Did an open Panama Isthmus correspond to an invasion of Pacific water into the Atlantic?

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Abstract

Recent general circulation simulations suggest that, prior to the closure of the Panama Isthmus (the narrow strip of land connecting North and South America), low salinity Pacific ocean water invaded the Atlantic ocean via the gap between North and South America. According to this scenario, the invasion decreased the Atlantic Ocean salinity to the point where North Atlantic deep-water formation (NADW) was impossible and, consequently, there was no "conveyer belt" to speak of. In line with this scenario, it has been suggested that the closure of the isthmus led to an increased salinity in the Atlantic which, in turn, led to the present-day NADW formation and the familiar meridional overturning cell (MOC).

Using simple dynamical principles, analytical modeling and process-oriented numerical experiments, it is shown that, in the absence of NADW formation, one would expect a flow from the Atlantic to the Pacific Ocean (rather than from the Pacific to the Atlantic) through an open Panama isthmus. An analogous present-day situation is that of the Indonesian Throughflow which brings Pacific water to the Indian Ocean rather than the other way around. "Island rule" calculations clearly show that the direction of the flow in both situations is determined by the wind field to the east of the gaps which imply a westward (rather than an eastward flow) in the gap. Exceptionally strong vertical mixing in the Atlantic (compared to the Pacific) or another means of warm water removal from the upper layer in the Atlantic (e.g., NADW) could reverse the direction of the flow through the open isthmus. However, there is no reason to suspect that, with no deep-water formation in the Atlantic, there was significant upper water removal.

On this basis it is suggested that if low salinity Pacific water did in fact invade the Atlantic Ocean prior to the closure of the Panama Isthmus, then this invasion took place via the Bering Strait rather than through the open Panama Isthmus. It is also suggested that if there were 20 Sv

of NADW formation and the Panama Isthmus were to be suddenly open today, then Pacific water would indeed invade the Atlantic via the Panama Gateway. In turn, this would collapse (or at least reduce) the existing NADW formation rate and thereby cause an ultimate reversal of the flow through the open isthmus. The final outcome would again be a westward flow in the open isthmus.

1. Introduction

Determination of the paleo-circulation in the ocean is important to our understanding of climatic variations. The construction of various numerical models is very useful for this determination as such models help us understand what paleoceanographic data implies. However, these models by themselves cannot provide unequivocal answers to questions brought about by the observations because of the uncertainty in the diffusion and frictional coefficient that must be, explicitly or implicitly, specified in advance. Analytical and process-oriented models of the kind presented here are important supplemental tools for two reasons. First, they do not require the specification of such diffusion and friction coefficients and, second, they provide a clear insight into the processes in question. However, as is frequently the case, most of our scientific issues do not have simple answers and these analytical models have their own flaws and weaknesses. Their main weakness is that they require simplifications in the geometry and forcing. Despite these simplifications, however, they do provide information that would otherwise not be available to us and, hence, should be an integral part of an attempt to understand the paleo-circulation. Here, we present the first attempt to analytically calculate the flow through an open Panama Isthmus. We shall argue that, in the absence of NADW formation, there will be a westward flow of surface water from the Atlantic to the Pacific, much like the present-day flow through the Indonesian Seas.

a. Earlier investigations

Proxy data suggest that it is the emergence of the Panama Isthmus which is responsible for the establishment of the meridional overturning cell (MOC) in the Atlantic as we know it today (see e.g., Berggren and Hollister 1974; Lyle et al. 1995; Burton et al. 1997; Tiedemann and Franz 1997; Haug and Tiedemann 1998; Blankenburg 1999). In line with this, it has been argued that, prior to the closure of the Panama Gateway (which enabled the Pacific and Atlantic to communicate via the equatorial ocean), there was almost no NADW formation.

The first numerical model that attempted to determine the flow through an open Panama Isthmus is that of Maier-Reimer et al. (1990) who used the Hamburg ocean model to show that, with an open isthmus, low salinity Pacific water invades the Atlantic through the Panama Gateway and (by lowering the surface density) inhibits the formation of NADW. Observations suggest, however, that the NADW was initiated *prior* to the *complete* closure of the isthmus and, using a coupled ocean-atmosphere numerical model, Mikolajewicz and Crowley (1997) argue that even a partial opening of the isthmus is sufficient to collapse the NADW cell. The reader is also referred here to Mikolajewicz et al. (1993) for related modeling issues associated with the Drake Passage closure and to Luyendyk et al. (1972) for earlier laboratory experiments on the circulation in the paleocean. Using a coupled ocean-atmosphere model, Huber (2002) has recently argued that, with an open isthmus, the MOC is reduced but is not completely eliminated.

b. Approach

In contrast to the earlier global circulation numerical simulations and the laboratory experiments mentioned above, we shall use analytical techniques and process oriented numerical experiments. Specifically, we shall use the recently discovered and much discussed "island rule" approach (Godfrey 1989) to analytically show that, in the absence of NADW formation, the natural tendency of the system is to establish a westward rather than an eastward flow through an open Panama Isthmus (**Fig. 1**). We shall verify this analytical result using process oriented numerical simulations of a single moving upper layer in two basins separated by an island corresponding to South America.

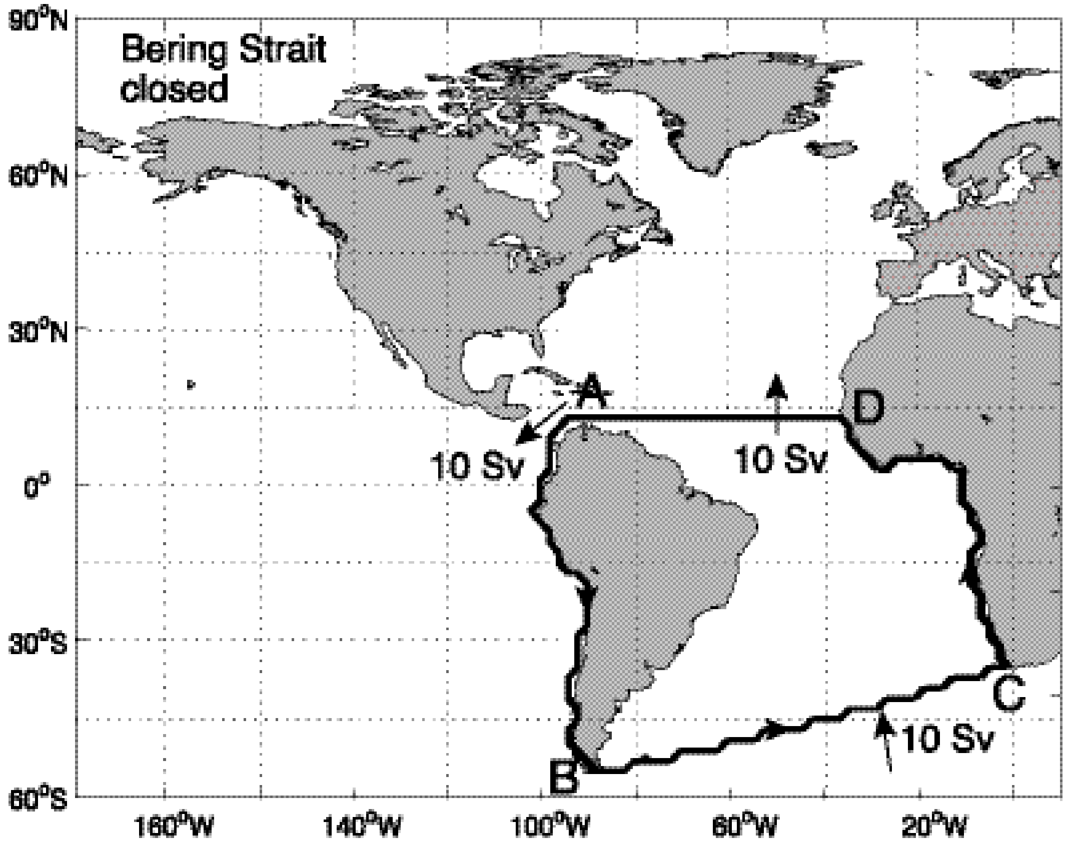

Fig. 1a. *Scenario I:* Open Panama Isthmus, closed Bering Strait, no diapycnal mixing and no NADW in the Atlantic. In this case, 10 Sv are flowing northward in the South Atlantic and exiting the equatorial Atlantic via the open isthmus. This conceptual case is considered merely for a better understanding of the problem. It could, however, be relevant to glaciation periods (closed Bering Strait) prior to the emergence of the Panama Isthmus (i.e., open Panama Gateway). We used the NCEP Reanalysis data for present-day monthly mean wind stress (averaged over 40 years). The integration was done over $2^{\circ} \times 2^{\circ}$ boxes along the chosen path.

