LETTERS

The Exhaust Valve of the North Atlantic

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ABSTRACT

During glacial periods, climate records are marked by large-amplitude oscillations believed to be a result of North Atlantic (NA) freshwater anomalies, which weakened the thermohaline circulation (THC) and introduced instabilities. Such oscillations are absent from the present interglacial period. With the aid of a semiglobal analytical model, it is proposed that the Bering Strait (BS) acts like an exhaust valve for the above NA freshwater anomalies. Specifically, it is suggested that large instabilities in the THC are only possible during glacial periods because, during these periods, the BS is closed. During interglacial periods (when the BS, the exhaust valve, is open), low-salinity anomalies are quickly flushed out of the North Atlantic by the strong Southern Ocean winds.

1. Introduction

Recently, the difference between the climate stability during the Holocene and glacial periods (shown in Fig. 1) has been attributed to changes in the location of the North Atlantic Deep Water (NADW) formation region (e.g., Schmittner et al. 2002; Ganapolski and Rahmstorf 2001). It was also suggested that, during the glacial period, the meridional overturning cell was weak and, hence, less stable (e.g., Tziperman 1997). All of these results are based on numerical and climate models, which display a very gradual glacial–interglacial transition. As such, they do not explain the extremely rapid climate transition so clearly visible in Fig. 1 (left and right of the thick dashed line).

These relatively complex climate models also suffer from the familiar weakness from which all general ocean circulation models suffer—the results of simulations involving convection of roughly 10–20 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}) are often too sensitive to the specified vertical eddy diffusivities (roughly 0.5 cm^2 s^{-1}), which are typically an order of magnitude higher than the observed values (0.1 cm^2 s^{-1}; see Bryan 1987). This is not a trivial matter considering that the commonly used numerical diffusivity of 0.5 cm^2 s^{-1} is associated with a conversion of as much as 10 Sv of upper-ocean water to lower-layer water or vice versa. (This scaling estimate is based on a thermocline 500 m deep and an Atlantic surface area of 5000 km × 20 000 km.) Even though attempts are being made to overcome these difficulties using nonuniform diffusivities, the issue is very troublesome, particularly for simulations involving flows through straits and passages. This is so because the transport in many passages is of the order of 1 Sv, much smaller than the (excess) diffusion-induced transport. As a result, several numerical simulations predict flows (through straits) that are not even in the same direction as the observations (e.g., Nof and Van Gorder 2003).

Here, we present a simple analytical model related to the opening of the Bering Strait (BS) during the onset of the Holocene. We shall show that an open BS acts as an open exhaust valve, allowing the flushing of anomalies out of the Atlantic. The analytics will be followed by process-oriented numerical simulations (using the primitive equations). We shall see that the model provides a compelling new explanation for the difference between the climate stability during glacials and interglacials, and that it can explain the abrupt transition between the two regimes if (as argued below) the onset of the flow through the Bering Strait occurred suddenly. The change in stability will be related to our new Atlantic flushing mechanism whereas the sudden onset of the flow will be attributed to the initial jamming of the

