RISK ESTIMATION OF COLLAPSE OF THE WEST ANTARCTIC ICE SHEET

DAVID G. VAUGHAN [1] and JOHN R. SPOUGE [2]

[1] *British Antarctic Survey, Madingley Road, Cambridge CB3 0ET, U.K.*
[2] *Det Norske Veritas, 3 Cathedral Street, London SE1 9DE, U.K.*

Abstract. Complete collapse of the West Antarctic Ice Sheet (WAIS) would raise global sea level by around 5 m, but whether collapse is likely, or even possible, has been 'glaciology's grand unsolved problem' for more than two decades. Collapse of WAIS may result from readjustments continuing since the last glacial maximum, or more recent climate change, but it is also possible that collapse will result from internal flow instabilities, or not occur at all in the present inter-glacial. Such complexity led the Intergovernmental Panel on Climate Change to conclude in its Second Assessment Report that 'estimating the likelihood of a collapse during the next century is not yet possible'. However, a refusal by scientists to estimate the risk leaves policy-makers with no sound scientific basis on which to respond to legitimate public concerns. Here we present a discussion of the likelihood of WAIS-collapse, drawing input from an interdisciplinary panel of experts. The results help to summarise the state of scientific knowledge and uncertainty. While the overall opinion of the panel was that WAIS most likely will not collapse in the next few centuries, their uncertainty retains a 5% *probability* of WAIS causing sea level rise at least 10 mm/year within 200 years. Since this uncertainty reflects both the unpredictability of the physical system and the scientific uncertainty, it will undoubtedly change as a better understanding is established.

1. Introduction

Collapse of the West Antarctic Ice Sheet (WAIS) would raise global eustatic sea level by around 5 m (Lythe et al., 2001). While WAIS-collapse is often presented in the media as an inevitable consequence of anthropogenic climate change, whether such an event is likely or even possible has remained as 'glaciology's grand unsolved problem' (Weertman, 1976) for more than two decades, and relevance to the problem is often cited in justifying allied scientific studies (e.g., Sammonds, 1999; Perissontto and Pakhomov, 1998).

The concept of climate related ice-sheet collapse originated as a qualitative hypothesis by Mercer (1968), was given a quantitative basis in modelling by Weertman (1974, 1976) and Thomas (1979), but has been brought into question by more recent analyses including those of Hindmarsh (1996) and others. Within the glaciological community, however, other causes of WAIS-collapse are probably more frequently cited. For example, the ice sheet might still be undergoing a period of re-equilibration after changes at the last glacial maximum (Bindschadler, 1997; Bindschadler et al., 1999). Indeed, many have suggested that collapse will not occur during the present interglacial (Huybrechts and De Wolde, 1999; Bentley,

Climatic Change **52:** 65–91, 2002.

1998a,b). So while the results from different climate prediction models appear to be converging (Houghton et al., 1990), there is still marked diversity of opinion in the debate concerning the WAIS-collapse (Oppenheimer, 1998).

The complexity of this issue led the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report to conclude that 'estimating the likelihood of a collapse during the next century is not yet possible' (Warrick et al., 1996). However, a refusal by scientists to estimate such *risk* (see Appendix I for a definition of terminology) leaves policy-makers with no sound basis on which to respond to legitimate public concerns. In order to evaluate the scientific disagreement in this and similar, policy-relevant, but scientifically contested issues, policy-makers are increasingly employing the techniques of quantitative *risk estimation* and *risk assessment* (Department of the Environment, 1995; U.S. Environmental Protection Agency, 1998). While controversial, *risk estimation* can help to rank particular issues in a complex debate, and provide a measure of the degree of accord within a community, helping to provide an informed basis for decision-making in the face of unresolved uncertainty. Here we present a discussion of the likelihood of WAIS-collapse that employs methods developed for risk assessment, and ultimately, drawing input from an interdisciplinary panel of experts.

Previous investigations of WAIS-induced sea level rise have either avoided giving estimates of likelihood, or have used estimates based on a highly simplified model of ice sheet collapse (Titus and Narayanan, 1995, 1996), which cannot fully represent the uncertainty about collapse mechanisms. The approach adopted in this study was to review knowledge about the WAIS itself and its possible behaviour in the future under the influence of climate change scenarios (Vaughan, 1999). This review formed the basis of a *hazard* identification panel discussion which followed a Structured What-if Technique (SWIFT, CCPS, 1992). This discussion allowed us to identify the most important scenarios, and the panel was later asked to make quantified estimates of likelihood and uncertainty of these scenarios. Judgements from the expert panel were made using a *Delphi* questionnaire (Dalkey, 1969).

Some, perhaps many, in the scientific community hold strong reservations over legitimacy of the Delphi technique, because it is not quantitative, is un-scientific, and is not objective, and we do not argue with the substance of those statements. We, however, believe that this approach has a useful indicative role in helping us assess and communicate the state of scientific understanding and uncertainty of complex environmental hazards. Managed and reported with due caution, Delphi exercises can provide an insight into the state of complex fields of study at a moment in time – they cannot be considered as a solid scientific foundation on which to determine policy, but do help clarify the level of scientific uncertainty on a particular issue to the non-specialist.

Figure 1. Location map indicating features named in the text.

1.1. THE ANTARCTIC ICE SHEET AND SEA LEVEL

The Antarctic ice sheet (including ice shelves and ice rises) covers an area of ≈13 million km^2 (Fox and Cooper, 1994) and contains ≈25.4 million km^3 of ice (Lythe et al., 2001), which is 90% of all the freshwater ice on Earth.

The Antarctic ice sheet is generally considered to comprise of two major parts, separated by the Transantarctic Mountains (Figure 1). The larger, East Antarctic Ice Sheet (EAIS) rests on land that would be generally above sea level if the ice were removed. The smaller, West Antarctic Ice Sheet (WAIS) is a *marine* ice sheet, resting mainly on ground that is far below sea level. It is mostly fringed by ice shelves, of which the largest are the Ross and Ronne-Filchner ice shelves.

1.1.1. *Rates of Sea Level Rise and the Antarctic Contribution*

During the most recent glacial period, ≈18,000 years ago, global sea level was around 120 m lower than at present (Fairbanks, 1989). Since then de-glaciation has driven sea-level rise at an average rate of rise of 0.7 m per century, but during periods of rapid de-glaciation, sea level rose at 2 m per century (Fairbanks, 1989). Both these figures are significantly higher than contemporary sea level rise which has been measured as 0.18 ± 0.08 m per century (Warrick et al., 1996).

Contemporary sea level rise is believed to result from several major contributions; thermal expansion of the oceans, melting of non-polar glaciers, changes in lakes, wetlands and ground-water, and ice-sheet changes. However, the best estimates for each contribution add up to less than the observed total (Warrick et al., 1996). Although some have speculated that the difference arises from additional ice discharge from WAIS (Paterson, 1993), this does not give a reliable estimate of the WAIS contribution as it is not supported by direct measurements.

Estimates of the contribution from the Antarctic ice sheet, based on estimates of the mass of water entering and leaving the continent, carry considerable uncertainty. So much uncertainty, in fact, that they are not significantly different from zero (Warrick et al., 1996; Jacobs et al., 1992; Vaughan et al., 1999). A direct assessment of imbalance based on surface elevation change over a four-year period showed, however, that the overall contribution from the Antarctic may be close to zero (Wingham et al., 1998). Although, this study did show that the ice surface in the basin of Thwaites Glacier, West Antarctica was lowering, perhaps as a result of negative mass balance.

In summary, ice discharge from the Antarctic Ice Sheet is not measurably different to the overall accumulation, but the accuracy of these measurements is so poor that we cannot rule out a significant contribution during the 20th Century.

1.2. OUTLINE OF THE COLLAPSE HAZARD

The potential for the collapse of WAIS is generally considered higher than either the East Antarctic or Greenland Ice Sheets, because it is a *marine* ice sheet. By this we mean that it largely rests on ground that is well below sea level. Some have argued that it is buttressed by the ice shelves at its edge (Thomas, 1979) on which it relies to maintain its stability. Ice shelves themselves are vulnerable to warming from both the air above (Vaughan and Doake, 1996) and the water below (Nicholls, 1997). Some ice shelves, around the Antarctic Peninsula, are already disintegrating, but neither the Ronne-Filchner nor the Ross ice shelves are likely to be vulnerable to the same processes for some considerable period (Vaughan and Doake, 1996).

Exactly what control ice shelves exert on grounded ice is, however, uncertain and controversial. Weertman (1974) developed a theoretical model showing that, where the sea bed slopes down inland, the grounding line is unstable and will tend to migrate inland or out to the edge of the continental shelf. Thomas (1979) argued that ice shelves provided a stabilising or ‘buttressing’ force on the WAIS grounding lines, and the loss of the ice shelves could lead to increased flux through ice streams and ultimately WAIS-collapse. Despite continuing theoretical debate (e.g., Hindmarsh, 1996; Bentley, 1998) and growing empirical evidence, there is no consensus on whether such stability mechanisms are realistic.

