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Is there a simple bi-polar ocean seesaw?

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Abstract

Using an atmosphere–ocean coupled model, the climate response to an idealized freshwater input into the Southern Ocean is studied. In response to the freshwater input, the surface waters around Antarctica freshen and cool. As the addition of freshwater continues, the fresh, surface anomalies spread throughout the world ocean in contrast to ocean-only experiments and North Atlantic experiments using coupled models. Because of the fundamental difference in altering sea surface salinity (SSS) from the two sources (northern hemisphere and southern hemisphere), a bi-polar seesaw fails to develop in the ocean, at least in our coupled atmosphere–ocean experiments. Control ocean-only experiments with mixed boundary conditions and similar short-term southern freshwater impacts match the results of the coupled experiments. Based on these experiments, we argue that the concept of ocean bi-polar seesaw should be taken with some caveats.

Keywords: Southern Ocean; thermohaline ocean circulation; climate change; freshwater; numerical modeling

1. Introduction

The balance between the North Atlantic Deep Water (NADW, i.e., a northern hemisphere deepwater source) and the Antarctic Bottom Water (AABW, i.e., a southern hemisphere deepwater source) formation controlling thermohaline ocean circulation (THC) could be fragile. Computer simulations show that freshwater input in key deepwater production areas can disturb this balance (e.g., Weaver et al., 2003; Seidov et al., 2001). Proxy evidence and the present-day paradigm of the global THC also give these indications (Broecker, 1991, 1997; Gordon, 1986; Gordon et al., 1992; Stommel and Arons, 1960).

The sea surface salinity (SSS) is affected by surface fluxes differently in the two locations of bottom water formation—the northern North Atlantic (NA) and Southern Ocean (SO). The existence of these two (de-) densification sensitive areas favors the idea of an ocean "bi-polar seesaw", a strengthening and weakening of the Atlantic thermohaline overturning (Broecker, 1998; Seidov et al., 2001; Stocker, 1998). The seesaw in the THC behavior is accompanied by heating/cooling of the surface climate in the two

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hemispheres. When the NA THC is weak, the northern hemisphere (NH) is relatively cool and the southern hemisphere (SH) is relatively warm because of weakening the northward cross-equatorial oceanic heat transport (e.g., Seidov and Maslin, 2001). When the NA THC is strong, the NH is relatively warm and the SH is relatively cool. These changes are due to the changes in the cross-equatorial heat transport associated with the THC. This seesaw, if it exists, may be a special case of a broader feature known as multiple stability of the ocean circulation driven by freshwater impacts in the high latitudes (Bryan, 1986; Manabe and Stouffer, 1988).

The bi-polar seesaw metaphor has to be taken with caveats. Given the differences in geography in the two hemispheres, the ocean response to northern and southern high-latitudinal freshening/diluting may be substantially different so that a symmetric seesaw may not exist. Therefore, the relationship of the bi-polar seesaw, if any, to the THC response and feedback to climate change may be more complicated than previously discussed (e.g., Broecker, 1998; Stocker, 1998; Seidov et al., 2001).

2. Freshwater and meltwater in climate models

The freshwater source for the ocean can be of four types—precipitation, river runoff, and sea and land ice melting. The land ice sources of freshwater to the ocean are sometimes called meltwater or glacial meltwater and icebergs. Presumably, it is meltwater impulses that might have caused some of the abrupt climate changes on decadal and longer time scales seen in the paleo-record (e.g., Broecker et al., 1990).

The glacial meltwater can strongly influence THC and climate by freshening the high latitude oceans. During major deglaciations, the ice sheets are thought to have supplied large amounts of meltwater and/or icebergs into the NA (e.g., Bond and Lotti, 1995; Broecker, 1998; Clark et al., 2002; Peltier and Solheim, 2004; Duplessy et al., 1992, 1996) and SO (e.g., Duplessy et al., 1996). Many believe that both the Medieval Warm Period (~800–1300 AD) and the Little Ice Age (~1400–1900 AD) climate excursions are possibly related to changes in the strength of the North Atlantic THC (e.g., Broecker, 2000; Broecker and Sutherland, 2000; Cronin et al., 2003).

