Expert judgements on the response of the Atlantic meridional overturning circulation to climate change

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Abstract

We present results from detailed interviews with 12 leading climate scientists about the possible effects of global climate change on the Atlantic meridional overturning circulation (AMOC). The elicitation sought to examine the range of opinions within the climatic research community about the physical processes that determine the current strength of the AMOC, its future evolution in a changing climate and the consequences of potential AMOC changes. Experts assign different relative importance to physical processes which determine the present-day strength of the AMOC as well as to forcing factors which determine

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its future evolution under climate change. Many processes and factors deemed important are assessed as poorly known and insufficiently represented in state-of-the-art climate models. All experts anticipate a weakening of the AMOC under scenarios of increase of greenhouse gas concentrations. Two experts expect a permanent collapse of the AMOC as the most likely response under a $4\times CO_2$ scenario. Assuming a global mean temperature increase in the year 2100 of 4 K, eight experts assess the probability of triggering an AMOC collapse as significantly different from zero, three of them as larger than 40%. Elicited consequences of AMOC reduction include strong changes in temperature, precipitation distribution and sea level in the North Atlantic area. It is expected that an appropriately designed research program, with emphasis on long-term observations and coupled climate modeling, would contribute to substantially reduce uncertainty about the future evolution of the AMOC.

1 Introduction

The difference in radiative energy reaching Earth's surface in the Tropics compared to high latitudes results in a meridional transport of heat by Earth's fluids. About one third of the global northward heat transport of 1 PW (10^{15} W) is achieved by the Atlantic meridional overturning circulation (AMOC) (Ganachaud and Wunsch 2000; Trenberth and Caron 2001). This large scale ocean circulation (Broecker 1991) flows northward near the surface in the Atlantic, sinks in cold high northern latitudes and returns to the Southern Ocean at a depth of between 1500 m and 3500 m (Talley et al. 2003). Evidence from palaeoclimatic reconstructions (Dansgaard et al.

1993; McManus et al. 2004), theoretical considerations (Stommel 1961) and model simulations (Manabe and Stouffer 1988; Rahmstorf 1996; Rahmstorf et al. 2005) suggests that the AMOC could be bistable, i.e. in addition to the present state there may exist a stable so called "off-state" without formation of North Atlantic Deep water (NADW) and the associated AMOC. Model simulations suggest that a cessation of the circulation will have direct large scale consequences for the North Atlantic region such as a strong cooling by several degrees (Winton 2003) and an increase in sea level of up to 1 m in magnitude (Levermann et al. 2005). Indirectly, global effects can be expected. These include a shift of the Intertropical Convergence Zone (Vellinga and Wood 2002) and a warming of the Southern Ocean (Stocker 1998; Knutti et al. 2004).

Intercomparison studies with climate models of different complexity (Gregory et al. 2005; Petoukhov et al. 2005) show a weakening of the overturning under increasing atmospheric CO_2 concentration. The weakening of the AMOC in these simulations is caused mainly by changes in heat flux between atmosphere and ocean as opposed to changes in freshwater flux from precipitation, evaporation or river runoff. However, the simulations do not include additional possible sources of freshwater flux from, for example, melting of the Greenland ice sheet (Gregory et al. 2004). Even without such additional forcing, a regional shutdown of deep-water formation in the Labrador or in the Greenland-Iceland-Norwegian Seas may occur, as indicated by climate model simulations (Wood et al. 1999; Schaeffer et al. 2002; Goosse et al. 2002).

In recent decades a freshening of the North Atlantic has been observed

(Dickson et al. 2002; Curry et al. 2003). This may inhibit northern sinking and therefore slow down the AMOC (Curry and Mauritzen 2005). Some authors have indeed reported a weakening of the AMOC (Häkkinen and Rhines 2004; Bryden et al. 2005), although limited data coverage means that the evidence is not conclusive. In model simulations the observed freshening does not lead to a weakening of the AMOC (Wu et al. 2004). It is suggested that a recent increase in the salinity of the waters flowing northwards into the Nordic Seas could even have a stabilizing effect on the AMOC (Hátún et al. 2005).

These various sources of evidence can be used to make inferences about possible changes in the nature and intensity of the Atlantic meridional overturning circulation in the face of ongoing climate change. However, none allow definitive predictions to be made. Rather the multiple sources of evidence must be synthesized and combined using expert judgment. One strategy for doing this is through expert consensus reviews of the sort conducted by the IPCC (Houghton et al. 2001). Such reviews can be complemented by quantitative elicitation of individual experts judgments, using formal expert assessment protocols. Elicitation methods allow explicit quantification of uncertainty based on the experts' synthesis of published literature and knowledge that is not explicit in the formal literature. In addition, elicitation of individual experts judgments document the diversity of opinion more effectively than is possible in consensus reviews, which may tend to understate uncertainty (Morgan and Keith 1995; Moss and Schneider 2000; Morgan et al. 2006).

This paper presents results of detailed expert elicitations with 12 leading climate scientists (Table 1) on the possible impacts of global climate change on the Atlantic meridional overturning circulation. This work builds on procedures developed for, and experience gained in previous expert elicitations conducted by two of the authors on the climate change effects of a doubling of atmospheric CO_2 concentrations (Morgan and Keith 1995), the impacts of climate change on forest ecosystems (Morgan et al. 2001) and the forcing associated with anthropogenic aerosols (Morgan et al. 2006).

As detailed in Morgan and Henrion (1990) and in Morgan et al. (2006), such formal elicitation of expert judgment has been widely used in applied Bayesian decision analysis, in a variety of business strategic planning and other applications, and in climate and other areas of environmental policy. The most recent of these studies have used carefully developed individual interviews or survey materials. Typically they provide experts an opportunity to review their results, and compare them with those of others, but they do not push experts to reach consensuses. There are group-based methods such as Delphi (Dalkey 1969; Linstone and Turoff 1975) or the more recent expert group method developed by Budnitz et al. (1995), which involve much greater levels of interaction among experts and do strive for consensus. However, since our objective is to explore the range of expert opinion across the set of main-stream expert views, we have not adopted a consensus-oriented approach.

2 The Interviews

A 60-page written interview protocol was developed and refined over a period of two years. We first identified a set of questions in AMOC research that are at the same time policy relevant and subject to large uncertainty. Given the comprehensiveness of the subject we had to make trade-offs in order to reduce the questionnaire to something that could be completed in a day-long interview. We refined the interview protocol following an expert workshop that we ran during the meeting of the European Geophysical Union (EGU) in Nice in May 2004. Before starting with the actual elicitations, we conducted a pilot interview with a senior climate scientist in order to test whether the whole questionnaire worked. The responses suggested that we were successful in compiling questions that were clearly defined and were readily understood.

The elicitations were conducted between July and September 2004 in face-to-face interviews that took place at the experts' home institutions and generally lasted five to seven hours. All interviews were recorded. In addition, the first and second authors, who jointly conducted all the interviews, took extensive notes. Finally, experts annotated specific responses in written form in the interview workbook. About two weeks before the interviews we provided the participants with the protocol, giving them the opportunity to get prepared on specific topics. Consultation of literature, simulation results, notes and other materials was encouraged during the interview in order to obtain the experts' carefully considered opinion.

The interview consisted of five distinct parts. We began the interview with a set of general tasks designed to learn the experts' views about the factors and processes that are important in determining the present-day strength of the AMOC. In the second part we explored the experts' opinion on the effects of climate change on the AMOC. We started with a qualitative discussion about the forcing processes that experts believed we need to know more about in order to predict the response of the AMOC. We then elicited experts' judgment about the evolution of the AMOC in the face of specific climate change scenarios. Part three was devoted to the consequences of changes in the AMOC, with a focus on climate changes and sea level rise in the North Atlantic area. In part four we asked the experts to identify research needs and priorities in the field of oceanography and climate science and asked them to design a detailed research program. The interviews concluded with a set of questions about the possibility of reducing uncertainty about the future evolution of the AMOC through research and the feasibility of an early warning system.

Table 1 lists the experts interviewed in the study. In choosing the experts we relied upon our own knowledge of the field and our review of recent publications. We also solicited advice from a range of colleagues working in this field. Our objective was to include experts who represented a range of scientific backgrounds (e.g. observationalists vs. palaeoclimatologists vs. modelers), geographic origins and schools of thought, seeking representation across the range of main-stream opinion in the field. After creating an initial

[1] S. Rahmstorf is a co-author of this study and was involved in conceiving the expert elicitation (design of the interview protocol, choice of experts). However, he did not see the results of others before giving his own responses. Thus, we expect no bias arising from this dual role.

Name	Affiliation
Bond, G.C.	Lamont-Doherty Earth Observatory, Palisades, NY, USA
Hansen, B.	Faroese Fisheries Laboratory, Torshavn, Faroe Islands
Hasumi, H.	University of Tokyo, Tokyo, Japan
Joyce, T.M.	Woods Hole Oceanographic Institution, Woods Hole, Ma, USA
Latif, M.	Leibniz-Institute for Marine Research, Kiel, Germany
Marotzke, J.	Max Planck Institute for Meteorology, Hamburg, Germany
Rahmstorf, S.[1]	Potsdam Institute for Climate Impact Research, Potsdam, Germany
Stocker, T.F.	University of Bern, Bern, Switzerland
Stouffer, R.	Geophysical Fluid Dynamic Laboratory, NOAA, Princeton, NJ, USA
Visbeck, M.	Lamont-Doherty Earth Observatory, Palisades, NY, USA
Weaver, A.	University of Victoria, Victoria, Canada
Wood, R.	Hadley Center for Climate Prediction and Reserch, Exeter, UK

Table 1: Experts interviewed in this study. The numbers that identify experts in the text and figures were randomly assigned and do not correspond to the order in which they are listed in the table.

list we consulted with a senior expert before developing the final list in a form that we believed achieved the desired balance, while remaining within the constraints of budget and time. Two experts declined to participate when invited and were substituted with other experts from our larger list who had similar backgrounds.

It is important to note that the process of choosing experts for inclusion in this study is fundamentally different from the process of sampling to estimate some uncertain value such as a physical quantity, or polling the public to predict the results of an election. The route to scientific truth is not a matter of voting. One of the outliers among the respondents may be correct, and those who appear to be in close agreement may all be wrong.

