LONG-TERM GLOBAL WARMING SCENARIOS COMPUTED WITH AN EFFICIENT COUPLED CLIMATE MODEL

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Abstract. We present global warming scenarios computed with an intermediate-complexity atmosphere-ocean-sea ice model which has been extensively validated for a range of past climates (e.g., the Last Glacial Maximum). Our simulations extend to the year 3000, beyond the expected peak of CO_2 concentrations. The thermohaline ocean circulation declines strongly in all our scenarios over the next 50 years due to a thermal effect. Changes in the hydrological cycle determine whether the circulation recovers or collapses in the long run. Both outcomes are possible within present uncertainty limits. In case of a collapse, a substantial long-lasting cooling over the North Atlantic and a drying of Europe is simulated.

1. Introduction

In the present climatic state, the northern North Atlantic and northwestern Europe are exceptionally warm for their latitude because they benefit from ocean heat transport. The data analysis presented in Figure 1 illustrates this; annual-mean air temperatures off Scandinavia exceed the zonal average by more than 10 °C. Hydrographic measurements (Roemmich and Wunsch, 1985) and simple heat budget calculations confirm that the thermohaline (i.e., density-driven) component of the ocean circulation, sometimes dubbed 'conveyor belt', is responsible for the unusual warmth. Paleoclimatic records from Greenland ice cores (Bond et al., 1997) suggest that this mode of operation has persisted, with some smaller fluctuations, since the last major reorganisation of ocean circulation terminated the Younger Dryas cold event ca. 11,500 years ago (Severinghaus et al., 1998) and the Holocene began. The time period before that, going back at least 100,000 years, is characterised by repeated large cooling and warming events associated with mode changes of the Atlantic thermohaline circulation (Bond et al., 1993; Dansgaard et al., 1993).

Based on the past instability of the Atlantic 'conveyor belt' and on physical considerations, warnings have been raised repeatedly that anthropogenic climate change might trigger another instability of the circulation and a severe cooling over the North Atlantic and parts of Europe (Broecker, 1987, 1997; White, 1993). A large number of model simulations (reviewed in Rahmstorf et al., 1996) have confirmed the sensitivity of the circulation to freshwater input and the fact that a collapse would cause a strong cooling. The pattern of this cooling, seen in atmospheric models driven by cold North Atlantic conditions (Schneider et al., 1987) and in coupled models (e.g., Manabe and Stouffer, 1988, and also in the

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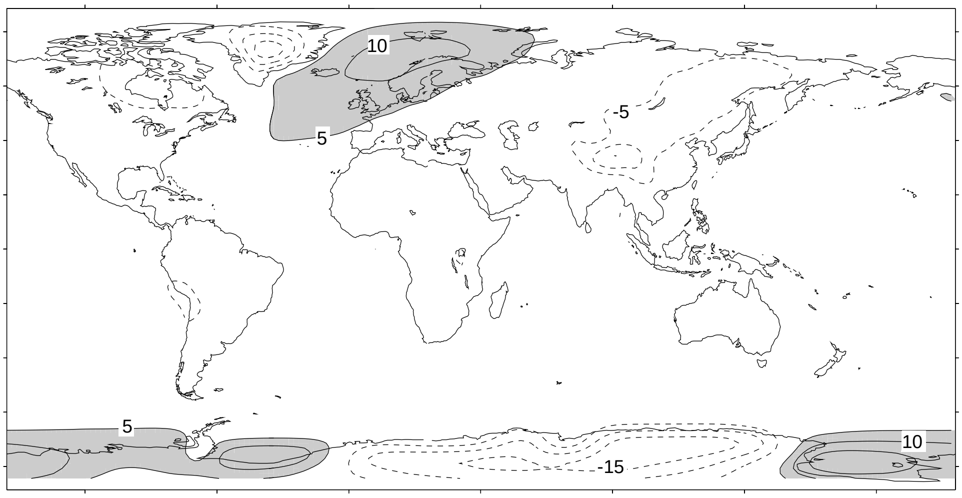

Figure 1. Deviation of the annual-mean surface air temperature from its zonal average, computed from the NCAR air temperature climatology. Anomalously cold areas are found over some continental regions, anomalously warm areas over ocean deep water formation regions.

