An Integrated Assessment of Changes in the Thermohaline Circulation

T. Kuhlbrodt*, S. Rahmstorf and K. Zickfeld†

Potsdam Institute for Climate Impact Research, Potsdam, Germany

F. B. Vikebø and S. Sundby

Institute for Marine Research, Bergen, Norway, and Bjerknes Centre for Climate Research, Bergen, Norway

M. Hofmann

Potsdam Institute for Climate Impact Research, Potsdam, Germany

P. M. Link

Research Unit Sustainability and Global Change, Hamburg University, Germany

A. Bondeau, W. Cramer and C. Jaeger

Potsdam Institute for Climate Impact Research, Potsdam, Germany

Abstract. This paper discusses the risks of a shutdown of the thermohaline circulation (THC) for the climate system, for ecosystems in and around the North Atlantic as well as for fisheries and agriculture by way of an Integrated Assessment. The climate model simulations are based on greenhouse gas scenarios for the 21st century and beyond. A shutdown of the THC, complete by 2150, is triggered if increased freshwater input from inland ice melt or enhanced runoff is assumed. The shutdown retards the greenhouse gas-induced atmospheric warming trend in the Northern Hemisphere, but does not lead to a persistent net cooling. Due to the simulated THC shutdown the sea level at the North Atlantic shores rises by up to 80 cm by 2150, in addition to the global sea level rise. This could potentially be a serious impact that requires expensive coastal protection measures. A reduction of marine net primary productivity is associated with the impacts of warming rather than a THC shutdown. Regional shifts in the currents in the Nordic Seas could strongly deteriorate survival chances for cod larvae and juveniles. This could lead to cod fisheries becoming unprofitable by the end of the 21st century. While regional socioeconomic impacts might be large, damages would be probably small in relation to the respective gross national products. Terrestrial ecosystem productivity is affected much more by the fertilization from the increasing CO_2 concentration than by a THC shutdown. In addition, the level of warming in the 22nd to 24th century favours crop production in northern Europe a lot, no matter whether the THC shuts down or not. CO_2 emissions corridors aimed at limiting the risk of a THC breakdown to 10% or less are narrow, requiring departure from business-as-usual in the next few decades. The uncertainty about THC risks is still high. This is seen in model analyses as well as in the experts' views that were elicited. The overview of results presented here is the outcome of the Integrated Assessment project INTEGRATION.

Keywords: Integrated Assessment, Thermohaline Circulation, Atlantic Meridional Overturning Circulation, Climate Impacts, Global Change, Mitigation Strategies, Tipping Point

* Now at: Department of Meteorology, NCAS-Climate, University of Reading, Earley Gate, P.O. Box 243, Reading RG6 6BB, UK, phone +44 118 378 6014, email `t.kuhlbrodt@reading.ac.uk`, fax +44 118 378 8316

† Now at: School of Earth and Ocean Sciences, University of Victoria, Canada

1. Introduction

Since the first warnings in the 1980s (Broecker, 1987), changes in ocean circulation have been increasingly discussed as a possible risk associated with future anthropogenic climate change (e.g. Manabe and Stouffer, 1993; Wood et al., 1999; Keller et al., 2000; Vellinga and Wood, 2002; Hulme, 2003; Vellinga and Wood, 2008). This discussion has mostly focused on the ocean currents of the northern Atlantic. A strongly simplified sketch of the surface currents is given in Fig. 1. **FIG. 1**

The North Atlantic is one of the two major regions on Earth (the other one being the Southern Ocean) where surface waters sink down to supply the global ocean with its deep water masses, in a process called deep water formation. This deep water formation is a key element of the global thermohaline circulation (THC), a recent introductory review of which is found in Rahmstorf (2006). If deep water formation in the entire North Atlantic were to decline or stop, on a time scale of decades the large-scale overturning circulation of the Atlantic would do likewise. Physical considerations and modelling show that this deep water formation process – and thus the pattern of Atlantic ocean circulation – depends on a subtle density balance in northern high latitudes.

In climate models it its generally seen that, if the surface density in the critical regions (Nordic Seas and Labrador Sea) declines, then deep water formation is weakened (Gregory et al., 2005) and beyond a critical value stops altogether (Winguth et al., 2005; Stouffer et al., 2006). (Some climate models have a sensitive deep water formation region in the Irminger Sea too.) A decline in ocean surface density can be brought about by a warming of the surface waters (thermal expansion) and/or by a freshening (reduction of salinity due to inflow of freshwater from precipitation, river flow or ice melt).

Observed surface densities have been subject to strong decadal variability in the past decades (Curry and Mauritzen, 2005; Boyer et al., 2007). This variability has been attributed to natural variability, especially the North Atlantic Oscillation (Peterson et al., 2007). Whether a weakening of the circulation is already occurring cannot be stated with confidence due to that variability and the poor data coverage (Bindoff et al., 2007). One observational study that has found indications of a surprisingly large weakening (Bryden et al., 2005) relies on too few data points to be statistically significant (Cunningham et al., 2007). Climate model scenarios for global warming, even "pessimistic" ones where the Atlantic THC collapses around the year 2100 (Rahmstorf and Ganopolski, 1999), show only a minor weakening by the year 2005 (by generally less than 10%) which would not be detectable in observations against a background of internal variability.

A critical question is: how much weakening can we expect due to global warming, and what is the risk of a qualitative shift in the circulation pattern, such as a complete shutdown of Atlantic overturning? The answer to this question is complicated by the fact that many of the relevant processes are not currently well resolved in climate models. First, the stability of the ocean circulation itself is highly uncertain. For instance, how much freshwater it takes to cause a given weakening or a shutdown is known only roughly as an order of magnitude; as intercomparison studies show, models differ widely in this respect for reasons not fully understood (Rahmstorf et al., 2005). And second, future freshwater input is also highly uncertain, as it depends strongly both on precipitation and river runoff changes and on ice melting rates.

Meltwater runoff from a shrinking Greenland ice sheet is not included at all in most models (e.g. those evaluated for the fourth IPCC assessment report); yet it alone could supply a critical amount of freshwater (Swingedouw et al., 2006). The uncertainty ranges for how much freshwater is required for a shutdown, and how much may be expected in future, unfortunately overlap. Model simulations thus far suggest that warming alone, without substantial freshwater input, could weaken but not shut down the Atlantic THC, while the critical amount of freshwater needed for a shutdown is of the order 0.1 Sv or larger (1 Sv= 10^6 m^3s^{-1}). This amount is similar to that implicated in past THC shutdowns in climate history (Heinrich events, see Rahmstorf, 2002, and Hemming, 2004), although the stability of the ocean circulation in a glacial climate state need not be the same as today.

Present changes in freshwater input to the northern Atlantic are not well constrained and the freshwater budget urgently requires further study, but some early estimates suggest that runoff from Eurasian rivers has increased by 0.005 Sv (Peterson et al., 2002), the shrinking sea ice cover contributes 0.014 Sv (Lindsay and Zhang, 2005), while the mass loss of the Greenland ice sheet amounts to 0.007 Sv (Rignot and Kanagaratnam, 2006). Together this amounts to about a quarter of the critical magnitude, although not all terms are included: river runoff from North America is missing, as is the potentially increasing precipitation over the northern Atlantic ocean. Thus the observed trends, if they are the result of the global warming that has occurred over the historical period, make it conceivable that the much larger warming expected in future could lead to amounts of freshwater influx that would seriously alter the ocean circulation.

Given the large uncertainties discussed, it is hardly surprising that the elicitation among leading ocean experts presented later in this paper reveals widely differing views about the probability of a shutdown being triggered this century, with some estimates even exceeding the 50% level for scenarios with high global temperature rise. Narrowing down this uncertainty will first of all require a better physical understanding of what determines ocean circulation stability; sensitivity studies with model ensembles and model intercomparison projects are needed for this. Until this basic issue is understood, it is very difficult to interpret individual model results, since we do not know what makes a particular model more or less stable. Anecdotal evidence suggests that at least some modelling groups have had difficulty with a highly unstable ocean circulation during model development, leading to an unrealistic present-day climate, and have modified their models to stabilize the circulation. The very unstable end of the model uncertainty range would thus have been filtered out, unlike the overly stable end of the range, possibly biasing our sample of models in this respect.

If the critical freshwater input leading to a THC breakdown in models exists in the real ocean as well, then the THC is one of the "tipping elements" in the climate system. Lenton et al. (2008) identified a number of these elements that are characterized by having a critical control value; if this value is transgressed a qualitative change is triggered. Other examples than the THC are the melting ice sheets of Greenland and West Antarctica.

The overall risk of ocean circulation changes is not only determined by their likelihood, but also by their potential impacts. They are inversely related: a moderate weakening of, say, 25% is considered very likely for non-mitigation scenarios (Meehl et al., 2007), but the impacts would probably be regionally confined (Schaeffer et al., 2004; Bryan et al., 2006). A complete shutdown is widely considered very unlikely (the IPCC fourth assessment report [Meehl et al., 2007] gives this a probability of up to 10%), but some impacts could be wide-spread and serious, as we show in the present study. Both types of scenario – the high probability/ moderate impact, and the low probability/ high impact type – could be considered "dangerous" (in terms of Art. 2 UNFCCC) in different ways, and both types of risk need to be taken into account in climate policy decisions. Unfortunately, the second type is associated with much greater uncertainty, as it is not so amenable to modelling ("best guess" scenarios are obviously not a suitable tool to study low-probability risks) and the impacts are much further from our experience and more difficult to foresee. Therefore, a major thrust of this paper is to provide an overview over potential impacts of a shutdown of the THC. We have focussed on Europe and the North Atlantic region; global teleconnections are only briefly touched upon.

The impacts of THC changes have already been studied in a number of papers. They can be divided in three classes:

1. Those which compare the present-day climate with a hypothetical climate that has the same present-day boundary conditions (e.g. greenhouse gas concentrations), but a weakened THC. This weakening is usually obtained by abruptly "hosing" a large amount of freshwater into some region in the North Atlantic. Examples for this approach are Vellinga and Wood (2002), Higgins and Vellinga (2003), Schmittner (2005), Jacob et al. (2005) and the intercomparison study by Stouffer et al. (2006).

2. Those which study scenarios of the future evolution of the climate, driven by increasing greenhouse gas (GHG) concentrations. Examples of this type, where the THC weakens without being explicitly triggered to do so, are Wood et al. (1999), Schaeffer et al. (2002) and Winguth et al. (2005).

3. Those that study the impacts of a THC weakening or shutdown, triggered by additional freshwater input, in scenarios of future climate. We mention here Rahmstorf and Ganopolski (1999), Jungclaus et al. (2006), Vellinga and Wood (2008), Swingedouw et al. (2007) and Zickfeld et al. (2008). These studies are most useful in the present context as they allow to analyse the net effect of a

THC shutdown by taking the anomalies (GHG scenario with THC shutdown) minus (GHG scenario only).

Most studies address the cooling effect of a THC weakening or shutdown. For comparing the studies it is however crucial to look at the timescale and regional extent of the cooling. The cooling looks drastic—several K over large parts of the North Atlantic region—in studies with a sudden THC breakdown and in the absence of global warming (Vellinga and Wood, 2002; Jacob et al., 2005). Even if a greenhouse gas scenario is assumed, the cooling due to such a sudden breakdown, when triggered in the mid-21st century, is so strong that the warming is overcompensated (i.e. net cooling with respect to present day conditions) in the North Atlantic region (Vellinga and Wood, 2008). Note however that such a net cooling, confined e.g. to the Nordic Seas region, can also happen in response to regional changes of the thermohaline currents that do not necessary entail strong global THC changes (Wood et al., 1999; Schaeffer et al., 2002; Jungclaus et al., 2006). Global mean temperature typically drops by a few tenths of a degree due to a THC shutdown (Rahmstorf and Ganopolski, 1999; Swingedouw et al., 2007), which means a slight reduction of the global warming trend, i.e. a relative cooling compared to a non-shutdown scenario. Our climate scenarios are largely in line with these studies.

Precipitation changes have less often been looked into. Vellinga and Wood (2002, 2008) and many models in Stouffer et al. (2006) see a southward shift of the intertropical convergence zone (ITCZ) that brings with it a shift of the tropical precipitation regions. This southward movement compensates the northward drift due to global warming (Vellinga and Wood, 2008). For Europe, regional precipitation reductions are seen in studies with (Vellinga and Wood, 2008) and without (Vellinga and Wood, 2002; Jacob et al., 2005; Stouffer et al., 2006) taking global warming into account.

The impacts on land ecosystems have been addressed, to our knowledge, in only two papers so far (Higgins and Vellinga, 2003; Higgins and Schneider, 2005) which we discuss in the beginning of sec. 4. Our results in this respect are new in that consistent scenarios of global warming together with a THC shutdown are used. Zickfeld et al. (2008) used a complex Earth system model to investigate the reaction of the global carbon cycle and found a weak net effect of a THC shutdown that would raise the atmospheric CO_2 concentration by a few percent. If only the marine carbon cycle is concerned, the impact of a THC shutdown on the oceanic carbon uptake is negligible according to Swingedouw et al. (2007). We are aware of only one study about the impacts of a THC shutdown on marine planktonic ecosystems (Schmittner, 2005) which however does not take global warming into account (see sec. 3.1).

As our interest lies in the risk of a future THC shutdown our study is to be part of class (3) mentioned above. We use the method of Rahmstorf and Ganopolski (1999), combining global warming scenarios with a smooth additional freshwater input that scales with the warming. To this end we have conducted a number of climate model simulations with Climber-3α (Montoya et al., 2005), an Earth system model of intermediate complexity. Different strengths of freshwater forcing are realized by varying the scaling constant for the freshwater flux. This reflects the uncertainties in future freshwater fluxes, mentioned earlier in this section, and leads to a moderate weakening or a full shutdown of the Atlantic THC in the course of the 21st to 23rd centuries. We also used different scenarios for rising GHG concentrations. Given that the moderate weakening of the THC actually occurs in most of the 21st century scenarios in Meehl et al. (2007), we use this case as the baseline for the comparison with the shutdown scenario.

The impacts of a THC shutdown were investigated in some detail with the help of models for regional climate change, land ecosystems, agriculture, marine ecosystems and fisheries. The domains of the impact models span the range between a global extent and a local focus (Fig. 1). In order to develop a consistent picture of the impacts of a THC weakening we strived to use the same climate scenarios for all impact models throughout the marine and terrestrial ecosystems. This was achieved with the exception of the model for the growth and transport of cod larvae and juveniles. Here the very high spatial resolution foreclosed the use of the Climber-3α scenarios. Instead, we had to use a freshwater hosing scenario from the Bergen Climate Model (BCM), as is detailed in sec. 3. In addition, the fishery model uses a parameterization from the cod larvae and juveniles model. Therefore it implicitly relies on the scenarios from the Bergen climate model too.

The results from the model studies are supplemented with results from an expert elicitation. This expert elicitation consisted of detailed interviews with 12 leading ocean scientists about the effects of global climate change on the THC. The elicitation aimed at examining the range of opinions within the oceanographic research community about the physical processes that determine the current strength of the THC, its future evolution in a changing climate and the consequences of potential THC changes. In addition, the experts were questioned on the research needs to reduce uncertainty about the THC, and on the possibility of predicting the THC. In summer 2004, the 12 interviews were conducted at each expert's home institution, with every interview lasting for about 7 hours. The elicitation is extensively described in Zickfeld et al. (2007).

We present here a synthesis of results of the interdisciplinary research project INTEGRATION. This project has interpreted the term "Integrated Assessment" in two ways. First, we consider the entirety of the project results presented here as an Integrated Assessment. It draws on a wide range of disciplines, encompassing climate research, oceanography, meteorology, marine and terrestrial biology, biogeochemistry and economics. Contributions from all these disciplines are integrated to an appraisal of the impacts of changes in the THC that is as wide as possible. In order to come up with policy recommendations we have developed an Integrated Assessment Model. In this model, the term "Integrated Assessment" adopts its second meaning: that a simple climate model is coupled to a simple model of the world economy to estimate future emissions reductions required to limit the risk of "dangerous" THC changes in the sense of Art. 2 UNFCCC.

Due to the large uncertainties, the scenarios investigated need to be considered as illustrative—they give an idea of the kinds of impacts that might be expected, but confidence in many specific quantitative and regional aspects has to be considered low. Although every effort was made to prepare climate scenarios, regional downscaling and impact models that are as realistic as possible, this study should be read as an early exploration of impacts of THC changes; much work remains until these impacts can be modelled with greater confidence.

We have structured the paper in the following way. Section 2 describes the climate scenarios, starting with the GHG scenarios, and progressing to the oceanic and atmospheric impacts of changes in the THC. Impacts on marine ecosystems are dealt with in section 3, including phytoplankton, zooplankton, and fish. Section 4 studies the impacts on land-borne ecosystems. Both section 3 and section 4 address aspects of the global carbon cycle. Changes in ecosystem productivity can entail socioeconomic impacts; these are described in section 5, with a focus on fisheries and crop yields. Section 6 aims at a risk assessment using different probability estimates for a THC breakdown. The penultimate section 7 presents the results from the Integrated Assessment model that defines carbon emissions corridors reducing the risk of "dangerous" THC changes. The outcome of this study is eventually resumed and discussed in section 8.

2. Atmospheric and Oceanic Impacts

2.1. Climate Scenarios

Global warming will very likely continue during the 21st century and beyond. Therefore we consider in this paper the effects of global warming and a weakening THC in combination. The main cause for global warming lies in the rising concentrations of greenhouse gases in the atmosphere (Hegerl et al., 2007). In our climate model simulations this is expressed in scenarios for the future emissions of these gases. The cause for THC changes, on the time scale of decades to a few centuries, are mainly changes in the fluxes of heat and freshwater at the ocean's surface (Gregory et al., 2005; Kuhlbrodt et al., 2007; see also discussion in sec. 1). Both the input of heat and freshwater can slow down the THC because they reduce the sea water's density and hence the volume and depth of the sinking waters in the North Atlantic.

While the heat input due to global warming is captured by climate models, there are sources for freshwater input that are not taken into account by most of the state-of-the-art climate models (Climber-3α included). Notably, the potential melting of the Greenland ice sheet is often not adequately modelled, although the observed net mass loss is expected to continue throughout the 21st century (Meehl et al., 2007). Recent studies (e.g. Velicogna and Wahr, 2006; Rignot and Kanagaratnam, 2006) emphasize the acceleration of Greenland ice melt along with its contribution to the North Atlantic freshwater budget and to sea level rise. In the opinion of some of the experts we interviewed, the melting of the Greenland ice sheet is the main determinant of the future development of the THC. Hence the freshwater input from inland ice melt needs to be parameterized. For the climate scenarios we computed with Climber-3α an additional amount of freshwater was put into the North Atlantic. To mimic the melting process the freshwater flux was scaled with the temperature increase in the Northern Hemisphere. Apart from capturing the ice melt, this parameterization includes the uncertainty about how strongly the atmospheric hydrological cycle is amplified in a warmer climate (Rahmstorf and Ganopolski, 1999). The scaling constant is dubbed hydrological sensitivity (HS) and determines the amount of additional freshwater per degree warming. This linear parameterization is fairly crude, but still, as we believe, better than "hosing" freshwater with a sudden onset and a following prescribed rate. There is still a very large uncertainty about the future freshwater balance of the ocean (see also sec. 1); as discussed below we vary HS over a wide range to cover that.

