

# The Freshening of Surface Waters in High Latitudes: Effects on the Thermohaline and Wind-Driven Circulations

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(Manuscript received 18 October 2005, in final form 20 July 2006)

## ABSTRACT

The impacts of a freshening of surface waters in high latitudes on the deep, slow, thermohaline circulation have received enormous attention, especially the possibility of a shutdown in the meridional overturning that involves sinking of surface waters in the northern Atlantic Ocean. A recent study by Fedorov et al. has drawn attention to the effects of a freshening on the other main component of the oceanic circulation—the swift, shallow, wind-driven circulation that varies on decadal time scales and is closely associated with the ventilated thermocline. That circulation too involves meridional overturning, but its variations and critical transitions affect mainly the Tropics. A surface freshening in mid- to high latitudes can deepen the equatorial thermocline to such a degree that temperatures along the equator become as warm in the eastern part of the basin as they are in the west, the tropical zonal sea surface temperature gradient virtually disappears, and permanently warm conditions prevail in the Tropics. In a model that has both the wind-driven and thermohaline components of the circulation, which factors determine the relative effects of a freshening on the two components and its impact on climate? Studies with an idealized ocean general circulation model find that vertical diffusivity is one of the critical parameters that affect the relative strength of the two circulation components and hence their response to a freshening. The spatial structure of the freshening and imposed meridional temperature gradients are other important factors.

## 1. Introduction

The surface waters in high-latitude oceans are likely to freshen over the next few decades should polar ice caps melt or should precipitation increase in those re-

gions. Recent data indicate that this has already happened over the last several decades in the Atlantic Ocean (Dickson et al. 2002; Curry et al. 2003). What are the possible climate impacts? A vast number of studies have concentrated on the changes in the thermohaline circulation (THC)—a component of the global meridional overturning circulation associated with the surface temperature and salinity gradients and involving the deep ocean. That a freshening in high latitudes can lead to a shutdown of the thermohaline circulation is the topic of many papers (e.g., Manabe and Stouffer 1995,

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2000; Rahmstorf 1995; Stocker and Schmittner 1997; Alley et al. 2003; Seidov and Haupt 2002, 2003, and many others). The impact of such a shutdown on the earth's surface temperatures is prominent mainly over the northern Atlantic and western Europe.

Recently, Fedorov et al. (2004) demonstrated, by means of an idealized general circulation model configured for the size of the Pacific Ocean basin, that a similar freshening can also affect the shallow, wind-driven circulation of the ventilated thermocline and its heat transport from regions of gain (mainly in the upwelling zones of low latitudes) to regions of loss in higher latitudes. A freshening that decreases the surface density gradient between low and high latitudes reduces this poleward heat transport, thus forcing the ocean to gain less heat in order to maintain a balanced heat budget. This is achieved through a deepening of the equatorial thermocline. (A weakened meridional density gradient implies a deeper thermocline. The deeper the thermocline in equatorial upwelling zones is, the less heat the ocean gains.) For a sufficiently strong freshwater forcing, the poleward heat transport from the equatorial region all but vanishes, and permanently warm conditions with absent zonal SST gradient along the equator ("permanent El Niño" in the case of the Pacific; e.g., Fedorov et al. 2006) prevail in the Tropics.

What is the connection between the wind-driven and thermohaline components of the oceanic circulation? Although some studies of the THC give the impression that the Gulf Stream is exclusively one of its features, this current will be absent should the wind stop blowing (to the extent that its volume transport is proportional to the integrated wind stress curl in the interior of the ocean), even though a THC will still be possible. On the other hand, the theories of the ventilated thermocline (e.g., Luyten et al. 1983; Huang 1986; Pedlosky 1996) are incomplete and require specification of the thermal structure of the ocean along the eastern boundary of a basin. Alternatively, the oceanic stratification in the absence of winds needs to be specified. Presumably that stratification is determined by the thermohaline circulation that therefore is implicit in the theories for the ventilated thermocline. (The latter theories can be regarded as three-dimensional versions of Stommel's 1948 model of the Gulf Stream.) A number of studies looked at particular features of the oceanic circulation when both buoyancy and wind forcing are present (e.g., Veronis 1976, 1988; Luyten and Stommel 1986; De Szoeke 1995), but the overall picture remained incomplete. Boccaletti et al. (2004) recently attempted to eliminate the indeterminacy of the ventilated thermocline theories, and integrated them with theories for

the thermohaline circulation by invoking the constraint of a balanced heat budget for the ocean.

In Fig. 1 the ocean is seen to gain a very large amount of heat in the equatorial upwelling zone. This would lead to a rapid deepening of the thermocline were it not for the currents that transport the warm water poleward so that the heat is lost in higher latitudes, especially where cold, dry continental air flows over the warm Gulf Stream (and the Kuroshio in the Pacific). In a state of equilibrium the gain must equal the loss. Should there be a warming of the atmosphere in mid-latitudes that reduces the oceanic heat loss, then warm water accumulates in low latitudes so that the thermocline deepens. The winds then fail to bring cold water to the surface at the equator, the gain of heat is reduced, and a balanced heat budget is restored. It follows that the thermal structure depends critically on the fluxes of heat across the ocean surface. If the loss of heat in high latitudes is large then the ocean poleward transport of heat is large, and the gain of heat in low latitudes must be large. Exactly how the ocean gains heat depends on its vertical diffusivity. If the latter parameter is small, then the thermocline is sharp and has to be shallow for the ocean to gain a large amount of heat. If, on the other hand, the diffusivity is large then the thermocline is diffuse and the ocean gains heat by diffusing it downward into the deep ocean.

How a freshening of the surface waters can cause a "shutdown" of THC, and change the wind-driven circulation, follows from the linearized expression for the equation of state that describes the dependence of density  $\rho$  on temperature  $T$  and on salinity  $S$ :

$$\rho = \rho_0(1 - \alpha T + \beta S), \quad (1)$$

where  $\rho_0$ ,  $\alpha$ , and  $\beta$  are constants (in general,  $\alpha$  and  $\beta$  are functions of temperature and salinity). The maintenance of warm conditions in low latitudes, and of cold conditions in polar regions, drive a circulation. If density should depend on temperature only, then this circulation disappears when the imposed meridional temperature gradient  $\Delta T$  vanishes. In the presence of salinity variations, the meridional density gradient, and hence the thermal circulation, can disappear even in the presence of a meridional temperature gradient. Equation (1) implies that this happens when

$$\Delta\rho = \rho_0(\alpha\Delta T - \beta\Delta S) \rightarrow 0 \quad \text{or} \quad R \rightarrow 1, \quad (2)$$

where  $R = \beta\Delta S/\alpha\Delta T$ . Thus, for the case of the thermohaline circulation the limit  $R \rightarrow 1$  is known to be associated with a shutdown of that circulation (e.g., Zhang et al. 1999).