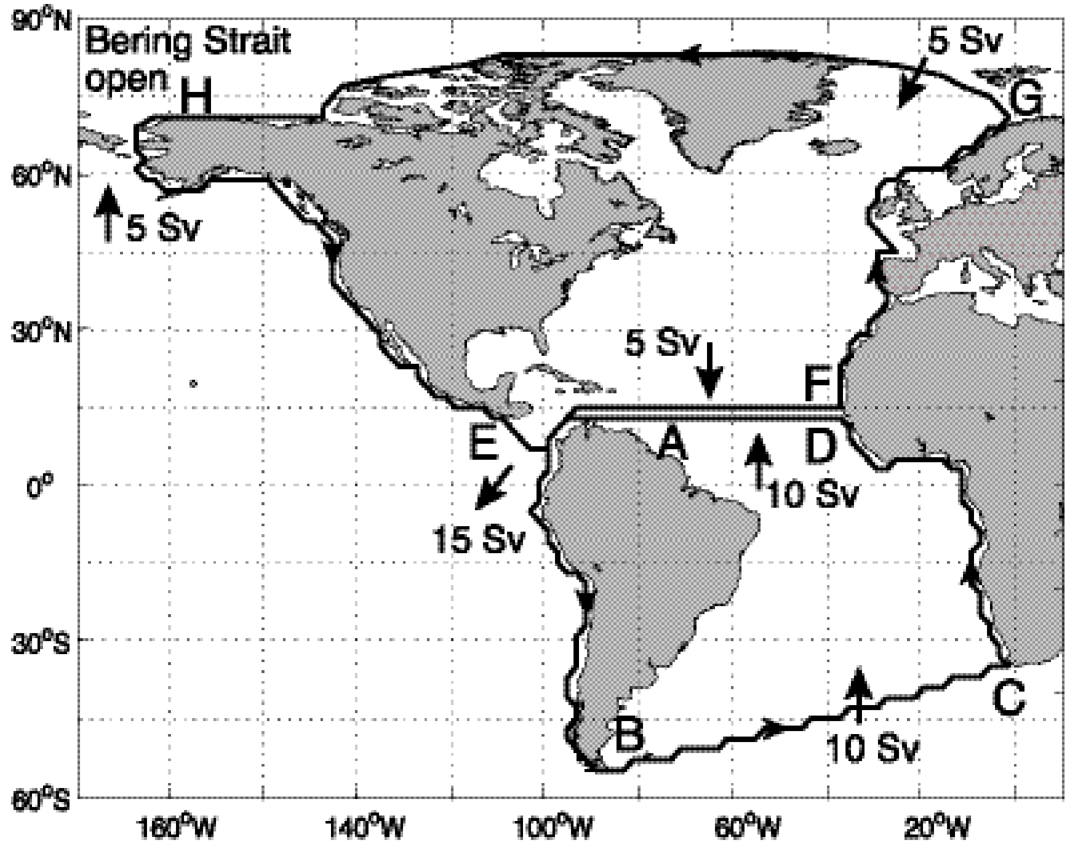

Fig. 1b. *Scenario II:* Open Panama Isthmus, open Bering Strait, no diapycnal mixing and no NADW. In this case, 5 Sv enter the North Atlantic via the Bering Strait so that 15 Sv exit the equatorial Atlantic via the open Panama Isthmus. This conceptual case is supposedly relevant to interglaciation periods (open Bering Strait) prior to the emergence of the Panama Isthmus and is the main result of this work.

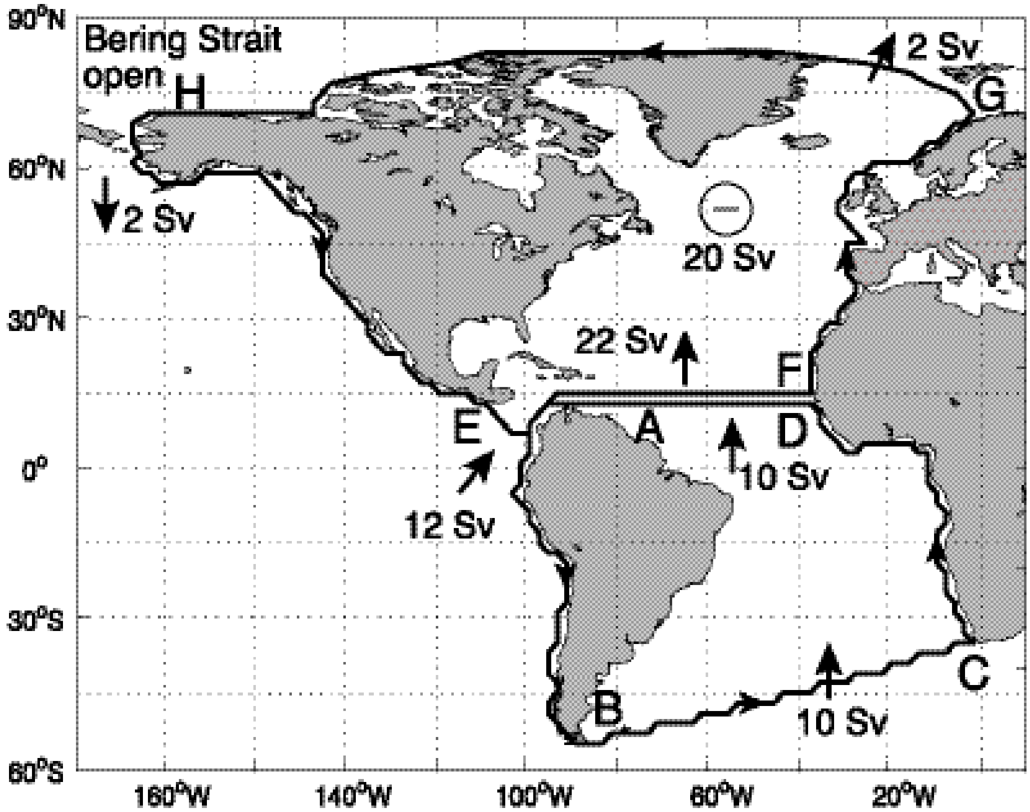

Fig. 1c. *Scenario III:* Open Panama Isthmus, open Bering Strait, and 20 Sv of NADW (specified). Here, 2 Sv leave the North Atlantic to exit through the Bering Strait and 12 Sv enter the equatorial Atlantic via the open Panama Isthmus. As in scenario I, this is a hypothetical case corresponding to what would happen if the Panama Isthmus were to be open today. It is expected that the invasion of Pacific water would reduce the salinity in the Atlantic. With our model (which contains no explicit thermodynamics) it is impossible to say whether this (approximately 1:1) mixture (10 Sv of South Atlantic water and 12 Sv of Pacific water) would be sufficient to prevent the formation of NADW. However, the T-S diagram shown in **Fig. 2** and a linear interpolation suggest that the resulting (1:1) mixture of South Atlantic-Pacific water (dashed line) would not allow NADW formation because cooling of the surface water would reach the freezing point before encountering the bottom water density.

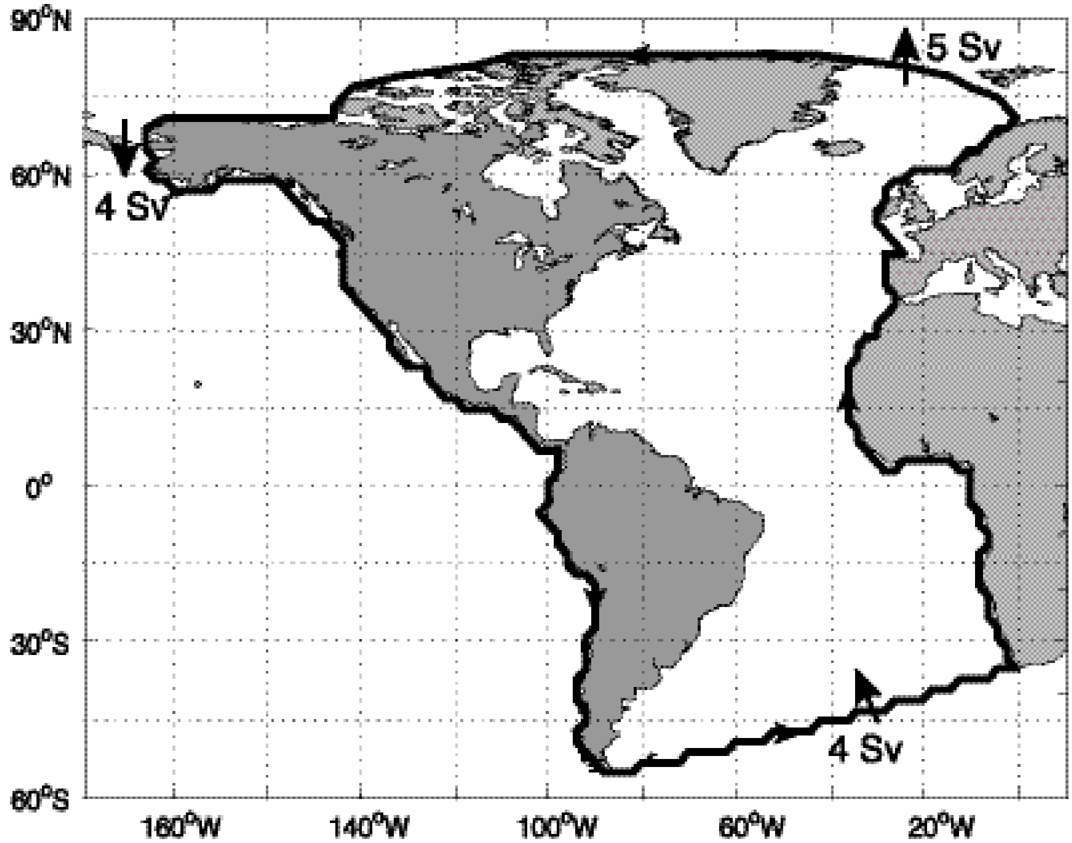

Fig. 1d. *Scenario IV:* Closed Panama gateway, open Bering Strait, no diapycnal mixing and no deep water formation. In this hypothetical case the wind would force 4 Sv in and out of the Atlantic. This scenario was already discussed in Nof (2000) and is presented here merely for completion.

These experiments are followed by a set of experiments that consider the Bering Strait to be either completely or partially open. These experiments are consistent with the idea that if Pacific water did, in fact, invade the Atlantic Ocean prior to the emergence of the Panama Isthmus, then this invasion must have taken place via the Bering Strait rather than the Panama Gateway.