1.3. DEFINITION OF WAIS-COLLAPSE

WAIS-collapse means the loss of most or all of the WAIS land-based ice, over a period of hundreds or thousands of years. The term ‘collapse’ gives an impression of an event involving avalanches and armadas of massive icebergs; actually the process might be rather more sedate lasting for several centuries. But in terms of the hazard to human populations and activities, we believe that the most important factor is not the integrated sea level rise over many centuries, but the rate of sea level rise. For the purposes of this study, we have defined ‘collapse’ as a change that would contribute a sea level rise of at least 1 m per century, or 4 m in total. A less dramatic scenario that we have also considered is ‘significant sea level rise’; we define this as resulting in a sea level rise of at least 0.2 m/century, or 1 m in total.

WAIS forms only one of several contributions to global sea level change. In the future, global sea level is likely to rise due to thermal expansion of sea water, partial melting of non-polar glaciers and perhaps the Greenland Ice Sheet. The East Antarctic Ice Sheet may raise or lower global sea level (Warrick et al., 1996). The contribution from WAIS considered in this study, is additional to those contributions.

2. Risk Estimation in Environmental Issues

Risk estimation involves the systematic evaluation of the likelihood and consequences of uncertain phenomena in order to provide input to a decision-making process. In recent years, countries such as the U.S.A., U.K. and the Netherlands have made increasing use of risk assessment to help manage environmental hazards (e.g., DoE, 1995; EPA, 1998; EEA, 1998). Examples of studies where these techniques have been used include: estimation of the risk from the disposal of material infected with bovine spongiform encephalopathy (BSE) (Det Norske Veritas, 1997), assessment of Prince William Sound, Alaska, following the *Exxon Valdez* oil spill (Fowler et al., 1997), risk estimation of dioxin releases from municipal waste incineration (Her Majesty’s Inspectors of Pollution, 1996).

3. Hazard Identification

An important stage of any risk estimation exercise is 'hazard identification', in which all possible adverse events are identified and compared, usually employing a group-based technique. For the hazard identification phase of this exercise , DNV hosted a workshop that was run under the SWIFT protocol (CCPS, 1992). The outcome of the workshop is summarised below and described in detail elsewhere (Spouge and Vaughan, 1999).

3.1. THE SWIFT TEAM

The SWIFT workshop was intended to secure expert input for the project, reflecting the diversity of views among experts in the field. The team was chosen from researchers who have published papers on the subject or who were nominated by organisations active in the field. The requirement to travel to London for the two-day workshop inevitably introduced a European bias. While the theories of WAIS-collapse have largely centred on the hypothesised instability of grounding lines, several other plausible mechanisms that would result in large-scale change in the ice sheet have also been proposed. The SWIFT workshop identified many mechanisms that may contribute to WAIS-collapse and these are outlined below.

3.2. ICE SHELF EROSION

Melting of the large ice shelves that fringe WAIS occurs predominantly from the base, and will be increased by a rise in the temperature of the sea water, which may result from changes in ocean circulation. This might result from anthropogenic climate change, or natural ocean-circulation changes. Many studies have assumed that increased basal melting is the primary mechanism by which climate change could alter the Antarctic Ice Sheet (Titus and Narayanan, 1996).

Several small ice shelves around the Antarctic Peninsula have collapsed in recent years, and theoretical models suggest that in some circumstances a modest retreat of the ice front could lead to a dynamically unstable ice shelf that would collapse very rapidly (Doake et al., 1998). Melting or collapse of the ice shelves does not itself affect sea level, as this ice is already floating. It is through the effects on the grounded ice sheet that this mechanism may become important.

3.3. REDUCED THERMOHALINE CIRCULATION

Another effect of anthropogenic climate change might be a reduction in sea ice production in the Southern Ocean. Nicholls (1997) showed that it is the wintertime production of sea ice that drives the thermohaline circulation under the Filchner-Ronne Ice Shelf and causes basal melting. In the spring, when sea ice production is reduced, thermohaline circulation is reduced – atmospheric warming might have a similar effect. This would result in an *increase* in ice shelf thickness, and hence would counteract the ice shelf erosion described above.

3.4. PRECIPITATION INCREASE

Theoretical climate predictions show that increases in global atmospheric temperature would cause increases in precipitation over Antarctica (Ohmura et al., 1996). In simple terms, increased temperature allows greater pole-ward transport of moisture, although changes in storm-tracks and possible reduced sea ice production are also important factors. Increased precipitation results in a *fall* in sea level, and thus can be considered to offset any increase in discharge of grounded ice.

This effect could apply over the entire Antarctic ice sheet, and thus for this mechanism a distinction between WAIS and EAIS is arbitrary. Given continued atmospheric warming, the effect is highly likely to occur and might begin quite soon, perhaps in the next few decades.

3.5. ICE-STREAM VARIABILITY

Measurements have shown that individual ice streams may switch on and off completely or substantially alter their flow rates within a few decades (Shabtaie and Bentley, 1987; Rose, 1979). While the causes are not fully understood, it appears that instabilities in conditions at the bed of the ice stream play an important role. If several ice streams were to change their flow, this might have a significant effect on sea level.

A large-scale example of internal variability in ice sheets is the ‘binge-purge’ theory (MacAyeal, 1992). In this, the ice sheet is quiescent for thousands of years, with no ice streams. During this time, its thickness slowly builds up from precipitation, forming a dome. This increases pressure and insulates the base, leading to basal melting. Ice streams then establish and deplete the entire ice sheet in a purge-phase. It is not clear whether this model is realistic, or at what stage of the cycle the Antarctic might presently be.

This effect could apply to the entire Antarctic ice sheet, although the evidence of recent and rapid changes comes mainly from ice streams on WAIS. This effect acts over time-scales of centuries is probably independent of climate change.

3.6. GLACIAL READJUSTMENT

A simple scaling analysis (Hindmarsh, 1990) of the WAIS suggests that the time-constant for relaxation of the ice sheet to a new equilibrium after a change in the external boundary conditions is on the order of 10,000 years. Thus the response to the transition from the last glacial maximum, $\sim$20,000 years ago, may not yet be complete. Ongoing changes in the behaviour of the Antarctic may be due to readjustment from glacial conditions. It has also been suggested (Bindschadler and Vornberger, 1998; Bindschadler, 1998) that the WAIS grounding line and ice fronts have retreated, perhaps continuously, perhaps in a series of jumps, since the last glacial maximum, and that this process may continue. This effect would be independent of recent global climate change, although it is a delayed consequence of global climate change from 20,000 years ago.

3.7. SUB-GLACIAL ERUPTION

Blankenship et al. (1993) identified what they believed to be a recently active volcano under Ice Stream B on WAIS. It has been suggested that sub-glacial volcanism could accelerate an existing grounding line retreat, promoting WAIS-collapse. However, while this scenario has clear parallels with recent events in Iceland (Gudmundsson et al., 1997), it has not been widely discussed as a major threat to WAIS.

3.8. SURFACE MELTING

Surface melting on the Antarctic ice sheet might become significant if atmospheric temperatures increased substantially ($>10\,°C$). Surface melting can severely alter the thermal structure in the ice sheet by advecting heat down and eliminating the previous winter 'cold wave'. The warming can significantly reduce ice-sheet viscosity. However, the required atmospheric warming is greater than is generally predicted by GCMs for the next century, and so this is more likely to be a long-term response.

3.9. CONCLUSIONS OF HAZARD IDENTIFICATION WORKSHOP

The SWIFT team discussed each mechanism in turn, defining it as necessary, considering the consequences that might result from it, the importance of the link to these consequences, and the time-scale over which the consequences might occur. The approach included all the mechanisms that the panel considered important, with the intention of quantifying the relative importance later in the project. The discussion was recorded by an observer who was not an expert in this subject, and took no part in the discussion. This record allowed us to summarise the discussions in a block diagram (Figure 2) where each mechanism is illustrated as a box, with possible mechanistic links between them illustrated as arrows. The diagram illustrates the complexity of the system and is generally valid for both WAIS and EAIS.

In summary, the SWIFT workshop determined that: (a) we should consider both climatic and ice dynamic processes, and the complex interaction between them; (b) there are divergent views about the relative importance of the different mechanisms which cannot be resolved as they reflect genuine scientific uncertainty about ice-sheet processes; (c) the distinction between WAIS-collapse and sea level rise due to overall changes in the Antarctic is largely arbitrary – it is, however, maintained here to preserve the scope of the present study.