As an Earth system model of intermediate complexity, Climber-3α consists of a full three-dimensional ocean (MOM-3) coupled to a coarse-resolution statistical-dynamical atmosphere (POTSDAM-2). No flux adjustments are used, meaning that the ocean-atmosphere fluxes evolve in time without imposed constraints. Since the cpu usage of the model is small, we were able to use an equilibrium obtained from a multi-millennium run as the initial condition for the runs presented here. Montoya et al. (2005) describe Climber-3α in detail.

We computed four scenario runs. All of them are driven by observed greenhouse gas concentrations until 1989. Afterwards, three CO_2 equivalent scenarios were applied (Fig. 2a). CO_2 equivalent scenarios convert the radiative forcing of other greenhouse gases (like methane or nitrous oxide) and aerosols (sulphates) into the equivalent effect of CO_2. From SRES (Nakićenović and Swart, 2000), a high-emission (A1FI) and an intermediate-emission (B2) scenario were chosen and used until 2100. After that, a reduction of emissions such that they reach zero in 2200 was assumed. We used a smooth curve for this purpose (cubic spline). The resulting decline of the CO_2 equivalent concentration was then computed until 2400. In addition, we used a low-emission scenario (Azar et al., 2006) based on the assumption that major emissions reductions combined with carbon capture technology are able to stabilize the CO_2 equivalent concentration below 400 ppmv after 2100.

In order to induce a range of different THC responses we used four combinations of CO_2 scenarios and HS values. These are A1FI_000, A1FI_090, B2_000, and Azar_035. The numbers denote the value of HS, where e.g. 090 stands for $HS{=}0.09 \times 10^6 m^3 s^{-1} K^{-1}$. This latter value, applied to the A1FI scenario (hence the label A1FI_090), is extremely high since it leads to a maximum freshwater flux of about 0.5 Sv. It was chosen to induce a shutdown of the THC in order to study its consequences. In the A1FI_000 scenario, by contrast, the freshwater fluxes were not altered. Therefore, by taking the difference A1FI_090 - A1FI_000, we could study the net effect of a THC shutdown while still accounting for the fact that it happens in the course of global climate change. The other two scenarios show how the model reacts to weaker CO_2 and freshwater forcing. In the Azar scenario, an additional freshwater flux of $0.035 \times 10^6 m^3 s^{-1} K^{-1}$ was applied (Azar_035), and the B2 scenario was left unchanged (B2_000).

Fig. 2b shows that the THC markedly weakens in the A1FI_090 case. Within the 21st century, it reduces by two thirds, and does not recover over the following centuries. In its three-dimensional extent it is then virtually inexistent (not shown), and therefore we call this case “THC breakdown” or equivalently “THC shutdown”. In the A1FI_000, B2_000, and Azar_035 cases, the THC is reduced by 15% to 30%, and fully recovers during the 22nd and 23rd century. We note that the THC weakens anyway under global warming scenarios, even without any additional freshwater input, as the A1FI_000 and B2_000 cases show. The effect of the additional freshwater input in A1FI_090 is thus an enforced THC weakening that leads to the breakdown around the year 2100. A direct comparison between the two scenarios A1FI_000 and A1FI_090 shows the net effect of a THC breakdown triggered by the additional freshwater input (by taking the anomaly A1FI_090 - A1FI_000). **FIG. 2**

The experts’ views differ from the model results to a certain degree. 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 modelling, like observational and paleo-data. For instance, in case that the CO_2 equivalent concentration rises to 1120 ppmv by 2140, 4 of 12 experts expect a shutdown of the THC by 2200 (best guess estimate). Five experts even think that a long-time absence of the THC at least until 2300 is possible. The experts are clearly more pessimistic than climate models, as in the Climber-3α scenarios a shutdown occurs only for a huge freshwater input in addition to the effect of global warming. Likewise, many other models (Gregory et al., 2005; Meehl et al., 2007) do not show a THC shutdown in global-warming-only scenarios without mass loss from the Greenland ice.

2.2. Impacts on the Ocean

In assessing the impacts we need to distinguish between the consequences of global warming in general and the consequences of a THC shutdown. During the 21st century the THC weakens in all scenarios (Fig. 2b), even if no additional freshwater forcing is applied (e.g. case B2_000). This THC weakening especially concerns the Nordic Seas. Reduced deep water formation goes along with sea surface temperature (SST) falling several K below 1989 values (Fig. 3a) for a few decades in the mid-21th century. However, in the region west of Svalbard, deep water formation is enhanced and SST rises by up to 3 K. The THC extends more northwards, with subsequent changes in the surface currents throughout the Nordic Seas. **FIG. 3, FIG. 4**

A full THC shutdown occurs in our A1FI_090 scenario in the 22nd century. One outstanding impact of a THC shutdown is a rising sea level all over the North Atlantic (Levermann et al., 2005; Vellinga and

Wood, 2008). For the A1FI scenario, the sea level rise resulting from a THC shutdown (i.e. the difference A1FI_090 - A1FI_000) can amount to 80 cm on the shores of Europe and Russia and to 50 cm in Greenland and eastern Canada by 2150 (Fig. 4). This effect adds up to the global thermal sea level rise that will continue during the next centuries. This regional sea level change is due to changes in the slope of the sea surface, which is needed to balance the Coriolis force associated with ocean currents. The rise in the North Atlantic is compensated by a drop mainly in the Southern Ocean. The global mean sea level change due to this dynamic effect is zero. In the elicited opinions of four experts, in the case of a THC shutdown the sea level rise could even exceed 1 m (in a scenario that considers a shutdown without ongoing global warming).

A further strong impact of a THC shutdown is the total disappearance of winter-time deep mixing in the North Atlantic. Presently the waters are mixed from the surface to a depth of 2000 m and more in many winters (Fig. 5a) in the Labrador Sea (not reproduced by Climber-3α) and the Nordic Seas. This mixing is essential for deep water formation and for the supply of nutrients to the upper layers. Global warming (scenario A1FI_000) reduces this mixing drastically (Fig. 5b). In the THC shutdown scenario A1FI_090 deep mixing stops completely (Fig. 5c), with further impacts for the marine ecosystem (see sec. 3.1). **FIG.**

In a coarse grid ocean model like Climber-3α, regional changes of **5** the currents have to be interpreted with care. Still we would like to note that the changes of the currents due to the THC shutdown in 2150 (Fig. 4) show a weakened subpolar gyre and a reduced inflow into the Barents Sea along the Norwegian coast.

2.3. Impacts on the Atmosphere

Again we need to distinguish between the consequences of global warming in general and the consequences of a THC shutdown. In all scenarios there appears a net cooling of the sea surface (with respect to 1989) in the Nordic Seas (Fig. 3a). This net cooling occurs transiently for a few decades in the mid-21st century. It is related to a shift and a weakening in the deep water formation regions in the Irminger and Nordic Seas (see Fig. 5).

The impact of the THC breakdown in the 22nd century on surface air temperatures is essentially confined to the Northern Hemisphere. The relative cooling (after having subtracted the strong global warming trend) is around 1 K in most parts of Europe (Fig. 3b), with coastal regions in northwestern Europe being affected most strongly (2.5 K cooling in Svalbard). The overall pattern is qualitatively similar to the AOGCM simulations by Stouffer et al. (2006) and Vellinga and Wood (2008). Global mean surface air temperature drops by about 0.2 K in response to the THC shutdown (Fig. 2c).

Since the land surface grid of Climber-3α is coarse (7.5° latitude by 22.5° longitude), a statistical downscaling to a 0.5°×0.5°grid was applied for driving the vegetation and agriculture model and to look at regional features. See Appendix for a detailed description. We preferred downscaling over using a regional climate model because the downscaling algorithm consumes much less computing time, thus making it feasible to drive the vegetation model with centuries-long climate scenarios.

The results from the downscaling (Fig. 6) show some distinct features. Again, we show the relative changes after having subtracted the global warming signal. For the temperature signal (Fig. 6a), it appears that some northern and eastern European regions are not affected by a THC shutdown. Coastal parts of western Europe, by contrast, show a clear signal of relative cooling as expected from the proximity to the Atlantic. Concerning precipitation (Fig. 6b), a THC shutdown leads to strong reductions in northeastern Europe, while some coastal regions around the North Sea receive more. Southeastern Europe and Turkey would receive more precipitation as well, while southern Italy and Greece would receive less. However, due to the linearity of the applied downscaling algorithm, statements on precipitation changes have to be made with reservation. A comparison with THC breakdown simulations from an AOGCM (Vellinga and Wood, 2008) reveals differences: in that model, precipitation increases occur only over the Mediterranean, and large parts of Europe experience drier conditions. **FIG. 6**

3. Impacts on Marine Ecosystems

3.1. Plankton and Carbon Cycle

The North Atlantic Current transports not only heat but also nutrients to the subpolar North Atlantic. According to estimates by Ganachaud and Wunsch (2002), there is an average northbound flux of nitrate and phosphate into the high latitudes of the North Atlantic at 47°N on the order of 10 ± 35 and 1.1 ± 2.5 kmol s^{-1}, respectively. Although the Nordic Seas are relatively depleted in macronutrients such as phosphate and nitrate [the concentrations of the latter rarely exceed annual mean sea surface values of 8.0 μmol/L (Conkright et al., 1994)], a pronounced phytoplankton bloom during spring with maximum chlorophyll concentrations of more than 1.0 mg m^{-3} is observed (Falkowski et al., 1998). Deep mixing during winter and early spring (see Fig. 5) replenishes the utilized nutrients at the sea surface. The other main source that provides the Nordic Seas at upper intermediate depth with macronutrients is the North Atlantic Current that enters at the Faroe-Shetland channel. The nutrient-rich current, which then follows the Norwegian coastline as the Norwegian Atlantic Current, forms a relatively warm and salty shallow layer in the upper ocean. A reduction or even the cessation of this ocean current owing to global warming could weaken or disrupt the nutrient supply to the Nordic Seas.

The present investigation aims at studying the impact of the reorganization of the THC under global warming, driven by elevated atmospheric CO_2 levels as provided by the high-emission A1FI_00 and A1FI_090 scenarios, on the marine biological net primary production (NPP; defined as the gross photosynthetic carbon fixation minus the carbon losses by respiration) and on zooplankton stocks in the North Atlantic. Since NPP is the first step in the food chain of marine organisms, its decline could have severe consequences for fish stock and fisheries.

For the purposes of this study we have coupled Climber-3α with the marine ecosystem model by Six and Maier-Reimer (1996). The model prognostically computes the kinetics of nutrients, phytoplankton, zooplankton, dissolved organic matter and detritus (the non-living particulate organic material). In each integration time step the sources and sinks of these substances, called biogeochemical tracers, were calculated and subsequently transported by the three-dimensional velocity field provided by the ocean circulation model MOM-3 (Pacanowski and Griffies, 1999). It should be noted that we have implemented a new tracer advection scheme to be employed in MOM-3 as a part of Climber-3α (Hofmann and Maqueda, 2006). Traditional numerical tracer advection schemes in OGCMs tend to produce spurious mixing and/or over- and undershoots in tracer fields, leading to distorted physical and biogeochemical properties. The second-order moments (SOM) tracer advection scheme employed in Climber-3α avoids the occurrence of such problems by greatly reducing spurious diffusive effects.

The model is integrated forward in time starting from a spin-up state representing conditions in the year 1797. The spin-up involves simulating 1000 years of constant climate to allow the model to reach a steady state. Subsequently, the model is integrated forward in time starting at year 1797 until 1989 by using observed atmospheric CO_2 equivalent concentrations as described in sec. 2.1, followed by an integration for further 411 years until 2400 under the A1FI_000 and A1FI_090 CO_2 equivalent concentration scenarios. **FIG. 7**

Compared to observations (Antoine et al., 1996; Gregory et al., 2003; Behrenfeld et al., 2006), Climber-3α simulations of the present day NPP (1990) in the North Atlantic appear to reveal too low values by at least a factor of 2. The reason for this underestimation is a too strong density stratification notably in the Labrador and Greenland Seas. However, this deviation has to be seen in the light of the uncertainty of observational NPP data from remote sensing, which is very high. In the North Atlantic values of NPP from Antoine et al. (1996) and Gregory et al. (2003) deviate by more than a factor of 3, caused by the different algorithms applied. There is also a considerable spread among the NPP values in models. For instance, Schmittner (2005) show NPP values in the Nordic Seas (their Fig. 2) that are too low as well, similar to our results. Within this context we believe that our simulated numbers of NPP in the North Atlantic are acceptable such that we can provide reasonable estimates at least of the relative changes.

The highest model values of NPP, phytoplankton- and zooplankton concentration in the North Atlantic are localized off the Canadian coast in the vicinity of the Grand Banks and in the South East Irminger Sea. Simulated present day values of NPP in the Irminger Sea vary between 0.33 to 0.38 mol N $m^{-2}yr^{-1}$. In the Norwegian Sea this value is unrealistically low and stays almost below 0.15 mol N $m^{-2}yr^{-1}$ (see Fig. 7a).

Since in our extended A1FI scenarios the greenhouse gas concentrations peak around 2150, the analysis of our model runs primarily focuses on this year. Using the high-emission scenarios A1FI_000 and A1FI_090, the marine NPP drops by more than 70% in the North Atlantic compared to values in 1990 (Fig. 7). The scenario A1FI_090, which causes a breakdown of the THC up to 2150, leads to the strongest reduction in NPP (Fig. 7c), whereas with A1FI_000 the effect is slightly less pronounced. It should be noticed that the simulated decrease in NPP is not simply caused by a reduced lateral transport of nutrients along the path of the North Atlantic Current, as anticipated, but also by the strong reduction of mixed layer depths (Fig. 5). Increasing SSTs tend to make the northbound water masses in the North Atlantic Current less dense and inhibit convective mixing processes in the Nordic Seas, leading to shallower mixed layer depths. As a consequence, the reduced replenishment of nutrients, usually provoked by the vertical entrainment of nutrient-rich subsurface waters into the euphotic zone associated with mixing processes, entails a weakening of the NPP. (The euphotic zone is the uppermost ocean layer in which the intensity of the incoming light from the surface is sufficient enough to allow for photosynthesis.) We stress that in the simulations presented here the impact of global warming on the NPP is clearly stronger than that of a THC breakdown. This is important to note because in a study that considered only a THC breakdown and not a concomitant global warming (Schmittner, 2005), a NPP reduction by more than 70% was diagnosed. In that study the THC breakdown caused the reduction of mixed layer depth and the NPP decrease. By contrast, here this is due to the warming of the mixed layer in the course of global warming.

A global consequence of global warming is a reduced CO_2 uptake by the oceans (Sarmiento et al., 1998). There are three reasons for this: Higher SSTs lead to lower solubility of CO_2 in seawater (note however the regional and transient sea surface cooling as in Fig. 3a); a shallower mixed layer will take up less CO_2; and with a reduction in deep water formation less CO_2-rich water is transported to depth. The reduced CO_2 uptake is a positive feedback: the CO_2 not taken up by the ocean will contribute to the global warming and further suppress the uptake. A THC reduction might slightly aggravate this positive feedback (Zickfeld et al., 2008).

Simulated annual mean zooplankton concentrations in the North Atlantic in 1990 are realistic and compare quite well with the sparse observational data. According to the latter, typically observed values hover around 1.0 to 2.0 μmolC/L (Buitenhuis et al., 2006). The model yields values of about 1.4 μmolC/L in the southeastern Irminger Sea (not shown). Owing to the elevated atmospheric CO_2 levels and their impact on the mixed layer depth, NPP and the THC, the size of the zooplankton stock is projected to drop remarkably by the year 2150 and on to 2400 (not shown). In 2150 annual mean zooplankton concentrations reduce to values of about 1.0μmolC/L when applying the

A1FI_090 and A1FI_000 scenarios. In 2400 the zooplankton concentration in the A1FI_000 scenarios is lowest and even falls below 0.6 μmolC/L, whereas in A1FI_090 simulated zooplankton concentrations show values of about 0.8 μmolC/L. Interestingly, as shown in Fig. 7a-c, our results reveal that the main reduction in NPP and zooplankton stocks in the North Atlantic is caused by the reduction of the mixed layer depth as a consequence of global warming. Compared to that, the impact of a THC shutdown is only of minor importance.

We should note that the zooplankton model used here is fairly simple, including only a single component. With this caveat, we conclude from the above results that even under the A1FI_000 scenario, without a THC breakdown, the NPP, and hence the size of the zooplankton stock, might become too low to sustain the fish stocks in the North Atlantic at current levels by 2150.

3.2. Fish

The thermal regime of the ocean is influenced by climate change through two main natural processes occurring in the ocean: by advection of water masses and by ocean-atmosphere heat exchange. The ecosystem of the Nordic Seas and the Barents Sea is dominated by these two processes, i.e. through temperature in the mixed layer and through advection of zooplankton-rich water masses (Sundby, 2000). Therefore we focus on their changes in the following. We have explicitly modelled the impact on one specific species by considering changes in larval growth and transport of Arcto-Norwegian cod (ANC). However, climate variables influence marine organisms indirectly as well as directly by affecting trophic levels (i.e. positions in the food chain) above and below. Impacts on other fish species and trophic levels are therefore included, by drawing conclusions from the existing body of literature. We note however that the impacts of THC changes on fish and fisheries, to our knowledge, have not been studied so far. The literature to which we refer in this section mostly covers the impacts of climate and ocean variability in the past.

3.2.1. *Climber-3α and BCM*

During the 21st century, the Climber-3α scenarios display a mixed layer temperature increase in the northern North Atlantic of 1 K (Azar_035, B2_000) to 4.5 K (A1FI_000, A1FI_090). An exception are the central Nordic Seas away from the coasts, where we see a mixed layer temperature decrease of up to 1 K in the course of the 21st century (see Fig. 3a), such that in the end of the century the SST again reaches the level of 1989 (Azar_035, B2_000) or has already increased by 3 K (A1FI_000, A1FI_090). At the same time the THC, with its major deep water formation regions in the Nordic Seas and in the Irminger Sea, is transiently reduced by up to 30% (Azar_035, B2_000, A1FI_000) or permanently by about 80% (A1FI_090).

