

A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO₂ concentration

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In an experiment coordinated 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 CO₂ concentration. Over 140 years, during which the CO₂ concentration quadruples, the circulation strength declines gradually in all models, by between 10 and 50%. This weakening is consistent with the expected effect of reduced heat loss and increased net freshwater input in the north Atlantic. No model shows a rapid or complete collapse. The models having the strongest overturning in the control climate tend to show the largest THC reductions. Despite the reduced ocean heat transport, no model shows a cooling anywhere, because the greenhouse warming is dominant. In all the models, the THC weakening is caused more by changes in surface heat flux than by changes in surface water flux.

1. Introduction

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]. Modelling studies indicate that it is primarily a thermohaline circulation (THC) [Saenko et al., 2002]. We define the THC as the part of the ocean circulation which 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.

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. These differences in THC response imply large uncertainties in projected climate change, especially in the north Atlantic and Europe.

The present study is one of the coordinated THC experiments, described in the companion paper [Stouffer et al., in preparation], 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 in Table 1 of Stouffer et al. [in preparation], 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 this experiment additionally includes a dynamic vegetation scheme (VECODE).

2. Experimental design

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. for the integrations described below.

The first integration is a CONTROL with constant CO₂ 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 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.

The TRANSIENT integration follows an idealised scenario of CO₂ 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

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CO₂ 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 CO₂ concentration to a very good approximation over a wide range of CO₂ concentrations, and climate response to CO₂ forcing is fairly linear, the precise choice of CONTROL CO₂ concentration is not critical.

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 CO₂ concentration is held constant at the CONTROL value and the daily water fluxes saved from TRANSIENT are imposed, while in TRAD_CH2O the CO₂ 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.

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 CO₂ 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 windstress 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, windstress changes seem unlikely to have a dominant influence, but it would be useful to evaluate it in other models.

3. CONTROL integrations

The magnitude of the THC is, as usual, measured by the maximum of the overturning streamfunction in the north Atlantic in sverdrups ($1 \text{ Sv} \equiv 10^6 \text{ m}^3 \text{ s}^{-1}$), excluding the shallow wind-driven overturning. The control experiments (constant CO₂) of the various models have overturning between 10 and 30 Sv (Figure 1). None of them has a statisti-

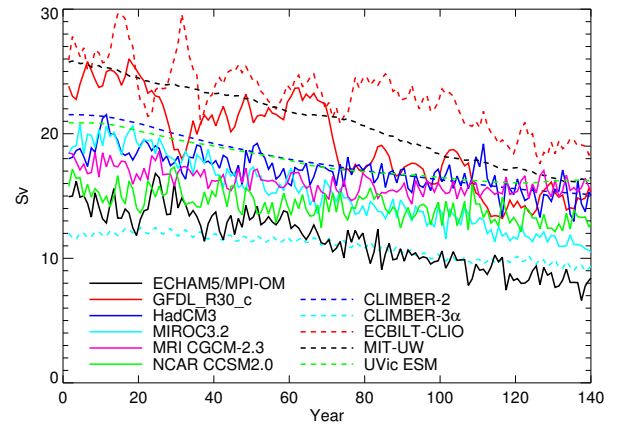


Figure 2. Annual timeseries of the THC strength (maximum of the overturning streamfunction in the north Atlantic) in the TRANSIENT integrations.

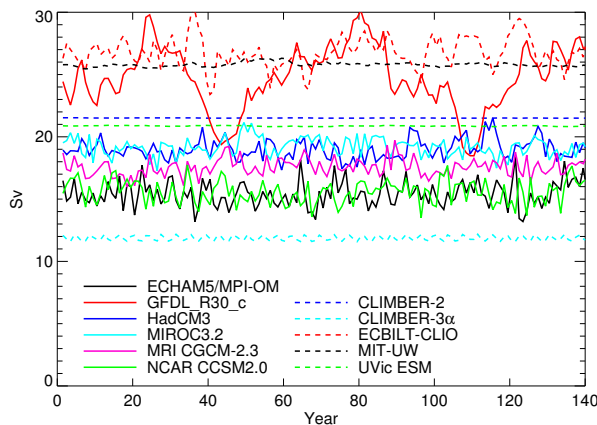


Figure 1. Annual timeseries of THC strength (maximum of the overturning streamfunction in the north Atlantic) in the CONTROL integrations. Solid lines are plotted for AOGCMs, dashed lines for EMICs.