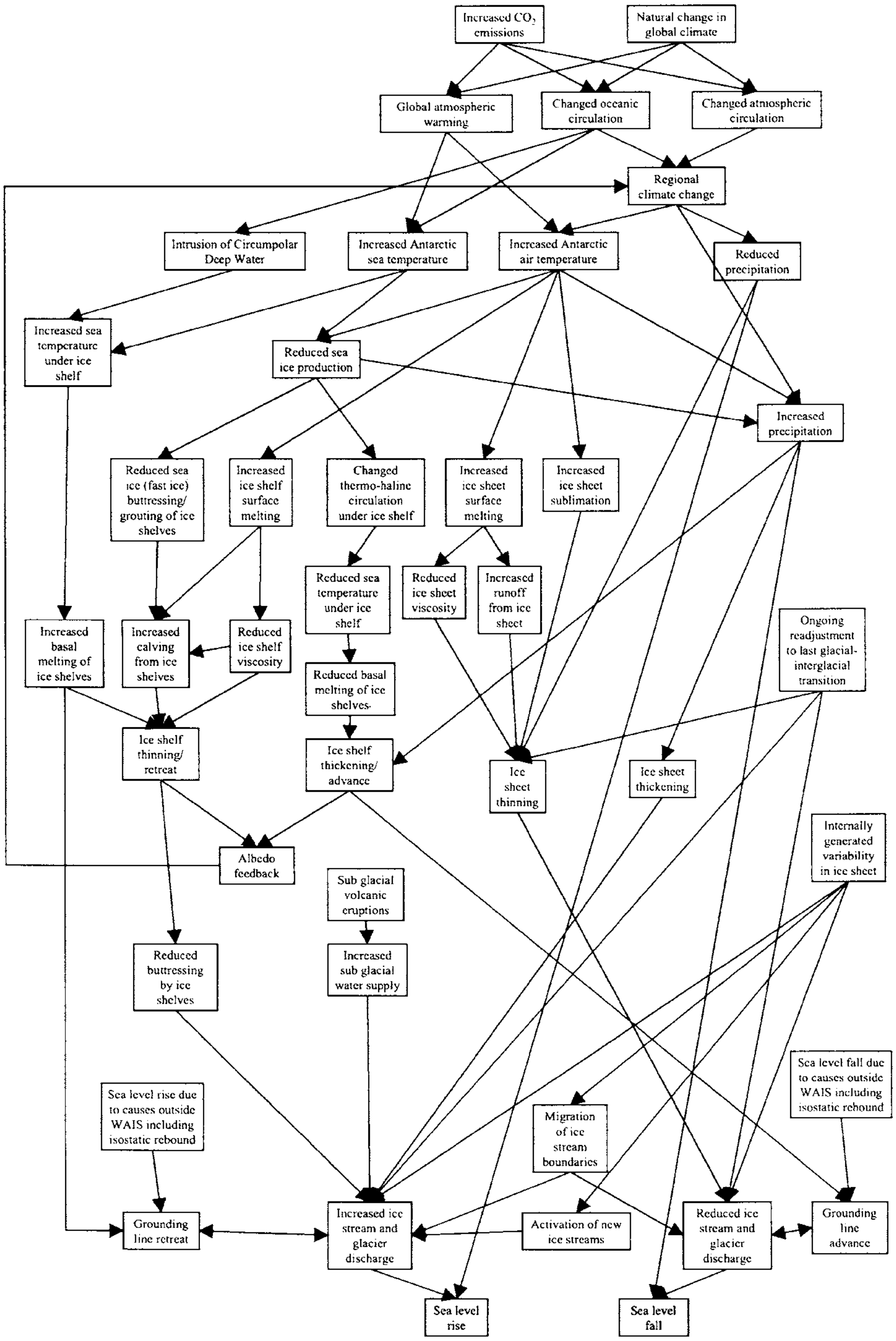

Figure 2. Result of the hazard identification workshop SWIFT analysis. This blocks shows mechanisms which the group believed might result in significant change in the Antarctic ice sheet. The arrows indicate likely causal mechanisms that link them.

3.10. EVALUATION OF THE WORKSHOP

Overall, the SWIFT workshop proved effective at identifying and structuring the mechanisms involved in WAIS-collapse. It elicited a vigorous discussion but there was little consensus as to the most important mechanisms, or the most likely pathways through the block diagram. In this sense, the SWIFT workshop failed to distil the complex hazard into a simplified form. Indeed, while the block diagram may have captured most of the important mechanisms, the workshop agreed that the complexity of interactions is probably under-represented. The high degree of complexity in the hazard identified by the SWIFT workshop meant that some techniques for risk estimation were inappropriate. It is this complexity that guided the choice of the risk estimation techniques, which are described below.

4. Three Approaches to Risk Estimation

Having identified the hazard, the next step in risk estimation is quantifying the likelihood of the particular hazard occurring. We used three methods to achieve this: statistical analysis, review of theoretical modelling and a Delphi exercise.

In many fields, the quantification of risk is based on *statistical analysis* of previous experience (e.g., in life-insurance or road accidents). In principle, the behaviour of WAIS in previous inter-glacials might support such an approach. Our attempt to apply this method is described in Section 4.1, but in practice there is insufficient data available to justify this approach, nor can behaviour in previous glaciations account for new factors such as anthropogenic carbon dioxide emissions.

In the absence of satisfactory statistical data, *theoretical modelling* of the physical system leading to the hazard can give deterministic or probabilistic risk predictions. Such models are available for WAIS, since many individual workers have developed ice sheet models that can predict WAIS-collapse given specific inputs. In Section 4.2, we describe our attempt to estimate collapse risk by considering published results from these models. A major limitation of this approach is, however, that different workers have very different opinions about the relative importance of particular mechanisms in controlling the likely future behaviour of WAIS-collapse. In principle, progressive scientific research and debate should proceed toward consensus over which theories are valid. In practice, such a consensus has not yet been reached in relation to WAIS collapse.

In the absence of a consensus model that could be used to investigate the ice-sheet response to various altered boundary conditions, it is still desirable to have a risk estimate that synthesises the view of experts in the field. There has been one previous attempt to achieve this, as part of a study of the overall likelihood of sea level change (Titus and Narayanan, 1995; Titus and Narayanan, 1996). This study used an expert panel to propose values of parameters for models of sea level change, including the contribution from WAIS; those values were then combined using a Monte Carlo simulation to obtain probability distributions for sea level change. The study by Titus and Narayanan is the most advanced risk estimation of sea level change published to date. However, it considered only one mechanism – one pathway through Figure 2 – and so did not consider the entire hazard. The solution adopted here was to use a Delphi technique to combine the risk estimates of an expert panel for the entire hazard. The details of the Delphi exercise are described in Section 4.3.

4.1. STATISTICAL ANALYSIS BASED ON PAST BEHAVIOUR

The Earth has experienced many successive periods of glaciation, during which the Antarctic ice sheet must have waxed and waned in response to changing environmental conditions. The past evolution of WAIS is, however, not well-recorded, and provides an inadequate basis for a risk estimate. Nevertheless, it can be helpful to consider WAIS behaviour over many glacial cycles, and to ask, what data would be required to perform a risk estimate using this approach.

If WAIS-collapse were simply linked to global temperature, its occurrence would be linked to the occurrence of interglacials. Under this assumption, each interglacial might be seen as an independent trial, with a chance of inducing WAIS-collapse. If the response of WAIS to a long series of interglacials were known, and all other relevant factors being equal, the proportion of past interglacials in which WAIS-collapse had occurred could be interpreted as an estimate of the probability of WAIS-collapse in the present interglacial. Additional anthropogenic warming might be considered as a further perturbation. The assumption that other factors are equal is questionable, but is not uncommon in risk estimation where there is no method of quantifying them.

Evidence for past WAIS behaviour, however, comes from the Sangamon interglacial, 120,000 years ago. There is evidence that sea level then, was 6 m higher than at present, and this may have resulted from WAIS-collapse (Mercer, 1968). This possibility is supported by evidence from marine diatoms retrieved from beneath WAIS, which suggest complete collapse has occurred in at least one recent interglacial (Scherer, 1993; Scherer et al., 1998), although whether this was the Sangamon is still to be determined.

Some believe that collapse occurred in the last interglacial, and hence will also occur in the current one, perhaps within a few hundreds or thousands of years. Others accept that collapse *may* have occurred in some previous interglacials, and hence accept a *possibility* of collapse in future interglacials.

For the statistical method to give results that might help future predictions, we need far more precise data concerning climatic conditions during recent interglacials, together with more precise records of the ice sheet configuration over at least the last million years.

