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Will the North Atlantic Ocean thermohaline circulation weaken during the 21st century?

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Abstract. The North Atlantic Ocean thermohaline circulation is examined in three experiments using the Climate System Model. They are a control integration for 1870 conditions, and particular emission scenarios for the 20th and 21st centuries. It is found that the strength of the thermohaline circulation does not change significantly over the 21st century. This is in contrast to several other recent studies, which have projected a significant reduction over the 21st century. The reason for the difference is that the Northwest Atlantic becomes warmer and more saline in the Climate System Model. These changes combine to make little change to the surface ocean density in this region, and hence to the rate of deep water formation. Caveats about the Climate System Model and other coupled climate models are then discussed.

Introduction

Broecker [1987] warned that a possible unpleasant surprise due to the greenhouse effect is a slow down in the North Atlantic thermohaline circulation (THC). This question has since been addressed many times, using a variety of numerical models. For example, *Rahmstorf* [1995] used a coarse resolution ocean model coupled to an energy-balance atmosphere model and showed that the THC could collapse if there was an increased fresh water input to the North Atlantic. *Stocker and Schmittner* [1997] used a three-basin zonally averaged ocean model, coupled to an energy-balance atmosphere model, and showed a possible THC collapse due to a large increase in the concentration of atmospheric carbon dioxide. More recently, several climate centers have been running simulations of the 20th and 21st centuries using the latest versions of their coupled general circulation models. Some have reported a significant weakening of the THC during the 21st century. For example, *Dixon and Lanzante* [1999] and *Dixon et al.* [1999] show a possible reduction of up to 40% in the THC strength before 2100, using models developed at the Geophysical Fluid Dynamics Laboratory (GFDL). The Hadley Centre's latest model was used in the work of *Wood et al.* [1999]. This model shows a significant reduction in the component of the THC centered in the Labrador Sea in the first half of the 21st century. In contrast, *Latif et al.* [2000] report that the THC does not weaken over the 21st century in the Max-Planck-Institute's (MPI) latest coupled model. This letter reports on similar experiments performed with the Climate System Model (CSM), and the response of its THC during the 21st century.

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Model Description and Experiments Performed.

The CSM is a coupled general circulation model with atmosphere, ocean, land and sea-ice components. This work uses the CSM version 1.3, which is documented in *Boville et al.* [2000]. The drag coefficient between the atmosphere and sea-ice is corrected compared to version 1.0, and this very significantly reduces the trends in the deep ocean temperature and salinity. The atmospheric component now has a prognostic cloud water formulation, the direct radiative effects of sulfate aerosols and several greenhouse gases as prognostic tracers. Its horizontal resolution is about 2.8°, and there are 18 layers in the vertical. The ocean component is fully described in *Gent et al.* [1998]. The zonal resolution is 2.4°, the meridional resolution varies between 1.2°near the equator and at high latitudes to 2.3°in midlatitudes, and there are 45 levels with four levels in the upper 50 m.

The first experiment is a control integration for 1870 greenhouse gas conditions that has been integrated for 270 years. It was initialized as for the earlier coupled integration using version 1.0, and again there is virtually no trend in the sea surface temperature (SST) in this experiment, even though no flux adjustments are used. Results from this experiment are shown in *Boville et al.* [2000]. Unfortunately, the data from just the ocean component for years 51 to 118 of this experiment were corrupted, and are not available. The second and third experiments have been integrated in an attempt to simulate the earth's climate in the 20th and 21st centuries. The 20th century experiment starts from year 40 of the control integration, and simulates the period from 1870 until 1998. This experiment uses reconstructed and observed, time-varying concentrations for all the trace gases, and a constant solar input. The 21st century experiment is started from 1980 conditions in the 20th century integration, and simulates the period from 1981 to 2100. The trace gas concentrations follow observations to begin with, and then follow the IPCC SRES A1 emission scenario for the 21st century. Two other 20th century and four other 21st century experiments have been integrated using the CSM. They all show very similar responses in terms of the North

Atlantic THC. Thus, the conclusions reached about the THC are not dependent on the particular CSM simulations of the 20th and 21st centuries shown here.

Results

a) Globally averaged reference-height temperature.