If we aim at assessing the impact of climate change on regional marine ecosystems like in the Nordic and Barents Seas, a conceptual problem appears. Earth system models of intermediate complexity like

Climber-3α do not sufficiently resolve regional features like the Barents Sea and a downscaling of Climber-3α data is therefore not feasible for this purpose. Our approach is therefore to use output from another climate model, with a higher spatial resolution in the northeastern North Atlantic, and to subsequently downscale this output to an even finer-meshed regional ocean model. Specifically, we use a freshwater experiment performed with the Bergen Climate Model (BCM; Furevik et al., 2003) downscaled to a regional ocean model (ROMS; Haidvogel et al., 2008, `www.myroms.org`) as defined below.

While the resolution of Climber-3α is 3.75° for the ocean and 7.5°×22.5° (latitude, longitude) for the atmosphere, BCM has a finer resolution of about 1°×2.5° (latitude, longitude) for the ocean and 2.8° for the atmosphere. ROMS resolves oceanographic details on a scale of about 5 to 10 km, adequate for representing the inflow of Atlantic Water to the Barents Sea and the transport of larvae and pelagic juveniles of fish, the latter being the actual aim here.

In the BCM simulation the river runoff to the Nordic Seas and the Arctic ocean was increased by a factor three over the simulated present day value, keeping all other initial- and boundary values at the present day level (Otterå et al., 2004), as simulated in a 300 year control run with BCM (Furevik et al. 2003). Hence, there were no increases in greenhouse gases and consequently global warming was not taken into account. The freshwater input led to a decrease of the THC by 35% (from 18 to 12 Sv), along with a reduced inflow into the Barents Sea. This constitutes an important link between the BCM scenarios and the Climber-3α, as the latter also show a THC weakening of about the same magnitude in the mid-21st century and a reduced inflow into the Barents Sea.

Moreover, the response pattern in sea level pressure on the THC weakening might well be similar in both models. In BCM, the increase in the river runoff gave a larger sea ice extent in the Barents Sea. The model results indicate that this caused a weakening in the quasi-stationary atmospheric low pressure at the entrance to the Barents Sea. Consequently, the inflow of Atlantic Water to the Barents Sea was reduced by more than 70 %, which is reflected in a reduced ocean temperature of about 3-4 K, while the West Spitsbergen Current (WSC) increased proportionally (see Fig. 1 for the locations of the Barents Sea and the West Spitsbergen Current). In Climber-3α, the reduced flow to the Barents Sea is related to a lower sea level pressure in the central Nordic Seas following the cooler SST there. As the Climber-3α scenarios show, such a transient temperature reduction could be compensated by the effect of global warming by the end of the 21st century, depending on how the temperature increase is distributed globally. The point here is however that the sea level pressure response and thus the inflow into the Barents Sea are thought to be similar in both models. In addition, the THC weakening is quite similar in the BCM scenarios (being freshwater hosing scenarios) compared to the Climber-3α scenarios (being driven by greenhouse gas scenarios plus a freshwater flux). Obviously, great caution is required when assessing the marine ecosystem implications of the Climber-3α scenarios by downscaling the

BCM scenarios. However, the approach taken here still may provide us with indications of what regional ecosystem responses are to be expected.

3.2.2. *The dynamics of the key zooplankton species Calanus Finmarchicus*

The life cycles of zooplankton are very complex. No satisfying models of trophic coupling to zooplankton, particularly to higher trophic layers, exist to date. Therefore, to estimate the impacts of changing climate variables, we have to rely on drawing conclusions from literature (Planque and Fromentin, 1996; Fromentin and Planque, 1996; Sundby, 2000). *C. finmarchicus* is the key zooplankton species of the northern North Atlantic with the core production regions in the Subarctic Gyre and in the Nordic Seas. From these deep-sea core production areas *C. finmarchicus* is advected onto the surrounding shelves. This is an important food supply for larval and juvenile fish and for adult pelagic fish inhabiting the shelves, i.e. the North Sea, the Norwegian Continental Shelf and the Barents Sea. Hence, changes in circulation pattern as well as mixed layer temperature changes will affect abundance and distribution of *C. finmarchicus* and the shelf sea organisms at higher trophic levels that depend on the zooplankton import. In the core region of *C. finmarchicus*, the Norwegian Sea, a mixed layer temperature reduction will result in a southward displacement of the northern boundary located towards the Arctic regions. In this boundary region the number of generations per year will become reduced to less than one and the egg production will diminish. This will reduce the total production of the species. Conversely, an increase in mixed layer temperature will displace the habitat boundary northwards and possibly establish the species into the Arctic Basin. A higher mixed layer temperature has the potential of increasing the stock, unless the food supply becomes limited. However, a reduced Atlantic Water inflow into the Barents Sea will do exactly this: it reduces the abundance of *C. finmarchicus* in the region independent of mixed layer temperature changes.

3.2.3. *Fish*

The recruitment patterns of Northeast Arctic haddock and Norwegian spring-spawning herring are similar to those of the Arcto-Norwegian cod (Sundby 1994) because (1) they spawn at the Norwegian shelf at the same time during spring, (2) they rely on the same food items during the early larval and juvenile stages and (3) the are all advected as pelagic larvae and juveniles with the Norwegian Coastal Current and the Norwegian Atlantic Current into the Barents Sea. This implies that we expect similar response to climate change for all three species. Arcto-Norwegian cod (ANC) is, however, used as a model fish since there already exists a great deal of knowledge on the relations between ANC and climate.

Several studies have shown that there is a close link between the abundance and individual size of ANC at the 0-group (younger) stage and the year class strength of the 3-group (elder) fish. The approach taken is therefore a modelling study on the impact of a reduced THC on larvae and pelagic juveniles of ANC, supported by analysis of existing data on cod and climate.

3.2.4. *Spawning areas of Arcto-Norwegian cod*

The Arcto-Norwegian cod occupies distinct spawning areas along the Norwegian coast, with the Lofoten as the major spawning area (Sundby and Godø, 1994), and the time of spawning each year fixed to March and April (Ellertsen et al., 1989). A recent investigation (Sundby and Nakken, 2008) shows that long-term shifts of the cod spawning areas are linked to the multi-decadal climate variability: in warmer periods the spawning areas shift northwards , while during cold periods they are shifted southwards. However, with a general increase in temperature, but a potentially colder Barents Sea, the northward shift of spawning grounds is limited to the entrance to the Barents Sea. Hence, Lofoten is likely to remain as the most important spawning area within the first half of the 21st century (Sundby and Nakken, 2008).

3.2.5. *Larval growth and transport – implications for year class strength*

Predicting the impact of a reduced THC on ANC requires a model system able to recapture the transport and growth of ANC from spawning in Lofoten until the 0-group fish settle in the Barents Sea. Such a model tool is presented and validated in Vikebø et al. (2005). ROMS is set up for the habitat of ANC, simulating the transport of larvae and juveniles while keeping track of the individual temperature histories. This enables calculation of temperature-dependent growth, using temperature-growth relations taken from Otterlei et al. (1999) and Björnsson and Steinarsson (2002). We forced ROMS with the output from the BCM freshwater experiment (Otterå et al., 2004) described in sec. 3.2.1. The reduced THC results in (Fig. 8; see Vikebø et al., 2006, for a comprehensive description):

1. An increased flow west of Spitsbergen, while the inflow to the Barents Sea is considerably reduced.

2. A southward and westward displacement of the polar front in the Barents Sea.

3. A southward and westward shift in the distribution of cod year classes from the Barents Sea onto the narrow shelves of Norway and Svalbard.

4. A reduced individual growth of the pelagic juveniles with subsequent poorer year classes.

5. An increasing number of larvae and juveniles advected towards the western parts of Spitsbergen and possibly further into the Arctic Oceans where they are unable to survive.

FIG. 8

The results presented here rely on the assumption that the marine organisms of the ecosystems have time to adapt to the changes, i.e. changes on approximately decade scales. Abrupt changes, however, may lead to irreversible and less predictable changes of the marine ecosystems (Ottersen and Stenseth, 2001). The ROMS results assess the effect of a reduced THC without including an increased greenhouse gas level. The main result, as we see it, is its focus on how regional processes may modify the large scale signals, potentially introducing large spatial gradients in environmental conditions affecting marine life.

3.2.6. *Implications for the North Sea ecosystem*

The marine ecosystem of the northern North Sea has been dominated by boreal zooplankton species as *C. finmarchicus* while the southern part has been dominated by *C. helgolandicus*. The shift to a warmer climate, as observed from the cold 1960s and 1970s to the present warm state, has resulted in a considerable northward shift of the entire groups of zooplankton from the warm-water species to arctic species (Beaugrand et al., 2002). As a consequence, also *C. finmarchicus* and *C. helgolandicus* have shown a northward shift, with the result that temperate zooplankton species like *C. helgolandicus* are now dominating the North Sea. Along with this shift in zooplankton species a shift in fish species has occurred. The abundance of boreal species, like cod and haddock, has decreased during the recent 30 years of warming, while temperate species, like sardine and anchovy, has increased. Presently, the mechanisms behind the changes of species are unclear. It might be a result of the change in temperature itself as indicated by Beaugrand et al. (2002), or it might as well be linked to other associated climate variables like changes in advection and stratification. A global warming is likely to continue this trend, but caution is needed when extrapolating beyond the level of natural variations. Another complicating factor occurs if the THC at the same time is reduced. It has recently been shown (Sundby and Nakken, 2008) that the inflow of *C. finmarchicus* rich water to the North Sea is inversely correlated with the inflow of Atlantic Water to the Nordic Seas. Hence, a global warming and a reduced THC cause an enhanced inflow of *C. finmarchicus* rich water to a North Sea with *C. helgolandicus* favorable waters. This is assuming global warming has a larger impact on North Sea temperature than a THC reduction. Probably the THC reduction would dominate the North Sea temperature transiently, and if this results in a decrease in temperature it is likely that the zooplankton and fish species would be more dominated by boreal species which were also abundant during the cold period in the 1960s and 1970s.

4. Impacts on Terrestrial Ecosystems

Global consequences of a THC shutdown on land-borne ecosystems were studied by Higgins and Vellinga (2003) based on the scenario by Vellinga and Wood (2002). In their simulations greenhouse gas concentrations were kept stable. Therefore no global warming occurred, and hence the THC shutdown impacts were analysed directly. The resulting response of terrestrial ecosystems is attributed mostly to changes in the hydrological cycle rather than to changes in temperature. Vegetation changes are particularly strong in northern South America, where the rainfall belts shift, and in the Sahel zone, where desertification amplifies. Focusing on regional climatic impacts of a THC breakdown in England, Higgins and Schneider (2005) showed that ecosystem responses can depend heavily on patterns of seasonal temperature change.

The effects of climate change and atmospheric CO_2 changes during the 21st century on terrestrial ecosystems have been investigated at regional and at global scales using Dynamic Global Vegetation Models (DGVMs; Cramer et al., 2001). DGVMs simulate the distribution of the potential natural vegetation and the coupled carbon and water fluxes like net primary productivity (NPP, defined as photosynthetic assimilation minus growth and maintenance respiration), heterotrophic respiration (i.e. respiration from decay processes in the soil), and evapotranspiration. Most simulations indicate a likely increase of productivity due to the enhancing effect of CO_2 fertilization on photosynthesis, but regional increase in water stress may strongly reduce the productivity. In most models, heterotrophic respiration also increases in response to warming. Therefore, depending on the climatic scenarios and on the region studied, land ecosystems may become either a source or a sink of carbon in the future for global simulations, as shown by Schaphoff et al. (2006) using the Lund-Potsdam-Jena DGVM (LPJ, Sitch et al., 2003). Zaehle et al. (2007) found a similar uncertainty in Europe for several combinations of climate and land use scenarios.

In order to consider the dominant role of agricultural crops and managed grasslands in European landscapes, we use LPJmL (LPJ for managed Land; Bondeau et al., 2007) to analyse the impacts of global warming and a THC shutdown on land ecosystems in Europe for the

A1FI_000 and A1FI_090 climate scenarios described in sec. 2.1. Besides natural vegetation, LPJmL model simulates crop yields and harvested carbon due to land use and land use change. In order to operate on an appropriate spatial grid for the assessment, LPJmL was driven with the above two scenarios using the downscaling routine described in the Appendix.

4.1. Ecosystem productivity

As compared to the reference period (1961-1990), the dominant effect of both scenarios on land ecosystem NPP during the period 2121-2150 is a significant productivity increase which is primarily due to the CO_2 fertilization effect (Fig. 9). Some areas experience however strong to dramatic reductions of precipitation (see sec. 2.3 and Fig. 6) limiting NPP strongly or even bringing it down to zero, indicating vegetation die-back. Such areas are found in southern Finland, northwestern Greece, and southern Spain.

The general pattern is the same for A1FI_000 and A1FI_090 scenarios, so THC shutdown itself causes no qualitative differences. However most places with reduced precipitation under A1FI_090 as compared to A1FI_000 are less productive under A1FI_090 (Fig. 10). The strong NPP decrease simulated for 2121-2150 in the central Baltic is even stronger with a THC shutdown, while the NPP increase along the southern shore of the Baltic Sea, along the west shore of the Black Sea, in south Greece and in Sicily is slightly reduced. On the other hand, in most places with a simulated increase of NPP for 2121-2150 and wetter conditions under A1FI_090, NPP increases even more with a THC shutdown (most areas around the North Sea, northeastern Spain, Italy, eastern Europe, Turkey). In eastern Europe, the precipitation decreases are less pronounced under A1FI_090, therefore the NPP reduction is slightly moderated.

The same patterns are visible at the end of the simulation (2370-2399), with a stronger signal caused by a THC shutdown (not shown). However a new effect appears, connected with a relative cooling around the North Sea: Scotland, western and northern Norway increase their productivity less under A1FI_090. Nevertheless, the changes due to a THC breakdown are clearly smaller than those due to the increasing CO_2 concentrations. In a different study using a coarser model resolution, Zickfeld et al. (2008) show a widespread decline of NPP over Europe in 2500 after a THC shutdown. **FIG. 9, FIG. 10**

4.2. Carbon balance of land ecosystems

In order to assess the future carbon balance of land ecosystems we use LPJmL to analyse the release of carbon, either through soil respiration or through harvest (not shown). Apart from areas with extremely low precipitation (see Fig. 6), simulated soil respiration in 2121-2150, compared with 1961-1990, increases everywhere in response to warming. The harvested carbon increases, too, following the NPP increase. The amount of removed carbon from respiration and harvest grows stronger than the amount of carbon that is sequestered in the ecosystem (vegetation, litter, and soil carbon). On balance, European land ecosystems therefore become a carbon source, although cooler areas where the NPP is currently temperature-limited (Scandinavia, Alps, eastern Turkey) are still sinks because the soil respiration increase is not as strong as the NPP increase.

The influence of the THC shutdown in A1FI_090 on the carbon balance is minor. If we compare the A1FI_000 and A1FI_090 simulations in the 2121-2150 period, then notable (yet small) differences appear only in northern Europe. There, under a THC shutdown LPJmL sequesters more carbon. However this does not apply to the areas mentioned above that become very dry (e.g. southern Finland) in A1FI_000 and even drier in A1FI_090. At the end of the simulation in the years 2370-2399 differences appear only in southern Finland indicating a carbon sink under warming alone but a carbon source with THC weakening. We did not perform any uncertainty analysis, however these results differ from those of Zickfeld et al. (2008), who wind a weaker carbon sink in northern Europe and a stronger sink in central and southern Europe. The difference even in sign in some regions (e.g. western Scandinavia) between the two studies indicates the high uncertainty in the response of terrestrial ecosystem processes to a THC shutdown.

5. Socioeconomic Impacts

5.1. Fishery

The impacts of THC changes on fish stock and fisheries have not been studied so far. For the present study, the four climate scenarios outlined in sec. 2.1 were applied in a bio-economic fisheries model considering the age-structured stocks of the interacting species Northeast Arctic cod (*Gadus morhua*) and capelin (*Mallotus villosus*). Annual catch levels and profits of the associated fleets were determined for a time horizon of one century (2000 to 2100). The fishermen could either follow an adaptive harvesting strategy (Link and Tol, 2006a) or one that attempts to maximize profits over a given number of consecutive fishing periods (Link et al., 2004), which makes it possible to analyse the impact of the fishermen's behavior in scenarios of changing climate. These two strategies differ in the way in which information on stock development is incorporated. With adaptive harvesting, the fishing effort is adjusted depending on whether actually realized catches fall short of or exceed a previously set target catch size, which is based on the maximum sustainable yield. Information on previous harvest success is carried over to a certain extent. Profit maximization considers only the current situation and looks ahead for a given number of fishing periods. Information on past harvest success is disregarded. Therefore, the difference between two successive fishing efforts can be much greater with the profit-maximizing harvest strategy than with the adaptive strategy.

Global warming is assumed to have a generally beneficial influence on stock development by improving chances of good recruitment year classes (Link and Tol, 2006b), while a reduction in THC strength is considered to have a negative impact on the stocks due to lower natural survival rates of the youngest age class(es) as shown in sec. 3.2.5. Due to the underlying economic assumptions we could not extend the runs of the bio-economic fisheries model until 2150. The reduction of the overall THC strength was taken as a proxy for changes of the current systems in the Lofoten area where cod spawns. The results presented in the following comprise the 21st century, taking global warming and a declining THC into account.

An important factor influencing the success of fish stock development are the hydrographic conditions in the spawning areas at time of spawning. During the 20th century, the temperature has generally varied between 2 and 4°C (cf. Link and Tol, 2006b). The temperature signal from the Climber-3α scenarios is added to the natural annual variability—which is assumed to remain in a constant range throughout the simulations—utilizing the spring temperature of the top two model ocean layers in the area around the Lofoten Islands. In the A1FI_000 and A1FI_090 scenarios, this water temperature in the spawning grounds increases by 2.5 to 3.5°C during the 21st century, with a clear trend emerging only in the second half of the simulation period, thus improving chances of recruitment success of both species. By contrast, in the Azar_035 and B2_000 scenarios, the mean temperature remains practically unchanged while the decadal variability increases during the second half of the century. **FIG. 11**

As shown in section 3.2, a THC shutdown worsens the chances of survival of the youngest age classes of cod. Their survival rate depends on THC strength in the bio-economic model and is parameterized on the basis of the results presented in sec. 3.2 (Link and Tol, 2006b). It is assumed that the dependency of fish survival on circulation strength remains intact not only in the stable temperature conditions of the beginning of the 21st century but also in the period of warming of the spawning grounds in the latter half of the simulation period. In the A1FI_090 scenario, the THC strength declines by 80% until 2100, whereas in the other three scenarios the THC declines by only one quarter to one third.