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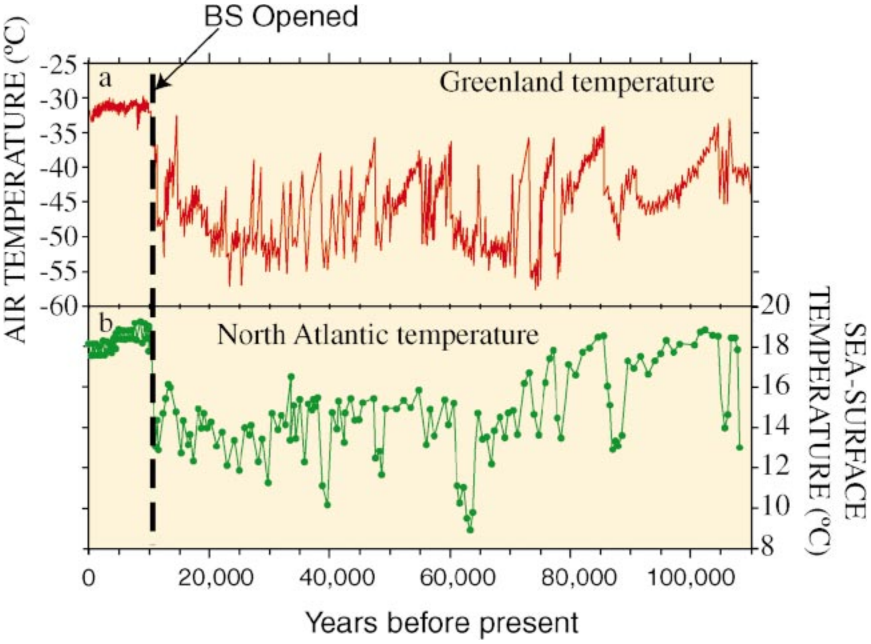


FIG. 1. Temperature record of Greenland and the North Atlantic [adapted from Bard (2002)]. Prior to the opening of the BS, large ice sheets and their induced albedo kept the mean temperature lower than it is today. The occurrence of high-amplitude rapid oscillations decreased abruptly immediately after the opening of the BS, 10.4 kyr B.P. (shown with the thick dashed line). We argue that, although the MOC recovers from a freshwater-induced collapse in both the open and closed BS cases, the recovery in the open BS case is much quicker than that in the closed case. This is related to our proposed BS flushing mechanism, which explains the very small fluctuations during the last 10 000 yr, compared to the large fluctuations in the period prior to that.

BS by icebergs and sea ice. Our model will clearly point to the physical processes responsible for the process—the strong southern winds (SW) and the geography of the American continent and the Atlantic Ocean.

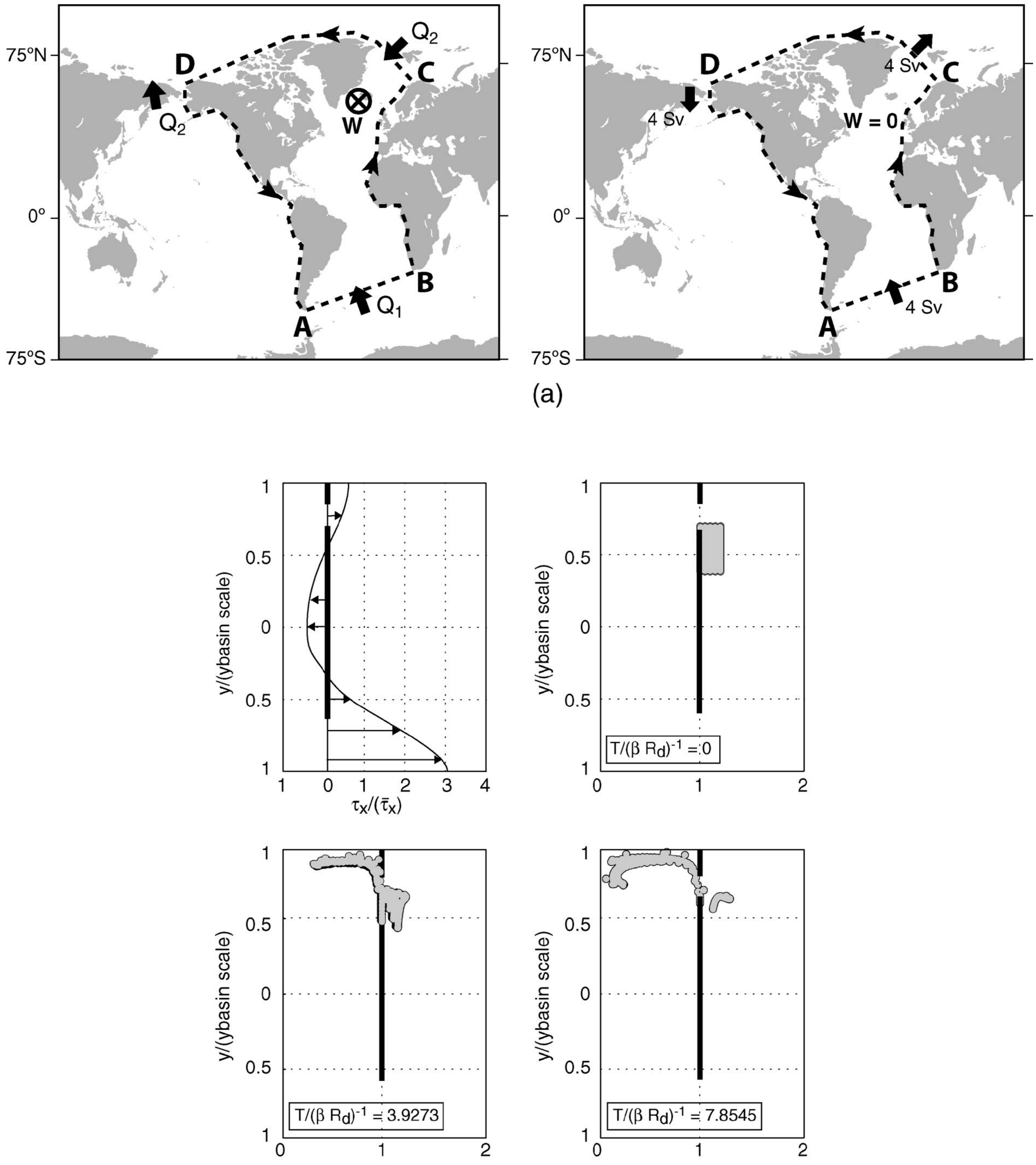
2. The Bering Strait as an exhaust valve