Figure 1 shows the annual-mean, globally averaged reference- height temperature anomalies from the 1870 control, 20th and 21st century experiments, plus an estimate of the observed temperature from 1850 onwards. The mean values for the model integrations and the data are calculated independently by averaging all 270 years from the 1870 control experiment, and the data between 1851 and 1875. The 20th century experiment is quite close to the observations until about 1930, but then the model does not capture the warming in the data between 1930 and 1943. The 20th century experiment and data coalesce again in 1975, and remain very close for the remainder of the integration. Both model and data show an increase of 0.65°C for the present day compared to the average in the late 19th Century. The model temperature increase from 1970 to present is much larger than the variability in the 1870 control experiment, strongly suggesting this increase is due to changes in the greenhouse gas forcing. This would remain true even if the model variability was somewhat higher, more comparable to the natural variability seen in observations. The 21st century experiment suggests that, if the IPCC SRES A1 scenario does occur, then the globally averaged reference-height temperature will increase by a further 1.75°C over the 21st century.

b) The North Atlantic thermohaline circulation.

Figure 2 shows the Atlantic Ocean meridional overturning streamfunction, calculated from the mean flow, averaged over years 164 to 169 of the 1870 control experiment. The topography shows the maximum depth of ocean at each latitude. The maximum overturning is 28.6 Sverdrups (Sv) located at 900 m depth and 35°N. Just over 20 Sv is transported across the equator between the depths of 1 and 3 kms. About 3 Sv overflows from the Arctic Ocean into the North Atlantic, and about 15 Sv sinks across 1 km depth between 60°and 65°N. The sinking region only reaches down to about 3 km, and below this depth the ocean is filled by Antarctic bottom water coming from the south. This deep overturning circulation is weak, with the transport being less than 2.5 Sv throughout the North Atlantic. Caution is required when comparing this streamfunction to observations, because it is a very difficult quantity to estimate accurately from observations. The overturning strength of 22 Sv at 24°N is somewhat larger than the observational estimates of 17-18 Sv by *Hall and Bryden* [1982], *Roemmich and Wunsch* [1985]. The amount of Antarctic bottom water crossing the equator in the model is somewhat lower than the observational estimate of 4.3 Sv by *McCartney and Curry* [1993]. The northward heat transport in the North Atlantic due to the THC is not shown, but is very consistent with observationally based estimates. The maximum value of 1.15 Petawatts at 24°N agrees well with the direct estimates from ocean observations by *Hall and Bryden* [1982], *Roemmich and Wunsch* [1985], from a model inverse calculation by *Macdonald and Wunsch* [1996], and from a residual calculation using atmospheric analyses by *Trenberth and Solomon* [1994].

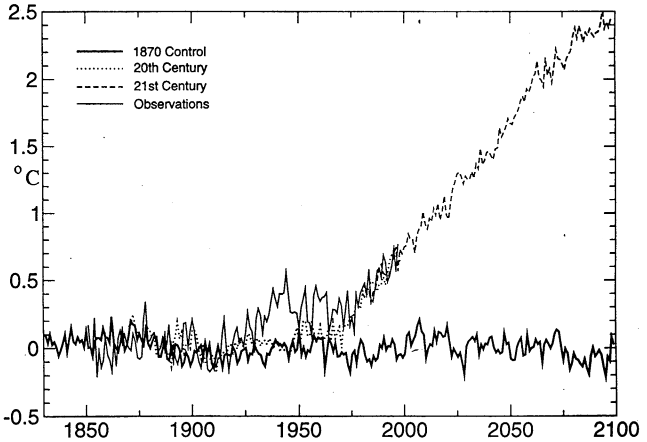

Figure 1. Timeseries of the annual-mean, globally-averaged reference-height temperature anomalies (°C) from the 1870 control, 20th and 21st century experiments, plus an estimate from observations.

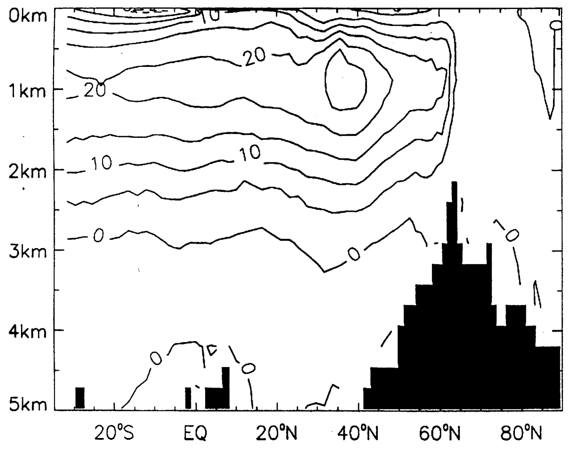

Figure 2. The Atlantic Ocean meridional overturning streamfunction (Sv), calculated from the mean velocity, averaged over years 164 to 169 of the 1870 control experiment. The contour interval is 5 Sv.

