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Changes in oceanic circulation of the North Atlantic as a result of an increase in atmospheric greenhouse gas concentrations

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The coupled ocean–atmosphere general circulation model developed at the Max-Planck-Institut für Meteorologie is forced with slowly increasing concentrations of atmospheric CO_2, corresponding to the International Panel on Climate Change "business as usual" scenario. As a consequence of this forcing the global mean surface air temperature increases by 2.9 K after 100 years of simulation. In the northern North Atlantic the warming is much less. This is connected with a continuous reduction in the formation rate of North Atlantic Deep Water. The thermohaline circulation of the Atlantic slows down and the structure of sea-surface salinity changes develops with negative values at 50°N and positive values at low latitudes.

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Introduction

During the last decade the problem of climate change as a consequence of the continuous increase in atmospheric greenhouse gas concentrations due to anthropogenic emissions has attracted an increasing interest from the public. Early three-dimensional modelling studies with atmospheric general circulation models (AGCM) coupled to a 50-m mixed layer ocean (e.g., Hansen *et al.*, 1984; Wetherald and Manabe, 1986; Wilson and Mitchell, 1987; Schlesinger and Zhao, 1989) focused public interest on global warming. More recent simulations with AGCMs coupled to three-dimensional ocean general circulation models (OGCMs) have shown the importance of a more realistic treatment of the thermohaline circulation of the ocean for a reliable estimate of future climate changes (e.g., Stouffer *et al.*, 1989; Cubasch *et al.*, 1992, 1993). The large heat capacity of the ocean makes the adaptation of the climate system to a change in the radiative forcing a much slower process than was estimated from the early modelling studies with AGCM plus slab ocean.

Model

In this paper we discuss results from simulations with the coupled ocean–atmosphere general circulation model (COAGCM) developed at the Max-Planck-Institut für Meteorologie in Hamburg. The atmospheric component of the model is the ECHAM1 AGCM (Roeckner *et al.*, 1989). This spectral model has a T21 resolution and 19 levels in the vertical. The oceanic component is the Large-Scale-Geostrophic OGCM (Maier-Reimer *et al.*, 1993). The horizontal resolution which has been adapted to match that of the AGCM, is 5.6° × 5.6°, and the model has 11 layers in the vertical. A sea-ice model with simplified treatment of stresses is included. Details of this coupled model, as well as of the coupling technique applied, have been described in Cubasch *et al.* (1992).

Results and discussion

With this model, two simulations have been carried out. In the first simulation the atmospheric concentrations of

