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 during interglacials. With the aid of a semi-global analytical model, we propose that the Bering Strait (BS) acts like an exhaust valve for the above NA freshwater anomalies. Specifically, we suggest 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 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 that all general ocean circulation models suffer from – the results of simulations involving convection of roughly 10–20 Sv (1 Sv = 10^6 m^3s^{-1}) are often too sensitive to the specified vertical eddy diffusivities (roughly 0.5 cm^2s^{-1}) which are typically an order of magnitude higher than the observed values (0.1 cm^2s^{-1}). This is not a trivial matter considering that the commonly used numerical diffusivity of 0.5 cm^2s^{-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 $\times$ 20,000 km.) It is particularly troublesome for simulations involving flows through straits and passages because the transport in many passages is of the order of one Sverdrup, much smaller than the diffusion-induced transport. As a result, several numerical simulations predict flows (through straits) that are not even in the same direction as the observations (Nof and Van Gorder 2003).

Here, we present a simple analytical model related to the opening of the 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 equation). We shall see that the model provides a compelling new explanation for both the difference in the climate stability during glacials and interglacials and the abrupt transition between the two regimes. The former will be related to our new Atlantic flushing mechanism whereas the latter will be attributed to the initial jamming of the BS by icebergs and broken ice sheets. 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), global sea level has risen by 130 m. The BS, being presently only 45 m deep, opened up to flow around 10.4 kyr BP (Before Present) 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 broken ice sheets. We suppose that such a jamming resulted from the funnel-like shape of the surrounding continents and 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. 2000; 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.

Following earlier analyses (Nof 2000, 2002) we use an analytical model which considers the Americas to be a gigantic island (when the BS is open). Using contour integrals, we show that, in the absence of NADW formation, the strong winds in the Southern 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. Hence, any salinity anomalies in the NA which are strong enough to completely collapse the meridional overturning cell (MOC) would be quickly (within several years) flushed out of the Atlantic via the open BS so that the MOC will quickly recover (**Fig. 2**). 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. 3a**), 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. The southern flow into the Atlantic, Q_1, differs from the pacific inflow, Q_2, by the amount of sinking within the Atlantic, W. Following Nof (2000, 2002) we find that these are,

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

where $\oint \tau^{\tau}\, dr$ is the counterclockwise integrated wind stress along the path shown in **Fig. 3a**, 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's are positive towards 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. The wind is included through τ whereas the thermohaline processes are explicitly included through ρ (constant with the Boussinesq approximation) and implicitly through W.

Integration of 40 years of National Centers for Environmental Protection (NCEP) annual winds along the path shown in **Fig. 3a** gives 4 Sv for the first term in equations (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 panel of **Fig. 3a**. Since the winds over the Arctic and NA are relatively weak, 60% of the 4 Sv is due to the strong SW. 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 panel of **Fig. 3a.**

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, i.e., 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 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 (a few or 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.

Although not clearly visible in **Fig. 1**, it has been suggested that during the LGM (when sea level was well below the present BS sill) the climate was also stable (McManus et al. 1999). We argue that this is not necessarily due to the presence of a stabilizing mechanism different from ours. Rather, we believe that it is due to the very cold global temperatures, the resulting low atmosphere moisture levels and the reduced melting and calving. All of these imply much less frequent freshwater perturbations during the LGM which, in turn, imply a relatively stable climate.

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.

4. **Acknowledgments**.

