

Eliciting Information from Experts on the Likelihood of Rapid Climate Change

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The threat of so-called rapid or abrupt climate change has generated considerable public interest because of its potentially significant impacts. The collapse of the North Atlantic Thermohaline Circulation or the West Antarctic Ice Sheet, for example, would have potentially catastrophic effects on temperatures and sea level, respectively. But how likely are such extreme climatic changes? Is it possible actually to estimate likelihoods? This article reviews the societal demand for the likelihoods of rapid or abrupt climate change, and different methods for estimating likelihoods: past experience, model simulation, or through the elicitation of expert judgments. The article describes a survey to estimate the likelihoods of two characterizations of rapid climate change, and explores the issues associated with such surveys and the value of information produced. The surveys were based on key scientists chosen for their expertise in the climate science of abrupt climate change. Most survey respondents ascribed low likelihoods to rapid climate change, due either to the collapse of the Thermohaline Circulation or increased positive feedbacks. In each case one assessment was an order of magnitude higher than the others. We explore a high rate of refusal to participate in this expert survey: many scientists prefer to rely on output from future climate model simulations.

KEY WORDS: Dangerous climate change; Europe; expert elicitation; rapid climate change; risk assessment; Thermohaline collapse

1. INTRODUCTION

Governments, particularly those in Europe, appear to be taking seriously the threats posed by climate change, judging by statements from presidents and prime ministers (Blair, 2005). Part of this concern arises from extreme events such as the European floods of 2000 and 2002 and heat waves in western Europe of 2003 (King, 2004). Awareness of the risks

associated with climate change appears to be high in both public and private institutions and organizations that may need to respond: in some sectors this concern has been high for more than a decade (Association of British Insurers, 2004; Connell & Willows, 2003). Until recently, this awareness has largely been focused around what could be termed “gradual” climate change—change occurring at historically very high rates, but within the range projected by the Intergovernmental Panel on Climate Change (IPCC), i.e., an increase of 1.5 to 5.8°C in global average temperature over the 1961–1990 mean by 2100 (IPCC, 2001). The potential threat of catastrophic climate change, resulting from the collapse of the Thermohaline Circulation in the North Atlantic, has been publicized in the popular media since late 2003; for instance, in the Hollywood movie *The Day After Tomorrow* released globally in May 2004, in a leaked report commissioned

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by the Pentagon in the United States into the potential consequences of rapid cooling (Schwartz & Randall, 2003), and, in the United Kingdom, by the screening in November 2003 of a BBC documentary (*The Big Chill*). These events generated substantial media coverage in Europe and North America and continue to be the object of study on both lay perceptions of risk (Brown, 2004; Balmford *et al.*, 2004; Leiserowitz, 2004) and the social and political construction of climate change risks (Shearer, 2005).

Substantial regional cooling following the collapse of the Thermohaline Circulation, which currently brings relatively mild conditions to western Europe is just one example of a “rapid” or “abrupt” climate change that may be triggered by an increasing concentration of greenhouse gases (Alley *et al.*, 2003; National Research Council, 2002). Another widely known potential abrupt change is a rapid and sustained rise in sea level following the collapse of the West Antarctic Ice Sheet (Oppenheimer & Alley, 2005). Less well known is the possibility that positive feedbacks in the Earth system would lead to accelerated warming through increased emissions from methane currently stored in the wetlands, the tundra, and on the sea floor (reviewed in Schneider, 2004).

The increasing profile given in the media to the so-called rapid or abrupt climate change has raised awareness among those who may need either to adapt to climate change or are developing mitigation policies (see, for example, the International Climate Change Task Force (2005)). However, while there is widespread scientific and indeed public acceptance that some climate change is occurring and will continue through the 21st century, there is considerable scientific uncertainty over the likelihood of rapid climate change and this hinders the development of adaptation and mitigation policies. The threat cannot be dismissed as unknown—abrupt climate shifts have occurred in the past (12,700 and 8,200 years ago, for example, following slow downs in the Thermohaline Circulation), and could conceivably occur in the future (Schneider, 2004)—but there have so far been no formal assessments of the likelihood of them occurring over time horizons relevant to adaptation and mitigation planners.

The aim of this article is to explore the issues associated with the assignment of likelihoods to the threat of rapid climate change and forms part of a wider initial assessment of vulnerability to rapid climate change in Europe (Arnell *et al.*, 2005). It begins with a more detailed discussion of the types of rapid climate

change before exploring why the estimates of likelihoods are relevant to climate adaptation and mitigation policy. The article then reviews ways of estimating likelihoods—analysis of past records, computer simulation, or expert judgment—before presenting results of a survey to elicit expert opinion on the likelihood of rapid climate change. The final section draws implications of the conclusions of the survey for assessing vulnerabilities, adapting to climate change, and developing climate policy.