Using specified sources and sinks in the two basins (corresponding to a specified vertical "mixing" or deep water formation, both of which remove upper layer fluid) we shall then show that the direction of the flow through an open isthmus can be reversed (i.e., change from westward to eastward) if there is a relatively large amount (say, 20 Sv) of vertical diffusion or deep water formation in the Atlantic Ocean. On the basis of the above three sets of experiments we shall argue that, without deep water formation or unusually high vertical diffusion in the Atlantic, low latitude Atlantic water would be flowing westward to the Pacific via the Panama Gateway. However, if the Panama Isthmus were to somehow be opened today (when there *is* NADW formation of, say, 20 Sv) then Pacific water would indeed invade the Atlantic via the Panama Gateway. This would quickly (within a few years) shut the NADW formation off due to a reduced salinity. The final outcome of this scenario will again be that the flow through the Panama Gateway would be westward (i.e, from the Atlantic to the Pacific) rather than the other way around.

We shall see later that this last result is sensitive to the choice of NADW formation rate. A choice of 10 Sv instead of 20 Sv would lead to a situation where there is an outflow of 2 Sv from the Atlantic to the Pacific via the Panama Gateway (instead of a 12 Sv inflow) and an inflow of 1 Sv from the Pacific to the Atlantic via the Bering Strait (instead of an outflow of 2 Sv). This would not collapse the reduced NADW formation rate of 10 Sv implying that the effect of opening the gap today may simply imply a reduced NADW formation rate.

Following Nof (2000, 2002), the approach presented here involves integration of the linearized (vertically integrated) momentum equations over the continents and the surrounding ocean. A level of no motion that lies somewhere between 500 and 1500 m is assumed, and the density is allowed to vary in space (i.e., the density of the entire moving layer is allowed to change). The speeds below the level of no motion are negligible (compared to the speeds in the upper layer) but, since the thickness of the nearly stagnant water is very large (say, 4000 m), the transport is not necessarily small (see e.g., Gill and Schumann 1979).

In contrast to the (diagnostic) approach taken in Nof (2000, 2002) where the observation of almost no flow through the Bering Strait entered the calculations and the rate of NADW was solved for, the present calculations take the rate of NADW formation (or its absence) to be known and the flow through the Bering Strait to be unknown. Specifically, for scenario III, we shall specify two extreme NADW formation rates that cover most of the acceptable range. First, we shall specify a relatively high rate of 20 Sv which, with a closed isthmus, correspond to 18 Sv or so entering the South Atlantic and 2 Sv through the conceptual Bering Strait (with a sill). Second, we shall specify 10 Sv of NADW formation which, with a closed isthmus, correspond to 9 Sv entering the South Atlantic and one Sverdrup entering through the Bering Strait.

The model involves two layers: an active continuously stratified upper layer and an inert deep layer. Due to heat exchange and diapycnal mixing, this lower boundary does not necessarily coincide with a particular isopycnal. The lower boundary of the active layer is defined here as the top of the layer whose velocities (but not necessarily the transports) are negligibly small.

c. Limitations

The two main limitations of the above general contour integration approach are the assumption of a level of no motion (which is particularly questionable in high latitudes) and the neglect of the pressure force acting on the Bering Strait sill. We shall take these two issues one by one.

Since the stratification decreases as one goes from the equator to the poles, the level-of-no-motion assumption is becoming less and less justified as one proceeds to high latitudes. The southernmost boundary of our integration contour is deep and appears to be well within the permissible range. On this basis, both Veronis (1973) and Godfrey (1989) have used the level-of-no-motion assumption there and we shall do the same. [Note, however, that further south, within the Antarctic Circumpolar Current (ACC), the assumption is clearly violated. Curiously, for the ACC, Munk and Palmén (1951) suggested that most of the sea-level drop occurs across the three main ridges. However, using satellite data, Gille (1997) argues that, in contrast to Munk and Palmén's analysis (suggesting that much of the form-drag encountered by the ACC is due to the three ridges), the ACC form drag is more evenly distributed with only 15–20% of the drag taken up by each of the three ridges.] Justifying our level-of-no-motion assumption for the northern part of the integration contour (in the vicinity of the Bering Strait) is more difficult [because it is relatively shallow (< 100 m)] but we shall experiment with a sill that occupies as much as 90% of the upper layer thickness and show that the assumption is reasonable for a first-order approximation such as ours. This completes our discussion of the level-of-no-motion assumption.

We shall now briefly discuss the second main limitation, i.e., the neglect of the pressure force acting on the Bering Strait sill. To see that this could potentially be a problem we note that, even if there is no flow through the strait (so that there is obviously no sea-level drop across the strait), there could still be a pressure force exerted on the sill (see Nof 2002). To show that this is not a serious issue we performed a set of numerical experiments (Section 5) with a variable depth sill. We shall see that, although the strait can obviously retard the flow, our results give a reasonable upper bound on the transport through it.

This paper is organized as follows. We begin by introducing the island rule calculation (Section 2) and then the numerical simulations (Sections). The results are discussed and summarized in Section 4.

2. The four scenarios

In this section we apply the island rule to four different scenarios. Fist, we shall apply it to the situation shown in **Fig. 1a** where the Bering Strait is closed and South America is an island (due to the open Panama Isthmus). In this hypothetical scenario (scenario I) both the South and North Atlantic do not contain any NADW or vertical diffusion so that no upper water is removed. We shall show that, under such conditions, 10 Sv are transported northward in the South Atlantic. This 10 Sv then flows westward from the Atlantic to the Pacific. Second (scenario II), we shall apply the island rule to the case where North America is also taken to be an island (**Fig. 1b**). This is a reasonable scenario if we take into account that the strait was open before the uplifting of the Panama Isthmus (e.g., Marinkovich and Gladenkov 1999; Sher 1999) and that there is really no reason for the flow through the Bering Strait to be almost zero as it is today. With a depth of 50 m (during interglaciation) and a width of 150 km the Strait could have easily transferred 10 Sv or more [if the hydraulic capacity were considered (see e.g., Nof 2002)]. The fact that it does not transfer a significant amount of mass is merely a reflection of the manner in which the wind, diapycnal mixing and thermohaline processes are combined today. This does not necessarily have any bearing on what conditions held in the past implying that there could have been much stronger flow through the strait.

Since the proxy data suggest that, prior to the closure of the Panama Isthmus, there was no NADW formation, we shall assume that in this scenario all the water that enters through the Bering Strait must pass through cross-section HG (**Fig. 1b**) and that there is no diapycnal mixing. Since the winds in the northern hemisphere are weaker than those in the southern hemisphere, we find that the southward transport between North America and the eastern boundary is about 5 Sv, so that there is a total westward transport of 15 Sv through the open Panama Isthmus.

Third (scenario III), we shall consider the hypothetical case (**Fig. 1c**) where there is a high rate of NADW formation (20 Sv) and the isthmus is open, i.e., we ask the question of what will happen if the Panama Isthmus were to be suddenly open today. In this case both North and South Americas are taken to be islands but there is now a sink of 20 Sv in the North Atlantic. We shall see that, in this case, there is indeed an invasion of Pacific water into the Atlantic. We find that 12 Sv enters the equatorial Atlantic through the open Panama Isthmus and about 2 Sv exit the Atlantic through the Bering Strait. It is expected that, through a reduction in the salinity (not explicitly present in our model), this invasion will shut the NADW formation off resulting in a transition of the system to the first scenario described above, i.e., to the situation where there is westward flow through the open Panama Isthmus.

Interestingly, this result is very sensitive to the choice of NADW formation rate. A choice of 10 Sv (instead of 20 Sv) would give a very different result of 2 Sv *exiting* the Atlantic via the Panama Gateway and 2 Sv entering the Atlantic via the Bering Strait. We shall see shortly that a 2 Sv inflow of Pacific water would probably not collapse the NADW, which brings us to the conclusion that a formation rate of10 Sv can be sustained even with an open Panama Isthmus.

This sensitivity demonstrates a critical point regarding numerical simulations of multi-layered oceans. Since diapycnal eddy diffusivity is essentially analogous to NADW (both remove or add water to the upper layer), the above results regarding the direction of the flow in the Panama Isthmus are extremely sensitive to the (specified) vertical eddy diffusivity.

Finally, we shall discuss a fourth scenario (scenario IV shown in **Fig. 1d**) where there is no NADW or diapycnal mixing so that all the water forced by the wind into the Atlantic must also leave the Atlantic (via the Bering Strait). This case was already addressed in Nof (2000) and is mentioned here (in passing) merely for completeness.

*a. Scenario I (**Fig. 1a**)*

As mentioned, in this case South America is an island and there is no upper water removal via diapycnal mixing. Integration of the present day wind stress along the contour shown in **Fig. 1a** (which passes along the western boundary of the island) in the same manner as done in Godfrey (1989), and Nof (2000, 2002) gives,

$$T_s = \oint \frac{\tau^l dl}{\rho_0 (f_1 - f_2)} \quad , \tag{2.1}$$

for the vertically integrated upper layer transport (i.e., the transport of all waters above the level of no motion) between the continent (South America) and the eastern boundary of the Atlantic. Here, f_1 and f_2 are the average Coriolis parameters along the northernmost and southernmost boundaries of integration. For clarity, all variables are defined in both the text and in the Appendix. Relation (2.1) implicitly assumes that all waters that enter through BC exit through AD implying that there is no diapycnal mixing in between. Detailed application of (2.1) (which includes the western boundary current, the Ekman transport and the interior geostrophic transport underneath) to the South Atlantic using spherical coordinates as well as actual present-day meridional and zonal winds [adopted from 40 year averages given by the National Centers for Environmental Prediction (NCEP 1999)] gives 10 Sv for the transport of upper water *into* the South Atlantic. Without diapycnal mixing in the entire Atlantic and without NADW, these 10 Sv would be forced westward through the open Panama Isthmus.