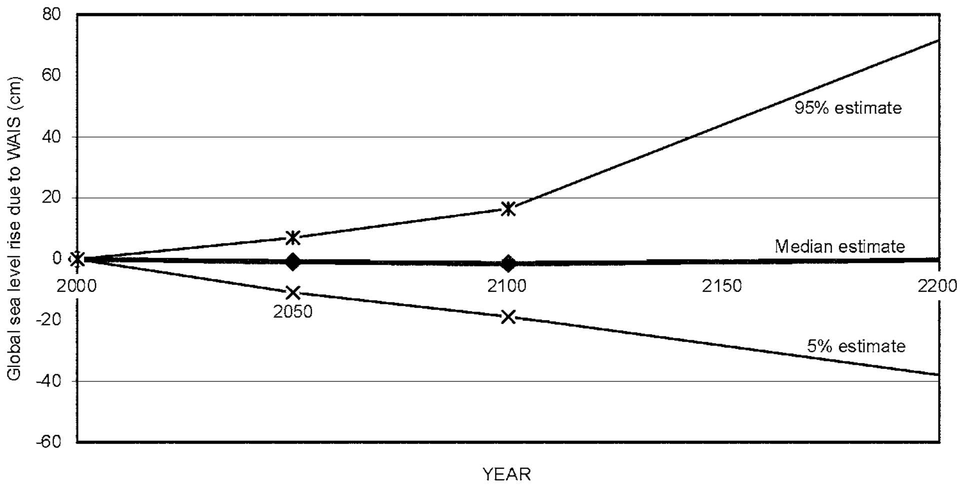

Figure 3. The likely effect of WAIS on global sea level in the near-future, according to a recent assessment that considered only one mechanism of ice-sheet change (Titus and Narayanan, 1996). The upper and lower bounds bracket the 90% confidence estimate.

4.2. RISK ESTIMATE BASED ON PUBLISHED PREDICTIONS

Several models have been developed to predict the future evolution of WAIS starting from current conditions. Although each addresses one aspect of the hazard – one pathway through Figure 2 – most authors appear to have a high level of confidence in their own predictions, despite the fact that those predictions vary widely. Estimates by Titus and Narayanan (1995) perhaps provide the most detailed estimate of the overall uncertainty range among all workers over the time-scale of 200 years (Figure 3). The detailed distribution for the year 2200 AD showed that significant sea level rise (over 0.2 m/century) had approximately a 10% chance of occurring, while collapse (over 1 m/century) had approximately a 1% chance of occurring within this time period.

There have been several other published estimates of the time before collapse occurs. These are summarised in Table I and Figure 4. The chronological presentation indicates a general trend towards predicting longer time-scales for collapse. However, the major problem with these comparisons is that like is not being compared with like – each model being applied to some particular subset of the complete hazard. One way to overcome this limitation is to define specific questions and explicitly prompt researchers to consider the complete hazard – this is what was attempted in the Delphi exercise described below.

4.3. RISK ESTIMATES BY THE DELPHI TECHNIQUE

A key feature of WAIS-collapse, apparent from both the literature review and the hazard identification exercise, is the diversity of views about the likelihood and

Table I
Published estimates of time to collapse of the West Antarctic ice sheet

Source	Collapse-time (years)	Notes
(Mercer, 1968)	150	Time not stated but inferred assuming stated trends continue
(Hughes, 1973)	6000	Hypothetical scenario for complete un-grounding
(Mercer, 1978)	50	Time until collapse 'imminent or in progress'
(Thomas, 1979)	400	Assuming 5° warming per century
(Hughes, 1982)	200	Best-estimate?
(Bentley, 1982)	500	Minimum estimate
(Lingle, 1985)	1400	Including negative feedback
(Budd et al., 1987)	2000	Time for 4-m sea level rise
(Bindschadler, 1997)	3600	Mean of stated range 1200 to 6000 years if surge continued
(Oppenheimer, 1998)	600	Mean of stated range 500 to 700 years in Scenario 1. Full range is 250 to 700 years.
(Bentley, 1998b)	50,000	Expected time for collapse randomly distributed with mean 1 every 100,000 years

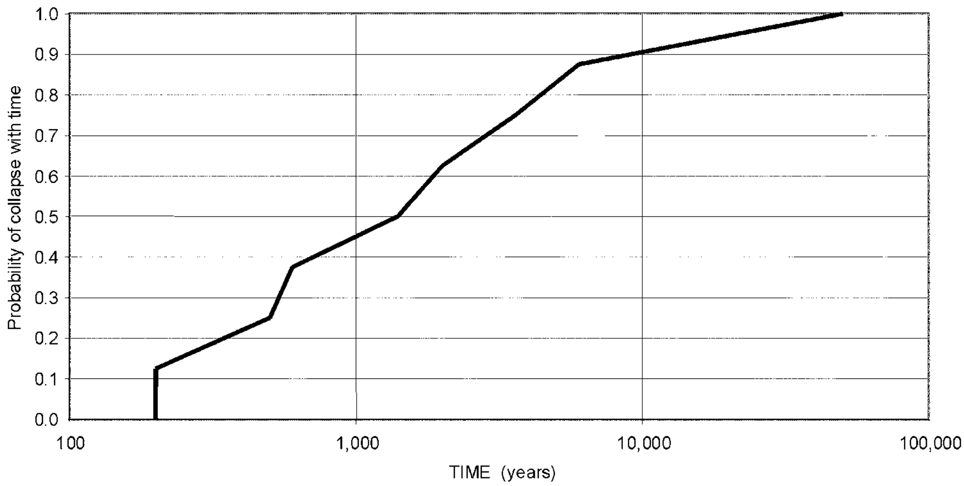

Figure 4. The combined probability distribution of estimates of collapse of WAIS published since 1980. Based on the 11 estimates shown in Table I.

mechanism of WAIS-collapse. It was essential for the risk estimate to reflect this. The estimate based on literature (Section 4.3) achieves this in part, but it suffers from bias towards proponents of collapse. Therefore, the present study convened a new expert panel, and adopted a Delphi technique to combine their views.

The Delphi technique is a well-established technique for combining expert judgements for a risk analysis. In applying it to WAIS-collapse, we encouraged panel members to use their own ice sheet models, or subjective reasoning based on previous research if they preferred. This gave a more comprehensive coverage of model uncertainty. The Delphi technique is an iterative process, which allows the panel members to see how their response compares to that of the others, and modify it if they see fit, without experiencing undue pressure to do so.

4.3.1. *The Delphi Panel*

The expert panel for the Delphi exercise was chosen from people who had been involved in the SWIFT workshop, or who had expressed interest but been unable to attend. The panel was asked to respond to questionnaires by e-mail, allowing us to reduce the European-bias present in the SWIFT workshop.

As in any group exercise, the composition of the panel strongly affected the results. We tried hard to achieve a balanced panel, representative of the main workers writing primary research in this and closely allied fields, and believe that we have succeeded. In combining the panel's quantitative responses, we allocated an equal probability to each response received. In an attempt to reflect the views of those who felt unable to quantify their responses, we have included qualitative comments in (Appendix II).

4.3.2. *The Delphi Exercise*

Our procedure was as follows. We first developed a questionnaire, using several approaches to obtaining the quantitative response that we sought. In Round 1, we circulated the questionnaire to 16 experts who had consented to be involved. We then combined and analysed the responses, and circulated them to those who had responded, so that they could check that their responses had been interpreted correctly and revise them if they wished. We also took the opportunity to clarify the questions that had caused confusion. We gave each expert a code letter, so that they could see the responses of others, as well as their own, without knowing who had written which. In Round 2, six of the experts revised their responses to varying degrees. Since these revisions had only a minor effect on the overall results, we considered that 2 rounds were sufficient to obtain stable responses.

We expected that some experts would have numerical ice sheet models, whereas others would rely on a judgmental interpretation of available literature. We therefore invited them to make use of all knowledge, information, literature, models, advice, beliefs and even 'gut feelings' that they had at their disposal. They were encouraged to discuss with colleagues, but not with other members of the expert panel. They were requested to give a brief justification of each answer, indicating the main factors or sources of information that influenced their response. However, while some gave detailed explanations of their reasoning, others gave little indication, presumably due to time constraints. For this reason, it proved impossible to characterise the basis of the responses in any other way than as a mix of models, literature and judgement.

Anticipating that some would have philosophical difficulties with the quantification, we offered several different approaches to it, in the hope that everyone would find at least one acceptable approach.

We combined their responses, giving equal weight to each, regardless of the sophistication of the underlying modelling or their degree of reliance on judgmental interpretation of the literature. Although the combination of different experts' views has been criticised (Keith, 1996), it provides a valuable encapsulation of the current state of expert opinion regarding important uncertainties (Clemen and Winkler, 1999).

