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# A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric $CO_2$ concentration

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[1] As part of the Coupled Model Intercomparison Project, integrations with a common design have been undertaken with eleven different climate models to compare the response of the Atlantic thermohaline circulation (THC) to time-dependent climate change caused by increasing atmospheric $CO_2$ concentration. Over 140 years, during which the $CO_2$ concentration quadruples, the circulation strength declines gradually in all models, by between 10 and 50%. No model shows a rapid or complete collapse, despite the fairly rapid increase and high final concentration of $CO_2$. The models having the strongest overturning in the control climate tend to show the largest THC reductions. In all models, the THC weakening is caused more by changes in surface heat flux than by changes in surface water flux. No model shows a cooling anywhere, because the greenhouse warming is dominant. **Citation:** Gregory, J. M., et al. (2005), A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric $CO_2$ concentration, *Geophys. Res. Lett.*, *32*, L12703, doi:10.1029/2005GL023209.

## 1. Introduction

[2] Because it conveys a large heat flux northwards, the Atlantic meridional overturning circulation has a substantial influence on northern hemisphere climate [*Vellinga and Wood*, 2002]. It is commonly called a ‘‘thermohaline circulation’’ (THC); it involves warm saline surface water flowing northward in the Atlantic basin to high latitudes, where it is cooled and sinks, and cold dense water flowing southward at depth.

[3] The THC is potentially sensitive to anthropogenic climate change in coming centuries [*Dixon et al.*, 1999; *Mikolajewicz and Voss*, 2000; *Thorpe et al.*, 2001], which is generally expected to reduce ocean heat loss and increase freshwater input at high latitudes, lowering the density in the sinking region. The main tools that are used for making climate change projections are coupled atmosphere-ocean general circulation models (AOGCMs). Such models give widely divergent results for changes in the Atlantic THC, even with the same scenario for future greenhouse-gas and other emissions. For instance, AOGCMs forced with the IS92a scenario predict changes in the THC by 2100 ranging from no response to a nearly complete disappearance [*Cubasch et al.*, 2001, Figure 9.1]. These differences in THC response imply large uncertainties in projected climate change, especially in the north Atlantic and Europe.

[4] The present study is one of the coordinated THC experiments, described by R. J. Stouffer et al. (Investigating the causes of the response of the thermohaline circulation to past and future climate change, submitted to *Journal of Climate*, 2005, hereinafter referred to as Stouffer et al., submitted manuscript, 2005), of the Coupled Model Intercomparison Project (CMIP). The purpose of the experiments is to assess differences in THC responses and investigate reasons for those differences in simulations of a common design undertaken at a number of institutions worldwide with AOGCMs and Earth system models of intermediate complexity (EMICs). In the present paper, results are used from six AOGCMs and five EMICs. Brief details of the models are given by Stouffer et al. (submitted manuscript, 2005, Table 1), who describe the other coordinated THC experiment, on the response of the THC to an abrupt freshwater input (‘‘hosing’’). The version of ECBILT-CLIO used in the present experiment additionally includes a dynamic vegetation scheme (VECODE).

## 2. Experimental Design

[5] The experiment comprises four integrations of 140 years each and was based on the design of *Dixon et al.* [1999] and *Mikolajewicz and Voss* [2000]. We adopt the naming convention of *Dixon et al.* [1999] for the integrations described below.

[6] The first integration is a CONTROL with constant $CO_2$ and a steady-state climate, typically beginning after several centuries of model spin-up. The other integrations all begin from the initial state of the CONTROL. To

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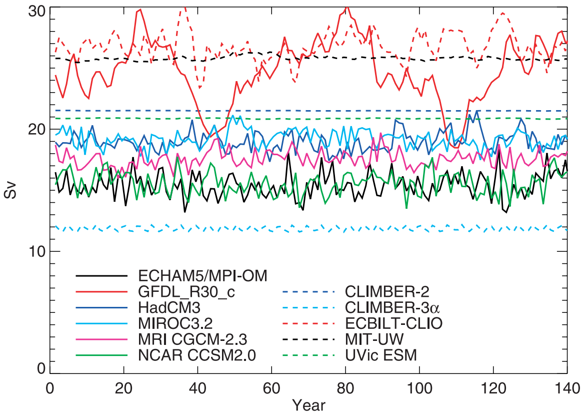

**Figure 1.** Annual time series of the THC strength (maximum of the overturning stream function in the north Atlantic) in the CONTROL integrations. Solid lines are plotted for AOGCMs, dashed lines for EMICs.

evaluate the signal of climate change at any time in these integrations, the corresponding part of the CONTROL is subtracted, in order to eliminate any climate drift remaining from insufficient spin-up.