The simulation results indicate that the positive influence of warming on cod stock dynamics in the A1FI_000 scenario leads to stable annual cod catches throughout the simulation period (Fig. 11). By contrast, the negative influence of a THC shutdown on the stock development leads to drastically reduced cod landings in the A1FI_090 scenario, in which average annual landings decrease by up to three quarters, regardless of the harvesting strategy employed. In the Azar_035 and B2_000 scenarios, there is a slightly declining trend of cod catches over time with a somewhat higher variability in the Azar_035 scenario.

The interannual variability (not shown) is larger if a profit-maximizing harvesting strategy is employed since the fleet utilization can vary freely from one fishing period to the next. With an adaptive harvesting strategy, the change in fleet utilization between two consecutive fishing periods is limited to 10%. This leads to a much more stable development of economic activities. Average annual cod catches are higher for adaptive harvesting strategies than for profit-maximization. This is because the optimization of profits over a time period of four years allows the fishermen to postpone harvesting activities to improve future profits.

A look at the profitability of the cod fishery shows that it can maintain a high level of profitability under warmer conditions in the spawning grounds only if this warming coincides with an intact THC, as the negative influence of a THC breakdown on stock dynamics together with continued fishing pressure reduce the standing stock biomass such that significant cuts in harvesting activities become necessary. In case of a THC breakdown, this would render the fishery unprofitable in the second half of the century (Fig. 12). A more detailed analysis of the scenarios and an assessment of the impacts on the Barents Sea fishery of capelin, which is the most important prey of cod, are given in Link and Tol (2006b). We note that these results are based on idealized and purely economical assumptions. However, management measures such as a total allowable catch of fish are taken into account and are set on the basis of previously observed management decisions. This considerably constrains the results in the simulations, preventing the collapse of the cod stock regardless of the fate of the THC. Without management considerations in the model, profit maximization would be rather unsustainable, posing a distinctly greater threat to the long-term survival of the fish stocks. **FIG. 12**

In the long run, the profit-maximizing harvesting strategy leads to higher returns from fishing in all scenarios despite slightly lower average landings. This is because of the development of the fleet sizes, which tend to be lower under profit maximization, improving the cost efficiency of the fishery and therefore its profitability (Link and Tol, 2006b). Furthermore, the adaptive harvesting strategy, which creates initially higher returns in times of stable environmental conditions, tends to be too slow in adjusting to higher environmental variability in the latter half of the century due to the limit on the extent to which the fishing effort may change from one harvest period to the next. This causes average annual profits to decline in the Azar_035 and B2_000 scenarios. Relaxing the constraints that govern the speed of the adaptation process would improve the success of this kind of strategy; however, this would also increase the risk of the strategy becoming unsustainable. With profit maximization, large shifts in fishing effort can be performed more readily. This makes it is possible to limit the reduction in profitability that arises from more difficult harvesting conditions due to an increased temperature variability coinciding with a slightly weaker THC.

Since fishery accounts for 2% of the Norwegian gross national product and 6% of the exports, economic losses from unprofitable cod fishery are within the usual macro-economical fluctuations and hence do not appear to be serious. One would however expect public opinion to pay quite a lot of attention to such a development. For instance, in some regions where fishery is the main employer, a large amount of lost jobs might be perceived as severe.

5.2. Crop production

Changes in production were simulated by LPJmL (see model description in sec. 4) for temperate cereals (wheat, barley, oat, rye), being the major economic crops in Europe. Total crop production depends on yield (productivity) as well as on the area cultivated. Previous studies with crop models have shown that crop suitability increases particularly in the northern latitudes because of warming (Fischer et al., 2002). In contrast, crop suitability might be reduced in the Mediterranean region as a consequence of increased water stress.

Analysing the changes in crop productivity only for the present distribution of temperate cereals might be misleading since their future optimum distribution to which farmers could adapt their activities would not be considered. In this study, we do not consider land use change scenarios in detail (cf. Rounsevell et al., 2006 and Zaehle et al., 2007), but we need to avoid biased results due to unrealistic land use, which would arise from considering the actual distribution of temperate cereals throughout the simulation (e.g. Fischer et al., 2005, Fig. 3). Assuming that any future change in land use will most likely occur inside the total area of actual arable and grazing lands delineated by the

Corine Land Cover classification (EEA, 2000), we therefore compute the potential yields of temperate cereals for this area.

We do not assume yields to increase due to technological progress (in management and/or plant breeding): European farmers mostly employ high-input agricultural systems (e.g. strong fertilizer application and pest control), and potential yields could well approach their biological limits (Ewert et al., 2005). The choice of the most appropriate variety for local climate conditions (with respect to growing season) is made in LPJmL by computing the sowing date as a function of climate, giving a first level of adaptation by farmers to warming. For a specific variety, the length of the growing period depends on genetic characteristics that determine the accumulated heat requirement for a full phenological cycle between sowing and maturity. Warming accelerates the development, and therefore may reduce the crop productivity as the NPP is accumulated during a shorter period. When moving to late varieties, and as long as no other damaging stress increases (water, nutrients, pests), farmers compensate this negative warming effect.

The degree to which CO_2 fertilization will boost yields is still subject to debate—crop models therefore remain uncertain in this respect (Tubiello and Ewert, 2002; Long et al., 2006; Ewert et al., 2007). The process-based modelling of photosynthesis in LPJ (following Farquhar et al., 1980 for C3 plants), associated with the representation of the coupled CO_2 and water exchanges (Gerten et al., 2004), suggests that the CO_2 fertilization effect is reasonably represented in LPJmL according to the current knowledge. Hickler et al. (2008) show that LPJ reproduces the magnitude of the NPP enhancement at temperate forest FACE experiments. For C3 crops, (unpublished) model tests result in a yield increase of 10-15% at 550 ppmv (relative to 370 ppmv), which is in the same range as the responses of widely used crop models like DSSAT, EPIC or AEZ (Tubiello et al., 2007). At higher CO_2 concentrations, the fertilization effect simulated by LPJ for yields of C3 crops is reduced and saturates at approx. 40% around 1000 ppmv, which agrees with experimental observations (Amthor, 2001).

LPJmL runs for climate conditions under SRES emission scenarios for the 21th century over Europe (e.g. Zaehle et al., 2007) generally simulate increasing productivity of temperate cereals in the northern latitudes, and strongly reduced productivity due to increased water stress in the Mediterranean. Within the expected range of CO_2 concentrations at the end of the 21th century (516-958 ppmv), and the associated climate change (3-6 K warming, significant shifts in the precipitation regime), the changes in simulated LPJmL yields (not shown) are comparable to the synthesis shown in Fig. 5.2 (c) of Easterling et al. (2007). The LPJmL simulations presented here go beyond this range, since we use the A1FI emission scenario with up to 1650 ppmv in the 22nd century.

Three different factors impact the LPJmL simulated production of the temperate cereals under the A1FI_000 and A1FI_090 climate scenarios:

1. CO_2: The very high CO_2 concentration in 2121-2150 does not increase crop yields in LPJmL more than their maximal response (30-40% in the absence of water or nitrogen stress), which saturates around 1000 ppmv.

2. Climate change: The rather large temperature increase has both positive and negative effects. Extended growing periods in the northern latitudes increase the suitable area for temperate cereals. The precipitation changes under A1FI_000 and A1FI_090 are extremely variable and it is therefore difficult to predict how the balance between increased water stress in some places and increased moisture availability in other places will impact the European productivity. Nevertheless, despite yield reductions in some regions, the total suitable area increases the simulated production.

3. Adaptation: The acceleration of the phenological cycle due to the higher temperature (which reduces crop productivity) is compensated by the displacement of the sowing date and the shift to other varieties requiring more heat units.

Overall, the combination of these three factors leads us to expect a significant increase of the production of temperate cereals in Europe. However, other, negative impacts may occur under a warmer climate which are not considered here: increased tropospheric ozone could reduce photosynthesis, crops might be subject to more extreme events such as heat waves and severe droughts, farmers may face increased risks of pest proliferation. The CO_2 fertilization effect probably favours weeds too. These effects are not accounted for in today's models. In addition, despite increasing quantity, the food quality of cereals could decline, since the protein content of crops grown under enhanced CO_2 concentration has been observed to decrease (Taub et al., 2007).

By modelling the combined effects of the above listed three factors, LPJmL simulates for both scenarios an approximate doubling of the production of temperate cereals in Europe by 2121-2150 (Fig. 13). This is partly due to the CO_2 fertilization (under CO_2 levels above 1000 ppmv), but to a larger extent due to the extension of suitable areas. Production decreases then as expected by 2370-2399 as the CO_2 concentration again decreases below 1000 ppmv, but the warming remains important and is still beneficial to wheat cultivation in northern latitudes. This general behaviour shows regional variation. For example, cereal production in Italy increases only at the end of the simulation, probably due to strong precipitation increases. Differences between A1FI_000 and A1FI_090 are mostly minor, because the difference between the future CO_2 and climate compared to the CO_2 and climate of the reference period are much larger than the climate differences between the scenarios (Figs. 2a, b). Also, CO_2 is at the same level in A1FI_000 and A1FI_090, reaching an amount 5 times that of the reference period. In Europe overall (Fig. 13a) simulated production is slightly higher (5% to 11%) under a THC breakdown, especially at the end of the simulation, due to the changes in net primary production that are discussed in sec. 4.1. Wetter areas under A1FI_090 may have even larger production increase (+40%) under a THC breakdown, e.g.

in Italy (Fig. 13b). By contrast, in the Ukraine (Fig. 13c), the strong production gains from CO_2 increase and climate change are reduced under a THC breakdown by about 5%, due to reduced precipitation.

Overall, according to our simulations, the effect of reduced global warming and additional precipitation in some parts of Europe due to a THC breakdown could be positive because of the increased potential profits from agriculture. This assessment however does not take into account the potentially detrimental effects of climate change not captured by LPJmL mentioned above. **FIG. 13**

5.3. Further socioeconomic impacts

In our simulation of a THC breakdown (sec. 2.2) we see an additional sea level rise of up to 80 cm on the European coasts by 2150. This would threaten coastal cities and lowlands around the North Atlantic and the Arctic Ocean. The impacts of the sea level rise that is projected under the A1FI scenario (26 cm - 59 cm; Meehl et al., 2007) would be aggravated in this way. We have assessed the costs of these impacts using data from Stern (2007). By the end of the 21st century, the maximum additional sea level rise amounts to about 50 cm (not shown). The costs of an additional sea level rise of 50 cm can approximately be taken as the difference between a 1 m sea level rise scenario and a 50 cm sea level rise scenario. (Note that the costs of sea level rise are a nonlinear function of its magnitude, therefore a 50 cm difference added to another baseline would lead to different results.) For Europe and for the decade 2080-2089, Stern (2007) estimates the costs for protection measures against permanent inundation, for wetland and dryland losses, and for migration to be 90 million USD/year for a 50 cm rise and 760 million USD/year for a 1 m rise (in prices of 1995). Taking the difference of these two numbers, this means that an additional SLR of 50 cm by the 2080s would cause costs of 670 million USD/year for Europe as a whole (in prices of 1995). These costs are small in terms of the gross national product. For instance, the European Union has a gross national product of 14.5 trillion USD (2006 figure). Still, the sums involved are such that serious political bargaining is to be expected, since obviously a few European countries will be hit hard by sea level rise (e.g. the Netherlands), while other countries with a mostly steep and rocky coastline will have less problems (e.g. Norway).

There are other possible impacts of THC changes that we did not explicitly deal with in this study, but that we would like to mention in the following. Firstly, regional reorganizations of the THC currents might lead to regional climatic changes of a few degrees within a decade or so (Schaeffer et al., 2002), which could be perceived as an abrupt change. The task of adapting to the risk of abrupt climate change is very difficult and has scarcely been addressed so far. Hulme (2003) points out that, in the case of the THC, there are two fundamental challenges: firstly the large uncertainty about the probability of a THC shutdown (see sec. 6), and secondly the potential of a sign reversal of the temperature trends, i.e. a local cooling in some regions of the Nordic Seas.

Secondly, the impacts of a THC shutdown may well extend beyond Europe. A possibly serious global impact is the southward shift of the tropical rainfall belts (Stouffer et al., 2006; Vellinga and Wood, 2008). For regions like Central America and South East Asia this could mean the aggravation of precipitation decreases due to global warming, which might affect agricultural yields. In other regions however (e.g. Brazil), the impact of a THC shutdown could compensate a trend towards less rainfall. Finally, there are further potential impacts that deserve an investigation, e.g. on energy demand or on biodiversity.

6. Uncertainty and Risk

The risk of a given climate event is commonly defined as the impact of that event times the probability of its occurrence. While the largest part of this paper is dedicated to the impacts of a THC shutdown, we want to give estimates of its probability in this section. We use two approaches: a model-based uncertainty analysis and an elicitation of subjective probability estimates from experts. For the model-based uncertainty analysis we used the climate model of intermediate complexity Climber-2 (Petoukhov et al., 2000). It is different from Climber-3α, the model used in other parts of this study, in that its resolution is coarser. Yet it has the advantage of running fast enough on the computer to allow a systematic uncertainty analysis. Therefore, Schneider von Deimling et al. (2006) were able to use Climber-2 to conduct an ensemble study with 5000 members, varying 11 climate parameters. The equilibrium state of each ensemble member (assumed to be reached after 3500 model years) was tested for consistency with the observed preindustrial climate in the atmosphere and the ocean. The 110 members that passed the consistency test were driven with the A1FI climate scenario used above, once with and once without an additional freshwater flux. This flux was scaled with the warming in the Northern Hemisphere as described in sec. 2.1. Choosing HS=$0.04 \times 10^6 \mathrm{m}^3\mathrm{s}^{-1}\mathrm{K}^{-1}$ resulted in a maximum freshwater input of 0.15 Sv around the year 2150.

The THC in Climber-2 is more sensitive than in Climber-3α. Hence, if an additional freshwater flux is applied, 38 members of the total 110 members show a breakdown of the THC at some point in the 22nd century. Under the A1FI scenario alone, without freshwater input, no breakdown occurs. With the additional freshwater flux, the breakdown reduces the overall global warming by 0.2 K to 0.4 K, similar to Climber-3α (sec. 2.3).

From the ensemble simulations with the Climber-2 model the probability of a THC breakdown can be computed by relating the number of runs with a breakdown to the total number of runs. Table I displays the probability of THC breakdown (p_{br}) as a function of global mean temperature change (ΔT) by 2100. No THC breakdown occurs for an unchanged freshwater flux. If the freshwater flux described above is applied, p_{br} increases from zero for ΔT of 1.5–2.5 K to one for ΔT of 4.5–5.5 K. Note that in most cases the breakdown occurs after 2100. **TAB. I**

We computed p_{br} also as a function of the climate parameters that Schneider von Deimling et al. (2006) varied to set up their ensemble. For instance, we found a tendency for a higher vertical diffusivity in the ocean to stabilize the THC, in line with the results from Schmittner and Weaver (2001). Within the ensemble that was subject to the additional freshwater forcing, we found $p_{br} = 0.74$ if the vertical diffusivity lies between $0.5 \times 10^{-4} m^2 s^{-1}$ and $0.7 \times 10^{-4} m^2 s^{-1}$, but $p_{br} = 0.00$ for the vertical diffusivity interval $1.3 \times 10^{-4} m^2 s^{-1}$ to $1.5 \times 10^{-4} m^2 s^{-1}$. This finding sheds a light on the need to improve the representation of mixing in models, particularly since in most models the intensity of mixing appears too high (Hofmann and Maqueda, 2006).

We caution that the probabilities reported above depend on the specific model used and the setup of the uncertainty analysis, like the choice of parameters or the variational ranges.

One part of the expert interviews mentioned earlier (Zickfeld et al., 2007) was devoted to the elicitation of subjective probabilities that a collapse of the THC (defined as a reduction by more than 90% relative to present-day) will occur or will be irreversibly triggered by the year 2100, given specific changes in global mean temperature. The results are presented in Fig. 14. Out of twelve, eight experts assessed the probability of THC collapse as non-zero. For 2 K of global warming, four experts assessed the probability of collapse $\geq 5\%$. 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 of $\geq 10\%$, four assess the probability of collapse as $\geq 50\%$, and two are almost certain ($p = 90\%$) that a collapse would occur. **FIG. 14**

The experts' estimates are based not only on evidence from climate modelling but also on their own judgement about the skillfulness of climate models (e.g. in the representation of processes at scales smaller than those resolved by the models) as well as information from sources other than modelling (observational evidence, paleo-data). This may be the reason why some of the estimated probabilities are higher than those derived from climate models. In a recent model intercomparison of THC behaviour under CO_2 quadrupling (Gregory et al., 2005), for instance, none of the eleven models showed a collapse in the 140 years of simulation (note however that no meltwater from Greenland ice mall loss was assumed). In a similar study, the influence of a 0.1 Sv freshwater hosing was explored (Stouffer et al., 2006). Again, no breakdown occurred. In the present study we investigate the combined effect of global warming and additional freshwater forcing. The behaviour of Climber-2 and Climber-3α (which took part in these model intercomparisons) agrees well with that of the other models: the THC does not shut down under global warming except if an additional freshwater flux of sufficient magnitude is applied.

The IPCC have recently come up with probability estimates for THC changes (Meehl et al., 2007). They give a probability of 5% to 10% for a "large abrupt transition" of the THC by 2100, and a probability of 90% to 95% for a "slowdown" of the THC. These numbers are independent from the greenhouse gas scenarios. For the SRES A1B scenario, Meehl et al. (2007) specified that the multi-model average THC reduction is 25%. It is not straightforward to compare these numbers with our results. The 5% to 10% “large abrupt transition” probability lies in the lower range of the breakdown probabilities we elicited. Yet our probabilities include the possibility of a THC breakdown occurring after 2100, which has not been taken into account in the IPCC numbers.

When compared with more traditional applications of risk assessment, e.g. in engineering (risk of plane crash, bridge collapse or nuclear accident) or for medical operations, a 5% risk of a major system failure would appear very high. Given the potentially serious impacts (e.g. the additional sea level rise), one might conclude that the precautionary principle would argue for limiting this kind of risk to a probability several orders of magnitude smaller. In other words, the risk of a THC breakdown, defined as impact times probability, can hardly be regarded as negligible. The existence of this non-negligible risk is why we study the impacts here, even if it requires a THC breakdown to be triggered somewhat artificially in our model by a large additional freshwater flux.