2. “RAPID” CLIMATE CHANGE

There are no clear definitions of “rapid” or “abrupt” changes, and the terms are often used interchangeably.³ The glossary of the IPCC’s *Third Assessment Report*, for example, describes some “rapid” climate changes, but does not attempt a formal definition. Essentially, these changes are implicitly assumed to result in a rate of climate change outside the range (increase of 1.5°C to 5.8°C in global average temperature and an increase in sea level of 10 cm to 87 cm by 2100, relative to 1961–1990) projected in the *Third Assessment Report*.

A broad distinction can be drawn between two types of rapid change. The first can be seen as *abrupt* changes, where the climate system either globally or regionally crosses a threshold and switches to a new state (National Research Council, 2002): these changes include the collapse of the Thermohaline Circulation and the collapse of the ice sheets. The second can be seen as *accelerated* change, where the rate of climate change increases rapidly: these include changes due to large positive feedbacks, such as the release of methane into the atmosphere following warming at the sea bed or of permafrost. This accelerated change *may* result in an abrupt change in climate, but will not necessarily do so. There is also a scale issue: “abrupt” climate changes are generally implicitly taken to affect large geographic areas. Gradual climate change will mean that some localized marginal areas will experience substantial changes in climate regime, which may locally be perceived as rapid and abrupt.

The Thermohaline Circulation brings warm water across the North Atlantic and relatively mild climates to western Europe. This Thermohaline Circulation has abruptly switched off in the past, leading to large and rapid falls in temperature across western Europe

³ UK usage favors “rapid” (e.g., the NERC RAPID program), while U.S. usage favors “abrupt” (e.g., the NRC (2002) report).

(Clark *et al.*, 2002). These past collapses have been triggered by the sudden release of fresh water from glacial lakes in North America into the North Atlantic, and although this source of water is currently not available, there is evidence that the Thermohaline Circulation is currently weakening (Hansen *et al.*, 2001) and moving closer to a threshold that may trigger collapse. Current climate models simulate a future weakening of the Thermohaline Circulation and only simulate a collapse under certain parameter combinations and model forms. Vellinga and Wood (2002) simulated the effects of a collapse in the Thermohaline Circulation on global climate (by effectively switching it off artificially in the model), showing reductions in temperatures across Europe of up to 3°C, relative to 1961–1990, in little more than a decade. In practice, such a reduction would be superimposed on the effects of global warming, and in a subsequent simulation Wood *et al.* (2003) showed that collapse in 2050 would lead to temperatures in northern Europe falling to between 1°C and 2°C below present values within a decade.

The climate system is characterized by a large number of feedbacks, both positive and negative (National Research Council, 2003). Most of these feedbacks are incorporated into climate models and therefore influence projections of future climate change. However, many of the feedbacks are not well understood or adequately modeled, and there are some additional feedbacks that have the potential to produce substantially larger increases in temperature than currently projected. Three types of feedbacks have the greatest potential to lead to an accelerated rate of climate change. Higher temperatures may lead to increased release of methane from high latitude wetlands, particularly where permafrost thaws, and higher temperatures at the sea bed may lead to the release of methane currently stored as methane hydrates (Ehhalt & Prather, 2001). The increased methane would enhance still further the greenhouse effect. Recent research also suggests that higher temperatures would increase further the rate at which carbon is released from the soil (Knorr *et al.*, 2005). The magnitude of the effect is unknown, and potential effects on forcings and hence on climate have not yet been simulated.

Clearly, “rapid,” “abrupt,” and “accelerated” are relative terms. These changes are usually perceived to be important in policy circles because they represent discontinuities with potentially significant impacts. Such changes may be considered dangerous because they are difficult or impossible to adapt to, because

they are likely to involve significant costs, or because they are irreversible in some sense.

3. WHY ARE LIKELIHOODS RELEVANT?

There are three primary reasons why it is not possible to predict precisely future climate or, more specifically, whether or when some singular event such as the collapse of the Thermohaline Circulation or the West Antarctic Ice Sheet could occur. First, the climate system is not perfectly understood and it is not currently possible to simulate climate and its response to perturbation precisely. In principle, this relative ignorance should reduce over time and the ability to simulate and predict responses to a given forcing should improve (although there is little evidence of this at present). Second, it is possible that some aspects of the climate system are indeterminate: a given forcing may not always produce the same response, and some drivers are by their nature random (e.g., volcanic eruptions). Third, it is inherently impossible to estimate precisely future emissions of greenhouse gases because they are endogenous to the economic and political system. They depend on future economic, demographic, and political pathways along with deliberate climate control policies. The future state of the world’s climate is therefore uncertain, and it is difficult to estimate the extent to which this is so.

