delta regions has a typical magnitude of 10mm/yr (Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin and Woodworth, 2001 p.659). As an example of an upper estimate, local sea level in the Bangladesh delta could be 447cm higher than at present by 2100 as a result of enhanced subsidence (due to groundwater/petroleum withdrawal) and a maximum projected eustatic sea-level rise of 217 cm (Milliman et al., 1989 p. 344). Relative sea level changes are further influenced by isostatic movements. When ice sheets melt, vertical land movements occur due to the redistribution of mass

[1] Relative sea level change is the change in mean sea level as measured by coastal tide gauges. Mean sea level at the coast is "the height of the sea with respect to a local land benchmark, averaged over a period of time, such as a month or a year, long enough that fluctuations caused by waves and tides are largely removed " J. A. Church *et al.*: 2001, Changes in Sea Level', in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* J. T. Houghton *et al.*, Eds. (Cambridge University Press, Cambrige, United Kingdom and New York, NY, USA, 2001) pp. 881..

within the earth and oceans. There are still such glacio-hydro-isostatic effects, for example, occurring from the melting of the ice sheets 6,000 years ago (Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin and Woodworth, 2001 p. 654).

Relative sea level changes also depend on the distribution of global average sea level rise. The distribution of global average sea level rise depends on ocean surface fluxes, interior conditions, and circulation. (Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin and Woodworth, 2001 p. 644). The IPCC notes: "Our confidence in the regional distribution of sea level change from AOGCMs is low...However, models agree on the qualitative conclusion that the range of regional variation is substantial compared with the global average sea level rise. Nearly all models project greater than average rise in the Arctic Ocean and less than average rise in the Southern Ocean" (Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin and Woodworth, 2001 p. 642). Local meteorological changes and changes in the frequency of extreme events also influence the relative sea level changes in a particular coastal region (Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin and Woodworth, 2001 p. 674).

The impacts of a large sea level rise are still little studied, particularly as they involve interactions between physical and ecological change with human systems. Since human responses will emerge as the sea level rise occurs, both the rate of the rise and the adaptive capacities of impacted human systems are essential issues. We need to know much more about the circumstances under which the coping and adaptive capacities of human systems will be overwhelmed. These will surely be highly place specific, and will interact with other stresses confronting these places, thereby compounding the assessment task.

3. Potential collapse of the West Antarctic ice sheet

The principal current scenario for a widespread global catastrophic risk of rapid large sea level rise, and not just local cases of a high and rapid sea level rise, is the potential collapse of the West Antarctic ice sheet. The West Antarctic ice sheet is a marine ice sheet, meaning that it rests largely on ground that is well below sea level (although part of its mass involves floating extensions, ice shelves, that move seaward but are confined by the rocky coast). Release of the grounded ice to the ocean would contribute four to six meters of rise in global mean sea level. By *collapse*, following Oppenheimer (1998), we mean "the loss of most or all of the land-based (grounded) ice on a timescale that is much shorter than its accumulation turnover timescale". The West Antarctic ice sheet assumes central importance in that other ice sheets either are largely grounded above sea level, are subject to only gradual ablation from moderate warming (as in Greenland), or have no clear history of major, rapid ice changes in the recent geological past (as in East Antarctica) (Oppenheimer, 1998 p. 325).

Timescale is a crucial factor with respect to estimates of potential West Antarctic ice sheet contributions to sea level rise. Three questions are involved: When will the West Antarctic ice sheet start to disintegrate? How long will such disintegration take? Will the rate of disintegration as measured in sea-level rise equivalent be constant or change (and if so how?) over time? Answers to these questions are not always clear when disintegration of the West Antarctic ice sheet is discussed. The following table (Table 1: Estimates of sea-level rise due to disintegration of the West Antarctic ice sheet) gives some examples of a number of estimates that have been made since the late 1960's, and the forcings and explanations given.

Table 1 to follow.

Large uncertainty characterizes the assessment problem of West Antarctic ice sheet collapse. It arises from a number of different sources: incomplete scientific understanding of the physical phenomena and their interrelationships involved, incomplete data and measurements; and overly simplistic and unvalidated models. The complexity of the physical systems suggest the inherent magnitude of the assessment challenge. An expert panel was once convened to identify possible adverse events, system components and mechanisms, and causal interactions that could lead to a collapse of the West Antarctic ice sheet (Vaughan and Spouge, 2002 p. 73). A number of important events and mechanisms were identified, including ice shelf erosion, reduced thermohaline circulation, increases in precipitation, ice stream variability, glacial readjustment, sub-glacial eruption and surface melting. The Workshop sought to assess the degree of consensus through a Delphi process on the relative importance of the various mechanisms. But the result indicated both little consensus on this question and substantial disagreement as to the most likely pathways through the complex web of relationships. More importantly, the workshop pointed up a classic uncertainty problem in risk assessment-that of completeness. It is unclear that the complexity shown in diagrammatic form (Vaughan and Spouge, 2002 p. 73) has captured fully the important mechanisms at work and workshop members did agree that "the complexity of interactions is probably under-represented" (Vaughan and Spouge, 2002 p. 74). Moreover, many of the causal relationships are not adequately understood scientifically, such as the tendency of individual ice streams to switch on or off completely or to alter substantially their flow rates within a few decades (Vaughan and Spouge, 2002). This lack of scientific understanding and consensus of basic phenomena and their behavior and interactions constitutes one of the most serious types of uncertainty – *epistemic uncertainty* – which, if large, is highly likely to generate *surprises*, behavior of the system unanticipated by current models and expert expectations.

The Delphi Panel reported on by Vaughan and Spouge (Vaughan and Spouge, 2002) did identify the main sources of large uncertainty emerging in the Delphi exercise to estimate the possible collapse of WAIS and the list speaks to the pervasiveness of the substantial and often interacting types of uncertainties that currently exist:

- What is the current mass balance of WAIS?
- Will ice shelf loss cause significant increases in discharge rates of grounded ice? (This has been a major issue in WAIS research for decades, and is still not resolved).
- Will increases in precipitation resulting from global warming outweigh possible increases in ice discharge?
- Will reduced thermohaline circulation be a consequence of atmospheric warming, and could this would (sic) outweigh ice shelf melting that results from increased sea surface temperatures?
- What are the causes of ice stream variability, and how significant is this mechanism?
- What are the continuing effects of the last glacial to interglacial transition?
- Can substantial increases in ice stream flow be sustained long enough to cause collapse?
- Has WAIS-collapse occurred in previous inter-glacials?

(Vaughan and Spouge, 2002 p. 84)

It is quite clear that many of these uncertainties will not be removed, or perhaps even significantly reduced, during the near term but also that new sources of uncertainty are likely to emerge.

One troublesome source of uncertainty in the study of the West Antarctic ice sheet and its possible collapse involves making spatial inferences from one part of the ice sheet to another. Inferences are made when data from one part of the ice sheet are extrapolated to other parts of the ice sheet or when physical mechanisms studied in one part of the ice sheet are assumed to function as well in other parts of the ice sheet. Future studies of yet inadequately analysed parts of the ice sheet may reveal different sets of data and/or different physical mechanism at work than inferred by previous studies. As long as systematic data of the entire ice are lacking, these problems of inference will remain.

Climate change introduces uncertainties to the problem of rapid large sea-level rise. The relationship between West Antarctic ice sheet collapse and global warming is itself uncertain. Furthermore, uncertainties in climate change add to that uncertainty, especially the possibilities for extreme or abrupt climate change. Climate change is problematic as a causal factor since it itself is surrounded with uncertainties that relate to a lack of data, a lack of scientific understanding of mechanisms at work, and the difficulties of making projections. With respect to the collapse of the West Antarctic ice sheet, some uncertainties of climate change stem from uncertainties in the future local air and ocean temperatures as a result of global warming. It should also be noted that a much greater global warming than presently estimated would open up the possibility of surface melting as a new disintegration mechanism (Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin and Woodworth, 2001 p. 679).