CLIMBER-2 model, Ganopolski et al. 1998c), is similar to the pattern of anomalous warmth shown in Fig. 1. Until now, however, the hypothesis that *global warming* could lead to a cooling of Europe has not been supported by model simulations. None of the published greenhouse scenarios shows such a cooling, even though most show a decline and some even a complete shutdown of the thermohaline circulation (Rahmstorf 1997).

We present a new set of long-term greenhouse scenarios which demonstrate that a permanent and large cooling over the northern Atlantic and parts of Europe may indeed be triggered by anthropogenic greenhouse gas emissions. Our scenarios assume that greenhouse gas concentrations will peak in the 22nd century and decline afterwards. The results suggest that the climate system may not recover from the temporary peak in greenhouse gas concentrations for a very long time, but may be pushed into a different quasi-stable mode of operation without North Atlantic Deep Water (NADW) formation. In a sensitivity study we explore the causes of anthropogenic ocean circulation changes; we find that an initial decline of the Atlantic circulation over the next century is mainly caused by direct thermal forcing, while the long-term fate of the circulation is determined by the amount of freshwater input. We address the uncertainty in the freshwater forcing, the most probable cause for differences between different models, by introducing a hydrological sensitivity parameter. Within the current range of uncertainty, both outcomes of the anthropogenic peak in atmospheric CO_2 content are equally possible: a decline and subsequent recovery or a complete collapse of the Atlantic thermohaline circulation.

2. Simulations with a Computationally Efficient Climate Model

The CLIMBER-2 model and its pre-industrial equilibrium climate are described in Ganopolski et al. (1998b) and in more detail in Petoukhov et al. (1998). The atmosphere model is based on the statistical-dynamical approach and does not resolve synoptic variability; the synoptic fluxes are parameterised as diffusion terms with a turbulent diffusivity computed from atmospheric stability and horizontal temperature gradients. The predicted three-dimensional fields of velocity (including e.g., Hadley circulation, jet streams), temperature and moisture are used to compute advective fluxes. The radiation scheme (16 levels) accounts for water vapour, ozone, CO_2 and the computed cloud cover (stratiform and cumulus). The ocean model is a multi-basin zonally averaged model similar to Stocker and Wright (1991). The sea ice model predicts ice thickness and concentration and includes ice advection. In the model hierarchy, our model is placed in between energy balance models and general circulation models (GCMs). The model describes a large set of processes and feedbacks in the climate system, comparable to that of GCMs, but due to low spatial resolution and simplified governing equations our model has a much faster turnaround time.

The high computational speed of the model is associated with some drawbacks; it predicts only continental or basin-scale climatic features (such as the Azores high and the Aleutian low pressure systems) and a very limited amount of internal climate variability. Nevertheless, for the large-scale climatological features which the model is designed to capture, the quality of the simulation is within the range of current GCMs. This can be seen by comparing the CLIMBER-2 climate with results from GCMs participating in model intercomparison projects (AMIP, CMIP), with respect to annual means and seasonal variability of atmospheric and oceanic temperature, sea level pressure, cloudiness, precipitation, radiative fluxes etc. A number of sensitivity studies (e.g., reproducing the climate state without North Atlantic Deep Water formation found in Manabe and Stouffer, 1988) has also demonstrated good agreement with GCM results (Ganopolski et al., 1998b, c). The stability diagram showing the freshwater sensitivity of the coupled model agrees well with the one calculated by Rahmstorf (1996); an additional freshwater input of $\sim$0.15 Sv to the present climate brings the model to the bifurcation point for a circulation shutdown.

We integrated the CLIMBER-2 model for 5,000 model years with a prescribed atmospheric CO_2 concentration of 280 ppm to obtain a pre-industrial equilibrium climate (with no climate drift), from which the CO_2 scenario simulations were started. Model parameters that were not fixed a priori were determined by tuning the atmospheric and oceanic components separately for present conditions before coupling (e.g., constants in the cloud parameterisation). No space-dependent parameters were tuned (so-called 'hidden flux adjustments'), neither were any flux adjustments used in the coupling. The model has been validated against the climate of the Last Glacial Maximum at 21 kyr b.p. (Ganopolski et al., 1998b) and found to agree well with paleo-climate reconstructions, not only for surface temperatures but also for the simulated changes in thermohaline ocean circulation. Other time slices (Holocene optimum at 6 kyr b.p., Ganopolski et al., 1998a, Eemian interglacial at 125 kyr b.p., glacial inception at 115 kyr b.p.) as well as a transient Holocene experiment (9 kyr b.p. up to the present; manuscripts in preparation) have also been analysed and have not revealed any major discrepancies between model and paleo-data.