Since the last glacial maximum (LGM), the global sea level has risen by 130 m. The BS, being presently only 45 m deep, opened up to flow around 10.4 kyr before present (B.P.), which is coincident with the onset of the stable Holocene. We suggest that this opening took place abruptly (relative to the slow sea level rise) due to an initial jamming of the strait by icebergs and sea ice. We suppose that such a jamming resulted from the funnel-like shape of the surrounding continents. It persisted until the sea level difference between the Arctic and Pacific rose to a level high enough to break the ‘‘dam.’’ Such a scenario is not unusual. It has been argued that Lake Agassiz was dammed in a similar fashion and that icebergs also jammed the Denmark Straits (Van Kreveld et al. 2000). Unfortunately, because of the shallowness of the modern BS and because of the currents associated with it, it is unlikely that any iceberg-generated scouring can still be identified on the bottom.

Ocean general circulation model (OGCM) studies indicate that NADW formation is reduced by the buoyancy provided by the BS throughflow (e.g., Wadley and Bigg 2002; Weijer et al. 2001; Reason and Power 1994). In line with this idea, Shaffer and Bendtsen (1994) employed a three-box model with a geostrophically controlled density-driven BS flow to show that the overturning could be arrested by the freshwater flux. Here, a strikingly different mechanism, which considers the global ocean and the dynamical role of the open BS in the general oceanic circulation (rather than merely the buoyancy effect of an open BS) is proposed.

We consider the Americas to be a gigantic island (when the BS is open) and, as in Nof (2000, 2002), we apply an extension of the ‘‘island rule’’ (Godfrey 1989), which takes the NADW into account. The essence of the approach is that by (horizontally) integrating the (vertically integrated) equations of motion along a *closed* contour, which does not pass through any frictional western boundary currents, the pressure term drops out and, as a result, one obtains a direct connection between the transports and the wind stress. Using the contour shown in Fig. 2a, we show that, in the absence of NADW formation, the strong winds in the southern boundary of the Atlantic Ocean would push about 4 Sv into the South Atlantic (SA) and then out of the North Atlantic (NA) into the Arctic, and then the Pacific.

