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The influence of transient surface fluxes on North Atlantic overturning in a coupled GCM climate change experiment

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Abstract. The mechanism by which the model-simulated North Atlantic thermohaline circulation (THC) weakens in response to increasing greenhouse gas (GHG) forcing is investigated through the use of a set of five multi-century experiments. Using a coarse resolution version of the GFDL coupled climate model, the role of various surface fluxes in weakening the THC is assessed. Changes in net surface freshwater fluxes (precipitation, evaporation, and runoff from land) are found to be the dominant cause for the model's THC weakening. Surface heat flux changes brought about by rising GHG levels also contribute to THC weakening, but are of secondary importance. Wind stress variations have negligible impact on the THC's strength in the transient GHG experiment.

Introduction

Many numerical models of the coupled climate system simulate a weakening of the North Atlantic's meridional overturning circulation (often referred to as the thermohaline circulation or THC) as the modeled climate changes in response to increasing greenhouse gas (GHG) concentrations [*Kattenberg et al.*, 1996]. The tendency for the THC to weaken as the climate warms in global coupled general circulation models (CGCMs) was first noted by *Stouffer et al.* [1989] and *Manabe et al.* [1991] in their analyses of a version of the GFDL coupled climate model. The amount of projected THC weakening varies from model to model, with the *Manabe et al.* [1991] model exhibiting somewhat greater than average amounts of THC reduction and global warming as compared to other CGCMs [*Kattenberg et al.*, 1996].

By analyzing changes in the simulated surface water densities, *Manabe et al.* [1991] hypothesized that weakening of the North Atlantic meridional overturning during enhanced GHG forcing is caused by an increase in the amount of freshwater supplied to high latitudes. As the atmosphere warms, its ability to hold water vapor increases. Greater amounts of water vapor in the warmer air lead to additional poleward transport of water by the atmosphere, increasing the supply of freshwater (liquid and solid) provided to the high latitude ocean via precipitation and runoff. Freshening of the high latitude surface waters reduces surface densities, inhibiting convection and the downward penetration of these waters in the THC's sinking branch. As a result, the simulated North Atlantic overturning circulation is reduced (*i.e.*, North Atlantic Deep Water formation decreases). This reduces the advection of high salinity surface waters poleward by the THC's upper branch, which further hinders water mass formation - a positive feedback.

The purpose of this letter is to investigate the causes for the weakening of the THC in the GFDL coupled climate model under enhanced GHG conditions. More specifically, we examine the relative contributions of surface freshwater, heat, and momentum fluxes to the THC reduction seen in the coupled model. This is accomplished by conducting a set of five coupled model experiments. In some of the experiments, the ocean model's surface forcing conditions are altered in a manner that allows one to clearly isolate the influence that GHG-induced changes in the various model-projected surface fluxes have on the ocean simulation.

Model Description and Experimental Design

The GFDL coupled climate model used here is an updated version of that used by *Manabe et al.* [1991]. It combines three-dimensional GCMs of the global ocean and atmosphere with simpler sea ice and land hydrology models. The earlier version of the climate model's control state and its responses to transient climate change forcings have been described previously [*e.g., Manabe et al.*, 1991; *Delworth et al.*, 1993; *Manabe and Stouffer*, 1994; *Haywood et al.*, 1997]. *Dixon and Lanzante* [1999] report on an ensemble of climate change experiments produced with the newer version of the GFDL coupled model used here, and provide a summary of differences between the two versions, which share the same relatively coarse spatial resolution. An overview of the coupled model is given below, with an emphasis on model-predicted surface water fluxes.

The coupled GCM is forced by seasonally varying insolation, without a diurnal cycle. To reduce climate drift, heat and water flux adjustments are added to the ocean model's surface (see *Manabe et al.* [1991] for a more complete description of the model initialization and flux adjustment techniques). The flux adjustments vary seasonally and spatially, but have no interannual variability.