As will become evident in sections 3–6, we elicited a number of subjective probability distributions of quantities related to the AMOC and its future evolution. One problem in expert elicitation is the consistent finding in the literature that both experts and non-experts tend to be systematically overconfident. That is, their elicited subjective probability distributions tend to be too narrow. In addition, there are other biases which can arise because of heuristic procedures that people employ when making judgments under uncertainty (Kahneman et al. 1982; Dawes 1988; Morgan and Henrion 1990). Although there is no way to completely eliminate these problems, there are some procedures that allow one to minimize their influence (Spetzler and Stal von Holstein 1975; Morgan and Henrion 1990). Thus, in eliciting probability distributions in this study, we always began by asking for extreme values (not the "best-estimate") so as to reduce the impact of "anchoring and adjustment", next asking the expert to consider counterfactual conditions that might widen their distributions so as to minimize "over confidence", and only then eliciting interior points in the distribution, before finally asking for a best-estimate.

A few caveats are relevant: (i) Even though we are aware that caution should be exercised when combining experts quantitative estimates (Keith 1996), we have done so when we thought it useful for discussing the results. (ii) We have reported arguments as presented by the respondents without making any judgement about their correctness, in order to make the line of thought transparent for the reader. (iii) Where possible, we checked for consistency in the responses and found that not all experts were consistent in all their answers. Where inconsistencies arose, these are indicated in the text.

3 The AMOC today

Since there is some ambiguity about the meaning of "Atlantic Meridional Overturning Circulation" we started the interview by suggesting the following definition: "The AMOC shall denote the basin-scale deep overturning circulation in the Atlantic which transports warm surface water northwards and cold water southwards at depth". All experts accepted this definition for the course of the interview.

In recent years, there has been vigorous debate about the driving mechanisms of the AMOC (e.g. Toggweiler and Samuels 1993, Munk and Wunsch 1998, Kuhlbrodt et al. 2005). As the experts' judgements about the future evolution of the AMOC can be expected to be determined by their view about the drivers, we started with a qualitative discussion about the physical processes that the experts believe drive the AMOC. Experts were given a set of cards which listed nine physical processes. After reviewing the cards for completeness, and possibly making revisions, the experts rank-ordered the cards "in terms of their relative importance in determining the long-term mean[1] pre-industrial strength of the AMOC".

The results are summarized in Table 2. In order to synthesize the expert's responses in one number (which we term 'global ranking'), we applied the following ordering procedure: first, we counted the number of times one process was ranked first. In the case of equal number of mentions, we considered the times the process was ranked second, then third, and so on. Note that this procedure tends to give priority to the entries that were as-

[1]The expression 'long-term mean' was specified to exclude variability on decadal and shorter time-scales.

signed high ranks in relation to those that received a good average ranking. This is not unreasonable as experts' confidence can be expected to decrease with the decreasing assessed importance of the process under consideration. Note that the resulting ordering is not completely robust with respect to the procedure used.[2]

Among the experts' responses, one dominant view about the physical mechanism driving the AMOC can be identified (which is also reflected in the global ranking). According to this view, the processes of greatest importance are the heat fluxes, which are central in setting the meridional density gradient that drives the circulation, and the diapycnal mixing (i.e., the small-scale, diffusive mixing across layers of equal density, which roughly corresponds to vertical mixing), which determines the return path of the AMOC through upwelling in the low latitudes. Another process that is assigned a high rank by most respondents is the 'inter-basin' (i.e. between basins) atmospheric freshwater transport. Experts argued that this transport exports freshwater from the Atlantic, rendering the latter saltier and allowing for an overturning circulation there in contrast to the Pacific, where presently no deep circulation exists. "Intra-basin" freshwater transport (i.e. within the Atlantic basin) ranks fourth. Some of the respondents argued

[2]Other ordering procedures were also applied. For instance, the weighted sum of the weighted number of mentions was calculated. Thereby, the expert's assignment of a rank to an entry was weighted inversely by the number of entries the expert gave that same rank, in order to take into account the fact that many experts assigned the same rank to more than one entry. Further, rank 1 is weighted 1, rank 2 is weighted 0.9, rank 3 is weighted 0.8, and so on. These numbers are then summed up and the entries with the largest sum ranked first. By this procedure, the heat fluxes and diapycnal mixing are again the top actors, followed by overflows, wind-driven upwelling in the Southern Ocean, inter- and intra-basin freshwater transport, freshwater flux from glaciers and sea ice and isopycnal mixing.

that this transport is important in that it affects the freshwater budget of the northern North Atlantic. Experts are split about the importance of convective mixing in determining the present-day strength of the AMOC. This process was often associated with the heat fluxes, as these make the surface water denser than the underlying water and create the instabilities which lead to vertical mixing of the water column. With the exception of expert 11, wind-driven upwelling in the Southern Ocean (SO) is not considered a key process in determining the present-day AMOC. Freshwater flux from glaciers and sea ice is deemed too small in the present-day climate to play an important role. Some experts, however, point out that this flux could become increasingly important in the wake of climate change. The effect of the overflow across the Greenland-Iceland-Scotland ridge on the overturning is controversial among experts. To some, it is a crucial process in driving the AMOC (e.g. expert 7). To others, the overflows play a role mainly in modulating the strength of the circulation through entrainment of ambient water. On average, isopycnal mixing (i.e., the small-scale, diffusive mixing within layers of equal density, which roughly corresponds to horizontal mixing) is considered the least important process.

Physical process	Global rank	Expert											
		1	2	3	4	5	6	7	8	9	10	11	12
Heat fluxes	1	1	1	1	1	3	1	3	2	1	2	1	2
Diapycnal mixing (rough topography, internal waves)	2	3	1	4	4	6[5]	1	6	1	2	1	6	1
Inter-basin atmospheric freshwater transport	3	2	2	2	1	2	1	5	4	1[6]	2	2	3
Intra-basin atmospheric freshwater transport	4	2	3	2	2	1	1	4	2	1[6]	3	4	6
Convective mixing	5	5	2	1	7	3	1	1	5	4	4	5	2
Wind-driven upwelling in the Southern Ocean	6	4	2	3	3	6[5]	3	7	3	5	5	1	5
Freshwater flux from glaciers and sea ice[3]	7	7	4	4	2	5	3	9	5	1[6]	3	3	6
Overflows[4]	8	6	5	2	5	4	2	2	5	3	4	5	4
Isopycnal mixing (eddies)	9	7	7	4	6	6[5]	4	8	5	6	6	6	5
Wind in the North Atlantic	–	–	6	–	–	–	–	–	–	–	–	–	–
Atlantic gyre circulation	–	–	–	–	5	–	–	–	–	–	–	–	–
North to South density difference	–	–	–	–	3	–	–	–	–	–	–	–	–

Table 2: Experts' ranking of physical processes in terms of relative importance in determining the long-term mean pre-industrial strength of the AMOC. The first column lists the factors exactly as they appeared on the cards (note that the last three processes were suggested by single experts). The second column lists the ranking that was computed according to the ordering procedure described in the text. The other numbers in the body of the table report individual responses of each expert.

We were interested in learning how well experts believe the driving processes are currently understood. We asked experts to express their judgment on a scale from one to five (1=not known at all; 5=very well known). Most respondents assigned mid-range marks to the listed processes and factors (Table 3). An exception is the freshwater flux from sea ice that one experts believes is very well known. Freshwater flux from glaciers, wind-driven upwelling in the SO, convective and diapycnal mixing were indicated by single experts as not known at all. On average, heat fluxes are estimated to be the best known process, followed by intra- and inter-basin freshwater transport, overflows, convective mixing, freshwater flux from sea ice, SO upwelling, freshwater flux from glaciers and, finally, diapycnal and isopycnal mixing.

We asked "how well these factors and processes are represented in state-of-the-art coupled ocean-atmosphere models", again on a scale from one to five (1=poorly represented; 5=very well represented). Two respondents declined to answer the question as they felt they had not enough expertise in climate modeling. Most of the processes are assigned mid-range to low marks (Table 4). An exception is sea ice processes that two experts think are very well represented in state-of-the-art climate models. In contrast,

[3] We meant "glaciers" to include all glaciers and ice sheets relevant to the freshwater budget of the NA.

[4] We specified the overflows across the Greenland-Iceland-Scotland ridge to include the effects of entrainment of ambient water.

[5] Expert 5 ranked these processes last as he was not confident enough to put them in rank order.

[6] Expert 9 considered these processes together as 'North Atlantic freshwater flux'.

[7] In the questionnaire, freshwater flux from glaciers and sea ice was given as one entry. In the table we separate the two processes as some experts had chosen to assign different marks to them.

[8] The mean value is computed by averaging over eleven experts only, as one expert placed very low confidence in his estimates.

Physical process	mean[8]	min	max	σ
Heat fluxes	3.5	2	4	0.7
Intra-basin atmospheric freshwater transport	3.4	2	4	0.7
Inter-basin atmospheric freshwater transport	3.2	2	4	0.8
Overflows	3.2	3	4	0.4
Convective mixing	3.1	1	4	1.0
Freshwater flux from sea ice[7]	3.0	2	5	1.1
Wind-driven upwelling in the Southern Ocean	2.7	1	4	0.9
Freshwater flux from glaciers[7]	2.5	1	4	0.9
Isopycnal mixing (eddies)	2.4	2	3	0.5
Diapycnal mixing (rough topography, internal waves)	2.4	1	4	0.8

Table 3: Experts' judgment of how well the physical processes listed in the first column are currently known. Experts assigned marks on a scale from one to five (1=not known at all; 5=very well known). Columns 2–4 list the mean, assigned minimum (min) and maximum (max) values and the standard deviation (σ), respectively. Processes are listed in the order of decreasing mean values.

modeling of glaciers is indicated by half of the experts to be very poor. The reason is that 3-dimensional coupled general circulation models do not incorporate interactive ice-sheet models. Among the poorly represented processes some experts also include convective mixing (3 experts), diapycnal mixing (3 experts), overflows (2 experts) and intra-basin atmospheric transport (1 expert, who gave a ranking of "poor" because of the poor representation of river runoff). On average, respondents believe that the best represented process is the heat flux, followed by freshwater flux from sea ice, wind-driven upwelling in the SO and intra-basin and inter-basin freshwater transport. The mixing processes and the overflows, which take place on spatial scales smaller than that resolved by most state-of-the-art climate models, all receive low average marks. The freshwater flux from glaciers ranks last.