For the wind-driven circulation the same limit ( $R \rightarrow 1$ ) leads to the establishment of warm tropical condi-

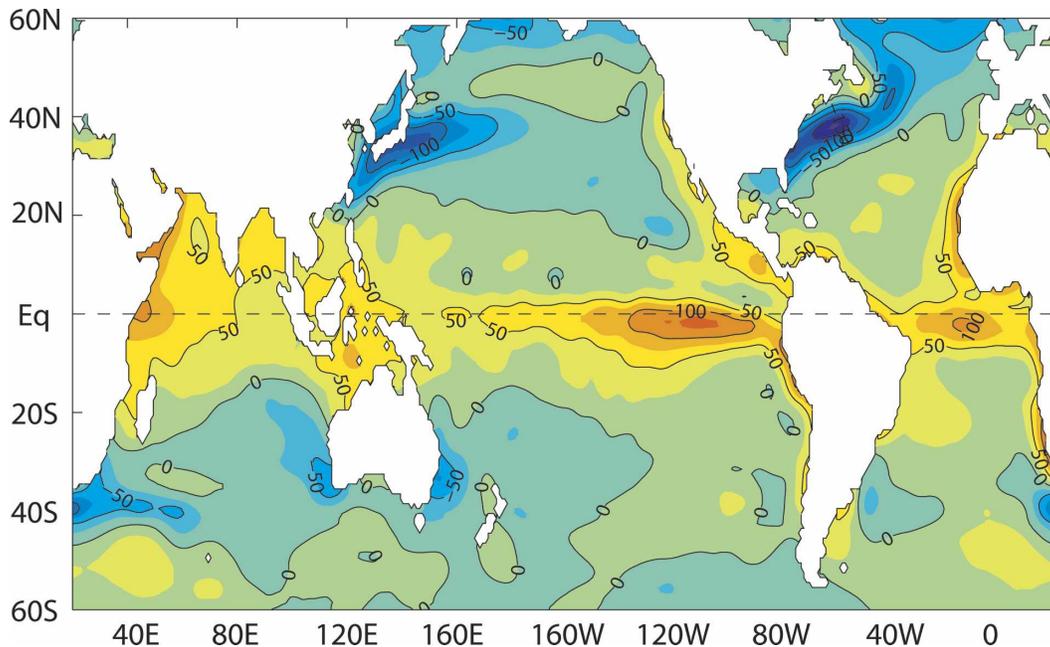


FIG. 1. Annual mean net heat flux across the ocean surface ( $\text{W m}^{-2}$ ; after Da Silva et al. 1994). The heat gain in the upwelling zones of low latitudes is roughly equal to the heat loss in high latitudes. In a steady state an increased heat loss in high latitudes implies a larger poleward heat transport from the Tropics. (The ocean heat transport through a given latitude is an integral of the surface flux from the equator to this latitude.) Exactly how the ocean gains heat depends on its vertical diffusivity. If this parameter is small, then the thermocline is sharp and has to be shallow for the ocean to gain a large amount of heat. If the diffusivity is large, then the ocean gains heat by diffusing it downward into the deep ocean.

tions with no zonal SST gradient (Fedorov et al. 2004). Such singular behavior occurs because the equator-to-pole density difference  $\Delta\rho$  at the surface is also a measure of the vertical density gradient (or the vertical stability of the ocean) in low latitudes. (Note that meridional density gradients that control the wind-driven circulation can be effectively different from those controlling the THC.) When the freshwater forcing exceeds a critical value and  $R$  becomes greater than unity, the thermocline deepens, its slope in the equatorial plane collapses, the cold equatorial tongue at the surface vanishes, and permanently warm conditions prevail in the Tropics (permanent El Niño in the case of the Pacific). The collapse of the thermocline eliminates the confined equatorial region where the ocean gains a large amount of heat (in the Tropics it is the depth of the thermocline that controls the heat intake by the ocean). As a result, the constraint of a balanced heat budget is no longer satisfied by transporting heat from regions of gain to regions of loss. Rather, the heat budget tends to be balanced more locally, and the heat transport from the equatorial region is significantly reduced. Apparently such a state of affairs can be induced merely by freshening the surface waters in the extratropics.

The calculations on changes in the wind-driven circulation, as described in Fedorov et al. (2004), were conducted with high resolution models for relatively short periods not exceeding 30–60 yr. The time scales of the upper ocean adjustment are much shorter than those for the deep ocean so that by the end of the integrations the upper ocean reaches a quasi-steady state while the deep ocean still undergoes a gradual adjustment. This approach allows many calculations with relatively modest computer resources but does not provide any information about changes in thermohaline circulation. Nor does it give any indications of how the shallow wind-driven circulation can interact with the deep meridional overturning. (The main application for that study was the Pacific basin where the THC does not play a major role.) Would our arguments on the shutdown of the wind-driven circulation change in the presence of an active thermohaline circulation? What are the factors that determine whether a freshening of the surface waters of the Northern Atlantic results in a colder climate for northwestern Europe (in accord with results from studies of the thermohaline circulation), or a deeper equatorial thermocline [in accord with the results of Fedorov et al. (2004)]?

## 2. The model

To address the questions raised above we follow the approach used by Zhang et al. (1999) but extend their model to include the Tropics. Those authors confined their attention to the thermohaline circulation and its response to a freshening of surface waters, and systematically studied the effect of changing the thermal diffusivity and of other relevant parameters in a general circulation model in a basin stretching from 60° to 5°N. A large number of calculations with different strengths of the freshwater forcing were conducted. In each experiment the model was run to reach a steady state, unless none was found. By varying freshwater forcing Zhang et al. observed a classical hysteresis in which increasing freshwater forcing leads to a gradual reduction and then a sudden collapse in the poleward heat transport (with decreasing forcing the system would recover to the original values of the poleward heat transport but at a much slower pace).

In this study the Modular Ocean Model, version 4, general circulation model (MOM4) was first used to reproduce the results of Zhang et al. (1999). Then we extended the domain to the latitude band 60°N–60°S. To speed up the calculations, we use a version of the model with a relatively coarse resolution ( $3.75^\circ \times 3.75^\circ$ ) as Zhang et al. did. The width of the basin matches that of the Atlantic. There are 15 levels in the vertical and the bottom at 4500-m depth is flat. In many instances a steady or a quasi-steady state can be reached in the course of 4000 years of integration. The zonal wind stress is specified as in Bryan (1987)—see the appendix—and does not change from one experiment to the next. Free-surface boundary conditions rather than the rigid lid (as in Zhang et al.) are used, which affects the model solutions only slightly. Given the coarse model resolution and simple geometry, the intent is not to reproduce reality in detail but rather to study the main tendencies for the problem.

The oceanic processes that we explore affect sea surface temperatures in the Tropics and, hence, can have an impact on the global climate, but those processes are entirely different from the ones that cause El Niño and La Niña. Whereas the latter phenomena are associated with an adiabatic redistribution of warm surface waters in the tropical Pacific, the processes to be explored here involve changes in the oceanic heat budget and, hence, are diabatic. To change the heat content of the ocean, two mechanisms are available: the one is direct and involves changes in the heat flux across the ocean surface and the other is indirect and involves changes in meridional salinity gradients, which can also interfere with the oceanic heat budget [see Eqs. (3)].