The ocean model component has ~4.5° latitude by 3.75° longitude grid spacing, 12 vertical levels and a maximum depth of 5000m. It is based on the GFDL Modular Ocean Model version 1 [*Pacanowski et al.*, 1991]. The sea ice model's prognostic variable is sea ice thickness, and its horizontal grid duplicates the ocean GCM's. Sea ice formation increases the salt content of the underlying ocean model grid point, while melting lowers surface salinities. Fourier filtering is applied to oceanic potential temperature, salinity, and sea ice thickness variables poleward of ~68° latitude.

The atmospheric spectral model uses rhomboidal 15 truncation (the transform grid resolution is ~4.5° latitude by 7.5° longitude) and has 9 sigma levels in the vertical. Prognostic water exchange with land and ocean surfaces is accomplished by precipitation (rain and snow), surface evaporation, sublimation and the deposition of dew and frost, the sum of which is referred to hereafter as *P-E*.

Soil moisture calculations employ a 0.15m bucket hydrology model, with runoff instantaneously routed to the ocean according to observed river drainage basin geography. Similarly, if the predicted snow depth at a grid point exceeds a critical value, the excess is considered runoff and is routed to the ocean. The volume and extent of the Antarctic and Greenland ice caps are prescribed and time invariant. Potential ice cap melting or growth is neglected and does not contribute to the model's freshwater balance.

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Once per day, fluxes of freshwater, heat and momentum are communicated between the coupled model's atmosphere-land surface component and the ocean-sea ice component. Here we define the daily surface freshwater fluxes passed to the ocean-sea ice component as consisting of *P-E* simulated over the ocean by the atmospheric GCM and the runoff (*R*) of both liquid and frozen water computed by the land surface model. A positive surface freshwater flux (positive *P-E+R*) indicates water (liquid and solid) is being added to the ocean-sea ice component (consistent with decreases in surface salinity and/or increases in sea ice thickness). Note that surface salinity changes arising from sea ice tendencies (melting or formation) predicted by the sea ice model's thermodynamics are not included in the *P-E+R* term studied here.

A set of five coupled GCM experiments (Table 1) are utilized to determine the roles that changes in various surface fluxes have on the North Atlantic thermohaline circulation in simulations with imposed, transient atmospheric radiative forcing. The segment of the CONTROL (constant GHG levels) simulation examined here is 330 years in length and begins 1100 years after the coupled model was initialized. Surface water and momentum fluxes are archived at each model grid point for each day of this period, producing time series of two-dimensional horizontal fields 120,450 days in length.

The TRANSIENT experiment is initialized from the CONTROL simulation's state at the beginning of model year 1101. This point in time is taken to represent 1 January 1766 for purposes of the GHG and tropospheric sulfate aerosol (GHG+SUL) forcing scenario. Time-varying tropospheric sulfate distributions and GHG levels derived from historical reconstructions are prescribed in the TRANSIENT simulation until scenario year 1990. A one percent per year compounded increase in effective CO_2 levels (the model's proxy for GHGs) is imposed after 1990. Spatial and temporal surface albedo variations associated with the sulfate aerosols' direct effects are implemented as in *Haywood et al.* [1997], with future aerosol levels following the IS92a IPCC scenario [*Leggett et al.*, 1992]. Model-predicted *P-E+R* and surface momentum fluxes are archived each day of the TRANSIENT experiment's 330-year long run, representing scenario years 1766 to 2095.

Three additional 330-year long model experiments are conducted to shed light on the role of changing surface fluxes on the TRANSIENT experiment's climate change response. All three are initialized from year 1101 of the CONTROL simulation. In one model run, named CRAD_TH2O, atmospheric GHG levels are held constant, but the ocean-sea ice component of the coupled model is forced with the 330-year long time series of daily varying *P-E+R* fluxes archived during the TRANSIENT experiment. In the simulation named TRAD_CH2O, the transient GHG and sulfate aerosol scenario is prescribed for the atmospheric GCM, but the time series of daily *P-E+R* fluxes from the CONTROL run is imposed upon the ocean-sea ice component. To determine the role that wind stress changes play in altering the THC, an experiment named CRAD_TWIND is conducted. In CRAD_TWIND, atmospheric GHG levels are held constant, but the 330-year long time series of daily wind stresses archived during the TRANSIENT experiment are imposed on the ocean-sea ice component.

