Have anthropogenic aerosols delayed a greenhouse gas-induced weakening of the North Atlantic thermohaline circulation?

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Received 18 October 2005; revised 3 December 2005; accepted 9 December 2005; published 21 January 2006.

[1] In many climate model simulations using realistic, time-varying climate change forcing agents for the 20th and 21st centuries, the North Atlantic thermohaline circulation (THC) weakens in the 21st century, with little change in the 20th century. Here we use a comprehensive climate model to explore the impact of various climate change forcing agents on the THC. We conduct ensembles of integrations with subsets of climate change forcing agents. Increasing greenhouse gases – in isolation – produce a significant THC weakening in the late 20th century, but this change is partially offset by increasing anthropogenic aerosols, which tend to strengthen the THC. The competition between increasing greenhouse gases and anthropogenic aerosols thus produces no significant THC change in our 20th century simulations when all climate forcings are included. The THC weakening becomes significant several decades into the 21st century, when the effects of increasing greenhouse gases overwhelm the aerosol effects. **Citation:** Delworth, T. L., and K. W. Dixon (2006), Have anthropogenic aerosols delayed a greenhouse gas-induced weakening of the North Atlantic thermohaline circulation?, *Geophys. Res. Lett.*, *33*, L02606, doi:10.1029/2005GL024980.

1. Introduction

[2] The response of the thermohaline circulation (THC) in the North Atlantic to changes in radiative forcing has been extensively studied over the past decade using climate models [*Manabe et al.*, 1991; *Dixon et al.*, 1999; *Rahmstorf and Ganopolski*, 1999; *Thorpe et al.*, 2001; *Cubasch et al.*, 2001; *Gregory et al.*, 2005; *Dai et al.*, 2005]. This topic has generated considerable interest, in part because of the implications of such changes for regional climate and fisheries over the North Atlantic region. Potential future melting of the Greenland ice sheet could result in a rapid weakening of the THC with regional climate impacts [*Fichefet et al.*, 2003; *Wood et al.*, 2003]. Multidecadal changes in the THC modulate sea surface temperature (SST) in the North Atlantic, and thus have the potential to influence climate on both regional [*Sutton and Hodson*, 2005] and global scales [*Dong and Sutton*, 2002; *Zhang and Delworth*, 2005]. In this paper we use the term THC to refer to the total meridional mass circulation in the North Atlantic, which is also referred to as the Meridional Overturning Circulation, or MOC.

[3] Models provide a crucial perspective on the past and future behavior of the THC. Most models simulate a weakening of the THC in response to substantial increases of greenhouse gases [*Cubasch et al.*, 2001], which warm and freshen the upper ocean in the North Atlantic. These changes act to weaken the THC by reducing the vertical and meridional density gradients in the North Atlantic. The details of the simulated response of the THC to increasing greenhouse gases appear to have a substantial model dependence [*Gregory et al.*, 2005].

[4] In most simulations with fully coupled ocean-atmosphere general circulation models that incorporate realistic climate change forcing agents for the 20th and 21st centuries, THC weakening is usually not apparent until sometime in the 21st century [see *Cubasch et al.*, 2001, Figure 9.21]. The relatively large decadal and multidecadal THC variability present in many simulations makes it more difficult for a climate change signal to stand out against the background of climate noise.

[5] The time at which simulated THC changes are statistically significant also depends on the model response to various climate change forcing agents. In this paper we examine the impact of various climate change forcing agents on THC changes in the 20th century by conducting ensembles of experiments with a newly developed global climate model (GFDL CM2.1, described below). These experiments suggest that greenhouse gases – in isolation – would produce a statistically significant weakening of the THC during the latter part of the 20th century, but this decrease is offset by anthropogenic aerosols, which tend to strengthen the THC. By preferentially cooling the Northern Hemisphere, the aerosols (a) increase the ocean to atmosphere surface heat flux in the North Atlantic, thereby increasing upper ocean density, and (b) reduce the flux of fresh water to the higher latitudes of the North Atlantic, thereby increasing the salinity of near-surface waters in the Arctic and higher latitudes of the North Atlantic. Both effects tend to strengthen the THC.