The standard mixed boundary conditions on temperature and salinity satisfy the above requirements:

$$kT_z = -A(T - T^*) \quad \text{and} \quad kS_z = (E - P)S_0, \quad (3)$$

where  $A = 0.6 \text{ m day}^{-1}$  is a constant (equivalent to  $25 \text{ W m}^{-2} \text{ K}^{-1}$  in terms of the appropriate heat flux),  $z$  is the vertical coordinate,  $(E - P)$  is evaporation minus precipitation and river runoff,  $S_0$  is the mean salinity in the basin,  $T$  is the sea surface temperature and  $T^*$  is an imposed temperature, and  $k$  is the coefficient of vertical diffusivity near the surface. To have a realistic equatorial cold tongue in the eastern equatorial part of the basin, in a relatively coarse model, the factor  $A^{-1}$  [proportional to the restoring time scale; see Haney (1971)] is chosen to be somewhat smaller than commonly used—otherwise the positive surface heat flux in the Tropics would overwhelm equatorial upwelling and the cold tongue in the eastern equatorial part of the basin would disappear.

## 3. Results: Freshening experiments

Here we describe in detail our numerical experiments with an intermediate (presumably realistic) value of the background diffusion coefficient ( $0.5 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ ) and then outline the main differences with low and high diffusion. The methodology of this study is as follows: First, we produce standard initial conditions for use in subsequent perturbation experiments by integrating the model for 4000 years until a steady state is reached. The restoring temperature  $T^*$  for these experiments is taken from the observations along the 30°W longitude (Levitus and Boyer 1994) but made symmetric with respect to the equator (Fig. 2a). A small, linearly varying with latitude  $E - P$  flux is added to the forcing [this flux is positive in the Northern and negative in the Southern Hemisphere; see Eq. (A.2) of the appendix]. These boundary conditions produce a realistic structure of the Atlantic meridional overturning circulation with preferential sinking in the Northern Hemisphere and the maximum overturning streamfunction of about 17 Sv ( $\text{Sv} \equiv 10^6 \text{ m}^3 \text{ s}^{-1}$ ) (Fig. 3a).

Next, we proceed to the perturbation experiments— from one experiment to the next we keep  $T^*$  the same but vary the  $E - P$  flux and explore changes in the relevant characteristics of the ocean circulation and thermal structure after 100 years of integrations. The shape of the  $E - P$  forcing for these perturbation experiments [Eq. (A3) of the appendix] is chosen to induce a freshening of surface waters in high latitudes but to conserve mean salinity.

Figure 2 shows the forcing used in some of the fresh-

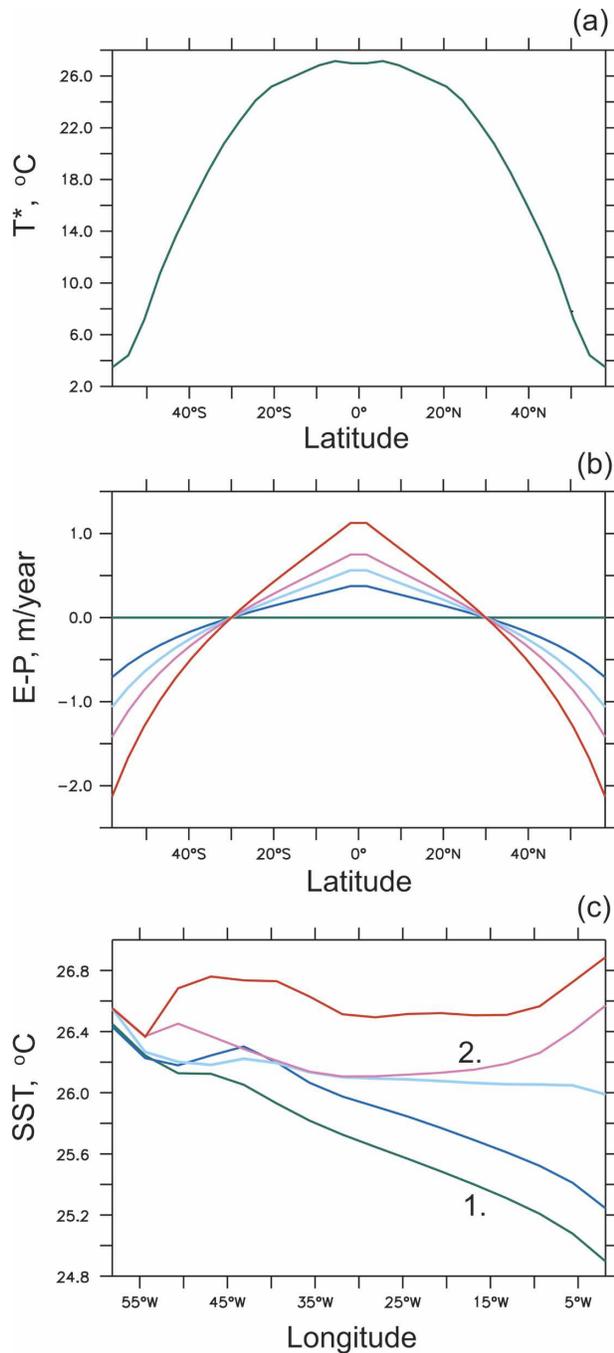


FIG. 2. The forcing and the ocean response in the equatorial region for different values of the freshwater flux in high latitudes. Intermediate values of background diffusion,  $k_b = 0.5 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ , are used. In (c) the color of each line matches the respective color in (b). Case 1: the anomalous freshwater forcing is zero. Case 2: the SST gradient along the equator has collapsed. (a) The meridional structure of the restoring temperature  $T^*$ . (b) The meridional structure of the anomalous  $E - P$  flux ( $\text{m yr}^{-1}$ ). Negative values indicate an excess of precipitation over evaporation. (c) The SST along the equator after 100 years of integrations.

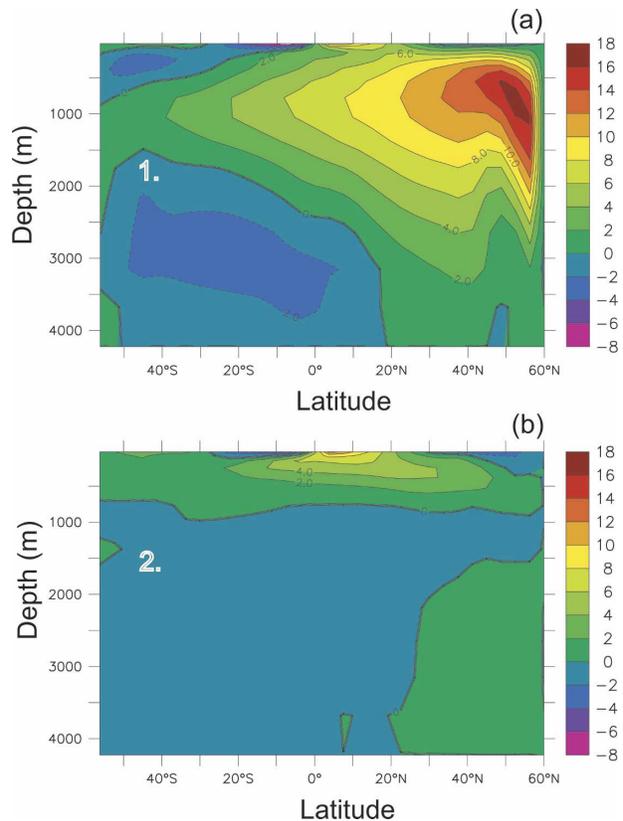


FIG. 3. The meridional overturning circulation (Sv) for experiments (a) 1 and (b) 2 after 100 years of calculations. Notice a deep overturning associated with the THC in (a) and a shallow overturning (upper 200 m) associated with the wind-driven component of the circulation in (a) and (b). The THC has collapsed in (b).

ening experiments and simulated changes in the zonal SST along the equator for five different strengths of the  $E - P$  flux with the freshwater forcing at  $55^\circ\text{N}$  corresponding to 0, 0.5, 0.8, 1.1, and  $1.7 \text{ m yr}^{-1}$ . The calculated meridional overturning for cases 1 and 2 is shown in Figs. 3 and 4. Summary plots, which include several additional experiments, are presented in Fig. 5 combining changes in the equatorial SST gradient, the depth of the tropical thermocline, and the THC volume transport as a function of the freshwater flux.

