NOTES AND CORRESPONDENCE

The Stability of NADWF under Mixed Boundary Conditions with an Improved Diagnosed Freshwater Flux

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ABSTRACT

Ocean general circulation models can be run using Haney boundary conditions (BCs) for both temperature and salinity, or using mixed boundary conditions, which consists of a Haney BC for temperature and a flux BC for salinity. A switch from Haney BCs to mixed BCs often causes the model North Atlantic Deep Water Formation (NADWF) to either collapse or intensify. Recently, Tziperma et al. found that the collapse was due to an unrealistic freshwater flux field diagnosed from a spinup using a too short relaxation timescale for salinity. They replaced the unrealistic freshwater flux with a more realistic freshwater flux diagnosed from a spinup using a longer relaxation timescale for salinity and found that NADWF stabilized. In this study, the author shows that mixed BCs are not suitable for studying the stability of the present ocean climate, regardless whether a realistic freshwater flux is realistic or not. Further, the instability associated with mixed BCs is due more to the use of a Haney BC for temperature than to an unrealistic freshwater flux. This is shown in a series of numerical experiments using a global Bryan-Cox ocean general circulation model. In these experiments, although a more realistic freshwater flux is used, NADWF is still very sensitive to a perturbation in high-latitude freshwater flux and to an enhancement of the implied hydrological cycle. This is because a Haney BC for temperature, when used with a flux BC for salinity, promotes a positive feedback between surface salinity and overturning. When the Haney BC for temperature is replaced by a Schopf BC, the overturning circulation associated with NADWF is quite stable.

1. Introduction

The stability of North Atlantic Deep Water formation (NADWF) has been investigated extensively using ocean general circulation models (OGCMs) in numerous studies (e.g., Bryan 1986; Maeler-Reimer and Mikolajewicz 1989; Marotzke 1989; Stocker et al. 1992; Weaver and Sarachik 1991a,b; Weaver et al. 1993; Zhang et al. 1993; Power et al. 1994; Cai and Godfrey 1995). All of these studies employed a common procedure involving several steps. First, the model is spun up to an equilibrium by restoring the model surface temperature and surface salinity via the Haney (1971) scheme to the present-day climatologies using the same relaxation timescale for temperature and salinity. Second, an implied freshwater flux is diagnosed from the equilibrium state. Third, the restoring boundary condition (BC) for model surface salinity is switched to the diagnosed flux, but the restoring BC for surface temperature is maintained (that is, mixed BCs).

Upon switching to mixed BCs, OGCMs display various behavior patterns. These include a polar halocline catastrophe (Bryan 1986), a “flush” (Marotzke 1989; Weaver and Sarachik 1991b), low-frequency oscillations (Marotzke 1989), and oscillations on decadal timescale (Weaver and Sarachik 1991a,b; Cai 1995a). In addition, under mixed BCs the thermohaline circulation is extremely sensitive to perturbations in the freshwater flux. A small perturbation can “flip” the ocean circulation from an equilibrium with an NADWF to one without (Marotzke 1990; Marotzke and Willebrand 1991; Hughes and Weaver 1994).

In a recent paper, Tziperma et al. (1994, hereafter TTFB) found that the instability associated with mixed BCs is due to an unrealistic freshwater flux diagnosed from a spinup using too short a relaxation timescale for salinity. They replaced the unrealistic flux with a more realistic one, which is diagnosed from a spinup using a relaxation timescale for surface salinity four times greater than that for surface temperature and found that NADWF stabilized. TTFB concluded that it is the unrealistic freshwater flux that leads to the collapse of the modeled NADWF upon switching to mixed BCs. This result was further explained in a series of analytical, mechanistic experiments. I will refer to their mixed
BCs as the TTFB mixed BCs. The only difference from the traditional mixed BCs is that a more realistic freshwater flux is used.

Although the TTFB mixed BCs provide a way of stabilizing the model NADWF, it has not yet been determined whether these BCs are suitable for studying the response of the present-day ocean climate to changes in atmospheric conditions. Given that mixed BCs are widely used to study the ocean climate variability, it is of interest to address such an issue. This is the task of this study. I conduct a set of experiments in a global OGCM with realistic bathymetry and geometry using the TTFB mixed BCs. The results are contrasted with those of comparable experiments in which the Haney BC is replaced by a Schopf BC (1983).

2. Model and results

a. Model and spinups

The OGCM used here is based upon the primitive equation model of Bryan (1969) and is described in detail by Pacanowski et al. (1991). The global model configuration used in the present study is the same as that in Moore and Reason (1993), Power et al. (1994), and Cai (1994, 1996). Unless stated otherwise, the model is integrated forward in time using the accelerated convergence scheme of Bryan (1984). This allows the model to be integrated to an equilibrium state at a reduced computational cost.