3. Greenhouse Gas Scenario and Sensitivity

The CO_2 scenario investigated in this study is shown in Figure 2a. Other anthropogenic greenhouse gases or aerosols were not considered. We start the simulation at the pre-industrial equilibrium climate in the year 1800 and use the observed CO_2 concentration (Neftel et al., 1990; Keeling and Whorf, 1991) until the present. The forcing then follows the IPCC IS92e scenario (Houghton et al., 1995) to the year 2100. This is the scenario with the fastest increase in CO_2 (but as we do not include other greenhouse gases our scenario may underestimate future radiative forcing); it is used here to investigate possible long-term climatic risks of unchecked fossil fuel use, in particular for the thermohaline ocean circulation. After the year 2100, carbon dioxide concentrations peak in 2150 at 1200 ppm ($\sim$3.3 times the present level) and then decline as shown in the figure. The scenario assumes that fossil fuel use will eventually cease as diminishing reserves, increased extraction costs and new energy technologies bring an end to the fossil fuel era (Campbell and Laherrère, 1998). After the year 2200 we assumed zero emissions; with an e-folding time of 150 years, the CO_2 concentration then asymptotically declines, due to oceanic absorption, to a level of 395 ppm (Maier-Reimer and Hasselmann, 1987). The sensitivity to different radiative forcing scenarios will be the focus of a future study.

As a benchmark test, we also computed the sensitivity of the model climate to a permanent doubling of CO_2, by running the coupled model to equilibrium with a CO_2 level of 560 ppm. The resulting global mean temperature is 3.0 °C warmer than the pre-industrial climate; this sensitivity is in the middle of the range given by the IPCC (Houghton et al., 1995). It is not prescribed or tuned in the CLIMBER-2 model but is the net result of several feedback loops, including ice and snow albedo, water vapour and cloud cover. The Atlantic thermohaline circulation in the CO_2 doubling experiment declines from 19 Sv to 14 Sv and then gradually recovers.

4. Climate of the Next Century

The modelled global temperature increases by 0.7 °C between 1860 and 1990. This is close to the observed estimate of 0.6 °C (Houghton et al., 1995). The increase