The results from each approach are summarised in turn below. The responses of the individual panel members are given in full elsewhere (Spouge and Vaughan, 1999). In addition, we asked for general comments on the process which were illuminating in understanding scientists attitudes toward the techniques involved (see Appendix II).

We received replies from 12 experts, including one who gave comments but no quantitative estimates. Among the 11 who responded with estimates, there were seven who replied to all of them.

4.3.3. *The Direct Approach*

In the first approach, we asked directly for judgements about the likelihood of WAIS-collapse, which was the main project objective. Panel members were requested to allow for any modes of change that they regarded as relevant (e.g., ice stream changes, grounding line movements, precipitation changes etc.), and to assume what they regarded as the most likely conditions.

In Round 1, we asked for their estimate of the time before collapse occurs, as both an expectation value and a confidence range, using both definitions of collapse and significant sea level rise. In Round 2, we converted their responses into probability distributions, and allowed them to modify these where necessary.

Figure 5 shows the individual probability distributions for time to collapse (1 m/century or 4 m total sea level rise). This shows that two panel members were rather certain that collapse would occur within the next 1000 years, while nine showed a high degree of uncertainty about when collapse might next occur. Several gave very non-linear representations of their uncertainty.

In Figure 6, the individual responses have been combined, giving equal weighting to each response to the question. This shows the results for both collapse and significant sea level rise. The 90% range for collapse time of 200 to 1 million years by this approach in effect implies greater uncertainty to the results shown in Figure 4.

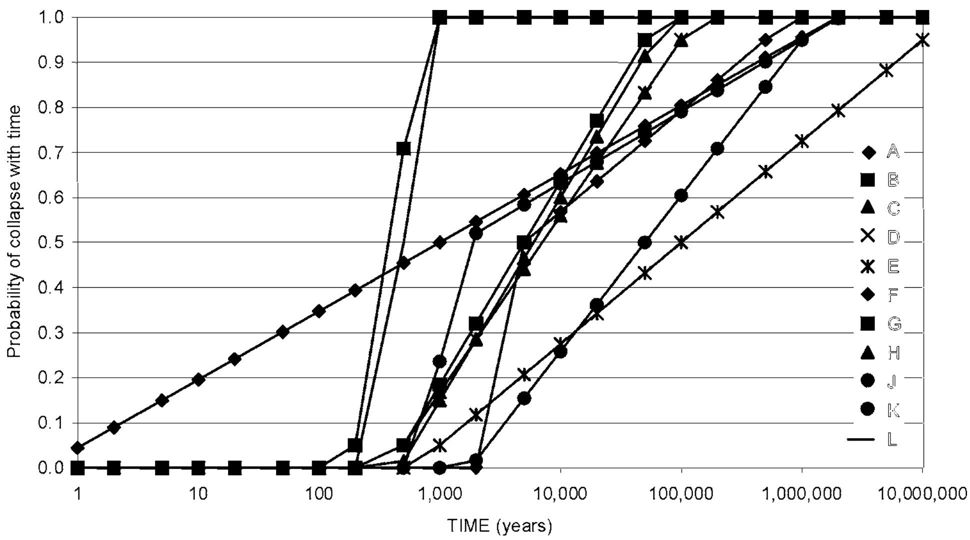

Figure 5. Individual estimates of the time to collapse of WAIS by members of the Delphi Panel. Each quantified estimate is shown and the spread indicates the level of agreement across the panel.

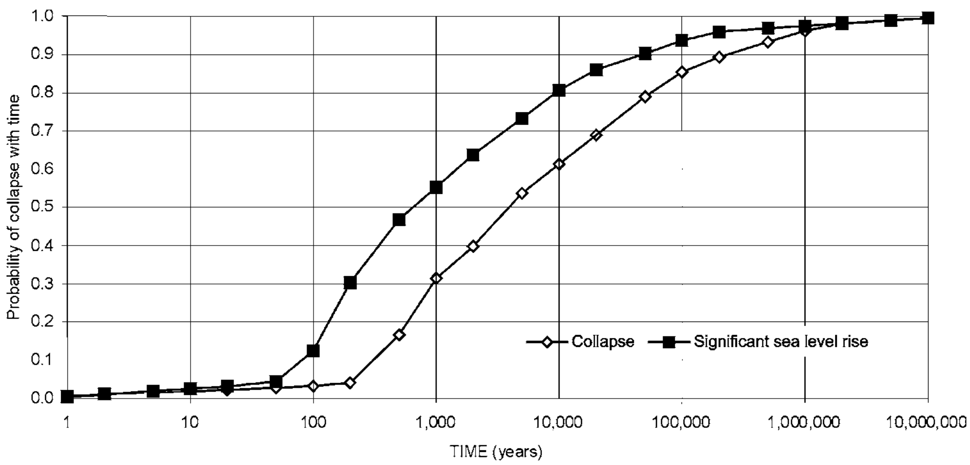

Figure 6. The combined estimates of the Delphi Panel of the probability that collapse of WAIS will occur, or significant sea level rise will result from changes in it, within a given time.

As part of the direct approach, we also asked the panel to estimate the probability of significant sea level rise (as defined above) occurring by the year 2200. Several panel members were reluctant to give a quantitative response to this question, and we had to make some interpretations of the qualitative response. The result was also sensitive to the averaging method used. Our best interpretation of the response was a geometric average probability of 0.027. Other interpretations, and definitions of averaging methods, are given elsewhere (Spouge and Vaughan, 1999). The result is an order of magnitude lower than the value of 0.3 shown on

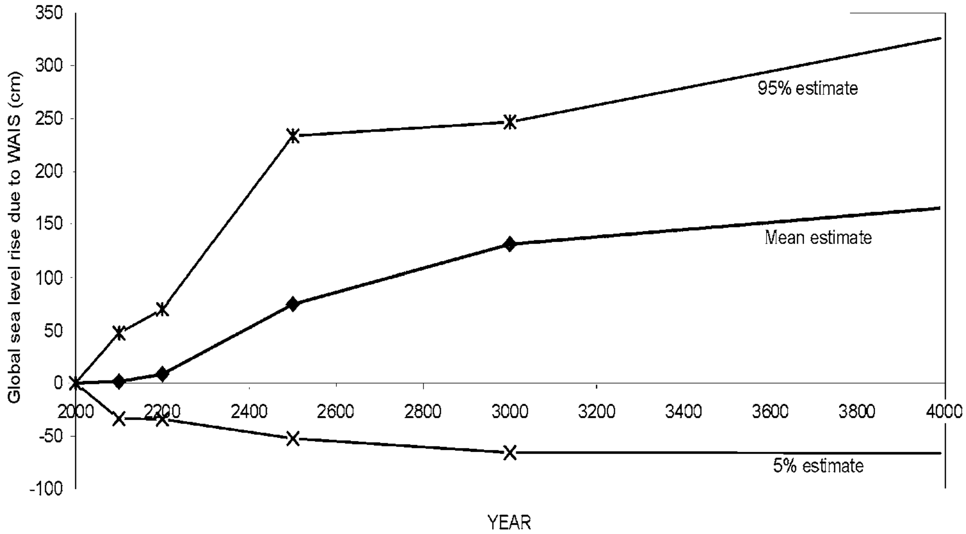

Figure 7. The combined predictions of the likely contribution to sea level rise from the WAIS. The upper and lower bounds bracket the 90% confidence estimate.

Figure 6, and we were not able to resolve this discrepancy within the two rounds of the Delphi exercise. It forms a useful reminder that this type of analysis is approximate. Quantitative measures of uncertainty in a risk estimate are themselves inevitably very uncertain.

We consider that the estimates of time to collapse give more reliable estimates of collapse probability than asking for this directly. Certainly the panel members were more ready to respond quantitatively, although the approach may have suffered bias due to a presumption that collapse *will* happen eventually. However, the discrepancy above does indicate that our estimates of collapse probability by this method may over-estimate the collapse likelihood.

4.3.4. *The Time-Profile Approach*

In the time profile approach we asked for the panel's judgement about the likely future changes in global mean sea level due to changes in WAIS. As before, we asked them to include any modes of change that they regarded as relevant (e.g., ice stream changes, grounding line movements, precipitation changes etc.). In order to combine the individual responses, we took arithmetical averages of the individual means, and the 5% and 95% confidence limits. Figure 7 shows the resulting combined responses for sea level change. These are consistent with earlier results (Titus and Narayanan, 1995), while extending them to a longer time-scale as necessary to address the collapse issue. As might be expected, the level of uncertainty grows, looking further into the future. This growth is limited by the maximum possible sea level rise due to WAIS. Even 2000 years from now there remains a significant probability that the WAIS contribution will be negative, not positive.