Recent data provide mixed messages about disintegration. Recent empirical measurements of the behavior of the West Antarctic ice sheet has offered some evidence that the behavior of the West Antarctic ice sheet may not be as threatening or as unstable as thought earlier, at the same time as it has introduced new sources of risk and uncertainty. Reports have emerged that the ice sheet may not have thinned as much in recent years as previously thought (Bindschadler and Bentley, 2002). Improved measurements of the Ross ice streams have indicated that new snowfall is generally keeping pace with ice loss in this sector, suggesting almost no overall net shrinkage in process. This could be comforting in part. But in the past several years it has also become clear that all sections of the West Antarctic ice sheet are not behaving in the same way. In a poorly understood region adjacent to the Amundsen Sea, for example, scientists have discovered that glaciers are disappearing at a faster rate than hypothesized even for the Ross ice streams. In the Antarctic Peninsula, meanwhile, summer-time atmosphere has been warming rapidly, threatening disintegration of ice shelves that have been relatively stable. Also, some reports have suggested that warmer ocean waters mixing from lower latitudes may be melting the ice sheet's grounded edges faster than previously assumed (Bindschadler and Bentley, 2002). In 2004 reports appeared on accelerated ice discharge and glacier acceleration and thinning following the collapse of the Larsen B ice shelf. Satellite remote sensing techniques has allowed direct observations of the effect of ice shelf removal on glacier flow. Rignot et al. conclude: "Radar interferometry observations of the Antarctic Peninsula suggests that its glaciers accelerated dramatically in response to the collapse of Larsen B ice shelf" (Rignot et al., 2004 p. 2). Scambos et al. report "Ice velocities derived from five Landsat 7 images acquired between January 2000 and February 2003 show a two-to six-fold increase in centerline speed of four glaciers flowing into the now-collapsed section of the Larsen B Ice Shelf" (Scambos et al., 2004 p. 1). In short, the flow of new scientific measurements and analyses suggests both potential feedbacks previously underestimated or unidentified and new sources of risk uncertainty. All these assessments of course rest precariously on assumptions concerning uncertainty, possibilities of abrupt change, thresholds, and feedback mechanisms. So we next turn to these issues.

Oppenheimer, in his review in *Nature*, concludes that: "It is not possible to place high confidence in any specific prediction about the future of WAIS" (Oppenheimer, 1998, p. 330). Assuming continued growth in greenhouse gas emissions according to rates characteristic of most of the IPCC "IS92" emission projections, he identifies three risk scenarios: 1) gradual dynamic response to removal of the Ross ice shelf, 2) no dynamic response, and 3) substantial (or rapid) dynamic response. He goes on to provide some hypothetical detail for each of these possibilities.

Oppenheimer judges scenario 1 to be most likely (but with low confidence), scenarios intermediate between 1 and 2 with lower sea-level rise to be conceivable, and scenario 3 to be least likely. He also opines that no convincing model exists for a sudden collapse that would cause a 4-6 m sea-level risk over the coming century, although more recent work on abrupt climate change and recent observations of dynamic behaviour of ice sheets might alter this view. One problem with Oppenheimer's three scenarios is that they are not fully specific with regards to time. As discussed earlier in this paper, a time specific estimate of West Antarctic ice sheet collapse needs to answer when the ice sheet will start to disintegrate, how long it will take, and at what rates through the disintegration period. The first Oppenheimer scenario is not specific with respect to the disintegration rate for the first 200 years (it is given at 0-0.19m per century). As interpreted by Oppenheimer, the third scenario may imply a sea-level rise of 4-6m in 250 or 400 years.

Estimating the likelihood of West Antarctic ice sheet collapse may also proceed on observations of the West Antarctic ice sheet together with mechanistic assumptions. Since there is still controversy over what the mechanisms are and their causal relationships, this approach is ambiguous. However, the Vaughan and Spouge Delphi exercise is informative in this regard. Although one may well question the basis of probability estimates that combine the estimates from experts who disagree, the exercise of having various experts confront the same questions and provide their basis for estimation helps to clarify the state of scientific debates and the practical implications of different positions. Several observations may be made based on this exercise and our review of the risk estimation literature:

- There are many disagreements over the relative importance of various mechanisms, of various observations, and of the validity of extrapolations over time and over different regions of the ice sheet;
- Quantitative estimates of time until collapse or significant contribution to sea level rise were somewhat easier to obtain than direct estimates of likelihood, but the findings were similar;
- Across the group, no one asserted that collapse or significant contribution to sea level rise was impossible; there was considerable support for likelihood estimates of a few percent in a few centuries; and some support for likelihood estimates of a few percent for significant changes in the next 200 years;
- The disagreements and difficulties in obtaining estimates of likelihood at the level of a few percent strongly imply that credible estimates of likelihood at the level of .1% are not feasible at present. Rephrasing, this also means that we lack a capability to rule out likelihoods that are of great concern for events this potentially catastrophic;
- The discussion indicates a clear expectation among those participating that new research could well clarify many issues about mechanisms and they suggest a research agenda. Given the complexity of the mechanistic picture and the overlap in current likelihood estimates from people with very different perspectives, such clarification may not, however, lead to a great improvement or increased expert consensus in

the likelihood estimates. However, there is the potential for findings that would help mitigation efforts such as better understanding of the connection to greenhouse gas (GHG) induced climate change, or the identification of signals that could better indicate accelerated movement toward collapse.

4. Abrupt climate change

While there is a large and growing body of research on the ecological and societal impacts of climate change, virtually all of this research has relied on smoothly varying scenarios with slow and gradual changes and impact responses. This is understandable in part as analysts have wished to avoid the appearance of undue confidence in any single projection. Surprisingly little work has been done on the potential implications of abrupt climate change for human societies. Yet we know from climatic records that large, widespread, and abrupt climate changes have occurred repeatedly in the past. Paleoclimatic data, for example, reveal a sensitive climate system subject to large and perhaps difficult-to-predict abrupt changes (Alley, 2003). Large changes have occurred repeatedly in the past and with little net forcing. Meanwhile global circulation models have often underestimated the magnitude, speed, or extent of past changes (Alley, 2003).

The recent report by the U.S. National Research Council (U.S. National Research Council, 2002) on abrupt climate change points out that such change is a common feature of the global climate system, that such change has reached up to 10°C in a decade in some regions, and that "available evidence suggests that abrupt climate changes are not only possible but likely in the future, potentially with large impacts on ecosystems and societies" (U.S. National Research Council, 2002). The report also documents striking examples from past experience. Initial and final temperature change in central Greenland, for example, reached about 15°C at the end of the Younger Dryas, while the warning rate reached fully 8°C in a single decade and snow accumulation doubled in only three years. A strong climatic change occurred about 6200 BP cooling temperatures by about 10°C in the Atlantic and 2°C in Europe. During more recent historical times, multi-decadal droughts led to the collapse of early Mesopotamian and Egyptian cultures around 2200 BC and of the Mayan cultures after 750 AD (Michaelowa, 2004 p. 378).

The picture that emerges from recent writings is a climate system with threshold behavior involving large and rapid threshold transitions between multiple locally stable states. Triggers are known to exist in the climate system that can precipitate rapid change, and can be either fast, slow, or potentially chaotic. Small incremental changes can induce flips from one state to another in ways that can be irreversible or only slowly reversible. Amplifiers also exist that can produce large changes with only minimal forcing. From many past risk studies dating back to the “rapid onset” natural hazards (Burton et al., 1993) we know that abrupt changes are heavily implicated in risk events associated with large damage and loss of life. This is particularly germane to the large sea-level rise hazard because, as noted above, abrupt changes are possible in ice sheets affecting sea level and ocean circulation. We have already seen above the difficulty in identifying and quantifying all causes of a West Antarctic ice sheet collapse. In a review article in Science, the authors (the members of the panel of the above mentioned US NRC report) call attention to the same problems in assessing abrupt climate change, as well as the problem of lack of predictability near thresholds. They caution that although climate models are improving rapidly, they have "not yet reached the level of sophistication that will enable them to be used to simulate the likelihood of occurrence of the more abrupt and possibly spontaneous climate shifts described in this paper" (Alley, Marotzke, Nordhaus, Overpeck, Peteet, Pielke Jr, Pierrehumbert, Rhines, Stocker, Talley and Wallace, 2003 p. 2009). Meanwhile, (Alley, Marotzke, Nordhaus, Overpeck, Peteet, Pielke Jr, Pierrehumbert, Rhines, Stocker, Talley and Wallace, 2003) concludes that there should be serious consideration that future climate changes will be larger than indicated by the mean of the major climate-model projections and may involve abrupt changes not projected accurately by existing models.

