GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 22, PAGES 4223-4226, NOVEMBER 15, 2001

Atlantic Thermohaline Circulation and its Response to Increasing CO_2 in a Coupled Atmosphere–Ocean Model

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Abstract. We discuss aspects of the Atlantic thermohaline circulation (THC) and its response to increased greenhouse gas concentration, using a coupled atmosphere-ocean general circulation model (AOGCM) whose oceanic component is a new hybrid-isopycnal model. Two 200-year model integrations are carried out – a control run assuming fixed atmospheric composition and a perturbation run assuming gradual doubling of CO_2. We employ no flux corrections at the air-sea interface, nor do we spin up the ocean prior to coupling. The surface conditions in the control run stabilize after several decades. When doubling CO_2 at the rate of 1% per year, the model responds with a 2°C increase in global mean surface air temperature (SAT) after 200 years and a virtually unchanged Atlantic meridional overturning circulation. The latter is maintained by a salinity increase that counteracts the effect of global warming on the surface buoyancy.

Introduction

The global climate to a large extent is a result of the interaction between ocean and atmosphere. In this process, the ocean contributes a seemingly innocuous single variable, sea surface temperature (SST), whose ability to vary and thereby modulate the ocean-atmosphere heat flux nevertheless cannot be fully understood without taking into account the 3-dimensional THC. Roughly one-fourth of the thermal energy flowing poleward in the northern hemisphere, for example, is transported by a vertical-meridional overturning mode in the Atlantic Ocean which is part of the global THC.

Atmospheric greenhouse gases have been changing rapidly in the last few decades. How this affects the climate, and how the ocean is likely to respond, has been a topic of considerable interest to the climate community and to society at large. Several AOGCMs have simulated a slowdown or even a complete shutdown of the Atlantic THC in the more extreme warming scenarios developed by the *IPCC* [1996]. Examples in point are the coupled model runs of the Hadley Centre [*Wood et al.*, 1999], the Max-Planck-Institute (MPI) [*Mikolajewicz and Voss*, 2000], and the Geophysical Fluid Dynamics Laboratory [*Manabe and Stouffer*, 1994; *Dixon and Lanzante*, 1999] – although in the latter model the THC did recover after 500 years [*Manabe and Stouffer*, 1999]. However, another coupled model from MPI [*Latif et al.*, 2000] and the Climate System Model at NCAR [*Gent*, 2001] show no significant change in the Atlantic THC in the warming scenarios.

Here we report results similar to the last-mentioned case, using a coupled atmosphere-ocean-sea ice model recently assembled at the Goddard Institute for Space Studies (GISS).

Model configuration

The atmospheric module employed in the coupled runs is the SI2000 GISS atmospheric model [*Hansen et al.*, 2001], based on model SI95 with finer vertical resolution and improved physics packages [*Hansen et al.*, 1997]. It has 12 levels in the vertical and a $4^\circ \times 5^\circ$ spherical grid in the horizontal.

The oceanic component is HYCOM, the hybrid coordinate version [*Bleck and Boudra*, 1981; *Bleck*, 2001] of the Miami Isopycnal Coordinate Ocean Model (MICOM) [*Bleck et al.*, 1992]. This model uses σ_2 (potential density referenced to 20 MPa) as vertical coordinate and includes thermobaric effects [*Sun et al.*, 1999]. The bottom topography is obtained by spatially integrating ETOPO5 data of 5' spatial resolution over each grid cell. A Mercator mesh of resolution $2^\circ \times 2^\circ \cos(\phi)$ is used south of latitude $\phi' = 60^\circ$ N. At ϕ', the Mercator projection adjoins a bipolar projection with poles over Canada and Siberia. The Bering Strait is closed in this experiment. River runoff is incorporated by accumulating net freshwater input on each land point and directing it to prescribed river mouth locations where it is added as a point source to the precipitation field. (Diagnostics carried out after a positive salinity transient became apparent in the model runs indicate that the hydrological cycle in the model is not completely closed, leading to a 0.09 psu/century salinity drift.)