Figure 3a shows timeseries of the maximum annually-averaged meridional overturning in the North Atlantic from the 1870 control, and the 20th and 21st century experiments. Note the 1870 control experiment data is missing between 1881 and 1948. The mean value from the 1870 control experiment is about 29 Sv, but the variability is rather large. The largest excursions are about ±7 Sv, or ±25% of the mean. The mean of the 20th century experiment is slightly lower at about 28 Sv, and the mean of the 21st century experiment is slightly higher at about 30 Sv, and there is also large variability in these experiments. Figure 3a shows the maximum value of the meridional overturning streamfunction, which is nearly always used as the measure of the strength of the THC. However, because of the local-

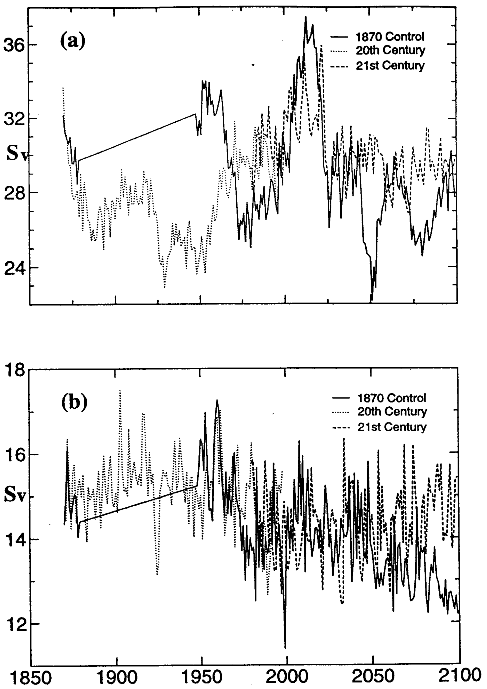

Figure 3. Timeseries from the anually-averaged meridional overturning streamfunction (Sv) in the North Atlantic Ocean from the 1870 control, 20th and 21st century experiments. a) The maximum value, and b) the transport between 60° N and 65° N across 1km depth.

ized maximum in the subtropics, it could be argued that a better measure of the THC is the transport across 1km depth between 60°and 65°N. Timeseries of this measure from the 1870 control, and the 20th and 21st century experiments are shown in Figure 3b. The mean value of this transport is 14.5 Sv in the 1870 control experiment, and it does have somewhat smaller variability than the maximum streamfunction value shown in Figure 3a. However, the average value of this alternative measure of the THC remains close to 14.5 Sv throughout the 20th and 21st century experiments. The conclusion from these experiments using the CSM is that there is no evidence of a significant weakening of the THC or the northward heat transport across 24°N over the 21st century.

Discussion

The obvious question to ask is why does the CSM give a different result for the North Atlantic THC compared to other coupled climate models? *Rahmstorf* [1995] documents the sensitivity of the THC to a variety of fresh water flux perturbations, and *Stocker and Schmittner* [1997] also conclude that an increased fresh water flux can cause the collapse of the THC. *Dixon et al.* [1999] conclude that changes in the fresh water flux are the main reason for the weakening of the THC in the GFDL model. Heat flux changes also contribute, but are of secondary importance. Changes in both fluxes act to make the surface ocean less dense in the Northwest Atlantic, and this reduces the strength of the THC. *Wood et al.* [1999] also conclude that the Labrador Sea convection reduces in the Hadley Centre model as a result of surface freshening and warming. In contrast, *Latif et al.* [2000] conclude that, in the MPI model, high salinity water from the tropical Atlantic Ocean is advected into the sinking region, compensating the effects of local warming and freshening.

