

LETTERS

On the Link between the Two Modes of the Ocean Thermohaline Circulation and the Formation of Global-Scale Water Masses

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ABSTRACT

A close link between the formation of global-scale water masses, such as North Atlantic Deep Water (NADW) and Antarctic Intermediate Water (AAIW), and two stable modes of the thermohaline circulation (THC) is investigated in a coupled model. In the upper 2–3 km of the Atlantic, the THC modes are characterized by meridional overturning circulations of opposite sign, with either a dominance of the AAIW cell over the NADW cell (“off” THC mode) or vice versa (“on” THC mode). A transition between these THC modes is controlled by the relationship between the densities in the source regions of formation of AAIW and NADW water masses. This is shown by applying a freshwater perturbation in the region of enhanced AAIW formation in the Southern Ocean to obtain a hysteresis loop of the NADW circulation. Transitions between the two modes of the THC occur when the densities in the source regions of AAIW and NADW become comparable to each other.

1. Introduction

Bryan (1986) has shown that by applying a freshwater perturbation to the polar oceans, a transition between different stable modes of the ocean thermohaline circulation (THC) can be triggered, with predominant deep water formation in one of the hemispheres. He used an ocean model with an idealized, hemispherically symmetric and closed basin geometry. In the real ocean, the existence of circumpolar flow in the Southern Hemisphere due to the Drake Passage makes the THC more complex. Primarily, it enables ocean ventilation by intermediate water originating from the Southern Ocean (e.g., Cox 1989). In terms of the THC stability, this creates the potential for a cross-hemispheric interplay between three, rather than two, global-scale water masses. These are the North Atlantic Deep Water (NADW), the Antarctic Intermediate Water (AAIW), and the Antarctic Bottom Water (AABW).

In the present-day climate, the formation of NADW in the North Atlantic is fed by the less dense AAIW and, in part, by the upper-thermocline water (e.g., Rin-

toul 1991). The AABW is formed largely in the Weddell and Ross Seas and spreads below the NADW, whereas the AAIW is thought to form most intensively around the southern tip of South America (McCartney 1977; England et al. 1993) and spreads above the NADW. Such a vertical distribution of these three global-scale water masses in the Atlantic is illustrated in Fig. 1a. The distribution is obtained by employing three water mass age tracers Tr , defined as (e.g., Thiele and Sarmiento 1990): $\partial Tr/\partial t + A(Tr) = 1$, where $A(Tr)$ refers to the advection and mixing in a global model (see the next section); the initial condition is $Tr = 0$; the boundary conditions are $Tr = 0$ at the surface in the regions of either NADW or AAIW or AABW formation (see Fig. 2) and zero tracer flux otherwise. We will refer to the climate state with active NADW formation and with the corresponding vertical distribution of these water masses as the “on” mode.

Several modeling studies have shown an existence of another stable mode of THC operation, which does not have deep water formation in the North Atlantic (e.g., Stocker and Wright 1991; Rahmstorf 1996; Manabe and Stouffer 1999). The climate model employed in this study also has a stable climate state without NADW formation and the NADW circulation strength is characterized by a hysteresis loop (Schmittner et al. 2002).