Isopycnal coordinate models have the advantage of rather faithfully preserving water mass properties in the oceanic interior, but they are inherently unable to provide vertical resolution in unstratified regions such as the surface mixed layer. The latter shortcoming is being remedied, at least to some extent, by HYCOM which redeploys outcropped isopycnal layers as z coordinate layers beneath the sea surface. By providing some near-surface resolution even in unstratified water columns, the hybrid approach has the potential of combining the advantages of fixed-grid and density coordinate ocean models. We report here on the first use of HYCOM in a coupled model. For the sake of computational economy, we adhere to MICOM's Kraus-Turner protocol of near-surface mixing, that is, homogenization of the water

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Paper number 2001GL013325.
0094-8276/01/2001GL013325$05.00

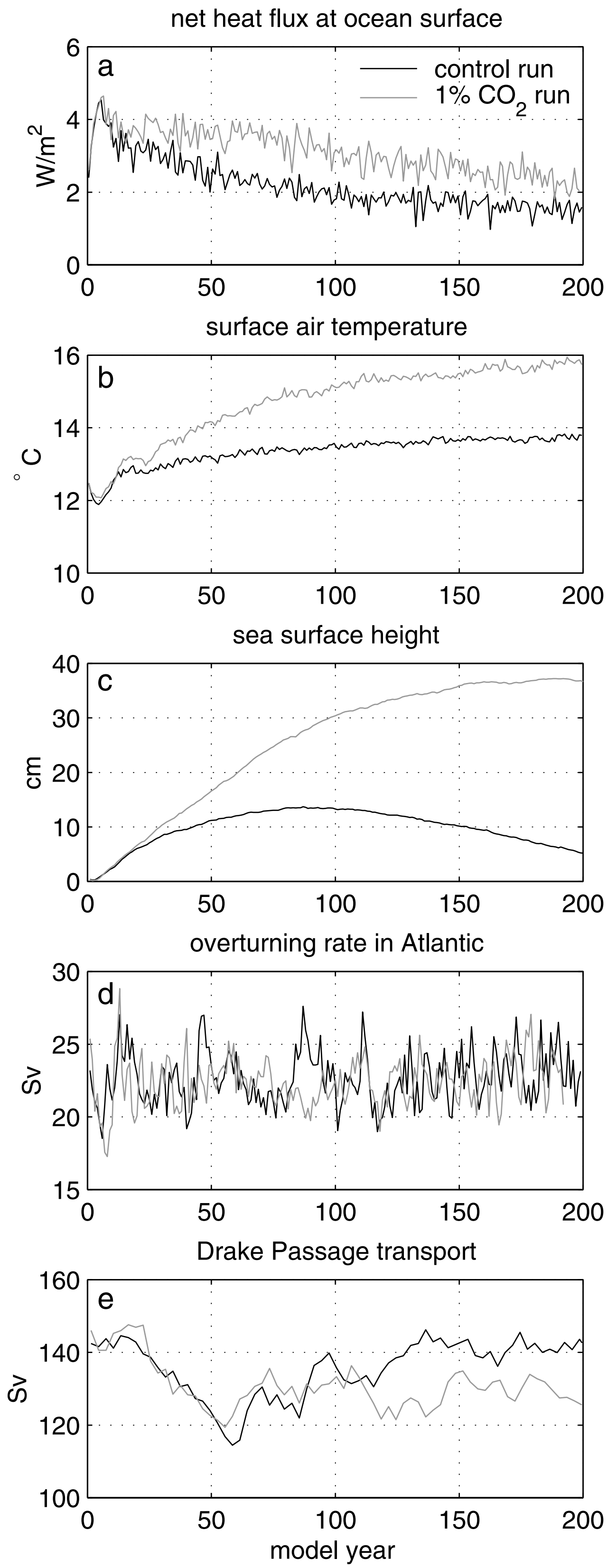

Figure 1. Results from the control run (black lines) and CO_2 run (grey lines). a: net heat flux at the ocean surface (W/m^2); b: global mean surface air temperature (°C); c: sea surface height (cm); d: annual overturning rate in Atlantic (Sv); e: Drake Passage transport (Sv).

column to a depth obtained by balancing sources and sinks of near-surface turbulence kinetic energy.

The ocean model is capped by the GISS 4-layer thermodynamic ice model [*Russell et al.*, 2000].

The model components are coupled as follows. The OCGM provides SST, ice temperature and ice extent to the AGCM, and receives surface fluxes of heat, freshwater, and momentum from the AGCM. This information exchange takes place at 2-hr intervals to resolve the diurnal cycle. The surface fluxes sent to the OCGM represents an average over the area enclosed by each OGCM grid box; SST sent to the AGCM is averaged in analogous fashion.

Two experiments are carried out, both initialized with 1951-level atmospheric trace gases, the oceanic climatology of *Levitus et al.* [1994], and the Hadley Centre ice climatology. We chose not to subject the ocean model to a separate spinup run. In the control run, the atmospheric composition remains fixed in time. In the CO_2 doubling ($2\times CO_2$) run, atmospheric CO_2 is increased at a rate of 1% per year until the initial amount is doubled at around year 70.