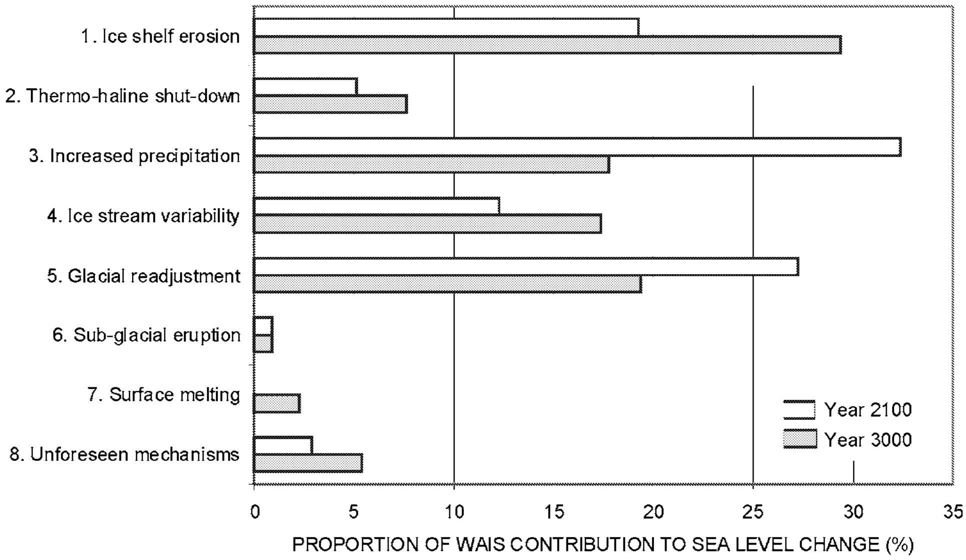

Figure 8. Estimated contributions to the overall estimate of sea level rise resulting from each of the most important mechanisms identified by the SWIFT analysis.

4.3.5. *The Scenario Approach*

In the scenario approach, we asked for the expert panel's judgement about the relative significance of various climate scenarios, as a proportion of the total change due to WAIS.

This question proved difficult to answer for people who considered that different mechanisms causing rise and fall would cancel out. In Round 2, we suggested they envisage the 'proportion' to refer to the sum of the modulus of the components. We asked for the distributions in the years 2100, 2200, 2500, 3000 and 4000. However, the distributions were not greatly different, and this is simplified to just 2100 and 3000 in Figure 8.

In order to combine the individual responses, arithmetic averages of the individual proportions are shown in Figure 8. This is not intended to show a consistent set of mechanisms, but simply to indicate the overall degree of importance of each mechanism for the panel as a whole. The relatively even split between several major mechanisms reflects a split of opinions among the panel members as to the dominant mechanisms, rather than agreement that all are important.

4.3.6. *Validity of Delphi Technique*

Many justified and sincere reservations were expressed over the validity of this, and indeed all, Delphi exercises. Several lesser reservations are discussed in Appendix B, but it is a very common concern that risk estimation results depend on the analysts involved and the approaches they select. In short, the most usual criticism is that the results are *'probably dependent on who the players are'*.

In this study, there is a particular concern about sensitivity to the SWIFT team and Delphi panel members. However, by giving panel members the opportunity to express their uncertainty in the *direct approach*, the sensitivity of the results to individual responses was much reduced. For example, panel members B and L were the main proponents of early collapse. But had they not been on the panel, the estimated 5% confidence limit on collapse time would have increased only from 200 to 300 years, which is a negligible change.

5. Conclusions

After extensive consultation with many of the eminent experts in the field of ice sheet behaviour, our simple conclusion is that the experts do not agree about when, or whether, WAIS will collapse. Some experts believe that continued global warming will cause the ice shelves to melt and ultimately allow the grounded ice to discharge into the sea, in a process lasting between several hundred and a thousand years. Other experts believe that changes in the ice sheet are largely independent of contemporary climate change and that, if such a collapse does occur, it might be thousands or even hundreds of thousands of years in the future.

Overall there was good agreement across the panel that there is a high likelihood that WAIS will eventually cause sea level rise, but they were widely divided on the times-scales over which that would happen. Some panel members estimated that there is a 50% probability of collapse within just a few hundred years. We interpret their responses to suggest that a significant sea level rise in the next 200 years is unlikely, but that this assessment retains considerable uncertainty – a 5% probability of collapse (causing sea level rise at least 1 m/century) and a 30% probability of significant sea level rise (over 0.2 m/century) due to WAIS in the next 200 years. However, it should be stressed that, in this study, *variability* and *epistemic uncertainty* are both expressed in the quoted uncertainty. This is in contrast to the ‘error bounds’ reported for many measurements, which only address the first type, i.e., variability.

The divergent views of the panel about the likelihood of WAIS-collapse and the mechanisms that may cause it reflect genuine scientific uncertainty about this issue, and cannot be simply resolved without further research. Increased understanding of the physics of the problem will reduce the epistemic uncertainty in the estimate. Furthermore, it is widely accepted that public perception of risk is magnified by particular factors that are well-known to social scientists (Pidgeon et al., 1992). Many of these factors apply to the problem of WAIS-collapse, probably magnifying the public perception of the risk it poses. The process of risk evaluation for WAIS-collapse will require these factors, as well as the high-degree of uncertainty, to be taken into account before a strategy for managing this risk can be settled.

5.1. FURTHER RESEARCH NEEDS

In general, the main sources of uncertainty in the risk estimation indicate high-priority topics for future research. In the present study, the main sources of the large uncertainty in the risk estimates are:

- 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 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?

Acknowledgements

DNV and BAS acknowledge extensive support received from the following experts who participated in the SWIFT Workshop and/or the Delphi Procedure or declined to be involved but made comments that caused us to revise the technique: Prof. Richard Alley, Pennsylvania State University, Prof. Charles Bentley, University of Wisconsin, Dr. Mike Bentley, University of Edinburgh, Dr. Bob Bindschadler, NASA, Dr. Jonathan Gregory, Hadley Centre, U.K., Dr. Richard Hindmarsh, British Antarctic Survey, Dr. Philippe Huybrechts, University of Brussels, Stan Jacobs, Columbia University, Dr. Michael Oppenheimer, Environmental Defense Fund, Dr. Tony Payne, Southampton University, Dr. Sarah Raper, University of East Anglia, Dr. Bob Thomas, ex-NASA, Prof. Duncan Wingham, University College London, Dr. Jan-Gunnar Winther, Norwegian Polar Institute. We also thank R. Bindschadler, NASA, for comments on the work. The U.K. Department of the Environment, Transport and the Regions commissioned and funded the project, but after setting the initial objectives did not direct the outcome.

Appendix I – Risk Terminology

The following defines the key terms used in risk assessment, and illustrates how they are applied in this study.

A *hazard* is an event with the potential to cause harm – WAIS-collapse is a hazard, and so are increased precipitation, sea level rise, etc.

Probability is the chance or likelihood of a hazard occurring under specified circumstances.

Risk is the combination of probability and consequence of a hazard. For example, the risk of WAIS-collapse might be expressed as a 5% chance of WAIS causing sea level rise of 10 mm/year within 200 years.

Risk estimation (or risk analysis) is the technical process of quantifying risk. The present study is an example.

Risk evaluation is the quasi-political process of considering the significance of the estimated risk, taking account of risk perception and risk acceptability. These issues are not addressed in the present study.

Risk assessment is the combination of both estimation and evaluation of risk.

SWIFT (Structured What-If Technique) – a group-based technique for identifying hazards, using a meeting of experts in different disciplines, involving brainstorming, systematic discussion and checklists.

Delphi technique – a technique for combining the judgements of a panel of experts, using iterative circulation of anonymous written responses, in order to obtain a consensus conclusion on a contested issue.

Uncertainty is lack of knowledge or degree of doubt about something. In the case of WAIS-collapse, uncertainty is one of the most important issues in the risk assessment, and it is essential for the risk estimates to take explicit account of it. Two types of uncertainty are often distinguished: *Variability* (or aleatory or Type A uncertainty), which is uncertainty due to natural randomness and can be defined more accurately, but cannot be reduced. *Epistemic uncertainty* (or Type B uncertainty) which is uncertainty due to lack of knowledge which can in principle be reduced by further research.

Appendix II – Views on the Risk Estimation Approach

Several panel members, and some experts who were invited but declined to be involved, expressed doubts about the validity of the Delphi technique and about risk estimation in general. In order to reflect their views, their comments are given in full elsewhere (Spouge and Vaughan, 1999) and summarised below. Other members of the Delphi panel and SWIFT workshop expressed great enthusiasm for the approach, primarily as a fresh look at a difficult problem where little progress seems to have been made over several years.

In the following sections, we summarise these concerns and present our responses.