3. Northern versus southern meltwater sources

The possible effects of large-scale northern freshwater impacts in coupled atmosphere–ocean models (AOGCMs) are a well-discussed issue (e.g., Manabe and Stouffer, 1997; Meissner et al., 2002). In idealized freshwater experiments of Manabe and Stouffer, one half of the seesaw emerged when they added an external source of freshwater to the NA surface (Manabe and Stouffer, 1997, 1988). In these integrations, the Atlantic THC and the associated northward heat transport both weaken. The reduced northward heat transport across the equator causes cooling of the NH and warming of the SH.

Here we focus on the southern source of meltwater in a coupled atmosphere–ocean model. Our goal is to seek the other half of the seesaw. Can freshwater input in the SO cause a strengthening of the NA THC? Since we do not know how much or how long freshwater should be added in the SO, our experimental design is idealized.

Some studies point out that the THC could be in oscillatory regime for some sets of boundary conditions during, especially related to, Dansgaard–Oeschger events and 1500-period oscillation in the North Atlantic (e.g., Alley et al., 2001; Bond et al., 1997; Sakai and Peltier, 1997). However, the true seesaw behavior where a weakening of the SH THC causing the NA THC to strengthen has not yet been clearly shown in AOGCM results.

4. Setup of experiments using coupled atmosphere–ocean model

The most complete and recent description of the GFDL coupled atmosphere–ocean model is given in Delworth et al. (2002). In the 2001 IPCC report, this model was labeled GFDL_R30 (IPCC, 2001). The coupled model consists of general circulation models of the atmosphere and ocean, with relatively simple formulations of land surface and sea ice processes (the details of the model are discussed in Delworth et al., 2002; Dixon et al., 2003).

The atmospheric part solves the primitive equations on a sphere using a spectral transform method. The grid uses 14 vertical levels and has an effective resolution of roughly 3.75° longitude by 2.25° latitude. The ocean component of the coupled model uses version 1.1 of the Modular Ocean Model (Pacanowski et al., 1993) with resolution of 1.875° longitudes by 2.25° latitude, with 18 unevenly spaced levels in the vertical.

The results of the sensitivity runs are compared with a control run (CR). The CR starts up from prior integrations of atmosphere and ocean-only models and is driven by solar radiation with all internal atmospheric parameters (e.g., CO_2 and other greenhouse gases concentration, vegetation, etc.), as observed in the present-day atmosphere. Flux adjustments for heat and water have been used to produce realistic climate and reduce climate drift. At year 501 of the control integration, a second integration is started where a freshwater flux of 1 Sv (1 $Sv=10^6$ m^3/s) for 100 model years has been introduced in the strip between 60°S and the coast of Antarctica. The word "hosing" is used here as a shorthand way of describing the addition of the freshwater at the ocean surface. After 100 model years of hosing, it was switched off and the integration continued for an additional 100 years. Within this period, the whole system gradually recovers towards a state that is close (though not identical) to the control integration thus showing no significant hysteresis.

5. Results of experiments

In the following analysis, the focus is on the THC and SSS changes. To save space, we present only some key variables. A longer paper is in preparation to document the full climate changes. The CR climate is very similar to that obtained using other similar course resolution models (see a review in IPCC, 2001). There is about 20 Sv of NADW formed, with approximately 17 Sv exported from the Atlantic Ocean into the SO (see Delworth et al., 2002 for more details). The three major water masses, NADW, AABW, and Antarctic Intermediate Water (AAIW), are seen in layering of salinity in the Atlantic Ocean.

Southern hosing did not have a large influence on the NA THC, contrary to what might have been expected based on the bi-polar seesaw concept (and ocean-only experiments with restoring boundary conditions (e.g., Seidov et al., 2001). The hosing causes the deep oceanic convection to shut down around Antarctica, cooling and freshening the surface and warming the deeper layers. We also see slight weakening of the Atlantic overturning (Fig. 1a, a strengthening is expected in a bi-polar seesaw), and there is a near shutdown of the overturning cells near the Antarctica coast (Fig. 1b). The hosing experiment using the coupled model has not led to as large a change in the NA THC as in the ocean-only runs in Seidov et al. (2001). In those runs, SSS anomalies, rather than anomalies of freshwater fluxes, were imposed to the south of Antarctic Circumpolar Current (ACC) and retained there. Thus, we have a weak response of the Atlantic THC in the AOGCM versus a strong response in the ocean-only experiments.