Two spinups are carried out in which the model upper-level temperature and salinity are relaxed to Levitus (1982) annual mean climatologies using Haney BCs. These are designated RR and Rr. In run RR, the relaxation timescale is 30 days for both temperature and salinity. In run Rr, the timescale is 30 days for temperature and 120 days for salinity (“R” and “r” refer to a strong and weak restoration, respectively). Both runs continue until a steady state is reached. The model is also forced by the annual mean wind stress of Hellerman and Rosenstein (1983). Seasonal effects are not considered here.

Figures 1a and 1b show a plot of meridional volume transport streamfunction for the global ocean from runs RR and Rr, respectively, and Figs. 1c and 1d show the diagnosed implied freshwater flux fields. As found by TTFB, the fluxes from run Rr are more realistic. In effect, the TTFB approach suppresses the unrealistic small-scale features that arise with a short restoring time for salinity. It also reduces the strength of the hydrological cycle, as revealed by a comparison of the zonally averaged freshwater flux field (see their Fig. 5). These features suggest that the TTFB approach is suitable in terms of improving the diagnosed freshwater flux. However, the reduction of the hydrological cycle is small. The fact that the stability can be achieved through such a small reduction indicates that the thermohaline circulation under mixed BCs is very sensitive to freshwater flux forcing. This may not be the case in the real ocean.

b. Model behavior under various BCs

In this section, three experiments are considered. These are designated RF, Rf, and Zf. Run RF continues
from the steady state of RR, and the surface BCs are switched to the traditional mixed boundary BCs, that is, with the flux BC for salinity diagnosed from run RR and the Haney BC for temperature. Run RF continues from the steady state of Rr, and the surface BCs are switched to the TTFB mixed BCs, that is, with the flux BC for salinity diagnosed from Rr and the Haney BC for temperature. Run Zf is the same as RF except that the Haney BC for temperature is replaced by a Schopf BC.

The Schopf BC assumes that the atmosphere has zero heat capacity (hence Z in the naming of the experiments). The BC is diagnosed from the steady state of run Rr using a radiative cooling timescale of 300 days. I chose 300 days because sea surface temperature (SST) anomalies are damped by radiative cooling to space at approximately this timescale. For a detailed description of the Schopf BC, readers are referred to Zhang et al. (1993), Cai and Greatbatch (1995), and Cai et al. (1995b). In short, the model surface temperature is restored to an equilibrium temperature $T_s$ that the ocean would reach in the absence of currents and heat transport. Note that $T_s$ has been referred to as the “radiative equilibrium temperature” (Schopf 1983; Cai and Greatbatch 1995). However, a comparison between the diagnosed $T_s$ and radiative equilibrium temperature inferred from observation shows that the two fields are quite different. Therefore, $T_s$ should not be referred to as the radiative equilibrium temperature. Previous work has found that this BC for temperature is more suitable for climate variability studies. This is because under this BC the atmospheric temperature is not explicitly included and is free to seek its equilibrium value. However, there are limitations as well. For example, it assumes that $T_s$ is the same under different climatic conditions, but there is no justification for this.

In reality, the response of NADWF to an anomaly is determined by several major feedbacks between the thermohaline circulation and the high-latitude temperature and salinity, which have opposing effects on density. Consider a positive anomaly in the strength of the thermohaline circulation. The anomaly may induce the following two processes simultaneously. First, the positive anomaly transports more salt northward, increasing the salinity and density at high latitude. In turn, this process enhances deep-water formation and the overturning circulation. This is a positive feedback (Stommel 1961). Second, as the overturning circulation increases, the northward heat transport strengthens. This increases the high-latitude temperature and reduces the high-latitude density. The reduced density in turn weakens convective activity and hence thermohaline circulation. This is a negative feedback (e.g., Rahmstorf and Willebrand 1995; Cai and Godfrey 1995). Under a Haney BC, the negative feedback is limited. Under a Schopf BC, the negative feedback operates.

In run RF, NADWF intensifies to 23.4 Sv (Sv = $10^6$ m$^3$ s$^{-1}$), as a result of the positive feedback. In run RF, NADWF settles to a state hardly different from that of run Rr [panel (i) of Fig. 2a], similar to the finding by TTFB. This is because the weak restoring for salinity...
during the spinup produces weak freshwater fluxes. This generates a smaller density change upon switching to mixed BCs, and this change is able to be offset by the limited negative feedback. In Zf, NADWF (panel (ii) of Figs. 2a and 2b) differs only slightly from the steady state of run Rf. This is expected, because compared to run RF, two more factors contribute to the stability: One is the weak freshwater flux, as in run RF, and the other is the negative feedback. I have carried out another experiment, which is identical to run Zf except that it uses the freshwater flux diagnosed from run RR. Under this strong freshwater flux, NADWF stabilizes. This suggests that the modification of the hydrological cycle is not required for stability under the Schopf BC.