2. Model and Experimental Design

[6] A suite of experiments has recently been completed with GFDL's newly developed coupled ocean-atmosphere climate model CM2.1. As described by *Delworth et al.* [2006], the coupled model consists of newly developed atmosphere, ocean, land, and sea ice component models. The horizontal resolution of the atmospheric model is 2.5° longitude by 2.0° latitude, with 24 levels in the vertical. The horizontal resolution of the ocean model is 1° in the extratropics, with meridional grid-spacing in the Tropics gradually reducing to 1/3° near the Equator. The ocean model has 50 levels in the vertical, with 22 evenly spaced levels over the top 220 m. The model has a diurnal cycle of insolation, with atmosphere-ocean coupling every two

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hours. The model does not employ flux adjustments. For further information and model output see http://nomads.gfdl.noaa.gov/CM2.X/.

[7] The suite of experiments consists of the following: (a) a 1500-year control experiment (CONTROL), in which atmospheric constituents and external forcings are held constant at 1860 conditions. Output from this integration is used to provide a statistical description of unforced, internal variability in the model, as well as initial conditions for the forced experiments described next. (b) A 5 member ensemble of experiments is conducted using estimates of the observed time-varying radiative forcing agents from 1861–2000 (these experiments are referred to as "ALL"). The time-varying forcing agents include changes in well-mixed greenhouse gases (CO_2, CH_4, N_2O, and halons), volcanic aerosols, solar irradiance, and the distribution of land cover. Also included were changes in tropospheric and stratospheric ozone, anthropogenic tropospheric sulfates, as well as black and organic carbon. Only the direct effect of aerosols is included. (c) A 3 member ensemble of experiments is conducted in which only changes in well-mixed greenhouse gases, and stratospheric ozone, are included. This set is referred to as WMGGO3 (Well Mixed Greenhouse Gases plus Ozone). (d) A 3 member ensemble of experiments is conducted in which only changes in anthropogenic aerosols are included (sulfates, plus black and organic carbon, but not volcanic aerosols). This set is referred to as "AEROSOL". Additional details on the formulation of these experiments, including the specifications of the climate change forcing agents, is given by *Delworth et al.* [2005] and *Knutson et al.* [2006]. The time evolution of the prescribed CO_2 and sulfate aerosols is shown in auxiliary material Figure s01.[1]

[8] Ensemble members differ only in their initial conditions, which are taken from periods 40 years apart in the control integration. The response of the climate system is calculated as the ensemble mean of the perturbation experiments minus the mean of the corresponding segments of the control integration.

3. Results

[9] The time evolution of the simulated North Atlantic THC from the various ensembles is shown in Figure 1. We first examine the evolution from 1861 to 2000. The dashed lines indicate the 1% and 99% limits of the distribution of annual mean THC values derived from a 1500 year control integration. (The distribution is calculated by repeatedly averaging three individual years selected at random in order to emulate the three member ensemble means. Individual years selected are at least 40 years apart in order to reduce the effects of serial correlation. This process was repeated 1000 times to build a distribution from which the 1% and 99% limits were calculated.) The black curve denotes the mean of the control run segments that cover the same period as the perturbation runs. The green curve denotes the THC time series from the ALL ensemble. While a few years around 1900 and 1970 exceed the 1% and 99% limits, most of the ALL time series is within those lines, suggesting that the simulated THC from the ALL ensemble is consistent with internal variability of the model. Thus, by this measure, we do not detect a significant change in the THC over the 20th century in the ALL ensemble, although there is some suggestion of a downward trend.