6. Southern escape

The reason why the southern freshwater impact does not lead to substantial changes of the Atlantic THC in the AOGCM is that the geometry of the SO prevents the low-salinity waters from being contained near the hosing (and bottom water formation) locations (see Fig. 2). Although a large reduction of AABW formation takes place (Fig. 1b), the freshwater hosed in the SO spreads over entire SH and eventually into the NA. As a result, instead of a strong increase of the Atlantic THC as seen in ocean-only integrations with permanent reduction of SSS in the SO south of the ACC (e.g., Seidov et al., 2001), the overturning becomes weaker in the Atlantic by the end of hosing period. The spreading of the freshwater anomaly over all the ocean basins is in sharp contrast to the northern hemisphere hosing experiments (e.g., Manabe and Stouffer, 1997). In these experiments, the NA becomes fresher but the SSS over the rest of the world oceans becomes slightly saltier.

7. Ocean-only experiments with short-term freshwater hosing

Recent ocean-only experiments (e.g., Seidov et al., 2001, Seidov and Haupt, 2002) employed an idea that there could be a long-term (permanent in their runs) reduction of SSS in the Southern Ocean around Antarctica. The nature of a freshwater source and how it maintained long-term low-salinity anomaly was not

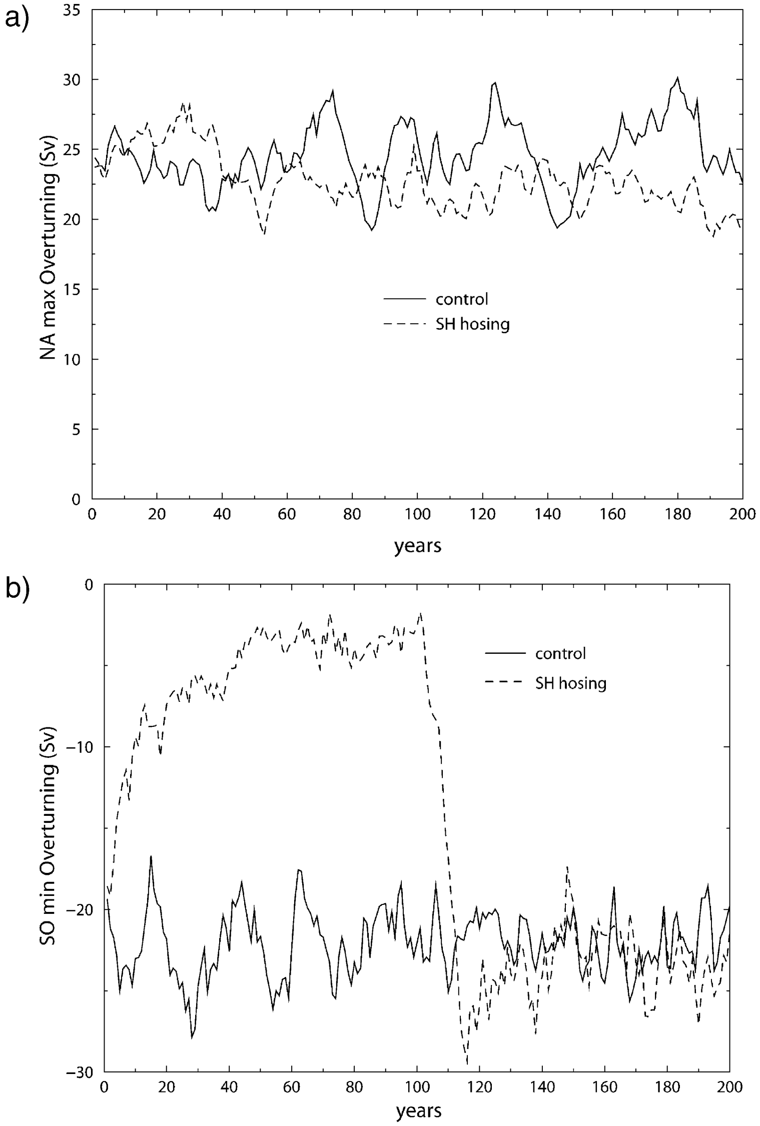

Fig. 1. Maximum value of the annually averaged overturning stream function in the NA (a) and in the SO (b) (in Sv). It represents the strength of the THC in NA, or the rate of the NADW (a) and AABW (b) formations. Years are counted from the beginning of hosing experiments (501 years of the control run). A positive stream function value indicates a clockwise circulation looking towards the west.