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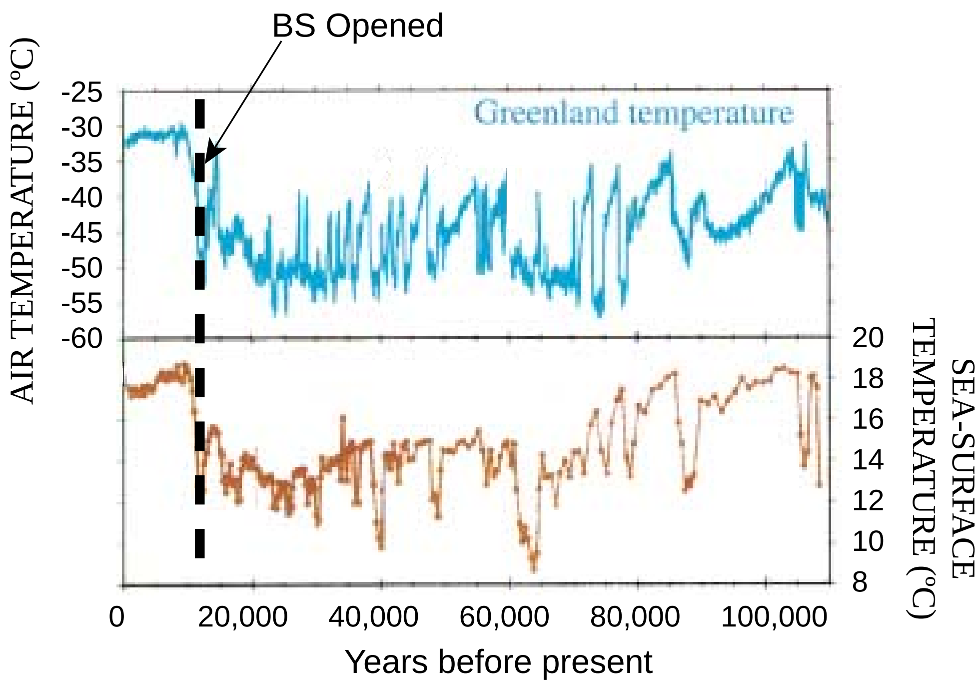


Figure 1: Temperature record of Greenland and the North Atlantic (adapted from Bard 2002). Prior to the opening of the BS (the Atlantic's "exhaust valve"), large ice sheets and their induced albedo kept the mean temperature lower than it is today. The occurrence of high amplitude rapid oscillations decreased *abruptly* immediately after the opening of the BS, 10.4 kyr BP (shown with the thick dashed line). We argue that, although the meridional overturning cell (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 years compared to the *large* fluctuations in the period prior to that.

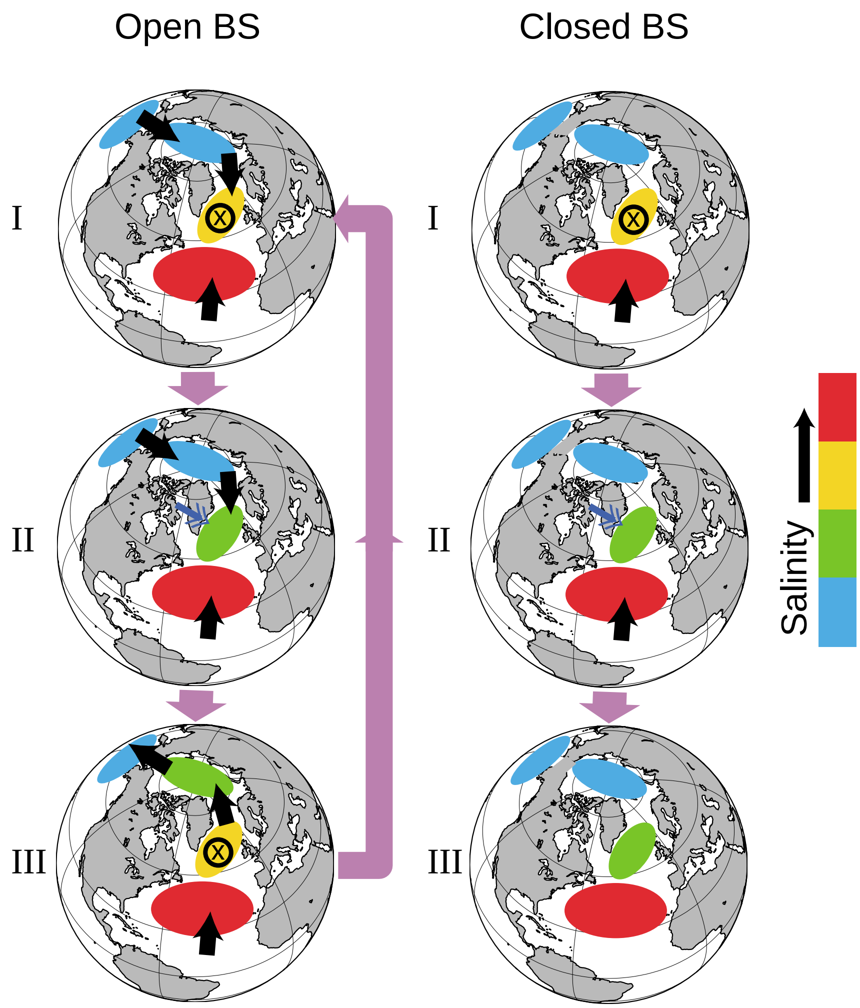
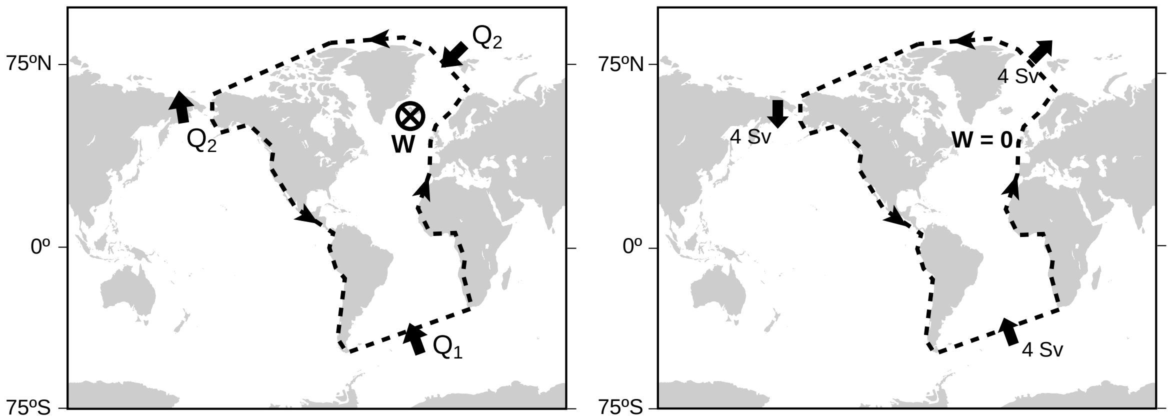