In comparison with other physical processes relevant for climate change, the uncertainty about the THC is large. This is due to a number of reasons, like the relatively poor knowledge of some oceanic processes involved (e.g. mixing), or to the small scales of the deep water formation that are very difficult to model. The response of the ice sheets to warming and the resulting freshwater fluxes are also insufficiently understood. And there is the possibility of abrupt circulation changes due to nonlinear dynamic feedbacks. Under these circumstances one can ask whether the THC is predictable in principle. Here the experts unanimously answer positively. However, this predictability is limited by lack of relevant knowledge and computational resources for modelling. Asked what research foci should be chosen to reduce the uncertainty, the experts named coupled ocean-atmosphere modelling and long-term observations of ocean circulation as well as collection and analysis of paleo-data. The vast majority of experts believe that major research programmes with those foci would truly be successful in uncertainty reduction. As a consequence, it is thought by nine of the twelve experts that an early warning system for THC changes could be devised—under the condition that such mentioned major research programmes be conducted through the next 15 years or so. Another question is the lead time such an early warning system needs to have to avoid a THC breakdown, given the inertia in the technological and socioeconomic systems; we had optimistically assumed 20 years for the expert elicitation.

7. Integrated Assessment Model

The scope of the Integrated Assessment is to come up with policy recommendations concerning the magnitude and timing of emissions reductions required to limit the risk of THC changes that might be perceived as “dangerous”, while taking into account expectations about the socioeconomically acceptable pace of emissions reductions. For this scope, we use an Integrated Assessment Model which consists of a globally-aggregated multi-gas climate model (ICM; Bruckner et al., 2003) coupled to a model of the world economy for assessing the monetary costs of climate protection (DICE; Nordhaus, 1994; for a detailed description of the coupled framework the reader is referred to Bruckner and Zickfeld, 2008). The model used here has been improved over the version described in Bruckner and Zickfeld (2008) to be able to process information provided in probabilistic terms, such as probability density functions (PDFs) for climate sensitivity.

The THC is taken into account not by explicit modelling, but via subjective probability estimates that were elicited from leading experts in oceanography (Zickfeld et al., 2007). These estimates relate the probability that a specific THC change is triggered to the change in global mean temperature in the year 2100 (see Fig. 14). In this study, we focus on two distributions: one for a complete THC shutdown and one for a 20% THC reduction. The former is the distribution of expert 1 in Fig. 14 (which we have chosen because it lies in the middle of the elicited probability range), the latter was elicited from the same expert in a post-elicitation exercise (not shown). Note that the probability that a certain THC change occurs, given a specific change in temperature, is conditional on the probability that this temperature change is actually realized. Therefore, we have to make assumptions about the climate sensitivity, which enters the climate module of the Integrated Assessment Model as a parameter. In this study, we adopt a log-normal distribution for climate sensitivity with a median of 2.7 K (see also Rahmstorf and Zickfeld, 2005).

The integrated assessment is conducted along the lines of the "tolerable windows" or "guardrail" approach (Bruckner et al., 1999, Petschel-Held et al., 1999). This framework seeks to identify the bundle of emissions paths ("emissions corridor") that are compatible with pre-defined policy goals or "guardrails". Guardrails are normative constraints imposed on the coevolution of the natural and human systems and are meant to exclude intolerable outcomes (Bruckner et al., 1999). In the present study, we determine emissions corridors that are compatible with two kinds of guardrails: (i) guardrails of the physical system which limit the probability of "dangerous" THC changes to a level that may be considered tolerable, and (ii) socioeconomic guardrails which constrain the rate and costs of emissions reductions to admissible values.

In defining the THC guardrails, we assume that both a complete shutdown and a 20% weakening of the THC may be considered as "dangerous anthropogenic interference" that Article 2 of the UNFCCC calls to avoid. Whether stakeholders and society actually do consider such THC changes as dangerous cannot be fathomed in the present study. Rather, the scope of this analysis is to illustrate the CO_2 emissions ranges allowable under different definitions of "dangerous" THC changes. The tolerable risks associated with THC changes are varied between 2% and 10% in the case of a THC shutdown, and between 5% and 20% in the case of a 20% THC weakening.

The socioeconomic guardrails are intended to ensure that the pace and costs of emissions reductions do not exceed tolerable limits. They are expressed by two conditions constraining (1) maximum percentage welfare loss $l_{\max}$ (relative to welfare in the "business as usual" case) and (2) the emissions reduction rate, which is not allowed to increase faster than some prescribed value $\mu_{\max}$. In the present analysis, l_{max} is varied in the range 0.5–4% and $\mu_{\max}$ in the range 0.7–2.5% (the default values being 2% and 1.33%, respectively). These guardrails are defined ad hoc rather than representing true societal choices. Our approach, however, is valuable to illustrate the sensitivity of the corridors to different normative guardrails. **FIG. 15, FIG. 16**

Fig. 15 displays emissions corridors that limit the probability of a shutdown of the THC to 10%, 5% and 3%, respectively. The corridors should be interpreted as follows: any emission trajectory leaving the x% risk-corridor implies a probability larger than x% that a breakdown of the THC will be triggered. Comparison with Fig. 16 shows that the upper corridor boundary is sensitive to both the THC and economic guardrails (in particular the maximum admissible emissions reduction rate), whereas the lower boundary is determined solely by the economic constraints. Fig. 15 indicates, for instance, that the business-as-usual (BAU) path obtained with the DICE model transgresses the upper boundary of the 5% risk corridor by the year 2050. This implies that, in the case a 5% risk of a THC breakdown is perceived as intolerable, a deviation from BAU would be necessary before this date. Note that the BAU carbon emissions path of DICE is significantly lower than other non-intervention scenarios used in the present study (i.e. the SRES scenarios B2 and A1FI). If the world economy initially follows one of these alternative paths, limiting the risk of THC shutdown to 5% may require effective emissions reductions well before 2050.

Fig. 16 exemplarily displays the sensitivity of the 5% risk corridor to the economic guardrails. Comparison of the panels a) and b) shows that the sensitivity of the upper corridor boundary to changes in the admissible welfare loss l_{max} is small compared to changes in the admissible rate of emissions reduction μ_{max}. The admissible welfare loss reflects normative decisions concerning the amount that societies are willing to pay to contain the risk of a THC shutdown, whereas the rate of emissions control reflects both the willingness to reduce emissions fast and the technical ability to do so. Improving the worldwide mitigation capability, by making available technologies that allow one to realize high emissions reduction rates at lower costs, would therefore considerably broaden the 5% risk corridor.

Our analysis further indicates that under default economic constraints and the chosen probability distributions for the physical parameters it is not possible to contain the probability of a 20% weakening of the THC to less than 50% (i.e., no "open" corridor exists). If the socioeconomic constraints are relaxed, however, this goal can be attained: for instance, increasing μ_{max} to 2.5% leads to the existence of an emissions corridor (not shown). This illustrates that in the case of tight emissions corridors a trade-off between THC guardrails and socioeconomic guardrails may be required.

8. Discussion

This Integrated Assessment explores the impacts of changes in the THC on climate, ecosystems, and economy, and outlines limits for future CO_2 emission paths to avoid THC risks. Since this transdisciplinary study builds on climate scenarios from one climate model its results should be understood as exemplary. We investigate the effects of a THC shutdown occurring during ongoing global warming. Since a moderate THC weakening is already part of most of the IPCC AR4 scenarios (Meehl et al., 2007), we use this as a baseline scenario against which we compare the impacts of a THC shutdown. We apply an extended SRES A1FI greenhouse gas scenario and trigger the THC shutdown by a freshwater flux that scales with Northern Hemisphere atmospheric warming. Our focus is on the mid-22nd century because by then global warming is maximal and the THC shutdown is complete.

Our simulations show that a shutdown of the THC does not lead to a persistent temperature drop relative to the present-day climate. As already pointed out by Rahmstorf (1997), global warming can compensate for the reduced oceanic northward heat transport, thus preventing any cooling on land below present-day temperatures if the THC winds down gradually (and not abruptly) in response to anthropogenic climate change. Hence it appears that temperature changes per se are unlikely to be a serious impact of a THC shutdown. Precipitation changes are strong in some regions in our simulations, but are subject to large uncertainty.

We note that in all simulations, irrespective of the applied greenhouse gas scenarios and freshwater fluxes, a net cooling of a few degrees is simulated which is confined to the central Nordic Seas. This net cooling appears transiently in the mid-21st century; it resembles the regional cooling reported by Schaeffer et al. (2002).

Concerning the impacts on land ecosystem productivity, our simulations show that the positive effect of the greatly increased atmospheric CO_2 content under the A1FI scenario is much larger in magnitude than any changes due to the THC shutdown. The impacts of a THC shutdown can be either positive or negative depending on the region and the precipitation changes. This applies similarly to agricultural production, where a THC shutdown has not much impact. Rather the strong CO_2 increase and the warming that allows for more cropland in northern Europe have positive impacts and dominate some local water stress problems. A THC shutdown leads to a slight further increase of agricultural production as a whole (because of reduced water stress), while regionally its impacts can also be negative (e.g. in eastern Europe). Nevertheless, under the level of climate change analysed in this study, the positive agricultural results may be hampered by an increased crops vulnerability (not accounted for in our simulations) to pests and atmospheric pollution.

An impact of a THC shutdown that might be perceived as serious is an additional sea level rise. Our simulations (scenario A1FI_090) show that this may amount up to 80 cm on some parts of the North Atlantic shores by the mid 22nd century. This adds to the sea level rise by thermal expansion and land ice melt, projected by the IPCC to be between 28 cm and 59 cm (Meehl et al., 2007), which has to be expected as a consequence of global warming. A very rough estimate of the implied costs, based on the analysis by Stern (2007), yields 670 million USD/year for Europe in the 2080s, assuming that the maximum additional sea level rise is around 50 cm by then. While this sum is not negligible, it is small in comparison to the gross national product of the affected countries.

Shifts in the deep-water formations sites that go along with a shallower mixed layer of the ocean could occur due to global warming, a THC shutdown or a combination of both. This decrease in deep vertical mixing would cut the supply of nutrients from the deep water masses to the upper layer of the ocean where the nutrients are consumed. The result would be a declining phytoplankton population, with possible impacts on all the subsequent links of the food chain, e.g. zooplankton and fish. In our simulations the effect of global warming on the net primary production of the Atlantic is clearly stronger than that of a THC shutdown. The oceanic carbon uptake would be regionally reduced as well by such a reduction of the mixed layer depth. However, taking into account carbon uptake by the land biosphere and the other ocean basins, a THC breakdown would give rise to an increase in atmospheric CO_2 by only a few percent (Obata, 2007; Zickfeld et al., 2008).

Regionally the impacts of a declining THC on marine ecosystems might become strong and detrimental, as we show for the Nordic Seas and the Barents Sea. Note however that used a different climate scenario here: the regional ocean model could not be forced with the Climber-3α scenarios due to the large difference in spatial resolution. Instead we had to use a freshwater input scenario from a higher-resolution model that does not include global warming. The impacts result from a complex interaction of reorganizing currents and temperature changes of both signs in the oceanic mixed layer. A very important zooplankton species (C. finmarchicus) has favourable growth conditions in a given temperature window. While a general warming trend has the capability to open up Arctic waters for their growth, this effect can be overridden by the reduction of the mixed layer depth that limits the food supply. Also, changing currents might carry the cod larvae and juveniles away form their nursing grounds. In these ways, stocks of Arcto-Norwegian cod that feed on C. finmarchicus could be severely endangered. Consequently, Arcto-Norwegian cod fishery could become unprofitable if the THC breaks down, as our simulations with a bio-economic fishery model show. A similar response can be expected for other fish species like Northeast Arctic haddock and Norwegian herring. However, these complex interactions depend on regional details of the oceanic and atmospheric circulation that are hard to capture with current climate models.

On the global scale, other potentially serious impacts might occur outside of Europe. Model simulations (Vellinga and Wood, 2002; Stouffer et al., 2006; Vellinga and Wood, 2008) suggest that a THC shutdown shifts the tropical precipitation patterns. This would mean significantly less rain for Central America and the Caribbean, the tropical Atlantic, East Africa and South East Asia. The North-East Atlantic would also be affected. In terms of temperature changes, the smaller northward heat transport implies an additional warming for the tropical and southern Atlantic, if not for the whole Southern Hemisphere.

It is difficult to assess how likely a THC shutdown is. The probability given in the IPCC 4th Assessment Report (Meehl et al., 2007) is 5% to 10% for a "large abrupt transition during the course of the 21st century". However, if individual experts are asked the numbers vary widely. For instance, if a 5 K temperature increase until 2100 is assumed, the elicited subjective probabilities lie between 0% and 80% for a breakdown to happen or to be irreversibly triggered before 2100 (Zickfeld et al., 2007). As long as there is so much uncertainty about the future evolution of the THC, research efforts concerning the THC need to be continued in order to reduce it. Asked to design a 15-year research program about the THC funded at 500 million USD per year, experts on average allocate the largest budget to long-term hydrographic measurements and coupled climate modelling. Most experts are confident by at least 60% that an appropriately conceived research program would contribute to reducing uncertainty about the future evolution of the THC. 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 modelling and monitoring which could provide human society with an "early warning" capability with respect to the future evolution of the THC. These beliefs will be hopefully substantiated by the ongoing research efforts (e.g. the RAPID programme; Cunningham et al., 2007) in this field.

Given the definition of risk as the product of probability and impact, we find that the assessment of the risk of a THC breakdown is still fraught with considerable uncertainty regarding both factors. From the current knowledge and the results of this study it becomes clear that in the foreseeable future we will not be able to make reliable forecasts of when or whether global warming might trigger a THC breakdown, and we stress that the results of the integrated assessment of THC changes performed here should be seen as not much more than a prospect on possible impacts, associated with considerable uncertainty. Yet, with the probability of 5-10% estimated by the IPCC and even larger estimates found in our expert elicitation, combined with some potentially serious impacts (additional sea level rise, shifting tropical rainfall patterns), a THC breakdown might be considered a "dangerous anthropogenic interference with the climate system" in the sense of Art. 2 of the UNFCCC. Of course, this cannot be decided by scientists alone, as it involves a value judgment by society as to what level of risk is considered acceptable or "dangerous". However, if we assume that society does choose to reduce the risk of a THC breakdown, be it because it is considered as dangerous or be it out of precaution, then the results from our Integrated Assessment model suggest that carbon emissions need to be curbed within the next few decades.

Acknowledgements

The authors gratefully acknowledge the funding of the project INTEGRATION by the German Federal Ministry for Education and Research (grant 01LD0016). Markus Erhard thankfully has provided us with land use scenarios for the crop yield simulations. We are grateful to Malte Meinshausen for computing the CO_2 concentration scenarios. We thank Gerd Bürger for developing the downscaling algorithm. The extensive comments of three anonymous reviewers have led to considerable clarifications in the paper.

Appendix

The principal assumption for the downscaling algorithm is a dependence of the monthly variability of local meteorological variables over Europe on the monthly variability of a few global atmospheric variables over the North Atlantic region. This is assumption is often used for regionalizing output from global climate models (Wilby and Wigley, 1997). Multiple linear regression is used to estimate a correlation matrix between those two fields. The residual local variability is modelled by an autoregressive process of first order (which includes, by definition, a stochastic term). This involves a second matrix for the correlation between subsequent steps of the realization. The global variables are surface air temperature, sea level pressure, vertical velocity at 700 hPa, and specific humidity at 700 hPa. The local variables are surface air temperature, daily temperature range, cloudiness, precipitation sum, precipitation rate, and vapour pressure.

The coefficients of the above-mentioned two matrices are estimated by reproducing a high-resolution observational data set (Climatic Research Unit) from another dataset (NCEP) that is coarse-grained to the resolution of Climber-3α. This is done by using multiple regression. The same matrices are then used to compute the $0.5° \times 0.5°$ local fields from the Climber-3α output which comes at a resolution of $7.5° \times 22.5°$. It turns out that the covariance of the latter field is different from the covariance of the coarse-grained NCEP fields; therefore a correction factor for the local fields has to be introduced in order to obtain correct amplitudes. This correction factor consists of the ratio of the observed and the simulated variance. It is estimated for the present climate, and it is assumed that the same factor applies to the simulated future climates.

In summary, the downscaling used here is based on the assumption that the variations of the local variables on the order of magnitude of the seasonal cycle can be related linearly to the variations on the North Atlantic-European scale of a few atmospheric fields. This linear relation comprises the seasonal cycle itself and, notably, changes due to different greenhouse gas concentrations and a shutdown of the THC. To these slow, large-scale and deterministic variations a stochastic process of monthly fluctuations is added. Together, the linear and the stochastic process generate the desired overall variability. Spatial covariances are taken into account as well.

References

Amthor, J. S.: 2001, 'Effects of atmospheric CO_2 concentration on wheat yield: review of results from experiments using various approaches to control CO_2 concentration'. *Field Crops Research* **73**(1), 1–34.

Antoine, D., J.-M. André, and A. Morel: 1996, 'Oceanic primary production, 2. Estimation at global scale from satellite (Coastal Zone Color Scanner) Chlorophyll'. *Glob. Biogeochem. Cyc.* **10**(1), 57–69.

Azar, C., K. Lindgrena, E. Larson, and K. Möllersten: 2006, 'Carbon capture and storage from fossil fuels and biomass – Costs and potential role in stabilizing the atmosphere'. *Climatic Change* **74**(1-3), 47–79, doi: 10.1007/s10584-005-3484-7.

Beaugrand, G., P. Reid, F. Ibanez, J. Lindley, and M. Edwards: 2002, 'Reorganization of North Atlantic Marine Copepod Biodiversity and Climate'. *Science* **296**, 1692–1694.

Behrenfeld, M. J., R. T. O'Malley, D. A. Siegel, C. R. McClain, J. L. Sarmiento, G. C. Feldman, A. J. Milligan, P. G. Falkowski, R. M. Letelier, and E. S. Boss: 2006, 'Climate-driven trends in contemporary ocean productivity'. *Nature* **444**, 752–755, doi: 10.1038/nature05317.

Bindoff, N. L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. L. Qur, S. Levitus, Y. Nojiri, C. Shum, L. Talley, and A. Unnikrishnan: 2007, 'Observations: Oceanic Climate Change and Sea Level'. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller (eds.): *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental*

Panel on Climate Change. Cambridge, UK, and New York, NY, USA, Cambridge University Press.

Björnsson, B. and A. Steinarsson: 2002, 'The food-unlimited growth rate of Atlantic cod Gadus morhua'. *Canadian Journal of Fisheries and Aquatic Sciences* **59**, 494–502.

Bondeau, A., P. C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller, M. Reichstein, and B. Smith: 2007, 'Modelling the role of agriculture for the 20th century global terrestrial carbon balance'. *Global Change Biology* **13**(3), 679–706, doi: 10.1111/j.1365-2486.2006.01305.x.

Boyer, T., S. Levitus, J. Antonov, R. Locarnini, A. Mishonov, H. Garcia, and S. A. Josey: 2007, 'Changes in freshwater content in the North Atlantic Ocean 1955-2006'. *Geophys. Res. Lett.* **34**, L16603, doi: 10.1029/2007GL030126.