Table 1. Forcings of the Coupled Model Experiments

Experiment	Radiative Forcing	Ocean P-E+R Forcing	Ocean Wind Stress Forcing
CONTROL	Constant	Model-predicted	Model-predicted
TRANSIENT	Transient GHG+SUL	Model-predicted	Model-predicted
CRAD_TH2O	Constant	P-E+R from TRANSIENT	Model-predicted
TRAD_CH2O	Transient GHG+SUL	P-E+R from CONTROL	Model-predicted
CRAD_TWIND	Constant	Model-predicted	Winds from TRANSIENT

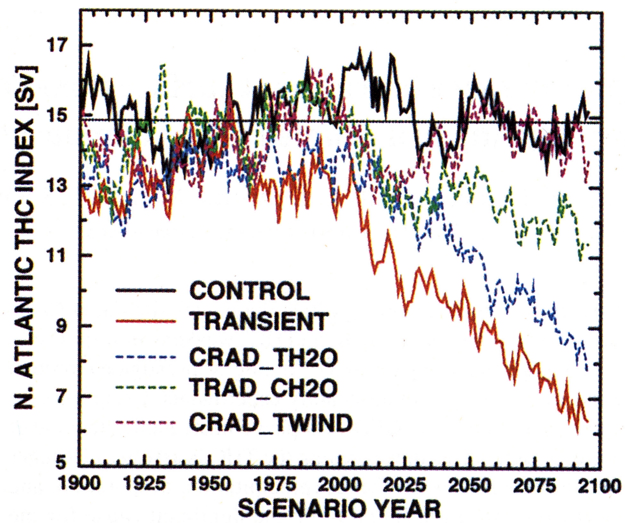

Figure 1. Time series of annual mean North Atlantic THC indices produced by the five coupled GCM runs for the period corresponding to scenario years 1900 to 2095 (years 1766 to 1899 not shown for clarity). See Table 1 and text for experiment descriptions. Horizontal black line at 14.9 Sv indicates the CONTROL run's 330-year mean. [1 Sverdrup = 10^6 m^3s^{-1}].

So, in these three additional experiments, the ocean-sea ice component is "tricked" into feeling surface water or momentum fluxes produced by a previous coupled model experiment run with different radiative forcings. In all other respects, the various surface fluxes are coupled (*i.e.*, the other surface fluxes are calculated as in the CONTROL and TRANSIENT model runs, and the atmosphere-land surface component predicts its own freshwater and momentum fluxes; however, the ocean receives one type of archived surface fluxes instead of those predicted by its own atmosphere-land surface component). By imposing daily varying surface flux time series, these runs experience surface fluxes with the same temporal and spatial variability as the fully coupled runs.

Differences between the CONTROL and CRAD_TH2O ocean-sea ice simulations can be attributed to the changes in *P-E+R* seen in the TRANSIENT experiment. Likewise, the TRAD_CH2O ocean-sea ice response can be considered a result of surface heat flux and wind stress changes brought about by rising atmospheric GHG concentrations. The CRAD_TWIND experiment isolates the influence of wind stress changes on the THC.

Model Results

Time series of the North Atlantic thermohaline circulation index (THC index) from the last 195 years of the five coupled model experiments are shown in Figure 1. As in *Delworth et al.* [1993] the THC index is defined as the maximum value of the streamfunction representing the annual mean meridional circulation (computed across the North Atlantic from the ocean GCM's annual mean northward component of the velocity field). The THC index is related to the model's rate of deep water formation, which in this model occurs primarily south of Greenland and in the Labrador Sea.

Relatively little climate drift is evident in the CONTROL model run. A least-squares regression line fit to the 330-year long THC index time series has a slope of -0.18 Sv century^{-1} (mean = 14.9 Sv, σ = 0.7 Sv, 1 Sv = 10^6 m^3s^{-1}). This trend is small compared to the amount of internally generated variability present in the CONTROL experiment, so that the regression line accounts for less than six percent of the THC time series' variance.

Typical of other GFDL coupled GCM climate change experiments, the TRANSIENT simulation's North Atlantic meridional overturning circulation is greatly reduced during the 21st century. Here, the TRANSIENT experiment's THC index is ~2Sv less than the CONTROL simulation's at scenario year 2000, and drops an additional 6Sv to below 7Sv by the final decade of the experiment.

