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 at which North Atlantic Deep Water (NADW) formation was impossible and, consequently, there was probably no ''conveyer belt.'' In line with this scenario, it has been suggested that the closure of the isthmus led to an increased salinity in the Atlantic that, in turn, led to the present-day NADW formation and the familiar meridional overturning cell (MOC). Using simple dynamical principles, analytical modeling, process-oriented numerical experiments, and modern-day wind stress, it is shown that, in the absence of NADW formation, one would expect a *westward* flow from the Atlantic to the Pacific Ocean through an open Panama Isthmus. This contradicts the suggestion made by the earlier numerical models that imply an eastward flow through the ''Panama Gateway.'' An analogous present-day situation (for a system without deep-water formation) is that of the Indonesian Throughflow, which brings Pacific water to the Indian Ocean rather than the other way around; that is, it is also a westward flow rather than an eastward flow. ''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. The authors show that exceptionally strong vertical mixing in the Atlantic (as compared with the Pacific) or another means of warm-water removal from the upper layer in the Atlantic (e.g., NADW or strong cooling) could reverse the direction of the flow through the open isthmus. This is most likely what happened in the earlier numerical simulation, which must have invoked (explicitly or implicitly) large quantities of upper-water removal even without NADW formation. 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 (Sv $\equiv 10^6$ $m^3 s^{-1}$) of NADW formation today 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 either collapse the existing NADW formation rate or reduce it to about 10 Sv, which can be maintained even with an open isthmus. In both cases the final outcome is a westward flow in the open isthmus.

1. Introduction

Determination of the paleocirculation in the ocean is important to our understanding of climatic variations. The construction of various general circulation models (GCMs) is very useful for this determination as such GCMs 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 paleocirculation. Here, we present the first attempt to analytically calculate the flow through an open Panama Isthmus. We shall argue that, in the absence of North Atlantic Deep Water (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.

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a. Earlier investigations

Proxy data suggest that it is the emergence of the Panama Isthmus that 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 GCM 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 argue 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. Similar results were obtained by Murdock et al. (1997). 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 closure of the isthmus is sufficient to initiate the NADW cell. The reader is also referred here to Mikolajewicz et al. (1993) for related modeling issues associated with the Drake Passage closure, to Luyendyk et al. (1972) for earlier laboratory experiments on the circulation in the paleocean, and to Shaffer and Bendsten (1994) who considered a simple three-box model that includes the Bering Strait. Using a coupled ocean–atmosphere numerical model, Huber and Sloan (2001) recently argued that, with an open isthmus, the MOC is reduced but is not completely eliminated.

b. General 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'' and quasi-island approach (Godfrey 1989; Nof 2000, 2002) 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 (asserted by the earlier studies) through an open Panama Isthmus. 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.

We performed a total of 51 numerical simulations. In some of those experiments we took the Bering Strait to be either completely or partially open. These are consistent with our 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.

In a limited number of experiments we imposed *specified* sources and sinks. With such 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 showed 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 (Sv $\equiv 10^6$ m^3 s^{-1})] of upper-water removal (via NADW, cooling or mixing). This must be why Maier-Reimer et al. (1990) and Mikolajewicz and Crowley (1997) obtained an eastward rather than a westward flow through the open Panama Gateway. Namely, they must have somehow generated large quantities of upper-layer removal even without NADW. This is most likely a result of their cooling representation and vertical mixing.

On the basis of the above analytical considerations and numerical experiments we shall argue that, without deep-water formation or other means of upper-water removal, 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 off the NADW formation because of a reduced salinity. The system will then shift and 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 that this last result is sensitive to the choice of present-day NADW formation rate. A choice of 10 Sv instead of 20 Sv would lead to a situation in which there is an outflow of 1 Sv from the Atlantic to the Pacific via the Panama Gateway (instead of an inflow of 12 Sv) and an inflow of 1 Sv from the Pacific to the Atlantic via the Bering Strait (instead of an outflow of 1 Sv). This would not collapse the NADW formation rate of 10 Sv, suggesting that the effect of opening the gap today may merely imply a reduced NADW formation rate.

c. Detailed calculations

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 of the moving layer is allowed to vary in space. The speeds below the level of no motion are negligible (in comparison with 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).