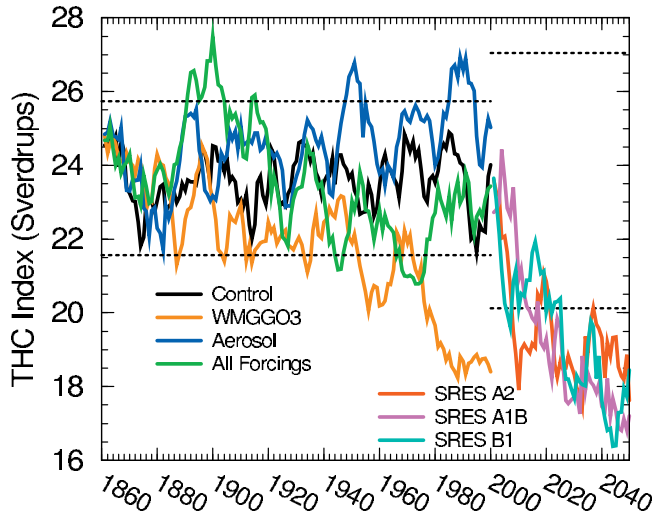

Figure 1. Time series of an index of the thermohaline circulation (THC) in various ensembles. To compute the THC index, a streamfunction field of the zonally averaged meridional flow field in the Atlantic is computed each year. The THC index is then computed as the maximum streamfunction value between 20°N and 80°N. For each year the ensemble members are averaged to form an ensemble mean that is plotted here. The dashed lines prior to 2000 denote the 1% and 99% limits of the distribution of three member ensemble means as computed from a 1500 year control integration (as described in the text). After 2000 the dashed lines denote the 1% and 99% limits for individual annual means derived from the control run; this distribution is used after 2000 since the SRES runs plotted after 2000 are single realizations.

[10] By the end of the 20th century there is a significant weakening of the THC in ensemble WMGGO3 (orange curve), with mean values over the last two decades more than 4 Sv (Sverdrups; 1 Sv = 10^6 m^3 s^{-1}) less than the control. This suggests that – for this model – increasing greenhouse gases alone produce a statistically significant weakening of the THC in the 20th century. The weakening is significant in all three individual members of the ensemble (not shown).

[11] For the AEROSOL ensemble (blue curve), there is an upward trend in THC intensity, with 12 of the last 50 years exceeding the 1% significance level. This upward trend induced by the aerosols helps to offset the weakening induced by the increasing greenhouse gases, with the result that there is no statistically significant THC trend during the 20th century for ensemble ALL.

[12] In order to interpret the THC changes physically, we note that the strength of the THC is closely related to the structure of the density field in the Atlantic. An increase (reduction) in the vertical density gradient, particularly in the Greenland and Labrador Seas, reduces (enhances) oceanic convection and weakens (strengthens) the THC. The vertical stability is determined partly by the air-sea fluxes of heat and water, which change upper ocean density.

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL024980.

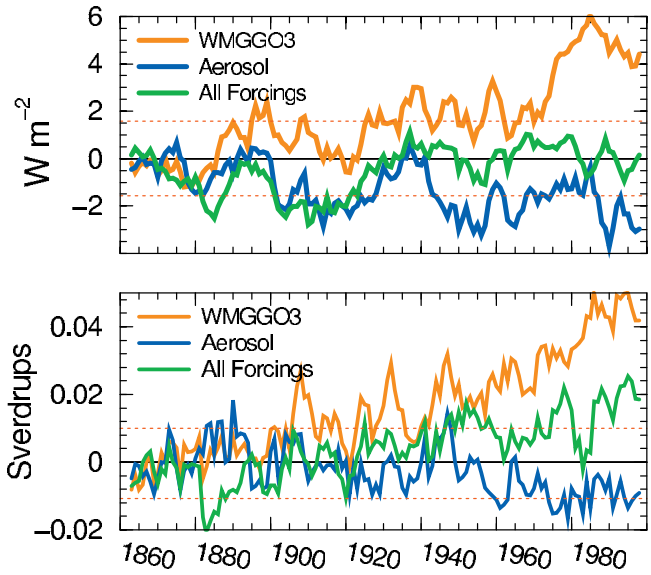

Figure 2. (top) Time series of ensemble mean, annual mean heat flux averaged over the Arctic ocean and North Atlantic poleward of 40°N. The values are computed as the ensemble mean of the perturbation experiments minus the ensemble mean of the relevant segments of the control integration. The heat fluxes are from the atmosphere-ice system into the ocean. Units are W m^{-2}. The red dashed lines denote the 1% and 99% limits of the distribution from the 1500 year control integration. (bottom) Same as top panel, but for water flux, summed over the same domain. Units are Sverdrups (10^6 m^3 s^{-1}).