The IPCC’s *Third Assessment Report (TAR)* did not assign probability levels to projected rates of change: it simply published a range of possible future temperature increases. This reluctance to assign probability levels has been criticized (Reilly *et al.*, 2001; Schneider, 2001, 2002). Mastrandrea and Schneider (2004) claim that “without explicit efforts to quantify the likelihood of future events, users of scientific results (including policy makers) will undoubtedly make their own assumptions about the probability of different outcomes, possibly in ways that the original authors did not intend” (p. 571). In contrast, it has been argued (Lempert *et al.*, 2004; Lempert & Schlesinger, 2000) that where uncertainty is “deep”—as in climate change assessments—it is more appropriate to rely on robust strategies that can cope with uncertain futures than to use a more formal risk-based strategy such as designing to a specified probability standard. With this line of argument, it is therefore unnecessary, and indeed misleading, to attempt to assess probabilities of climate change outcomes: efficient and effective adaptation should not rely on probabilities, which have a high degree of error attached to them. However,

while some adaptation strategies may be robust to any possible future outcome, it will often not be feasible to design strategies that can cope with everything: in practice some potential outcomes would be screened out as being “too unlikely,” although this would not necessarily be based on sophisticated quantitative analysis and, according to Sarewitz *et al.* (2003), may be based on subjective values of the decisionmaker.

It is therefore highly likely that climate mitigation and adaptation policies, at different scales, would be informed in practice by assessments (objective or subjective) of the likelihoods of different degrees or types of change. This is particularly likely to be the case when rapid climate change is considered. Discussions by the authors (in the course of five years of research and policy engagement across many sectors) with policymakers in the United Kingdom who are considering adapting to climate change revealed that perceptions of vulnerability to rapid or abrupt climate change are very much determined by perceptions of *likelihood*: if it happens it will almost by definition be “bad,” so what is important is the chance of it happening.⁴

4. ESTIMATING LIKELIHOODS

4.1. Introduction

All of the potential rapid and abrupt climate changes that have been identified are either physically plausible, have occurred in the past, or have been simulated with simulation models. In principle, there are three ways of estimating likelihoods of occurrence: through analysis of past records, through computer simulation using multiple drivers and process representations, or through expert judgment.

4.2. Analysis of Past Records

The traditional way of estimating the frequency of occurrence of an event is to use information on its occurrence in the past and undertake a statistical frequency analysis. However, it is very difficult to apply this approach to estimate the likelihood of future rapid changes, either because analogue events have not occurred in the past or, more problematically, when they did occur, the climatic and environmental conditions were very different from today.

⁴ One of the authors was present at a meeting to discuss the implications of sea level rise for a major British city. The chairman dismissed discussion of the implications of one very high scenario with “far too unlikely: we won’t bother with that.”

For example, there is considerable evidence that the Thermohaline Circulation in the North Atlantic has switched off on several occasions over the last few hundred thousand years (Rahmstorf, 2002). In each case, however, shutdowns have been triggered by the release of water from very large ice-dammed lakes in North America, and these lakes no longer exist. Also, the sensitivity of the North Atlantic to inputs of freshwater depends on the state of the Atlantic Ocean itself.

4.3. Computer Simulation

The second approach is to use computer simulation models to construct probability distributions of defined events from large numbers of simulations making different assumptions about, for example, the rates of change in driving forces, model formulations, initial boundary conditions, and parameter values (e.g., Knutti *et al.*, 2003; Murphy *et al.*, 2004; Raisanen & Palmer, 2001; Webster *et al.*, 2003; Wigley & Raper, 2001). The resulting probability distributions will be influenced by the underlying model form and the assumed probability distributions of model parameters and input drivers. It has been argued (Grubler & Nakicenovic, 2001) that it is inherently impossible to assign probabilities to narrative storylines describing possible future emissions scenarios, and therefore that it is impossible to construct credible probability distributions of, for example, temperature change.

Murphy *et al.* (2004) and Stainforth *et al.* (2005) sidestepped this latter problem by concentrating on “climate sensitivity,” the temperature change ultimately resulting from a doubling of CO₂ concentrations. Murphy *et al.* (2004) estimated that there was a 5% chance that climate sensitivity would exceed 5.4°C using multiple model runs (known as an ensemble of model runs, in this case 53 runs), and Stainforth *et al.* (2005), using an ensemble of 1,148 different runs, found a 4.2% chance that the warming rate when stabilized (the so-called equilibrium warming) would exceed 8°C.

Wigley and Raper (2001) assumed that all emissions scenarios were equally likely, and estimated the 90% confidence interval for change in global mean temperature by 2100 at 1.7–4.9°C; Webster *et al.* (2003) used a different set of assumptions and models and estimated the 90% range at 1.0–4.9°C.

While several studies have sought to identify critical thresholds for the collapse of the Thermohaline Circulation in the North Atlantic using simulation models (e.g., Rahmstorf & Ganopolski, 1999), no

published studies have so far attempted to estimate the likelihood of collapse. Schaeffer *et al.* (2002) ran 10 member ensemble simulations under different emissions scenarios to estimate the likelihood of abrupt *regional* cooling due to the disruption of ocean circulation patterns in part of the Arctic Ocean, showing a virtually 100% likelihood by the end of the 21st century under high emissions, a 33% chance under moderate emissions, and a 10% chance under stabilized emissions (they noted that the regional disruptions to ocean circulation did not necessarily affect the North Atlantic). Gregory *et al.* (2004) estimated the likelihood that the Greenland Ice Sheet would go into terminal decline, using an ensemble of different climate models run with different emissions scenarios.