Results

Some key results from the two 200-year runs completed to date are presented in Fig.1. Fig.1a shows the net heat flux at the ocean surface, indicating that the ocean in the control run is gaining heat at a rate of less than $2\,W/m^2$ by year 200. CO_2 addition increases this heat flux by an amount around $1\,W/m^2$. Fig.1b shows that the system reacts to the extra heat input by raising the global mean SAT by 1.0°C after 50 years and 2.0°C after 200 years. The globally averaged sea surface height, shown in Fig.1c, decreases slightly after year 100 in the control run, while it steadily increases in the $2\times CO_2$ run, resulting in a differential sea level rise of 16 – 17 cm per century. This rise, solely due to the thermal expansion of sea water, is assumed to account for more than half of the total sea level rise [*IPCC*, 1996].

The equilibrium sensitivity of the SI2000 AGCM, when coupled to a simple mixed-layer ("Q-flux") ocean, is 3°C for the $2\times CO_2$ scenario [*Hansen et al.*, 2001]. In our experiments with a full-fledged OGCM, there still remains an energy imbalance of about $1\,W/m^2$ after 200 years with 2°C warming. The delay in reaching thermal equilibrium is consistent with prevailing notions about the ventilation rate of the world ocean, estimated to be several thousand years.

The features revealed in this simulation have been subjected to extensive further analysis. The model exhibits a strong THC throughout the run, with an irregular 15 – 40 year oscillation in the North Atlantic overturning rate (Fig.1d), compared to a more regular 30 year oscillation seen in MICOM-CCM3 experiments conducted by *Cheng* [2000]. In both the control and the perturbation run, the overturning circulation appears to be persistent and within the observed magnitude range [*Molinari et al.*, 1992; *Speer et al.*, 1996]. The influence of CO_2 emission on the Atlantic THC appears to be small, at least in the course of this 200 year experiment.

The Antarctic Circumpolar Current (ACC) is an important conduit for water masses partaking in the global THC. Hence, the strength of the ACC is a commonly used index for the health of not only the wind-forced but also the thermohaline-forced part of the world ocean circulation. Fig.1e shows the annual mean Drake Passage transport in

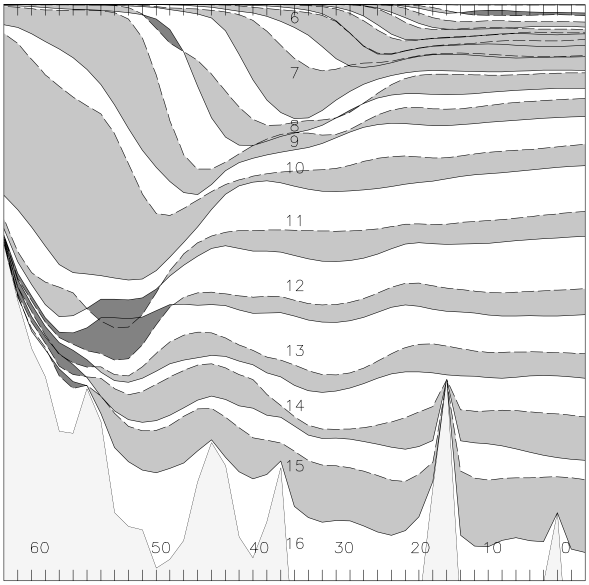

Figure 2. Vertical section at 30°W showing layer interfaces from the control run (dashed) and CO_2 run (solid). Light/dark shading highlights downward/upward interface displacement in CO_2 run relative to control run, indicative of warming/cooling. Depth (m) shown at right, latitude at bottom.

the two simulations. The model obtains a 200-year mean transport of 135 Sv in the control run and 131 Sv in the $2\times CO_2$ run, with an oscillation slower than what is shown in Fig.1d. This transport agrees with the observed value of 123 ± 10.5 Sv [*Whitworth and Peterson*, 1985].

The maximum northward heat transport in the North Atlantic, averaged over years 170–200, is 1.14 and 1.15 PW in the control and the $2\times CO_2$ run, respectively. During the same period, results from the $2\times CO_2$ run show a small increase both in surface temperature and salinity in the North Atlantic compared to the control run, resulting in a slightly lower surface density over most of the region.