[9]The mean value is computed by averaging over ten experts only, as two respondents

Physical process	mean[9]	min	max	σ
Heat fluxes	3.7	2	4	0.7
Freshwater flux from sea ice	3.0	2	5	1.3
Wind-driven upwelling in the Southern Ocean	3.0	2	4	0.8
Intra-basin atmospheric freshwater transport	2.9	1	4	0.7
Inter-basin atmospheric freshwater transport	2.9	2	4	0.6
Isopycnal mixing (eddies)	2.7	2	4	0.8
Convective mixing	2.3	1	4	1.2
Overflows	2.2	1	3	0.8
Diapycnal mixing (rough topography, internal waves)	2.0	1	4	0.9
Freshwater flux from glaciers	1.4	1	2	0.5

Table 4: Experts' judgment of the ability of state-of-the-art climate models to represent relevant physical processes. Experts assigned marks on a scale from one to five (1=poor; 5=very good). The first column lists the factors as they appeared in the questionnaire, ordered according to the mean of assigned marks. The other columns list the mean, assigned minimum (min) and maximum (max) values and the standard deviation (σ), respectively.

We concluded the first part of the interview by asking experts to make one quantitative judgment. Since climate models largely differ in their simulated present-day strength of the AMOC (10–30 Sv; Houghton et al. 2001, Gregory et al. 2005, Stouffer et al. 2006, Petoukhov et al. 2005), we were particularly interested in the range of experts' opinion on this quantity. We elicited the full probability distribution of experts' judgment of the present-day (i.e. averaged over the past decades) strength of the AMOC expressed in terms of "southward flow of North Atlantic Deep Water (NADW) at 30°N". Later, we asked experts whether their answer would have been different if we had elicited the pre-industrial value. If the response was affirmative, we elicited a second probability distribution. Results, summarized as box plots, are shown in Figure 1. In relation to the value simulated by climate

indicated they had not enough expertise to answer the question.

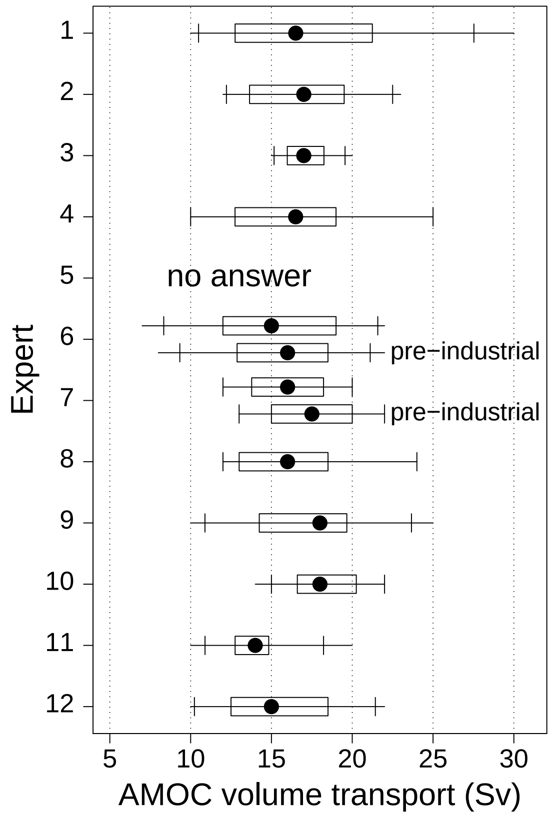

Figure 1: Box plots of elicited probability distributions for the present-day AMOC strength, expressed in terms of “southward flow of North Atlantic Deep Water at 30°N”. The horizontal line denotes the range from minimum to maximum assessed possible value. Vertical tick marks encompass the 90% confidence interval, the box spans the 50% confidence interval and the dot marks the median. Experts 6 and 7 believe that the AMOC has changed in strength since pre-industrial times.

models, there is little scatter in the estimated present-day NADW flow: the median values lie in the range from 14 Sv to 18 Sv, agreeing well with recent observations-based estimates of this quantity (Ganachaud and Wunsch 2000; Talley et al. 2003). Experts 6 and 7 gave us separate distributions for the pre-industrial climate, as they believe the AMOC has weakened since that time. For both experts the widths of the distributions for pre-industrial and present-day climate are similar, with the median shifted towards lower values for present-day climate conditions (by 1–2 Sv).

4 The effects of climate change on the AMOC

In the second part of the interviews we aimed at eliciting the experts' judgment about the future evolution of the AMOC. We started with a qualitative discussion about the factors and processes that, in the experts' opinions, are most important in determining the response of the AMOC to climate change. Experts were given a deck of cards that carried the names of seven forcing factors (Table 5). After reviewing the cards and possibly making additions or corrections, the interviewees sorted the cards "in the order of the processes and factors they would most want to know more about" in order to make a prediction about the response of the AMOC to global climate change. Experts' individual responses along with the global ranking, which is computed according to the ordering procedure described in section 3, are summarized in Table 5. The majority of respondents agree that changes in the freshwater and/or heat budget of the North Atlantic (NA) are most important in determining the future evolution of the AMOC on a time scale of a few centuries. Many also gave a high ranking to changes in the freshwater budget of the Tropical Atlantic (TA). Intermediate rankings were frequently assigned to changes in wind forcing in the NA. Changes in heat, freshwater and wind forcing outside the NA were deemed less relevant by most experts.

Expert 12 was alone in ranking changes in the wind forcing in the NA first. He argued that stronger winds possibly associated with a longer lasting positive phase of the North Atlantic Oscillation (NAO) would lead to increased heat loss to the atmosphere and stronger convection. Expert 8 believes that changes in the density gradient between North and South Atlantic, which can be modified by freshwater fluxes in the North and South alike, is most important in determining the future response of the AMOC. Forcing factors that were not listed on the cards but were deemed relevant by single experts are changes in the Deep Western Boundary Current around 30°N (expert 4) and changes in ocean northward salinity transport (expert 10). Note that in their responses the experts included not only their judgment about the relative importance of a factor in determining the future evolution of the AMOC but also their estimate about how much that factor would vary in the face of climate change.

Forcing factor or process	Global rank	Expert											
		1	2	3	4	5	6	7	8	9	10	11	12
Changes in heat fluxes in the convection regions of the NA	1	3	2	2	3	1	1	1	3	3	1	1	2
Changes in freshwater budget of the NA	2	1	1	1	1	3	1	2	1	1	2	3	2
Changes in freshwater budget of the TA	3	2	3	2	4	2	2	3	5	2	3	2	3
Changes in winds in the NA	4	4	4	3	4	4	5	4	4	6	5	4	1
Changes in winds in the SO	5	5	6	4	5	5	4	6	2	5	6	7	3
Changes in freshwater budget of the SA	6	6	5	4	5	5	3	5	1	6	6	5	3
Changes in heat fluxes outside the convection regions of the NA[3]	7	7	7	4	1[1]	5	2	7	3[2]	4	5	6	3
Changes in deep west boundary current around 30°N	–	–	–	–	2	–	–	–	–	–	–	–	–
Changes in ocean northward salinity transport	–	–	–	–	–	–	–	–	–	–	4	–	–

Table 5: Experts' ranking of forcing factors in terms of relative importance in determining the response of the AMOC to global climate change. The first column lists the factors exactly as they appeared on the cards (note that the last two factors were suggested by single experts). The second column lists the global rank, which was computed according to the ordering procedure described in section 3. The other numbers in the body of the table report individual responses of each expert.

Respondents were asked to judge on a scale from one to five the ability of state-of-the-art coupled ocean-atmosphere models to predict the forcing factors they had been discussing. Note that for this task we have grouped the above factors in a slightly different manner in order to better reflect the models' characteristics. Table 6 lists the factors as they were given in the questionnaire, along with the mean, assigned minimum and maximum values and the standard deviation. With the exception of experts 1 and 9 all others evaluated the ability to project changes in the mass balance of ice sheets and glaciers as very poor. All other processes were given mid-range marks except that expert 12 assigned a very poor mark to atmospheric freshwater transport because of the uncertainty in climate sensitivity. On average, the forcing factors that experts judged to be most reliably projected by state-of-the-art climate models are changes in heat fluxes and wind forcing, followed by changes in sea ice, changes in atmospheric freshwater transport, changes in river runoff and changes in the mass-balance of ice sheets and glaciers.

Before discussing the response of the AMOC in the face of climate change we were interested in the experts' view about the extent to which the response of the AMOC is predictable and what factors currently limit prediction. We suggested three statements asking the respondents to choose the one that best reflected their view about the predictability of the AMOC to a specified climate change scenario. The statements were as follows:

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[1]Changes in heat fluxes in the entire Atlantic north of 30°N are important.

[2]Changes in heat fluxes in the convection regions of the Southern Ocean are particularly important.

[3]While conducting the interviews we realized that the area of the North Atlantic we associated with the 'convection regions' was not well defined. We therefore specified this area to include the North Atlantic north of 45°N.

Forcing factors	mean	min	max	σ
Changes in heat fluxes	3.2	2	4	0.6
Changes in wind forcing	3.2	2	4	0.9
Changes in transport and melting of sea ice	2.7	2	4	0.9
Changes in atmospheric freshwater transport	2.6	1	4	0.8
Changes in river runoff	2.5	2	3	0.5
Changes in mass balance of ice sheets and glaciers	1.2	1	2	0.4

Table 6: Experts' judgment of the ability of state-of-the-art climate models to predict relevant forcing factors. Experts assigned marks on a scale from one to five (1=poor; 5=very good). The first column lists the factors as they appeared in the questionnaire, ordered according to the mean of assigned marks. The other columns list the mean, assigned minimum (min) and maximum (max) values and the standard deviation (σ), respectively.

