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Uncertainties in thermohaline circulation response to greenhouse warming

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Abstract. The uncertainty in the response of the thermohaline circulation to greenhouse forcing due to the use of flux adjustments in coupled ocean-atmosphere models is evaluated. This is done by using a different yet physically justifiable flux adjustment procedure and examining its effect on the thermohaline response to greenhouse forcing in a three dimensional primitive equations coupled ocean atmosphere general circulation model. It is found that while the initial thermohaline circulation weakening is robust, its eventual recovery which is seen in some coupled model simulations may be more sensitive to the details of the flux adjustment procedure and may therefore be less certain.

Introduction

A fairly robust feature of many coupled ocean - atmosphere model integrations under greenhouse scenarios is the weakening of the North Atlantic thermohaline circulation (THC) [*Stouffer et al.*, 1989; *Manabe and Stouffer*, 1993; *Kattenberg et al.*, 1996]. The mechanism of this weakening is due to a combination of two factors: first, the additional precipitation induced by greenhouse warming over polar deep water formation areas, and the resulting sea water freshening leading to lighter surface density and a weakened deep water sinking rate; second, the atmospheric heating and its effect on the surface water density. The relative role of these two effects seem to vary between different coupled models [*Dixon et al.*, 1999; *Mikolajewicz and Voss*, 1998; *Rahmstorf and Ganopolski*, 1999]. In the $2 \times CO_2$ greenhouse scenario of [*Manabe and Stouffer*, 1993], the THC weakens and then recovers after a few hundreds of years, while in a $4 \times CO_2$ scenario, the THC collapses and remains collapsed for thousands of years. [*Schmittner and Stocker*, 1999] found that the fate of the THC depends not only on the final CO_2 concentration, but also on the rate of CO_2 increase: a fast increase of atmospheric CO_2 results in a THC collapse, while a slow one in a THC weakening and an eventual recovery. The degree to which the THC may weaken, whether it may collapse, or whether it may eventually recover, is clearly model-dependent and thus uncertain. Because this is a quantitative issue, one would like to see it addressed by 3D coupled general circulation models that attempt to be as realistic as possible. However, one major factor of uncertainty in these 3D coupled models is their use of flux adjustments (FA) [*Manabe et al.*, 1991; *Neelin and Dijkstra*, 1995; *Marotzke and Stone*, 1995].

In spite of many efforts [*Bryan*, 1998], it has been difficult over the past decade to produce a coupled model run which does not drift over a time scale of 300-500 years without using FA. Most recently, a coupled model integration of some 300 years was carried out with no FA and with a remarkably small climate drift [*Wood et al.*, 1999]. However, much of what we presently know about the longer term behavior of the THC under greenhouse forcing still depends on flux-adjusted model results. It is of interest, therefore, to explicitly test the sensitivity of THC response to greenhouse forcing to the FA procedure. Flux adjustments compensate for inconsistencies between the ocean and atmosphere models [*Weaver and Hughes*, 1996]. Consider, for example, a coupled model in which the atmospheric model calculates a air-sea heat flux of 1PW (10^{15} watts) into the mid-latitude ocean and out of the polar ocean. The atmospheric model implicitly expects in this case the ocean model to transport this 1PW from equator to pole. If the ocean model only transports 1/2 a PW, then FA need to be added to the air-sea fluxes to effectively transport the remaining 1/2 PW. The FA then do not vary when the model is used with different forcing such as under greenhouse scenarios. Without the FA, the discrepancy between atmosphere-only and ocean-only model fluxes results in a climate drift of the coupled model.

The FA procedure is based on a linearization about a mean climate state and is valid as long as the climate is not far from this mean state. However, when the climate deviates significantly from the mean state, as it does during a greenhouse-induced THC collapse, the FA may be invalid [*Neelin and Dijkstra*, 1995]. Furthermore, as the THC collapses, it stops transporting heat northward, but the flux adjustments still continue doing that(!). An important question is, therefore, what is the confidence one has in the long-term results of greenhouse model scenarios based on the FA procedure.