3. Sensitivity to North Atlantic high-latitude freshening

To test the response of NADWF in run Rf and Zf to an imposed high-latitude freshening, runs Rf4GSA and Zf8GSA are carried out. They continue from the steady states of runs Rf and Zf, respectively. In run Rf4GSA, NADWF is subject to a perturbation in freshwater flux lasting for five years. This, in total, represents a salt deficit four times greater than the observed great salinity anomaly (GSA) (Dickson 1988). In run Zf8GSA, the associated salt deficit is eight times greater. The acceleration techniques of Bryan (1984) are switched off (both the momentum and the tracer equations use the same time step of 2400 seconds, and no lower-level acceleration is used) during the first 400-year integration. Thereafter, they are switched on again, and each experiment is run until a steady state is reached. In the steady state of run Rf4GSA, NADWF is absent. In the steady state of run Zf8GSA, NADWF fully recovers (Fig. 3 and panel (ii) of Fig. 4). In light of these results, I carried out another run, Zf24GSA, which is the same as run Zf8GSA except that the anomaly is increased to 24 times that of the observed. NADWF again recovers (Fig. 3 and panel (i) of Fig. 4).

Recent studies into the stability of NADWF using different surface BCs (Rahmstorf and Willebrand 1995; Cai and Godfrey 1995) found that in the presence of the negative feedback, NADWF is very stable. In a global OGCM identical to that used in this study, Power et al. (1994) showed that under traditional mixed BCs, NADWF can sustain seven times as large as the observed GSA. This difference may be due to the fact that they only integrated for 30 years. From Fig. 3, we see that if the integration stops at year 30, we may be misled to believe that NADWF recovers.

We now examine the time evolution of NADWF. In each case, NADWF experiences an initial weakening and an immediate recovery. However, in run Rf4GSA, the recovery is incomplete. Twenty years or so after the recovery is initiated, NADWF reaches a strength smaller than that of the steady state of run Rf. The smaller NADWF and the associated weaker salt transport lead to a slow freshening in the northern North Atlantic region. Since the adjustment of SSTs is limited, the system undergoes a slow transition to a steady state without NADWF via the positive feedback process. As the freshwater accumulates, the deficit of the advected salt becomes greater and greater. Gradually, NADWF tapers and eventually it collapses. The transition is a very slow process, on a timescale of hundreds of years.

By contrast, the recovery in run Zf8GSA is complete. This is because the Schopf BC allows SSTs to evolve. An accumulation of freshwater due to the precipitation is constantly offset by the negative feedback process.

In run Zf24GSA, after the immediate recovery, the strength of NADWF and the associated salt transport are weaker than they were prior to the freshwater perturbation. But because the negative feedback is allowed to operate, the overturning is not further weakened by the high-latitude precipitation. Thereafter, a diffusion process leads to a recovery.

To understand the diffusion process, it is necessary to recall the forcing mechanism of the thermohaline circulation associated with NADWF. Dense surface water sinks in the northern North Atlantic through buoyancy-driven convection, and a north–south pressure gradient is established. This N–S pressure gradient then drives a zonal flow. The zonal flow sets up an
east–west pressure gradient that forces a stronger N–S flow and intensifies NADWF. This process continues until a balance is reached between the supply of water in the meridional upper-layer flow and the withdrawal of water through sinking.

In Zf24GSA, after the immediate recovery, the surface water in NADWF region is less dense than it was prior to the GSA perturbation. This lower-density surface water reduces the penetration depth of the buoyancy-driven convection, and any newly formed deep water must lie over the old deep water. Vertical mixing between the young and old deep water then takes place. The timescale associated with the mixing is of the order of hundreds of years. As the erosion of the old deep water by the overlying young, less dense deep water, the N–S pressure is felt at a greater depth. The thermal wind equation then implies a stronger zonal flow, which in turn sets up a greater E–W pressure gradient and an accordingly stronger meridional overturning. NADWF recovers when all the old deep water is absorbed into the circulation and the buoyancy-driven convection reaches its previous depth. A similar process is responsible for stabilizing the overturning circulation under a global warming (Cai 1996) and conjugate atmospheric variabilities (Cai et al. 1995b).

The diffusion process also operates in run Rf4GSA. However, it appears that the gradual positive feedback process dominates. Nevertheless, the diffusion process may have played a role in slowing the transition to the state with no NADWF.