Estimates of likelihood based on computer simulation models, however, are only as robust as the simulation model itself and the assumed probability distributions of input drivers. Weaver and Hillaire-Marcel (2004), for example, emphasize how different types of ocean-climate model imply different sensitivities of the ocean circulation in the North Atlantic to perturbation. Distributions of some input drivers, such as key model parameters, can be based on calibrations with observed experience, but there may often be either no or conflicting empirical evidence on which to construct probability distributions: in these cases, some form of expert judgment is necessary.

4.4. Expert Judgment

In one sense, all scientific assessments are based on some form of expert judgment: the judgment of the individual or group responsible for collating relevant past experience or constructing accurate and reliable simulation models. However, a third approach to estimating the likelihood of rapid or abrupt climate change is to elicit formally the opinions of a number of experts. Formal approaches have been used for many years both to elicit expert opinion and to use expert judgment to develop risk assessments (see Ayuub, 2000; Morgan & Henrion, 1990). Formalized procedures are essential to ensure reliability and credibility (Cooke & Goossens, 2004), and these may involve two stages.

The first is the *elicitation* of information from a group of identified experts. Cooke and Goossens (2004) suggest that the selection criteria for experts include reputation, experience, and published track record in the field of interest, diversity of background, balance of views, and, of course, interest and avail-

ability. Information can be elicited using a variety of methods, ranging from unstructured in-depth interviews through focus groups to the use of structured questionnaires. One variant is the Delphi approach, which essentially involves iteration around the group of experts, giving individuals the opportunity to revise their estimates or comment on the estimates of others. Acknowledged pitfalls of expert elicitation include different interpretations of the questions posed and a widely reported observation that experts can be overconfident in their assessments (Morgan *et al.*, 2001).

A second stage involves the *aggregation* of the information elicited from the experts to produce a consensus risk assessment. Cooke and Goossens (2004) state that the goal of formal expert elicitation methods “is to achieve rational consensus in the resulting assessments” (p. 644). This aggregation could produce, for example, a probability distribution of the magnitude of some state parameter reflecting different possible futures or various sources of uncertainty (Keith, 1996). There are several ways of constructing aggregated expert assessments (see Cooke & Goossens, 2004), all based on different ways of weighting the views of individual experts.

Surveys of expert judgment do not necessarily need to aggregate information from individual experts. While in some cases it may be appropriate to aggregate in order to construct a single probability distribution, in many others the range of expert opinion may be much more important (Keith, 1996): information on the diversity of opinion may be extremely valuable to policymakers. Lempert *et al.* (2004) claim that the attempt to construct consensus probability distributions for key climate parameters is fundamentally flawed due to the deep uncertainty over many of the drivers and processes of global change.

Expert elicitation has been used in a number of climate change assessments. Morgan and Keith (1995) interviewed 16 experts to assess possible future changes in temperature and precipitation: each expert gave a “best estimate” and a range, and these were represented individually without aggregation. Morgan *et al.* (2001) surveyed 11 ecologists to obtain individual qualitative and quantitative estimates of the impact of climate change on minimally disturbed forest ecosystems, finding a greater diversity of opinion than apparent in consensus summaries, such as those of the IPCC. Again, the results were not aggregated. Vaughan and Spouge (2002) conducted a more formal Delphi survey of the likelihood of rapid sea level rise following the collapse of the West Antarctic Ice

Sheet, and aggregated individual expert assessments to produce a single probability distribution function describing likelihood of collapse. Murphy *et al.* (2004) based the upper and lower limits for the changing parameters of their climate model on expert opinion, although they did not use a formal elicitation approach. Mastrandrea and Schneider (2004) and Webster *et al.* (2003), however, used formal expert elicitation processes to, respectively, construct probability distributions of climate sensitivity and estimate the likelihood of different rates of future emissions of greenhouse gases. These two studies both used aggregate constructions from the individual experts.

5. ASSESSING THE LIKELIHOOD OF RAPID CLIMATE CHANGE: METHODOLOGY AND RESULTS

5.1. The Approach

An expert survey approach was adopted to assess the likelihood of Thermohaline Circulation collapse and different rates of accelerated climate change. The approach involved the identification of relevant experts and the circulation *via* email of a standardized questionnaire for each of the two rapid climate changes (see Appendix). The survey involved two iterations: the second iteration presented the results and sought both revisions to original estimates and comments on the estimates. No attempt was made to aggregate the individual expert assessments to produce consensus probability distributions: from the comments of the experts outlined below, it is very unlikely that a consensus could in any case have been reached. The two surveys were slightly different in that the Thermohaline Circulation collapse survey sought estimates of the *likelihood of collapse*, without asking for estimates of consequent rates or magnitudes of change in global or regional climate, while the accelerated change survey sought estimates of the *likelihood of different rates of change*.