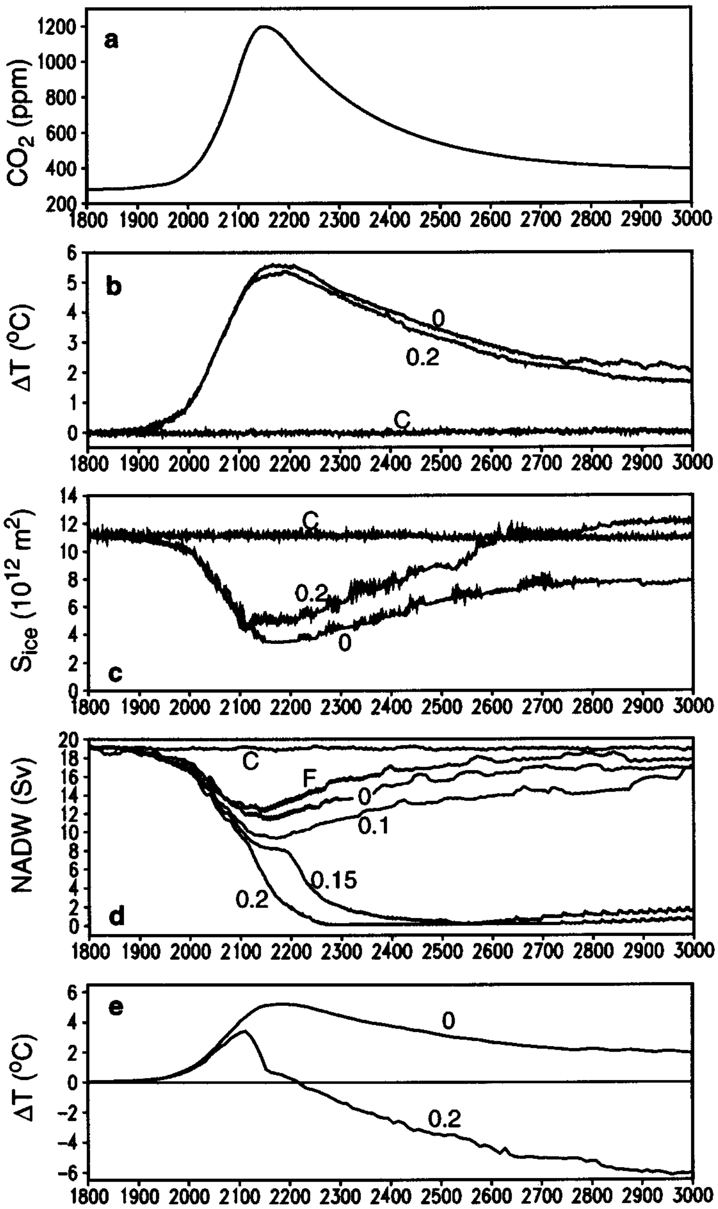

Figure 2. Time series of key model variables: (a) prescribed CO_2 forcing scenario, (b) global annual-mean surface air temperature change, (c) annual-mean area of Northern Hemisphere sea-ice cover, (d) North Atlantic Deep Water circulation rate (i.e., maximum value of the meridional transport stream function), and (e) winter (DJF) surface air temperature change over the Atlantic at 55° N. The experiment labelled 'C' is a pre-industrial control run, 'F' is a run with fixed pre-industrial freshwater forcing, '0' is the standard scenario, and '0.1' etc. are scenarios with enhanced freshater forcing as explained in the text.

to the year 2100 is 4.3 °C (Figure 2b); by this time the annual mean Arctic sea ice area has shrunk by half, mostly due to a reduction in its summer extent (Figure 2c). These results are consistent with other models using comparable forcing scenarios (Manabe et al., 1992).

For a more detailed comparison with previous GCM simulations, we show the patterns of temperature and precipitation changes by the year 2100 in Figure 3. These show the major robust features also found in GCM scenarios. The warming is amplified in high latitudes, with the Southern Hemisphere warming more slowly than the Northern Hemisphere. Maximum warming occurs in the Arctic in winter and over the boreal continents in summer. The North Atlantic region warms less than other areas at the same latitude, due to deep mixing and a reduction in thermohaline ocean circulation. Precipitation increases in the tropics, high latitudes and summer monsoon regions. The patterns in the year 2200 (the time of maximum warming, see Figure 3b for temperature) resemble those in the year 2100 albeit with a larger amplitude.

Overall our results agree with previous scenario simulations performed with coupled GCMs. Some critics (e.g., Lindzen, 1990, 1993) have questioned greenhouse simulations on the grounds that models use flux adjustments, that their control climates are not equilibrated and drift, and that the models have not been validated for climatic states other than the present. While our model has other limitations, it is worth noting that it does not use flux adjustments, has an equilibrium control climate with zero drift and has been successfully validated in a range of paleo-climate simulations. In this sense, our scenarios add to the credibility of previous greenhouse simulations and provide additional evidence that their results are robust.

5. Ocean Circulation

Previous scenario simulations have suggested that for an increase in greenhouse forcing, the formation of deep water in the oceans and the thermohaline circulation would be reduced and could even shut down altogether (Manabe and Stouffer, 1993, 1994; Stocker and Schmittner, 1997). Our standard scenario shows a reduction in North Atlantic Deep Water (NADW) formation from 19 Sv to 12 Sv by the end of the next century (Figure 2d). As major changes in ocean circulation could have serious (still largely unexplored) consequences, we will examine the sensitivity of the ocean circulation and the cause of the simulated reduction in flow.

To this end, several modified scenario simulations were performed. In scenario 'F' the surface freshwater forcing of the ocean (precipitation, evaporation, runoff and meltwater from sea ice) was kept fixed at the pre-industrial level. This is to isolate the effect of surface warming from the effect of changes in the hydrological cycle. The hydrological cycle is harder to predict than temperature changes, and

shows greater variation between different models. Our model shows only weak changes in hydrological forcing in the Atlantic compared to the GCM of Manabe and Stouffer (1994). For a quadrupling of CO_2, the latter model shows an additional freshwater flux of 0.22 Sv into the North Atlantic (north of 50° N) and the Arctic Ocean, while the same number for the CLIMBER-2 model is only 0.05 Sv. We therefore also consider scenarios with an enhanced hydrological response.