- There is no inherent limit to the predictability of the AMOC, i.e., its future evolution can in principle be predicted quite accurately. The current limitations arise from our limited:
  1. Knowledge of the values of relevant climatic variables.
  2. Knowledge of the physics of the ocean system.
  3. Computational resources.
- Even with full knowledge of climatic variables and the relevant physics, the future behavior of the AMOC can only be predicted within a broad range.
- The future response of the AMOC is inherently unpredictable.

Half of the experts believe that the future response of the AMOC would in principle be predictable. These experts indicate that the reasons for the current limitations to predictability arise in roughly equal proportion from lack of knowledge about relevant climatic variables and the physics of the ocean as well as computational resources. The other half of the experts belief that the AMOC is predictable only within a broad range. Some of these respondents indicated that their choice was motivated by the existence of a critical threshold in the system and the large uncertainty about both the location of this threshold on the freshwater axis and the freshwater forcing. Not a single respondent believes that the AMOC is inherently unpredictable.

In a subsequent task, we provided the experts with two stylized scenarios of change in global mean temperature that might result from a doubling and a quadrupling of atmospheric pre-industrial CO_2 concentrations, respectively, reached at 1% increase per year (see upper panel in Figure 2 and Manabe and Stouffer 1994). We asked the experts to give us a general qualitative discussion of the likely consequences of the two scenarios for the AMOC as a whole and for deep-water formation in the Labrador and the Greenland-Iceland-Norwegian (GIN) Seas. Based on these considerations, we asked the experts to draw a curve reflecting their best estimate of the transient response of the AMOC (again expressed in terms of southward NADW flow at 30°N) up to the year 2500, both for the $2\times CO_2$ and the $4\times CO_2$ scenarios. If their response involved shutdown of convection in the Labrador and/or GIN Sea we asked them to mark in their drawing the point in time when this would occur. Further, we asked them to sketch a 90% confidence interval on their projection for the years 2200 and 2300. We also elicited a full subjective probability distribution in the year 2100 for "the percentage change in NADW flow at 30 °N" assuming a global mean temperature increase of 2.7 K and 4 K, respectively, that was achieved according to the two scenarios displayed in Figure 2 (upper panel). The results are summarized in Figs. 2–4.

For the 2×CO_2 scenario most experts expect a weakening of the AMOC and a subsequent recovery as the most likely response. The estimated maximum amount of weakening lies in the relatively broad range of 5% to 55% reduction relative to the present-day strength. The time scale of the recovery differs among experts because of different views about the strength of the feedbacks that would take effect, e.g. the tropical salt advection feedback suggested by Latif et al. (2000), and the associated time scales. Expert 7 believes that the AMOC response scales linearly with the forcing. Expert 9 assigns an equal probability to a recovery and a collapse of the AMOC arguing that the probability of a collapse is high despite most models showing a recovery of the circulation under a 2×CO_2 scenario. He indicates the reason to be the poor ability of climate models to capture the physical processes associated with deep ventilation in the Nordic Seas and the response of the Greenland ice sheet. Expert 12 gives a moderate reduction of the AMOC only a little higher probability than a strengthening as he believes that feedbacks such as increased heat loss to the atmosphere (through a longer residence of the NAO in the positive phase, which is a possible response to climate change) and the advection of saltier water from the Tropics could compensate for the freshening in the northern latitudes due to melting of sea ice.

For the 4×CO_2 scenario most experts also project a temporary weakening of the AMOC. The weakening, however, is expected to be more pronounced than in the 2×CO_2 case and the recovery to take place more slowly.

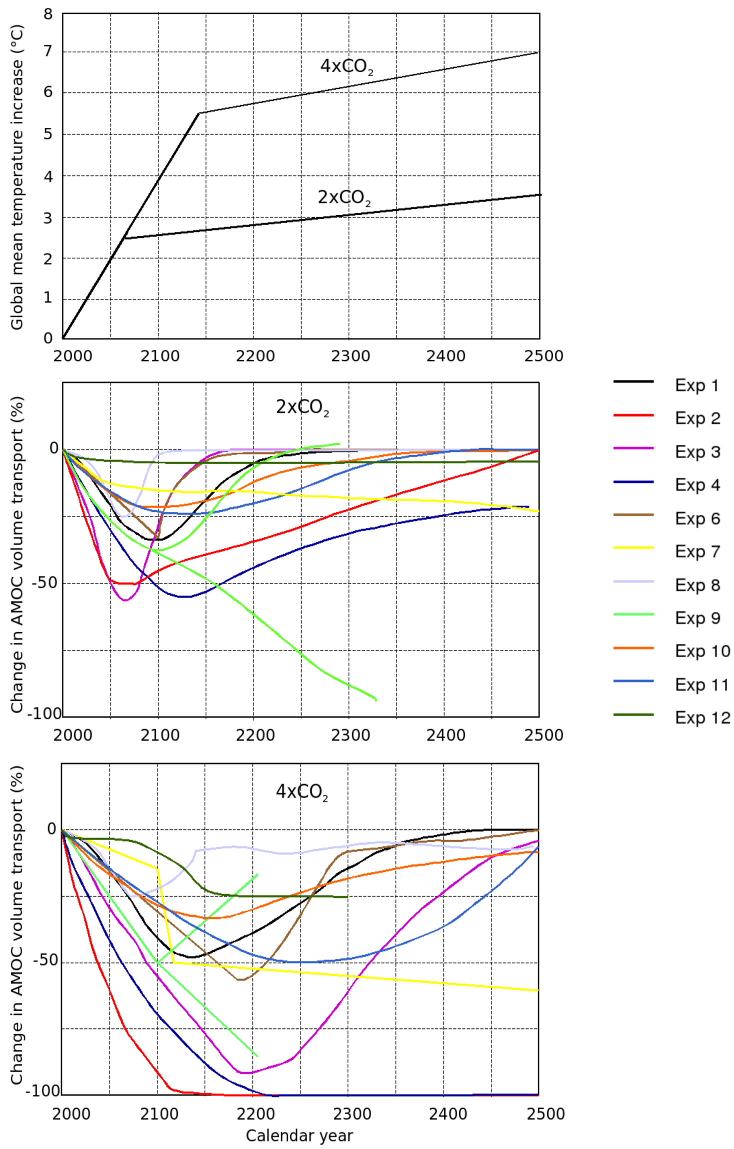

Figure 2: Summary of experts' judgments about the transient response of the AMOC to $2\times CO_2$ (middle panel) and $4\times CO_2$ (lower panel) scenarios. The scenarios of global mean temperature change displayed in the upper panel result from doubling and quadrupling of atmospheric pre-industrial CO_2 concentrations reached at 1% increase per year. The temperature values are taken from greenhouse gas simulations with the GFDL model (Manabe and Stouffer, 1994).

Expert 3 assigns the highest probability to a temporary shutdown of the circulation. Experts 2 and 4 expect a permanent collapse of the AMOC as the most likely response. Expert 4 argues that a quadrupling of atmospheric CO_2 concentrations would most probably lead to the disappearance of the Arctic sea ice cover, producing a stable surface layer in the Arctic and possibly the Nordic Seas. He characterizes the resulting off-mode as a "shallow reverse circulation" in the Nordic Seas. Expert 2 believes that the off-mode, which he describes as a "southern sinking mode" i.e. a circulation with deep-water formation in the south, would be reached through a "forced" response, in contrast to a "triggered" one. The qualitative difference between the two is the following: If a stable off-state exists under present-day boundary conditions, a temporary perturbation through, for example, a large freshwater pulse into the Atlantic, could trigger a transition to that state. The consequences would be a rapid and irreversible reduction of the AMOC. In contrast, if no stable off-state exists, the reduction of the AMOC would follow the changes in forcing. The time scale of the response would be set by the rate of change of the perturbation. The two responses would differ in their consequences for the climate in the North Atlantic: under global warming, a triggered response would possibly be associated with a net cooling in that area whereas a forced AMOC shut-down would not. The kink in the curve of expert 7 is due to the expected shutdown of one of the deep water formation sites, most likely in the GIN Sea (see discussion below). As for the $2{\times}CO_2$ scenario, expert 9 is split between a recovery and a collapse of the circulation. Some experts argue that the fate of the AMOC will be mainly determined by the response of the Greenland Ice Sheet, with

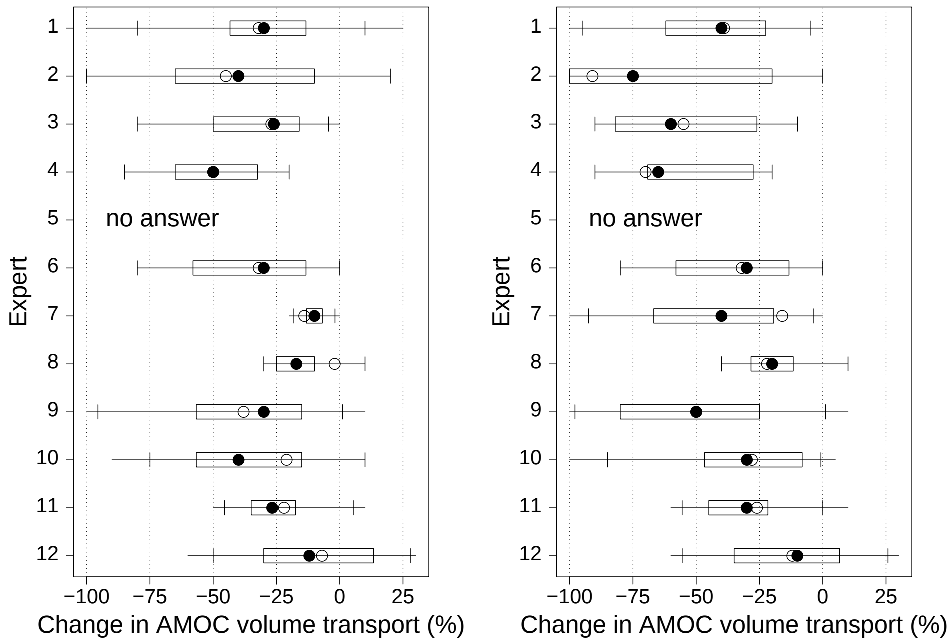

Figure 3: Change in AMOC strength in the year 2100 as a percent of the present-day value for a doubling (left panel) and quadrupling (right panel) of the pre-industrial CO_2 concentration. Shown are the complete ranges (horizontal lines), the 90%-quantiles (vertical tick marks), the 50%-quantiles (boxes) and the medians (solid dots) from experts elicited probability distributions. The experts' best estimates (open dots) are derived from Figure 2.

the probability of significant changes increasing with the chance for rapid ice discharge into the ocean.