5.2. Identifying Experts

Central to any survey of expert opinion is the definition of the experts to be surveyed. Experts on rapid and abrupt climate change can fall into several different categories:

1. Scientists actively studying the physical processes of rapid and abrupt climate change.
2. Scientists reviewing the work of other scientists (through the IPCC, for example).

3. Scientists involved in assessing the implications of rapid and abrupt climate change scenarios.
4. Policymakers and civil society advocacy groups concerned about the implications of rapid and abrupt climate change for adaptation or mitigation policies.

Any of these may have opinions on the likelihood of rapid and abrupt climate change, but the basis for these opinions and agendas will be different. The survey was restricted to the first two categories above: scientists involved in directly studying the physical processes and reviewing rapid climate change science (although no known climate change skeptics were included). The experts identified included those who lead major research programs into rapid and abrupt climate change, those who had published on the processes of change, and those who had participated in the IPCC's *Third Assessment Report* reviews of rapid and abrupt change. A total of 22 experts on Thermohaline Circulation collapse were identified, together with 18 experts on accelerated climate change with a small number of overlapping respondents between the two surveys. Experts were based in the United Kingdom, Europe, and the United States. Some of the experts were common to both categories. Table I summarizes the characteristics of the surveyed experts.

5.3. Responses

5.3.1. Participation

Usable responses were elicited from 13 and 9 experts for the Thermohaline and accelerated surveys, respectively. Despite reminders, a total of 17 failed to respond. Four of the Thermohaline survey respondents declined to participate, as did five of the accelerated change survey: their reasons are summarized in Table II. One declined because the risk of adverse impacts in Europe due to Thermohaline Circulation collapse was believed to be low. It is not clear from this response whether this was due to the likelihood of collapse or the impact of collapse being low, and this may reflect ambiguities in the questionnaire and covering email. Two of the decliners preferred to use the output from simulation models and were not prepared to make subjective assessments. Three declined because of conceptual problems with either the elicitation or aggregation of judgments associated with subjective assessments and one declined on the apparent grounds of lack of expertise. Of those who declined to participate, most felt they did not have

Table I. Summary of Identified Experts

Respondent Code	Description	Category	
Thermohaline Circulation Survey			
THC1	Ocean modeler	1	Participated
THC2	Ocean modeler	1	Declined
THC3	Climate modeler	1	nr
THC4	Climate modeler	1	nr
THC5	Palaeoclimatologist	1	nr
THC6	Ocean modeler	1	Participated
THC7	Hazard scientist	2	nr
THC8	Earth system modeler	2	Participated
THC9	Ocean modeler	1	Participated
THC10	Ocean modeler	1	Declined
THC11	Climate modeler	1	Participated
THC12	Climate modeler	1	Declined
THC13	Earth system modeler	1	nr
THC14	Ocean modeler	1	nr
THC15	Ocean modeler	2	Participated
THC16	Climate modeler	1	nr
THC17	Ocean researcher (observations)	1	Participated
THC18	Earth system modeler	2	Participated
THC19	Ocean researcher (observations)	1	nr
THC20	Climate modeler	1	Participated
THC21	Climate modeler	2	Declined
THC22	Climate modeler	1	nr
Accelerated Change Survey			
AC1	Climate modeler	1	Participated
AC2	Climate modeler	1	Declined
AC3	Climate modeler	1	nr
AC4	Earth system modeler	2	Participated
AC5	Climate modeler	1	nr
AC6	Climate modeler	1	Participated
AC7	Earth system modeler	1	nr
AC8	Climate modeler	1	nr
AC9	Climate modeler	1	Declined
AC10	Earth system modeler	2	nr
AC11	Climate modeler	1	Declined
AC12	Climate modeler	1	Participated
AC13	Climatologist	2	Participated
AC14	Chemist	2	nr
AC15	Chemist	2	Declined
AC16	Earth system modeler	1	nr
AC17	Climate modeler	2	Declined
AC18	Climate modeler	1	nr

Notes: Category 1 = active researcher. Category 2 = reviewer. nr = no response.

the competence to comment on the questions. This is exemplified by one respondent:

I doubt if there are more than five or six people in the UK [though the survey was not restricted to the UK]... who could express an independent expert view on this. The rest would all be second hand (and hence distort the statistics) or, worse, second hand plus a bit of their own subjective biases. Unless you limit your canvassing to the handful of hands-on experts, your result could be misleading. [Respondent THC21]

Six of the nine Thermohaline Circulation survey respondents participated in the second round, as did four of the five accelerated change survey respondents. The relatively poor participation rate in the second round may have improved by repeated reminders.