After scenario year 2000, the THC index time series for both the CRAD_TH2O and TRAD_CH2O experiments lie between those of the CONTROL and TRANSIENT model runs. During the runs' last 50 years, the CRAD_TH2O simulation's THC index averages 2.6Sv less than that of the TRAD_CH2O run. Results from the *Dixon and Lanzante* [1999] ensemble of nine experiments (all configured similarly to the TRANSIENT run), suggest that the difference seen here is a robust result and unlikely to be due to internally generated variability.

These results indicate that *P-E+R* changes are the predominant reason for the weakening of the North Atlantic THC in the TRANSIENT run. Surface heat flux changes that occur in the coupled GCM during the TRANSIENT run also contribute to THC weakening, but are of secondary importance (they can reduce surface water densities by melting sea ice and by the thermal expansion that occurs as near-surface waters warm). The results of experiment CRAD_TWIND show that wind stress changes have negligible impact on the TRANSIENT run's THC strength.

The results of adding together the THC index responses of the CRAD_TH2O and TRAD_CH2O model runs are shown in Figure 2. During the period of rapid THC weakening, the sum of these two

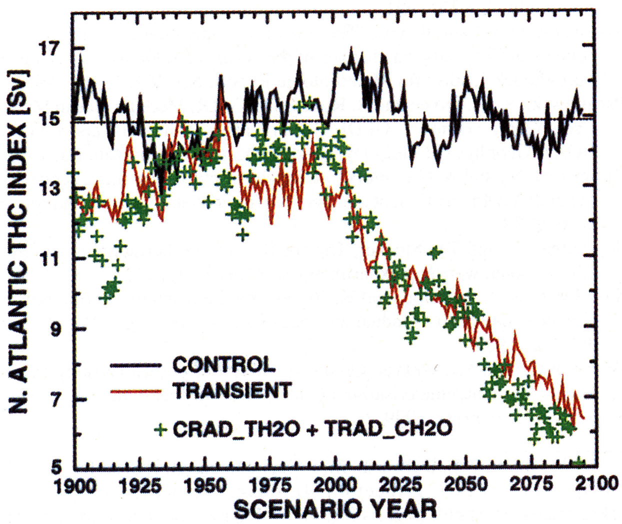

Figure 2. As in Fig. 1, black and red lines show the CONTROL and TRANSIENT runs' THC indices. The green crosses show the additive effects of the CRAD_TH2O and TRAD_CH2O THC index responses (computed separately as deviations from the CONTROL's 330-year mean of 14.9 Sv, and then summed).

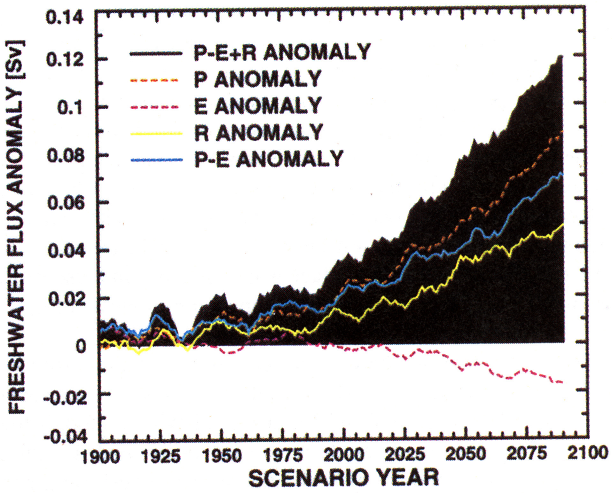

Figure 3. 10-year running means of the TRANSIENT run's freshwater flux anomalies integrated over the Arctic and North Atlantic north of 50°N. Anomalies are computed relative to the CONTROL run's 330-year means. The black area represents the *P-E+R* anomalies. Solid cyan and yellow curves show the *P-E* and runoff terms, respectively. Dashed orange and magenta curves show precipitation and net evaporation anomalies over the ocean, respectively.

responses roughly approximates that of the TRANSIENT experiment's THC response. The amount of variability present within the THC time series and the fact that this analysis includes just one set of model experiments preclude a more quantitative assessment of the extent to which these are truly additive effects.