considered—whatever added freshwater source is, it was assumed of being capable to sustain lowered surface salinity south of the ACC.

The ocean model was integrated to a steady state and generated a reduced AABW formation, with a strong spur in NADW formation. However, these experiments, though fully legitimate within their limits, cannot give a clue of how the ocean model reacts to a relatively short-term freshwater hosing, similar to the one used in the coupled ocean runs described above. To address this issue, we have carried out an ocean-only experiment with the so-called mixed boundary conditions, i.e., with specified SST and freshwater fluxes over the sea surface. The freshwater fluxes that that yielded reasonably close to observed SSS were generated using the National

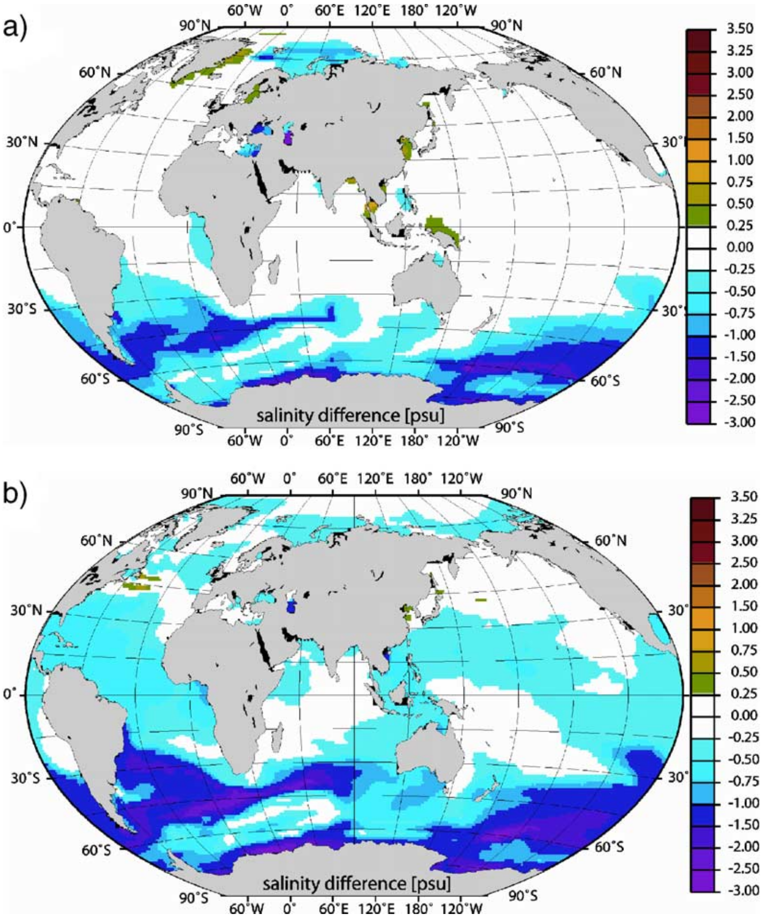

Fig. 2. Differences in sea surface salinity between the hosing and control runs after 25 years (a) and after 100 years (b) after beginning of the hosing experiment.

Center for Atmospheric Research Community Climate Model (NCAR CCM, Kiehl et al., 1998) and kindly provided by John Dickens (Dickens, 2004). The freshwater fluxes into the ocean were disturbed in the SO by hosing of 1 Sv of freshwater south of 60°S during 100 years at the end of 2000-year control run. The hosing was switched off at the model year 2101 and the run then was extended to another 500 years to reveal how the ocean recovers from the impact.