5.3.2. Likelihood of Thermohaline Circulation Collapse

Table III summarizes the expert assessments of the likelihood of Thermohaline Circulation collapse by three dates: 2020, 2050, and 2100. The first question in the questionnaire asked for a single estimate of likelihood, and a subsequent question asked for estimates under different rates of global warming. Three of the respondents provided estimates of likelihood for different rates of change, but six could not: one explicitly stated that the uncertainty was too high to allow the first estimate to be broken down further. In contrast, one of the second-round respondents expressed surprise that estimates were independent of emissions scenarios. Seven of the nine respondents stated explicitly that they assumed a 50% reduction in the magnitude of the Thermohaline Circulation in the North Atlantic would be sufficient to trigger rapid climate change.

There are clear orders-of-magnitude differences between the nine experts who provided an assessment, although with one exception all estimated likelihoods are less than 1% by 2000, less than 20% by 2050, and less than 40% by 2100. The one exception, THC8, provided estimates of likelihood of Thermohaline collapse of 10%, 30%, and 75% over the same three time periods. Most respondents based assessments on a combination of analysis of model output with general knowledge of the ocean/climate system: one based the assessment partially on interpretation of recent ocean behavior. Three experts explicitly stated that they believed that current models underestimated the sensitivity to collapse and hence the likelihood of change. The expert with the highly anomalous assessment

Table II. Reasons for Declining to Participate

Collapse of Thermohaline Circulation

- I don't consider abrupt cooling of Europe due to a collapse of the Thermohaline circulation during the next century to be a serious risk (THC10)
- I don't believe that any statement I make without reference to models would be more than a guess, with no reliable information content, whereas if I refer to models you should get the same, more accurately, by analyzing their output yourself (THC12)
- The approach adopted is not sufficiently sophisticated and the results are therefore potentially misleading (THC2)
- I'm not an expert (THC21)

Accelerated Climate Change

- I participated in an earlier assessment. On reflection, I found the process unsatisfactory and therefore decline to take part in another (AC2)
- I believe there are serious drawbacks to expert elicitations and the subsequent use of their subjective probability distributions (AC9)
- Why can't you obtain results from modeling groups worldwide and do some sort of probabilistic analysis of the likelihood of suitably defined abrupt changes? In any case, I don't really think there is much useful information I can give to such a survey (AC11)
- I find it difficult to answer and therefore will abstain (AC15)
- I'm not an expert (AC17)

was particularly skeptical about the ability of climate models to simulate perturbations (“GCMs [general circulation models] are probably unrealistically well-behaved”). Three of the experts (all modelers) stated that it should be possible within “a few years” to attempt to estimate likelihoods using either individual climate/ocean models or ensembles of models.

None of the seven respondents who participated in the second round changed their estimates. One (THC17: an expert using observations rather than simulations) commented that some of the reasons given for the refusal to participate showed an over-reliance on the potential use of climate models, and another (THC18: a modeler) noted that some of the comments in Table II suggested that modelers were being a “little coy” in the interpretation of their models. One was surprised at the high probabilities estimated by some respondents—but “would need to know who these experts are to assess whether to believe these estimates.” One respondent expressed increased skepticism over the approach and hence the reliability of any conclusions, and another was surprised by the low response rate.

5.3.3. Likelihood of Accelerated Climate Change

Expert assessments of the likelihood of climate change exceeding different high rates of change per decade are summarized in Table IV. Note that the top of the IPCC TAR range is approximately 0.5°C/decade: Wigley and Raper (2001) estimated that the likelihood of change by 2100 greater than 5.8°C (approximately 0.53°C/decade) was 0.6%, and Webster *et al.* (2003) estimated a 2.5% chance that the increase would be greater than 4.9°C (0.45°C/decade). Again, there is a considerable range of assessments, with one particularly anomalous assessment given by AC4 (who also, as THC8, gave the highest estimates for the likelihood of the collapse of the Thermohaline Circulation). A range of methods were used to construct these likelihoods. Two experts used direct model simulations. A third started from an explicit assumption about the likelihood of change occurring at the top IPCC TAR rate, assumed an order of magnitude likelihood for the highest rate, and then interpolated. A fourth expert adopted a similar approach, but using much higher estimates of likelihood because of a belief that the TAR “very likely underestimates

Collapse by	THC1*	THC8	THC9	THC11	THC17	THC18*	THC20*	THC6	THC15
2020	1	10	0.1	0	1	0.05–0.2	0.5–1	0	Very low
2050	5–20	30	1	0	10	0.5–7	1.3–4	0	Low
2100	5–40	75	10	5	25	5–40	4–10	Possible	Possible

*Varies with emissions scenario.

Table III. Expert Estimates of the Likelihood (%) of Collapse of the Thermohaline Circulation

Table IV. Expert Estimates of the Likelihood (%) of Accelerated Climate Change

Global Temperature Change Exceeds ...	AC1	AC4	AC6	AC12	AC13
0.5°C/decade	1	90	20	3	2
0.6°C/decade	0.1	80	10	0.5	0.5
0.7°C/decade	0	70	5	0.1	0.1
0.8°C/decade	0	60	2	0	0.01
>0.9°C/decade	0	50	1	0	0.001

sensitivity.” The remaining expert explicitly adopted a subjective approach.

