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Response of the Atlantic meridional overturning circulation to increasing atmospheric CO_2: Sensitivity to mean climate state

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[1] The dependence on the mean climate state of the response of the Atlantic meridional overturning circulation (AMOC) is investigated in 17 increasing greenhouse gas experiments with different initial conditions. The AMOC declines in all experiments by 15% to 31%, with typically the largest declines in those experiments with the strongest initial AMOC. In all cases, changes in surface heat fluxes, rather than changes in surface freshwater fluxes, are the dominant cause for the transient AMOC decrease. Surface freshwater fluxes actually switch from reducing the transient AMOC decrease, for low values of atmospheric CO_2, to reinforcing the transient AMOC decrease, for higher values of atmospheric CO_2. In addition, we find that due to changes in the strengths of feedbacks associated with water vapour and snow/sea ice, the climate sensitivity and transient climate response of the UVic model strongly depends on the mean climate state. **Citation:** Weaver, A. J., M. Eby, M. Kienast, and O. A. Saenko (2007), Response of the Atlantic meridional overturning circulation to increasing atmospheric CO_2: Sensitivity to mean climate state, *Geophys. Res. Lett.*, *34*, L05708, doi:10.1029/2006GL028756.

1. Introduction

[2] North Atlantic Deep Water (NADW) and the intermediate depth Labrador Sea Water (LSW) are currently formed in the Greenland-Iceland-Norwegian and Labrador Seas, respectively. Their rate of formation tightly governs the strength of the Atlantic meridional overturning circulation (AMOC) and its associated heat transport in the North Atlantic (see *Weaver et al.* [1999] for a review). Numerous coupled models have examined the transient response of the AMOC to increasing greenhouse gases [see *Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. Coupled atmosphere-ocean model responses range from no reduction of the AMOC to a more substantive weakening of the AMOC over the 21st century, although none projects its complete shutdown [*IPCC*, 2001].

[3] A reduction in AMOC strength leads to a negative feedback to anthropogenic warming in and around the North Atlantic through reducing the transport of heat from low to high latitudes. That is, SSTs are cooler than they would otherwise be if the AMOC remained unchanged, so that warming is reduced over and downwind of the North Atlantic [*IPCC*, 2001]. In all models where the AMOC weakens, warming still occurs downwind over Europe due to the radiative forcing associated with increasing greenhouse gases. In different models, the strength of the AMOC-SST feedback is fundamentally determined by the competing effects of differential heat and freshwater flux forcing between low and high latitudes [*Gregory et al.*, 2005].

[4] Recently, *Schmittner et al.* [2005] analyzed the 21st century response of the AMOC to increasing greenhouse gases in 28 simulations from 9 different coupled atmosphere-ocean general circulation models. They argued that a best estimate of the projected 21st century AMOC weakening under the SRES A1B emission scenario was 25 ± 25%. This result was further supported by additional projections used in the 4th Assessment of the Intergovernmental Panel of Climate Change (IPCC AR4).

[5] As noted by *IPCC* [2001], a common feature of all climate model projections of 21st century climate is a poleward intensification of warming and an increase in high latitude precipitation. Both of these responses act to decrease the density of high latitude surface waters and hence increase their stability. In some early coupled model simulations [e.g., *Dixon et al.*, 1999; *Wiebe and Weaver*, 1999], the increase in high latitude freshening was the dominant cause of the AMOC weakening whereas in others [e.g., *Mikolajewicz and Voss*, 2000], increased warming dominated over increased freshening.

[6] *Gregory et al.* [2005] reported on a systematic intercomparison of eleven models assessed in the IPCC AR4, including six coupled atmosphere-ocean general circulation models and five Earth Models of Intermediate Complexity (EMICs). They found that all models showed a transient AMOC weakening of between 10% and 50% in response to an idealised 1%/year increase in atmospheric CO_2, with those models associated with the strongest AMOC in the control climate typically yielding the greatest AMOC reduction in the transient climate. *Levermann et al.* [2007] point out that models with a weaker initial AMOC strength typically have more extensive North Atlantic sea ice cover due to the reduced poleward oceanic heat transport associated with the weaker AMOC. *Saenko et al.* [2004] and *Levermann et al.* [2007] further noted that in their simulations, a colder and more extensive sea ice coverage in the control model North Atlantic lead to an AMOC that was more stable to increasing greenhouse gases.