VALIDITY OF APPROACH

A few panel members expressed fundamental disagreement with the overall approach of risk estimation. These views are of importance because they are probably shared by others with relevant expertise who for that reason felt unable to join in the project.

Panel member F disliked the questionnaire concept in the Delphi exercise:

> *'I am reminded of measuring the length of the emperor's nose by polling numerous individuals who have not seen the emperor.'*

However, the response given by Panel Member A is probably more representative of those who took part:

> *'We have at least seen the emperor, even if we haven't measured his nose – our guesses as to its length are probably more accurate than the guesses of someone who hasn't even seen him!'*

Panel member I expressed fundamental disagreement with our invitation to the Delphi panel to combine scientific information with judgement:

> *'Results based, even in part, on "advice, beliefs and gut feelings" are not scientific. I serve as an editor of a professional journal and I am constantly trying to weed out just this latter type of input. Yet you are inviting it!! I'm afraid I have to disregard any scientific value of your results before you even have them.'*

Risk estimation is often criticised as being *unscientific* since it combines scientific information with judgement or intuition, belief or gut-feeling. It shares these characteristics with several other predictive fields, such as weather forecasting, economic prediction, medical diagnosis – and should be considered in the same light. Furthermore, for WAIS-collapse, the experts have no previous examples to validate the predictions. In the absence of precise analytical prediction of WAIS-collapse, any risk estimate is necessarily strongly influenced by judgement. Even if such an analytical prediction were available, assessment of its significance would still require judgement.

SENSITIVITY TO COLLAPSE DEFINITION

Panel member E criticised the definitions of collapse, but we found the absence of any established definition of WAIS-collapse to be inconvenient, and acknowledge that our selected definitions were sometimes simplistic. The use of two different definitions does, however, allow exploration of the sensitivity of the results. For example, if we had used 0.2 m/century to mean collapse instead of significant sea level rise), the 90% confidence range on collapse time would have been 50 to 100,000 years instead of 200 to 1 million years.

SENSITIVITY TO QUESTIONNAIRE WORDING

Several panel members identified ambiguities in the wording of the questionnaire, and inconsistencies in the responses that suggested panel members may have interpreted some questions in different ways. We were able to resolve some of these during the second round of questioning, and we do not think they had any significant effect on the results.

Panel member E was concerned about the bias towards collapse inherent in the direct approach, in which we asked for a prediction of the time to collapse. This approach gave a higher likelihood of significant sea level rise than when we asked for this probability directly, which we assume is evidence of such a bias. If so, the difference between the approaches gives a measure of the degree of bias, equivalent to an order of magnitude in the probabilities.

In mitigation, we found it difficult to word the questionnaire in such a way as to elicit comparable responses from people who have a wide variety of beliefs about future WAIS behaviour. The project objectives required us to estimate the likelihood of an event that some regard as certain and imminent, while others regard it as highly improbable, or almost certain not to occur, and still more would prefer not to quantify the risk at all. Our attempts to be inclusive were successful, but perhaps we gave too little attention to being unambiguous.

UNCERTAINTY IN RESULTS

The main concern about the quantification stage is that the results are extremely uncertain. Appropriate emphasis on these uncertainties is essential in presenting the results. Some panel members were concerned that the results will be meaningless, or misleading, if presented as probabilities. The sensitivity to the averaging method – arithmetic or geometric – observed in the analysis supports this view.

A further concern is that quantitative expressions of uncertainty such as confidence limits or probability distributions in risk estimates are even more uncertain than average values. Hence the numerical results may seem meaningless, regardless of the way they are presented. We respond to this by observing that it is well accepted that WAIS-collapse is a very uncertain field, but in this risk estimation we have, at least, addressed the uncertainties systematically.

PROBABILITY AND UNCERTAINTY

Panel member F confessed to being *'nervous of the exact distinction between probability and uncertainty'*. Other panel members also appeared unfamiliar with the concepts of probability and uncertainty as they are used in risk estimation.

Most future events are uncertain to some degree, although few are quite as uncertain as WAIS-collapse. A risk estimation expresses this uncertainty as a 'risk', measured in terms of probabilities, i.e., the chance of WAIS-collapse occurring in a given period.

It is important to ask what a risk estimation means by ‘a 5% probability of collapse within 200 years’. A Bayesian interpretation is that this reflects our ‘degree of belief’ that this event will occur. Perhaps more meaningfully, it can be interpreted as saying the majority believes there will be no collapse in this period, but that we estimate based on the range of views expressed) a 5% chance that they will be proved wrong and that collapse will occur in this period. We believe this is comprehensible to decision-makers.

UTILITY OF RESULTS

Are uncertain risk estimates, strongly influenced by judgement, any more useful than no risk estimates at all?

Panel member F considered the results would be *‘not particularly helpful’*. Panel member C suggested it might decrease support for research, perhaps by giving an incorrect impression that WAIS-collapse was adequately understood. Our response is that this appears unlikely, given the very large uncertainty range in the present results shows that the issue is not well-understood.

Panel member J considered that the study had not identified any new areas requiring better field data or models – *‘these are already well known to the glaciological and glacial-geological community’*. Given that the risk estimation is entirely based on the expertise of these communities, this is perhaps not surprising. Nevertheless, we hope that our review of existing knowledge can still be useful for people not familiar with it.

The objective of the project was to improve quantitative understanding of the likelihood of WAIS-collapse. This refers in particular to the understanding of DETR scientists who have the task of responding to public concern on the issue, and through IPCC the understanding of the global scientific and political communities.

Therefore, to test whether the risk estimates are any use, we need to ask whether the conclusion of this study that ‘there is a 5% chance of WAIS-collapse within 200 years, although this could be over-estimated by an order of magnitude’ is preferable to the prior position that ‘estimating the likelihood of collapse is not yet possible’.

References

Bentley, C. R.: 1982, ‘West Antarctic Ice Sheet: Diagnosis and Prognosis’, *Carbon Dioxide Research Conference: Carbon Dioxide, Science and Consensus, Conference 820970*, Dept. of Energy, Washington, D.C.

Bentley, C. R.: 1998a, ‘Ice on the Fast Track’, *Nature* **394**, 21–22.

Bentley, C. R.: 1998b, ‘Rapid Sea-Level Rise from a West Antarctic Ice-Sheet Collapse: A Short-Term Perspective’, *J. Glaciol.* **44**, 157–163.

Bindschadler, R. A.: 1997, ‘West Antarctic Ice Sheet Collapse?’, *Science* **276**, 662–663.

Bindschadler, R. A.: 1998, ‘Future of the West Antarctic Ice Sheet’, *Science* **282**, 428–429.

Bindschadler, R. A., Alley, R. B., Anderson, J., Shipp, S., Borns, H., Fastook, J., Jacobs, S., Raymond, C. F., and Shuman, C. A.: 1999, 'What is Happening to the West Antarctic Ice Sheet?', *EOS.* **79**, 257, 264–265.

Bindschadler, R. A. and Vornberger, P.: 1998, 'Changes in the West Antarctic Ice Sheet since 1963 from Declassified Satellite Photography', *Science* **279**, 689–692.

Blankenship, D. D., Bell, R. E., Hodge, S. M., Brozena, J. M., Behrendt, J. C., and Finn, C. A.: 1993, 'Active Volcanism beneath the West Antarctic Ice Sheet and Implications for Ice-Sheet Stability', *Nature* **361**, 526–529.

Budd, W. F., McInnes, B. J., Jenssen, D., and Smith, I. N.: 1987, 'Modelling the Response of the West Antarctic Ice Sheet to a Climatic Warming', in van der Veen, C. J., and Oerlemans, J. (eds.), *Dynamics of the West Antarctic Ice Sheet*, Kluwer Academic Publishers, Dordrecht, pp. 321–358.

Center for Chemical Process Safety: 1992, 'Guidelines for Hazard Evaluation Procedure', 2nd edition, American Institute of Chemical, Engineers, New York.

Clemen, R. T. and Winkler, R. L.: 1999, 'Combining Probability Distributions from Experts in Risk Analysis', *Risk Analysis* **19**, 187–203.

Dalkey, N. C.: 1969, 'The Delphi Method: An Experimental Study of Group Opinion', RM-5888-PR. The Rand Corporation.

Department of the Environment: 1995, *A Guide to Risk Assessment and Risk Management for Environmental Protection*, The Stationery Office, London, pp. 1–92.

Det Norske Veritas: 1997, *Risks from BSA via Environmental Pathways*, Report to the Environment Agency 1997, Det Norske Veritas, London.

Doake, C. S. M., Corr, H. F. J., Rott, H., Skvarca, P., and Young, N. W.: 1998, 'Breakup and Conditions for Stability of the Northern Larsen Ice Shelf, Antarctica', *Nature* **391**, 778–780.