In view of this, any salinity anomalies in the NA that are strong enough to completely collapse the meridional



(a)

(b)

Fig. 2. (a) At left, the general flow pattern and the integration path around the Americas and the Atlantic (black dashed line) for the case of a convective Atlantic, where $Q_{1,2}$ are the transports into the Atlantic from the south and north, respectively, and W is the convection (indicated by $\otimes$). At right, the flow pattern in the no-convection case ($W \equiv 0$). (b) ''Reduced gravity'' numerical experiments showing how a freshwater anomaly (shaded region), which is strong enough to shut off the NADW, is flushed out of the Atlantic within a short time. The island in the center represents the Americas and the northern gap represents the BS. The shown experiment does not involve a sill, but experiments with a sill (protruding up to 50 m from the free surface) show very similar results with deviations of less than 40% from the no-sill values. The upper layer has one density and the anomaly is represented by dyed fluid. Even though the thermodynamics and the NADW shut off are not explicitly present here, their absence has no bearing on the issue at hand, because this single-layer model accurately reflects relation (1), which does contain the thermodynamics. The wind profile reflecting the relatively weak (strong) winds in the northern (southern) Atlantic is shown in the upper-left panel. The numerical parameters are the same as those given in Nof and Van Gorder (2003). The nondimensional time ($T/\beta R_d$, where T is the dimensional time and R_d is the Rossby radius) is given in the left corner of each panel.