As in many previous studies, with increasing freshwater forcing the strength of the THC decreases and ultimately its meridional overturning “breaks down” or collapses (Figs. 3b, 4b, and 5). At the same time, with increasing freshwater forcing and in accordance with the arguments of the previous section, the equatorial SST gradient weakens and then collapses, which occurs in this set of experiments almost simultaneously with the THC collapse. As further calculations suggest, however, the simultaneous collapse of the SST gradient and

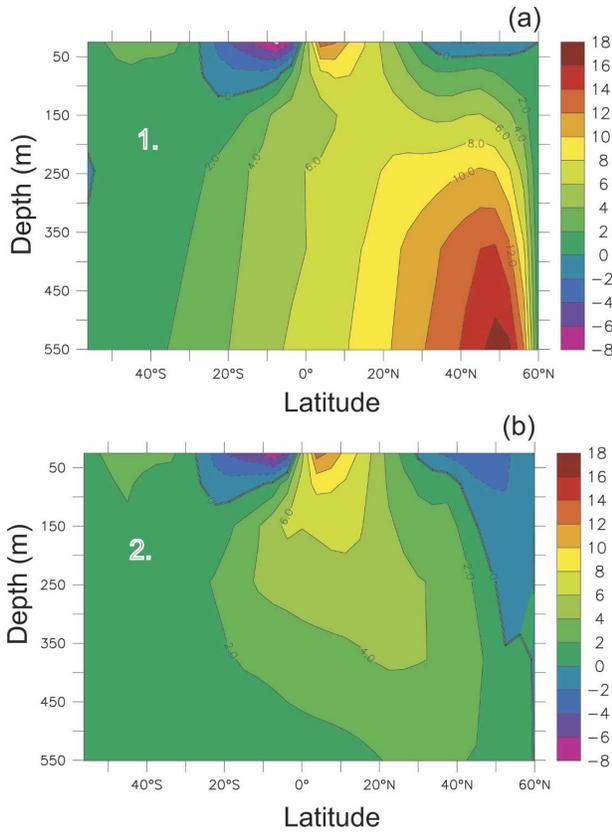


FIG. 4. Detailed structure of the meridional overturning (Sv) for the upper 500 m of the ocean for the cases shown in Fig. 3. Notice the shallow wind-driven circulation (the upper 200 m) and the upper branch of the deep overturning associated with the THC in (a). The shallow wind-driven cell affects a large part of the heat transport from the Tropics. The THC has collapsed in (b).

the THC in these particular calculations is a mere coincidence—a slightly different combination of the restoring time scale and/or background diffusion would make possible a collapse of only one of the two.

The reduction and then reversal of the equatorial SST gradient (Fig. 5a) is associated with the reduction in the meridional density gradient (measured from high latitudes to the equator) and with the deepening of the equatorial thermocline as seen in Fig. 5b. [Note that Johnson and Marshall (2002) studied changes in the thermocline depth within a reduced-gravity model when a THC strength is varied and also noticed a deepening of the tropical thermocline associated with heat accumulation in the upper ocean. Their model, however, did not have mechanisms allowing for the equatorial upwelling or wind controls of the equatorial thermocline.]

Figure 4 provides a detailed view of the overturning circulation for cases 1 and 2 for the upper 500 m of the

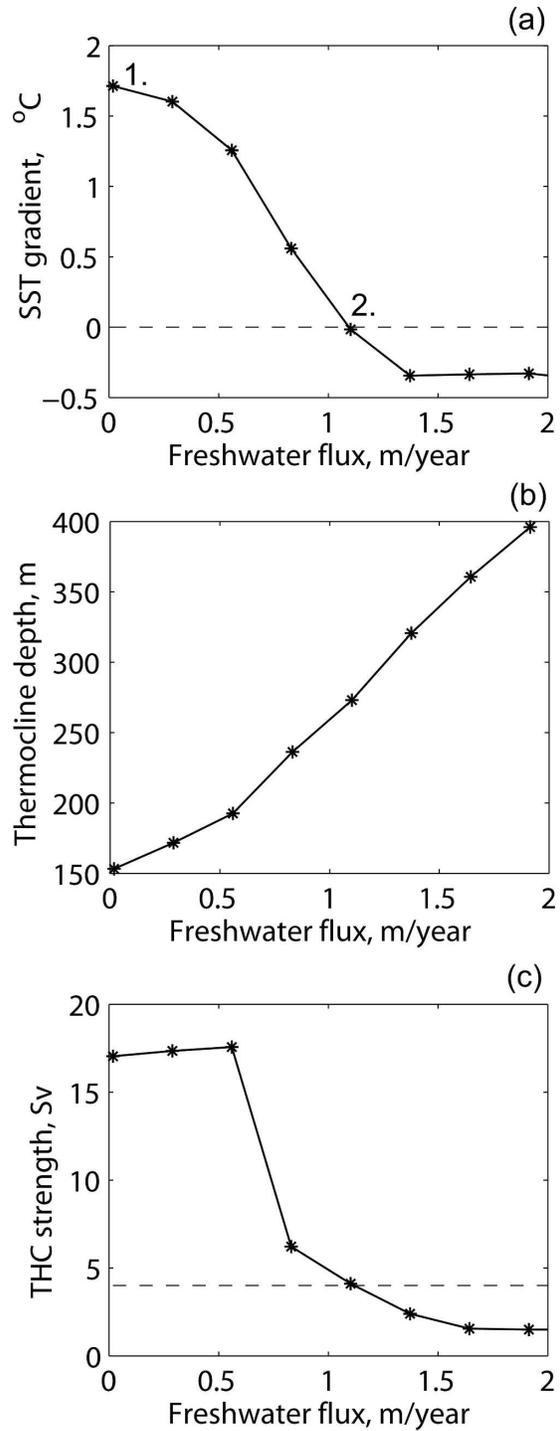


FIG. 5. Summary plot for several perturbation experiments including those shown in Fig. 2 (cases 1 and 2 are specifically marked). The freshwater flux is measured at 55°N. (a) Reduction and reversal of the zonal SST gradient along the equator; (b) deepening of the tropical thermocline (thermocline depth is measured in the middle of the basin); (c) reduction and collapse in the strength of the THC (dashed line corresponds to 4 Sv).

TABLE 1. The main results of the freshening experiments for different values of the ocean vertical diffusivity. While particular numbers can change from one model to another the main tendencies should persist.