[7] The TRANSIENT integration follows an idealised scenario of $CO_2$ concentration increasing at 1% per year compounded, bringing it to four times its initial concentration after 140 years. The 1% rate is the standard for CMIP; though fairly large when compared to estimates of future $CO_2$ concentration growth, it nonetheless implies a smaller rate of increase in radiative forcing than some of the IPCC scenarios for the 21st century, neglecting aerosol effects. Standard CMIP integrations are only 70 years; the double length of the ones used here makes the signal of climate change clearer. Note that, since radiative forcing depends logarithmically on $CO_2$ concentration to a very good approximation over a wide range of $CO_2$ concentrations, and climate response to $CO_2$ forcing is fairly linear, the precise choice of CONTROL $CO_2$ concentration is not critical.

[8] Daily fields of ocean surface water fluxes (precipitation, evaporation and river inflow) are saved from CONTROL and TRANSIENT. In the remaining two integrations, the surface freshwater fluxes are specified rather than being computed interactively. Surface water fluxes can be imposed because there is no direct feedback of sea surface salinity on water fluxes. By contrast, surface heat fluxes are strongly coupled to sea surface temperature (SST), sea ice and atmospheric conditions, and are computed interactively in all integrations. In CRAD_TH2O the $CO_2$ concentration is held constant at the CONTROL value and the daily water fluxes saved from TRANSIENT are imposed, while in TRAD_CH2O the $CO_2$ concentration increases at the same rate as in TRANSIENT and daily water fluxes from CONTROL are used. These two integrations are called "partially coupled" [*Mikolajewicz and Voss*, 2000] because the water fluxes computed from the atmosphere and surface components do not equal those applied to the ocean. This could imply a non-conservation of water, but it will not be serious under the reasonable assumption that long-term accumulation of water on land or in the atmosphere is small on these time scales.

[9] The idea of the partially coupled integrations is that changes in the THC in CRAD_TH2O will be caused by surface water flux changes and in TRAD_CH2O by surface heat flux changes, thus allowing us to quantify the relative importance of these influences as $CO_2$ rises. The TRAD_CH2O integrations will also include the effect of surface wind stress (momentum flux) changes; no separate integrations were done to quantify this. *Mikolajewicz and Voss* [2000] found wind stress changes to account for about one-quarter of the THC weakening in the ECHAM3/LSG model; their effect was negligible in the experiment of *Dixon et al.* [1999] with the GFDL_R15_a model, and this is also the case in GFDL_R30_c and HadCM3. On the basis of these results, wind stress changes seem unlikely to have a dominant influence, but it would be useful to evaluate it in other models.

## 3. CONTROL Integrations

[10] The magnitude of the THC is, as usual, measured by the maximum of the overturning stream function in the north Atlantic in sverdrups (1 Sv $\equiv 10^6$ $m^3$ $s^{-1}$), excluding the shallow wind-driven overturning. The control experiments (constant $CO_2$) of the various models have overturning between 10 and 30 Sv (Figure 1). None of them has a statistically significant trend. Stouffer et al., (submitted manuscript, 2005) used an earlier portion of the HadCM3 control run, during the initial centuries of which the THC slowly weakens by about 5 Sv and becomes steadier. Tests showed that the transient response of the THC to $CO_2$ in HadCM3 is unaffected. Our version of CLIMBER-3α, which has the weakest THC, uses a small ocean tracer vertical diffusivity of $0.1 \times 10^{-4}$ $m^2$ $s^{-1}$; with $0.4 \times 10^{-4}$ $m^2$ $s^{-1}$ the overturning is 15 Sv.