*b. Scenario II (**Fig. 1b**)*

Here, both North and South America are islands (i.e., the Bering Strait is also open) and there is no upper water removal (i.e., no diapycnal mixing, and no NADW). In this case (**Fig. 1b**), we apply (2.1) to both South and North America. We find that, since the winds in the Southern Hemisphere are much stronger than those in the Northern Hemisphere, 10 Sv enter the Atlantic from the south but only 5 Sv enter from the north. Both of these amounts must leave via the open isthmus implying that 15 Sv enter the Pacific from the equatorial Atlantic. Since here there is no NADW formation, North Atlantic waters are entirely replaced by North Pacific waters. On the basis of the idea that, prior to the emergence of the isthmus, there was no NADW formation, this situation may correspond to earlier interglaciation periods. It is the main result of our work.

*c. Scenario III (**Fig. 1c**)*

In this case, both North and South America are islands and there is 20 Sv upper water removal from the North Atlantic (**Fig. 1c**). As mentioned, this is a hypothetical situation corresponding to what would happen if the Panama Isthmus were to be suddenly opened today while the high NADW production rate of 20 Sv is somehow (at least initially) maintained. We see that, in this case, 10 Sv enter the North Atlantic from the South Atlantic, 2 Sv exit the Atlantic via the Bering Strait and 12 Sv enter the Atlantic through the open Panama Isthmus.

Examining the T-S diagram of present-day North Atlantic and North Pacific water (**Fig. 2**), we see that, in the Atlantic, convection occurs whenever the surface water (C) is cooled by about 11.5˚C making its density (F) equal to that of the bottom water (D). In the Pacific, on the other hand, convection does not occur because the surface Pacific water (A) cannot be cooled to the density of the bottom water (B) no matter how much cooling is applied. This is because the freezing point (D) is reached before the bottom water density (B) could be reached.

With both the Panama Isthmus and the Bering Strait open, 12 Sv of Pacific water and 10 Sv of South Atlantic water enter the North Atlantic and mix there (**Fig. 1c**). Without detailed (thermohaline and wind driven) modeling of the region (which we really don't know how to do), it is impossible to say for certain what would be the T-S structure of the resulting mixture. However, for simplicity, we can assume that the mixing would be linear in the sense that, for each temperature, the resulting salinity would simply be the average of the two salinities. Given that less than one Sverdrup flows from the Pacific to the Atlantic today so that the present-day Atlantic water can be taken to be nondiluted, we find that the new (approximately) one-to-one Pacific-South Atlantic mixture will correspond to the dashed curve (GH) shown in **Fig. 2**. It is easy to see that, in a similar fashion to the North Pacific water today, such new water cannot be convected because the freezing point is reached prior to reaching the bottom water density. These considerations imply that had the Panama Isthmus been broken today and had the NADW production rate been 20 Sv, then the NADW formation would indeed be terminated due to an invasion of Pacific water. In this context the reader is referred to Shaffer and Bendsten (1994) where a simple three-box model that includes the Bering Strait is considered.

As alluded to earlier, it turns out that the above result is very sensitive to the (specified) rate of NADW formation. A specification of 10 Sv instead of 20 Sv would correspond to 2 Sv exiting the equatorial Atlantic (via the Panama Gateway) and 2 Sv entering the North Atlantic (via the Bering Strait). This situation is very different from that corresponding to the earlier 20 Sv of NADW formation. It is apparent from **Fig. 2** that such a flow structure would probably not alter the NADW production dramatically (though it may slightly decrease it). This demonstrates the extreme sensitivity of multi-layered numerical models to the specified diapycnal mixing which is really no different than the specified NADW formation rate as both processes remove (or add) upper layer water.

d. Scenario IV

In this hypothetical situation the Panama Gateway is closed, the Bering Strait is open, and there is no NADW or diapycnal mixing. This case was already discussed in Nof (2000) and is mentioned here merely for completion. Application of (2.1) to the contour shown in **Fig. 1d** gives 4 Sv for the northward meridional transport that exits the basin through the Bering Strait.

3. Numerical Simulations

Instead of verifying the above general transport formula using very complicated numerical models (corresponding to **Fig. 1**), the application of (2.1) to the models shown in **Figs. 3 and 4**

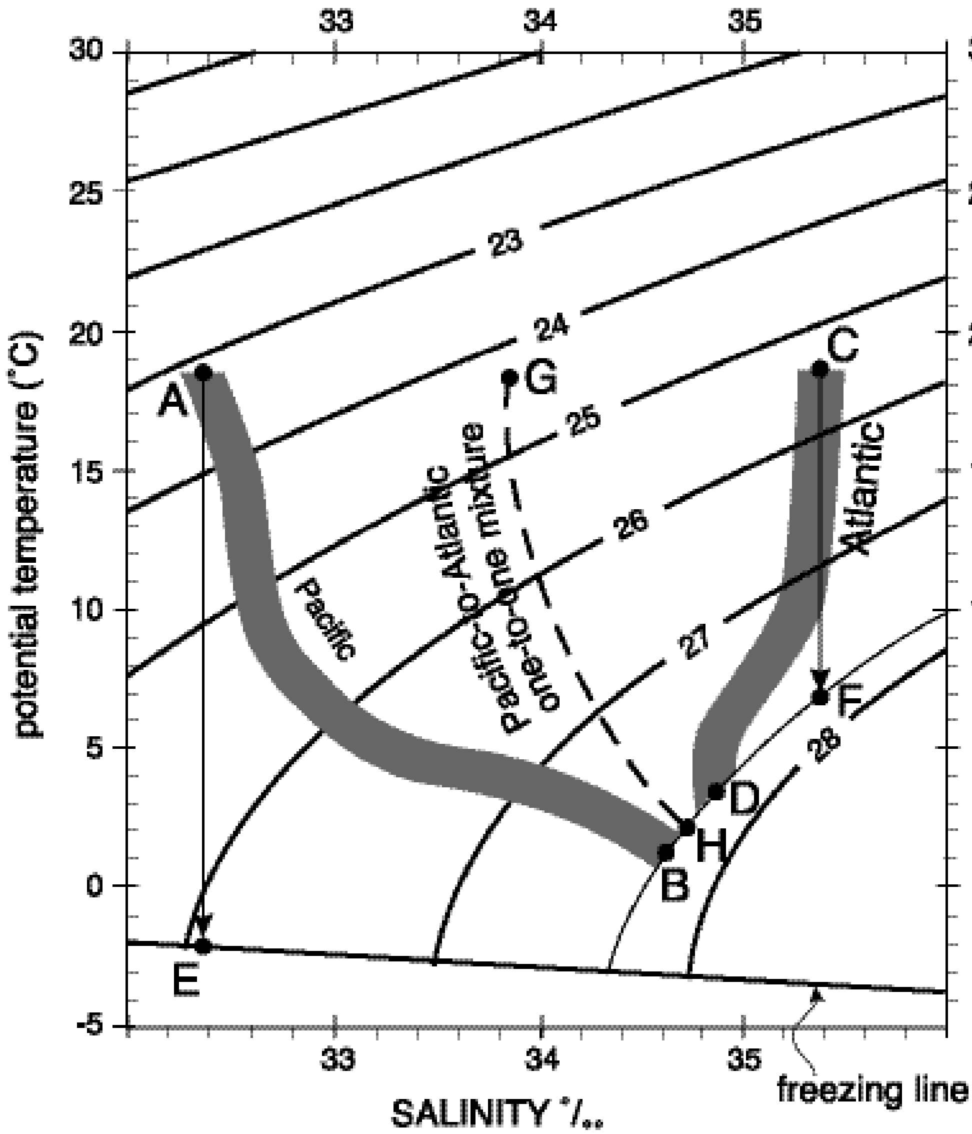

Fig. 2. TS diagram of North Pacific (AB) and North Atlantic (CD) water (all values are from Emery and Dewar 1982) as well as the interpolated water that would be formed in the North Atlantic had the Panama Isthmus been opened today (GH). A comparison of AB and CD vividly shows why there is presently deep water formation in the Atlantic but not in the Pacific. For the Atlantic (CD) a cooling of merely 11.5° is sufficient to form NADW as it brings point C down to F which is of the same density as D. For the Pacific (AB), on the other hand, no cooling is sufficient to make the surface water (A) as dense as the bottom water (B) because the freezing point is reached prior to reaching the necessary density. Scenario III (**Fig. 1c**) corresponds to an approximately 1:1 mixture of Atlantic and Pacific surface water (dashed line). Linear interpolation imples that the resulting surface Atlantic water would correspond to point G. As in the present-day Pacific case, it is impossible to bring this diluted surface water G to the density of the bottom water H because the freezing point is reached prior to reaching the bottom water