Broecker, W.: 1987, 'Unpleasant surprises in the greenhouse?'. *Nature* **328**, 123.

Bruckner, T., G. Hooss, H. M. Füssel, and K. Hasselmann: 2003, 'Climate system modeling in the framework of the tolerable windows approach: the ICLIPS climate model'. *Climatic Change* **56**, 119–137.

Bruckner, T., G. Petschel-Held, F. Tóth, H. M. Füssel, C. Helm, M. Leimbach, and H. J. Schellnhuber: 1999, 'Climate change decision support and the tolerable windows approach'. *Env. Mod. Ass.* **4**, 217–234.

Bruckner, T. and K. Zickfeld: 2008, 'Emissions corridors for reducing the risk of a collapse of the Atlantic thermohaline circulation'. *Mitigation and Adaptation Strategies of Global Change*. In press.

Bryan, F. O., G. Danabasoglu, N. Nakashiki, Y. Yoshida, D.-H. Kim, J. Tsutsui, and S. C. Doney: 2006, 'Response of the North Atlantic thermohaline circulation and ventilation to increasing carbon dioxide in CCSM3'. *J. Clim.* **19**, 2382–2397.

Bryden, H. L., H. R. Longworth, and S. A. Cunningham: 2005, 'Slowing of the Atlantic meridional overturning circulation at 25°N'. *Nature* **438**, 655–657.

Buitenhuis, E., C. Le Quéré, O. Aumont, G. Beaugrand, A. Bunker, A. Hirst, T. Ikeda, T. O'Brien, S. Piontkovski, and D. Straile: 2006, 'Biogeochemical fluxes through mesozooplankton'. *Glob. Biogeochem. Cyc.* **20**, GB2003, doi: 10.1029/2005GB002511.

Conkright, M., S. Levitus, and T. Boyer: 1994, 'World Ocean Atlas 1994, Volume 1: Nutrients'. Technical report, NESDIS 1, U.S. Department of Commerce, Washington, D.C.

Cramer, W., A. Bondeau, F. I. Woodward, I. C. Prentice, R. A. Betts, V. Brovkin, P. M. Cox, V. Fisher, J. Foley, A. D. Friend, C. Kurcharik, M. R. Lomas, N. Ramankutty, S. Sitch, B. Smith, A. White, and C. Young-Molling: 2001, 'Global response of terrestrial ecosystem structure and function to CO_2 and climate change: results form six dynamic global vegetation models'. *Global Change Biology* **7**, 357–373.

Cunningham, S. A., T. Kanzow, D. Rayner, M. O. Baringer, W. E. Johns, J. Marotzke, H. R. Longworth, E. M. Grant, J. J.-M. Hirschi, L. M. Beal, C. S. Meinen, and H. L. Bryden: 2007, 'Temporal Variability of the Atlantic Meridional Overturning Circulation at 26.5°N'. *Science* **317**, 935–938.

Curry, R. and C. Mauritzen: 2005, 'Dilution of the northern North Atlantic Ocean in recent decades'. *Science* **308**, 1772–1774.

Easterling, W., P. Aggarwal, P. Batima, K. Brander, L. Erda, S. Howden, A. Kirilenko, J. Morton, J.-F. Soussana, J. Schmidhuber, and F. Tubiello: 2007, 'Food, fibre and forest products'. In: M. Parry, O. Canziani, J. Palutikof, P. van der Linden, and C. Hanson (eds.): *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK, and New York, NY, USA: Cambridge University Press.

EEA: 2000, *CORINE land cover technical guide—addendum.* European Environment Agency, Copenhagen. Report No.40.

Ellertsen, B., P. Fossum, P. Solemdal, and S. Sundby: 1989, 'Relation between temperature and survival of eggs and first-feeding larvae of northeast Arctic cod *Gadus morhua* L.'. *Rapp. P.-v. Reun. Cons. Int. Explor. Mer.* **191**, 209–219.

Ewert, F., J. Porter, and M. Rounsevell: 2007, 'Crop Models, CO_2, and Climate Change – Comments to Long'. *Science* **315**, 459.

Ewert, F., M. Rounsevell, I. Reginster, M. Metzger, and R. Leemans: 2005, 'Future scenarios of European agricultural land use: I. Estimating changes in crop productivity'. *Agriculture, Ecosystems and Environment* **107**(2-3), 101–116.

Falkowski, P. G., R. T. Barber, and V. Smetacek: 1998, 'Biogeochemical Controls and Feedbacks on Ocean Primary Production'. *Science* **281**, 200–206.

Farquhar, G., S. von Caemmerer, and J. Berry: 1980, 'A Biochemical Model of Photosynthetic CO_2 Assimilation in Leaves of C3 Species'. *Planta* **149**, 78–90.

Fischer, G., M. Shah, F. N. Tubiello, and H. Van Velthuizen: 2005, 'Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990-2080'. *Philosophical Transactions—Royal Society of London. Biological sciences* **360**(1463), 2067–2083.

Fischer, G., H. van Velthuizen, M. Shah, and F. Nachtergaele: 2002, *Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results*. IIASA, Laxenburg, Austria, and FAO, Rome, Italy.

Fromentin, J. and B. Planque: 1996, 'Calanus and environment in the eastern North Atlantic. 2.Influence of the North Atlantic Oscillation on C. finmarchicus and C. helgolandicus'. *Marine ecology – Progress series* **134**(1-3), 111–118.

Furevik, T., M. Bentsen, H. Drange, I. H. T. Kindem, N. G. Kvamstø, and A. Sorteberg: 2003, 'Description and validation of the Bergen Climate Model: ARPEGE coupled with MICOM'. *Clim. Dyn.* **21**, 27–51.

Ganachaud, A. and C. Wunsch: 2002, 'Oceanic nutrient and oxygen transports and bounds on export production during the World Ocean Circulation Experiment'. *Glob. Biogeochem. Cyc.* **16**, doi: 10.1029/2000GB001333.

Gerten, D., S. Schaphoff, U. Haberlandt, W. Lucht, and S. Sitch: 2004, 'Terrestrial vegetation and water balance—hydrological evaluation of a dynamic global vegetation model'. *Journal of Hydrology* **286**, 249–270.

Gregory, J. M., K. W. Dixon, R. J. Stouffer, A. J. Weaver, E. Driesschaert, M. Eby, T. Fichefet, H. Hasumi, A. Hu, J. H. Jungclaus, I. V. Kamenkovich, A. Levermann, M. Montoya, S. Murakami, S. Nawrath, A. Oka, A. P. Sokolov, and R. B. Thorpe: 2005, 'A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO_2 concentration'. *Geophys. Res. Lett.* **32**, L12703, doi: 10.1029/2005GL023209.

Gregory, W. W., M. E. Conkright, P. Ginoux, J. E. O'Reilly, and N. W. Casey: 2003, 'Ocean primary production and climate: Global decadal changes'. *Geophys. Res. Lett.* **30**(15), L12703, doi: 10.1029/2003GL016889.

Haidvogel, D., H. Arango, W. Budgell, B. Cornuelle, E. Curchitser, E. D. Lorenzo, K. Fennel, W. Geyer, A. Hermann, L. Lanerolle, J. Levin, J. McWilliams, A. Miller, A. Moore, T. Powell, A. Shchepetkin, C. Sherwood, R. Signell, J. Warner, and J. Wilkin: 2008, 'Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modelling System'. *Dynamics of Atmosphere and Oceans* **227**(7), 3595–3624.

Hegerl, G. C., F. W. Zwiers, P. Braconnot, N. P. Gillett, Y. Luo, J. A. M. Orsini, N. N. J. E. Penner, and P. A. Scott: 2007, 'Understanding and Attributing Climate Change'. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller (eds.): *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York, NY, USA, Cambridge University Press.

Hemming, S.: 2004, 'Heinrich events: Massive late pleistocene detritus layers of the North Atlantic and their global climate imprint'. *Rev. Geophys.* **42**, doi: 10.1029/2003RG000128.

Hickler, T., B. Smith, I. Prentice, K. Mjøfors, P. Miller, A. Arneth, and M. T. Sykes: 2008, 'CO_2 fertilization in temperate FACE experiments not representative of boreal and tropical forests'. *Global Change Biology* **14**(7), 1531–1542.

Higgins, P. A. and M. Vellinga: 2003, 'Ecosystem responses to abrupt climate change: teleconnections, scale and the hydrological cycle'. *Climatic Change* **64**(1-2), 127–142.

Higgins, P. A. T. and S. H. Schneider: 2005, 'Long-term potential ecosystem responses to greenhouse gas-induced thermohaline circulation collapse'. *Global Change Biology* **11**, 699–709, doi: 10.1111/j.1365-2486.2005.00952.x.

Hofmann, M. and M. A. M. Maqueda: 2006, 'Performance of a second-order moments advection scheme in an Ocean General Circulation Model'. *J. Geophys. Res.* **111**, C05006, doi: 10.1029/2005JC003279.

Hulme, M.: 2003, 'Abrupt climate change: can society cope?'. *Phil. Trans. R. Soc. Lond. A.* **361**, 2001–2021, doi: 10.1098/rsta.2003.1239.

Jacob, D., H. Goettel, J. Jungclaus, M. Muskulus, R. Podzun, and J. Marotzke: 2005, 'Slowdown of the thermohaline circulation causes enhanced maritime climate influence and snow cover over Europe'. *Geophys. Res. Lett.* **32**, L21711, doi: 10.1029/2005GL023286.

Jungclaus, J. H., H. Haak, M. Esch, E. Roeckner, and J. Marotzke: 2006, 'Will Greenland melting halt the thermohaline circulation?'. *Geophys. Res. Lett.* **33**, L17708, doi: 10.1029/2006GL026815.

Keller, K., K. Tan, F. M. M. Morel, and D. F. Bradford: 2000, 'Preserving the ocean circulation: implications for climate policy'. *Climatic Change* **47**(1-2), 17–43.

Kuhlbrodt, T., A. Griesel, M. Montoya, A. Levermann, M. Hofmann, and S. Rahmstorf: 2007, 'On the driving processes of the Atlantic meridional overturning circulation'. *Rev. Geophys.* **45**, RG2001, doi: 10.1029/2004RG000166.

Lenton, T. M., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber: 2008, 'Tipping elements in the Earth's climate system'. *Proceedings of the National Academy of Sciences* **105**(6), 1786–1793.

Levermann, A., A. Griesel, M. Hofmann, M. Montoya, and S. Rahmstorf: 2005, 'Dynamic sea level changes following changes in the thermohaline circulation'. *Clim. Dyn.* **24**, 347–354.

Lindsay, R. W. and J. Zhang: 2005, 'The Thinning of Arctic Sea Ice, 1988-2003: Have We Passed a Tipping Point?'. *J. Clim.* **18**(22), 4879–4894.

Link, P. M., U. S. Schneider, and R. S. J. Tol: 2004, 'Economic impacts of changes in fish population dynamics: the role of the fishermen's harvesting strategies'. Working Paper FNU-50, Research Unit Sustainability and Global Change, Hamburg, Germany.

Link, P. M. and R. S. J. Tol: 2006a, 'Economic impacts of changes in population dynamics of fish on the fisheries in the Barents Sea'. *ICES J. Mar. Sci.* **63**(4), 611–625.

Link, P. M. and R. S. J. Tol: 2006b, 'Economic impacts on key Barents Sea fisheries arising from changes in the strength of the Atlantic thermohaline circulation'. Working Paper FNU-104, Research Unit Sustainability and Global Change, Hamburg, Germany.

Long, S. P., E. Ainsworth, A. Leakey, J. Nösberger, and D. Ort: 2006, 'Food for Thought: Lower-Than-Expected Crop Yield Stimulation with Rising CO_2 Concentrations'. *Science* **312**, 1918–1921.

Manabe, S. and R. Stouffer: 1993, 'Century-scale effects of increased atmospheric CO_2 on the ocean-atmosphere system'. *Nature* **364**, 215–218.

Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver, and Z.-C. Zhao: 2007, 'Global Climate Projections'. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller (eds.): *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK, and New York, NY, USA, Cambridge University Press.

Montoya, M., A. Griesel, A. Levermann, J. Mignot, M. Hofmann, A. Ganopolski, and S. Rahmstorf: 2005, 'The Earth System Model of Intermediate Complexity

CLIMBER-3α. Part I: description and performance for present day conditions'. *Clim. Dyn.* **25**, 237–263.

Nakićenović, N. and R. Swart (eds.): 2000, *IPCC Special Report on Emissions Scenarios.* Cambridge, UK: Cambridge University Press.

Nordhaus, W.: 1994, *Managing the global commons: the economics of climate change.* Cambridge, MA: MIT Press.

Obata, A.: 2007, 'Climate-carbon cycle model response to freshwater discharge into the North Atlantic'. *J. Clim.* **20**(24), 5962–5976, doi: 10.1175/2007JCLI1808.1.

Otterå, O. H., H. Drange, M. Bentsen, N. G. Kvamstø, and D. Jiang: 2004, 'Transient response of the Atlantic Meridional Overturning Circulation to enhanced freshwater input to the Nordic Seas-Arctic Ocean in the Bergen Climate Model'. *Tellus* **56**, 342–361.

Otterlei, O., G. Nyhammar, A. Folkvord, and S. O. Stefansson: 1999, 'Temperature- and size-dependent growth of larval and early juvenile Atlantic cod: a comparative study of Norwegian coastal cod and northeast Arctic cod'. *Canadian Journal of Fisheries and Aquatic Sciences* **56**, 2099–2111.

Ottersen, G. and N. C. Stenseth: 2001, 'Atlantic climate governs oceanographic and ecological variability in the Barents Sea'. *Limnol. Oceanogr.* **46**(7), 1774–1780.

Pacanowski, R. C. and S. M. Griffies: 1999, 'The MOM-3 Manual'. Technical Report 4, GFDL Ocean Group, NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ. 680 pp.

Peterson, B. J., R. M. Holmes, J. W. McClelland, C. J. Vörösmarty, R. B. Lammers, A. I. Shiklomanov, I. A. Shiklomanov, and S. Rahmstorf: 2002, 'Increasing river discharge to the Arctic Ocean'. *Science* **298**, 2171–2173, doi: 10.1126/science.1077445.

Peterson, B. J., J. McClelland, R. Curry, R. M. Holmes, J. Walsh, and K. Aagard: 2007, 'Trajectory shifts in the Arctic and Subarctic freshwater cycle'. *Science* **313**, 1061–1066.

Petoukhov, V., A. Ganopolski, V. Brovkin, M. Claussen, A. Eliseev, C. Kubatzki, and S. Rahmstorf: 2000, 'CLIMBER-2: A climate system model of intermediate complexity. Part I: Model description and performance for present climate'. *Clim. Dyn.* **16**, 1–17.

Petschel-Held, G., H.-J. Schellnhuber, T. Bruckner, F. Tóth, and K. Hasselmann: 1999, 'The tolerable windows approach: theoretical and methodological foundations'. *Climatic Change* **41**, 303–331.

Planque, B. and J. Fromentin: 1996, 'Calanus and environment in the eastern North Atlantic. 1. Spatial and temporal patterns of C. finmarchicus and C. helgolandicus'. *Marine ecology – Progress series* **134**(1-3), 101–109.

Rahmstorf, S.: 1997, 'Risk of sea-change in the Atlantic'. *Nature* **388**, 825–826.

Rahmstorf, S.: 2002, 'Ocean circulation and climate during the past 120,000 years'. *Nature* **419**, 207–214.

Rahmstorf, S.: 2006, 'Thermohaline Ocean Circulation'. In: S. A. Elias (ed.): *Encyclopedia of Quarternary Sciences*. Amsterdam: Elsevier.

Rahmstorf, S., M. Crucifix, A. Ganopolski, H. Goosse, I. V. Kamenkovich, R. Knutti, G. Lohmann, R. Marsh, L. A. Mysak, Z. Wang, and A. J. Weaver: 2005, 'Thermohaline circulation hysteresis: a model intercomparison'. *Geophys. Res. Lett.* **32**, L23605, doi: 10.1029/2005GL023655.

Rahmstorf, S. and A. Ganopolski: 1999, 'Long-term global warming scenarios computed with an efficient coupled climate model'. *Clim. Change* **43**, 353–367.

Rahmstorf, S. and K. Zickfeld: 2005, 'Thermohaline circulation changes: a question of risk assessment'. *Climatic Change* **68**, 241–247.

Rignot, E. and P. Kanagaratnam: 2006, 'Changes in the Velocity Structure of the Greenland Ice Sheet'. *Science* **311**(5763), 986–990, doi: 10.1126/science.1121381.

Rounsevell, M., I. Reginster, M. Araujo, T. Carter, N. Dandonker, F. Ewert, J. House, S. Kankaanpaa, R. Leemans, M. Metzger, C. Schmit, P. Smith, and G. Tuck: 2006, 'A coherent set of future land use change scenarios for Europe'. *Agriculture, Ecosystems and Environment* **114**(1), 57–68.

Sarmiento, J. L., T. M. C. Hughes, R. J. Stouffer, and S. Manabe: 1998, 'Simulated response of the ocean carbon cycle to anthropogenic climate warming'. *Nature* **393**, 245–249.

Schaeffer, M., F. M. Selten, J. D. Opsteegh, and H. Goosse: 2002, 'Intrinsic limits to predictability of abrupt regional climate change in IPCC SRES scenarios'. *Geophys. Res. Lett.* **29**(16), 1767, doi: 10.1029/2002GL015254.

Schaeffer, M., F. M. Selten, J. D. Opsteegh, and H. Goosse: 2004, 'The influence of ocean convection patterns on high-latitude climate projections'. *J. Clim.* **17**(22), 4316–4329.

Schaphoff, S., W. Lucht, D. Gerten, S. Sitch, W. Cramer, and I. C. Prentice: 2006, 'Terrestrial biosphere carbon storage under alternative climate projections'. *Clim. Change* **74**(1-3), 97–122, doi: 10.1007/s10584-005-9002-5.

Schmittner, A.: 2005, 'Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation'. *Nature* **434**, 628–633.

Schmittner, A. and A. Weaver: 2001, 'Dependence of multiple climate states on ocean mixing parameters'. *Geophys. Res. Lett.* **28**(6), 1027–1030.

Schneider von Deimling, T., H. Held, A. Ganopolski, and S. Rahmstorf: 2006, 'Climate sensitivity estimated from ensemble simulations of glacial climate'. *Clim. Dyn.* **27**(2-3), doi: 10.1007/s00382-006-0126-8.

Sitch, S., B. Smith, I. C. Prentice, A. Arneth, A. Bondeau, W. Cramer, J. O. Kaplan, S. Levis, W. Lucht, M. T. Sykes, K. Thonicke, and S. Venevsky: 2003, 'Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model'. *Global Change Biology* **9**(2), 161–185.