Differences between the TRANSIENT and CONTROL runs' net *P-E* and runoff terms integrated spatially over the Arctic Ocean and North Atlantic north of 50°N are shown in Figure 3. On decadal time scales, surface water fluxes (liquid and solid) in this domain presumably influence surface salinities where the model's version of North Atlantic Deep Water is formed. Over the region of integration, both runoff and net *P-E* contribute to the increased net surface freshwater flux passed to the TRANSIENT run's ocean-sea ice component. During the last 50 years of the simulation, runoff from the land surface accounts for ~43 percent of the increase in *P-E+R*. There is negligible drift in the CONTROL model's 330 years of annual mean *P-E+R* data computed over this region, with the regression line's slope being only -0.001 Sv century^{-1}.

The global mean surface air temperature warms ~4.2K by the last decade of the TRANSIENT run. The TRAD_CH2O run warms by ~4.8K. With constant GHG forcing and the TRANSIENT model's *P-E+R* forcing, CRAD_TH2O's global mean SAT cools by ~0.4K. This indicates that in addition to weakening the THC, *P-E+R* changes simulated in the enhanced GHG scenario actually counter the GHG-induced global warming trend, in this version of the GFDL coupled climate model. A comparable freshwater-induced cooling was seen in a similarly forced CGCM experiment performed by *Mikolajewicz and Voss* [1998].

Summary and Discussion

The set of coupled GCM experiments examined here reveals that changes in surface freshwater fluxes (*P-E+R*) are the primary reason that the North Atlantic meridional overturning weakens in coarse resolution GFDL coupled model simulations forced with increasing GHGs. Surface heat flux changes play a secondary role in weakening the THC, while wind stress changes have negligible impact. The dominance of the freshwater flux term becomes very clear during the second half of the model-simulated 21st century.

Over the Arctic Ocean and North Atlantic north of 50°N, increases in precipitation and runoff are larger than the increase in net evaporation. These changes contribute to lower surface salinities and densities in the ocean model, which lead to reduced North Atlantic deep water formation rates (lower THC index). Changes in surface heat fluxes that occur when transient atmospheric radiative forcing is imposed lead to warmer SSTs and surface freshening as sea ice melts. By reducing surface water densities in these ways, the surface heat flux changes also contribute to weakening the model's THC, but to a lesser extent than the *P-E+R*.

The results reported here are specific to the coarse resolution GFDL coupled model. The THC of different models will respond differently to increasing GHG forcing. And even in models that yield similar THC responses, different mechanisms may dominate.

Using a simplified coupled climate model to perform global warming experiments, *Schmittner and Stocker* [1999] found that an increase in atmospheric poleward water transport is chiefly responsible for the cessation of North Atlantic deep water formation - a result broadly consistent with those reported here.

Wiebe and Weaver [1999] also conclude that high latitude surface water fluxes are primarily responsible for THC weakening during the early stages (first several decades) of transient GHG forcing. However, the importance of heat flux changes grow over time in their experiments, which were conducted with an ocean GCM coupled to an energy-moisture balance atmosphere model.

Conversely, *Rahmstorf and Ganopolski* [1999] find that heat fluxes are primarily responsible for THC weakening during the first several decades of their GHG experiments, while freshwater fluxes become dominant in the 22nd century. By increasing the hydrological sensitively in their simplified coupled model, the freshwater fluxes play a more important role in weakening the THC further.

S. Power [submitted to J. Phys. Oceanogr., 1999] forced an ocean GCM with various combinations of time-averaged surface fluxes derived from coupled model runs. Heat flux anomalies were reported to be largely responsible for THC weakening, but runoff was not included in the surface freshwater flux term.

The study of *Mikolajewicz and Voss* [1998] (MV98) is the most analogous to ours, in both its experimental design and in the use of a fully coupled GCM (the ECHAM3/LSG model). However, the MV98 results differ from those reported here, in that heat flux changes were mainly responsible for THC weakening during simulated global warming. MV98 conclude that a change in interbasin freshwater transport (enhanced freshwater export from the Atlantic) in their CGCM is responsible for minimizing the impact of the increased hydrological cycle when GHGs increase. In our TRANSIENT experiment, the atmospheric model does not produce a marked change in interbasin freshwater transport over time.