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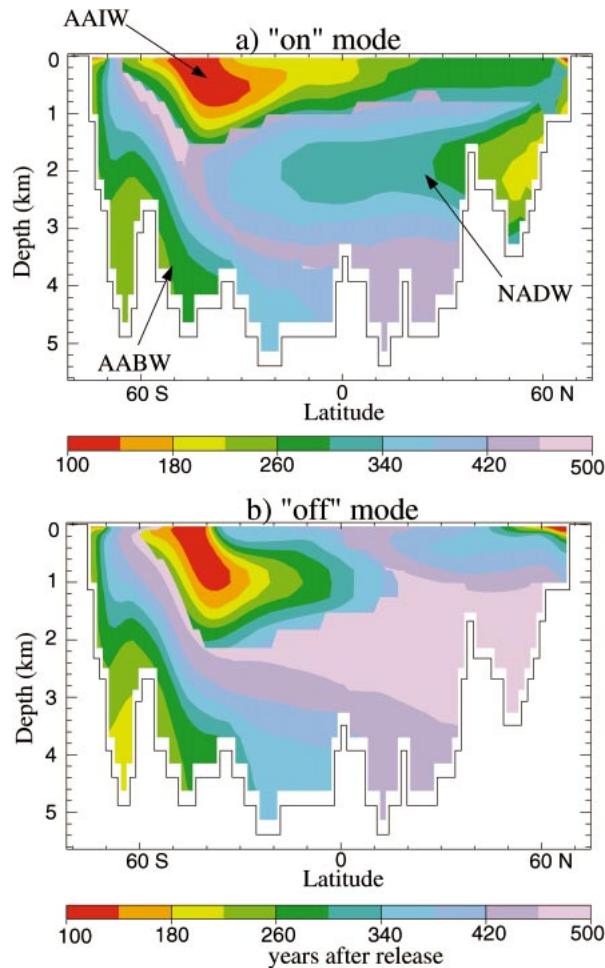


FIG. 1. Atlantic section (at 30°W) showing the simulated distribution of three passive age tracers after 500 yr, representing NADW, AAIW, and AABW water masses (see Fig. 2). Shown are the tracer distributions corresponding to (a) the “on” THC mode and (b) the “off” THC mode. For better illustration, the three tracers for each THC mode are shown on one plot. Note an “old” water mass in the deep North Atlantic in (b), suggesting a very weak ventilation there associated with the off THC mode. The tracer fields have been limited for the purposes of this illustration.

We will refer to the stable climate state without active NADW formation as the “off” mode. The simulated vertical distribution of the passive tracers in the Atlantic corresponding to the off climate mode, is illustrated in Fig. 1b. The AAIW is now spreading below the NADW and the absence of active NADW formation makes the deep North Atlantic a stagnant, poorly ventilated basin (Fig. 1b).

In previous studies, hysteresis behavior of the strength of NADW circulation and/or the associated transitions between its two stable modes has normally been forced by applying freshwater perturbations within the Atlantic, that is, north of 30°S . Here we show that similar hysteresis behavior can be obtained by applying freshwater forcing in the Southern Ocean within the region of enhanced AAIW formation. This suggests a

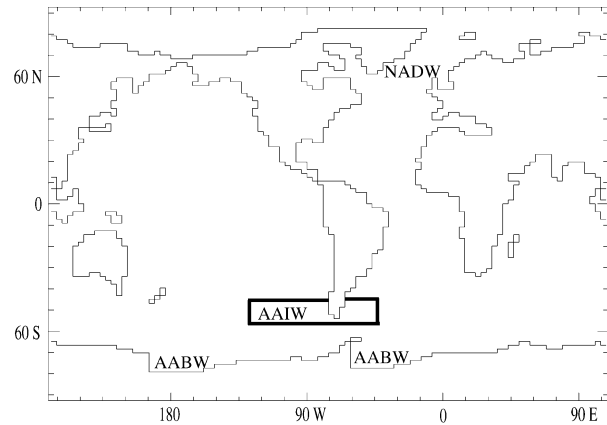


FIG. 2. Model domain. The enclosed region around the southern tip of South America shows the location where the freshwater perturbation was applied in the model experiment discussed in the text. Also shown are the approximate positions of the regions where the intense formation of, respectively, NADW, AAIW, and AABW occurs. These regions represent “sink” areas for the passive age tracers shown in Fig. 1. The regions were also used to diagnose the surface densities, representing NADW, AAIW, and AABW (see the text).

close link between the formation of NADW and AAIW and the existence of (and the transitions between) the two modes of the THC operation.