To define these scenarios, we use the fact that the modelled increase in freshwater flux north of 50° N is approximately proportional to the increase in hemispheric temperature:

$$\Delta F = k \Delta T^{NH}, \tag{1}$$

where ΔT^{NH} is the change in the mean Northern Hemisphere temperature (relative to the pre-industrial value) and k is the proportionality factor; in the CLIMBER-2 model this has a value of $k_c = 0.01$ Sv/K. Such a linear relationship can be supported by theoretical arguments and seems to hold also in other models (Manabe and Stouffer, 1994), but with a different sensitivity k. Another possible freshwater source, not taken into account in the GCM simulations cited above and in our standard scenario, is increased meltwater runoff from the Greenland Ice Sheet and from glaciers. This can also be approximately described by Equation (1), making the total hydrological sensitivity the sum of a vapour transport and a glacier melt component.

To study the effect of a stronger hydrological response we add an additional freshwater input $\Delta F' = k_a \Delta T^{NH}$ into the North Atlantic (50° N–70° N) in some simulations, so that the effective hydrological sensitivity becomes $k = k_c + k_a$. The proportionality constant k_a is chosen to give a maximum freshwater anomaly $\Delta F'$ of 0.1 Sv, 0.15 SV or 0.2 Sv at the time of maximum warming (scenarios labelled ‘0.1’, ‘0.15’ and ‘0.2’, corresponding to $k = 0.03$, 0.04 and 0.05). The GCM of Manabe and Stouffer (1994) has a hydrological sensitivity of $k = 0.03$ (0.22 Sv for a 7.5 °C hemispheric warming) resulting from vapour transport changes. In addition, that GCM predicts a melting rate of the Greenland ice sheet of 0.11 Sv giving a total of $k = 0.045$. According to other mass-balance estimates (Houghton et al., 1995), the contribution from Greenland could be 0.02–0.04 Sv at the height of warming. Taking uncertainty and other glaciers into account, a ‘worst case’ estimate of 0.1 Sv is thus not unrealistic. These considerations motivate our scenarios with enhanced freshwater input. We cannot yet say which of our scenarios is the most realistic. As a consistency check, we repeated the scenarios for a permanent doubling and quadrupling of CO_2 described in Manabe and Stouffer (1994) with CLIMBER-2. With a consistent choice of hydrological sensitivity ($k = 0.03$) we obtained qualitatively consistent results, i.e., a weakening and recovery of the Atlantic thermohaline circulation for CO_2 doubling and a shutdown for CO_2 quadrupling.

In further sensitivity tests, the freshwater added to the northern Atlantic in our simulations was either removed from the Pacific (‘interbasin vapour transport case') or from the tropical Atlantic (20° S–20° N; 'meridional vapour transport case') or not compensated at all ('meltwater case'). The difference in the circulation response between these three cases is small, e.g., the critical freshwater flux differs by less than 25% between the meltwater case and the meridional transport case. The reason is that on the time scale of greenhouse warming, the circulation responds directly to forcing in the northern North Atlantic, with little sensitivity to changes elsewhere. This is an important difference between the transient response to global warming and the equilibrium response studied by Rahmstorf (1996).

Figure 2d shows that in all scenarios NADW formation weakens substantially during the first half of the next century. The temporary reduction in NADW formation, even for a fixed hydrological cycle, can be reproduced in the conceptual model of NADW flow of Rahmstorf (1996); it happens because the North Atlantic takes up more heat than the stratified South Atlantic and the meridional density gradient which drives NADW flow is reduced. This reduction is amplified by Stommel's positive salt advection feedback (Stommel, 1961), so that reduced salinity contributes as much as warming to the weakening of density gradient and circulation, even for fixed freshwater forcing.

After the year 2100, the scenarios diverge, falling into two categories: those in which NADW formation recovers and those in which it shuts down completely. This indicates the existence of a threshold value, consistent with other model experiments and our theoretical understanding of thermohaline circulation stability (reviewed in Rahmstorf et al., 1996). For the given CO_2 scenario and climate sensitivity (3 °C), the critical threshold of k is $k_{\mathrm{crit}} = 0.04$ Sv/K. Figure 4 shows snapshots of the Atlantic circulation at different times for two scenarios on either side of the threshold. These show that the initial weakening of NADW formation also leads to a shallower NADW flow. At year 2100 both scenarios still have a very similar circulation; there are no warning signs that the circulation in the '0.2' scenario is about to collapse. The formation rate of Antarctic Bottom Water declines by up to 50% in the simulations.