In the present paper we use a FA procedure that is significantly different from the one normally used in 3D coupled models, in which the FA vary with the model solution. The procedure is similar to that used by [*Marotzke and Stone*, 1995] in a simple coupled box model. We show that this procedure can be motivated on physical grounds to a similar level of physical justification possible with the more standard FA procedure. We then show that the use of this FA procedure in a coupled GCM integration using the GFDL coupled model results in a different behavior of the THC, that is, a weakening with no later recovery of the THC. This allows us to estimate the uncertainty of predictions of the THC behavior under greenhouse scenarios by finding out how sensitive greenhouse/ THC scenarios are to the FA procedure.

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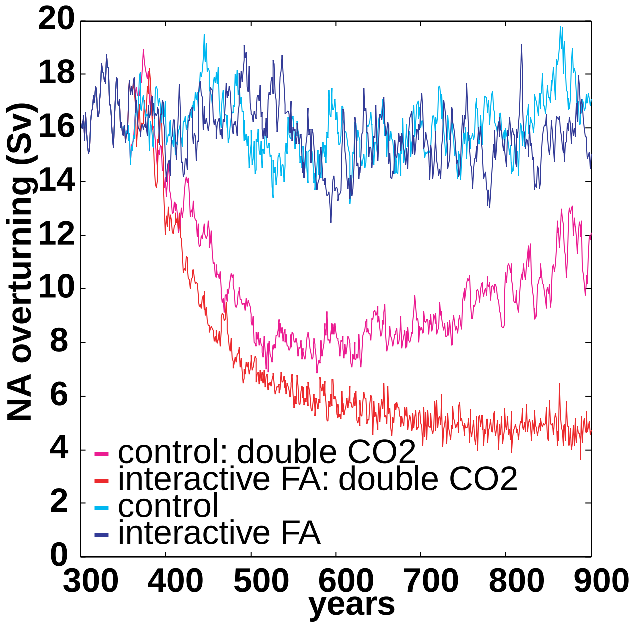

Figure 1. The THC index as function of time for the runs described in this paper: a control run using standard FA (cyan); a control run using "interactive" FA (blue); a 1% increase rate, double CO_2 scenario with standard (pink) and interactive (red) FA.

Relating the FA amplitude to the ocean model meridional transports

In the standard FA procedure as used, for example, by [*Manabe and Stouffer*, 1993], the atmosphere-only model is run with a specified observed SST to a statistical steady state, and the monthly averages of the air-sea heat and fresh water fluxes are calculated. Then, the ocean-only model is run, forced by the atmospheric air-sea fluxes calculated during the first stage, and with additional restoring to observed SST and sea surface salinity. The flux adjustments are calculated by monthly averaging the temperature and salinity restoring terms over 500 years after the ocean-only integration reaches a steady state. The flux adjustments thus depend on geographical location and month, but have no interannual variations and do not depend on the model state during the coupled model integration. During the coupled model run, the ocean and atmosphere models exchange fluxes and SST daily, and the FA are added to the air-sea fluxes calculated by the atmospheric model and used to force the ocean model.

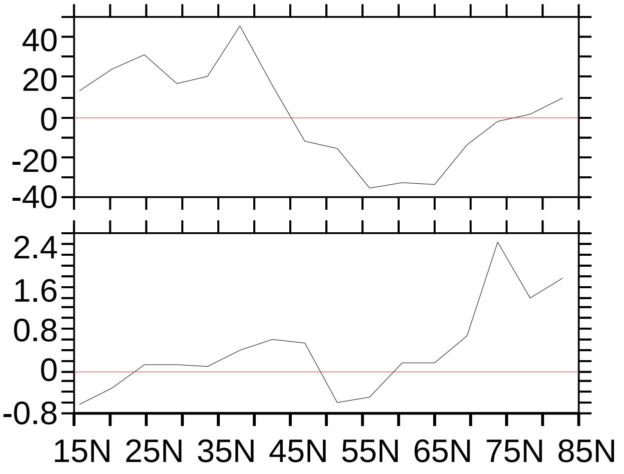

Figure 2. Annually and zonally averaged heat (upper panel, $watts/m^2$) and fresh water (lower panel, m/yr) flux adjustments in the North Atlantic