The differences between the undisturbed SSS at 2000 year and the SSS after 25, 100, 200, and 300 years are shown in Fig. 3. The figure shows practically the same pattern of low-salinity signal escaping the SO. It also indicates almost full recovery by 200 years after the hosing was switched off.

Two snapshots of the overturning in the Atlantic Ocean Fig. 4 at the years 2000 and 2100 confirms that there is no significant change in the overturning pattern, though some weakening of AABW can be seen in Fig. 4b. However, this weakening does not cause any significant NADW reduction and the THC is therefore not affected even in the Atlantic Ocean, not speaking of the global conveyor. Thus, both ocean-only and coupled atmosphere–ocean models agree that intermittent short-term freshening of the sea surface in SO does not invoke hypothesized increased rate of NADW formation and, therefore, do not support the idea of bi-polar seesaw. However, these experiments, ocean-only or coupled, cannot definitively reject the idea because the nature of southern freshwater impacts remains unclear. If the

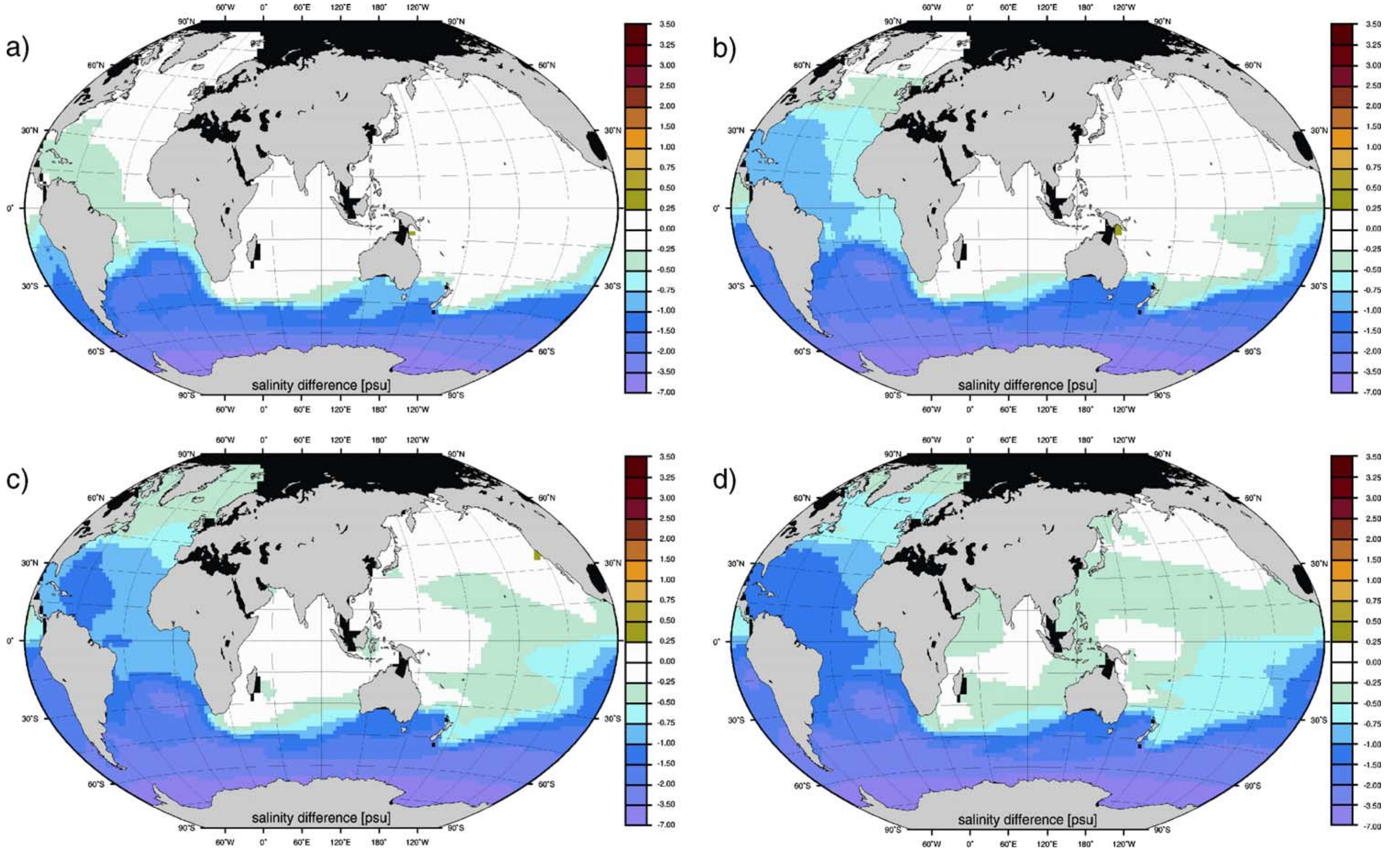

Fig. 3. Differences in sea surface salinity between the hosing and control runs in ocean-only experiments with mixed boundary conditions (see text) at model years 2025 (a), 2100 (b), 2200 (c), and 2300 (d). Freshwater hosing begins at the model year 2001 and is switched off at the model year 2101.