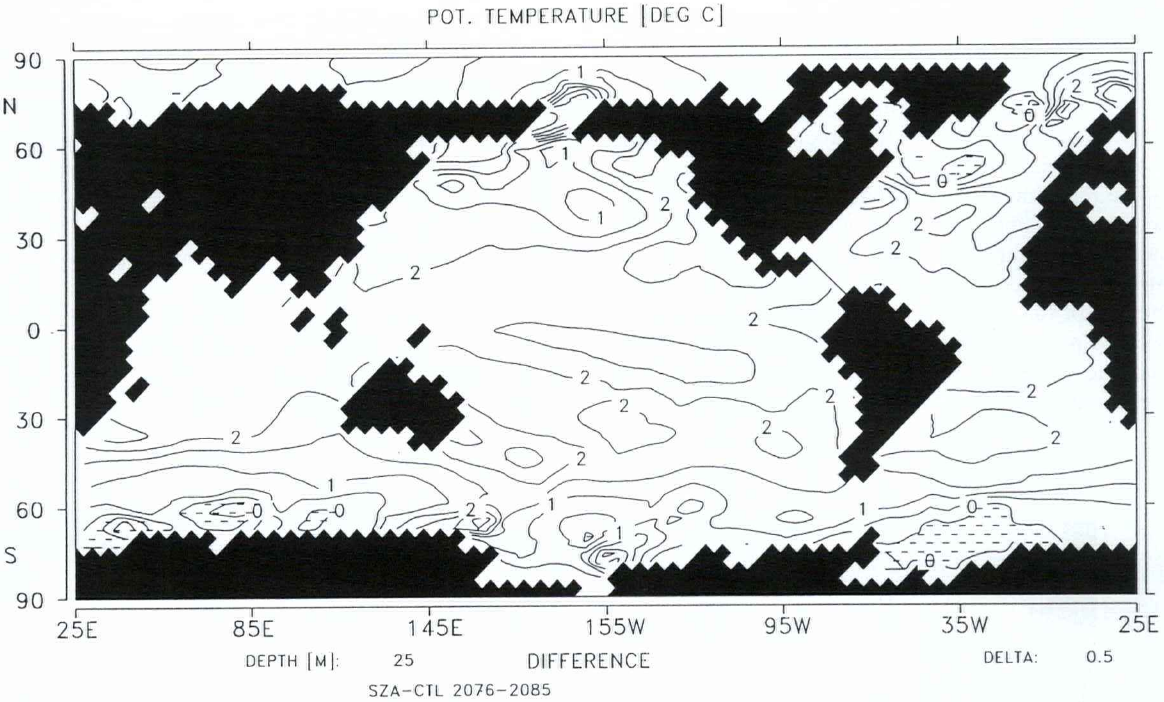

Figure 1. Annual mean difference in sea-surface temperature of the last decade between the greenhouse experiment and the control run.

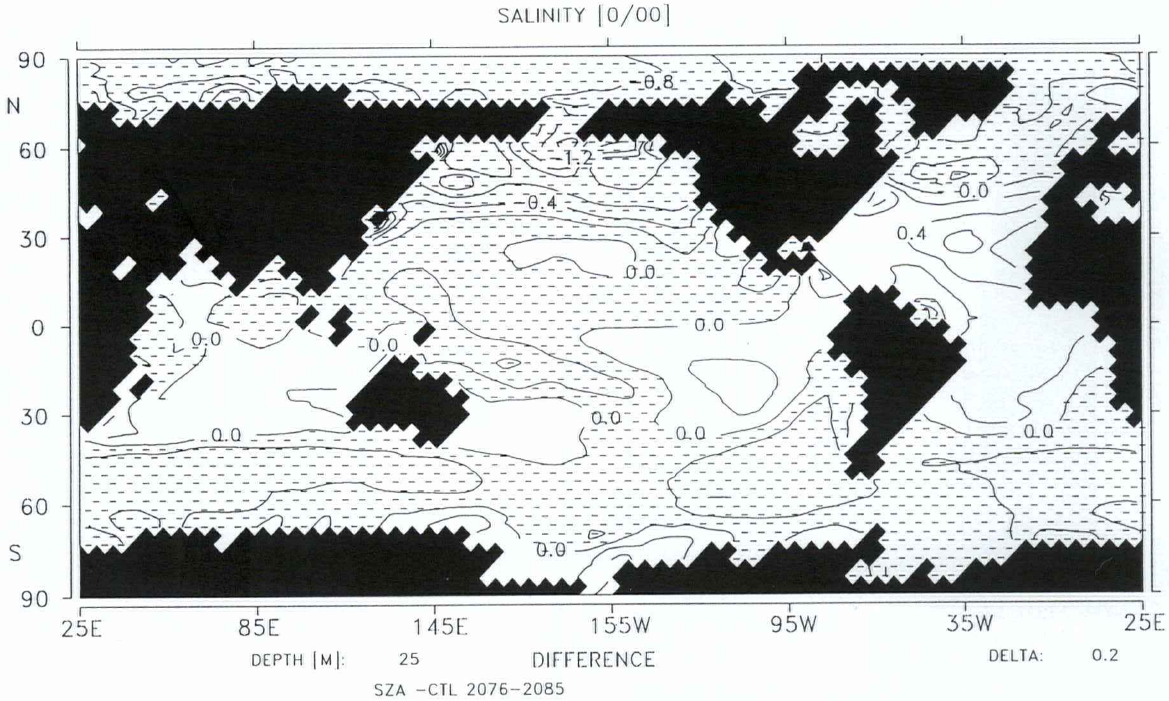

Figure 2. Annual mean difference in surface salinity between the greenhouse experiment and the control run averaged over the last decade.

greenhouse gases varied in accordance with the IPCC "business as usual" scenario (Houghton *et al.*, 1990). This simulation started with a forcing corresponding to 1986 conditions and was run for 100 years. In a second integration, termed the control run, the forcing was kept constant at conditions corresponding to 1985.