[7] *Gregory et al.* [2005] also noted that the AMOC reduction in the transient simulations from all models was predominantly caused by changes in surface heat flux, rather than by changes in the surface freshwater flux (precipitation, evaporation and river runoff). In addition, they pointed out that for 5 of the 11 models that they analyzed, the AMOC response was a linear combination of

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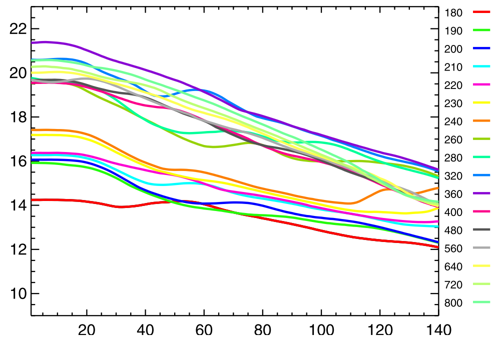

Figure 1. Maximum strength of the Atlantic meridional overturning in Sv for the 140 year integration of the 17 TRANSIENT experiments.

the AMOC responses to heat and freshwater flux changes separately. One of the purposes of this article is to explore the analysis of *Gregory et al.* [2005] further. In particular, we wish to determine whether or not the heat versus freshwater flux dominance and the linearity of the AMOC response to these forcings, depends on the mean climate state itself.

2. Experimental Design

[8] We report upon the results of 17 experiments using version 2.8 of the intermediate complexity University of Victoria Earth System Climate Model (UVic ESCM). For a complete description of the UVic ESCM, as well as an evaluation of it's climatology, the reader is referred to *Weaver et al.* [2001]. This version of the UVic ESCM consists of a 3-D ocean general circulation model coupled to a thermodynamic/dynamic sea-ice model, an energy-moisture balance atmospheric model with dynamical feedbacks, a single layer land surface model and a dynamic vegetation model. The model is global in coverage and has a resolution of 3.6° (zonal) and 1.8° (meridional). The atmosphere model is based on a formulation of the vertically-integrated thermodynamic energy balance equations, which assume an exponentially decreasing vertical distribution of thermal energy and humidity (from surface values) with specified e-folding scale heights. Other major simplifications include the fact that momentum conservation equations are replaced by specified wind data. A large-scale wind feedback parameterization is included that calculates anomalous rotated/contracted geostrophic surface (frictional near the Equator) winds in response to changing atmospheric surface temperature. These wind anomalies are added to the specified seasonally varying wind field [see *Weaver et al.*, 2001]. Atmospheric sensible heat and moisture transports are achieved through advection and diffusion. Precipitation occurs when the relative humidity is greater than 85%. The model is driven by the annual cycle of incoming solar radiation at the top of the atmosphere.

[9] The ocean and ice components of the coupled model are forced by a monthly wind stress climatology, created from 40 years (1958–1998) of daily NCEP reanalysis data [*Kalnay et al.*, 1996], to which the wind anomalies are added. Ice and snow albedo feedbacks are included in the coupled model by locally changing the surface albedo. The atmospheric model includes a parameterization of water vapour/planetary long-wave feedbacks, and the radiative forcing associated with changes in atmospheric CO_2 is included as a modification of the planetary longwave flux. A specified lapse rate is used to reduce the surface temperature over land where there is topography. The dynamic global vegetation model TRIFFID [*Cox et al.*, 1999], together with a single soil-layer land surface scheme [*Meissner et al.*, 2003], were included in the coupled model. As with the models discussed by *Gregory et al.* [2005], this version of the UVic ESCM does not include an interactive ice sheet model. As such, runoff associated with melting land-based glaciers or ice sheets is not included.

[10] Each of the 17 experiments we conducted differed in its initial condition. The different initial conditions were obtained by integrating the UVic ESCM to equilibrium under prescribed levels of atmospheric CO_2 (varying from 180 ppmv to 800 ppmv; see Table 1) and preindustrial orbital conditions and ice sheet elevation and areal extent. The equilibrium strength of the AMOC varied from 14.2 Sv (1 Sv $\equiv 10^6 m^3 s^{-1}$) for the 180 ppmv equilibrium to about 21.5 Sv for the 360 ppmv equilibrium (year 0 in Figure 1; Table 1). In general, the equilibrium AMOC was weaker with reducing atmospheric CO_2, provided that the atmospheric CO_2 concentration was lower than 360 ppmv. The equilibrium AMOC weakened between 360 and 400 ppmv and only slightly increased again between 400 and 800 ppmv.