	Background diffusion coefficient $k_b$ ( $\text{m}^2 \text{s}^{-1}$ )	Initial strength of the THC (Sv)	Critical $E - P$ flux (at $55^\circ\text{N}$ ) for the SST gradient collapse ( $\text{m yr}^{-1}$ )	THC for the critical $E - P$ flux
1	$0.05 \times 10^{-4}$	3–4	0.8	Has collapsed
2	$0.5 \times 10^{-4}$	17	1.1	Is collapsing
3	$5 \times 10^{-4}$	42	2.5	Persists

ocean, which emphasizes the role of the shallow wind-driven cell affecting a significant fraction of the heat transport from the Tropics. The strength of this component of the overturning circulation changes only slightly, from one experiment to the next; however, its impact on the Tropics and its relative contribution to the heat transport varies significantly.

Numerous studies have established that the strength of ocean mixing is one of the key factors that determine the strength of the THC in ocean models (e.g., Park and Bryan 2000). To explore this issue we repeated most of the experiments of this study with large ( $5 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ ) and small ( $0.05 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ ) values of the coefficient of vertical diffusion. In agreement with previous studies, our calculations indicate that in a model with large values of diffusivity the thermohaline circulation is dominant. The wind-driven component of the circulation gains in importance as diffusivity decreases, dominating the circulation for small values of diffusivity. The volume transport of the shallow overturning associated with the wind-driven circulation remains largely unchanged; rather, the strength of the THC varies. In the experiments with small values of diffusivity ( $0.05 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ ) the thermohaline circulation is all but nonexistent, and the poleward heat transport is maintained almost exclusively by the wind-driven circulation.

A series of perturbation freshening experiments was conducted for the low and high values of the diffusion coefficient. In the experiments with low diffusion the zonal SST gradient along the equator collapses at a relatively low magnitude of the freshening ( $0.8 \text{ m s}^{-1}$ ). In the experiments with large diffusion, there is a vigorous thermohaline circulation, and a larger freshwater forcing ( $2.5 \text{ m yr}^{-1}$ ) is needed to collapse the equatorial SST gradient. Even a stronger forcing would be necessary to collapse the THC. The results of these experiments, on the role of vertical diffusivity, are summarized in Table 1.

Note that in the ocean model we use the full coefficient of vertical diffusion  $k$  as a sum of three components: background vertical diffusivity  $k_b$ , the part dependent on the Richardson number (negligible except in the narrow equatorial region), and the part related to

wind mixing (negligible below the first model layer). Except in the aforementioned few regions, the difference between  $k$  and  $k_b$  is small, so we use the terms background vertical diffusivity and vertical diffusivity interchangeably.

Another important factor that determines the ocean response to a freshening is the spatial structure of the forcing, that is, the location of areas with excess/deficit precipitation. Figure 6 shows some of the results of the experiments with an idealized, cosine-like structure of the anomalous freshwater forcing, which has a maximum in precipitation at about  $25^\circ\text{N/S}$  and two minima at the equator and at  $45^\circ\text{N/S}$ . This shape, perhaps somewhat artificial, is chosen to impose surface freshening (negative  $E - P$  flux) over the regions of subduction associated with the wind-driven circulation, but to maintain excessive evaporation (positive  $E - P$  flux) over the regions of sinking associated with the thermohaline circulation. As one could expect, this experiment results in the collapse of the SST gradient along the equator (Fig. 6, case 3) but the thermohaline circulation is affected only slightly, as seen from summary plots in Fig. 7. The mechanism of the equatorial SST gradient collapse is again related to the reduction of the meridional density gradient (between the subtropical subduction regions at about  $30^\circ$  of latitude and the equator) and the deepening of the tropical thermocline (see Fig. 7b). While the  $E - P$  anomaly used in these experiments is very idealized, such a result underlines the importance of where the freshwater forcing is applied.

Thus, an important finding of these experiments is that the collapse of the THC and that of the equatorial thermocline can occur independently. A simple explanation for this result is that the meridional density gradients controlling the THC and the wind-driven circulation are two different parameters that can vary independently from each other. For example, the forcing used in Fig. 6, does not change the meridional density gradient between  $0^\circ$  and  $60^\circ\text{N}$  where the sinking of the THC water occurs, but reduces the density gradient between the equator and the regions where water is subducted into the wind-driven circulation (at  $30^\circ$  latitude). In the experiments with different diffusion coef-

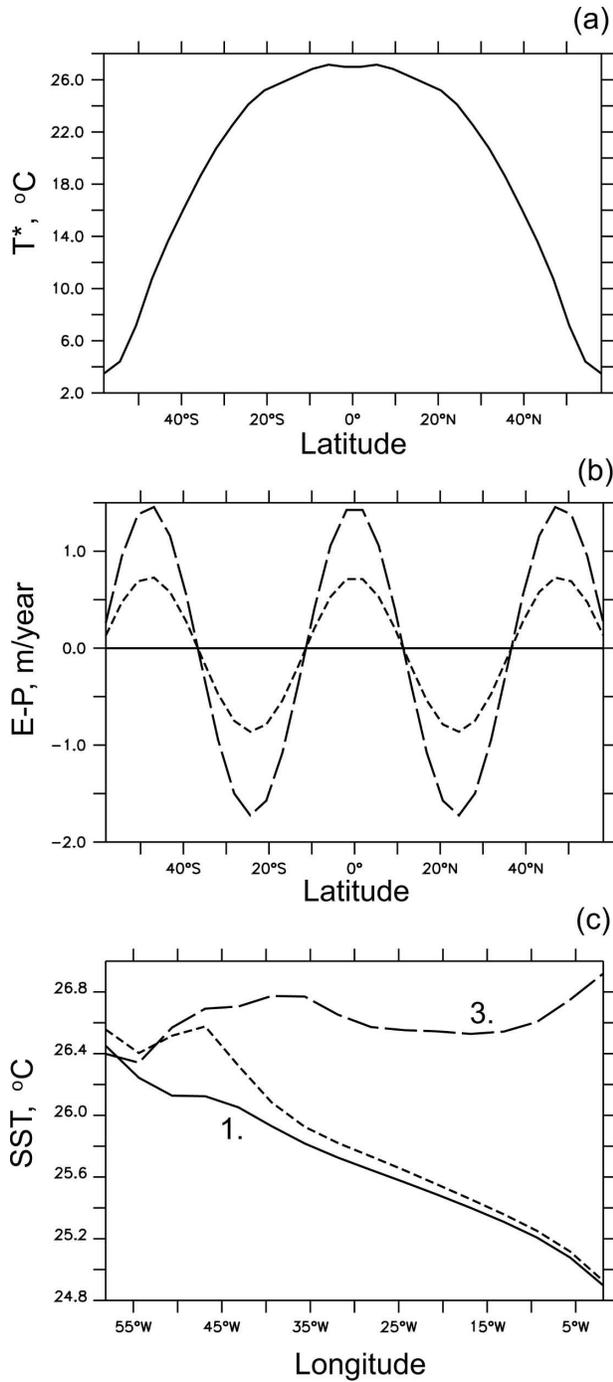


FIG. 6. Forcing, and the ocean response in the equatorial region, for different amplitudes of the cosine-like  $E - P$  forcing. The structure of the  $E - P$  flux is given by Eq. (A.3). The restoring temperature  $T^*$  is as in Fig. 2. Case 1: the anomalous freshwater forcing is zero. Case 3: the SST gradient along the equator has collapsed, but the THC is affected only slightly [see (b)]. For intermediate values of background diffusion,  $k_b = 0.5 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ . (a) The meridional structure of the restoring temperature  $T^*$ . (b) The meridional structure of the anomalous  $E - P$  flux ( $\text{m yr}^{-1}$ ). Negative values indicate an excess of precipitation over evaporation. (c) The SST along the equator after 100 years of integrations. The style of each line in (b) matches the respective line style in (c).