Figure 3 displays the complete range, the 90% and 50% confidence intervals, the median and best estimate of experts' subjective probability distributions for the percentage change in AMOC strength in the year 2100. Consistent with the previous figure, the median values of the distributions are shifted towards stronger AMOC reduction in the $4{\times}CO_2$ case relative to the $2{\times}CO_2$ case. The differences, however, are not large, reflecting the fact

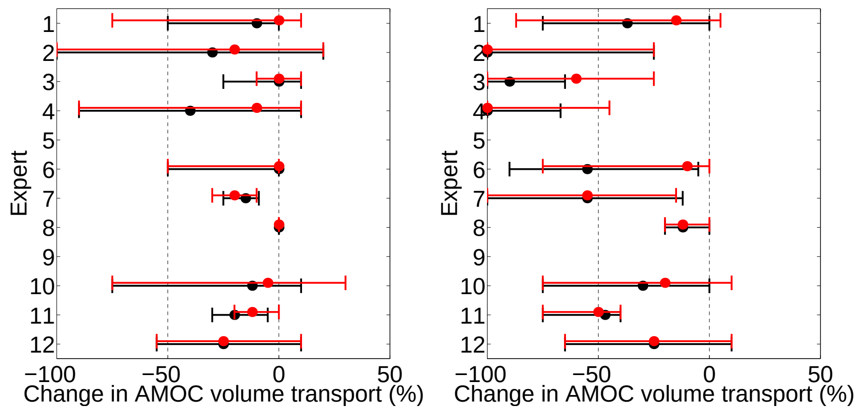

Figure 4: Change in AMOC strength in the year 2200 (black symbols) and 2300 (red symbols) in percent of present-day value for a doubling (left panel) and quadrupling (right panel) of the pre-industrial CO_2 concentration. Shown are the 90% confidence interval and the best estimate value from experts' subjective probability distributions.

that the temperature increase in the year 2100 differs by only 1.3 K in the two scenarios. The median of the distributions lies in the range 10%–50% reduction for a doubling and 10%–70% reduction for a quadrupling of the CO_2 concentration. In the doubling case, experts 2 and 9 include a collapse of the AMOC (which we defined as reduction in AMOC strength by more than 90% relative to present-day) in their 90% confidence interval. For a quadrupling, in addition experts 1 includes a collapse within the 90% confidence interval. Expert 2 estimates the probability of collapse as greater than 25%. Seven experts include a strengthening of the AMOC of up to 30% relative to present-day in their 90% confidence interval in the doubling case. For a quadrupling, three experts assign strengthening a chance higher than 5%. Expert 12 gives an AMOC strengthening a relatively high chance because of the stabilizing feedbacks discussed previously.

Some experts anticipate the AMOC response to lag the forcing by decades to centuries and therefore assign a significant probability to an AMOC collapse only from the year 2200 on (Figure 4). Under the 2×CO_2 scenario, interviewees 2 and 4 include a long-term collapse in their 90% confidence interval. Under 4×CO_2, in addition to experts 2 and 4, which expect a collapse of the AMOC as the most likely response, experts 3 and 7 give such a response a probability higher than 5%.

Respondents provided us with their judgments of the timing of a long-term shutdown of convection in the two main regions of deep-water-formation in the North Atlantic, i.e. the Labrador and GIN Seas, given the two scenarios (not shown). For the 2×CO_2 scenario four experts anticipate a permanent shutdown of convection in the Labrador Sea. One anticipates such a shutdown in the GIN Sea. For the 4×CO_2 scenario seven experts include a Labrador Sea shutdown in their response curve and four a GIN Sea shutdown. This indicates that Labrador Sea convection is thought to be more vulnerable than GIN Sea convection by most experts. They base this judgement on modeling results, which show a cessation of Labrador Sea convection in the first decades of this century (Wood et al. 1999), and the observed sensitivity of Labrador Sea convection to climate variability, e.g the NAO (Dickson et al. 1996). An exception is expert 7 who believes that GIN Sea convection has a higher chance of being shut down because of freshwater inflow through the Fram Strait (connecting the Nordic Seas with the Arctic). Expert 9 is of the opinion that GIN Sea convection may be more prone to surprises as the physical processes involved in the ventilation of deep waters there take place on a small scale and are difficult to capture

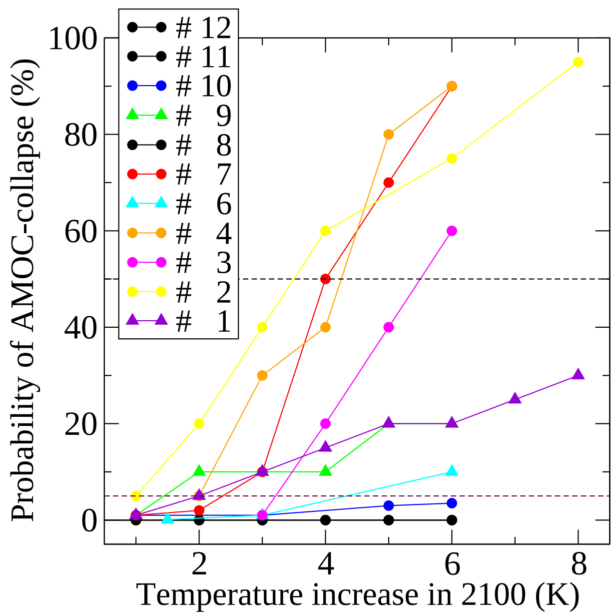

Figure 5: Experts' subjective probability "that a collapse of the AMOC will occur or will be irreversibly triggered" as a function of the global mean temperature increase realized in the year 2100.

in climate models. Note that some experts argued that dramatic changes in one or either of the deep convection sites would not necessarily affect the AMOC as a whole. Expert 2, for instance, expects that the deep water formation sites would make up for each other, leaving the total amount of downwelling unaffected. Expert 4 believes that deep ventilation of the two basins is not a necessary condition for overturning.

Figure 5 presents experts' subjective probability that a collapse of the AMOC will occur or will be irreversibly triggered by the year 2100, given a specified increase in global mean temperature. Respondents were asked to specify the minimum and maximum increase in global mean temperature they considered possible in the year 2100, relative to the temperature in

2000. In most cases, experts provided the temperature range of about 1 K to 6 K reported by the IPCC (Houghton et al. 2001). These values defined the range across which each experts was asked to judge the probability of a collapse of the AMOC. Experts 8, 11 and 12 consider a collapse of the AMOC impossible during the next 100 years. Eight experts assessed the probability of an AMOC collapse as non-zero, and one did not answer this question. For 2 K of global warming four experts assessed the probability of collapse as $\geq 5\%$. For a warming of 4 K, three experts assign a probability of at least 40% to a shutdown. For an increase of 6 K, six experts assign a probability $\geq$10% to a collapse, four a probability $\geq 50\%$ and two of these are almost certain (p = 90%) that a collapse would occur.

For a temperature increase of 4 K we did a simple check on experts' consistency. We compared the experts' judgments of the probability of AMOC collapse for this temperature increase as reported in Figure 5, with the subjective probability distributions for the change in AMOC strength in the year 2100 given a quadrupling of atmospheric CO_2 concentrations (Figure 3, right panel), which also results in a warming of 4 K in 2100 (top scenario in Figure 2). While nine experts showed reasonable consistency, experts 4 and 7 had assessed rather low probabilities that a collapse would have occurred in 2100 (Figure 3). Of course, because the results reported in Figure 5 are for "the probability that a collapse of the AMOC will occur or will be irreversibly triggered" the two results are not strictly inconsistent. One could believe that the collapse had been "irreversibly triggered", but that by 2100 it had not proceeded to completion because of time lags in the system. We contacted both experts and asked them to clarify. Expert 4 told us he could not readily reconstruct his thinking, but did not ask us to modify his answers. Expert 7 also had an opportunity to review the paper but did not respond with corrections.

Another minor inconsistency arose in some of the experts' judgment of the transient response of the AMOC to the 2×CO_2 and 4×CO_2 scenarios (Figure 3). In order to be consistent, experts should have drawn identical trajectories for the strength of the AMOC over the first 70 years. In fact, some of the sketched scenarios show a somewhat stronger response in the 4×CO_2 curves. Experts did not view their 2×CO_2 curves when responding to the 4×CO_2 question, so the modest differences should probably be viewed as an indication of the magnitude of the vertical error bars that should be attached to those experts' responses.

5 The consequences of changes in the AMOC

In the third part of the interview we discussed the consequences of AMOC changes. We were particularly interested in experts' judgments of changes in climate and sea level in the North Atlantic area. We provided the experts with four scenarios: 1) Weakening of the AMOC by 30% relative to present-day, 2) Shutdown of deep-water formation in the Greenland-Iceland-Norwegian Sea only, 3) Shutdown of deep-water formation in the Labrador Sea only, 4) Complete shutdown of the AMOC. In order not to confound the effects of a changing climate, caused by ongoing changes in greenhouse gases, with the regional effects of changes in the AMOC, we asked the experts to assume that GHG concentrations remained stable at present levels, and that the above changes were induced through some mechanism such as a large freshwater pulse to the North Atlantic. Further, we asked them to assume that the climate system persisted in those perturbed states for at least two decades in order to allow for atmospheric adjustment to the perturbed ocean state.