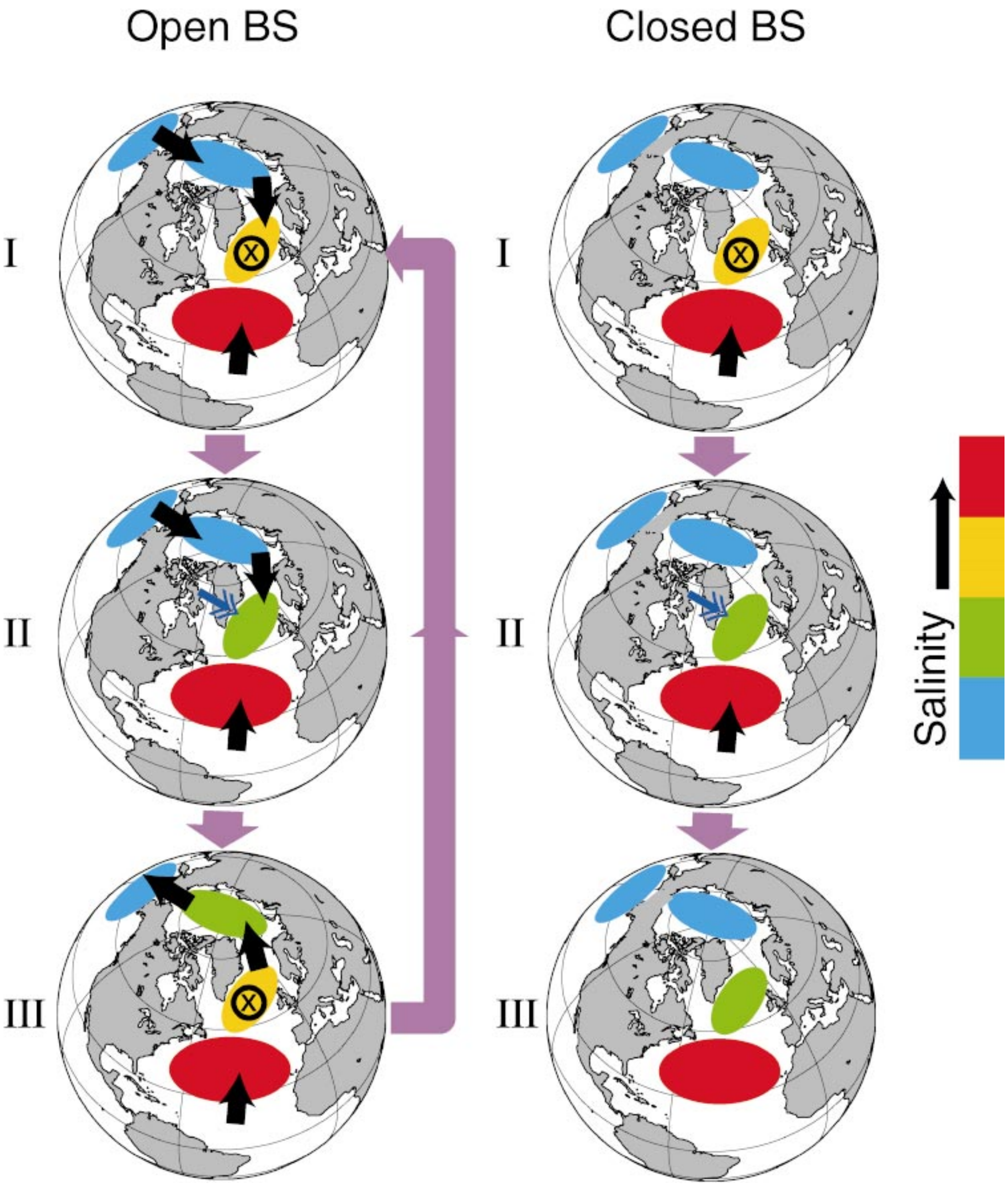


FIG. 3. The response of the MOC to a large NA freshwater anomaly in the (left) open BS case and (right) closed BS geometry. The colors blue, green, yellow, and red represent increasing salinity (in that order). NADW formation is indicated with $\otimes$. Black arrows show the direction of flow and the blue double-headed arrows represent anomalous freshwater discharge. When the BS is open and the NADW is active, a mix of fresh Pacific and salty SA water sinks in the NA (I). A hypothetical freshwater anomaly (e.g., ice sheet discharge) renders the NA too fresh for deep convection (II). Our calculation implies that, under such conditions, the southern winds would flush the anomaly out of the NA and into the Pacific (III). Hence, the MOC recovers quickly [*O*(10 yr)] and returns to the original steady state (I). On the other hand, when the BS is closed, a hypothetical freshwater anomaly (from an ice sheet), which freshens the NA to a degree that it is too fresh for deep convection (II), is trapped in the NA and cannot be flushed out (III). Under such conditions, the MOC can still recover, but much more slowly (hundreds or thousands of years).

overturning cell (MOC) would be quickly (within the horizontal advection time scale, which is several years) flushed out of the Atlantic via the open BS so that the MOC will quickly recover (Fig. 3). On the other hand, when the BS is closed, the anomalies are trapped in the Atlantic and cannot be flushed out. The MOC can still recover (e.g., Schmittner et al. 2002; Bard 2002), but much more slowly than in the open BS case. Although not shown here (due to space limitations), small freshwater perturbations, which are not sufficient to shut down the NADW completely, are also quickly flushed out with an open BS (de Boer 2003). We argue that it is because of this flushing that the perturbations to the temperature field are *large* prior to the opening of the BS and *small* after the opening (Fig. 1).

In our analytical model, we take not only the sea level to be continuous across the BS (Fig. 2a), but the entire vertically integrated pressure is also taken to be continuous (even though there can be a pressure exerted on the BS sill). This assumption can be relaxed without altering the fundamental results and our numerical simulations will show that the BS sill does not alter the results significantly. This, as well as other related issues, cannot be presented here in detail (due to space limitations) and, therefore, reference is made to de Boer and Nof (2003, manuscript submitted to *Deep-Sea Res.*) where all of the needed clarifications are presented in detail. The southern flow into the Atlantic, Q_1, differs from the Pacific inflow, Q_2, by the amount of sinking within the Atlantic, W. Note that W is not a free parameter, but rather is a function of the surface fluxes, geography, and wind field. Following Nof (2000, 2002) we find that these are