Six, K. D. and E. Maier-Reimer: 1996, 'Effects of phytoplankton on seasonal carbon fluxes in an ocean general circulation model'. *Global Biogeochem. Cycles* **10**(4), 559–583.

Stern, N.: 2007, *The Economics of Climate Change: The Stern Review*. Cambridge, UK: Cambridge University Press. xix + 692 pp.

Stouffer, R. J., J. Yin, J. M. Gregory, K. W. Dixon, A. J. Weaver, M. J. Spelman, W. Hurlin, and participating groups: 2006, 'Investigating the causes of the response of the thermohaline circulation to past and future climate changes'. *J. Clim.* **19**, 1365–1387.

Sundby, S.: 2000, 'Recruitment of Atlantic cod stocks in relation to temperature and advection of copepod populations'. *Sarsia* **85**, 277–298.

Sundby, S. and O. R. Godø: 1994, 'Life history of Arcto-Norwegian cod stock'. *ICES Coop. Res. Rep.* **205**, 12–45.

Sundby, S. and O. Nakken: 2008, 'Spatial shifts in spawning habitats of Arcto-Norwegian cod induced by climate change'. *ICES Journal of Marine Science* **65**(6), 953–962, doi: 10.1093/icesjms/fsn085.

Swingedouw, D., L. Bopp, A. Matras, and P. Braconnot: 2007, 'Effect of land-ice melting and associated changes in the AMOC results in little overall impact on oceanic CO_2 uptake'. *Geophys. Res. Lett.* **34**, L23706, doi: 10.1029/2007GL031990.

Swingedouw, D., P. Braconnot, and O. Marti: 2006, 'Sensitivity of the Atlantic Meridional Overturning Circulation to the melting from northern glaciers in climate change experiments'. *Geophys. Res. Lett.* **33**, L07711, doi: 10.1029/2006GL025765.

Taub, D. R., B. Miller, and H. Allen: 2007, 'Effects of elevated CO_2 on the protein concentration of food crops: a meta-analysis'. *Global Change Biology* **14**(3), doi: 10.1111/j.1365–2486.2007.01511.x.

Tubiello, F. and F. Ewert: 2002, 'Simulating the effects of elevated CO_2 on crops: Approaches and applications for climate change'. *European Journal of Agronomy* **18**(1-2), 57–74.

Tubiello, F. N., J. S. Amthor, K. J. Boote, M. Donatelli, W. Easterling, G. Fischer, R. M. Gifford, M. Howden, J. Reilly, and C. Rosenzweig: 2007, 'Crop response to elevated CO_2 and world food supply: A comment on "Food for Thought..." by

Long et al., Science 312:1918-1921, 2006'. *European Journal of Agronomy* **26**(3), 215–223.

Velicogna, I. and J. Wahr: 2006, 'Acceleration of Greenland ice mass loss in spring 2004'. *Nature* **443**, 329–331, doi: 10.1038/nature05168.

Vellinga, M. and R. Wood: 2002, 'Global Climatic Impacts of a Collapse of the Atlantic Thermohaline Circulation'. *Clim. Change* **54**(3), 251–267.

Vellinga, M. and R. Wood: 2008, 'Impacts of thermohaline circulation shutdown in the twenty-first century'. *Clim. Change* **91**(1-2), 43–63, doi: 10.1007/s10584-006-9146-y.

Vikebø, F. B., S. Sundby, B. Ådlandsvik, and Ø. Fiksen: 2005, 'The combined effect of transport and temperature on distribution and growth of larvae and pelagic juveniles of Arcto-Norwegian cod'. *ICES J. Mar. Sci.* **62**(7), 1375–1386.

Vikebø, F. B., S. Sundby, B. Ådlandsvik, and O. H. Otterå: 2006, 'Impacts of a reduced THC on transport and growth of Arcto-Norwegian cod'. *Fisheries Oceanography* **16**(3), 216–228.

Wilby, R. L. and T. M. L. Wigley: 1997, 'Downscaling general circulation model output: a review of methods and limitations'. *Prog. in Phys. Geogr.* **21**, 530–548.

Winguth, A., U. Mikolajewicz, M. Gröger, E. Maier-Reimer, G. Schurgers, and M. Vizcaíno: 2005, 'Centennial-scale interactions between the carbon cycle and anthropogenic climate change using a dynamic Earth system model'. *Geophys. Res. Lett.* **32**, L23714, doi: 10.1029/2005GL023681.

Wood, R. A., A. B. Keen, J. F. B. Mitchell, and J. M. Gregory: 1999, 'Changing spatial structure of the thermohaline circulation in response to atmospheric CO_2 forcing in a climate model'. *Nature* **399**, 572–575.

Zaehle, S., A. Bondeau, T. R. Carter, W. Cramer, M. Erhard, I. C. Prentice, I. Reginster, M. D. A. Rounsevell, S. Sitch, B. Smith, P. C. Smith, and M. T. Sykes: 2007, 'Projected changes in terrestrial carbon storage in Europe under climate and land-use change, 1990-2100'. *Ecosystems*, doi: 10.1007/s10021-007-9028-9. Published online.

Zickfeld, K., M. Eby, and A. Weaver: 2008, 'Carbon-cycle feedbacks of changes in the Atlantic meridional overturning circulation under future atmospheric CO_2'. *Global Biogeochemical Cycles* **22**, GB3024, doi: 10.1029/2007GB003118.

Zickfeld, K., A. Levermann, M. G. Morgan, T. Kuhlbrodt, S. Rahmstorf, and D. W. Keith: 2007, 'Expert judgements on the response of the Atlantic meridional overturning circulation to climate change'. *Climatic Change* **82**(3-4), 235–265, doi: 10.1007/s10584-007-9246-3.

Table: Probability of a THC breakdown

Table I. Probability of a THC breakdown p_{br} as a function of the global temperature rise ΔT by 2100. The numbers are derived from a 110-member ensemble of global warming runs from Climber-2 with additional freshwater input. Only four of these members show a warming of more than 4.5 K, while the other bins contain more than 30 members. Hence the probability estimates have differing levels of reliability. If no additional freshwater input is applied, p_{br} is zero in any case.

ΔT interval [K]	1.5–2.5	2.5–3.5	3.5–4.5	4.5–5.5
Probability p_{br}	0.00	0.39	0.61	1.00
Number of members in bin	37	36	33	4

Figures

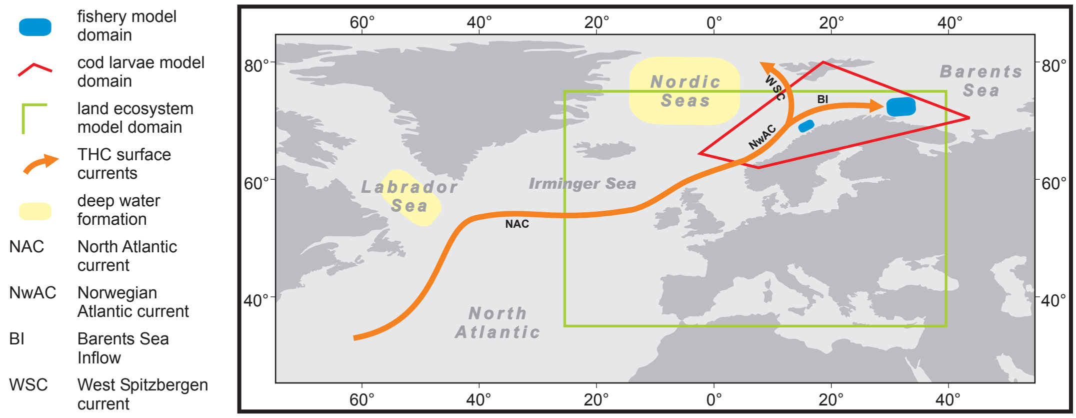

Figure 1. The domains of INTEGRATION's impact models. For the land-borne impacts (green) the focus is on Europe as a whole, while two marine impact models (red, blue) are set in the region of direct influence of the THC surface currents (orange). The coupled climate models Climber-2 and Climber-3α extend over the full globe.

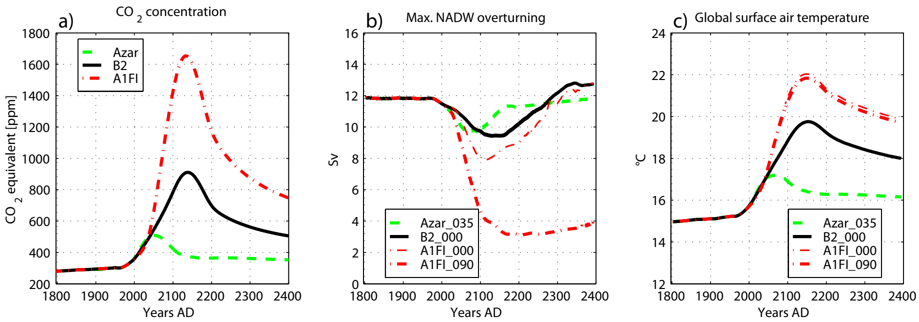

Figure 2. (a) Scenarios of CO_2 equivalent concentrations used in this study. A1FI and B2 are SRES scenarios. The scenario by Azar et al. (2006) assumes strong mitigation efforts. For the SRES scenarios a simple reduction function was assumed after 2100. (b) Maximum of the North Atlantic Deep Water (NADW) volume flux in Sverdrup (Sv; 1 Sv= 10^6 m^3s^{-1}) in the Climber-3α scenarios. The NADW volume flux is a common measure for the THC strength. The THC weakens in all scenarios, even without an additional freshwater input. Only in the A1FI_090 scenario a full breakdown of the THC occurs. (c) Global surface air temperature (annual averages) in the Climber-3α scenarios. The THC breakdown in A1FI_090 triggers a global cooling of about 0.2 K.

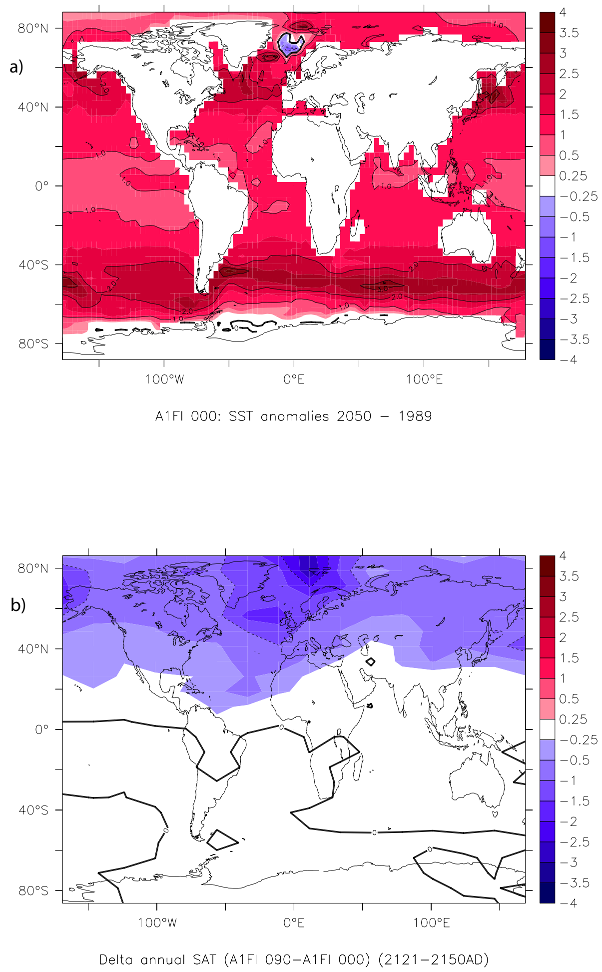

Figure 3. (a) Sea surface temperature anomalies (K), 2050 minus 1989, for the A1FI_000 scenario. The net cooling in the Nordic Seas occurs transiently in the middle of the 21st century in all scenarios. (b) Annual surface air temperature (SAT) difference (K), 2121-2150 averaged, between the A1FI_090 and A1FI_000 scenarios. While there is an absolute warming everywhere (not shown), the THC breakdown triggered by freshwater input in the A1FI_090 scenario leads to a relative cooling compared to a THC weakened by global warming. The relative cooling amounts to more than 2.5 K west of Svalbard.

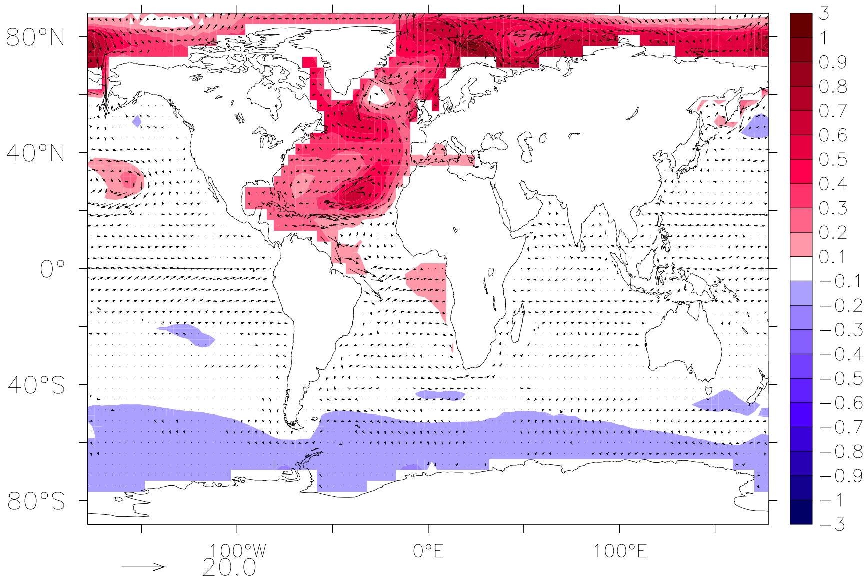

Figure 4. Sea level difference (m) by 2150 between the A1FI_090 and the A1FI_000 scenarios. The displayed sea level rise is the effect of the THC breakdown only. The effect of global warming was subtracted. The arrows show the difference in the surface currents in cm/s. The maximal coastal sea level rise is 80 cm in the Barents Sea.

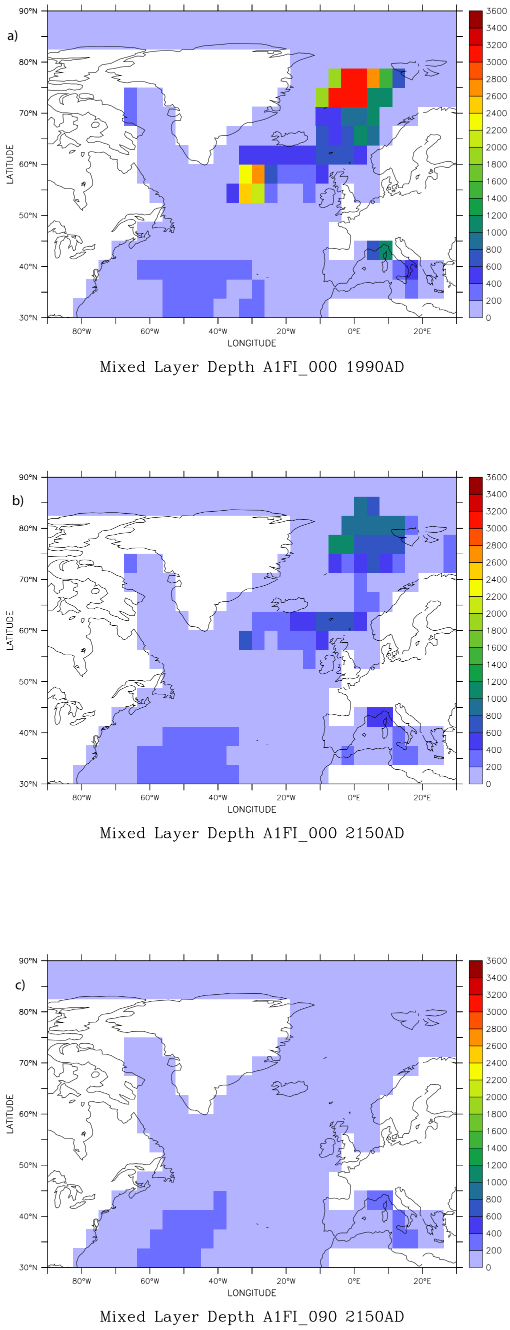

Figure 5. Oceanic mixed layer depth in the A1FI_000 scenario in (a) 1990 and (b) 2150 as well as in the A1FI_090 scenario in 2150 (c). The panels show the winter maximum mixed layer depth. The THC shutdown in the A1FI_090 scenario (c) results in a mixed layer depth of 200 m or less everywhere north of 45°N. This means the complete absence of mixing with deeper water masses.

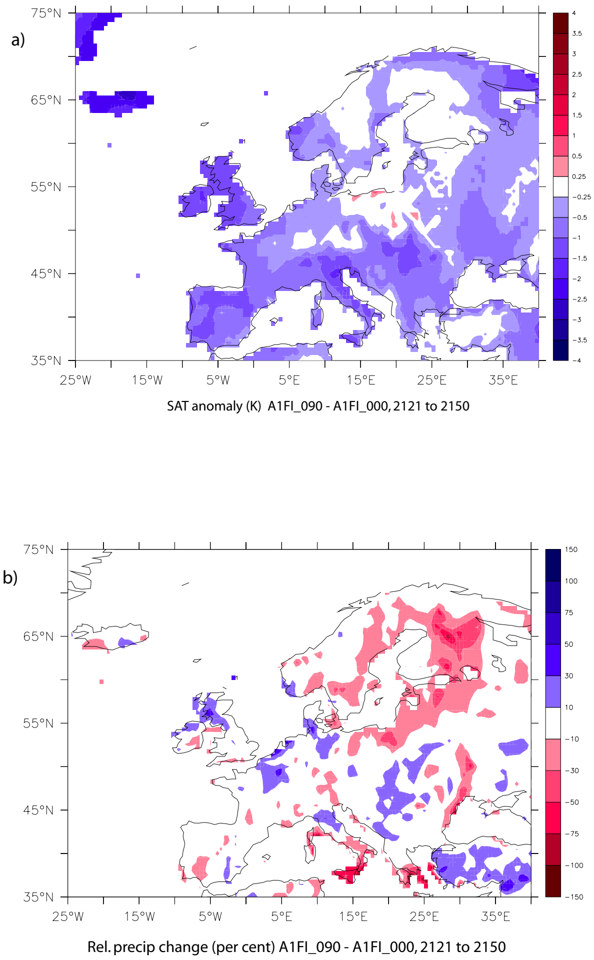

Figure 6. Data from the Climber-3α scenarios downscaled to a $0.5° \times 0.5°$grid. (a) Annual surface air temperature difference (K), 2121-2150 averaged, between the A1FI_090 and A1FI_000 scenarios. The THC breakdown triggers a relative cooling (reduction of global warming trend) of around 1 K in western Europe. (b) Relative changes of the annual precipitation between the same two runs (per cent). Red regions indicate decreasing precipitation while blue indicates precipitation increases. In the white regions the relative changes are less than 10%. The THC breakdown leads to precipitation reductions in northern and eastern Europe.