Shown in Figure 2 (top panel) are time series of anomalous surface heat fluxes averaged over the Atlantic and Arctic ocean basins poleward of 40°N (we include the Arctic since it is tightly coupled to the higher latitudes of the North Atlantic). For ensemble WMGGO3 there is a clear upward trend of heat fluxes (positive departures mean more heat is going into the ocean in ensemble WMGGO3 than in the control). This warming reduces ocean density in the near-surface layers, thereby stabilizing the water column, inhibiting convection, and weakening the THC. For ensemble AEROSOL the opposite is true. The aerosol effect (strongest at middle and higher latitudes of the Northern Hemisphere, not shown) reduces the heat flux into the ocean, thereby cooling the higher latitudes of the North Atlantic, destabilizing the water column, and enhancing the THC. This tendency for AEROSOL is seen in Figure 1, although the THC increase is of marginal statistical significance. For ensemble ALL the trend in surface heat fluxes is small, largely a result of compensation between AEROSOL and WMGGO3.

[13] The time series of water flux anomalies summed over the Arctic and North Atlantic north of 40°N are shown in Figure 2 (bottom panel). The water flux into or out of the liquid ocean is defined here as the sum of (a) river inflows, (b) precipitation minus evaporation, (c) long-term trends associated with melting or growth of sea-ice, and (d) a simple representation of ice calving (at continental locations, snow in excess of 1 m depth is transported to the ocean). Consistent with the warming signal in WMGGO3, there is a strong upward trend in total water flux, which appears to accelerate in the latter part of the 20th century. This is consistent with many previous results [e.g., *Manabe et al.*, 1991; *Dixon et al.*, 1999, Figure 3] showing an enhanced poleward atmospheric water vapor flux in response to increasing greenhouse gases. The enhanced water flux contributes to the strong freshening of the North Atlantic in WMGGO3 (shown below) and the weakening of the THC. For ensemble AEROSOL, the cooler climate reduces the transport of water vapor into the high latitude Arctic-North Atlantic. This reduces precipitation and river inflows, thereby increasing near-surface salinity in the North Atlantic, which tends to enhance the THC. For ensemble ALL the freshening effect of WMGGO3 is stronger than the salinification effect of AEROSOL, resulting in a net increase of the fresh water flux into the surface over the higher latitudes of the North Atlantic and Arctic, and a net freshening of the upper ocean (shown below).

[14] It has been suggested [*Hughes and Weaver*, 1994; *Thorpe et al.*, 2001] that the strength of the THC in the