[11] The models show a range of interannual variability, but there is no significant relation between the mean and the variability (the correlation is 0.27). Internal variability of the climate system in models of this resolution derives from the atmosphere. (The small oscillation in the CLIMBER-3α runs is due to numerical instability affecting the sites of ocean convection.) ECBILT-CLIO has a quasi-geostrophic dynamical atmosphere model, which generates substantial variability, but the other EMICs have little or none. The MIT-UW atmosphere uses zonally averaged dynamics,

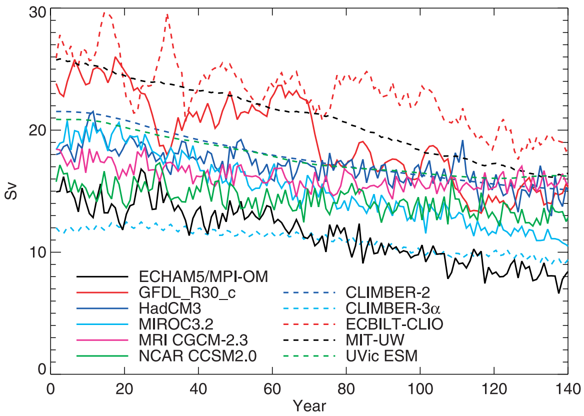

**Figure 2.** Annual time series of the THC strength (maximum of the overturning stream function in the North Atlantic) in the TRANSIENT integrations.

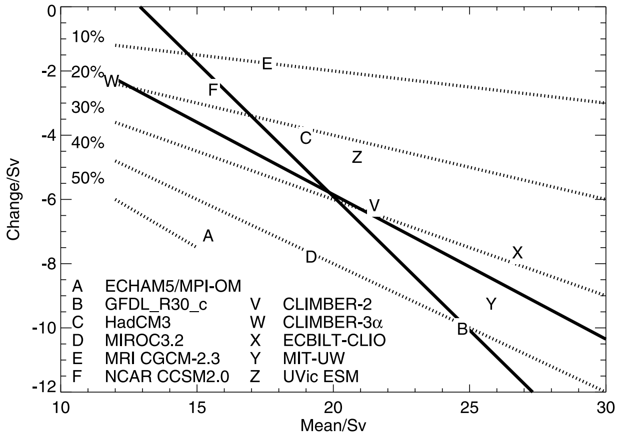

**Figure 3.** Change in the THC strength averaged over the last 20 years of the TRANSIENT integration with respect to the CONTROL long-term mean. AOGCMs have letters from the start of the alphabet and EMICs from the end. The dashed lines indicate reductions by the percentages marked. The solid lines are regressions.

which produces less variability than the 3D GCM from which it was derived. The CLIMBER atmosphere diagnoses advecting velocities from the temperature field but has no prognostic dynamics. The UVic atmosphere is diffusive.

## 4. TRANSIENT Integrations

[12] In all the models, the THC weakens when $CO_2$ is increased at 1% per year (Figure 2). The weakening is gradual in all the models, with no abrupt collapse. This is consistent with previous studies, in that no AOGCM published to date has produced a sudden complete THC collapse (i.e., within a decade or two) in response to greenhouse forcing. The disappearance of the circulation in the $4 \times CO_2$ experiment of *Manabe and Stouffer* [1994] was also gradual.

[13] Although THC weakening mitigates the $CO_2$ warming in the Atlantic region (see also section 3), there is no cooling over any substantial region in any of the TRANSIENT experiments, because the $CO_2$ effect is larger.

[14] The size of the weakening varies considerably among models (Figure 2), being greatest in GFDL_R30_c and least in MRI CGCM-2.3. Expressed as a fraction of the control value, it ranges between 10% and 50% (Figure 3), with no systematic difference between AOGCMs and EMICs. There is no correlation between the weakening and the rise in global average surface temperature, which is the usual metric of climate change used to compare climate model response to $CO_2$. There is however a strong correlation of $-0.74$ between control THC strength and the weakening (both in Sv); that is, the models with larger overturning have a greater weakening. The slopes from ordinary least squares regression are significantly different from zero ($-0.45 \pm 0.14$ for $y$ against $x$ and $-1.20 \pm 0.37$ for $x$ against $y$). ECHAM5/MPI-OM lies furthest from the regression lines in Figure 3, but a higher-resolution version of this model is nearer, having a CONTROL value of 21 Sv and a weakening of 8 Sv.