Wrestling with abrupt change possibilities must begin with the definition of “abrupt change” itself. The U.S. National Research Council (U.S. National Research Council, 2002) study defined it thus:

> technically, an abrupt climate change occurs 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. The cause may be chaotic and thus undetectably small (U.S. National Research Council, 2002 p. 14)

Such a definition, however, addresses only climate change as a biophysical phenomenon and not in its interaction with human vulnerabilities, coping, and adaptive behavior. Recognizing this, the report later, in its chapter on societal and ecological impacts, adopts a rather different definition:

> from the point of view of societal and ecological impacts and adaptations, abrupt climate change can be viewed as a significant change in climate relative to the accustomed or background climate experienced by the economic or ecological system being subject to the change, having sufficient impacts to make adaptation difficult (U.S. National Research Council, 2002)

The latter definitional approach is the more useful, particularly in impact and decision-making terms, as it views climate change in its interactions with ecology and society. Ultimately it is the effects of such changes upon the well-being of ecosystems and human populations that really matter.

These considerations have led Hulme (Hulme, 2003) to argue that neither of the definitions presented by the U.S. National Research Council suffice as an adequate conception of abrupt climate change. He contends that a more stringent definition is needed that takes account of three major dimensions, as follows:

> ***Rate***. Abrupt climate change globally, occurs if the rate of warming is greater than ca.0.55°C per decade, or if the rate of global sea-level rise is greater than ca. 10 cm per century (see IPCC 2001). For continental or smaller regions, the threshold rates at which climate change should be viewed as abrupt would be greater.
>
> ***Direction***. All the IPCC scenarios entail basically unidirectional curves of climate change, at least at global and large region scales. But abrupt change scenarios could occur when the *direction* of climate change alters in a sustained manner.
>
> ***Severity***. Two aspects are sometimes important—the exceedance of certain climate thresholds and the occurrence of one or more extreme or unprecedented climatic or weather events.

Setting aside for the moment the particular values chosen by the IPCC or Hulme, this conceptual discussion, and the categories chosen, are particularly instructive as they begin to move the notion of "abruptness" into the domain of interactive human-ecological systems and highlights the importance of considering climate change at varying scales and taking account of the large spatial variability of vulnerability to characteristics of the types of change occurring.

As yet we know little of these interactions and the limits to the abilities of society to cope over the short and long term. Two prominent examples from the past century are noteable, however, as reviewed by Hulme (Hulme, 2003). The Sahel region of Africa experienced a 30% reduction of precipitation between the 1960s and 1980s, following a period of sustained increase of precipitation between the 1920s and 1950s. This is a good example of major directional change. While the initial impacts of the drought period were severe and the abrupt change occurred in a region of weak institutional capacity, many communities turned out to be surprisingly resilient (Batterbury and Warren, 2001). In another case—the central European floods of August, 2002—several consequences occurred for large areas of southeastern Germany, the Czech republics, and Hungary, totaling many billion of euros, but also sparked efforts that will enhance the longer term resilience of these societies in flood management (Hulme, 2003).

In terms of anticipatory assessment of the societal implications of abrupt climate change, few studies have yet been conducted. Economists have paid relatively little attention to adaptation alternatives (Carraro, 2002) in climate change generally, much less abrupt change. An interesting effort to address the impacts of abrupt climate change is available in Mastrandrea and Schneider (Mastrandrea and Schneider, 2001). They explore the potential importance of abrupt non-linear climate damages with a modeling exercise that links a single integrated assessment model to a simple climate-ocean model capable of representing the weakening or collapse of the thermohaline circulation. The results point out the danger and high cost of abrupt changes compared with those that evolve more slowly and are better foreseen, and the need to examine a wide range of plausible climate effects, impacts, and mitigation assumptions. These are issues to which we return later in this review.

All this has considerable implications for future climate change research and impact assessment. It is worth noting in brief the research agenda called for in the U.S. NRC study:

- understanding thresholds and nonlinearities in geophysical, ecological and economic systems (to which the authors of this paper emphasize the importance of extending this to social and institutional systems);
- integrated modeling efforts to simulate abrupt climate change;

- more and better data on past abrupt climate change;
- developing realistic frequency distributions of climate variables to allow long-term societal planning;
- development of 'non-regrets' adaptations strategies, especially for developing countries and focusing on institution building.

5. Vulnerabilities and impacts

Reflecting the more general state of vulnerability and impact analysis for climate change, few studies have treated in depth the potential impacts of a large sea-level risk. Such assessments need to identify both the potentially impacted systems and then the vulnerability of such systems to the projected sea-level risk at an associated rate of change. Ideally, such assessments should also take into account other social and environmental stresses likely to exist. The vulnerability assessment should take account of at least three major dimensions – the degree of exposure to risk by ecological and human systems, their sensitivity to change, and their adaptive capacities over time. Needless to say, the human systems should be viewed as dynamic, instituting feasible mitigative and adaptive actions in the face of threat. The conceptual framework for coastal vulnerability assessment presented by the IPCC (McLean et al., 2001 p. 364) attempts to address both socioeconomic and natural systems, though not in their coupling.

Vulnerability assessments should also analyse the differential impacts across social groups. For instance, in Bangladesh, land that is subject to flooding is disproportionately occupied by people living a marginal existence. These people have few options and resources for adaptation. Assessments also need to analyse differential impacts across entire communities or states. Small island states are likely to be more seriously affected due to their high exposure and limited coping resources. Global vulnerability assessments have, irrespective of methodology, all identified the small island states as one of the highest risk areas. Coral reefs, mangroves, and seagrass beds, fundamental to many small island state economies, are threatened by sea-level rise (Nurse et al., 2001). Assessments sensitive to comparisons with other assessments can thus capture potential inequities that may result from sea-level rise, as well as livelihood systems (such as fishing or tourism) that are at exceptionally high risk.

The impacts of a complete disintegration of the West Antarctic ice sheet have yet to be explored in any depth, but the IPCC asserts that middle and high estimates of disintegration time scales (corresponding to a mean contribution of 10-15 mm of sea level rise per year) lie "outside human experience and would widely exceed the adaptive capacity of most coastal structures and ecosystems..." (Smith et al., 2001 p.951), though the assumptions and basis for this statement are unclear.

A complicating issue in assessing vulnerability and impacts is the role of extreme events, such as storm surges and high waves. There are two (main) ways in which the highest sea level at a given location can change. One is through an increase in mean sea level with which present extreme levels will occur more frequently. The impacts may involve a significant increase in the extent of the area threatened with inundation as well as increased risk within the existing flood plain. The other is through alterations to the occurence of strong winds and low pressures, which would bring changes to storm surge heights (Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin and Woodworth, 2001). An example of a study looking at both sea level rise and storm surges is a study of Tongatapu Island by Mimura and Pelesikoti (1997) where they predicted that land loss would be 14% greater with a storm-surge imposed on a one metre sea level rise, than with simply a one metre sea-level rise (Nurse, Sem, Hay, Suarez, Wong, L. and Ragoonaden, 2001 p. 855). Furthermore, the IPCC notes that: "Few studies have examined potential changes in prevailing ocean wave heights and directions and storm waves and surges as a consequence of climate change. Such changes can be expected to have serious impacts on natural and human-modified coasts because they will be superimposed on a higher sea level than at present" (White et al., 2001 pp. 35-36). In short, it is clear that increases in the frequency and severity of storminess and other extreme events are an important consideration in vulnerability and impact assessment but have yet to receive significant attention.

The thinness of the assessment literature on vulnerabilities and the magnitude of potential consequences, on the dependence of the magnitude on mitigation efforts, and on capabilities for mitigation and adaptation is typical in the analysis of emerging, highly uncertain hazards. Despite the "thinness" of vulnerability and impact analysis several observations may be made:

- While clearly the consequences would be very large, there is great uncertainty about relative vulnerabilities, consequences, and about the potential for mitigation and adaptation just as there is about likelihood of events. And, similarly, there are important opportunities to develop new information that can aid in managing the hazard;
- A key need is to understand better the circumstances that can lead to the overwhelming of response capabilities and adaptive capacity;
- Vulnerability analysis can help to identify those at especially high risk and the extent to which impacts can be avoided or reduced;
- Mitigation efforts do not always work as intended, and in some cases may even make things worse. Examples can be drawn from the classic experience in flood plain of those seeking to reduce risk relocating into even more hazardous locations. This is a phenomenon associated with the social amplification of risk and is particularly pertinent for a drawn out threat like sea level rise.

Continuing on the theme of vulnerability and the scope of vulnerability analysis, two observations about variability in the threat of sea level rise are of particular interest:

- The IPCC observation that variability among locations in the average height of sea level rise is similar in magnitude to the IPCC estimated average rise across locations is significant because that is itself a substantial contribution to sea level rise in some locations even if the average rise from West Antarctic ice sheet disintegration is greater. More importantly, it serves as both a contributor to local vulnerability in areas expected to have higher than average rise and as a reminder that a broad analysis of local vulnerability is needed in assessing the threat and opportunities for mitigation;
- Similarly, the average rise in sea level at a location is not the only indicator of impacts. Short duration events such as storm surges may be very significant, and again there may be substantial local variability in vulnerability to such events, both because of differences in the likelihood of severe short duration events, and because of differences in capabilities for responding to them.