[11] Following the methodology and terminology of *Gregory et al.* [2005], the atmospheric CO_2 level was increased at a rate of 1%/year for 140 years starting from each of the 17 equilibria (termed the TRANSIENT experiments). The control climate was also integrated for a further 140 years for each of these equilibria (termed the CONTROL experiments). During all CONTROL and TRANSIENT integrations, daily fields of ocean surface freshwater flux (precipitation, evaporation, river runoff, sea ice melt/brine rejection) were archived and used in two additional suites of experiments. In the first, termed CRAD_TH2O, the atmospheric CO_2 concentration was held fixed and the model was integrated for 140 years (starting from each of the 17 initial states) with prescribed surface freshwater fluxes from the TRANSIENT experiments.

[12] The purpose of these experiments was to determine to what extent any changes found in the TRANSIENT experiments was due to changes in the surface freshwater flux. In the second suite of experiments, termed TRAD_CH2O, atmospheric CO_2 concentrations were increased at a rate of 1%/year for 140 years but this time, freshwater fluxes from the CONTROL integrations were specified. The purpose of these experiments was to determine to what extent any changes found in the TRANSIENT experiments were due to changes in the surface heat flux. Should the TRANSIENT change in the AMOC be the same as the sum of the TRAD_CH2O and CRAD_TH2O AMOC changes, the model response would represent a linearly combined response to surface heat and freshwater forcing. In addition, by comparing the fraction of TRANSIENT that can be explained by TRAD_CH2O or CRAD_TH2O, we can determine whether or not the conclusion of *Gregory et al.*

Table 1. Atlantic Meridional Overturning Circulation and Global Surface Air Temperature Response as a Function of Initial Atmospheric CO_2 Concentration[a]

Initial CO_2, ppmv	Initial AMOC, Sv	Year 140 AMOC Sv	AMOC Reduction Sv	AMOC Reduction %	TCR, °C	CS, °C	WC, °C
180	14.2	12.1	2.1	15	2.3	4.3	2.0
190	15.9	12.3	3.6	23	2.2	-	-
200	16.1	12.3	3.8	24	2.1	4.0	1.9
210	16.3	13.0	3.3	20	2.1	-	-
220	16.4	13.3	3.1	19	2.1	-	-
230	17.2	13.9	3.3	19	2.0	-	-
240	17.4	14.8	2.6	15	2.0	3.7	1.7
260	19.5	15.3	4.2	22	2.0	-	-
280	19.8	15.3	4.6	23	2.0	3.5	1.5
320	20.6	15.5	5.1	25	2.0	3.3	1.4
360	21.4	15.6	5.8	27	1.9	3.3	1.4
400	19.5	13.9	5.6	29	1.9	3.3	1.3
480	19.7	14.1	5.6	28	1.9	-	-
560	19.7	14.0	5.7	29	1.9	-	-
640	20.0	14.0	6.0	30	1.8	-	-
720	20.3	14.0	6.3	31	1.8	-	-
800	20.6	14.2	6.4	31	1.8	-	-

[a]Initial CO_2 concentration; maximum strength of the Atlantic meridional overturning (AMOC), initially and at year 140 of the TRANSIENT experiments; the AMOC reduction, expressed in Sv and as a percent; the transient climate response (TCR); the climate sensitivity (CS); and the warming commitment (WC), which is the difference between the CS and the TCR.

[2005] concerning the dominance of heat flux changes in causing the weakening of the AMOC, is sensitive to the initial mean climate state.

3. Results

[13] Consistent with the general results of *Gregory et al.* [2005] the transient reduction of the AMOC during the 140 years of increasing greenhouse gases is largest for the experiments with the strongest AMOC in the control climate (Figure 1). Reductions vary from a drop from 20.6 to 14.2 Sv (31%) for the 800 ppmv initial condition to a drop from 14.2 Sv to 12.1 Sv (15%) for the 180 ppmv initial condition (Table 1). Not a single experiment exhibits a cessation of the AMOC and in all cases, there is warming downwind over Europe relative to the CONTROL experiments due to the radiative forcing associated with the elevated levels of atmospheric CO_2.

[14] In the UVic ESCM, the radiative forcing as a function of time, $F(t)$, associated with changes in atmospheric CO_2, $C(t)$, is given by: $F(t) = F_0 \times \log [C(t)/C_0]$ where $C_0 = 350$ ppmv and $F_0 = 5.35$ W m^{-2}, such that a doubling of CO_2 leads to 3.7 W m^{-2} forcing [*IPCC*, 2001]. The results in Table 1 show a striking correlation (r = 0.87) between the logarithm of the CONTROL climate carbon dioxide level (column 1 of Table 1) and the percentage reduction of the AMOC (column 5 of Table 1). *Gregory et al.* [2005] reported no significant correlation between the AMOC reduction and the transient rise in globally-averaged surface air temperature in the 11 models that they studied. Rather, they argued that the greatest correlation was with the initial strength of the AMOC in the CONTROL experiments.