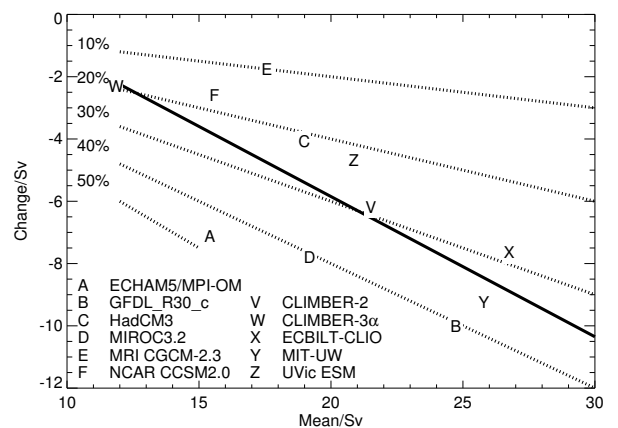


Figure 3. Change in the THC strength averaged over the last 20 years of the TRANSIENT integration with respect to the CONTROL long-term mean. AOGCMs have letters from the start of the alphabet and EMICs from the end. The dashed lines indicate reductions by the percentages marked. The solid line is a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

cally significant trend. *Stouffer et al.* [in preparation] 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 CO₂ in HadCM3 is unaffected. This version of CLIMBER-3 α , which has the weakest THC, uses a small ocean tracer vertical diffusivity of $0.1 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$; with $0.4 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ the overturning is 15 Sv.

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-3 α 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, 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

In all the models, the THC weakens when CO₂ 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 $4 \times \text{CO}_2$ experiment of *Manabe and Stouffer* [1994] was also gradual.

Although THC weakening mitigates the CO₂ warming in the Atlantic region (see also Section 5), there is no cool-

ing over any substantial region in any of the TRANSIENT experiments, because the CO₂ effect is larger.

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 CO₂. There is however a strong correlation of -0.74 between control THC strength and the weakening (both in Sv) *i.e.* the models with larger overturning have a greater weakening. (ECHAM5/MPI-OM lies furthest from the regression line 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.) The sign of correlation is the opposite of what would be expected from the idea that some models may be more sensitive because they are nearer to a point of collapse [*Tziperman*, 1997]. In that case, the ones which were weaker in the control would presumably be nearer to the critical point, and would respond with a greater weakening. On the contrary, assuming linear extrapolation is valid, the regression suggests that CO₂ forcing would cause the THC to *strengthen* in a model with a CONTROL value of less than 7 Sv. If this 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.

5. Partially coupled integrations

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. Uncertainties on these fractions were estimated by assuming the variability of 20-year means in CONTROL applies in the other integrations.

In all models, heat flux changes weaken the THC. This is expected because the THC is predominantly driven by high-latitude heat loss, which is reduced in the warmer climate of TRANSIENT and TRAD_CH2O. In all models, heat flux changes contribute more than water flux changes to weakening the THC (they all lie below the dashed line), but their relative importance varies.

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.

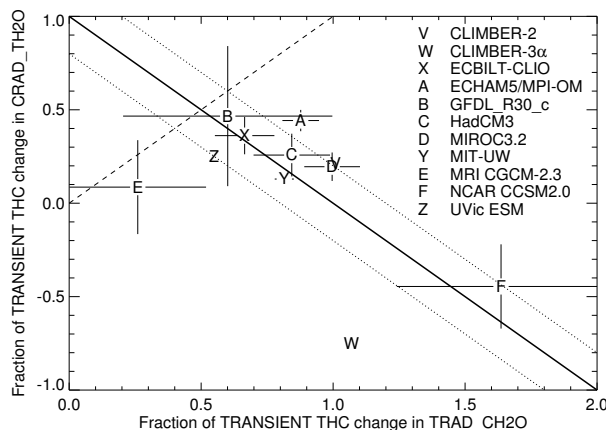


Figure 4. Contributions of heat (TRAD_CH2O) and water flux (CRAD_TH2O) changes to THC change, expressed as a fraction of the total weakening. Note that MIROC3.2 (D) and CLIMBER-2 (V) are almost coincident. The error bars show ± 2 standard deviations. The solid diagonal line indicates a sum of unity,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

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 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].

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 not satisfied for six (about half) of the models; of these six, two have sums in the range 0.8–1.2.

In two of the four markedly non-linear models (CLIMBER-2 and ECHAM5/MPI-OM), the THC weakens throughout the climate-change integrations; 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.

The other two (CLIMBER-3 α 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.

In all the CRAD.TH2O integrations, there is a cooling in the north Atlantic associated with the THC weakening, except 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.*, in preparation].

The CRAD.TH2O integrations also generally show a cooling in the Southern Ocean, in contrast to the hosing experiments, which generally showing a warming there. Probably this is because CRAD.TH2O integrations have water flux changes worldwide caused by CO₂-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

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 preliminary analysis is consistent with ear-

lier results in showing that the circulation strength declines gradually in all models during time-dependent climate change caused by CO₂ increase, but perhaps unexpectedly indicates that the weakening in all models is caused more by changes in surface heat flux than by changes in surface water flux. 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.*, in preparation] 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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