[15] This relationship is surprising; if it is a real effect, it could perhaps be due to a large model spread in the contribution of the hydrological cycle in determining both the CONTROL strength and TRANSIENT weakening. Extrapolation suggests that $CO_2$ forcing may cause the THC to strengthen in models with CONTROL values below ~10 Sv.

## 5. Partially Coupled Integrations

[16] We evaluate the influence of heat and freshwater changes in each of the models in the present experiment by dividing the weakening relative to the CONTROL in the final 20-year means of TRAD_CH2O and CRAD_TH2O respectively by the corresponding TRANSIENT weakening (Figure 4). Uncertainties on these fractions were estimated by assuming the variability of 20-year means in CONTROL applies in the other integrations. Heat flux changes weaken the THC in all models and water fluxes do in most. In all models, heat flux changes contribute more than water flux changes to weakening the THC (all lie below the dashed diagonal line), but their relative importance varies.

[17] GFDL_R30_c differs from the older GFDL_R15_a analysed by *Dixon et al.* [1999], in which water flux changes are about twice as important as heat flux changes, although not in the early decades of the integrations. *Wiebe and Weaver* [1999] found that water flux changes were more important also in an earlier version of the UVic ESM, which had less realistic precipitation. On the other hand, the dominance of heat in HadCM3 and MIT-UW is consistent with the conclusions of *Thorpe et al.* [2001] and *Kamenkovich et al.* [2003] respectively deduced by different methods for these models. In the ECHAM3/LSG model of *Mikolajewicz and Voss* [2000], heat flux changes are responsible for at least three-quarters of the weakening.

[18] In the NCAR CCSM 2.0 model, water fluxes changes overall tend to strengthen the circulation (hence the point is below zero on the vertical axis), counteracting

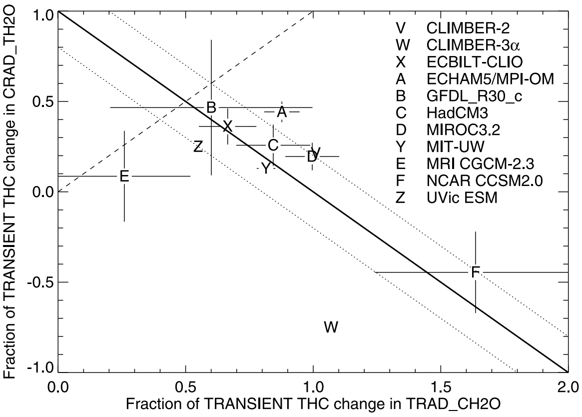

**Figure 4.** Contributions of heat (TRAD_CH2O) and water flux (CRAD_TH2O) changes to THC change, expressed as a fraction of the total weakening. Note that MIROC3.2 (D) and CLIMBER-2 (V) are almost coincident. The error bars show ±2 standard deviations. The solid diagonal line indicates a sum of unity, the dotted lines sums of 0.8 and 1.2. Any models lying above the dashed line would be dominated by water flux changes.

some of the weakening due to heat flux changes. In this model, contrary to the general rule, the net surface freshwater input to the ocean in the north Atlantic (south of Iceland) is less in TRANSIENT than in CONTROL [*Hu et al.*, 2004].

[19] If the weakening of the THC in the TRANSIENT integration is the linear combination of the effects of the heat flux changes in TRAD_CH2O and water flux changes in CRAD_TH2O, the fractions will sum to unity (solid diagonal line in Figure 4). Within uncertainties, linearity is satisfied for five (nearly half) of the models; of the other six, two have sums in the range 0.8–1.2.

[20] In two of the four markedly non-linear models (CLIMBER-2 and ECHAM5/MPI-OM), TRAD_CH2O has a similar weakening to TRANSIENT, and CRAD_TH2O a smaller one. In these models, there must be some interaction between the effects of heat and freshwater forcing.

[21] The other two (CLIMBER-3$\alpha$ and MRI CGCM-2.3) have the smallest reduction in THC, and its behaviour in the various integrations changes as time passes; this is also true of UVic ESM. For instance, during the second half of the integrations with MRI CGCM-2.3, the overturning returns to the CONTROL level in CRAD_TH2O, but the recovery is much less marked in TRANSIENT. The recovery is due to increasing salinity in the northern north Atlantic, perhaps through advection of more saline water from the lower latitudes, as found by *Latif et al.* [2000] and *Thorpe et al.* [2001]. In general, qualitative changes in behaviour may be due to the effect of different timescales of response to local buoyancy flux changes and advection.