[15] Further analysis of the model output shown in Table 1 reveals that the initial CONTROL climate AMOC strength is highly correlated (r = 0.76) with the reduction of the AMOC in the TRANSIENT experiments. As such, the strength of the AMOC in the CONTROL climate is itself highly correlated (r = 0.78) with the logarithm of the atmospheric CO_2. In order to determine whether or not the AMOC weakening is dominated by changes in surface freshwater or heat fluxes we examine the fraction of the TRANSIENT experiments that can be explained by each of the TRAD_CH2O and CRAD_TH2O experiments (Figure 2). What is readily apparent is that as shown by *Gregory et al.* [2005], contributions from heat flux change dominate contributions from freshwater flux changes in all experiments (all triangles and curves are below the solid

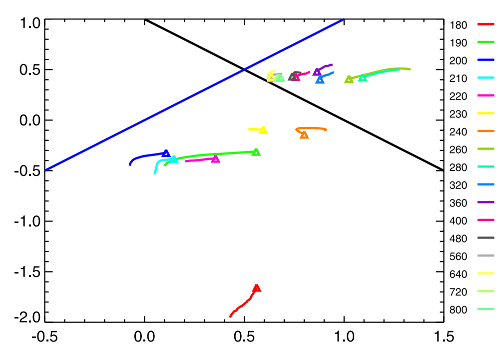

Figure 2. Fraction of AMOC change in the TRANSIENT experiments contributed by transient freshwater fluxes CRAD_TH2O (vertical axis) plotted against the fraction of AMOC change in the TRANSIENT experiments contributed by transient heat fluxes TRAD_CH2O (horizontal axis). The curves represent the fractions over the last 20 years of the experiments whereas the triangles indicate the fractions at year 140. The solid black line indicates where the sum of two fractional changes is unity and so indicates where the TRANSIENT AMOC changes would represent the linear superposition of the CRAD_TH2O and TRAD_CH2O changes. The solid blue line indicates the boundary between surface freshwater and heat flux dominant responses. Any point below the line indicates that heat flux changes are the dominant driver of the response.

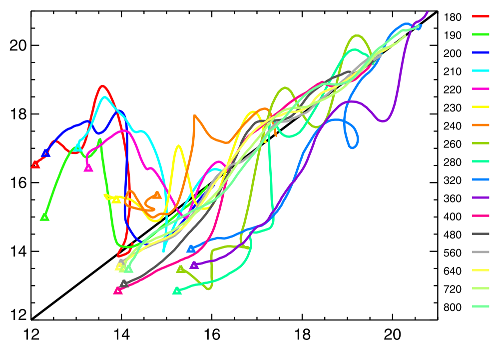

Figure 3. CRAD_TH2O + TRAD_CH2O − CONTROL (vertical axis) as a function of the maximum strength (horizontal axis) of the Atlantic meridional overturning in Sv over the 140 years of each TRANSIENT experiment. The triangles indicate the end of the integration at year 140. The solid black line indicates where the TRANSIENT AMOC changes would represent the linear superposition of the CRAD_TH2O and TRAD_CH2O changes.

blue line in Figure 2). In all cases, heat flux changes cause a reduction of the strength in the AMOC (all triangles are to the right of the zero line on the horizontal axis); however in all experiments where the initial atmospheric CO_2 concentration was 240 ppm or below (initial overturning strength of below 17.5 Sv - see column 2 in Table 1 and year 0 in Figure 1), freshwater fluxes acted to strengthen the AMOC (the points are all below zero on the vertical axis).

[16] This somewhat surprising result suggests there is a fundamental transition, somewhere between 240 and 260 ppmv, wherein the role of freshwater flux forcing changes. This region also marks a distinct gap in the strength of the AMOC at the different initial year 0 equilibria shown in Figure 1. Closer examination of the jump in column 2 of Table 1 and Figure 1 between 240 and 260 ppmv reveals that it is caused by the onset of convection in the Labrador Sea. This is consistent with the observations of *Hillaire-Marcel et al.* [2001] who found that the modern situation, with active LSW formation, has apparently no analogue throughout the last glacial cycle, and thus appears a feature exclusive to the present interglacial. As noted by *Cottet-Puinel et al.* [2004], the onset of Labrador Sea convection at preindustrial levels of atmospheric CO_2 is associated with the melting back of extensive sea ice coverage in the region which otherwise insulates the ocean from the atmosphere.