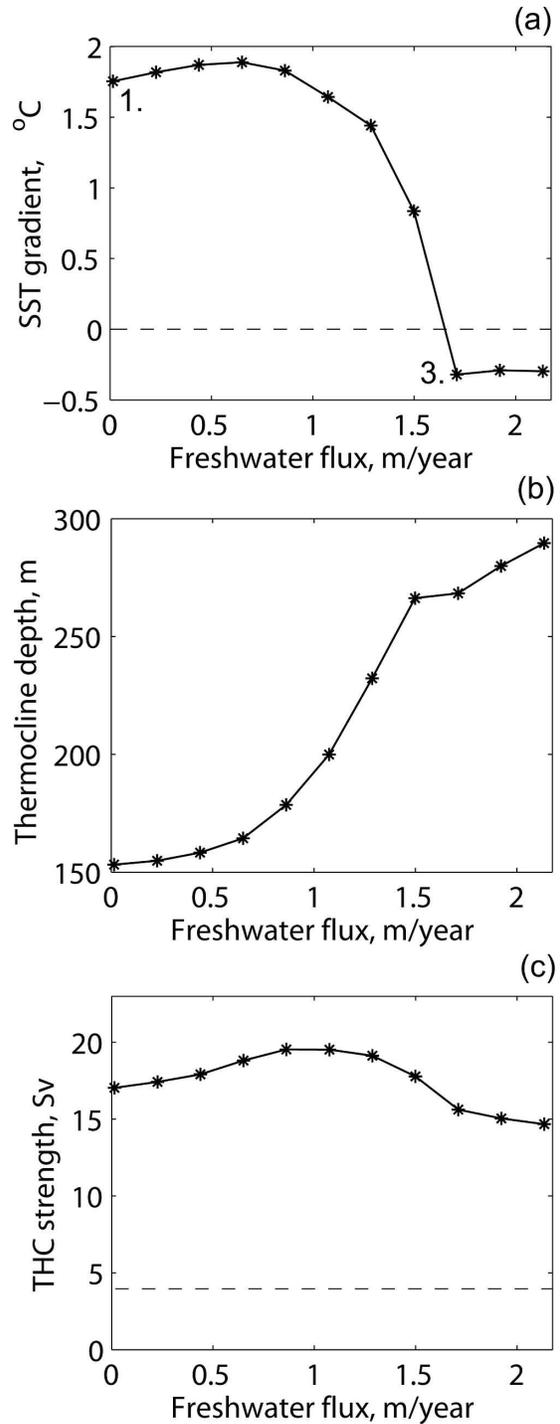


FIG. 7. Summary plot for several perturbation experiments with a cosine-like forcing including those shown in Fig. 6 (cases 1 and 3 are specifically marked). The freshwater flux is measured at  $25^{\circ}\text{N}$ . (a) Reduction and reversal of the zonal SST gradient at  $25^{\circ}\text{N}$ . (b) Deepening of the tropical thermocline (thermocline depth is measured in the middle of the basin); (c) changes in the strength of the THC (dashed line corresponds to  $4 \text{ Sv}$ ).

ficients, the separation of the two gradients is more intricate, but the same arguments still apply.

One important note is in order: The results of perturbation experiments presented here correspond to 100 years of calculations (which makes them relevant to the climate change problem). Longer calculations show that in some cases, especially those near critical or transitional regimes, a steady state cannot be reached but, instead, the system undergoes slow oscillations involving both the THC and the equatorial SST gradient. The oscillation period then ranges from centuries to millennia.

#### 4. Results: Anomalous warming of high latitudes

Numerous calculations with a coupled GCM show a pronounced warming of the northern high latitudes in greenhouse-warming simulations (e.g., Stainforth et al. 2005). To address this issue, in a separate series of experiments, we look at the effect of anomalous heating of the surface waters in high latitudes. An important prerequisite of these experiments is a superimposed weak  $E - P$  flux added when calculating the initial conditions. This additional background forcing, which corresponds to a freshening of surface water in high latitudes, remains constant from one experiment to the next (Fig. 8b). The variable parameter in these perturbation experiments is the restoring temperature  $T^*$ , chosen to induce a heating anomaly (with respect to the control case; i.e., experiment 1). The temperature anomaly is maximum at the northern and southern boundaries of the basin and tapers off at about  $40^\circ$  of latitude (Fig. 8a).

Since both freshening and warming of surface waters have similar effects on the density of seawater, one can expect that the results would be, to some degree, analogous to the experiments of the previous section. Indeed, our calculations show (again after 100 years of integrations) that when warmer high-latitude temperatures are imposed, the equatorial SST gradient weakens (Fig. 8c). This temperature gradient all but collapses for the warmest  $T^*$  we imposed, and so too does the thermohaline circulation (not shown here).

The value of the maximum temperature anomaly used in these experiments is  $8^\circ\text{C}$  (or about  $4^\circ\text{C}$  averaged over the area of the anomaly), which is relatively high. These values, however, would be smaller, had we chosen a somewhat stronger freshwater forcing. This and several other experiments suggest that the most efficient way to collapse both the THC and the equatorial SST gradient is to use a certain combination of anomalous surface freshening and warming. The equation of state of seawater, written as Eq. (2), suggests