The most important consequence of the inclusion of ocean circulation in these coupled model runs is the modification of the pattern of climate change in the near-surface air temperature and sea-surface temperature. At the end of the greenhouse simulation the global mean average near-surface air temperature is 2.9°C warmer than the average over the corresponding decade of the control run. Compared to the first decade of the control run, the warming is only 2.6°C (Cubasch *et al.*, 1992). Because of the much bigger heat capacity of the ocean, land warms faster than the ocean. The global mean change in SST is only 1.9°C at the end of the integration. The pattern shifts from almost zonal, with highest warming in high latitudes, especially in the winter season, to regionally strongly variable, with minima in the northern North Atlantic, in the North Pacific, and in the Southern Ocean (see Fig. 1). In small regions of the northern North Atlantic even a cooling is predicted. This cooling is a consequence of the reduction in the formation rate of North Atlantic Deep Water (NADW). At the surface a freshwater lens develops. Winter cooling is not strong enough to overcome the stable stratifi-

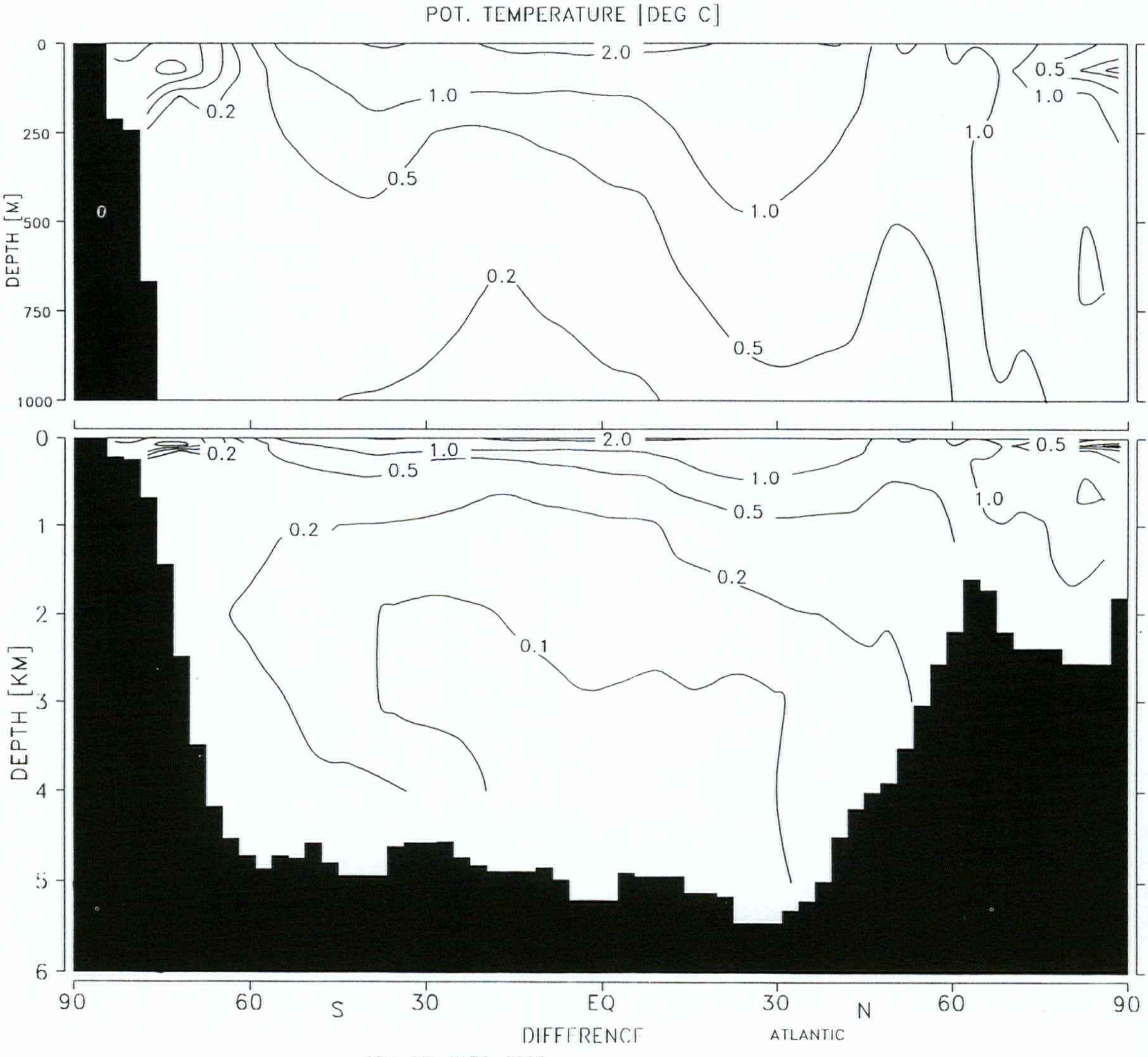

Figure 3. Difference in vertical temperature distribution between the greenhouse experiment and the control run in the Atlantic. The picture shows the zonally averaged response. Note the variable contour interval.

cation between the relatively fresh surface water and the warm and haline Atlantic water underneath. The effect is an intensification of the freshening at the surface. As a consequence, the formation of NADW is reduced and the thermohaline circulation of the Atlantic is slowed down by about 25% at the end of the integration. In the last decade of the greenhouse experiment the meridional overturning of the Atlantic has a maximum of 24 Sv compared with 33 Sv in the control simulation. The resulting enhanced residence time of a water particle at the surface leads to a stronger uptake of precipitation and thus to a further freshening. This mechanism provides a positive feedback for the negative salinity anomaly. In the subtropical gyre, a positive salinity anomaly develops at the surface as a consequence of the longer exposure to the net evaporation in the subtropics. Here the anomaly reaches values of more than 0.6 psu in the eastern subtropical North Atlantic. In the subpolar gyre the anomaly is weaker, but still with a strength of typically 0.2 psu. The resulting anomaly of near-surface salinity is shown in Figure 2. As a consequence, the stability in the near-surface layers is increased and the ventilation of intermediate and deep water is reduced.