6. What kind of risk problem is this?

Based on our review of the current state of knowledge concerning the risks of a large rapid sea level rise over the next several centuries, we may inquire into the nature of the risk in the context of other hazards of substantial human concern. In short, what kind of risk problem does a large sea-level rise represent? We have a number of initial observations, all of which are relevant to public policy and management considerations:

- This risk does not lend itself to traditional risk assessment, with a spelling out of the specifics of probabilities and consequences. This risk is not possible to quantify, nor to characterise explicitly;
- These risks are in a small class of low probability/catastrophic risks accompanied by unusually high levels of uncertainty. The potential size of adverse ecological and human consequences are among the largest threats currently facing the planet;
- The size of the potential consequences are somewhat ameliorated by the fact that the accumulation of large risk will likely build over the course of one or many centuries, affording time for mounting human responses aimed at risk mitigation and adaptation;
- Because of large epistemic uncertainties and the limited state of knowledge concerning abrupt changes scenarios, it is unlikely that the probabilities of a large rapid sea-level rise will be markedly

better understood in the near term (the next 5-10 years) and some new sources of uncertainty are likely to emerge;

- Due to the interlinkages and complexities of the climate system, an assessment of the risks entailed by of a collapse of the West Antarctic ice sheet is not restricted to sea-level rise;
- The assessment of ecological and human vulnerabilities has lagged seriously behind efforts to estimate the scientific aspects of climate forcing, the behavior of the West Antarctic ice sheet, and the dynamics of ice stream flows. Large efforts will be required to redress this imbalance, with particular attention needed to enhancing our understanding of likely adaptive behavior in different cultures and human-environment settings, the case studies of the ATLANTIS project, presented in this special issue, are an important contribution to such assessments (see Lonsdale et al., Poumadere et al., Olsthoorn et al. in this special issue);
- There are many disagreements over the relative importance of various mechanisms, of various observations, and of the validity of extrapolations over time and over different regions of the ice sheet.

Turning again to the nature of the risk, some further general remarks are pertinent:

The <u>consequences</u> of collapse of the West Antarctic ice sheet are uncertain, but potentially extremely large. They will be very widespread. The magnitude of the consequences will depend in part on details of the melting and how high and rapidly sea level rises. The nature and magnitude of the consequences will also depend on the timing and effectiveness of mitigation efforts. It should be feasible to identify areas particularly vulnerable to consequences from sea level rise.

The likelihood of collapse is very uncertain. There appears to be precedent in recent geological times (the past hundred thousand or a million years or so) for such melting, so the possibility cannot be ruled out. Furthermore we lack the knowledge to rule out probabilities suggesting that collapse appears a significant risk. The uncertainty extends to both the likelihood of collapse and the potential timing of collapse (how soon it might start and how quickly it will proceed to collapse). There is, at present, no scientific consensus on mechanisms for relatively rapid collapse or on whether such mechanisms exist. Also there is no agreed-upon relationship between mechanisms for collapse to the temperature rises that might occur from GHG emissions. Beyond the question of whether temperature rise can cause West Antarctic ice sheet melting, little is known about whether a temperature rise could significantly accelerate melting.

The news from this litany of uncertainty should not be entirely discouraging. Much new information has appeared in the past decade and there is considerable controversy over its interpretation. So it is reasonable to expect further findings and some clarification about their interpretation. It is likely, however, this process will not lead to very refined probabilities, nor will we be able any time soon to rule out West Antarctic ice sheet disintegration as a significant risk. On the other hand, there may be much useful information about possible signals for movement to collapse, and better estimates of the rates at which it might occur.

Given this kind of risk problem, we see two primary implications for management:

- Given the complexity of the risks and the primitive state of sea-level rise risk assessment, it is apparent that the long-term scenario at stake is surprise-rich risk management. It is almost certain, given the current scale of knowledge, that significant future surprises will occur, perhaps involving major reassessment of the risks. Management will need to proceed from a continuing spectre of potentially catastrophic planetary risks and a poor base of understanding of probabilities and likely effects. This suggests the need for greater attention to strategies for reducing ecological and human vulnerabilities, highly adaptive management regimes geared to responding to new information, and strategies for precautionary actions and building resilience.

- In addition to vulnerability reduction, the prompt development of capabilities for precautionary reduction of climate change forcings is urgently needed to mitigate the long term impacts of climate change as well as the higher levels of uncertainties regarding the future behaviour of the climate system and its impacts.

6.1 Risk analogues

Before proceeding to these management considerations, we first examine several analogues that may help to put the risk of a rapid large sea level rise in broader risk context and further inform alternative management approaches that could be taken to such a highly uncertain but potentially catastrophic risk.

Global climate change generally and the threat of West Antarctic ice sheet collapse particularly pose a unique set of challenges for risk analysis. However, many aspects of these problems and a number of useful lessons can be found from experience with other highly uncertain hazards for which the possibility of surprise is an important aspect of the threat. Two interesting examples come from the nuclear fuel cycle: planning for the possibility of severe nuclear power plant accidents and the long term management of radioactive wastes. Another set of examples come from experience coping with emerging and unusually virulent diseases. A further example of interest is another potential extreme event in climate change – a drastic change in thermohaline circulation with the attendant impacts on regional climate. Each of these examples has some relevant similarities to the West Antarctic ice sheet collapse threat, and distinctive differences as well. For each we provide a list of lessons that would be worth exploring in greater detail.

6.1.1 Planning for the threat of a severe accident at a nuclear power plant. This may seem at first sight to be far fetched as an analogue. Emergency decisions and the corresponding responses must be made very quickly, while major changes in the West Antarctic ice sheet, if they occur at all, will take place over decades or even centuries. However, an immediate lesson is that the relevant time scale is defined by the relationship between warning times and the time it takes to respond; any effective response to the threat of West Antarctic ice sheet melting is likely to take a substantial amount of time to implement. Thus planning for accidents serves as an analogy for considering responses to warnings in several respects: 1) opportunities for prevention and opportunities for mitigation both merit attention; 2) warnings will not necessarily leave much time for the necessary mitigation measures; 3) impacts will be localized and not very predictable; 4) planning for a variety of contingencies will thus be very important . There are also, of course, important differences that limit the analogy: 1) nuclear accidents occur over a smaller spatial and temporal scale; 2) the mechanisms and potential accident characteristics are better understood; 3) there already exists a concerned citizenry and a planning infrastructure. Partly because the threat of nuclear accidents has received more practical study and planning, there are a number of useful lessons to be drawn from the analogy:

- Credible risk analysis proved possible and provided numerous benefits that went beyond the original reasons for the analysis. These included guidance for reducing the likelihood of accidents, guidance for improving operating performance, insights into planning emergency response, and methodological development that has been used for other hazard analysis;
- Mitigation efforts can increase harm as well as reduce it. The most dramatic possibility is for evacuation into areas of greater radiation exposure. One dramatic possibility is for evacuation into areas of greater radiation exposure or more exposure due to evacuation than would be afforded by sheltering;
- Attention needs to be paid to the practical problems in implementing mitigation measures, including the need for in-place resources, the ability to assess conditions as they evolve, and community trust in the mitigation program.

6.1.2 Management of radioactive wastes

Unlike planning for nuclear plant accidents, radioactive wastes are generally regarded as a long term hazard. The reasons for considering it an analogy include: 1) the long time scales of concern; 2) the concern with geological behavior over time and, particularly, with low probability events and potential surprises; 3) and the lack of broad risk-based analysis. Of course there are also important differences that limit the analogy: 1) the magnitude of the threat is much smaller and it is far more localized: 2) many of the experts believe that the technical problems in risk management can be solved. The key lessons emerge from considering the implications of risk-based analysis and observing the current state of radioactive waste management are:

- Risk-based analysis could be used to structure management efforts over time so that urgent and accessible risks can be dealt with first without compromising preparations for longer term threats;
- An appropriate infrastructure could be established that would organize efforts over time, would monitor implementation, would seek out and assess new knowledge, and would assess changes in future management needs;
- These possibilities for adaptive management , however, have not been realized. It seems apparent that what is widely agreed to be a problem extending over tens of thousands of years cannot be fully solved in a decade. One critical reason for this failure is that there is little trust by interested parties

in the present authorities and infrastructure. Adaptive management requires that interested parties believe that there is a trustworthy process available on an ongoing basis for assessment and for making changes in management arrangements over time. Management, in short, is an evolving experience, even experiment, and cannot be achieved by one-time solutions based on risk analysis and repository performance models.