None of the four respondents who participated in the second round wished to change their estimates (one noted that if an estimate were revised, it would no longer be independent). Three of the respondents expressed surprise at AC4’s estimates.

5.3.4. *Compiling Results*

The criticisms of the expert elicitation of likelihoods of rapid climate change by the experts we engaged were varied: some believed that subjective assessments were inherently flawed or that it would be better to use a modeling-based approach; some noted that the models they had used to inform their assessments probably underestimated sensitivity to perturbation; some thought that it would be possible within a few years to use modeling approaches to provide more credible estimates of the likelihood of rapid climate change. The combination of these reasons, with the very small population size and because of the large diversity of opinion led us to decide that it is not appropriate to attempt to construct a consensus probability distribution describing the likelihood of rapid climate changes. It is possible that the response rate to the survey would have improved by identifying a wider range of potential experts and, most importantly, providing clearer information and guidance to respondents.

6. DISCUSSION AND CONCLUSIONS: EXTRACTING EXPERT OPINIONS ON THE LIKELIHOOD OF RAPID CLIMATE CHANGE

Most discussion of climate change is predicated on the assumption of a gradual rise in temperature, albeit at rates considerably higher than experienced

in the last few thousand years at least. Increasingly, attention is being directed toward the threat of “rapid,” or “abrupt,” or “singular” climate changes, with particular concern about the collapse of the Thermohaline Circulation (leading to lower temperatures across Europe), collapse of the West Antarctic Ice Sheet, irreversible decline of the Greenland Ice Sheet (both leading to very large increases in sea level), and accelerated climate change due to the release of greenhouse gases stored in the environment. One of the objectives of the efforts to seek to avoid “dangerous” climate change is to minimize the likelihood of such rapid or abrupt changes occurring (see, for example, the report of the International Climate Change Task Force (2005)).

Discussions with policymakers in a number of sectors, including water management, insurance, and forestry, revealed that any assessment of vulnerability to rapid or abrupt climate change and the development of adaptive strategies is fundamentally based on an assessment of the likelihood of rapid climate changes occurring. Hulme (2003) notes that one of the two fundamental problems for society associated with rapid climate change is that the probability of such a scenario remains fundamentally unknown. Yet the presence of uncertainty does not translate into a demand for the uncertainty to be reduced: the U.S. National Research Council’s (2002) review of abrupt climate change, for example, while recommending research into the processes of abrupt change, does not explicitly recommend research into probability assessments.

Estimates of likelihood cannot be based on past experience, as there is no precedent for many of the potential rapid and abrupt changes, and those changes that have occurred in the past occurred under very different climatic conditions. Several studies have used computer simulation models to construct probability distributions of, for example, the rate of future climate change (e.g., Palmer & Raisanen, 2002; Stott & Kettleborough, 2002; Webster *et al.*, 2003; Wigley & Raper, 2001), but these studies have not considered explicitly the likelihood of rapid climate change. The results also depend on the models used and the assumptions about the probability distributions of input drivers and parameters.

A third approach, widely used in assessing business and some environmental risks, is to use expert judgment, and this article describes one such assessment of estimates of the likelihood of (1) the collapse of the Thermohaline Circulation and (2) accelerated climate change. Expert judgment is not a substitute

for scientific analyses, but can provide useful insights while scientific research is ongoing (Morgan *et al.*, 2001).

The main conclusions—methodological and empirical—of the study are:

1. The potential pool of experts available for such a survey is extremely small, and as a result may be very skewed by “anomalous” perspectives.
2. Several experts declined to take part either because they believed subjective assessments were inherently flawed or because it would be better to take a modeling-based approach.
3. Assessments of likelihood were constructed in a variety of ways by different experts, some based explicitly on model simulations and some based on “gut-feeling.”
4. Several experts noted that the models they had used to inform their assessments probably underestimated sensitivity to perturbation.
5. Several of the experts believed that it would be possible within a few years to use modeling approaches to provide more credible estimates of the likelihood of rapid climate change.
6. While most experts assessed the likelihood of rapid climate change as being very small, in both surveys one expert assessed the likelihood as at least an order of magnitude greater than the others.
7. It is not appropriate to attempt to construct a consensus probability distribution describing the likelihood of rapid climate changes, partly because information on the specific judgments of individual experts is important, partly because the sample is inherently small, and partly because of the large diversity of opinion

Most of the experts surveyed assess the likelihood of either Thermohaline Circulation collapse or accelerated climate change to be well under 10%, but one expert appears to be highly anomalous. There is no justification, however, to exclude the views of this individual on the basis of our assessment of his/her expertise. However, herein lies a problem with the expert elicitation method, in that it does not factor in the process of judgment making; it focuses simply on the outcome of the judgment process. Because of the range of estimates generated by the experts in this survey, this makes it extremely difficult to judge whether a particular rate of climate change is likely to be “dan-

gerous,” and to hence to assess vulnerability to rapid climate change.