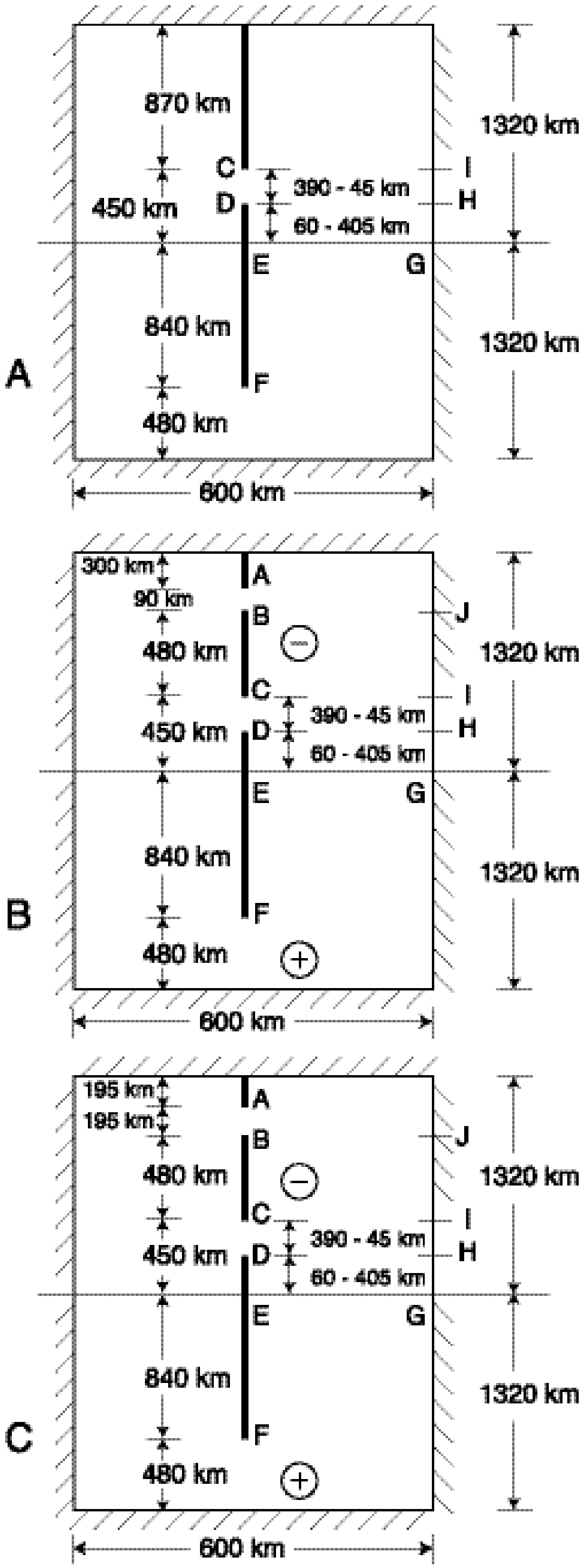

Fig. 3. Details of the basins used for all three sets of experiments (sets A, B and C shown in Table 1). The sources and sinks ⊖, ⊕ were only used in sets BIII and CIII. Note that set C has a sill across the Bering Strait (whereas set B does not). Set A does not contain a Bering Strait. In all experiments $\Delta x = \Delta y = 15$ km, $\Delta t = 360$ s.

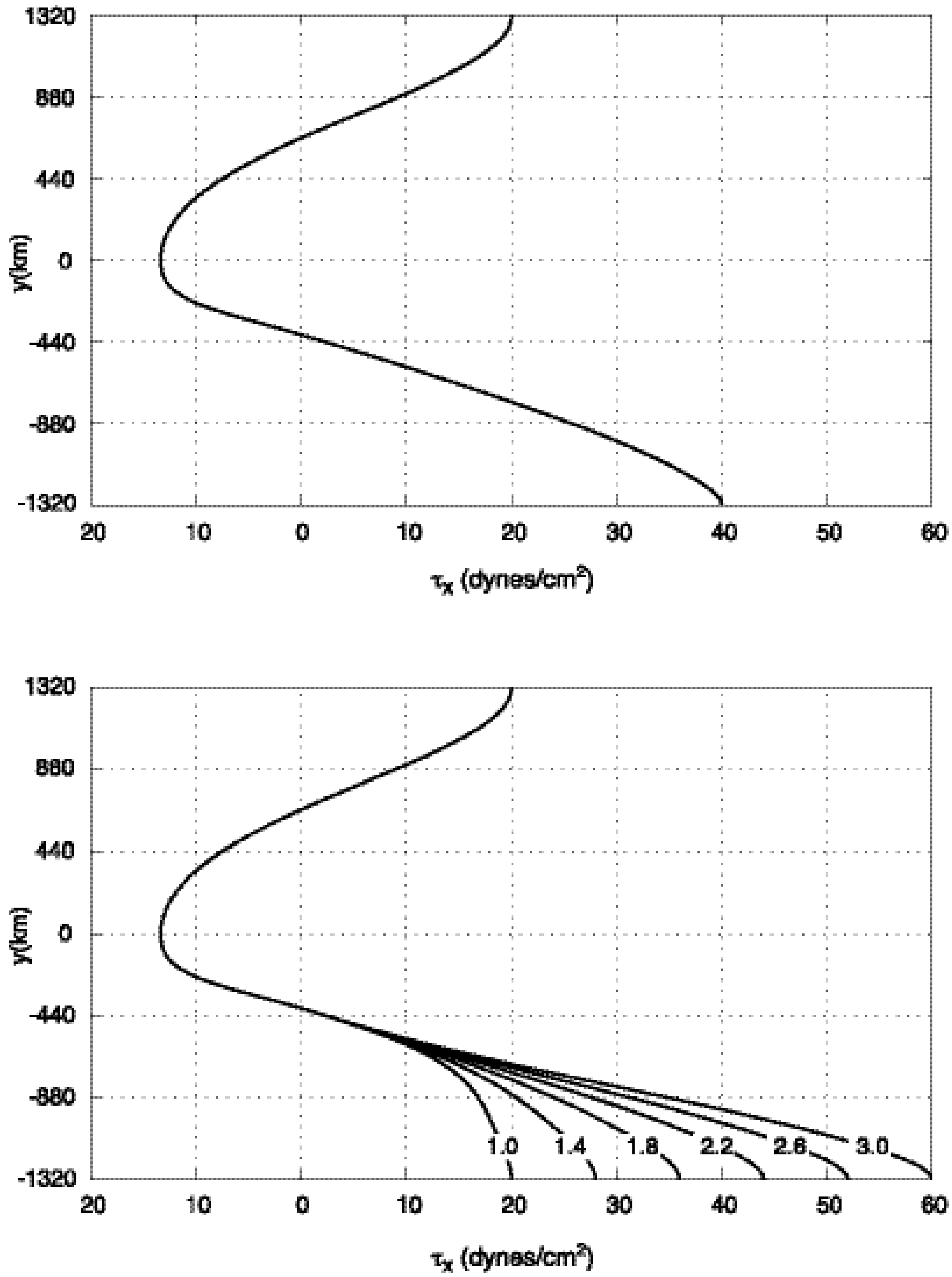

Fig. 4. The magnified (and simplified) zonal wind stress as a function of latitude (adapted from Hellerman and Rosenstein 1983). The upper panel shows the wind profile used for all subsets for which the wind is not varied (sets AI, BI, BIII, CI, CIII, and CIV). The lower panel shows the six wind profiles that were used (AII, BII and CIII). Each profile is labeled with the corresponding southern wind factor shown in Table 1, i.e., the ratio of the wind stress at the southernmost point of the basin to the wind stress at the northernmost point.

(which do not contain meridional winds) was examined. To do so, a "reduced gravity" version of the Bleck and Boudra isopycnic model (Bleck and Boudra 1981, 1986; Bleck and Smith 1990) was used. Namely, we took the upper layer density to be constant in our numerical simulations.

We performed three sets of experiments (sets A, B and C) totaling 51 experiments (Table 1). To examine the relationship between the numerical model and the analytical theory, experiments were initially performed where the gap width was varied for a fixed wind stress (sets AI and BI) and the wind stress (**Fig. 4**) was varied with a fixed gap (sets AII and BII). To examine how NADW formation and/or diapycnal mixing (both of which remove or add water from the upper layer) affect the transports, we also performed experiments with a sink in the North Atlantic (sets BIII and CIII). To verify that the presence of a *sill* across the Bering Strait is not important, we repeated the varying gap, wind, and upper water removal experiments with a sill extending all the way from the bottom to 40 m from the free surface [approximately 7% of the total undisturbed depth of 600 m (sets CI and CII)]. This sill corresponds to the situation associated with the Bering Strait. We also performed experiments with a variable sill depth (set CIV). We shall see that the results of the sill and no-sill experiments were similar but the sill clearly retards the flow.

The sill was implemented by keeping the upper layer depth fixed (at, say, 60 m) within the gap itself and leaving the depth east and west of the gap free. Hence, the presence of the sill enters the momentum equations directly only through the lateral friction terms. (Indirectly, it enters through the speeds and pressure.) Similarly, it directly enters the continuity equation by restricting the volume flux through the gap. (Note that the velocity and pressure adjust each other across the gap.) To represent the meridional transport, a (mass flux) source at the center of the southern boundary and a sink in the northern basin were introduced.

Table 1. A description of the three sets (A, B and C) of numerical experiments (employing a $1^1/_2$-layer version of the Bleck and Boudra model). In set A the Bering Strait is closed and there are two subsets in which we varied the width of the Panama gap and the strength of the Southern Ocean wind, respectively. In set B the Bering Strait is a fully open gap with no sill and we varied the strength of the upper water removal. For set C, the Bering Strait is broader, but now has a sill. Here, β is the linear variation of the Coriolis parameter with latitude (11.5×10^{-11} m^{-1} s^{-1}), g' the reduced gravity (0.15 m^2 s^{-1}), H the undisturbed thickness (600 m), ν the eddy viscosity (2000 m^2 s^{-1}), K the linear drag ($20 \times 10^{-7} s^{-1}$), $\bar{f}$ the average Coriolis parameter in the basin, R_{dg} the radius $[(g'H)^{1/2}/\bar{f}$ = 39.53 Km$]$, T_s the transport used for nondimensionalization $[(g'H^2/2\bar{f})$ = 35.57 Sv$]$, $\Delta x = \Delta y$ = 15 km, and Δt = 360 s.