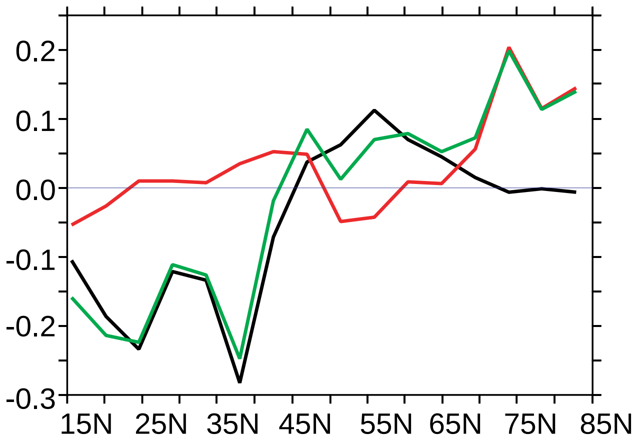

Figure 3. Annually and zonally averaged buoyancy flux ($10^8 m/s$) due to heat (black), fresh water (red), and total (green) Flux Adjustments in the North Atlantic.

To motivate the alternative FA formulation to be used in this paper, integrate the temperature equation,

$$\partial T/\partial t + \nabla(\vec{u}T) = \nabla_H(\kappa_H \nabla_H T) + \partial_z(\kappa_v \partial_z T),$$

over a control volume from the eastern boundary to western boundary, from the ocean top ($z = 0$) to its bottom ($z = D$), and from the northern boundary y_n (assumed closed for simplicity for the moment) to a latitude y; use boundary conditions at the surface of the ocean: $\kappa_v T_z|_{z=0} = H^{atm} + H^{FA}$ to obtain

$$\int\int\int (\partial T/\partial t)\, dx\, dy\, dz + F^{ocn} = F^{atm} + F^{FA}, \tag{1}$$

where $F^{ocn}(y,t) = \int_{x_e}^{x_w}\int_{z=0}^{z=D}(vT - \kappa_H T_y)$ and $F^{atm} = \int_{x_e}^{x_w}\int_{y_n}^{y} H^{atm}$ are the meridional heat transports carried by the ocean (advection and diffusion) and atmosphere, and $F^{FA} = \int_{x_e}^{x_w}\int_{y_n}^{y} H^{FA}$ is the equivalent meridional transport that is "carried" by the FA. Now, the FA in the North Atlantic in most coarse resolution coupled models largely compensate for the weak northward heat transport by the THC [*Tziperman and Bryan*, 1993]. It makes physical sense, therefore, to force the equivalent northward transport by the FA to be proportional to that carried by the THC itself. This way, when THC collapses and stops carrying heat and fresh water, the FA will also stop "transporting" heat and fresh water northward.

To make the equivalent heat flux "carried" northward by the FA vary in time like that carried by the ocean for all latitudes y during a model simulation, we need to have

$$\frac{F^{ocn}(y,t)}{F^{ocn}(y,t_0)} = \frac{F^{FA}(y,t)}{F^{FA}(y,t_0)}, \tag{2}$$

where $t = t_0$ is an initial time representing a steady state of the coupled model before external changes such as CO_2 increase are applied. Next, assume that the adjustments are multiplied by a factor $f(y,t)$ which will satisfy (2), and write (2) explicitly, to find

$$\frac{F^{ocn}(y,t)}{F^{ocn}(y,t_0)} = \frac{\int_{x_e}^{x_w}\int_{y_n}^{y} H^{FA}(x,y)f(y,t)}{\int_{x_e}^{x_w}\int_{y_n}^{y} H^{FA}(x,y)f(y,t_0)}. \qquad (3)$$