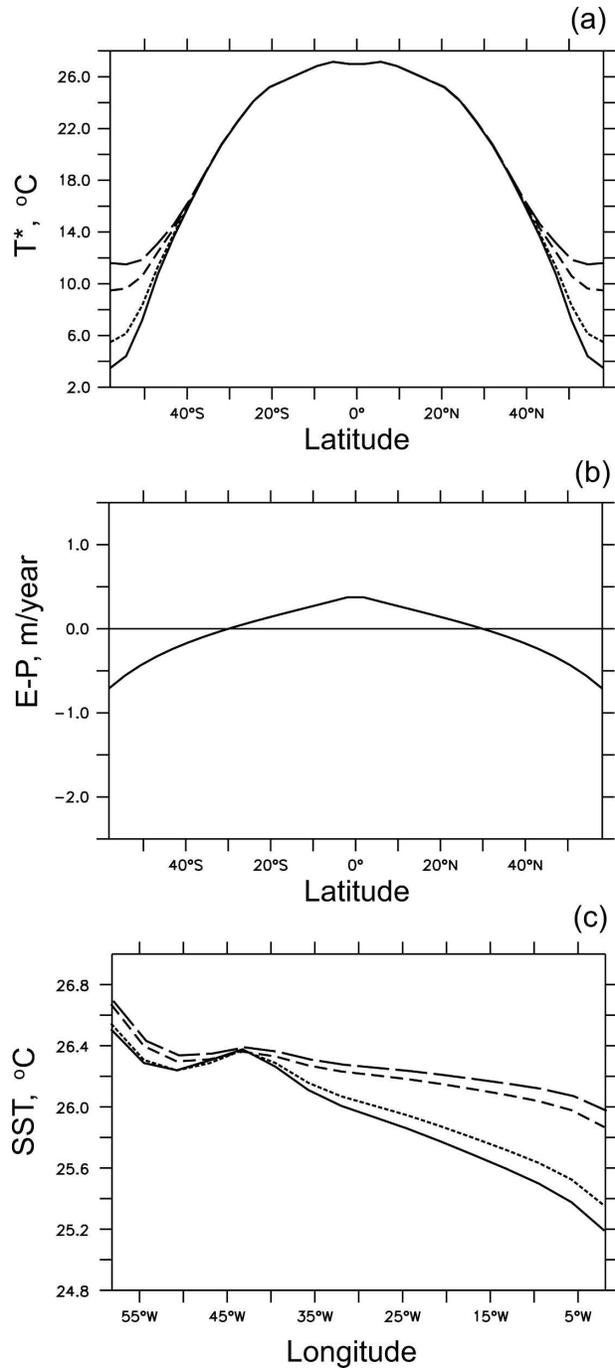


FIG. 8. Forcing and the ocean response in the equatorial region, for different values of the anomalous heating in high latitudes. For intermediate values of background diffusion  $k_b = 0.5 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ . (a) The meridional structure of the restoring temperature  $T^*$  in perturbation experiments. (b) The meridional structure of the background  $E - P$  flux ( $\text{m yr}^{-1}$ ). Negative values of  $E - P$  indicate an excess of precipitation over evaporation. (c) The SST along the equator after 100 years of integration. The style of each line in (c) matches the respective line style in (a).

that the effect of 1 psu (the unit of salinity) on density of seawater is equivalent to the effect of 3°–5°C, depending on mean temperature (see Fedorov et al. 2004). Thus, one could vary either the freshwater or thermal forcing accordingly with similar effects. Note, however, that, if the freshwater forcing is completely absent, the meridional temperature gradient must vanish as well for the THC and the equatorial SST gradient to collapse.

## 5. Conclusions

The effects of a freshening of the surface waters of the ocean in high latitudes have thus far been studied in connection with the thermohaline circulation, and separately in connection with the wind-driven circulation. In those modeling studies the focus has been on one or the other component of the oceanic circulation because of the choice of certain model parameters. In the present study we have integrated the two approaches. This paper focuses on mechanisms that interfere effectively with the oceanic heat budget, thereby changing the thermal structure in the Tropics and thus influencing tropical sea surface temperatures and the global climate. The time scale on which this can happen is that of the wind-driven circulation, a few decades. Hence these mechanisms amount to overlooked processes for rapid or abrupt climate changes. This emphasizes the necessity to take into account both the THC and the wind-driven circulation when considering such climate fluctuations.

Our experiments show that the freshening can induce either the collapse (weakening) of the THC with expected climate consequences, or the collapse (weakening) of the equatorial SST gradient leading to warm tropical conditions, or both. The factors that affect the strength of the necessary forcing include ocean diffusion, the relative magnitude of the freshening and warming anomalies (as they affect the oceanic heat transport), and the spatial structure of the forcing. Experiments with coupled general circulation models show some agreement with the results of this study. In particular, coupled simulations on the effect of high-latitude freshwater forcing demonstrate that, with a weakening of the THC, the intertropical convergence zone (ITCZ) and the maximum of tropical precipitation shift southward in the Atlantic Ocean (e.g., Vellinga and Wood 2002; Zhang and Delworth 2005). This would be consistent with the warming of the tropical SST in the eastern equatorial Atlantic controlled by changes in the wind-driven circulation. These important questions, as well as more realistic calculations, remain beyond the limits of the present study.

It is believed that variations or major disruptions of the THC occurred during rapid climate changes of the past (Rahmstorf 2002; Alley et al. 2003). Available evidence does indicate that this may have been the case on several occasions: during Heinrich event 1 (H1) 17 500 years ago (McManus et al. 2004), during the Younger Dryas some 12 700 years ago (McManus et al. 2004), and during the cold event of 8200 years ago (Barber et al. 1999). The main hypotheses explaining these climate fluctuations in the paleo records are based on the idea that a freshening of the North Atlantic after an influx of freshwater from a glacial lake or iceberg discharge led to a collapse or significant reduction in the strength of the THC. Our study suggests that, at least during some of those events, not only the THC was affected but also the wind-driven circulation, which may have led to a deepening of the ocean thermocline in the Tropics.

Several other issues remain unresolved. As the results of the present study stand now, they are applicable to the Atlantic Ocean. The results of Fedorov et al. (2004) are relevant to the Pacific. Both studies make the assumption of a closed basin. How restrictive is this? Can a freshening in the Atlantic result in the “permanent El Niño” in the Pacific? A tendency toward permanent El Niño is present, albeit weak, when the northern Atlantic is freshened in the recent study by means of a coupled climate model by Zhang and Delworth (2005), but the signal is more pronounced in the tropical Atlantic. In Dong and Sutton (2002) a temporary freshening of the northern Atlantic induces El Niño-like conditions in the equatorial the Pacific after 7 years. These authors suggested an atmospheric “bridge” as a possible explanation of the observed changes in the Pacific Ocean. An alternative explanation is that interfering with global oceanic heat transport leads to tropical changes in both basins (in other words, the surface heat fluxes in Fig. 1 do not need to be balanced in each single basin separately). Today the Pacific gains heat that is exported to, and is lost in, the Atlantic or the Southern Ocean. The connection between the oceans is through the Antarctic Circumpolar Current (Toggweiler and Samuels 1998; Gnanadesikan 1999). Hence a freshening of the Atlantic that affects its heat budget could influence the Pacific. Recent results of Seidov and Haupt (2005) suggest that a differential interhemispheric freshening can be another important factor for the stability of the thermohaline circulation.

*Acknowledgments.* This research is supported in part by grants from DOE Office of Science (DE-FG02-06ER64238 to AVF), NSF (OCE-0550439 to AVF), NOAA (NA16GP2246 to SGP), and by Yale University. We thank George Veronis for reading one of the

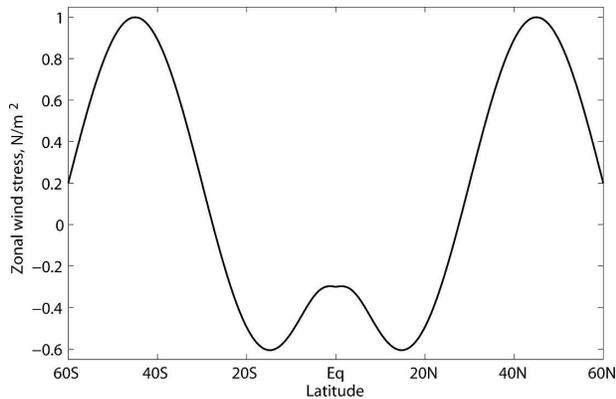


FIG. A1. The analytic approximation to the zonally averaged annual mean wind stress used in this study (after Bryan 1987).

early drafts of the manuscript and Dan Seidov and an anonymous reviewer for helpful suggestions.