6.1.3 Planning for the threat of emerging and unusually virulent diseases

Again this seems to address a more imminent concern than sea-level rise although, interestingly, there is considerable discussion currently on links between climate change and changes in the appearance and spread of disease. There are a number of reason why such planning may be considered an analogy: 1) the threat is widely distributed yet there is likely to be considerable local variability in the severity of impacts; 2) identifying highly vulnerable populations will be an important aspect for assessment; 3) development is needed of infrastructure that has the flexibility and capability for surveillance and for addressing a broad range of possibilities and that also can connect to strong local functionality. Important differences that limit the analogy are: 1) threats can appear very rapidly; 2) surveillance must be done directly on humans, with the added challenges this poses for maintaining trust, protecting people's rights, and keeping the surveillance effective over long periods of time. As with the other two examples, there is a history of management failures, specifically failure in adaptation, to suggest lessons:

- A particularly interesting observation is that in the most conspicuous recent failures - the emergence of HIV (AIDS), and BSE (mad cow disease) - the failure occurred early, but somewhat after the initial recognition. There appears to be a particularly difficult time period for adaptation, when the perception of the threat is only emerging and there are strong incentives for minimizing that perception;
- In the AIDS case, hindsight indicates that there were opportunities for a much more vigorous protection of the blood supply and for a much more serious effort to contain the epidemic at its center of origin in Africa;
- There was a similarly inadequate mobilization in the case of BSE. In both cases, the infrastructure was too vulnerable to interests within the infrastructure that wished to play down the significance of what was being observed;
- In contrast, the Swine Flu experience, shows an appropriate early identification and mobilization; however, there was a subsequent failure in adaptation as mass immunization was not put on hold pending more definitive evidence that a pandemic was imminent. This case shows that mobilization, once started, is difficult to stop and it provides

another example of how efforts at mitigation may cause harm rather than help;

- Finally the recent experience with SARS provides an example where, with some difficulties, a global response was achieved and the combination of surveillance and travel restrictions appeared to halt the development of an epidemic.

6.1.4 The threat of a substantial change in thermohaline circulation.

Climate across continents is very strongly influenced by large scale ocean circulation patterns. These result from differences in water density from the combination of differences in temperature and in salinity (hence the name thermohaline). Global warming will alter the circulation by changing the influx of fresh water in arctic regions; a serious question is what is the likelihood of a substantial change in circulation and what would be the magnitude of the consequences. In many respects the problem is analogous to West Antarctic ice sheet collapse. Drastic changes have occurred in previous eras so the possibility cannot be ruled out; the basic mechanisms for change are understood (just as for ice sheet movement); however, the nature of triggers and other key non-linear responses are not well known, and predictions are not feasible; the best estimates are that drastic change in the next century are unlikely, but small but significant probabilities cannot be ruled out. Two differences in the analysis are, however, significant: 1) unlike a description of West Antarctic ice sheet collapse, thermohaline circulation is already built (with varying levels of detail) into the global circulation models that are used for assessing global climate change; and 2) the possible link between global warming and the threat of significant changes in circulation is clear. The current state of assessment of this threat sheds light on climate change assessment generally (Alley, Marotzke, Nordhaus, Overpeck, Peteet, Pielke Jr, Pierrehumbert, Rhines, Stocker, Talley and Wallace, 2003) (Steffen et al., 2004).

- Most current assessment effort is directed toward the most likely possibilities; these may not be the most important from a risk perspective;
- There has been little study and little is known about the magnitude of the consequences for a substantial change in thermohaline circulation beyond the observation that severe regional disruption would be expected (Link and Tol, 2004, are an exception, (Link and Tol, 2004));
- There has also been very little study of human adaptation to such a change, or of the opportunities to improve adaptive capability;
- For modeling to meet this broader challenge more detail on a range of natural processes in addition to anthropogenic forcing will probably be required (Alley, Marotzke, Nordhaus, Overpeck, Peteet, Pielke Jr, Pierrehumbert, Rhines, Stocker, Talley and Wallace, 2003).

7. Implications for risk management

Given the nature of the risk problem presented by the potential collapse of the West Antarctic ice sheet and a concomitant large sea level rise over the next century or two, substantial implications exist for both the continuing assessment of these risks and uncertainties and for the evolution of an appropriate international management regime. It is not the task of this review paper to design either an ongoing assessment process or a robust future management regime, but it may be useful to explore the implications that we see for each stemming from our review.

While it is natural to associate the threat of West Antarctic ice sheet collapse with the general threat of global warming, the science presently available does not show clear links while feedback mechanisms are complex and poorly understood. Indeed there is great uncertainty about the workings of all identified or proposed mechanisms for collapse, and great uncertainty about the implications, if any, of a rise in global temperature for these mechanisms. So one could ask whether the threat of West Antarctic ice sheet collapse is most appropriately treated as a separate hazard, or whether it should be considered in the context of greenhouse gas-induced climate change. Here we argue that there are a number of reasons why for the foreseeable time West Antarctic ice sheet collapse is best considered in the context of GHG threats of climate change, specifically:

- there is a large existing assessment apparatus concerned with GHG-induced climate change that is acquiring information and making assessments that bear on the West Antarctic ice sheet issue;
- many data about the West Antarctic ice sheet are relevant to GHG-induced climate change;
- the link may be important and GHG control is thus a relevant mitigation approach;
- vulnerability to sea-level rise is a major concern even for the lower but still potentially severe rise in the sea level envisioned in GHG climate change studies (as in the IPCC) (see more particularily the potential sea level rise contribution from Greenland under climate warming, summarized in Appendix 1);
- most important, if there weren't a direct connection, there is considerable synergy in developing assessment capability and in many mitigation and adaptation initiatives.

Furthermore a risk estimate based on the minimal assumption that the start of a West Antarctic ice sheet collapse is a random event whose frequency can be roughly estimated from the time since the last such event (Bentley) gives a probability of roughly .1% for the initiation of collapse in the next century. Turning to the uncertainty that surround historical observations, the fact that there is a plausible case that a West Antarctic ice sheet collapse has occurred in the past (as we note in our above discussion on abrupt change) means that we should not encourage a scientific regime in which the debate centers on whether or not a West Antarctic ice sheet collapse is impossible. Furthermore the uniform risk estimate by Bentley of .1% in the next century or two is very high for any event with such severe and widespread consequences. It is instructive, for example, that a 10^{-5} to 10^{-6} likelihood of a core melt per reactor year in a nuclear plant is widely considered to be at the threshold of acceptability. The consequences of such events pale in comparison with those presented by a large future sea-level rise. Consequently, the most important estimates will be conditional on our knowledge of present circumstances and will involve questions as to how predictable significant changes in the ice sheet are and how rapidly such changes can occur. Satisfactory estimates of this sort can be created only with considerable mechanistic understanding which does not now exist nor is it likely to in the near future.

The IPCC predictions for GHG-induced climate change are helpful in that they set a scale for thinking about both the likelihood of West Antarctic ice sheet collapse and the magnitude of sea level rise. The predicted range is almost a meter (.09-.88m). One meter is a very serious rise in sea level by itself, approaching the levels discussed in connection with West Antarctic ice sheet melting (which woul be added). If the range presented were a conventional 95% confidence interval, the implied probability for a sea level rise exceeding close to a meter would be 2.5%, which is very large for such a serious threat, and the failure to consider abrupt changes more fully in the scenarios may suggest that this figure may be conservative. Even if the range presented were a 99% confidence interval, the implied probability would be .5% and that is still very large. Without new mechanistic information, there is no adequate basis for extrapolating the IPCC probability range to estimates of the likelihood of even greater sea level rise. Even a 0.1% probability for a large sea level rise between now and 2100, a 10^{-3} likelihood, should be considered extremely high when considering the even more severe threats of a sea level rise of 2 to 5 meters. These observations also underscore again that it is useful to treat the threat of West Antarctic ice sheet collapse in the context of other concerns about GHG-induced climate change.