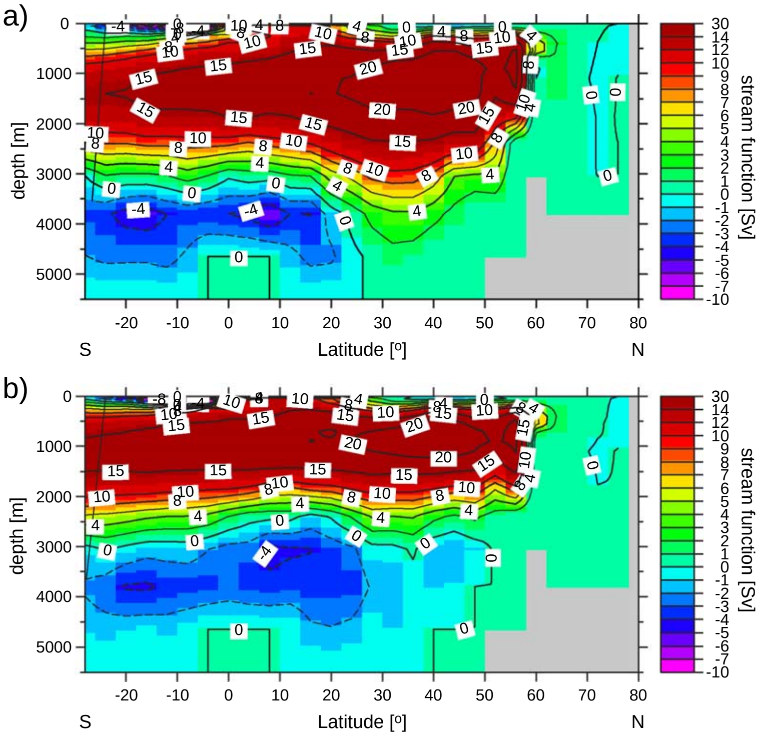

Fig. 4. Meridional overturning in the Atlantic Ocean in the ocean-only experiment at the model year 2000 (before freshwater hosing) and 2100 (at the end of freshwater hosing; see Fig. 3 and text). The overturning is in Sv (1 Sv=10^6 m^3/s).

freshening episodes are indeed strong but intermittent, the southern impacts on THC are negligible. However, if at some time in climate history they were persistent and could lower surface salinity around Antarctica and maintain it there, the THC could have been altered, as some data, physical hypothesis, and ocean modeling have suggested (e.g., Broecker, 1998; Stocker, 1998; Seidov and Maslin, 2001).

8. Discussion

A large concern exists about the future stability of the West Antarctic Ice Sheet (WAIS) and Greenland ice sheet as greenhouse gases increase (e.g., Gregory et al., 2004; for WAIS instability see the review in Oppenheimer, 1998). The line of thinking in Broecker (1998, 2000), Stocker (1998), and Weaver et al. (2003) implied that impact of meltwater from WAIS on AABW formation rate around Antarctica may cause (and may also be a result) of meridional ocean seesaw-type oscillations.