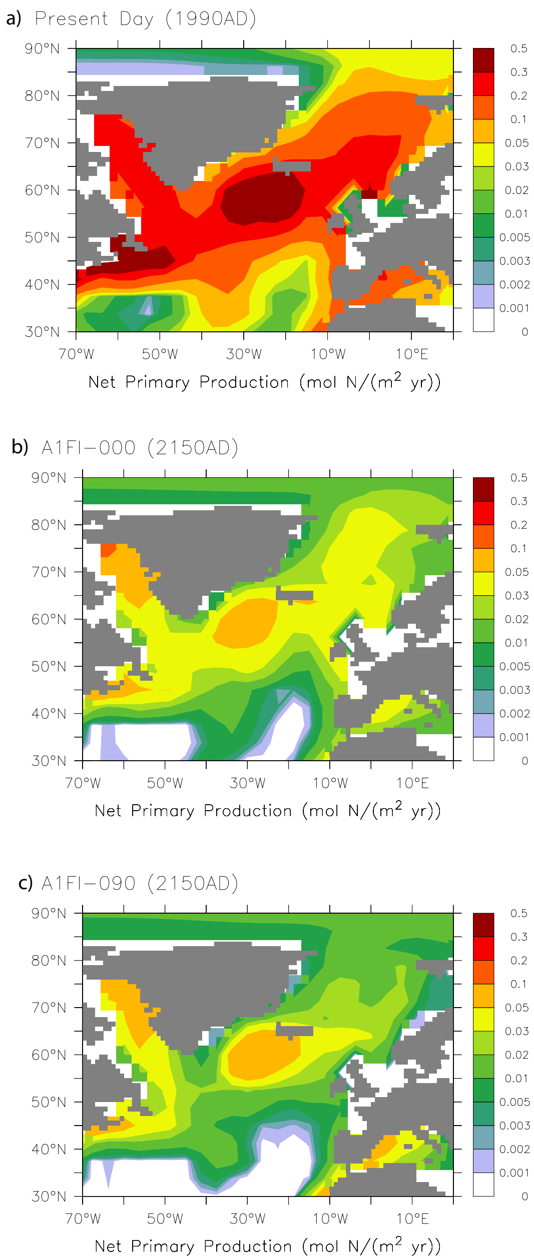

Figure 7. Net Primary Production (NPP) in the North Atlantic in mol N $m^{-2}yr^{-1}$ for (a) 1990, (b) A1FI_000 simulation in 2150 , and (c) A1FI_090 simulation in 2150. In the central Nordic Seas, the NPP reduction amounts to one order of magnitude. The effect of global warming [(b) compared to (a)] is much more pronounced than the effect of a THC breakdown [(c) compared to (b)].

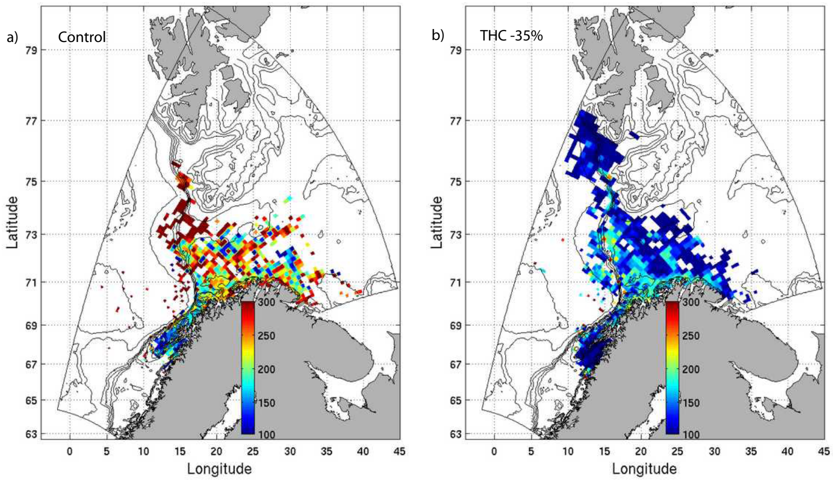

Figure 8. Simulated distribution of pelagic juvenile cod, 2-4 months old depending on the time of spawning, in (a) a control run and (b) a run with a 35% reduction of the THC. All modelled larvae are released in the Vestfjorden (around 13°E/ 68°N), the main spawning site. The colour scale indicates the wet weight of the larvae in mg. From Vikebø et al. (2006).

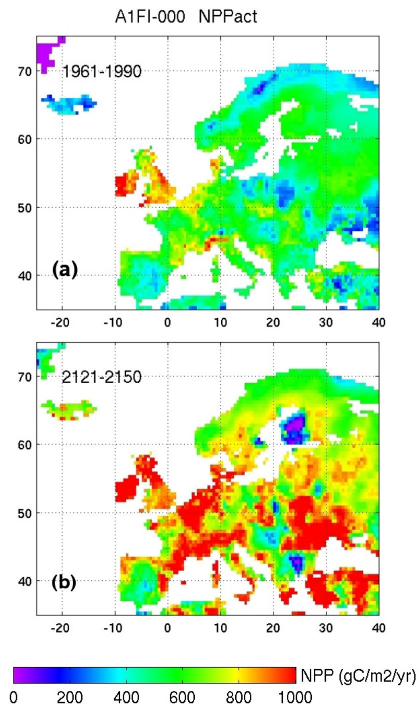

Figure 9. Net primary production (NPP) of the vegetation in Europe, (a) in the control period (1961-1990, averaged) and (b) in the period 2121-2150 (averaged) of the A1FI_000 scenario. These two panels show the impact of global warming, mostly due to CO_2 fertilization: NPP rises strongly in most parts of Europe. There are however areas of dramatic NPP losses, e.g. in southern Finland and northeast Greece.

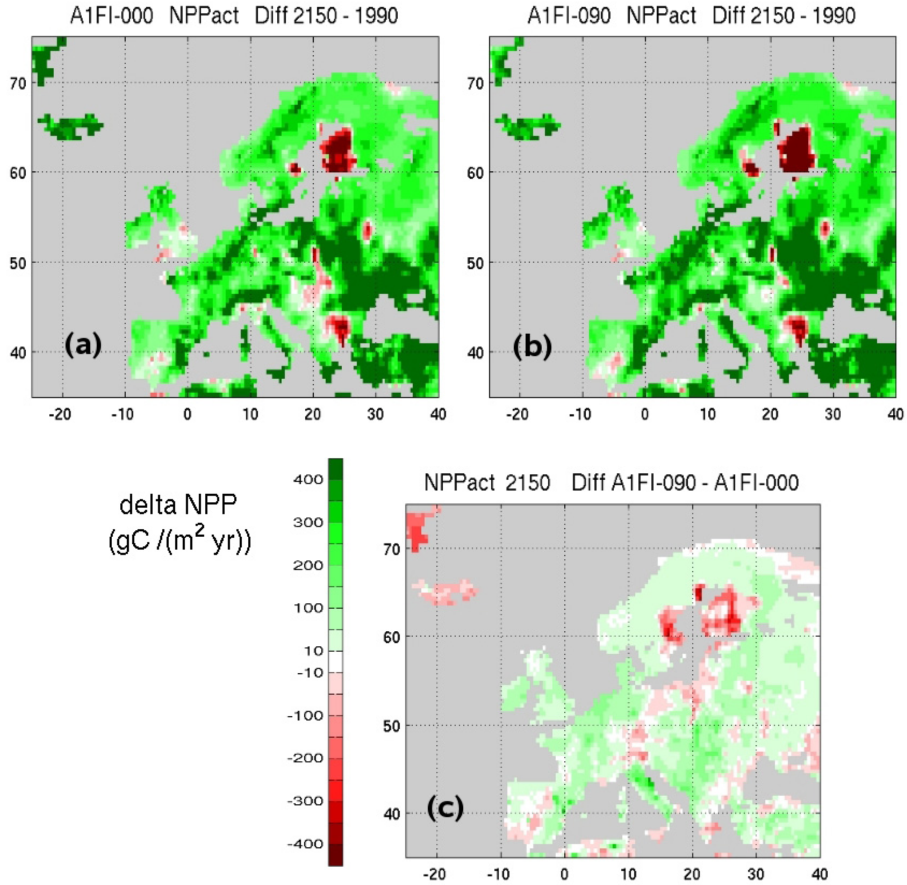

Figure 10. Anomalies of the net primary production (NPP) between the periods 1961-1990 (averaged) and 2121-2150 (averaged) for (a) the A1FI_000 scenario and (b) the A1FI_090 scenarios. The difference of these two plots is shown in (c), which thus displays the net effect of a THC breakdown on the NPP. The THC breakdown has either a positive or a negative impact depending on the region. In most areas the impact of a THC breakdown (c) is clearly smaller than the impact of rising CO_2 concentrations (a, b).

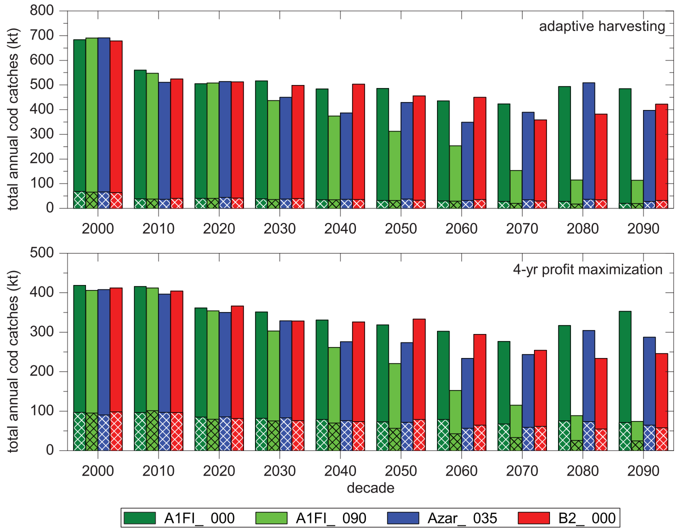

Figure 11. Development of total annual cod catches in the four scenarios A1FI_000, A1FI_090, Azar_035 and B2_000 for adaptive and profit-maximizing harvesting strategies. Shown are decadal averages throughout the 21st century. Hatched areas refer to coastal vessel catches, plain colouring to trawl catches. The A1FI_090 scenario includes a shutdown of the THC. Catches decline strongly in this scenario, irrespective of the harvesting strategy. In the other scenarios, in which the THC weakens but does not shut down, the catches stabilize on levels not much below today's.

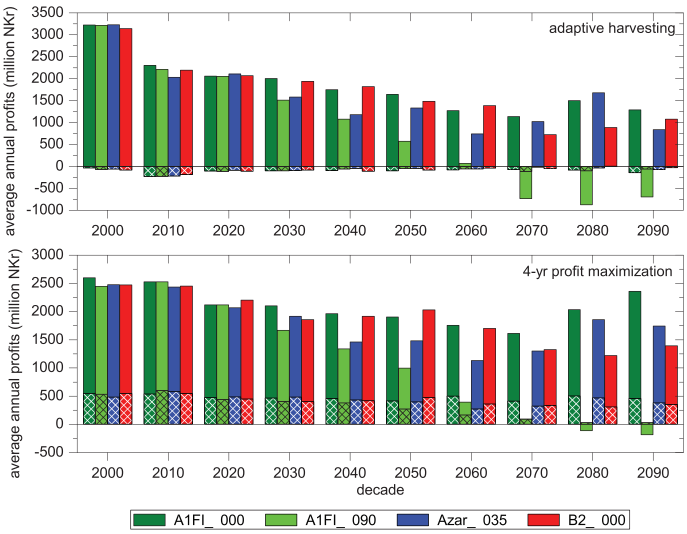

Figure 12. Development of average annual profits from fishing in the four scenarios for adaptive and profit-maximizing harvesting strategies. Shown are decadal averages throughout the 21st century. Hatched areas refer to profits of coastal vessels, plain colouring to profits of the trawl fishery. 7 NKr approximately equal 1 Euro. The A1FI_090 scenario includes a shutdown of the THC, rendering the fisheries of cod unprofitable towards the end of the 21st century.

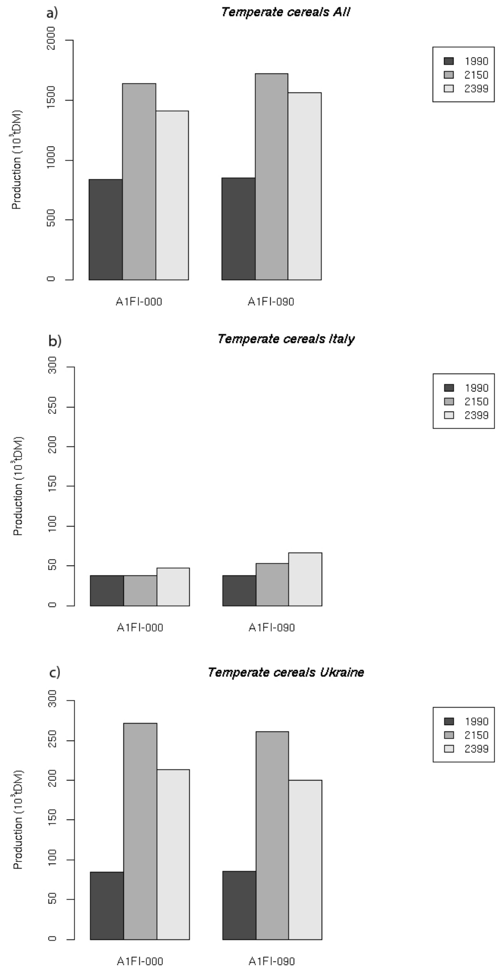

Figure 13. Annual cereal production (a) in Europe, (b) in Italy, and (c) in the Ukraine, based on the LPJmL simulations, in 1000 tons of dry matter. Shown are 30-year averages for the periods 1961-1990, 2121-2150, and 2370-2399. In each panel the left group of columns show the results from the A1FI_000 scenario (no THC breakdown), and the right group of columns refers to the A1FI_090 scenario (with THC breakdown). Integrated over Europe (a) there is a strong positive impact of CO_2 fertilization until 2121-2150 in our simulations. The THC breakdown has an additional, smaller positive impact on the cereal production. This holds true for Italy only as well (b), where the increasing precipitation up to the 24th century has a positive impact too. By contrast, the huge cereal production of the Ukraine (c) would experience losses through a THC breakdown, while still gaining much from CO_2 fertilization.

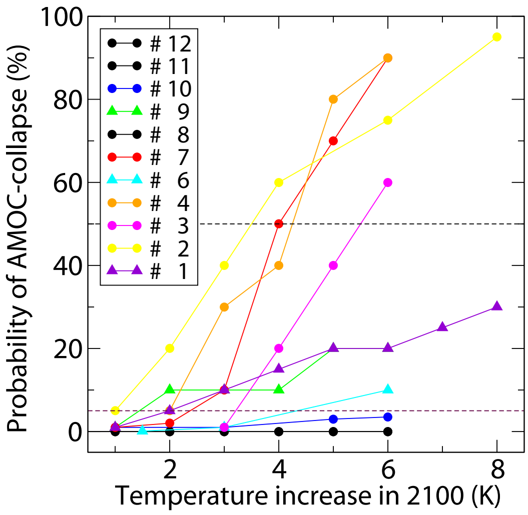

Figure 14. Elicited subjective probabilities of THC experts "that a collapse of the THC will occur or will be irreversibly triggered" as a function of the global mean temperature increased realized in the year 2100. Experts 8, 11, and 12 estimated zero probability in all cases, represented by the black line. Expert 5 gave no estimates. From Zickfeld et al. (2007).

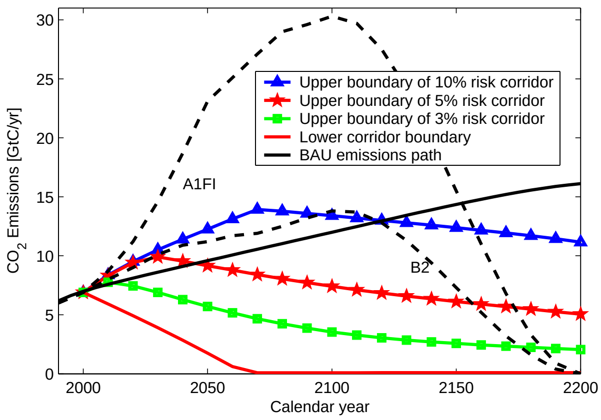

Figure 15. Emissions corridors—the area between respective upper and lower boundaries—limiting the probability of a breakdown of the THC to 10%, 5% and 3%, respectively. The lower boundary is the same for the three corridors as it is determined solely by the socioeconomic constraints (which are set to the same default values in all three cases). For comparison, we display the reference (business-as-usual, BAU) emissions path which is obtained by applying the DICE model without climatic and economic constraints, and the SRES scenarios A1FI and B2 with our tapering-off extension beyond 2100 (dashed).

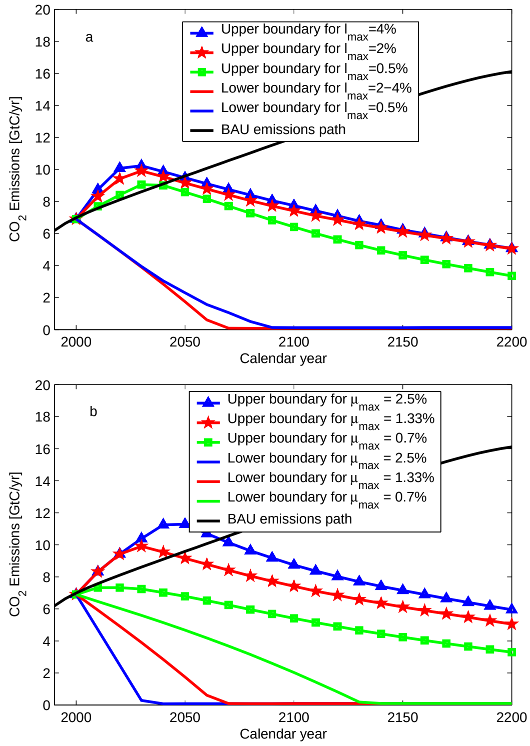

Figure 16. Sensitivity of the 5% risk-corridor to the socioeconomic guardrails: (a) 5% risk-corridor for different values of the maximum admissible welfare loss $l_{\max}$, (b) 5% risk-corridor for different values of the maximum admissible emissions reduction rate $\mu_{\max}$.