It is of course possible that the response rate to the survey would have improved by identifying a wider range of potential experts and, most importantly, providing clearer information and guidance to respondents. However, as also evidenced by the protest responses in our survey, there is a deep suspicion within positivist science cultures of the validity of expert judgment (as also found by Vaughan & Spouge, 2002). This suspicion of expert judgment has previously been explained as a product of the lack of training of scientists in the language and interpretation of risks. Scientists tend to ignore the fact that anchoring procedures of arriving at a consensus all rely on the same processes whether using model results or expert judgment (Shackley *et al.*, 1999; van der Sluijs *et al.*, 1998). However, even model-based assessments of the likelihood of rapid or other climate changes use expert judgment, either explicitly (e.g., Mastrandrea & Schneider, 2004; Murphy *et al.*, 2004; Webster *et al.*, 2003) or implicitly (Raisanen and Palmer (2002) implicitly assumed all 17 climate models in their ensemble were equally reliable, for example).

In our view, the perceptions and judgments of scientists involved in the field of abrupt or rapid climate change *are* important. The communication of these judgments can contribute to meaningful debate on policy and priorities in these areas, and indeed shape research and policy agendas (as, for example, on the definition of “dangerous” climate change).

The key substantive conclusion of this study, methodological considerations notwithstanding, is that it may currently not be possible to produce a robust estimate of the likelihood of rapid climate change (in this case, due to collapse of the Thermohaline Circulation or accelerated change due to positive feedbacks). The experts are not in agreement, and produce subjective estimates that vary over orders of magnitude. Most of the experts surveyed assess the likelihood of either Thermohaline Circulation collapse or accelerated climate change to be “low” (well under 10%), but one expert is highly anomalous. This uncertainty over the likelihood of different types of rapid climate change makes it extremely difficult to judge whether a particular rate of climate change is likely to be “dangerous,” and to assess vulnerability to rapid climate change. While simulation models will improve and the ability to run multiple simulations in order to assess chances of defined changes occurring will increase, it is likely that different model

experiments will provide different indications of the likelihood of rapid climate change: expert judgment will still be needed to evaluate and compare these different experiments.

A final, methodological conclusion of this study is that the mental processes of reaching judgments by experts are not necessarily adequately revealed in the forms of quantitative expert elicitation techniques as used here, which tend to focus solely on judgment outcomes. Expert elicitation generally does not reveal the way in which the experts make their judgments, the degree to which they rely on scientific models, data, or their own worldviews in generating judgments, something that may be particularly critical for highly complex risk issues such as those associated with climate change. If the approach used in this project were to be repeated, we would advise that the expert elicitation be supplemented by an assessment of the process by which the experts produce their estimates. While simulation models will improve and the ability to run multiple simulations in order to assess chances of defined changes occurring will increase, it is likely that different model experiments will provide different indications of likelihood of rapid climate change: expert judgment will still be needed to evaluate and compare these different experiments. Hence novel approaches such as mental model interviews might be adapted as a way of mapping expert appraisals (see, e.g., Cox *et al.*, 2003), alongside more traditional quantitative elicitation techniques, in order to reveal the processes, constructs, and assumptions underlying the formation of uncertainty judgments. Such forms of analysis might provide an indication of the sources of subjectivity built into experts' judgments about the dangers associated with climate change risks.

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APPENDIX: THE QUESTIONNAIRES

Risk Estimation of the Collapse of the Thermohaline Circulation

1. What is your estimate of the likelihood that the Thermohaline Circulation (THC) will weaken sufficiently to trigger abrupt changes in European climate by the following years? (i) 2020 (ii) 2050 (iii) 2100?
2. What is your definition of "weaken sufficiently"?
3. How did you arrive at these estimates?
4. How sensitive is your estimate to the assumed rate of climate change? Could you estimate the likelihood of THC collapse/weakening by 2020, 2050, and 2100 under the four SRES emissions scenarios below?

A1	A2
2020	2020
2050	2050
2100	2100
<i>Temperature change by 2100: 4.8°C</i>	<i>Temperature change by 2100: 4.1°C</i>
B1	B2
2020	2020
2050	2050
2100	2100
<i>Temperature change by 2100: 2.3°C</i>	<i>Temperature change by 2100: 3.0°C</i>

5. Comments on the questions
6. Comments on interpretation of the answers
7. Other information: could you, for example, construct a probability distribution function (pdf) of THC strength?
8. How would you describe your disciplinary background?

Risk of Accelerated Climate Change

1. What is your estimate of the likelihood that the rate of climate change will exceed:
 - (i) 0.5°C/decade
 - (ii) 0.6°C/decade
 - (iii) 0.7°C/decade
 - (iv) 0.8°C/decade
 - (v) 0.9°C/decade?
2. How did you arrive at these estimates?

3. What processes may generate accelerated climate change?
4. Comments on the questions
5. Comments on interpretation of the answers
6. How would you describe your disciplinary background?

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