An effect apparently not a unique feature of our model, as similar greenhouse integration with other COAGCMs show a similar region of strongly reduced warming or cooling in the northern Atlantic (for a review see Gates *et al.*, 1992). Although a simple sea-ice model is included, this has only a negligible effect on the formation rate of NADW in the model (as was shown by Maier-Reimer (1993), but rather influences Antarctic bottom water formation.

The warming is not restricted to the surface layers of the ocean, but penetrates into greater depths. The deepest penetration occurs in regions where the stratification is weak, i.e., in the northern North Atlantic and in the Southern Ocean. The change in the vertical temperature structure of the Atlantic resulting at the end of the greenhouse experiment is shown in Figure 3.

Whereas the model seems to give a reliable estimate of variations on large spatial scales and of the changes in integral properties of the ocean circulation, a direct estimate of local effects from these simulations remains of course limited because of the coarse resolution of the model. For example, the model does not resolve Iceland and thus the question of how the local hydrographic properties around Iceland might change as a result of the greenhouse effect cannot be answered directly from these simulations. Currently, a model with twice the resolution is under development at our Institute. Further refinement would be achieved by embedding a regional model of the North Atlantic in the global ocean model.

Another possible method would be to relate local properties of the hydrography around Iceland and their variation to large-scale patterns of the ocean and atmosphere (e.g., wind forcing) which the model can simulate. Estimates of the changes in local conditions could then be derived from the changes in the large-scale conditions. The relation between the large-scale properties and the local variations, however, should be estimated from observations. Storch *et al.* (1993) have recently applied this technique to Iberian rainfall.

Acknowledgments

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