For each of the four scenarios given above we asked for the land-areas adjacent to the North Atlantic which would experience the strongest change in temperature. For the region the expert had chosen, we asked to quantify the change in annual mean and winter temperature. Figure 6 shows the 90% confidence interval and the best estimate value from experts' subjective probability distributions. For the four scenarios, all experts exclude a warming at the 5% confidence level. The strongest regional cooling is expected for a complete collapse of the AMOC: the experts' best estimates range between -1 K and -9 K for the annual mean and between -2 K and -13 K for the winter temperature anomaly. Changes in winter temperature were in most cases about double changes in the annual mean. Most experts expect the temperature anomaly to be centered over the eastern North Atlantic, most strongly affecting Iceland, Scandinavia and the British Isles. In the case of a 30% reduction of the AMOC, many experts scaled the expected temperature response linearly with that for a complete collapse. Accordingly, the best estimates lie in the range -0.75 K to -4 K for the annual mean and -1 K to -6 K for the winter temperature. The second strongest effect is expected by most to result from a shutdown of convection in the GIN Sea. Best estimates of change in temperature range from -1 K to -7 K for the annual mean and from -2 K to -12 K for the winter. Experts 8, 9

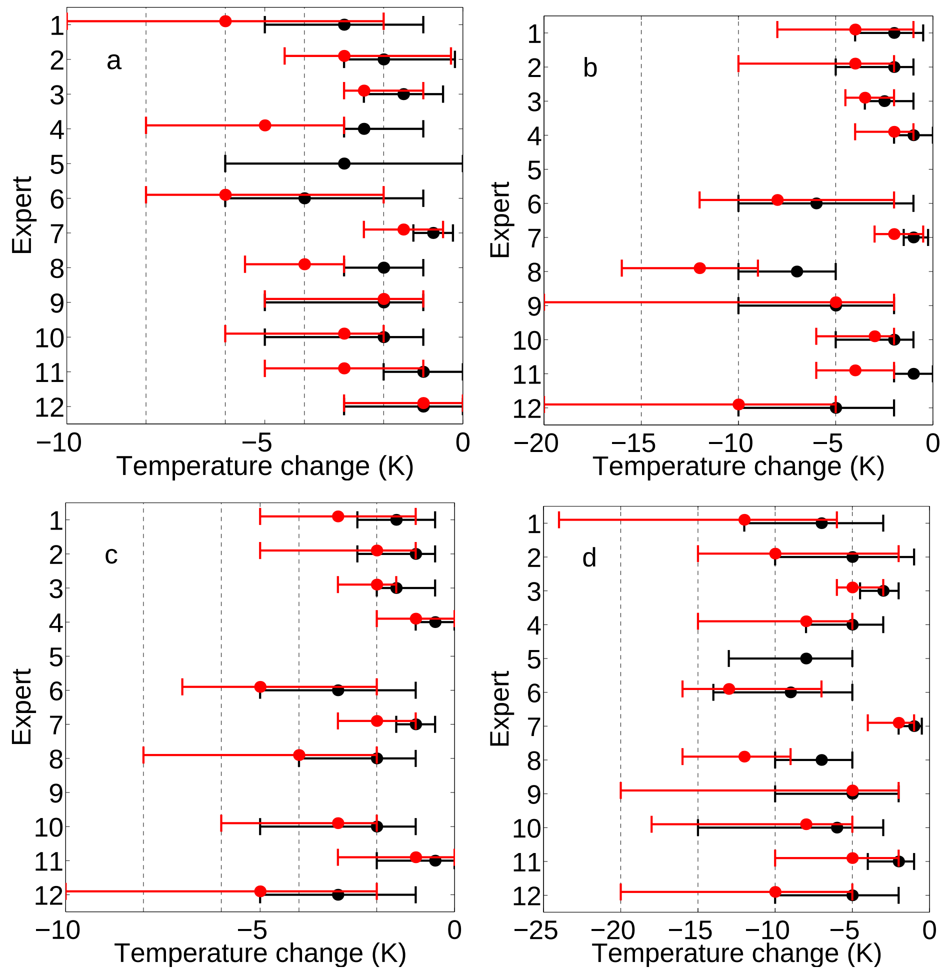

Figure 6: Experts' judgments of maximum changes in regional annual mean (black symbols) and winter (red symbols) temperature following (a) a weakening of the AMOC by 30% relative to present-day, (b) a shutdown of deep-water formation in the Greenland-Iceland-Norwegian Sea, (c) a shutdown of deep-water formation in the Labrador Sea, (d) a complete collapse of the AMOC. GHG concentrations are held at present-day levels. Shown are the 90% confidence interval and the best estimate value from experts' subjective probability distributions. Estimates refer to the region of strongest cooling, whose exact location differed among experts. Expert 5 delivered judgments for the change in annual mean temperature for scenario two and four only. Note that the panels have different scales.

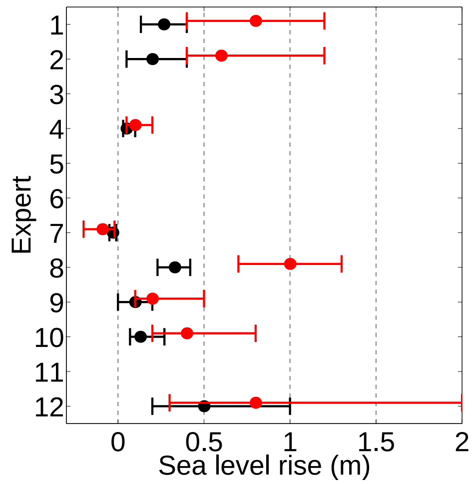

Figure 7: Changes in sea level in the North Atlantic area following a weakening of the AMOC by 30% relative to present-day (black symbols) and a complete collapse of the AMOC (red symbols).

and 12 believe that a shutdown in the GIN Sea would regionally have the same effect on temperature as a complete AMOC collapse. In relation to a complete shutdown, many experts expect the center of the anomaly to be displaced north-eastwards, mainly affecting Scandinavia. For a shutdown of deep-water formation in the Labrador Sea many experts expect only a relatively modest effect on temperature over land (best estimates range from -0.5 K to -3 K for the annual mean and from -1 K to -5 K for the winter), the reason being that the potentially affected land areas (Eastern Canada, Eastern US) are located upwind of the deep-water formation areas.

For scenario two (AMOC reduction by 30%) and four (complete shutdown of AMOC) we asked experts to provide us with estimates of changes in sea level in the Atlantic area north of 45°N, considering the contribution from both thermal and dynamic effects of circulation changes. By thermal effect we referred to the sea level rise due to the thermal expansion of the ocean. The dynamic effect is directly associated with a change in the spatial distribution of the sea surface elevation through the geostrophic balance (for a detailed explanation of this effect see Levermann et al. 2005). The results are presented in Figure 7, again in terms of experts' 90% confidence interval and best-guess value. Experts 3, 5, 6 and 11 declined to provide quantitative estimates arguing they had insufficient knowledge to make such a judgement. Experts 4, 7, 9, 10 did not consider the dynamic effect in their estimate[1]. Noting that the effect of thermal expansion would be small on a 20 year time scale, they gave best estimates of up to ± 40 cm of sea level rise for a complete collapse. Expert 7 attributed a slight decline in sea level to the cooling of the upper ocean, arguing that mixing of warm tropical waters would not reach far enough within 20 years. Experts taking into account the dynamic effect provided higher best-guess values of up to 1 m of sea level rise in the North Atlantic. For a 30% AMOC reduction most respondents scaled their estimates by a factor of 0.3 compared to the complete shutdown.

We concluded the third part of the interview by asking experts to come up with general impacts in the North Atlantic and other world regions. The results are summarized in Table 7. Concerning precipitation, the experts differed in opinion about whether the above scenarios of AMOC changes would lead to a wetting or drying over Europe. Some argue that cooler SSTs in the North Atlantic would be associated with less evaporation and hence a weakening of the hydrological cycle and, consequently, lower precipitation.

[1] This is not surprising, as the dynamic effect has only recently been discussed in the literature.

Consequences of changes in AMOC	
North Atlantic	Global
Weakening of hydrological cycle	Shift in tropical precipitation patterns
Change towards Pacific type of climate	Change in intensity of Monsoons
Progression of sea ice	Warming in TA and SA
Shift of oceanic fronts	Increase in hurricane activity in TA and SA
Shift of storm tracks	Cooling of Northern Hemisphere
Increase in extreme cold events	Change in atmospheric standing waves
Higher probability of storm surges	Changes in large-scale atmospheric circulation
Impacts on fisheries and fish-farming	Changes in sea ice extent in SO
Impacts on marine and terrestrial ecosystems	Changes in oxygen ventilation
	Reduction in oceanic carbon uptake
Impacts on water transportation	Destabilization of methane hydrates

Table 7: Potential consequences of AMOC changes in the North Atlantic and globally.

Others are of the opinion that changes in the AMOC could lead to a "Pacific type" of climate, with western Europe becoming wetter and northern Europe drier. Some experts indicate that cooler North Atlantic SSTs would lead to a shift in the route of the storm tracks. Most experts are uncertain about the sign of changes in frequency of extreme events, although there seems to be some consensus that the frequency of cold events would increase in the wake of an AMOC reduction. Non-physical consequences for the North Atlantic include changes in marine ecosystems, fisheries and fish-farming - mainly through changes in temperature and nutrient availability in the North Atlantic. Progression of sea ice in winter along the northern European and north-eastern American coasts could have large impacts on water transportation.

The majority of impacts the experts suggested for world regions other than the North Atlantic are associated with the reduced northward heat transport caused by a weakening of the AMOC and the consequent cooling in the north and warming in the south (this effect is often referred to as 'bipolar see-saw'; cf. e.g. Stocker 1998). These include the southward shift of the Intertropical Convergence Zone (ITCZ), which would result from a cooling of the Northern relative to the Southern Hemisphere, and the consequent change in tropical precipitation patterns (e.g. the Monsoons). Other examples are an increase in hurricane activity and shifts in the large-scale atmospheric circulation, both due to possibly higher sea surface temperatures (SSTs) in the South Atlantic. Further, some experts named shifts in planetary atmospheric standing waves, possibly resulting in a warming in North-West America and Eurasia. One consequence with potentially global repercussions could be the destabilization of methane hydrates along the continental shelves due to changes in deep-ocean temperature.

6 Research needs and priorities

In the fourth part of the interview we asked experts to identify research needs and priorities in the climate sciences in order to obtain better knowledge about the operation of the present-day AMOC and reduce uncertainty about its future evolution. To structure the discussion we used a play-board displaying a four by five taxonomy of research areas in the climate sciences (Figure 8). The experts were asked to allocate chips across the cells of the play-board. Because the marginal costs of acquiring knowledge through research varies substantially from area to area, we posed the question in two ways. First, the experts received 50 "relative importance chips", worth 2%

per chip. They were asked to allocate these chips on the play-board so as to indicate their judgment of the relative importance of making research progress in the various areas. In order to explain what each cell on the board meant, we provided examples of current research in each area.