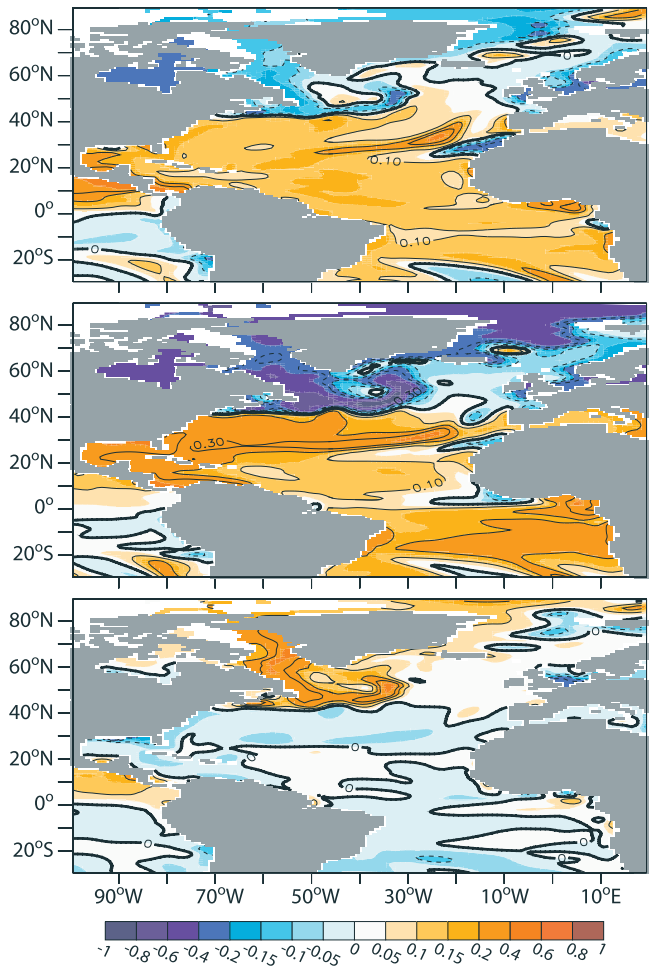

Figure 3. Difference in annual mean sea surface salinity between various ensembles and the control integration for the period 1981–2000. Units are lease. The interval for color shading is 0.05 between −.2 and +.2, and 0.2 otherwise. Contour lines are drawn only for values between −.3 and +.3 with an increment of 0.1. (top) ALL minus CONTROL. (middle) WMGGO3 minus CONTROL. (bottom) AEROSOL minus CONTROL.

North Atlantic is also related to the meridional density gradient. Separate analyses (not shown) reveal that the THC reduction in WMGGO3 is associated with a reduced meridional density gradient.

[15] The impact of the altered surface fresh water fluxes, combined with the oceanic circulation changes, results in the sea surface salinity (SSS) differences shown in Figure 3 for the period 1981–2000. For ensemble ALL there is a freshening in the northwest North Atlantic, Labrador and Greenland Seas, and the Arctic, with a general increase of salinity southward of 40°N. These differences in SSS are related to the opposing differences shown for WMGGO3 and AEROSOL. A visual inspection shows that the trends from WMGGO3 dominate the ALL response, but the impact of the aerosols tempers the response. Thus, while the THC reductions are statistically significant for WMGGO3 (Figure 1), they are not significant for ALL. Some of the SSS changes in WMGGO3 may be a response to the weakened THC. Similar maps were constructed for sea surface temperature (not shown), and reveal opposing patterns for AEROSOL and WMGGO3, with the warming pattern for WMGGO3 dominating the pattern for ALL.

4. Summary and Discussion

[16] We have examined the temporal evolution of the North Atlantic thermohaline circulation (THC) during the 20th century within an ensemble of simulations using GFDL's CM2.1 global coupled model. When the model is forced with a complete set of climate change forcing agents over the period 1861–2000, no statistically significant decrease in the THC is found. However, when we inspect additional ensembles of experiments that use subsets of the radiative forcing agents, we find that the lack of change is the result of compensation between greenhouse-gas forcing (which produces a statistically significant THC decrease when acting in isolation) and aerosol forcing (which tends to enhance the THC by cooling the North Atlantic and reducing the poleward transport of water vapor). It should be noted that there is considerable uncertainty with regard to the influence of aerosols on climate, but we anticipate that the essence of the results described above should be robust. *Haywood et al.* [1997] previously noted that simulated THC weakening in the 21st century was less pronounced when the effects of aerosols were included.

[17] Greenhouse gases have a relatively long lifetime in the atmosphere (of order centuries), but aerosols have much short lifetimes (of order weeks). Thus, the balance between the tendencies induced by aerosols and greenhouse gases could change relatively rapidly. One of the members of the ALL ensemble (incorporating a complete set of climate change forcing agents for 1861–2000) served as the starting point for three integrations of the 21st century using the IPCC SRES scenarios A2, A1B, and B2 [*Nakicenovic et al.*, 2000]. The THC values from these experiments for the years 2001–2050 are shown in Figure 1. It is clear that for all three scenarios the THC decreases significantly several decades into the 21st century. By this point the effects of increasing greenhouse gases dominate the aerosol effects, resulting in a substantial THC decline. The suggestion from these results is that increasing aerosols in the 20th century have delayed a greenhouse-gas-induced weakening of the THC by several decades (approximately 40 years for this model), but that compensation effect may wane rapidly in the future.

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