European Environment Agency: 1998, 'Environmental Risk Assessment – Approaches, Experiences and Information Sources', European Environment Agency, Copenhagen.

Environmental Protection Agency: 1998, 'Guidelines for Ecological Risk Assessment', Risk Assessment Forum, U.S. Environment Protection Agency, Washington D.C.

Fairbanks, R. G.: 1989, 'A 17,000-year Glacio-Eustatic Sea Level Record: Influence of Glacial Melting Rates in the Younger Dryas Event and Deep-Ocean Circulation', *Nature* **342**, 637–642.

Fowler, T., Gabroski, M., and Harrald: 1997, 'Overview of Prince William Sound Risk Assessment Project', Institute of Marine Engineers, Marine Risk Assessment Conference 1997, London.

Fox, A. J. and Cooper, A. P. R.: 1994, 'Measured Properties of the Antarctic Ice Sheet Derived from the SCAR Antarctic Digital Database', *Pol. Rec.* **30**, 201–206.

Gudmundsson, M. T., Sigmundsson, F., and Bjornsson, H.: 1997, 'Ice-Volcano Interaction of the 1996 Gjalp Subglacial Eruption, Vatnajokull, Iceland', *Nature* **389**, 954–957.

Her Majesty's Inspectors of Pollution: 1996, *Risk Assessment of Dioxin Releases from Municipal Waste Incineration Processes*. Her Majesty's Inspectors of Pollution, London.

Hindmarsh, R. C. A.: 1990, 'Time-Scales and Degrees of Freedom Operating the Evolution of Continental Ice-Sheets', *Transactions of the Royal Society of Edinburgh: Earth Sciences* **81**, 371–384.

Hindmarsh, R. C. A.: 1996, 'Stability of Ice Rises and Uncoupled Marine Ice Sheets', *Ann. Glaciol.* **23**, 105–115.

Houghton, J. T., Jenkins, G. J., and Ephraums, J. J.: 1990, *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, pp. 1–364.

Hughes, T. J.: 1973, 'Is the West Antarctic Ice Sheet Disintegrating?', *J. Geophys. Res.* **78**, 7884–7910.

Hughes, T. J.: 1982, 'The Stability of the West Antarctic Ice Sheet: What Has Happened and What Will Happen?', *Carbon Dioxide Research Conference: Carbon Dioxide, Science and Consensus, Conference 820970*, Dept. of Energy, Washington, D.C.

Huybrechts, P. and De Wolde, J.: 1999, 'The Dynamic Response of the Greenland and Antarctic Ice Sheets to Multiple-Century Climatic Warming', *J. Climate* **12**, 2169–2188.

Jacobs, S. S., Helmer, H. H., Doake, C. S. M., Jenkins, A., and Frolich, R. M.: 1992, 'Melting of Ice Shelves and the Mass Balance of Antarctica', *J. Glaciol.* **38**, 375–387.

Keith, D. W.: 1996, 'When Is It Appropriate to Combine Expert Judgements?', *Clim. Change* **33**, 139–143.

Lingle, C. S.: 1985, 'A Model of a Polar Ice Stream and Future Sea Level Rise Due to Possible Drastic Retreat of the West Antarctic Ice Sheet', in *Glaciers, Ice Sheets, and Sea Level: Effect of a CO_2—Induced Climatic Change*, Dept. of Energy, Washington D.C. DOE/ER/60235/1, 317–330.

Lythe, M., Vaughan, D. G., and The BEDMAP Consortium: 2001, 'BEDMAP: A New Ice Thickness and Subglacial Topographic Model of Antarctica', *J. Geophys. Res.* **106** (B6), 11335–11352.

MacAyeal, D. R.: 1992, 'Irregular Oscillations on the West Antarctic Ice Sheet', *Nature* **359**, 29–32.

Mercer, J. H.: 1968, 'Antarctic Ice and Sangamon Sea Level', *International Association of Scientific Hydrology Symposia* **79**, 217–225.

Mercer, J. H.: 1978, 'West Antarctic Ice Sheet and CO_2 Greenhouse Effect: A Threat of Disaster', *Nature* **271**, 321–325.

Nicholls, K. W.: 1997, 'Predicted Reduction in Basal Meltrates for an Antarctic Ice Shelf in a Warmer Climate', *Nature* **388**, 460–462.

Ohmura, A., Wild, M., and Bengtsson, L.: 1996, 'A Possible Change in Mass Balance of Greenland and Antarctic Ice Sheets in the Coming Century', *J. Climate* **9**, 2124–2135.

Oppenheimer, M.: 1998, 'Global warming and the stability of the West Antarctic Ice Sheet', *Nature* **393**, 325–332.

Paterson, W. S. B.: 1993, 'World Sea Level and the Present Mass Balance of the Antarctic Ice Sheet', *NATO ASI Series* **12**, 131–140.

Perissontto, R. and Pakhomov, E. A.: 1998, 'Contribution of Salps to Carbon Flux of Marginal Ice Zone of the Lazarev Sea, Southern Ocean', *Marine Biology* **131**, 25–32.

Pidgeon, N., Hood, C., Jones, D., Turner, B., and Gibson, R.: 1992, 'Risk Perception', in *Risk: Analysis, Perception and Management*, The Royal Society, London, pp. 89–134.

Rose, K. E.: 1979, 'Characteristics of Ice Flow in Marie Byrd Land, Antarctica', *J. Glaciol.* **24**, 63–75.

Sammonds, P. R.: 1999, 'Understanding the Fundamental Physics Governing the Evolution and Dynamics of the Earth's Crust and Ice Sheets', *Phil. Trans. Roy. Soc. London A.* **357**, 3377–3401.

Scherer, R. 1993: 'There is Direct Evidence for Pleistocene Collapse of the West Antarctic Ice Sheet', *J. Glaciol.* **39**, 716–722.

Scherer, R. P., Aldahan, A., Tulaczyk, S., Possnert, G., Engelhardt, H., and Kamb, B.: 1998, 'Pleistocene Collapse of the West Antarctic Ice Sheet', *Science* **281**, 82–85.

Shabtaie, S. and Bentley, C. R.: 1987, 'West Antarctic Ice Streams Draining into the Ross Ice Shelf: Configuration and Mass Balance', *J. Geophys. Res.* **92**, 1311–1336.

Spouge, J. and Vaughan, D. G.: 1999, 'Risk Estimation of the Collapse of the West Antarctic Ice Sheet', Final Report the Dept. of the Environment, Transport and the Regions, Det Norske Veritas, London, p. 40.

Thomas, R. H.: 1979, 'Effect of Climatic Warming on the West Antarctic Ice Sheet', *Nature* **277**, 355–358.

Titus, J. G. and Narayanan, V.: 1995, *The Probability of Sea Level Rise*, Environmental Protection Agency, Washington, D.C., pp. 1–197.

Titus, J. G. and Narayanan, V.: 1996, 'The Risk of Sea Level Rise: A Delphic Monte Carlo Analysis in which Twenty Researcher Specify Subjective Probability Distributions for Model Coefficients within their Respective Areas of Expertise', *Clim. Change* **33**, 151–212.

U.S. Environmental Protection Agency: 1998, 'Guidelines for Ecological Risk Assessment', Washington, D.C., U.S. Environment Protection Agency, Risk Assessment Forum.

Vaughan, D. G.: 1999, 'A Review of the Causes and Mechanisms that May Lead to Globally Significant Change in the Antarctic Ice Sheet 1999', British Antarctic Survey Report for DNV Ltd and DETR.

Vaughan, D. G., Bamber, J. L., Giovinetto, M., Russell, J., and Cooper, A. P. R.: 1999, 'Reassessment of Net Surface Mass Balance in Antarctica', *J. Climate* **12**, 933–946.

Vaughan, D. G. and Doake, C. S. M.: 1996, 'Recent Atmospheric Warming and Retreat of Ice Shelves on the Antarctic Peninsula', *Nature* **379**, 328–331.

Warrick, R. A., Le Provost, C., Meier, M., Oerlemans, J., and Woodworth, P. L.: 1996, 'Changes in Sea Level', in Houghton J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K. (eds.), Cambridge University Press, Cambridge, pp. 358–405.

Weertman, J.: 1974, 'Stability of the Junction of an Ice Sheet and an Ice Shelf', *J. Glaciol.* **13**, 3–11.

Weertman, J.: 1976, 'Glaciology's Grand Unsolved Problem', *Nature* **260**, 284–286.

Wingham, D. J., Ridout, A. J., Scharroo, R., Arthern, R. J., and Schum, C. K.: 1998, 'Antarctic Elevation Change from 1992 to 1996', *Science* **282**, 456–458.

(Received 10 July 2000; in revised form 6 April 2001)