Differentiating this last equation with respect to y leads to an equation for $f(y,t)$, but it turns out that this equation is not well behaved in some cases. Instead, we use a FA factor which is a function of time only, $f(t)$, and require that the equivalent meridional flux carried by the FA varies in time like the total meridional flux according to (2) at a the latitude $y_0 = 24N$ only, giving

$$\frac{F^{ocn}(y_0,t)}{F^{ocn}(y_0,t_0)} = \frac{\int_{x_e}^{x_w}\int_{y_n}^{y_0} H^{FA}(x,y)f(t)\,dx\,dy}{\int_{x_e}^{x_w}\int_{y_n}^{y_0} H^{FA}(x,y)f(t_0)\,dx\,dy}$$

which may be trivially solved for the factor $f(t)$

$$f(t) = F^{ocn}(y_0,t)/F^{ocn}(y_0,t_0).$$

The factor $f(t)$ is calculated separately for the heat and fresh water FA and makes the FA depend on the ocean state in a way that is physically justifiable. Given that the standard use of constant FA away from the state they are calculated at is problematic, the above "interactive" FA procedure ("interactive" in the sense that the flux adjustments depend on the model state) seems a reasonable alternative. In practice, when this formulae is applied, the term $f(t)$ is calculated based on a 5-year running average of the meridional heat transport, rather than on an instantaneous value. Now, some of the FA clearly compensate also for atmospheric model errors. One example is the large salt flux correction maximum at 75N in the Atlantic Ocean, compensating for the too large precipitation there. To avoid making this part of the FA a function of the THC strength, the FA are only modified by $f(t)$ from 6.8S to 69N in the North Atlantic ocean sector. Because the $f(t)$ factor is motivated physically as compensating for changes in the oceanic meridional transports, it should not affect the net heat flux into the ocean. A weakening oceanic meridional heat flux should be reflected, through $f(t)$, in a decrease in the equivalent heating of the ocean by the FA at mid latitude and an equal decrease in the cooling by FA at higher latitudes. If the adjustments are also required to compensate for model errors other than the too weak meridional oceanic transports, however, the $f(t)$ factor may affect the net heat/ fresh water flux into the ocean and create a drift of the globally averaged temperature and salinity, although this does not seem to occur in the runs described here.

Our interactive FA respond to the model state, like the "multiplicative" FA explored in a simple coupled box model by [*Marotzke and Stone*, 1995], and as opposed to the normally used constant in time additive FA [*Manabe et al.*, 1991]. [*Marotzke and Stone*, 1995] have shown that if their box model errors are due to an incorrect oceanic mass transport, the multiplicative FA was able to capture the correct stability properties of the coupled box model, while the additive FA could not.

Results

Before applying the alternative FA procedure to a coupled model run under a greenhouse scenario, we verified that it results in a stable control run, with a minimal climate drift over hundreds of years (Fig. 1, blue and cyan lines). Next, the coupled model was run under greenhouse forcing representing a 1% yearly increase rate in atmospheric CO_2 concentration until doubling is reached, and a fixed CO_2 thereafter. Fig. 1 (red and pink lines) shows that the use of interactive FA clearly makes a difference. While the THC in greenhouse run using standard FA recovers after a few hundreds of years [*Manabe and Stouffer*, 1993], the THC in the run using the alternative FA formulation does not recover, and is about 5Sv at the end of the integration.

The mechanism behind this difference is as follows. The Flux Adjustments in the North Atlantic water mass formation area input buoyancy into the North Atlantic ocean at low latitudes and extract buoyancy from the North Atlantic ocean at higher latitudes (Figs. 2,3). When the THC collapses due to the increased precipitation and heating induced by global warming [*Manabe and Stouffer*, 1993], the FA in the standard FA run continue to extract buoyancy from the ocean. In the case of CO_2 doubling, this extraction of buoyancy from the northern North Atlantic seems to allow the water mass sinking process to be renewed, and the THC therefore recovers. This interpretation of the recovery is consistent with the fact that even with $4 \times CO_2$ scenario in a flux adjusted model, the THC eventually recovers after a few thousands years of integration (R. Stouffer, personal communication). On the other hand, when the FA are a function of the ocean state ("interactive" FA) in the alternative FA formulation, the FA weaken together with the THC. The extraction of Buoyancy from the northern North Atlantic by the FA is also reduced when the THC weakens under CO_2 increase. The reduced FA make it more difficult for the THC to restart, and the THC does not recover within our integration in the $2 \times CO_2$ scenario.