Nonetheless, there are useful things to be undertaken in the ongoing assessment of sea-level rise risks. There is a considerable body of risk information much of which is still quite new and relevant to interpretation. Furthermore, it is very likely, indeed probably certain, that important new information—including some surprises—will emerge. The most useful information on forcing functions will be found in addressing questions that link mitigation possibilities to mechanistic information. One such example is that as long as there is any potential link between GHG-induced warming and West Antarctic ice sheet collapse, the seriousness of that threat should be a strong incentive to developing capabilities for reducing GHG emissions. Another example is that further analysis of vulnerabilities may indicate that the most relevant threat indicator is the rate of sea level rise rather than the total rise (or vice versa). Such a finding could help focus the search for signals as we gain greater mechanistic understanding. Some of these linkages deserve more attention—for instance is it worth inquiring as to whether a global rise in temperature might increase the rate of sea level rise from West Antarctic ice sheet disintegration, even it were not the initial trigger of collapse? And GHG climate-induced changes in storm severity and frequency could have implications for sea level rise mitigation efforts and for developing strategies for coping and adaptation.

Finally, the large uncertainties surrounding a potentially large sea-level rise make clear that assessments must give much greater attention to places, ecosystems, and peoples who are at disproportionately high risk. Such assessments will need to take account of scale differences and interactions, the interaction of sea-level rise with other stresses from other sources, and the differential sensitivity of impacted areas and peoples. Such assessments will need to be much more bottom-up in approach than the IPCC assessments conducted thus far. They will also need to be much more collaborative in nature with the people at-risk in these areas so as to draw upon both expert and local knowledge and to identify viable strategies for reducing vulnerabilities and enlarging adaptive capacities and resources. In short, the assessment process needs to become much more balanced in its attention to mitigation and vulnerability reduction, and more collaborative in how these assessments are conducted.

Turning to implications for management strategies and initiatives, the large uncertainties and the nature of the sea-level risk problem suggest that

- surprises are inevitable and often cannot be predicted or anticipated;
- management should start with what is already know, acknowledge openly the major scientific uncertainties, and address uncertainties about human behavior that affect the risks;
- management institutional systems must be highly flexible, possess a strong capability to respond rapidly to surprises, and view management as a continuing process of experiments and mid-course corrections;
- the most valuable management resource will be a high capability to learn—to seek out new data and interpretations, to challenge conventional wisdoms, and to learn from errors and false starts.

We go on to consider some of the attributes, or considerations, for management systems and strategy.

The first management necessity is high flexibility and a potential for ongoing rethinking and shifts in strategy. Given the large uncertainties surrounding the causes and consequences of sea-level rise, and the strong limitations to anticipatory risk assessment, societal response to sea-level rise will not be a one-time "fix," but a series of coping initiatives and adaptations unfolding over time. Whether the focus should be on mitigation or adaptation will also almost certainly also be a changing story over time. Surprises and major departures in understanding will surely occur and will demand a rapid response capability. This suggests that the preferred management approach should be what is usually described as *adaptive management* (Hollings, 1978) (Walters, 1986) (Lee, 1993).

Central to such a management approach is a high capability for *social learning* (Berkes et al., 1998). New information and assessments, and undoubtedly new uncertainties, will continue to appear. A high capability to learn will involve an openness to new problem framings and novel interpretations of the dynamics of ice sheet collapse. Open acknowledgment of uncertainties in the changing knowledge base will be important. Divergent views will need to be supported and encouraged within the management structures, as well as, through continuing interaction with critics and minority views outside the management institutions. Meanwhile, the management process will need to be construed as an interactive one, with continuing reassessment and mid-course correction. In essence, it needs to be inductive in approach. Indeed, management will need to be structured as an experimental process in which some number of assessments yield negative results and some interventions are expected to be less than optimal over time or even fail.

A natural conceptual approach in developing an appropriate management strategy is to imagine confronting the strategy with a series of events – a scenario – that represents a possible evolution of the risk of concern. In so doing, one tests (hypothetically) whether the strategy incorporates the needed capabilities and can coordinate their use. For highly uncertain risks, we don't know what scenario to expect, or even what scenario would represent the greatest risk, and, as described above, we would hope to develop a management strategy that would address a broad range of possibilities; we thus should confront each strategy with a range of scenarios. Furthermore, as we discussed previously, there is uncertainty in several critical dimensions: how large the sea level rise will be; how rapidly it will occur; when it will begin; how much fluctuation and change there will be in the rate of rise; and how predictable the rise will appear as it is occurring. We thus will want a portfolio of scenarios that 1) are reasonably representative across these five dimensions; 2) include the range of possibilities of most concern from our assessment of risks; 3) provide a suitable variety of challenges to proposed management structures. With such a portfolio one can test (conceptually) what capabilities are needed and what aspects of design must be in place for effective use across the portfolio. Comparisons along various dimensions may be particularly informative: we could hope to assess how sensitive management success is likely to be to the rapidity of sea level rise, or to the quality of predictions; and we might be able to draw inferences about the resilience of particular management approaches under a variety of conditions, or about vulnerabilities related to time of response.

Given the limitations to anticipatory risk assessment and to interpreting mechanisms and their interactions involved in potential ice sheet collapse, *monitoring* will need to occupy a central place in risk and uncertainty interpretation. Given the gains in knowledge associated with new measurements and data gathering, noted above over the past several years, expanded monitoring efforts to track changes in ice sheet dynamics, changes in mechanisms, and associated sea-level risk are a needed part of an adaptive management approach. Helpful in these efforts will be the identification of signals that may be linked to possible management initiatives and interventions and tracking trends in forcing functions and changes in disintegration mechanisms.

Since adaptive management is essential experimental, *social trust* is an important ingredient. Open acknowledgement of rethinking, evolving knowledge, and shifts in management strategies requires confidence in the institutions and peoples charged with management responsibility. This will place a substantial burden on management institutions for an uncompromised commitment to their mission to protect the global environment and people and a need for these institutions to be viewed as scientifically competent, fair and just in decisions, collaborative in assessment activities and open and accountable to those they serve. Missteps that lead to a loss in trust will likely prove difficult to correct and recover from, at least in the short term (Slovic, 2000).

Finally, the combination of potentially catastrophic consequences the irreversibility of changes, and poorly understood probabilities suggest that *precaution* should be an important ethical element in management strategy. Sea level rise, as we have noted above, is linked to other climate change risks so that appropriate precautionary measures may realize a spectrum of protection benefits. Just as assessment will involve an evolution of knowledge and understanding, so management strategies must range across different combinations of mitigation and adaptation options, taking account of the place-based nature of vulnerabilities and impacts. So effective management regimes and institutions will also need to be grown incrementally, and experimentally, particularly seeking win-win situations where they can be identified.

Four management arenas merit particular attention in light of this discussion of how to make management more effective and adaptive. These are 1) developing practical and implementable capabilities for limiting the levels of GHGs in the atmosphere, 2) developing monitoring and analytic capabilities that can provide ongoing assessments of knowledge about the West Antarctic ice sheet threat, linkages to GHG climate issues, opportunities and effectiveness of mitigation approaches, and identification of vulnerabilities, 3) the development of capabilities for directly responding to sea level rise in diverse localities, 4) the achievement of reductions in vulnerability to sea level rise. In each arena, there are key questions which should be addressed in a context of scenario portfolios.

For instance a key uncertainty regarding GHG reductions is just how effective approaches to make substantial reductions would be. While the technological and economic possibilities for reductions are reasonably familiar, there is very little practical experience with implementing control measures on the scale that would be required to have a significant impact on atmospheric levels of GHGs. Thus present day efforts to implement limits on GHG emissions can best be regarded as steps to develop capabilities that can be viewed as future management options when the threat of GHG induced climate change becomes better understood. The possibility of very severe effects, such as West Antarctic ice sheet collapse, implies that it is late rather than early to begin such capability development.

Further key questions linked to the remaining management arenas include:

- From an adaptive management perspective, a key question within threat surveillance and evaluation (likelihood and magnitude of West Antarctic ice sheet melting and sea level rise), is whether signals can be identified that will provide warning of impending rises, and which will offer some promise of predicting rates of rise;

- One key question linked to direct mitigation capabilities is under what circumstances (rate of rise, storm frequency) local mitigative and adaptive capabilities will be overwhelmed;
- Another key question in this arena is what are the possibilities for mitigation efforts to cause harm rather than help;
- In the indirect mitigation arena, key questions are what are the important determinants of vulnerability to sea level rise, and, based on those determinants what are effective measures to reduce vulnerability.

Appendix 1: Greenland ice sheet and sea level rise

IPCC notes 2.7 ^{o}C (for present ice-sheet topography and slightly warmer for a retreating ice sheet at higher latitude) as the annual average warming over the Greenland ice sheet at which ablation will have increased to equal accumulation (Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin and Woodworth, 2001 p. 677). When the offsetting effect between ablation and accumulation can no longer progress, i.e. when the mass balance becomes negative, the ice sheet will start to make a positive contribution to sea level rise. Given the amplification of warming at high latitudes, this magnitude of warming can be reached through several greenhouse gas concentration increases.