In a subsequent task we asked the experts to design a 15-year research program on the AMOC, funded at 500-million US dollars (USD) per year. We asked them to "assume that existing sources of support for research in oceanography and other geophysics will continue, but that any current support for studies of the AMOC will be subsumed within this new budget". Experts were given 100 chips, each worth 5-million USD, to allocate across the 20 research areas. To help the experts get calibrated on what things cost, we provided them with a list of the current budgets of a number of relevant activities such as the annual operation costs of the TAO/TRITON mooring array or the ARGO float array, the costs of complete research programs such as WOCE or RAPID, and the cost of a new super computer.

Figure 8 reports experts' judgement of the relative importance (in percentage terms) of making progress in the 20 areas of climate research displayed on the board. On average, the highest research priority was assigned to coupled ocean-atmosphere modeling that received 10.8% of the total weight. Long-term observations of ocean circulation ranked second (8.2% of total weight). Ocean circulation and hydrography was the "system under study" that received the largest attention (29.3% of total weight; this value was obtained by averaging over the respective row). Long-term observations, dedicated observational campaigns, modeling, and collection and analysis of paleodata were all deemed important. Further, respondents identified the need to improve the data on buoyancy fluxes (i.e. heat and freshwater fluxes), through both long-term and focused observations, and the representation of these fluxes in models. Relatively little importance was allocated to research on "ocean mixing", that received only 10.2% of the total weight. Experts argued that dedicated observational campaigns could well contribute to a better understanding of the mixing processes in the ocean, in contrast to paleo-studies or long-term observations.

Figure 9 summarizes the outcomes of the budget allocation exercise. Results are given in percentage of the total funding of 500-million USD per year. In relation to the previous figure, larger budgets were assigned to the long-term observational systems (34.3% compared to 23.7% in the previous figure), reflecting the fact that these are comparatively more expensive than modeling and theory (25% of the total compared to 33.0%). The category "atmospheric circulation and climate" was allocated a relatively small portion of the budget. Some respondents argued that a significant amount of money is already being spent on a continuous observation of the atmosphere in the context of weather forecasting.

In a final task we asked experts to allocate an open budget to nine other areas of climate change research, such as biogeochemistry, ecology, socio-economics, assuming that "society had decided that it is appropriate to spend 500-million USD per year in research on the AMOC". Investments in "socio-economic impacts and adaptation" and "strategies for abatement" (which included research on the sequestration of carbon into the deep ocean) were specified to subsume studies on how these might be done, including research and development (R&D) of technology, but *not* to include the costs

Type of activity / System under study	Collection and analysis of palaeodata	Long-term operational observing systems	Focused observational campaigns	Modeling and theory
Buoyancy fluxes	0 – **4.0** – 12 2 0 6 4 12 2 6 2 0 0 10 4 e.g.: analysis of sediments and ice cores	0 – **6.2** – 12 8 8 0 4 6 0 4 6 10 12 10 6 e.g.: river runoff monitoring	0 – **5.5** – 10 8 8 2 6 6 2 10 6 0 6 10 2 e.g.: evaporation and precipitation measurements	0 – **5.3** – 12 6 4 12 2 6 4 6 4 10 6 0 4 e.g.: ice sheet modeling
Atmospheric circulation and climate	0 – **4.2** – 12 2 4 8 8 12 2 4 4 0 2 0 4 e.g.: reconstructions from ice cores	0 – **2.8** – 10 6 0 0 4 0 0 2 4 0 10 0 8 e.g.: stationary weather stations on land	0 – **2.2** – 10 4 2 0 0 0 0 10 2 0 6 0 2 e.g.: aircraft observ. campaign	0 – **6.0** – 12 2 6 12 8 4 0 4 2 10 6 10 8 e.g.: atmosphere to ocean response changes
Oceanic mixing (e.g. turbulence, eddies, convection)	0 – **2.0** – 6 2 4 0 6 4 4 2 2 0 0 0 0 e.g.: paleotracer studies	0 – **0.8** – 4 0 4 0 0 1 0 0 4 0 0 0 1 e.g.: turbulence moorings	0 – **3.7** – 10 6 4 2 0 2 4 6 2 10 4 0 4 e.g.: turbulence measurements	0 – **3.7** – 10 6 2 2 4 0 2 4 4 10 4 0 6 e.g.: eddy parameterizations
Ocean circulation and hydrography (incl. overflows)	0 – **6.7** – 14 6 4 12 8 6 14 6 8 0 2 10 4 e.g.: analysis of sediment cores	2 – **8.2** – 14 6 12 10 6 4 14 6 10 8 10 10 e.g.: arrays of stationary flow meters	4 – **7.3** – 14 6 4 10 6 4 14 6 8 10 6 10 4 e.g.: drifters, floats	2 – **7.2** – 14 8 6 6 6 2 14 6 2 10 6 10 10 e.g.: global ocean models
Ocean atmosphere interaction	0 – **3.5** – 8 2 4 6 6 8 2 4 4 0 2 0 4 e.g.: ENSO reconstruction	0 – **5.7** – 10 6 6 0 6 10 8 2 10 10 4 0 6 e.g.: ocean weather stations	0 – **3.8** – 12 2 6 0 6 4 0 8 12 0 6 0 2 e.g.: air-sea exchange measurements	0 – **10.8** – 20 10 12 10 10 8 14 8 8 10 10 20 10 e.g.: coupled climate modeling

Allocation greater than 10% of total · Allocation between 5% and 10% of total · Allocation less than 5% of total

Figure 8: Experts' judgments of the relative importance of making progress in the 20 displayed research areas of climate research (in percent). Bold numbers denote average values. They are bounded by the lowest and highest values that were assigned. The smaller numbers report individual responses for each of the 12 experts. Shading denotes different levels of allocation, as given in the legend.

System under study \ Type of activity	Collection and analysis of paleodata	Long-term operational observing systems	Focused observational campaigns	Modeling and theory
Buoyancy fluxes	0 – **3.4** - 7 1 0 9 7 5 3 6 2 0 0 5 3 e.g.: analysis of sediments and ice cores	0 – **6.8** - 20 5 10 3 4 5 0 3 12 5 10 20 5 e.g.: river runoff monitoring	0 – **5.3** – 20 1 5 5 6 6 0 5 5 0 7 20 3 e.g.: evaporation and precipitation measurements	0 – **2.7** – 5 3 2 4 2 4 1 3 2 5 4 0 2 e.g.: ice sheet modeling
Atmospheric circulation and climate	0 – **4.0** – 10 5 2 10 9 5 3 4 2 0 4 0 4 e.g.: reconstructions from ice cores	0 – **5.7** – 26 10 0 0 6 5 26 10 1 0 8 0 4 e.g.: stationary weather stations on land	0 – **2.0** – 9 5 2 0 0 2 0 4 1 0 9 0 1 e.g.: aircraft observ. campaign	0 – **4.2** – 9 5 3 8 2 5 0 4 2 5 4 3 9 e.g.: atmosphere to ocean response changes
Oceanic mixing (e.g. turbulence, eddies, convection)	0 – **1.5** – 5 1 3 1 5 4 1 2 1 0 0 0 0 e.g.: paleotracer studies	0 – **1.8** – 5 1 3 1 2 5 0 3 4 0 0 0 3 e.g.: turbulence moorings	0 – **3.8** –15 4 3 2 2 4 2 3 1 15 4 0 5 e.g.: turbulence measurements	0 – **2.3** – 5 1 1 2 2 3 1 5 1 5 2 0 3 e.g.: eddy parameterizations
Ocean circulation and hydrography (incl. overflows)	0 – **5.2** -11 6 4 10 7 5 3 5 11 0 4 5 2 e.g.: analysis of sediment cores	5 – **13.8** – 27 15 20 12 8 6 27 5 10 15 7 20 20 e.g.: arrays of stationary flow meters	4 – **9.3** - 19 8 5 12 8 10 9 5 10 15 7 19 4 e.g.: drifters, floats	1 – **5.5** – 15 5 5 5 4 4 6 4 1 15 5 3 9 e.g.: global ocean models
Ocean atmosphere interaction	0 – **2.8** – 6 1 2 5 4 5 2 6 4 0 3 0 2 e.g.: ENSO reconstruction	0 – **6.3** – 14 4 10 0 6 6 10 10 14 5 4 0 6 e.g.: ocean weather stations	0 – **3.4** – 8 4 5 1 4 3 0 6 8 0 7 0 3 e.g.: air-sea exchange measurements	5 – **10.3** – 15 15 15 10 12 8 6 7 8 15 11 5 12 e.g.: coupled climate modeling

Allocation greater than 10% of total — Allocation between 5% and 10% of total — Allocation less than 5% of total

Figure 9: Experts' judgments concerning the allocation of a research budget of 500-million US dollars per year across the 20 areas of climate research. Results are given in percentage of the total budget.

of implementation. Similarly, investments in geoengineering (fertilizing the ocean, lofting particles into the stratosphere, etc.) include studies about possible approaches, including their secondary impacts, but again did *not* include the costs of implementation.

Experts' individual responses are summarized in Table 8. On average, respondents thought it appropriate to spend approximately twice as much on oceanographic research and five times as much on the other climate sciences than on AMOC research. This reflects the fact that most respondents consider the AMOC to be just one among several important components of the climate system. With the exception of "strategies for abatement", research on the socio-economic facet of climate change - human emissions, socio-economic impacts and adaptation, integrated assessment - received smaller budgets than AMOC research. "Strategies for geoengeneering" were allocated the lowest budget. It is notable that respondents assigned annual budgets of similar orders of magnitude to the research areas pertaining to the natural sciences (with the exception of "geoengineering strategies") while they were largely split on the appropriate amount of money to spend on the socio-economic aspects of climate change research. For instance, the budgets allocated to research on "socio-economic impacts and adaptation" in the face of climate change differ by three orders of magnitude.