2. The model and experimental design

The coupled model we use is described in detail in Weaver et al. (2001). It comprises an ocean GCM, an energy–moisture balance atmosphere model and a dynamic–thermodynamic sea ice model. All model components have the same horizontal resolution of $1.8^{\circ} \times 3.6^{\circ}$, in latitude and longitude, respectively. The ocean model uses isopycnal mixing after Gent and McWilliams (1990). The atmosphere model calculates surface heat and freshwater fluxes, as well as the transport of sensible heat and moisture. The annual cycle of winds is prescribed from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis.

Starting from the off mode with zero externally imposed freshwater flux, we apply a freshwater perturbation to the region around the southern tip of South America (see Fig. 2), with a rate linearly increasing by $0.2 \text{ Sv} (1000 \text{ yr})^{-1}$ ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$). The rate of the forcing increase is small enough to keep the system close to a steady state with the forcing, except for the transition events. Upon a transition to the on mode, the freshwater perturbation is reduced with the same rate back to zero. Next, it is reduced to negative values to trigger a transition from the on back to the off mode. To complete the whole hysteresis loop, the model was integrated for more than 11 000 yr.

3. Results

Excluding the wind-driven Ekman cells in the upper ocean, both off and on THC modes have two overturning circulation cells within the Atlantic (Fig. 3). One of the cells, the near-bottom cell, is associated with the AABW circulation and is similar between the modes (Figs. 3a,b). However, the overturning cell within the upper 2–3-km-deep ocean has a circulation of opposite sign in the two modes. Specifically, in the on mode the AAIW feeds the formation of NADW, whereas in the off mode it does not. Rather, the AAIW is being converted into light thermocline water and recirculates within the upper Atlantic Ocean (Fig. 3a). Such a circulation scheme appears to be a characteristic for the stable off mode [see, e.g., Fig. 4b in Manabe and Stouffer (1999); Fig. 2c in Ganopolski and Rahmstorf (2001)]. It favors an enhanced freshwater flux into the Atlantic due to the so-called overturning freshwater transport (the correlation between zonally averaged salinity and zonally averaged meridional velocity) by transporting relatively fresh intermediate water into the Atlantic and saline thermocline water out of the Atlantic. For comparison, in the on mode, the overturning component of the freshwater transport into the Atlantic at 30°S is rather small (Saenko et al. 2002; see also Rahmstorf 1996), whereas in the off mode it increases to 0.17 Sv. A detailed analysis of the Atlantic freshwater budget in the hysteresis of the meridional overturning circulation is presented in Gregory et al. (2003, manuscript submitted to *Climate Dyn.*).

The qualitative difference between the THC of the two modes in the upper 2–3 km of the Atlantic can be explained by the different relationship between the densities in the source region of NADW (ρ_{NADW}) and in the source region of AAIW (ρ_{AAIW}). In the on mode, $\rho_{\text{NADW}} > \rho_{\text{AAIW}}$, whereas in the off mode, $\rho_{\text{NADW}} < \rho_{\text{AAIW}}$. The former condition favors a dominance of the NADW circulation cell over the AAIW circulation cell, a well-known feature of the present-day climate, whereas the latter condition favors a dominance of AAIW over the NADW. This notion is illustrated below.

Starting from the off mode and increasing the freshwater flux into the AAIW source region (see Fig. 2) results in a gradual reduction of ρ_{AAIW} (Fig. 4a). Accordingly, the intensity of the AAIW circulation cell gradually weakens (Figs. 3c and 4b). Furthermore, ρ_{NADW} increases (Fig. 4a), even though no freshwater perturbation is applied within the Atlantic basin (i.e., north of 30°S). Rather, the initial gradual increase of ρ_{NADW} is due to the weakening of the overturning component of the freshwater transport into the Atlantic, associated with the weakening of the AAIW overturning cell (Figs. 3c and 4b).