6. Climate of the Next Millennium

The maximum global warming is reached several decades after the CO_2 concentration peak (Figure 2a, b), and the subsequent decline in global temperature is much slower than the CO_2 concentration decline. While the prescribed CO_2 anomaly is back to half its peak value in the year 2330, the temperature anomaly takes to around the year 2600 to go back to half its peak level.

The global mean temperatures of the different scenarios remain within 0.5 °C of each other, even after the ocean circulations have diverged. Regional differences are large, however, especially over the high-latitude North Atlantic. Figure 2e shows the evolution of the near-surface winter air temperature over the Atlantic at 55° N. In the '0.2' scenario it rises by 3 °C until the year 2100 but then drops by almost

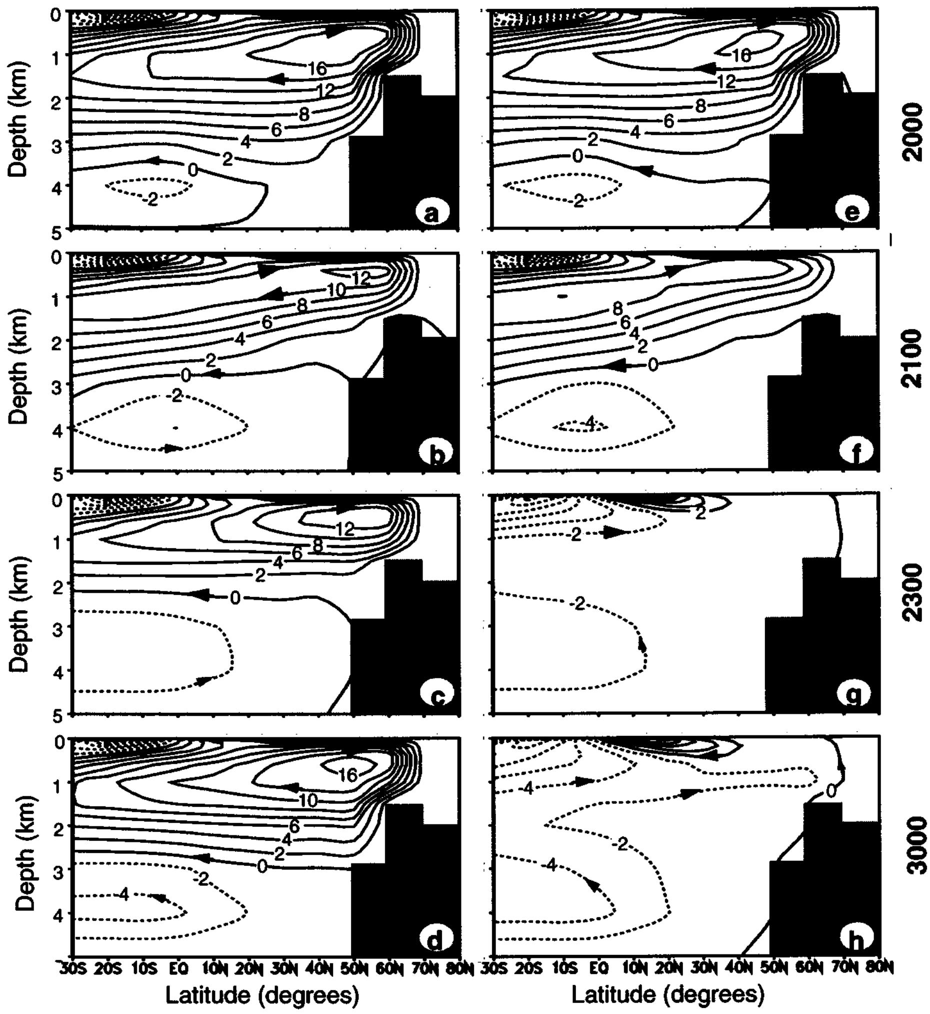

Figure 4. Model-simulated meridional overturning stream function of the Atlantic Ocean for the years 2000, 2100, 2300 and 3000, for the standard scenario (left) and the '0.2' scenario (right).