In previous expert elicitations with climate scientists (Morgan and Keith 1995) and forest ecologists (Morgan et al. 2001) the same question was posed (climate scientists were given one billion USD per year to invest in climate research and forest ecologist 500-million USD per year for research on the ecological impacts of climate change). A comparison of the results for the three groups is provided in Table 8. It is notable that the experts participating in this study thought it appropriate to spend much more in strategies for abatement than the experts interviewed previously. This probably reflects growing concern about the adverse consequences of climate change over the past five to ten years. On the other hand, experts in this study allocated a smaller budget to research on socio-economic impacts and adaptation than the forest ecologists. In relation to the study conducted in 1995, however, it seems that there has been a growth in awareness among climate scientists about the importance of investing in research on the socio-economic aspects of climate change. For example, the experts interviewed in this study thought it appropriate to spend 8.5 times more on "Integrated Assessment" than those participating in the elicitation in 1995.

Area of climate	Expert												Mean	Forest	Climate
change research	1	2	3	4	5	6	7	8	9	10	11	12	value	ecologists	scientists
Human emissions	1	1	2	1	1	1	5	0.01	0.5	0.1	2	1	1.3	1.9	0.6
Biogeochemistry (incl. carbon cycle)	16	5	20	15	5	10	10	10	0.5	10	10	10	10.1	–	–
AMOC research	5	5	5	5	5	5	5	5	5	5	5	5	5	–	–
Oceanography (other than AMOC)	5	5	5	25	15	15	10	5	5	5	5	15	9.6	–	–
Climate science and other geophysics	17	10	50	50	15	30	10	50	5	17	5	30	24.8 (38.7)[1]	10.6	10[3]
Ecosystem response	10	2	1	15	10	1	3	5	5	5	5	5	5.6	5[3]	3
Socio-economic impacts and adaptation	1	2	1	1	0.1	15	1	500	0.5	10	2	5	44.9 (3.8)[2]	4.6	1.2
Strategies for abatement	26	1	100	1	10	1	7	500	50	10	10	10	60.5 (20.5)[2]	$\geq$ 12.4	6.3
Strategies for geoengineering	0.01	0.5	3	1	1	0.01	1	0.1	0	5	10	1	1.9	1.3	0.5
Integrated Assessment	0.2	1	3	1	10	5	3	10	0	3	2	3	3.4	0.6	0.4

Table 8: Annual research budget, in hundreds of millions of US dollars, which the twelve experts considered appropriate to spend on nine other areas of climate change research if 500-million US dollars per year were budgeted for research on the AMOC. The last three columns compare average results from this study with those obtained in two previous rounds of expert elicitations with climate scientists (Morgan and Keith, 1995) and forest ecologists (Morgan et al., 2001).

7 Uncertainty reduction and monitoring for early warning

Given the large uncertainties identified in the study, a salient question is whether the experts believe that an appropriately designed research program would help in reducing uncertainty about the future evolution of the AMOC. In the last part of the interview we asked them to estimate the probability that the width of their subjective probability distribution about the "change in southward NADW flow at 30°N in 2100" given the $2\times CO_2$ scenario (cf. left panel of Figure 3) would decrease, remain unchanged or increase after completion of the 15-year research program they had discussed in the previous section. Experts' individual responses are summarized in Table 9. While experts 5 and 8 give probabilities of 80% or more that uncertainty would not be reduced, the vast majority of experts assigned probabilities of at least 60% to an uncertainty reduction.

We were interested in learning experts' view about the feasibility of a system with some appropriate combination of modeling and monitoring which could provide human society with an "early warning" capability with respect to the future evolution of the AMOC. We noted that in order to be truly useful such a system would have to detect a signal that a trigger point was reached at least two decades in advance. The state of knowledge was

[1] The number in parenthesis reports the sum of the average values for "oceanography" (including AMOC research) and "climate science and other geophysics", in order to make the entry comparable with the values derived in the previous studies.

[2] The numbers in parenthesis report the mean values that are obtained under exclusion of the outlier value assigned by expert 8.

[3] These amounts were specified in the studies by Morgan and Keith (1995) and Morgan et al. (2001).

specified to be after the completion of the 15-year research program. Nine respondents believe that such an early warning system could be developed, although most of them doubt that a lead time of twenty years could be achieved. Two experts noted that the accuracy of such a system would probably not be very high (i.e. $< 95\%$). One expert does not believe that such a system could be developed. Two experts were not able to say. Most respondents agreed that such a system should include real-time monitoring of key quantities in combination with high resolution modeling. For instance, the observations could be used to initialize climate models which are then run into the future, similarly to what is done in weather forecasting today. Some experts suggested that it would be most sensible to monitor the "choke points" of the AMOC such as the deep water formation in the Labrador Sea, the overflows across the Greenland-Iceland-Scotland ridge and the Deep Western Boundary Current. Expert 1 suggested that one would need to "have a very good grasp of the entire circulation", rather than look at individual sites.

8 Summary and conclusions

We presented results from detailed interviews with 12 leading experts in the field of climatology about the present-day state of the AMOC, its future evolution in the face of global climate change and the potential impacts of AMOC changes. Further, we provided experts' opinion about research needs in the field of climate science and the feasibility of an early warning system.

Experts differed in their views about the relative importance of a num-

	Expert											
	1	2	3	4	5	6	7	8	9	10	11	12
Reduction ≥ 0.5	45	60	10	20	5	20	50	5	50	70	30	60
Reduction ≤ 0.5	45	30	90	40	5	50	30	15	30	25	60	30
No Change	5	5	0	30	85	10	20	75	10	5	5	0
Increase	5	5	0	10	5	20	0	5	10	0	5	10

Table 9: Experts' judgment of the probability that uncertainty about the AMOC could be reduced. The numbers in the body of the table report experts' probabilities that their probability distribution about the "change in southward NADW flow at 30°N in 2100" under the $4\times CO_2$ scenario (Figure 3) would be reduced by more or less than half, remain unchanged or increase, assuming that the 15-year research program they designed had been conducted.

ber of physical processes in determining the long-term mean pre-industrial strength of the AMOC. Nevertheless, one dominant view can be identified among the experts' responses. According to this view, the heat fluxes and diapycnal mixing are key in determining the current state of the AMOC. Wind-driven upwelling in the Southern Ocean is judged to be relatively unimportant, in contradiction to theories proposed by some authors (Toggweiler and Samuels 1993; Toggweiler and Samuels 1995). Although receiving a high rank in terms of relative importance, diapycnal mixing is indicated by most experts to be only poorly known, as opposed to, for example, the heat fluxes and atmospheric freshwater transport. Concerning the ability of state-of-the-art climate models to represent the physical processes relevant to the long-term mean state of the AMOC, most respondents indicated that the heat and freshwater fluxes of the Atlantic are relatively well represented (with the exception of the freshwater contribution from ice sheets and glaciers), in contrast to the physical processes which take place on smaller scales such as mixing and the overflows. The experts' median estimates of the present-day strength of the AMOC (14–18 Sv) scatter less than the range spanned by climate models (10–30 Sv). The reason for this agreement is probably the high confidence the experts place in recent observations-based estimates of this quantity (15–18 Sv; Ganachaud and Wunsch 2000, Talley et al. 2003).

Almost all experts indicated that the most important forcing factors determining the response of the AMOC to increasing CO_2 concentrations are changes in the heat and freshwater fluxes in the North Atlantic. Changes in wind in that region received a top ranking from one expert only. Judging the ability of state-of-the-art climate models to project relevant forcing factors (which is different from the ability to simulate the present climate state), experts on average assigned mid-range marks to changes in heat fluxes, wind forcing and some components of the hydrological cycle. Again, most experts criticized the inability of climate models to adequately consider changes in the mass balance of ice sheets and glaciers.

Experts' best estimates of the weakening of the AMOC in the year 2100 in response to scenarios of doubling and quadrupling of the atmospheric pre-industrial CO_2 concentration range from about 2% to 55% for the doubling scenario, and from 10% to 90% for the quadrupling scenario. The latter is much larger than the range of responses simulated by state-of-the-art climate models (10% to 50%; e.g. Gregory et al. 2005). While most experts believe that the AMOC will most likely recover under the $4\times CO_2$ scenario, two respondents anticipate a permanent collapse of the AMOC as the most likely response. Assuming a global mean temperature increase in the year 2100 up to 6 K, eight experts out of eleven assessed the probability of an AMOC collapse as significantly different from zero, four of them larger then 50%. In this respect, the experts' judgements deviate from the results obtained with climate models. In a recent model intercomparison endeavor, the response of 11 different climate models to a quadrupling of CO_2 concentration was simulated (Gregory et al. 2005). None led to a collapse of the AMOC within the 140 years of the simulation. This disagreement can be explained by the fact that the experts include in their estimates their own judgement about the skillfulness of climate models as well as information from sources other than modeling. Recall, for example, that many experts assigned poor marks to the ability of models to capture important subgrid-scale processes. Furthermore, ice discharge from Greenland is not considered in the model simulations described in Gregory et al. (2005), despite indications that this ice sheet may be prone to rapid change (Joughin et al. 2004).

All respondents expect that weakening, complete or partial collapse of the AMOC would all be associated with a cooling over the North Atlantic area. Note, however, that we asked the experts to assume that the AMOC changes were induced through a large freshwater pulse to the North Atlantic, while CO_2 concentrations remained stable at present levels. Taking increasing CO_2 concentrations into account, the effects of global warming would have to be superimposed on the cooling, possibly compensating it over land areas (Rahmstorf 1997; Kuhlbrodt et al. 2006). Among other impacts, respondents included significant sea level rise in the North Atlantic area, changes in global precipitation patterns and reduced carbon uptake by the ocean.

Asked to design a 15-year research program about the AMOC funded at 500-million USD per year, experts on average allocated the largest budget to long-term observations of circulation and hydrographic measurements and coupled climate modeling. Maybe surprisingly, experts would invest only relatively little money in research on mixing processes in the ocean, although these (in particular diapycnal mixing) were identified as key in determining the long-term mean state the AMOC and assessed as only poorly known. Most experts are confident to at least 60% that an appropriately conceived research program would contribute to reducing uncertainty about the future evolution of the AMOC. Also, almost all experts believe that after completion of such a program it would be possible to develop a system with some appropriate combination of modeling and monitoring which could provide human society with an "early warning" capability with respect to triggering abrupt changes of the AMOC.

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