Figure 2: The response of the MOC to a large NA freshwater anomaly in the open BS case (left) and the closed BS geometry (right). The colors blue, green, yellow to red represent increasing salinity (in that order). NADW formation is indicated with ⊗. Black arrows show the direction of flow and the blue 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 years)] 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 stil recover but much more slowly (hundreds or thousands of years).

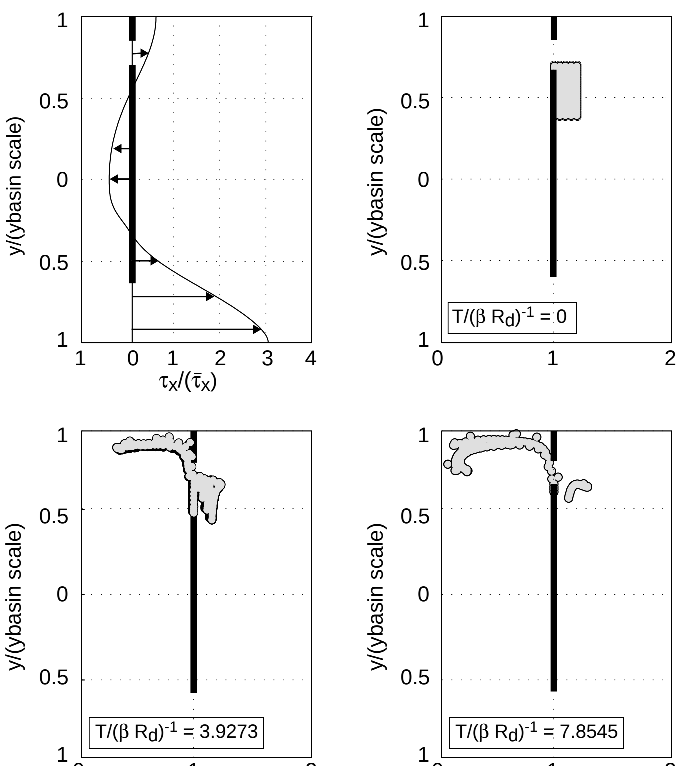
Figure 3. *(a)* Left panel: The flow pattern and the integration path around the Americas and the Atlantic (black dashed line) for the case of a convective Atlantic. Q1,2 are the transports into the Atlantic from the south and north, respectively and W is the convection (indicated by U). Right panel: The flow pattern in the no convection case (W ∫ 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 thermo-dynamics and the NADW shutoff 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).



75ºN
0º
75ºS
Q_2
Q_2
W
Q_1
75ºN
0º
75ºS
4 Sv
4 Sv
W = 0
4 Sv

(a)



y/(ybasin scale)
$\tau_x/(\bar{\tau}_x)$
$T/(\beta R_d)^{-1} = 0$
$T/(\beta R_d)^{-1} = 3.9273$
$T/(\beta R_d)^{-1} = 7.8545$

(b)