[17] It is interesting and relevant to also note that *Stouffer et al.* [2006] found a reduced transient weakening of the AMOC in one of the two most recent GFDL coupled models. Closer inspection of Stouffer et al.'s Figure 15 reveals that the model with an absence of LSW formation (and concomitant enhanced sea ice coverage) in its control state, is the model which exhibited a reduced AMOC weakening in response to increasing atmospheric CO_2. While it is clear that Labrador Sea sinking is sensitive to increasing atmospheric CO_2, it is also tempting to speculate that the lack of Labrador Sea convection in a model's control climate might precondition a reduced transient weakening to increasing greenhouse gases.

[18] In light of our results, it is not surprising that the response of the AMOC is not always a simple linear superposition of the response due to freshwater flux forcing (CRAD_TH2O) and the response due to heat flux forcing (TRAD_CH2O) for all values of initial atmospheric CO_2. In fact, those experiments which generally started with atmospheric CO_2 levels between 240 and 640 exhibited a more linear response than those which started with very high or very low levels of atmospheric CO_2 (Figures 2 and 3).

4. Discussion and Conclusions

[19] In this study we examined, through an extensive sensitivity analysis, the effect of the mean climate state on the response of the AMOC to idealized warming perturbations associated with increasing greenhouse gases. We found that the dominance of heat flux changes over freshwater fluxes in causing the AMOC weakening is independent of the mean climate from which the perturbation is initiated. The combination of this intramodel result with the analogous intermodel conclusion of *Gregory et al.* [2005], suggests that future transient AMOC changes associated with increasing greenhouse gases are likely to be largely driven by changes in radiative forcing directly, and not through indirect changes in the intensity of the hydrological cycle.

[20] Our intramodel analysis extends the conclusion of *Gregory et al.* [2005] concerning the larger transient intermodel weakening of the AMOC in experiments with a stronger initial AMOC strength. We also find that especially for cold (low atmospheric CO_2) initial mean states, the transient response of the AMOC to increasing greenhouse gases can not be expressed as a linear combination of the AMOC responses to heat and freshwater flux changes separately. This nonlinearity almost certainly arises from the complicated interaction between deep convection and the more extensive sea ice in the colder mean climates.

[21] We also found that the existence of convection (and concomitant reduced sea ice coverage) in the Labrador Sea in the initial mean climate determined whether or not subsequent changes in the freshwater flux forcing, associated with increasing greenhouse gases, acted to reduce or reinforce the transient AMOC decrease. For cold climates, freshwater flux forcing acted to reduce the transient AMOC decrease whereas for warmer climates, including those analogous to today, freshwater flux forcing acted to reinforce the transient AMOC decrease. This is likely linked to the freshwater fluxes (brine rejection/sea ice melt) associated with enhanced sea ice coverage in the Labrador Sea in the colder climates with no Labrador Sea convection.

[22] As a final remark, we note that our experimental design also allows us to examine the dependence of climate sensitivity and the transient climate response (TCR) on the mean climate state. The TCR is defined as the global mean surface air temperature warming at the time of CO_2 doubling (year 70), whereas climate sensitivity is defined as the equilibrium warming under a doubling of CO_2. We find that both climate sensitivity and the TCR of the UVic model strongly depend on the mean climate state. Over the atmospheric CO_2 range of 180 ppmv to 800 ppmv, TCR ranges from 2.3°C to 1.8°C; over the CO_2 range of 180 ppmv to 400 ppmv, climate sensitivity ranges from 4.3°C to 3.3°C (Table 1; Figure 4), with the resultant year 70 warming commitment ranging from 2.0°C to 1.3°C

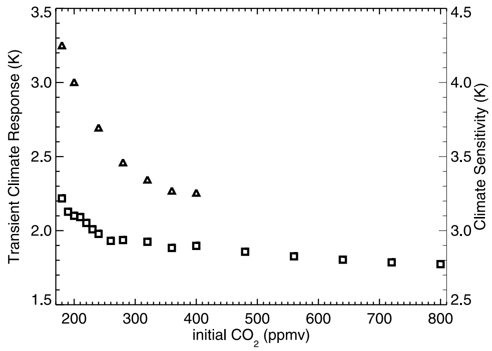

Figure 4. Transient climate response (squares) and equilibrium climate sensitivity (triangles) as a function of initial control climate atmospheric CO_2 level.

(Table 1). Control climates that have a more extensive initial sea ice coverage exhibit a stronger TCR, climate sensitivity and warming commitment [see also *Spelman and Manabe*, 1984]. This begs the question as to how much the intermodel variation of TCR and climate sensitivity [*IPCC*, 2001] is due to the intermodel variation in the control climate sea ice coverage.

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