The top-to-bottom density contrast in the Atlantic undergoes similar changes in the two experiments, implying that isopycnals in the $2\times CO_2$ run on average are displaced at all depths relative to those in the control run. We illustrate this by showing in Fig.2 a meridional section through the North Atlantic. Dashed and solid lines mark the isopycnal interfaces in the control run and $2\times CO_2$ run, respectively. (The density field in HYCOM's nonisopycnal surface region has been interpolated here to density space.) Coordinate layer indices pertain to the $2\times CO_2$ run. The depth difference between corresponding interfaces in the two runs is highlighted by either dark or light shading, depending on the sign of the depth difference. The lack of a systematic relative drift in stratification indicated in Fig.2 may explain why there is little difference in THC strength in the two runs.

Today's coupled ocean-atmosphere models fall short of representing the present climate as a near-steady state solution. We document model drift in the control run by showing in Fig. 3 a zonally-averaged meridional section through the modeled density field. The dashed and solid lines are the isopycnal layer interfaces at years 1 and 200, respectively. Above 1 km, temperature increase outweighs salinity increase, hence the water is becoming lighter. Below 2 km, salinity increase dominates, leading to a buildup of dense water. The stability of the THC in both runs, which comes somewhat as a surprise given the overall stratification increase depicted in Fig. 3, may be attributable in part to the suppression of numerically induced diapycnal mixing by isopycnic-coordinate models.

Summary

We have conducted two 200-year simulations using a global coupled model consisting of the GISS atmospheric model and HYCOM. This marks the first time that HYCOM has been tested in a coupled setting. We show in the control integration that, despite a ban on flux adjustments, the model shows little drift at the sea surface beyond 50 years. This is smaller than the drift seen in the GISS/GFDL coupled model combination [*Hansen et al.*, 1997]. In eliminating flux adjustments and a special ocean spin-up run we follow the example set by *Wood et al.* [1999]. When adding 1% CO_2 per year, the Atlantic overturning circulation remains persistent and strong throughout the 200 year run. This is consistent with recent results of *Latif et al.* [2000] and *Gent* [2001], but differs from many models where the THC is projected to weaken in the 21st century in response to greenhouse warming. The THC maintenance mechanism in this model seems similar to that in *Gent* [2001].

The THC strength is set by many factors involving thermal, haline, and wind forces. In this particular model, CO_2 addition leads in the North Atlantic to temperature/salinity increases whose combined effect on the top-to-bottom density contrast remains small. The model simulates a global mean SAT rise of 2°C and a sea level rise due to oceanic thermal expansion of 32 cm in 200 years in the warming scenario, less than the estimated 30 cm per degree warming obtained from experiments where the THC slows down [*Knutti and Stocker*, 2000]. Overall, our simulation of SAT and sea level rise is at the low end compared to most studies, suggesting that an intact THC reduces the rate of climate change.

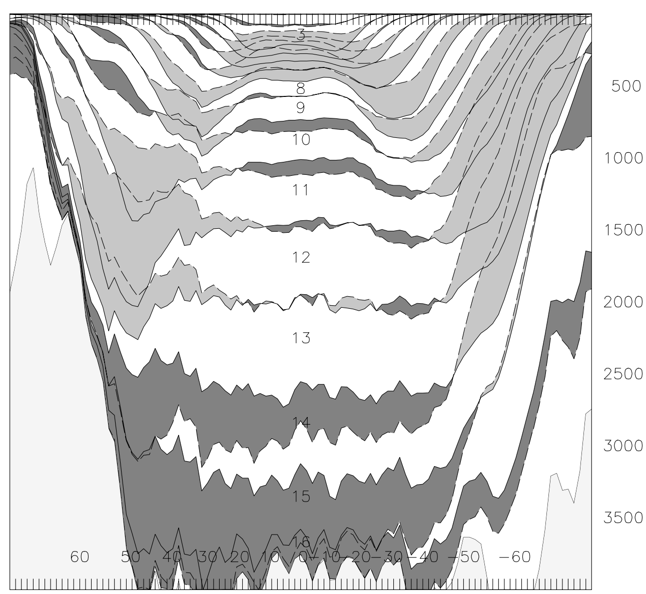

Figure 3. Zonally averaged section showing layer interfaces from the control run at year 1 (dashed) and year 200 (solid). See Fig. 2 for further details.

Acknowledgment. Research by SS is sponsored by NASA/Rutgers University Cooperative Agreement. Research by RB is sponsored by the U.S. Department of Energy under the Climate Change Prediction Program.

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(Received April 20, 2001; revised July 9, 2001;
accepted July 31, 2001.)