[22] In all the CRAD_TH2O integrations, there is a cooling in the north Atlantic associated with the THC weakening, except in NCAR CCSM 2.0, which shows a warming and THC strengthening. The GFDL_R30_c model has both the largest weakening and the greatest cooling. The correlation is 0.76 between THC change and surface air temperature change in the region 60–20°W and 45–70°N evaluated from the last 20 years of the integrations. The slope is 0.42 K $Sv^{-1}$, lying between the AOGCM (0.79) and EMIC (0.31) slopes found in the hosing experiments (Stouffer et al., submitted manuscript, 2005).

[23] The CRAD_TH2O integrations also generally show a cooling in the Southern Ocean, in contrast to the hosing experiments, which generally show a warming there. Probably this is because the CRAD_TH2O integrations have water flux changes worldwide caused by $CO_2$-induced climate change, including a general increase in high-latitude net freshwater input, which will tend to suppress convection and produce surface cooling in the Southern Ocean; in the hosing experiment, however, changes in the Southern Ocean are a remote response to the THC changes forced in the north Atlantic alone.

## 6. Conclusions

[24] The purpose of the CMIP coordinated THC experiment is to reduce the important systematic uncertainty in climate prediction arising from the spread of projected THC changes. Our results are consistent with earlier findings in showing that the circulation weakens during time-dependent climate change caused by $CO_2$ increase, but perhaps unexpectedly indicate that the weakening is caused more by changes in surface heat flux than by changes in surface water flux. The THC does not decline to zero or collapse in any of these models, despite the fairly rapid increase and high final concentration of $CO_2$. Although EMICs generally have smaller internal variability than AOGCMs, we see no systematic differences in their simulations of THC behaviour on decadal timescales. Further analysis of this experiment and the results from the hosing experiments (Stouffer et al., submitted manuscript, 2005) will aim to quantify the relation between changes in surface buoyancy fluxes and THC strength in the various models, the feedbacks and their timescales.

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## References

Cubasch, U., et al. (2001), Projections of future climate change, in *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., pp. 525–582, Cambridge Univ. Press, New York.

Dixon, K., T. Delworth, M. Spelman, and R. Stouffer (1999), The influence of transient surface fluxes on North Atlantic overturning in a coupled GCM climate change experiment, *Geophys. Res. Lett.*, *26*, 2749–2752.

Hu, A., G. A. Meehl, and W. Han (2004), Detecting thermohaline circulation changes from ocean properties in a coupled model, *Geophys. Res. Lett.*, *31*, L13204, doi:10.1029/2004GL020218.

Kamenkovich, I. V., A. P. Sokolov, and P. H. Stone (2003), Feedbacks affecting the response of the thermohaline circulation to increasing $CO_2$: A study with a model of intermediate complexity, *Clim. Dyn.*, *21*, 119–130.

Latif, M., E. Roeckner, U. Mikolajewicz, and R. Voss (2000), Tropical stabilisation of the thermohaline circulation in a greenhouse warming simulation, *J. Clim.*, *13*, 1809–1813.

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

Mikolajewicz, U., and R. Voss (2000), The role of the individual air-sea flux components in $CO_2$-induced changes of the ocean's circulation and climate, *Clim. Dyn.*, *16*, 627–642.

Thorpe, R. B., J. M. Gregory, T. C. Johns, R. A. Wood, and J. F. B. Mitchell (2001), Mechanisms determining the Atlantic thermohaline circulation response to greenhouse gas forcing in a non-flux-adjusted coupled climate model, *J. Clim.*, *14*, 3102–3116.

Vellinga, M., and R. A. Wood (2002), Global climatic impacts of a collapse of the Atlantic thermohaline circulation, *Clim. Change*, *54*, 251–267.

Wiebe, E. C., and A. J. Weaver (1999), On the sensitivity of global warming experiments to the parametrisation of sub-grid scale ocean mixing, *Clim. Dyn.*, *15*, 875–893.

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