IPCC projects for nearly all combinations of AOGCMs and SRES scenarios that the temperature increase over Greenland by 2100 will be more than 2.7 ^{o}C, with a maximum of 9 ^{o}C (Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin and Woodworth, 2001 p. 678). Running combinations of seven climate models and five stabilization levels, ranging from 450 p.p.m. to 1000 p.p.m., Gregory et al. find that 34 of these combinations pass through the 2.7 ^{o}C warming by 2350 if considering annual average warming. Looking at summer warming (which is more relevant since no melting takes place in winter) and allowing for a + or - 0.5 ^{o}C uncertainty in the warming threshold, 24 out of 35 combinations pass through 2.7 ^{o}C by 2350. Several simulations pass the threshold by 2100 (Gregory et al., 2004 p. 616). Uncertainties in the warming threshold for positive sea level rise contribution come from uncertainties in precipitation changes, in calculations of melting, in the geographical distribution of warming and in the effects of ice-sheet dynamics (Gregory, Huybrechts and Raper, 2004).

Table 2: Responses of the Greenland ice sheet to increased CO_2, is an overview of some estimates that have been made of Greenland contributions to sea level rise in response to climate change:

Table 2 to follow.

From this review, the upper estimates of Greenland ice sheet contribution to sea level rise in the 21st and 22nd centuries are 41.1cm in the period 1990-2130 (Huybrechts and De Wolde, 1999 p.2174) and 40 cm in the period 2000-2122 (Greve, 2000 p.294). The first estimate is based on a 8 x CO_2 concentration stabilising at 2130 and a +7.9 ^{o}C mean annual temperature increase over Greenland (also stabilising at 2130). The second estimate is based on a +12 ^{o}C mean annual air temperature increase over Greenland occurring over the present millenium. For a more extended time period, 1990-2500, the upper estimate is 360 cm in the period 1990-2500 for a +8.4 ^{o}C near annual temperature increase over Greenland due to a 8 x CO_2 concentration increase. Alternatively, the upper estimate could be cited as 582 cm here, if considering the upper estimate of the study, as opposed to its best estimate (Parizek and Alley, 2004 p. 1023).

For a 2 x CO_2 the estimates of Greenland contribution to sea level rise in this review range from negligible in 1990-2060 (Bugnion and Stone, 2002 p. 100), through -0.5-1.7cm in 1990-2100 (Bugnion and Stone, 2002 p. 103) and 6.8cm in the period 1990-2130 (Huybrechts and De Wolde, 1999 p. 2174), to 6+ (0.6-6.5)cm in the period 1990-2100 (Parizek and Alley, 2004 p.1024). The differences are of a small absolute magnitude in the century time scale, but where simulations have also been done for several centuries into the future the absolute differences between the estimates increase. Hence, Parizek et al. report an increase of 15-108cm, with a best estimate of 15 cm, over the estimate of 40cm given by Huybrechts et al. for the period 1990-2500. Buignon et al. end simulations in 2100.

The increse in melt compared to previous estimates which Parizek and Alley report, is due to a description of the melting process which includes surface-meltwater lubrication of ice flow. They conclude that "this recently discovered physical connetion between ice-sheet flow and above-freezinf surface temperatures should not be ignored when assessing the global impact of climate change"(Parizek and Alley, 2004 p. 1025). Research is needed to reduce local and regional uncertainties in the quantification of the speed-up mechanism. The authors believe that observations will help determine if local observations that have been made also apply to the equilibrium and /or ablations zones across the Greenland ice sheet (Parizek and Alley, 2004).

An almost complete disintegration of the ice sheet, resulting in almost a 7m sea level rise, is thought to be possible within the millenium with a +12 ^{o}C mean annual air temperature increase over Greenland (also occurring over the millenium) (Greve, 2000 p. 289). An interesting new result is that the complete melt of the Greenland ice sheet may be irreversible. Using the HadCM3 AOGCM model, the regional and global climate is simulated for the case where the Greenland ice sheet is removed and greenhouse gas concentrations are at preindustrial levels. Results show that in the long-term average there is no snow accumulation over Greenland (Tonazzio et al., 2004). However, the question remains "whether after the removal of the ice sheet the high ground in the southeast could support an ice cap, which might then begin a dynamic regrowth of an ice sheet over more of the Greenland landmass. This question needs to be answered with a dynamic ice sheet model " (Tonazzio, Gregory and Huybrechts, 2004 p.21).

In contrast to the WAIS, the GIS may have fewer ways to respond to climate change that involve thresholds and qualitative changes in the behaviour of the ice sheet. According to Greve, the process that may operate in Greenland is creep instability as increasing temperatures reduce ice viscosity. (Greve, 2000) However, as suggested above, the response time of the GIS to climate change may be faster than previously thought - the timescale of response of summer surface melt to climate change may be one of days to months as opposed to centuries to millennia (Parizek and Alley, 2004 p. 1014).

The Greenland ice sheet can thus make considerable contribution to sea level rise this century. Importantly, over the longer time scale of millenia, the sea level rise resulting from the melt of Greenland would exceed that of the collapse of the West Antarctic ice sheet in absolute magnitude. It should also be recalled that thermal expansion eventually reaches much higher levels than at the time of stabilisation of CO_2 concentration. The IPCC writes: "On account of the time-scale, the thermal expansion in the 2x CO_2 experiments after 500 years of constant CO_2 is 4 to 9 times higher than at the time when the concentration stabilises. Even by this time, it may only have reached half its eventual level, which models suggest may lie within a range of 0.5 to 2.0 m for 2x CO_2 and 1 to 4 m for 4x CO_2. For the first 1,000 years, the 4x CO_2 models give 1 to 3 m." (Church, Gregory, Huybrechts, Kuhn, Lambeck, Nhuan, Qin and Woodworth, 2001 p. 677) As already mentioned, for considerable CO_2 increases, simple melt of the WAIS is also to be considered.

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Sea level rise risk

Table 1: Estimates of sea level rise due to disintegration of the West Antarctic ice sheet

If a box is left blank the author did not comment that aspect.

Source	Forcing on the ice sheet	Mechanism/Explanation/ Calculation	Sea level rise(m)	Timescale for start (yrs)	Timescale for sea level rise (yrs)	Rate (m/100 yrs)
(Hughes, 1975)	Glacial cycle	Glacial instability[1]			12,100 - 13,100 yrs p.514	
(Thomas et al., 1979)	Warming sufficient to increase ablation rates from ice shelves	As buttressing effects of ice shelves decrease, flow rates from the ice sheet increase.	5m	0	400	Most of sea level rise in the final hundred years of the 400 year period.
(Thomas, 1985)	$2xCO_2$ by 2050. Basal melting rates of ice shelves increase between 2000-2050 and then remain constant.	Ice shelves exert backpressure on ice streams flowing into them. Warming melts ice shelves and backpressure is reduced , allowing ice streams to flow faster into the ice shelves. [2]	24 cm as best estimate; 13-239 cm; and 62-295cm[3]		2000-2100	
(Mercer, 1968)	7-10 ^{o}C or more higher summer temperatures in Reedy Glacier area.	Ice shelves and grounded ice sheet are in equilibrium. As (Ross and Filchner) ice shelves disappeared, changing horizontal forces made ice sheet thin and decrease in area as ice front receded. The grounded ice sheet lifted off the bottom and became an ice shelf.	4-4,5m	Historic		"rapid, perhaps even catastrophic" p. 220
(Mercer, 1978)	Atmospheric warming due to $2xCO_2$ atmosphere concentration by 1938	Same mechanism as above (p.323)	5m			"rapid" p. 321

1 "Inherent glacial instability leading to disintegration of an ice sheet is probably related in every way to the formation of subglacial water thick enough to effectively decouple the ice sheet from its bed. In the West Antarctic ice sheet, the subglacial water layer can be either injected under the ice sheet or produced by basal heating." pp. 508-509.

2 In the model ice-stream acceleration is consistent with ice-shelf weakening. (There is also a negative feedback of increased ice discharge on ice-shelf thinning.)

3 24 cm as best estimate (ice shelf basal melting rates increasing to maximum 1m per year); 13-239 cm with ice shelf basal melting rates increasing to maximum 1m per year; 62-295 cm with ice shelf basal melting rates increasing to maximum 3 m per year.