3 °C within 40 years during the rapid shutdown phase of the thermohaline circulation. This is an extremely rapid rate of change which would have serious ecological and socio-economic implications. The cooling does not stop there, however; it continues until the end of the next millennium, when it is over 6 °C colder than at pre-industrial times. In the scenarios without a circulation collapse, the North Atlantic temperatures remain warmer than at present.

A map of the surface temperature effect of the circulation shutdown is presented in Figure 5. The low resolution of our model does not allow for regional details, but the evidence from Figure 1 leaves little doubt that the large cooling over the North Atlantic would affect the northwestern parts of Europe. A comparable pattern can

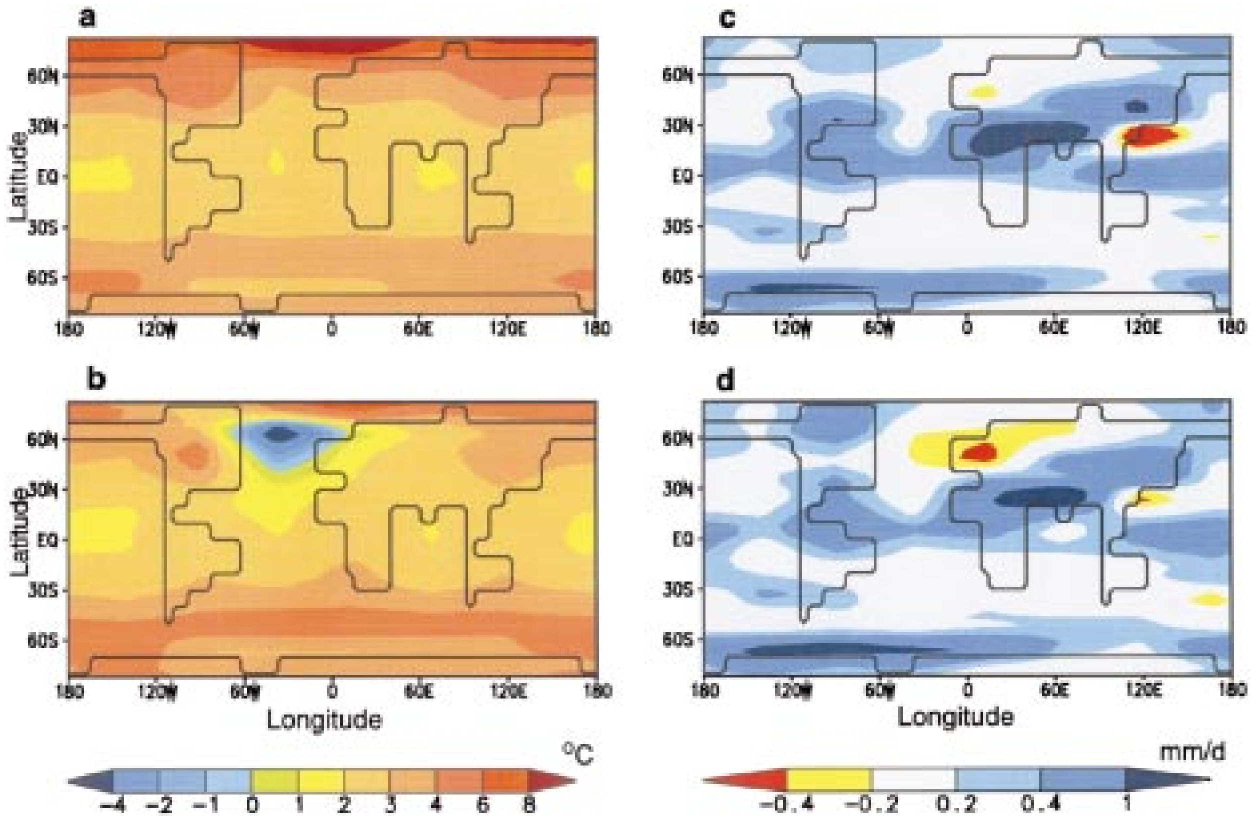

Figure 5. Simulated winter surface air temperature change (left) and summer precipitation change (right) for the year 2500 relative to the year 1800, for the standard scenario (top) and scenario ‘0.2’ with collapsed thermohaline circulation (bottom).

be seen in much greater regional detail in the circulation shutdown simulations (albeit without CO_2 changes) performed with coupled GCMs (Manabe and Stouffer, 1993; Schiller et al., 1997). Downwind of the colder North Atlantic, over large parts of Europe, the summer precipitation is reduced by over 0.4 mm/d.