It is difficult to speculate why the results of the ECHAM3/LSG model differ from those presented here, considering the very large differences in the dynamics and physical parameterizations employed in the two coupled models. We note that the GFDL coupled model's CONTROL simulation produces more precipitation at high latitudes than is observed - a trait found in many low resolution atmospheric models. Yet, qualitatively similar changes in the North Atlantic THC and *P-E+R* are seen in a higher resolution version of the GFDL coupled model having a much smaller high latitude precipitation bias [*Manabe and Stouffer*, 1994].

That a consensus has not emerged from modeling studies regarding the principal mechanism responsible for THC weakening under increasing GHG conditions illustrates that caution is needed when interpreting results from a single model. Models can produce similar climate change responses for different mechanistic reasons. Future efforts within the climate modeling community to identify the specific factors that govern the North Atlantic THC's response in different CGCMs would aid the evaluation of model performance, and will be valuable in assessing the models' ability to simulate observed climate changes. Ideally, ensembles of CGCM experiments could be used to determine levels of uncertainty regarding the results of a particular model.

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References

Delworth, T.L., S. Manabe, and R.J. Stouffer, Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model. *J. Climate, 6*, 1993-2011, 1993.

Dixon, K.W., and J.R. Lanzante, Global mean surface air temperature and North Atlantic overturning in a suite of coupled GCM climate change experiments, *Geophys. Res. Let., 26*, 1885-1888, 1999.

Haywood, J.M., R.J. Stouffer, R.T. Wetherald, S. Manabe and V. Ramaswamy, Transient response of a coupled model to estimated changes in greenhouse gas and sulfate concentrations, *Geophys. Res. Let., 24*, 1335-1338, 1997.

Leggett, J., W.J. Pepper, and R.J. Stuart, Emission scenarios for the IPCC: An update, in *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, edited by J.T. Houghton, B.A. Callander, and S.K. Varney, Cambridge Univ. Press, Cambridge, U.K., 200pp., 1992.

Kattenberg, A, F. Giorgi, H. Grassl, G.A. Meehl, J.F.B. Mitchell, R.J. Stouffer, T. Tokioka, A.J. Weaver, and T.M.L. Wigley, Climate models - Projections of future climate, in *Climate Change 1995: The Science of Climate Change*, edited by J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell, Cambridge Univ. Press, Cambridge, U.K., 572 pp., 1996.

Manabe, S., R.J. Stouffer, M.J. Spelman, and K. Bryan, Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2. Part I: Annual mean response, *J. Climate, 4*, 785-818, 1991.

Manabe, S., and R.J. Stouffer, Multiple-century response of a coupled ocean-atmosphere model to an increase of atmospheric carbon dioxide, *J. Climate, 7*, 5-23, 1994.

Mikolajewicz, U., and R. Voss, The role of the individual air-sea flux components in CO_2-induced changes of the ocean's circulation and climate, Max-Planck-Institut für Meteorologie Report, No. 263, 27pp., 1998.

Pacanowski, R., K. Dixon and A. Rosati, The GFDL Modular Ocean Model Users Guide version 1, GFDL Ocean Group Technical Report No. 2, NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, 1991.

Rahmstorf, S., and A. Ganopolski, Long-term global warming scenarios computed with an efficient coupled climate model, *Climatic Change, in press*, 1999.

Schmittner, A. and T.F. Stocker, The stability of the thermohaline circulation in global warming experiments, *J. Climate, 12*, 1117-1133, 1999.

Stouffer, R. J., S. Manabe, and K. Bryan, Interhemispheric asymmetry in climate response to a gradual increase of atmospheric CO_2, *Nature*, 342, 660-662, 1989.

Wiebe, E.C., and A.J. Weaver, On the sensitivity of global warming experiments to the parameterisation of sub-grid scale ocean mixing, *Climate Dynamics, in press*, 1999.

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