Source	Forcing on the ice sheet	Mechanism or explanation	Sea level rise(m)	Time-scale for start (yrs)	Timescale for sea level rise (yrs)	Rate m/100 yrs
(MacAyeal, 1992)	Climate forcing by sea-level and local surface temperature. [1]	Ice stream drainage once region containing deformable till connects with an open boundary through a frozen-bed zone.		Onset of collapse depends on the present distribution of deformable subglacial till.		0.25m/ 100yrs (max)
(Alley and Whillans, 1991)	A combined response to the end of the last glacial cycle and internal instability	e.g. changes in generation and transport of water and basal debris, variations in ice strenght.[2]		May be occurring		
(Bentley, 1998)	Glacial cycle	Collapse in response to glacial cycle with a long time constant in the subglacial system. [3 4]	5-6m			1m/100 yrs minimum 10mm/yr
(Bindschadler and Bentley, 2002)		Not specified.		Predicts this will be as of now		2 or 4mm/yr 1m/500yr
Bindschadler, 1998 #30]		Grounding line retreat, linear fit to historic data		Occurring		0.8mm/yr
(Bindschadler, 1998)		Grounding line retreat, erratic. Ice stream B is accelerating.		Occurring		currently 1.3mm/yr but varying

[1] Climate forcing by sea-level (effects grounding lines) and local surface temperature (effects accumulation).

[2] "Hypotheses to account for the observed ice-stream changes include changes in the generation and transport of water and basal debris, and variations in ice strength." p. 962

[3] Ice streams and their slippery beds incorporated in model. Based on MacAyeal 1992 study.
Unsynchronised collapse occurring once every glacial cycle.

[4] Bentley writes: "I estimate the chance of that to be on the order of one in a thousand. Obviously, this is not a number to be taken literally: nevertheless, I believe it puts the threat of rapid sea-level rise from a WAIS collapse in a realistic perspective." p. 161

Table 2: Responses of the Greenland ice sheet to increased CO_2

Source	Model	Scenario	Sea level rise	Period of sea level rise	Rate of sea level rise
(Huybrechts and De Wolde, 1999 p.2174)	Three dimensional thermomechanic ice sheet models driven by a two dimensional climate/ocean model subjected to greenhouse gas emission scenarios.	2 x CO_2 concentration, 1990 - stabilisation after 2130. +2.9 °C mean annual temperature increase stabilising at 2130	6.8cm	1990-2130	approximately 1cm 1990- 2050, 3cm 2050-2100
		4 x CO_2 concentration, 1990 - stabilisation after 2130. +5.5 °C mean annual temperature increase stabilising at 2130	20.3cm	1990-2130	approximately 2cm 1990-2050, 8.5cm 2050-2100
		8 x CO_2 concentration, 1990 - stabilisation after 2130. +7.9 °C mean annual temperature increase stabilising at 2130	41.1cm	1990-2130	approximately 4cm 1990-2050, 16.8cm 2050-2100
(Greve, 2000 p. 289-294)	A three dimensional dynamic/thermo-dynamic ice-sheet model (SICOPOLIS).	+3 °C increase in surface temperature, by 3000AD	72cm	ca 2000 - 3000 AD	
		+6 °C increase in surface temperature, by 3000AD	240 cm	ca 2000 - 3000 AD	
		+10 °C increase in surface temperature, by 3000AD	580cm	ca 2000 - 3000 AD	
		+12 °C increase in surface temperature, by 3000AD	close to 700cm	ca 2000 - 3000 AD	
		+12 °C increase in surface temperature, by 3000AD	40cm	2000-2122	
(Bugnion and Stone, 2002 p. 100-103)	Snowpack model with climate variable input from ECHAM 4	2 x CO_2 1990-2060	negligible at 2060[1]		
	Snowpack model with climate variable input from MIT 2D LO	REF (like IPCC IS92a with 2 x CO_2 concentration 2000-2100)	about 0.2cm	1990-2100	
(Thompson and Pollard, 1997 p. 895)	Using GENESIS Version-2 Global Climate Model with elevation-based correction to surface meteorology and a aposteriori correction for refreezing of melt water.	2xCO_2 concentration (345-690 p.p.m.v) by 2100.			+0.6-1.2mm/yr (at approximately 2100 compared to presently)

[1] Changes in mass balance translated into changes in sea level assuming that changes in runoff and accumulation proceed linearly in the period 1990-2060.

Source	Model	Scenario	Sea level rise	Period of sea level rise	Rate of sea level rise
(Gregory and Oerlemans, 1998 p. 476)	Seasonally and regionally differentiated glacier model (4 regions for Greenland). Temperature patterns from Had CM2 fed into the glacier model.	SUL-historical and future increases in GHG and effects of sulphate aoerosols. Global average temperature rise of 2.7K 1990-2100. GHG-historical and future increases of GHG and a global average temperarture rise of 3.3K 1990-2100. (GHG increases at 1% per year compounded, similar to IS92a, in both scenarios)	7.6cm (SUL) 9.3cm (GHG)	1990-2100	
(Parizek and Alley, 2004 p. 1023-1024)	A thermomechanic flowline model. Flow enhancement linked to surface meltwater production. Two dimensional coupled climate and ocean energy balance model (like Huybrechts and de Wolde 1999).	2 x CO_2 concentration	6cm + (0.6-6.5cm)[1]	1990(2000?)-2100	
		4 x CO_2 concentration	6cm + (0.9-14.0cm)[2]	1990(2000?)-2100	
		8 x CO_2 concentration	6cm + (1.5-21.9cm)[3]	1990(2000?)-2100	
		2 x CO_2 concentration, +3.2 °C over Greenland	55cm[4]	1990-2500	
		4 x CO_2 concentration, +5.8 °C over Greenland	172cm[5]	1990-2500	
		8 x CO_2 concentration, +8.4 °C over Greenland	360cm[6]	1990-2500	

[1] about 6 cm is cited as the present best estimate (from Church et al. IPCC 2001) of Greenland contribution to sea level rise if assuming approximately 2.5 degree increase in the global mean surface temperature by 2100. Numbers in parentheses are the ranges of additional rises using flow enhancement linked to surface meltwater production and assuming 2 x CO_2, 4 x CO_2 ,8 x CO_2 B. R. Parizek, R. B. Alley: 2004, Implications of Increased Greenland Surface Melt Under Global-Warming Scenarios: ice-sheet simulations', *Quaternary Science Reviews* **23**(9-10), 1013-1027..

[2] about 6 cm is cited as the present best estimate (from Church et al. IPCC 2001) of Greenland contribution to sea level rise if assuming approximately 2.5 degree increase in the global mean surface temperature by 2100. Numbers in parentheses are the ranges of additional rises using flow enhancement linked to surface meltwater production and assuming 2 x CO_2, 4 x CO_2 ,8 x CO_2 Ibid..

[3] about 6 cm is cited as the present best estimate (from Church et al. IPCC 2001) of Greenland contribution to sea level rise if assuming approximately 2.5 degree increase in the global mean surface temperature by 2100. Numbers in parentheses are the ranges of additional rises using flow enhancement linked to surface meltwater production and assuming 2 x CO_2, 4 x CO_2 ,8 x CO_2 Ibid..

[4] 40 cm is the estimate the authors take from Huybrechts and de Wolde 1999 (Huybrechts, P., de Wolde, J, 1999. The Dynamic response of the Greenland and Antarctic Ice Sheets to Multiple-Century Climatic Warming. Journal of Climate 12: 2169-2188), an estimate which is computed using a model without flow enhancement linked to surface meltwater production. 15-108 cm is the range of additional sea level rise using the model with flow enhancement linked to surface meltwater production, with 15 cm considered the best estimate by the authors Ibid.. 55cm is 40cm plus the best estimate.

[5] 150 cm is the estimate the authors take from Huybrechts and de Wolde, an estimate which is computed using a model without flow enhancement linked to surface meltwater production. 15-154 cm is the range of additional sea level rise using the model with flow enhancement linked to surface meltwater production, with 22cm considered the best estimate by the authors Ibid.. 172cm is 150cm plus the best estimate.

[6] 320 cm is the estimate the authors take from Huybrechts and de Wolde 1999, an estimate which is computed with a model without flow enhancement linked to surface meltwater production. 31-262 cm is the range of additional sea level rise using the model with flow enhancement linked to surface meltwater production, with 40 cm considered the best estimate by the authors Ibid.. 360 cm is 320 cm plus the best estimate.

Working Papers

Research Unit Sustainability and Global Change

Hamburg University and Centre for Marine and Atmospheric Science

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