The essence of the seesaw is that reduction of AABW formation leads to NADW increase, whereas a weakening of the NADW leads to an increase of AABW production (e.g., Broecker, 1998). Although an ocean-only model with SSS restored towards paleo-observations in the SO favors this line of thinking, it was not clear a priori, whether a coupled atmosphere–ocean model would yield and sustain fresher surface in the area of increased freshwater fluxes. As shown here, the experiments with either the coupled model, or the ocean-only model subjected to a short-term (about 100-year duration) freshwater impacts in the SO do not substantiate containment of fresher surface in the impact area and thus do not support the simple THC seesaw paradigm. However, ocean models indicate that if a freshwater signal were of a different nature and could have sustained a pronounced low-salinity band south of the ACC for a long time, the THC would have reacted in the predicted seesaw fashion.

Our interpretation of the radically different THC behavior in the case of sustained and intermittent southern freshening is that this is because of fundamentally different nature of southern low-salinity anomalies in the two types of experiments. The ocean-only experiments with the permanent low surface salinity in the SO are based on the fact that fresher surface water is indeed observed to the south of the ACC in the paleo-record and it is assumed to remain there, with the rest of the world ocean not being freshened. Adding freshwater in the form of anomaly of freshwater fluxes rather than as a SSS anomaly in either a coupled or an ocean-only model allows the freshwater anomaly to spread into the rest of the world ocean. The results in the ocean-only runs with long-term (“permanent”) lowering of SSS suggest that if it had been contained, then the seesaw could have emerged. Freshwater forcing, at least in the experiments using both models presented here, did not yield such containment. This is in a sharp contrast with the effect of adding an external freshwater source to the northern NA in coupled and ocean-only models generating a compact and isolated freshwater lens in the northern NA.

Thus, we have two different behaviors of ocean models in the SO, coupled and uncoupled, where the response is dependent on the boundary condition for the oceanic component. In the NA, both models (coupled and uncoupled) produce a common Atlantic THC response to freshwater impacts, regardless of whether the low surface salinity is specified (as in ocean-only models) or generated by freshwater fluxes (e.g., Rahmstorf, 1995; Schmittner and Clement, 2002). Moreover, the THC response to long-term low-salinity anomalies imposed over the sea surface or to short-term freshwater hosing in the same areas show similar patterns of THC reduction at the end of the hosing. This is because in both approaches there is a well defined and localized lens of freshened water remaining in the key areas. The attempts to simulate a confined, localized low-salinity surface lens in the SO, as in the northern NA, fails with both the coupled and the ocean models in the experiments with short-term freshwater impacts.

Additionally, the differences in the results of the runs with SSS anomalies retained in the ocean model and the anomalies in freshwater fluxes in the coupled model could be due to the difference in the model setups. The ocean model was run to a steady state, while the coupled model runs are transient, with the time of impact limited to 100 years. It is unclear what the final equilibrium state of the coupled simulation would be like.

9. Conclusions

The “failure” of localized southern freshwater hosing to generate a substantial Atlantic THC change is due to a fundamental difference in the nature of surface freshening processes in the SO and the northern NA. Because of this fundamental difference in altering sea surface salinity from the two sources, the simple bi-polar ocean seesaw fails to develop, at least in our coupled atmosphere–ocean experiments. Based on these experiments, we argue that the concept of ocean bi-polar seesaw has to be taken with some caveats, at least.

We also find that the boundary conditions for the ocean component play an important role in determining the response of the model. Both types of boundary conditions have their advantages and problems. The freshwater boundary condition used by the AOGCM has more realistic fluxes, but the SSS anomalies may not be realistic. In the prescribed SSS case, the anomalies are realistic, but the solution may be too constrained. Moreover, the nature of atmosphere–ocean–cryosphere interaction that could sustain a quasi-permanent low-salinity anomaly in the SO is not known.

Thus, a fundamental question remains—can SSS anomalies be effectively contained in the SO, instead of escaping from the SO, and thus whether or not an ocean seesaw can develop.

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