Conclusions

Given that the FA compensate for model errors in any of the two flux adjustment formulations we have used, it is not clear which THC behavior under greenhouse scenario is more reliable. However, given that both formulations can be justified to a similar degree (although clearly not to a satisfactory degree in either case), the comparison of the two formulations tells us something about the confidence one has in the results of each formulation. The fact that the THC recovers in one formulation but not in the other indicates that this recovery is sensitive to the FA procedure. This immediately implies that the THC recovery under the $2 \times CO_2$ greenhouse scenario must be assigned a larger degree of uncertainty than the predicted initial reduction in the THC amplitude. We therefore believe we have shown here that flux adjusted 3D coupled GCMs may not be sufficiently quantitatively accurate to investigate this issue of the eventual fate of the THC.

It is clear that there are still many possible deficiencies to the alternative FA formulation used here. In particular, much of the FA in the North Atlantic between 6.8S and 69N, where the alternative FA was used, is likely to be due to the deficiencies of the THC simulation in the ocean model as was discussed above. However, clearly some atmospheric model errors and other ocean model errors contribute to the FA even in this area of the ocean. Making these (hopefully small) FA components a function of the THC strength is clearly not physical, and may have influenced out results to some degree. In any case, one may expect that in the near future better coupled models could be integrated for long periods without flux adjustments and therefore may be used to investigate this issue with a larger degree of confidence than is possible today.

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References

Bryan, F., 1998: Climate drift in a multicentury integration of the NCAR climate system model. *Journal of Climate*, **11**, 1455–1471.

Dixon, K. W., T. L. Delworth, M. J. Spelman and R. J. Stouffer, 1999: The influence of transient surface fluxes on North Atlantic overturning in a coupled GCM climate change experiment. *Geophys. Res. Lett.*, **26 (17)**, 2749–2752.

Kattenberg, A., F. Giorgi, H. Grassl, G. A. Meehl, J. F. B. Mitchell, R. J. Stouffer, A. J. W. T. Tokioka and T. M. L. Wigley, 1996: *Climate Change 1995: The Science of Climate Change*. Chap. Climate models - projections of future climate, pp. 289–357. Cambridge University Press.

Manabe, S. and R. J. Stouffer, 1993: Century-scale effects of increased atmospheric CO2 on the ocean-atmosphere system. *Nature*, **364**, 215–218.

Manabe, S., R. J. Stouffer, M. J. Spelman and K. Bryan, 1991: Transient responses of a coupled ocean–atmosphere model to graduate changes of atmospheric co_2 part i: annual mean response. *J. Climate*, **4**, 785–818.

Marotzke, T. and P. H. Stone, 1995: Atmospheric transports, the thermohaline circulation, and flux adjustments in a simple coupled model. *J. Phys. Oceanog.*, **25**, 1350–1364.

Mikolajewicz, U. and R. Voss, 1998: The role of the individual air-sea flux components in co_2 induced changes on the oceans circulation and climate, report no 263. p. 27.

Neelin, J. D. and H. A. Dijkstra, 1995: Ocean-atmosphere interaction and the tropical climatology. Part I: The dangers of flux adjustment. *J. Climate*, **8**, 1325–1342.

Rahmstorf, S. and A. Ganopolski, 1999: Long-term global warming scenarios computed with an efficient coupled climate model. *Climatic Change*, **43**, 353–367.

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

Stouffer, R. J., S. Manabe and K. Bryan, 1989: Interhemispheric asymmetry in climate response to a gradual increase of atmospheric co_2. *Nature*, **342**, 660–662.

Tziperman, E. and K. Bryan, 1993: Estimating global air-sea fluxes from surface-properties and from climatological flux data using an oceanic general-circulation model, *Journal of Geophysical Research-oceans*, **98**, pp. 22629-22644,

Weaver, J. A. and M. C. Hughes, 1996: On the incompatibility of ocean and atmosphere models and the need for flux adjustments. *Climate Dynamics*, **12**, 141–170.

Wood, R. A., A. B. Keen, J. F. B. Mitchell and J. M. Gregory, 1999: Changing spatial structure of the thermohaline circulation in response to atmospheric co2 forcing in a climate model. *Nature*, **399**, 572–575.

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