Set	Description		Exp. No.	Panama Gap width (km)	W/R_{dg}	R_{dg} (km)	#grid cells in Panama gap	Southern wind factor	Upper water removal (Sv)	T/T_s	Sill Depth (m)	D/H	Shown in Fig.	
A	Bering Strait	varying	1	390	3.81	102	26	2	0	0	NA	NA	5	
	closed	Panama	2	315	3.53	89	21							
		gap	3	240	3.04	79	16							
		I	4	165	2.32	71	11							8
			5	90	1.4	64	6							
			6	45	0.74	61	3		0	0				
		varying	7	165	2.32	71	11	1	0	0	NA	NA		
		wind	9					1.4						
		II	8					1.8						
			10					2.2						
			11					2.6						
			12					3						
B	Bering Strait	varying	13	390	3.81	102	26	2	0	0	NA	NA	6	
	fully open	Panama	14	315	3.53	89	21							
		gap	15	240	3.04	79	16							
	6 grid cells	**I**	16	165	2.32	71	11							
	in Bering		17	90	1.4	64	6							
	Strait		18	45	0.74	61	3							
	(90 km);		19	165	2.32	71	11	1	0	0	NA	NA		
	R_{dg} = 26.75	varying	20					1.4						
		wind	21					1.8						
		II	22					2.2						
			23					2.6						
			24					3						
		var.upper	25	165	2.32	71	11	2	0	0	NA	NA		
		water	26						10	0.28				9
		removal	27						20	0.56				
		III	28						30	0.84				
C	sill at	varying	29	390	3.81	102	26	2	0	0	60	0.1	7	
	Bering Strait	Panama	30	315	3.53	89	21							
		gap	31	240	3.04	79	16							
	13 grid cells	**I**	32	165	2.32	71	11							
	in Bering		33	90	1.4	64	6							
	Strait		34	45	0.74	61	3							
	(195 km)		35	165	2.32	71	11	1	0	0	60	0.1		
	R_{dg} = 25.39	varying	36					1.4						
		wind	37					1.8						
		II	38					2.2						
			39					2.6						
			40					3						
		var.upper	41	165	2.32	71	11	2	0	0	60	0.1		10
		water	42						10	0.28				
		removal	43						20	0.56				
		III	44						30	0.84				
		varying	45	165	2.32	71	11	2	0	0	600	1		
		sill depth	46								500	0.83		
		IV	47								400	0.67		
			48								300	0.5		
			49								200	0.33		
			50								100	0.16		
			51								60	0.1		

To make our runs more economical we used a magnified β, a magnified wind stress τ, and a reduced basin size. **Figs. 5 and 6** show the numerical transports and their relationship to the analytics for the varying gap case without a sill, for varying wind and for varying upper water removal (Sets A and B). There is a good agreement of the nonlinear numerical simulations and the analytical computation no matter how narrow the gap is, how strong the wind is or how much upper water is removed. **Fig. 7**, which shows the effects of a sill, displays a fair (but not good) agreement of the analytics with the numerics (Set C). The discrepancy is greatest when the sill protrudes almost all the way to the surface (**Fig. 7**, lower right). As expected, the sill retards the flow through the gap when it occupies more than half of the fluid thickness. Note, however, that a shallow sill does not alter the direction of the flow. The flow patterns of typical experiments are shown in **Figs. 8 and 9**.

4. Summary and discussion

We have presented analytical calculations and process-oriented numerical simulations which examine the idea that there was no (or at least reduced) NADW formation prior to the emergence of the Panama Isthmus due to invasion of low salinity water from the Pacific.

The analysis takes into account that, with a Panama Gateway (i.e., open Isthmus), both the North and South American continents are essentially "islands" so that the flow around them can be analytically calculated with the aid of the "Island Rule." By and large, both the analytical and the numerical calculations show that if there were indeed no NADW formation due to the

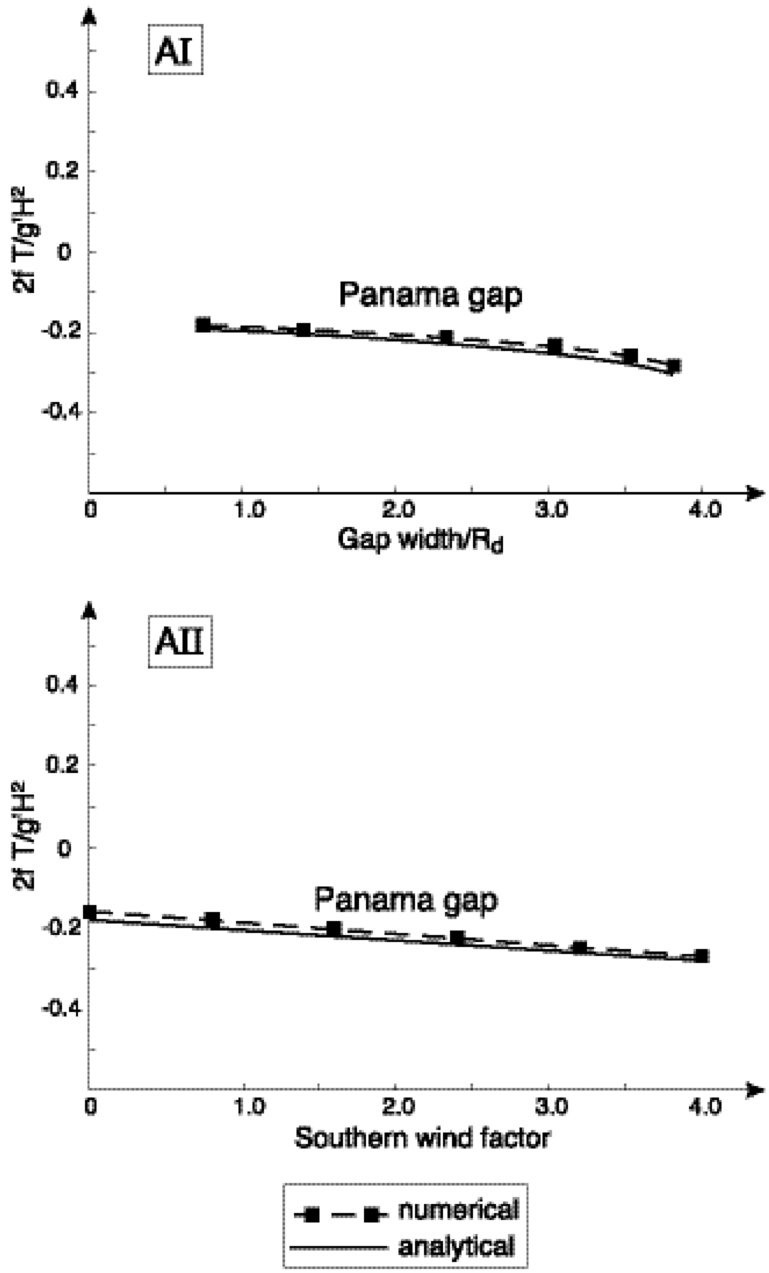

Fig. 5. A comparison of the numerical experiments of set A (Bering Strait closed; see Table 1) to the analytical theory. In the upper panel (set AI, varying Panama gap) the solid line shows the theoretical solution for the nondimensional transport through the Panama gap (CD in **Fig. 3**) as a function of the nondimensional Panama gap width. The gap width is scaled with the local R_d at the gap and the transport with $g'H^2/2f$ (see table 1). The dashed line with squares shows the results of the six numeical experiments. Note that the slight variation of the transport with gap width is because the width is varied by moving the northern tip of the southern island which senses a different wind stress (point D in **Fig. 3**). (Negative transport indicates westward flow.) The lower panel shows the same comparisons for the numerical experiments in set AII (varying wind). The transports are plotted as a function of the southern wind factor, the ratio of the wind stress at the southernmost point of the basin to the wind stress at the northernmost point (see **Fig. 4**).