When the densities in the source regions of NADW and AAIW become comparable (see Fig. 4a), a rapid transition from the off to the on mode is triggered (Fig. 4b). This transition is accelerated by a positive feedback

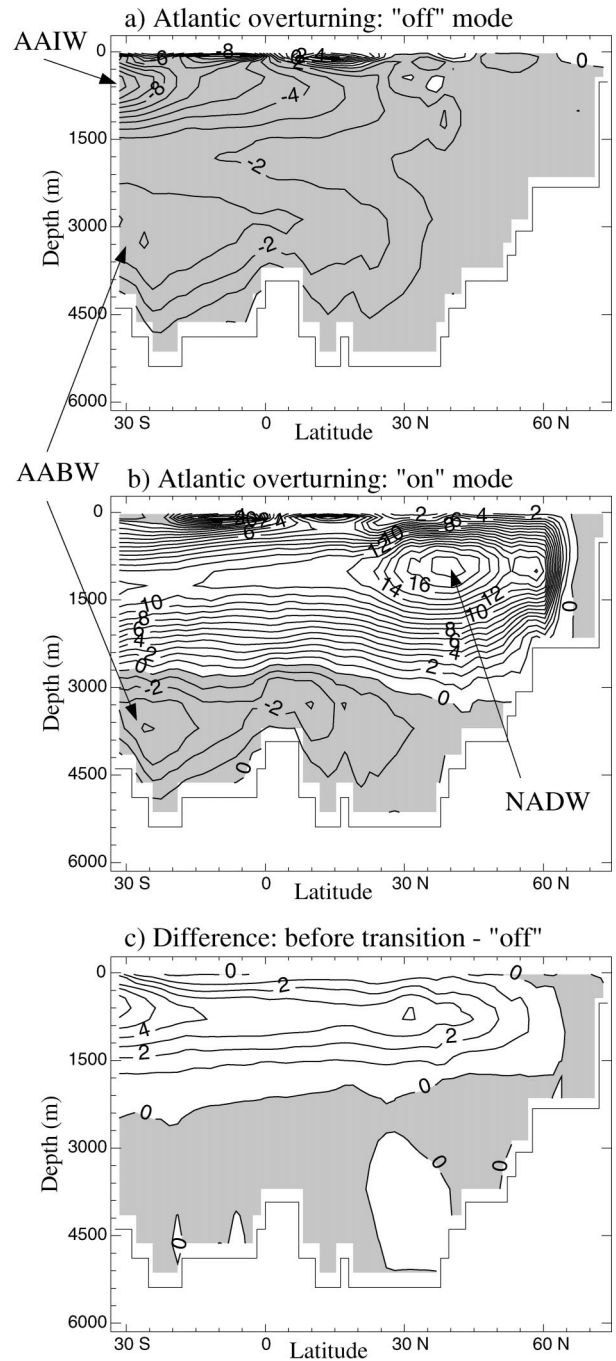


FIG. 3. The Atlantic meridional overturning circulation corresponding to (a) the off mode of the THC and to (b) the on mode of the THC. (c) The difference between the Atlantic THC just before its rapid transition to the active NADW formation and that corresponding to the off mode shown in (a). Arrows show the circulation cells discussed in the text.

between the Atlantic THC and its salinity (Stommel 1961). Specifically, the intensifying NADW circulation transports more saline subtropical water northward, thereby further intensifying the NADW formation.