$$Q_1 = \frac{\oint \tau^r \, dr + p f_2 W}{\rho(f_2 - f_1)}, \qquad Q_2 = \frac{\oint \tau^r \, dr + p f_1 W}{\rho(f_2 - f_1)}, \tag{1}$$

where $\oint \tau^r \, dr$ is the counterclockwise-integrated wind stress along the path shown in Fig. 2a, ρ is the oceanic density, and $f_{1,2}$ are the average Coriolis parameters at the southern and northern ends of the Atlantic, respectively (i.e., sections AB and CD). Both Q_1 and Q_2 are positive toward the Atlantic and represent water from the surface to a depth above the topography. It is important to realize that (1) contains both wind and thermohaline processes.

Integration of 40 yr of National Centers for Environmental Prediction (NCEP) annual winds along the path shown in Fig. 2a gives 4 Sv for the first term in Eq. (1) [i.e., $\oint \tau^\tau \, dr/\rho(f_2 - f_1)$, where f_1 and f_2 are the Coriolis parameters at 45°S and 75°N, respectively]. This 4 Sv is the amount that, in the absence of NADW (i.e., $W = 0$ and $Q_2 = -Q_1$), would be forced into the SA (Q_1) and out of the NA ($-Q_2$). This situation is shown in the right-hand panel of Fig. 2a. Because the winds over the Arctic and NA are relatively weak, 60% of the 4 Sv is due to the strong SA winds, that is, 60% of the wind stress contribution to the integral comes from the integration along section AB (Fig. 2). (Note that we have made the plausible assumption here that the wind field has not changed much during the last 12 000 yr.) With the present (nonzero) rate of NADW formation, Q_2 is almost 1 Sv (into the Atlantic) so that $W = 11$ Sv and $Q_1 = 10$ Sv. This situation is shown in the left-hand panel of Fig. 2a. Note that, as discussed in Nof (2000), two-thirds of the Agulhas rings contribution to the MOC is neglected here (because of our linearization). This amounts to a neglect of several Sverdups in our calculation.

These considerations show that, in the absence of NADW formation (due to a strong freshwater anomaly), there is a reversal of the flow through the BS; that is, without NADW, the flow is from the Arctic to the Pacific rather than the other way around. This is supported by our own process-oriented numerical simulations (Fig. 3b) employing the primitive equations without vertical eddy diffusivity. The ‘‘reduced gravity’’ model is only subject to wind forcing because we consider here the case of no NADW. The thin island represents the Americas and, as in the real world, the winds in the south are stronger than the winds in the north. Because of this asymmetry of the wind field, the flow around the island is counterclockwise, implying a flow reversal through the BS (during NADW shut-off periods). This flow reversal was also noted in more complicated primitive equation models (Schiller et al. 1997). Furthermore, although there is no direct observational evidence for this flow reversal during a NADW shutdown, isotopic records of the northern Pacific strongly suggest that, in the early Holocene, North Pacific waters were freshened by flows from the Arctic Ocean (Gorbarenko 1996).

3. Discussion and summary

As mentioned, it is argued that our open BS flushing recovery time (several years) is much faster than the closed BS recovery time, which is tens or hundreds of years (Stocker 2000; Schmittner et al. 2002; Van Kreveld et al. 2000). The latter is primarily due to diffusion (which gradually dissipates the freshwater anomaly), evaporation (which ultimately eliminates the anomaly), sea ice (which, through brine rejection, increases the salinity), strengthening of the local winds [which causes local upwelling, which, in turn, increases the surface salinity reducing the density difference that the cooling needs to overcome (Schiller et al. 1997)], and the cooling of the atmosphere due to a collapsed MOC and a reduction in the northward oceanic heat transport (Saravanan and McWilliams 1995). All of these recovery processes are considerably longer than our open-valve rapid-flushing mechanism.

In conclusion, an open BS acts like an open exhaust valve and allows the use of an integral constraint that links the flow through the BS to deep water formation in the NA. The interplay between the strength of the global winds and thermohaline-induced overturning act to stabilize (rather than destabilize) the climate.

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