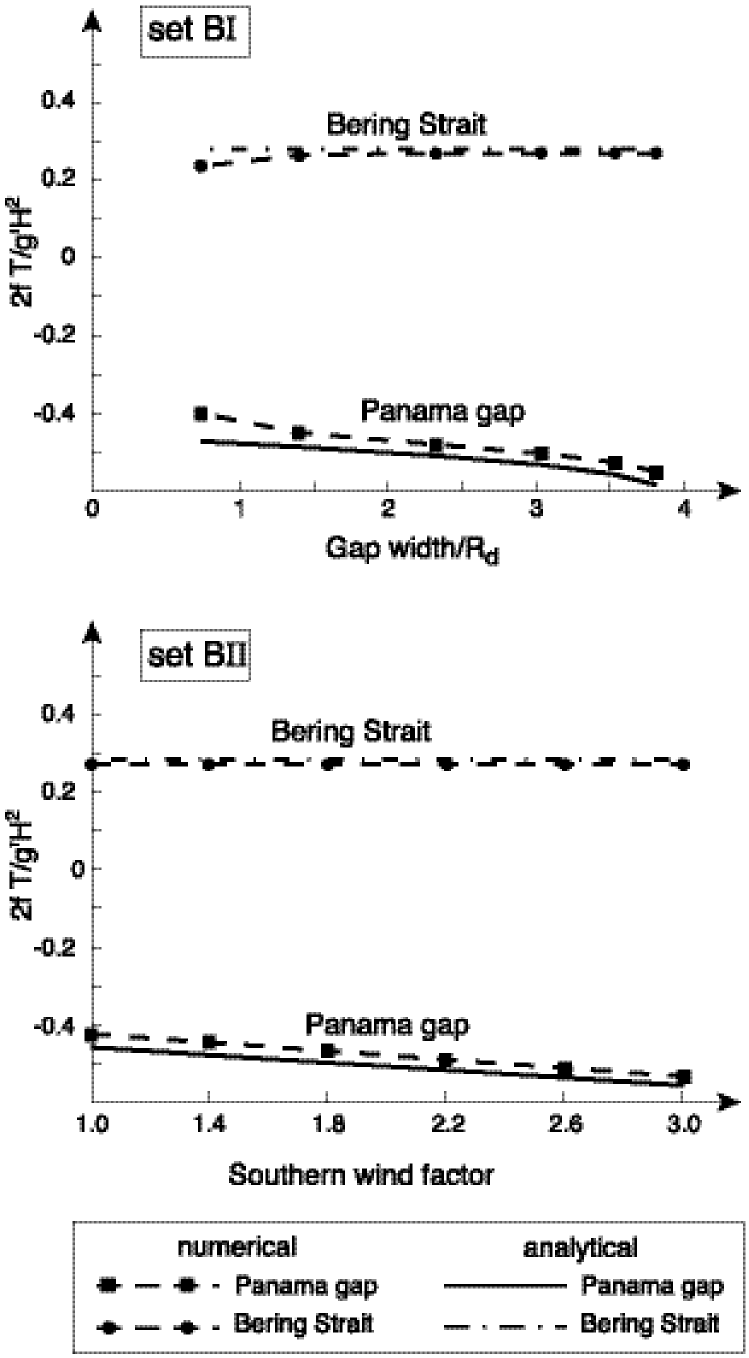

Fig. 6a. As in **Fig. 5**, a comparison of the numerical experiments in set B (Bering Strait fully open; see Table 1) to the analytical theory. In the upper panel (set BI, varying Panama gap) the dashed-dotted line and the dashed line with circles show the analytical and numerical transports, respectively, through the Bering Strait (AB) as a function of the nondimensional Panama gap width (CD). The solid line and the dashed line with squares show the analytical and numerical results for the flow through the Panama gap (CD). The lower panel shows the same comparisons for the numerical experiments in set BII (varying wind) as a function of the Southern wind factor.

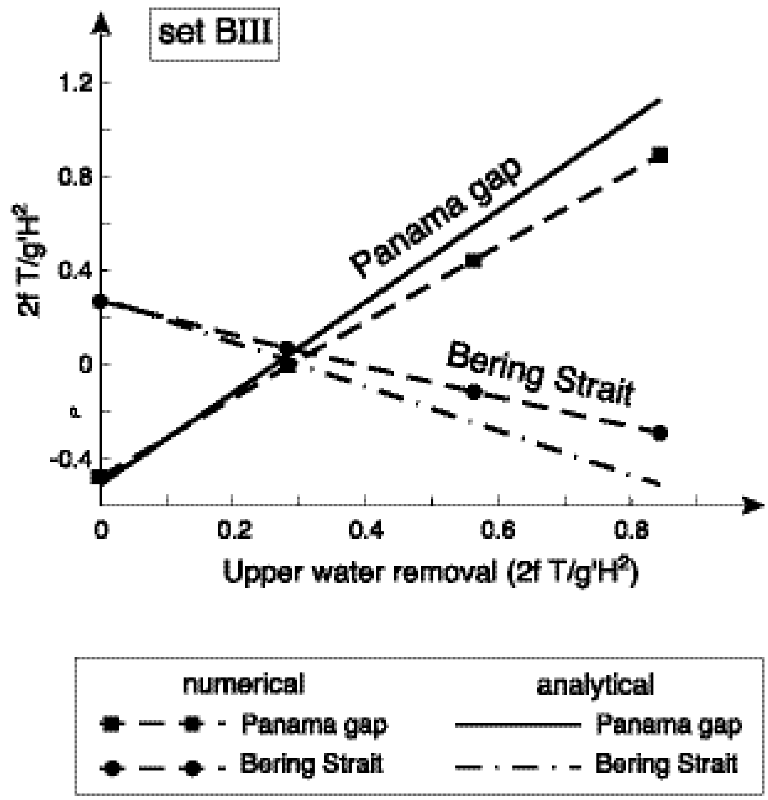

Fig. 6b. The numerical experiments in set BIII (varying upper water removal). These transports are plotted as a function of the nondimensional transport associated with the upper water removal. The solid line is the analytical transport through the Panama gap, and the dashed line with squares is the numerical transport through the Panama gap. The dashed-dotted and dashed line with circles are the analytical and numerical transports through the Bering Strait.

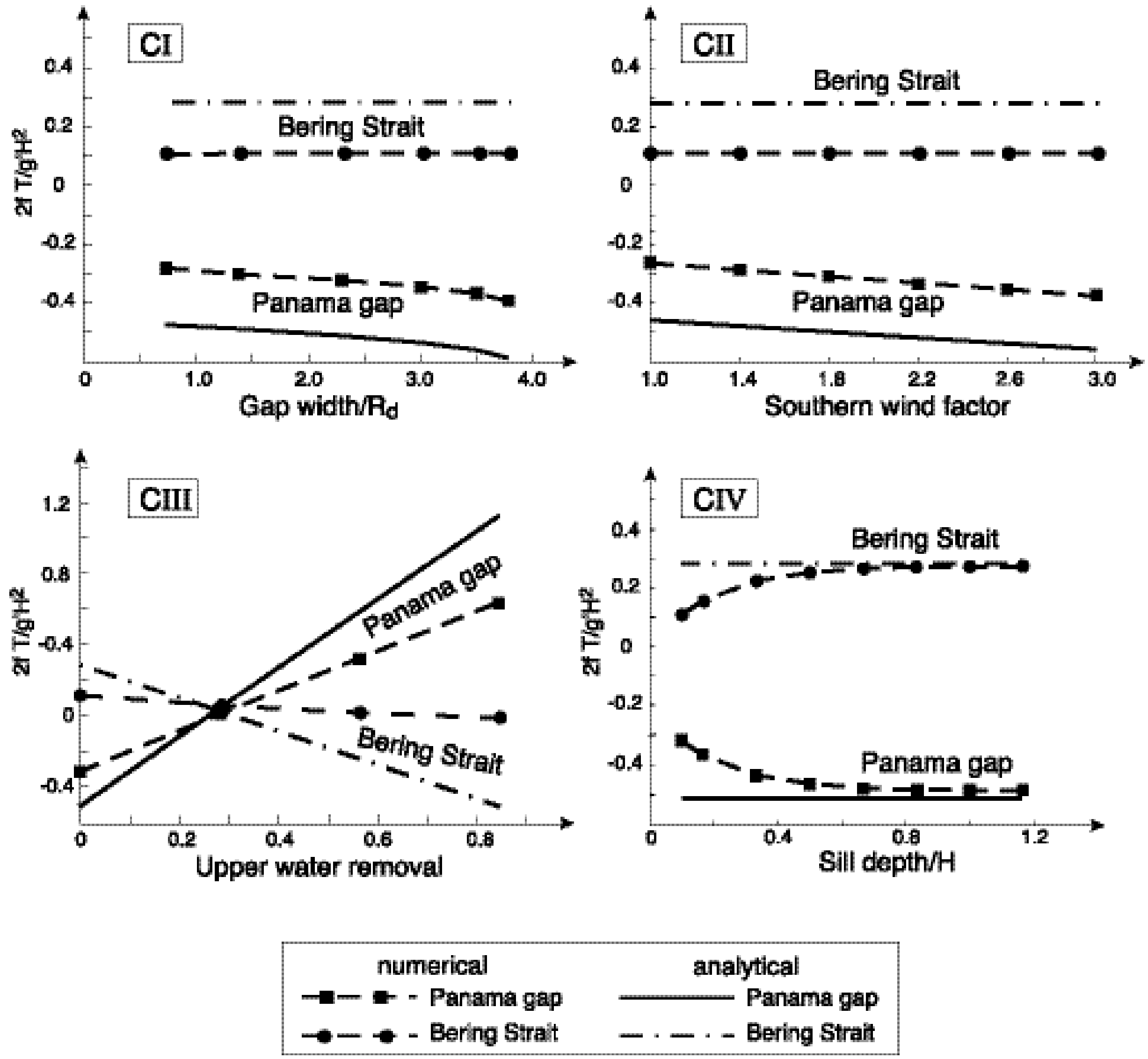

Fig. 7. As in **Figs. 5 and 6**, a comparison of the numerical experiments in set C (sill at Bering Strait; see Table 1) to the analytical (no-sill) theory. In the upper left panel (set CI, varying Panama gap) the dashed-dotted line and the dashed line with circles show the transport through the Bering Strait (AB in **Fig. 3**) as a function of the nondimensional Panama gap width (CD). The solid line and the dashed line with squares show the theoretical and numerical results for the flow through the Panama gap (CD). The upper right panel shows the same comparisons for set CII (varying wind), the lower left for set CIII (varying upper water removal), and the lower right panel for Set CIV (varying sill depth). Note that in all cases the effect of the sill (in the numerical model) is to reduce the magnitude of the flow, but not to change the direction of the flow predicted by the analytical model.