In the CSM 21st century experiment, the SST increase between 2000 and 2100 is considerably larger in the Northwest Atlantic than elsewhere in the ocean. Increases of up to 5°C occur off Newfoundland, and up to 3°C in the Labrador Sea and the East Greenland Current region. These increases in SST result in more heat and fresh water loss by evaporation. In the Northwest Atlantic region bounded by 40°N and 35°W, the precipitation increases between 2000 and 2100 by 0.035 Sv, but the evaporation increase is larger at 0.063 Sv. The evaporation increase is due, in part, to an increase in surface wind speed over this region. In addition, melt from sea-ice significantly reduces in this region between 2000 and 2100. Thus, the net fresh water flux into the Northwest Atlantic is reduced. This causes the sea surface salinity in this region to increase by up to one part per thousand. The changes in SST and sea surface salinity compensate each other, so that there are only small changes in the surface ocean density. This means that the deep water formation rate, and the strength of the THC, do not change significantly over the 21st century. The opposite sign of fresh water flux and sea surface salinity changes in the Northwest Atlantic Ocean between the CSM and most of the other climate models discussed, causes the difference in the THC evolution.

Caveats

There are several caveats that should be considered when evaluating the significance of the THC result from the CSM and other coupled climate models.

a) There are significant biases in the North Atlantic at the end of the CSM 20th century experiment compared to present day observations. There is a cold bias in the SST off Newfoundland and the sea-ice is too extensive in the Labrador Sea and along the east coast of Greenland. These mean biases are offset during the first part of the 21st century experiment. This would not be at all obvious from just looking at the three figures shown in this letter.

b) CSM version 1.3 does not have an explicit river runoff scheme. Instead, the fresh water balance is maintained in the model by multiplying the daily precipitation between the atmosphere and ocean by a spatially constant factor. The average value of this factor in the 1870 control experiment is 1.08. Thus, the Northwest Atlantic is not forced by the runoff from Hudson's Bay and the Saint Lawrence River, but is forced by an increase in the precipitation field over the open ocean. However, the increase in runoff in these two catchment basins between 2000 and 2100 is quite close to the increase in precipitation over the Northwest Atlantic due to the precipitation factor.

c) No flux adjustments are used in these CSM experiments, which means that there are slow, but persistent, drifts in the sea surface salinity. Thus, calculating salinity changes in the 21st century experiment compared to the 1870 control experiment means differencing solutions with different drifts. This is not so comfortable as when dealing with SST, which does not drift in the 1870 control experiment.

d) *Gent et al.* [1998] document the equilibrium solution from the CSM ocean component forced with observed winds and bulk fluxes. They clearly show that the vertical temperature and salinity profiles are worst in the North Atlantic and Arctic when compared to observations. The boundary between North Atlantic deep water and Antarctic bottom water is much too shallow in the model. This is most often attributed to the poor representation of overflow currents in z-coordinate models that do not include a bottom boundary layer scheme. In addition, *Roberts and Wood* [1997] have clearly shown the uncomfortably large sensitivity of these overflow currents and the THC to the precise specification of topography at the Denmark Strait and the Iceland to Scotland ridges in coarse resolution ocean climate models. Finally, the circulation of the North Atlantic is strongly affected by the presence of sea-ice in the Arctic Ocean and its export through Fram Strait. This combination of factors makes the North Atlantic much more difficult to simulate correctly in ocean general circulation models than other ocean basins.

Similar caveats could be given about all the model studies discussed. For example, the ocean components of all the studies, except *Latif et al.* [2000], use a z-coordinate, and the fourth caveat discussed above applies to them all. The GFDL and MPI models use heat and fresh water flux adjustments. These have the advantage of making the drifts in SST and sea surface salinity very small, but have the disadvantage that they often accomplish a significant percentage of the poleward heat and fresh water transports in the coupled model. *Rahmstorf* [1995] and *Stocker and Schmittner* [1997] both use a much simpler energy-balance atmosphere component, the latter study uses a zonally-averaged ocean model, and both models do not have an active sea-ice component. Both models are considerably simpler than the fully coupled climate models.

In summary, determining the response of the THC in the 21st century is a very demanding question to ask of current state-of-the-art coupled climate models. It requires a better simulation of the complex interaction of the atmosphere, ocean and sea-ice in a rather small region of the North Atlantic than is presently obtained. Different answers to the question of how the THC will evolve in the 21st century are being obtained in different models. I think that these results should be viewed as preliminary. However, the question of how the North Atlantic THC will evolve over the 21st century is very important, because it will affect the future climate of Europe and the projected rate of sea-level rise in the Atlantic Ocean, see *Knutti and Stocker* [2000].

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