4. Response to enhanced hydrological cycle

Recent fully coupled model experiments by Manabe and Stouffer (1993, 1994) have found that under greenhouse conditions, the hydrological cycle is intensified. In this section I examine the steady-state response of NADWF in runs Rf and Zf to an intensified hydrological cycle. This is done by enhancing the diagnosed freshwater flux $F_{\text{diag}}$ so that the new flux is $(1 + \alpha) \times F_{\text{diag}}$. Here $\alpha$ is the enhancement factor. Two experiments, designated Rf10%EH and Zf10%EH, are carried out. Rf10%EH continues from the steady state of run Rf and is subject to a 10% enhancement (with $\alpha$ equal to 10%). Run Zf25%EH continues from the steady state of run Zf and is subject to a 25% enhancement. The acceleration technique of Bryan (1984) is switched on. Each experiment is run for another 3000 surface years, by which time a steady state is reached.

When forcing an OGCM with a fixed freshwater flux, there is an implied fixed atmospheric freshwater.
transport that needs to be balanced by the oceanic salt (or freshwater) transport (Cai 1995a). The atmospheric and oceanic freshwater transports are in balance in the steady states of runs RF and Zf. An enhancement of the hydrological cycle means more evaporation in the low latitudes, stronger precipitation in the high-latitude region, and a larger poleward salt transport.

Figure 5 shows the time series of NADWF over the first 800 surface years. We see that the increase in the precipitation due to the enhancement initially weakens NADWF in both runs. In run RF10%EH, because of the positive feedback associated with the Haney BC for temperature, the overturning weakens more substantially, and a weaker recovery follows upon the cessation of the freshwater perturbation. Thereafter, the diffusion process and the gradual positive feedback process work antagonistically. In run RF10%, NADWF eventually collapses, suggesting that it cannot sustain even a 10% enhancement. The collapsed state is similar to that shown in panel (i) of Fig. 4 and is not shown here. In run Zf25%EH, because of the negative feedback associated with the Schopf BC for temperature, the initial weakening of the thermohaline circulation is much smaller. After an incomplete recovery, the diffusion process gradually works toward a full recovery of the NADWF.

An examination of the behavior of the Antarctic Circumpolar converging cell and southern sinking cell shows that they are less sensitive. Even in run RF25%EH, the initial weakening is much smaller than that of NADWF cell, and they both recover.

5. Conclusions

Recently, TTFB suggested that the instability associated with mixed BCs was due to an unrealistically strong diagnosed freshwater flux. They found that a freshwater flux diagnosed from a spinup using a longer relaxation timescale for salinity is more realistic and that a switch from Haney BCs to mixed BCs consisting of this more realistic freshwater flux does not lead to a collapse of NADWF. The motivation for this study is to investigate whether such mixed BCs are suitable for studying the response of the present-day ocean climate to possible changes in atmospheric conditions. I have shown that with the realistic freshwater flux field, NADWF is still very sensitive to a perturbation in high-latitude freshwater flux and to an enhancement of the hydrological cycle implied in this flux. This is because the Haney BC for temperature curtails the response of SST to changes in oceanic heat transport. When used in conjunction with a flux BC for salinity, a Haney BC suppresses the negative feedback process between surface temperature and overturning and promotes a positive feedback between surface salinity and overturning. When the Haney BC is replaced by a Schopf BC, which allows SST to respond with great freedom to changes in oceanic heat transport, NADWF

is very stable and robust. To examine whether it is likely that NADWF is excessively stable under the Schopf BC with a timescale of 300 days, I have conducted experiments similar to those described in the previous sections but using a timescale of 200 days. In all cases NADWF recovers. Zhang et al. (1993) and Cai (1995b) have examined the dependence of the stability upon this parameter and shown that as the timescale shortens the stability decreases. It is therefore expected that if one reduces the timescale further, in some cases, NADWF may not be able to recover.

The work of TTFB is useful for understanding the current state of the thermohaline circulation. Its usefulness can be further extended only if the proposed procedure is suitable for studying the response of the current ocean climate to possible changes in atmospheric conditions. Otherwise, if one aims to derive the present ocean circulation state, Haney BCs for both temperature and salinity may be the best BCs. Since the question of whether mixed BCs with a more realistic freshwater flux are suitable for studies of ocean climate variability was not addressed in TTFB, and since the use of a Haney BC for temperature has been widespread, a potential impression is that once the freshwater flux is realistic, the problem of the instability with respect to mixed BCs will disappear. This study shows that even with an improved freshwater flux mixed BCs are not suitable for ocean climate studies. This study further shows that the instability with respect to mixed BCs is due more to the use of a Haney

![Fig. 5. Time series of North Atlantic overturning circulation (Sv) at a location where during the spinup the overturning is at a maximum. Run RF10%EH continues from run RF and is under an enhancement of the hydrological cycle of 10%. Run Zf25%EH continues from run Zf and is under an enhancement of 25%.](image-url)
BC for temperature than to an unrealistic freshwater flux.

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