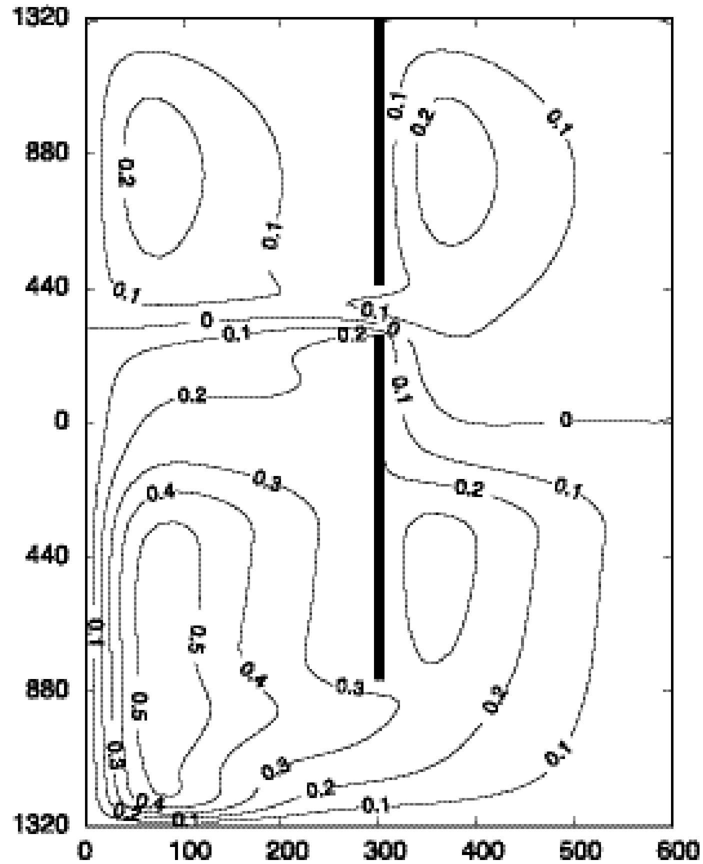

Fig. 8. Typical transport contours for the no-source no-sink experiments of set A (exp. 4). The transport is nondimensionalized with $gH^2/2f$ and the contour interval is 0.1. The nondimensional Panama gap width is 2.32, the southern wind factor is 2 and there is no upper water removal (see Table 1).

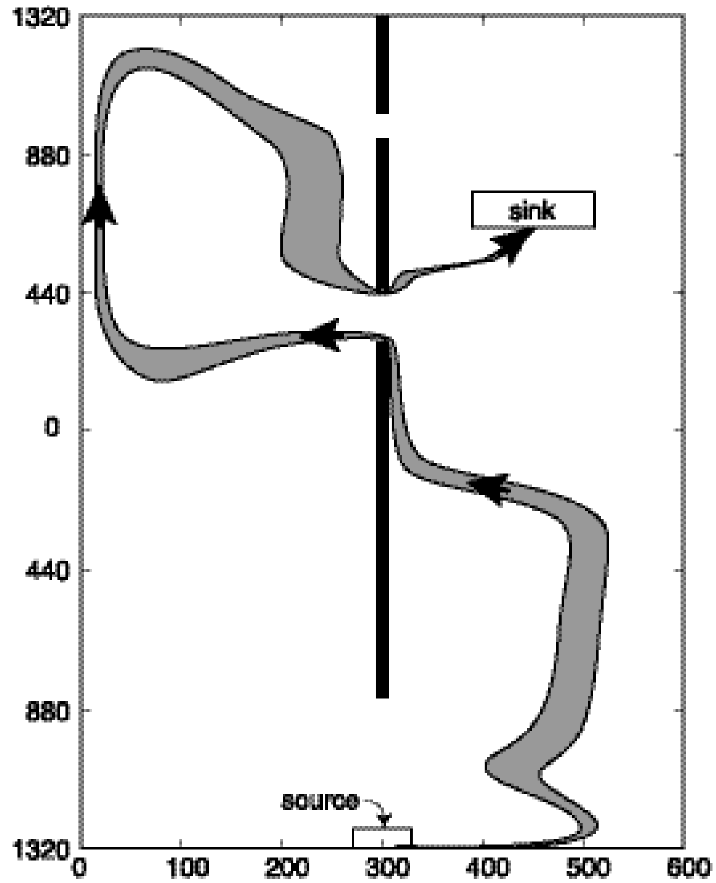

Fig. 9. Typical experiment of set B (exp. 26) showing the core of the flow. The nondimensional Panama gap width is 2.32, the Southern wind factor is 2 and the nondimensional upper water downwelling transport is .28 (see Table 1).

invasion of low salinity water from the Pacific Ocean, then the invasion must have taken place via the Bering Strait rather than the Panama Gateway. This is demonstrated with the aid of three different scenarios (**Figs. 1a,b, and c**).

In the first scenario (**Fig. 1a**) we merely show that without NADW (and diapycnal mixing) and a closed Bering Strait (i.e., glaciation period), 10 Sv would flow out of the Atlantic (via the open Isthmus), i.e., there is no invasion of Pacific water. The second scenario (**Fig. 1b**) is essentially the same as the first except that the Bering Strait is now open (i.e., the situation corresponds to interglaciation). In this case, there is indeed an invasion of 5 Sv but, as just mentioned, it takes place via the Bering Strait rather than the open Panama Isthmus. We then considered a third scenario (**Fig. 1c**) which is essentially the same as the second scenario except that we added 20 Sv of NADW. In this case, an invasion can indeed take place via the open isthmus. However, as this invasion would collapse the NADW, the eastward flow in the Panama Gateway could not be sustained.

a. Results

Overall, we can say that how much of an invasion took place and where has it originated (Bering Strait or Panama Gateway) depends on whether or not there was NADW in the Atlantic and how strong was it. Without NADW and any upper water removed (Scenario II, **Fig. 1b**), 5 Sv of Pacific water would enter the North Atlantic via a sill-free Bering Strait and exit via the Panama Gateway. With a sill occupying as much as 90% of the water column this amount would be reduced by a factor of three (but not ten, see **Fig. 7**, lower right).

With 20 Sv of upper water removal in the Atlantic (due to NADW), 2 Sv would exit the Atlantic via a sill-free Bering Strait and 12 Sv would invade the Atlantic via the open Panama Gateway (Scenario III, **Fig. 1c**). This situation corresponds to a hypothetical situation associated with an opening of the isthmus today. In this scenario the water in the North Atlantic would consist of an (approximately) one-to-one mixture of Pacific and South Atlantic water as the 20 Sv sinking in the North Atlantic would contain 10 Sv of South Atlantic water and 12 Sv of Pacific water. (Two Sv doesn't sink, but exits through the Bering Strait.)

The T-S diagram for present-day Pacific and present-day Atlantic water (**Fig. 2**) suggest that such a mixture would not convect because, just as with the present-day Pacific water, cooling of the surface water would cause the water to freeze before it could reach a density high enough for convection (see the dashed curve in **Fig. 2**). In this scenario, the inclusion of a sill would not make a large difference as much more water passes through the Panama Gateway than through the Bering Strait. Regardless of the presence of a sill, the 20 NADW cell would collapse.

Repetition of the above analysis with a 10 Sv of NADW formation rate instead of 20 Sv gives an entirely different result. In this case, 2 Sv would exit the Atlantic via the Panama Gateway and 2 Sv would enter the Atlantic via the Bering Strait implying that no collapse of the NADW formation would occur. This means that opening the Panama Isthmus today may simply reduce (but not eliminate) the rate of NADW formation. It also points to the extreme sensitivity of such a system to specified eddy diffusivity which, in this context, is really nothing more than NADW as both systems remove or add upper layer water.

Fifty-one process-oriented numerical experiments were performed in order to examine the applicability of (2.1) to the scenarios described above. We examined the sensitivity of the results to varying gap width, varying wind, varying upper water removal, and varying Bering Strait sill depth (Table 1, **Figs. 5-7**). All experiments show decent agreements with the analytics. As expected, however, the experiments with a very shallow Bering Strait (**Fig. 7**, lower right) and relatively large transport showed a retardation of the flow through it. The retardation is not linearly related to the part of the strait that is blocked by the sill. For instance, a sill occupying 10% of the upper layer thickness still allows more than 30% of the sill-free transport to go through.

b. Weaknesses

As in most analytical models, there are a few potentially serious weaknesses in our model. The most important one is the level-of-no-motion assumption which was already discussed in the introduction and needs not be repeated here. The second is the no-sill assumption which was carefully examined numerically. Finally, traditional island-rule calculations used to compute the Indonesian Throughflow or other bodies of water (e.g., Godfrey 1989; Wajsowicz 1993; Pedlosky et al. 1997; Pratt and Pedlosky 1998; Firing et al. 1999; Liu et al. 1999) ignore water conversions (and upwelling and downwelling) which are the main focus of our study. Note that such calculations usually take the integration lines east of the island to be zonal; this cannot be done in our problem [due to the geography, (**Fig. 1**)] implying that an error of 10–20% is introduced (through the variation of the Coriolis parameter along the southern portion of the contour).

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6. Appendix

f_1	average Coriolis parameter along the northernmost boundary of integration
f_2	average Coriolis parameter along the southernmost boundary of integration
$\bar{f}$	average magnitude of the Coriolis parameter over the entire basin
g'	reduced gravity (0.15 $m^2 s^{-1}$)
H	undisturbed thickness
l	closed integration path
R_{dg}	Rossby radius, $(g'H)^{1/2}/\bar{f}$
T_s	transport scale
β	linear variation of the Coriolis parameter with latitude ($11.5 \times 10^{-11} m^{-1} s^{-1}$)
Δt	numerical model time step
Δx, Δy	numerical model grid size
K	linear drag coefficient
ν	eddy viscosity
ρ_0	mean seawater density
τ	wind stress

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