By further changing the intensity of the freshwater

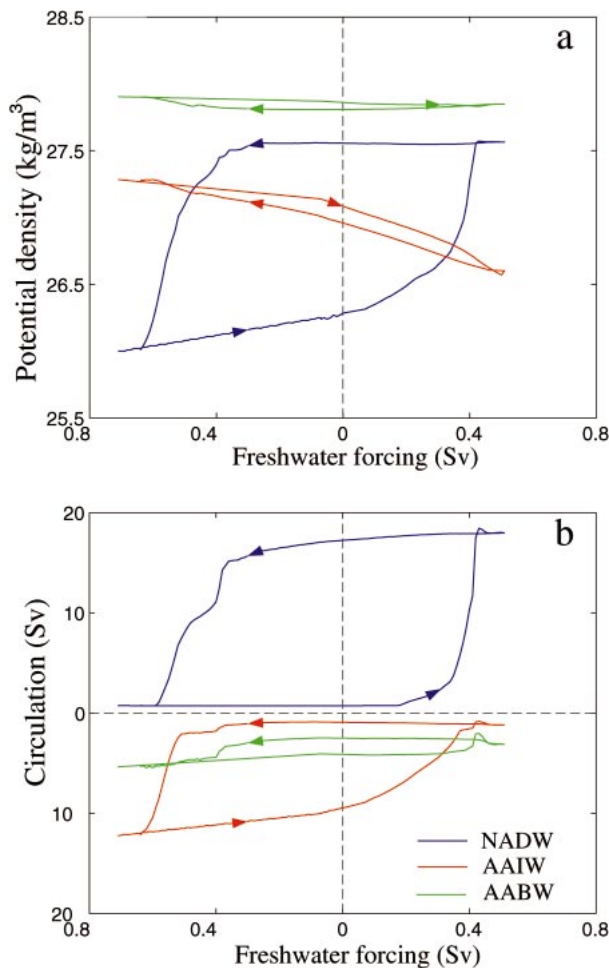


FIG. 4. The hysteresis of NADW (blue), AAIW (red), and AABW (green) showing (a) surface densities (σ) in the source regions of these water masses (see Fig. 2) and (b) maximum (or minimum) meridional overturning circulation cells associated with these water masses (see Figs. 3a,b).

perturbation as described in section 2, the circulations of NADW and AAIW undergo characteristic hysteresis loops (Fig. 4b). It can be seen that as long as the freshwater forcing is not negative enough to make the AAIW denser than NADW, the AAIW cell remains suppressed and the NADW cell is active (Figs. 4a,b). However, when the densities in the source regions of AAIW and NADW again become comparable (see Fig. 4a), a transition from the on back to the off mode is triggered (Fig. 4b). Accordingly, the formation of NADW collapses and its density reduces, whereas the (negative) AAIW circulation cell intensifies (Fig. 4b). Note that, because the freshwater forcing is applied north of the Antarctic Circumpolar Current (ACC), the AABW is not much affected (Figs. 4a,b).

4. Conclusions

Here we show that hysteresis behavior of the deep water sinking in the North Atlantic can be obtained by

applying freshwater forcing in the Southern Ocean, where enhanced AAIW formation occurs. The transition between the two stable modes of THC, that is, with and without active NADW formation, is controlled by the density relationship between these water masses. When $\rho_{\text{NADW}} > \rho_{\text{AAIW}}$, the NADW circulation cell dominates the AAIW circulation cell in the upper 2–3 km of the Atlantic and the system stays in the on mode. However, when $\rho_{\text{AAIW}} > \rho_{\text{NADW}}$ the dominance switches to the AAIW circulation cell and the system stays in the off mode.

Summarizing the above results, and based on results from the previous studies, we conclude that by applying positive (negative) freshwater perturbation to the region of AAIW formation (NADW formation), a transition from the off to on mode can be triggered. Further, by applying negative (positive) freshwater perturbation to the region of AAIW formation (NADW formation), a transition from the on to off THC mode can be triggered.

An understanding of this link between the formation of these global-scale water masses and the transitions between the two modes of the THC has important applications for climate studies. For example, Keeling and Stephens (2001) employed such a link to explain the origin of Pleistocene climate instability, using a hydraulic box model. Further, it has been recently shown that the hypothesis on the Antarctic origin of the meltwater pulse 1A, which was a prominent feature of the last deglaciation (Clark et al. 2002) can explain the following onset of the warm Bølling–Allerød interval in the North Atlantic (Weaver et al. 2003), if the link between the formation of the global-scale water masses and the THC is taken into consideration. In the present-day climate, the importance of surface salinity contrast between the North Atlantic and the Southern Ocean for driving global THC was illustrated by Seidov and Haupt (2003).

Finally we note that one of the reasons behind a relative stability of the modern climate could be the larger density difference ρ_{NADW} minus ρ_{AAIW} , as compared to the glacial climate, so that the modern climate is less prone to sudden jumps between the two climate states.

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