Sea ice in the model shows less than 10% reduction up to the present day (Figure 2c) but a rapid decline in the next century. In the Southern Hemisphere, the modelled sea ice area undergoes a particularly rapid loss between 2020 and 2030 (not shown). Unlike the Northern Hemisphere (Figure 2c), the Southern Hemisphere remains almost ice-free until the end of next millennium. Sea ice simulation in the Southern Ocean is questionable in the highly simplified geography of the CLIMBER-2 model (even though the simulated present-day seasonal sea-ice cycle is not unrealistic), so that this should not be considered a reliable result unless confirmed by further studies. Should such a loss of sea ice occur, serious consequences for wildlife would be expected.

Our results suggest that the reason most previous greenhouse studies have not found a cooling in the North Atlantic region is because the simulations did not extend far enough into the future (i.e., beyond the year 2100) to reach the point of circulation collapse. The pioneering long-term study of Manabe and Stouffer (1993, 1994) did find a circulation collapse, but in an idealised scenario in which atmospheric CO_2 rises to four times the pre-industrial level and is then kept indefinitely at this value. The warming associated with this extremely high atmospheric CO_2 content more than compensates the cooling due to the ocean circulation change, both in Manabe and Stouffer's model and in a rerun of the same scenario with the CLIMBER-2 model. Maintaining such a high CO_2 concentration requires ongoing high emissions, which we consider unlikely (Campbell and Laherrère, 1998).

7. Conclusions

We have presented a series of long-term global warming scenario simulations, assuming atmospheric CO_2 emissions continue to rise unchecked throughout most of the next century and then gradually decline to zero. For the next century our results are consistent with comparable scenarios with coupled GCMs of medium climate sensitivity (in terms of the IPCC range, Houghton et al., 1995). Our model was extensively validated with paleo-climate simulations, which suggest that its climate sensitivity is plausible. In particular, our model gave realistic cooling for the Last Glacial Maximum over the high-latitude ice sheets ($\sim$25 °C; a test mainly of ice-albedo feedback) as well as in the tropics ($\sim$4 °C; a test mainly of CO_2 sensitivity including water vapour and cloud feedback). Our results therefore strengthen the mainstream global warming assessment of the IPCC.

Our simulations extend beyond the peak CO_2 concentration, and we have focussed in particular on the possible long-term response of the thermohaline ocean circulation. As changes in hydrological cycle affect the ocean circulation and are one of the most uncertain aspects of model simulations, we have computed a range of scenarios with different hydrological changes. A significant reduction in North Atlantic Deep Water formation over the next 50 years occurs in all our scenarios (as it does in most comparable GCM experiments). We conclude that this *initial* reduction is largely due to surface warming, not to changes in the water cycle. The water cycle does, however, determine whether a critical threshold is exceeded and the Atlantic thermohaline circulation breaks down altogether, or whether it gradually recovers throughout the next millennium. Both atmospheric vapour transport changes and meltwater from continental ice could contribute significantly to a critical threshold in the climate system being reached. An ocean circulation breakdown would lead to a vary rapid cooling over the North Atlantic and adjacent land areas, and could eventually leave northwestern Europe several degrees colder and much drier than at present.

Our results confirm the conclusion of earlier studies (Manabe and Stouffer, 1993; Stocker and Schmittner, 1997) that unchecked greenhouse gas emissions could trigger a circulation shutdown in the Atlantic, and that this risk would be reduced if emissions are constrained. Unfortunately, the critical threshold value of the circulation is not exactly known and present models can only give a rough estimate (Rahmstorf, 1997); further studies are urgently needed. Modern GCMs, which are much improved over earlier versions, are computationally too expensive for performing many long-term simulations. Our sensitivity study provides a context in which a well-chosen single GCM scenario simulation of several centuries duration, combined with a diagnosis of the hydrological sensitivity parameter, could provide more accurate information about the critical threshold value of the Atlantic circulation.

Our results illustrate how the industrial development path chosen in the next decades may affect our planet's climate for a thousand years to come. In the '0.15' and '0.2' freshwater flux increase scenarios, the Atlantic circulation does not recover even when the simulation is extended for another 5,000 years; the climate system is shifted to a different stable mode with a much colder and dryer northwestern Europe.

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