## APPENDIX

### Analytic Expressions used in Numerical Calculations

The wind stress used in this study is given by the following expression (Bryan 1987):

$$\tau^x = 0.8[-\sin(6|\phi|) - 1] + 0.5[\tanh(5\pi - 10|\phi|) + \tanh(10|\phi|)], \quad (\text{A1})$$

where  $\phi$  is latitude. The shape of the wind is symmetric with respect to the equator (see Fig. A1).

The small  $E - P$  flux added to the forcing to induce preferential sinking in the Northern Hemisphere is given by the following expression

$$F = 0.2(\phi/\phi_{\max}), \quad (\text{A2})$$

where  $\phi_{\max} = 60^\circ$  and flux  $F$  is measured in meters per year.

For the experiments presented in Figs. 2–5 and 8, the shape of the  $E - P$  flux is calculated as

$$F = W_0(1 - 2|\phi|/\phi_{\max})/\cos(\phi), \quad (\text{A3})$$

where  $|\phi| \leq \phi_{\max}$ .

For the experiments presented in Figs. 6 and 7, the shape of the  $E - P$  flux is calculated as

$$F = W_0 \cos(2.5\pi\phi/\phi_{\max}). \quad (\text{A4})$$

Here  $W_0$  is a constant varied from one experiment to the next.

## REFERENCES

- Alley, R., and Coauthors, 2003: Abrupt climate change. *Science*, **299**, 2005–2010.
- Barber, D. C., and Coauthors, 1999: Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature*, **400**, 344–348.
- Boccaletti, G., R. C. Pacanowski, S. G. Philander, and A. V. Fedorov, 2004: The thermal structure of the upper ocean. *J. Phys. Oceanogr.*, **34**, 888–902.
- Bryan, F., 1987: Parameter sensitivity of primitive equation ocean general circulation models. *J. Phys. Oceanogr.*, **17**, 970–985.
- Curry, R., B. Dickson, and I. Yashayaev, 2003: A change in the freshwater balance of the Atlantic Ocean over the past four decades. *Nature*, **426**, 826–829.
- Da Silva, A., A. C. Young, and S. Levitus, 1994: *Anomalies of Fluxes of Heat and Momentum*. Vol. 3, *Atlas of Surface Marine Data 1994*, NOAA Atlas NESDIS 8, 411 pp.
- De Szoeke, R., 1995: A model of wind- and buoyancy-driven ocean circulation. *J. Phys. Oceanogr.*, **25**, 918–941.
- Dickson, B., I. Yashayaev, J. Meincke, B. Turrell, S. Dye, and J. Holfort, 2002: Rapid freshening of the deep North Atlantic Ocean over the past four decades. *Nature*, **416**, 832–837.
- Dong, B.-W., and R. T. Sutton, 2002: Adjustment of the coupled ocean–atmosphere system to a sudden change in the thermohaline circulation. *Geophys. Res. Lett.*, **29**, 1728, doi:10.1029/2002GL015229.
- Fedorov, A. V., R. C. Pacanowski, S. G. Philander, and G. Boccaletti, 2004: The effect of salinity on the wind-driven circulation and the thermal structure of the upper ocean. *J. Phys. Oceanogr.*, **34**, 1949–1966.
- , P. S. Dekens, M. McCarthy, A. C. Ravelo, P. B. deMenocal, M. Barreiro, R. C. Pacanowski, and S. G. Philander, 2006: The Pliocene paradox (mechanisms for a permanent El Niño). *Science*, **312**, 1485–1489.
- Gnanadesikan, A., 1999: A simple predictive model for the structure of the oceanic pycnocline. *Science*, **283**, 2077–2079.
- Haney, R. L., 1971: Surface thermal boundary condition for ocean circulation models. *J. Phys. Oceanogr.*, **1**, 241–248.
- Huang, R. X., 1986: Solutions of the ideal fluid thermocline with continuous stratification. *J. Phys. Oceanogr.*, **16**, 39–59.
- Johnson, H. L., and D. P. Marshall, 2002: A theory for the surface Atlantic response to thermohaline variability. *J. Phys. Oceanogr.*, **32**, 1121–1132.
- Levitus, S., and T. P. Boyer, 1994: *Temperature*. Vol. 4, *World Ocean Atlas 1994*, NOAA Atlas NESDIS 4, 117 pp.
- Luyten, J. R., and H. Stommel, 1986: Gyres driven by combined wind and buoyancy flux. *J. Phys. Oceanogr.*, **16**, 1551–1560.
- , J. Pedlosky, and H. M. Stommel, 1983: The ventilated thermocline. *J. Phys. Oceanogr.*, **13**, 292–309.
- Manabe, S., and R. J. Stouffer, 1995: Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean. *Nature*, **378**, 165–167.
- , and —, 2000: Study of abrupt climate change by a coupled ocean–atmosphere model. *Quat. Sci. Rev.*, **19**, 285–299.
- McManus, J. R., R. Francois, J.-M. Gherardi, L. D. Keigwin, and S. Brown-Leger, 2004: Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature*, **428**, 834–837.
- Park, Y.-G., and K. Bryan, 2000: Comparison of thermally driven circulations from a depth-coordinate model and an isopycnal layer model. Part I: Scaling-law sensitivity to vertical diffusivity. *J. Phys. Oceanogr.*, **30**, 590–605.

- Pedlosky, J., 1996: *Ocean Circulation Theory*. Springer-Verlag, 453 pp.
- Rahmstorf, S., 1995: Bifurcation of the Atlantic thermohaline circulation in response to changes in the hydrological cycle. *Nature*, **378**, 145–149.
- , 2002: Ocean circulation and climate during the past 120,000 years. *Nature*, **419**, 207–214.
- Seidov, D., and B. J. Haupt, 2002: On the role of inter-basin surface salinity contrasts in global ocean circulation. *Geophys. Res. Lett.*, **29**, 1800, doi:10.1029/2002GL014813.
- , and —, 2003: On sensitivity of ocean circulation to sea surface salinity. *Global Planet. Change*, **36**, 99–116.
- , and —, 2005: How to run a minimalist's global ocean conveyor. *Geophys. Res. Lett.*, **32**, L07610, doi:10.1029/2005GL022559.
- Stainforth, D. A., and Coauthors, 2005: Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature*, **433**, 403–406.
- Stocker, T. F., and A. Schmittner, 1997: Influence of CO<sub>2</sub> emission rates on the stability of the thermohaline circulation. *Nature*, **288**, 862–865.
- Toggweiler, J. R., and B. Samuels, 1998: On the ocean's large-scale circulation near the limit of no vertical mixing. *J. Phys. Oceanogr.*, **28**, 1832–1852.
- Vellinga, M., and R. A. Wood, 2002: Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Climatic Change*, **54**, 251–267.
- Veronis, G., 1976: Model of world ocean circulation. III: Thermally and wind-driven. *J. Mar. Res.*, **36**, 1–44.
- , 1988: Circulation driven by winds and surface cooling. *J. Phys. Oceanogr.*, **18**, 1920–1932.
- Zhang, J., R. W. Schmitt, and R. X. Huang, 1999: The relative influence of diapycnal mixing and hydrologic forcing on the stability of the thermohaline circulation. *J. Phys. Oceanogr.*, **29**, 1096–1108.
- Zhang, R., and T. L. Delworth, 2005: Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation. *J. Climate*, **18**, 1853–1860.