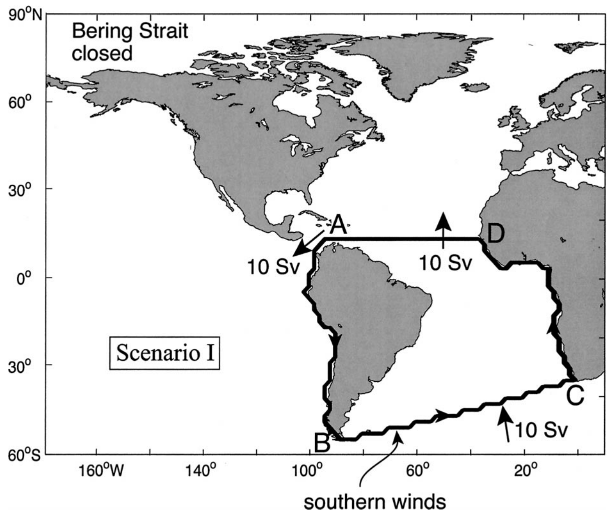


FIG. 1a. *Scenario I*: Open Panama Isthmus, closed Bering Strait, no diapycnal mixing, and no NADW in the Atlantic. In this case, 10 Sv are flowing northward in the South Atlantic and exiting the equatorial Atlantic via the open isthmus. This conceptual case is considered merely for a better understanding 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 yr). The integration was done over 2° × 2° boxes along the chosen path.

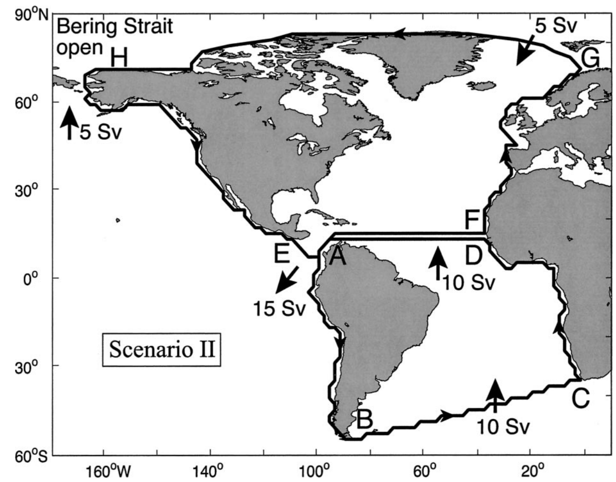


FIG. 1b. *Scenario II*: Open Panama Isthmus, open Bering Strait, no diapycnal mixing, and no NADW. In this case, 5 Sv enter the North Atlantic via the Bering Strait so that 15 Sv exit the equatorial Atlantic via the open Panama Isthmus. This conceptual case is supposedly relevant to interglaciation periods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

The density of the moving layer lower boundary coincides with a particular isopycnal because the density of the thick motionless layer is uniform. The numerical simulations employed a "reduced gravity" 1½-layer model.

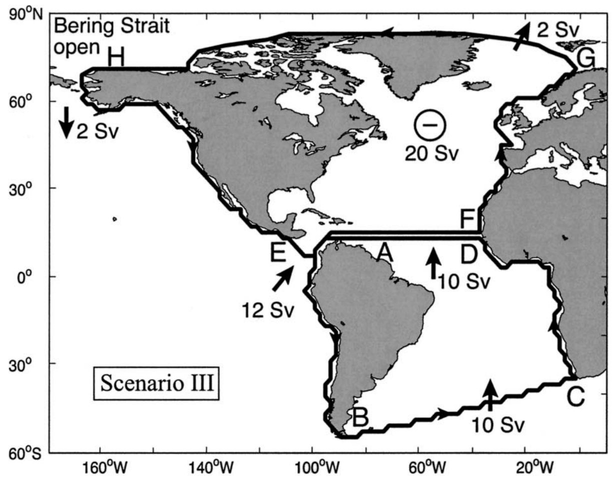
In contrast to the (diagnostic) approach taken in Nof (2000, 2002) in which the observation of almost no flow through the Bering Strait entered the calculations and the rate of NADW was solved for, the present calculations take the rate of NADW formation (or its absence) to be known and the flow through the Bering Strait to be unknown. Specifically, we shall specify two extreme NADW formation rates that cover most of the acceptable range (10–20 Sv). First, we shall specify a relatively high rate of 20 Sv that, with a closed isthmus, corresponds to 22 Sv or so entering the North Atlantic and 2 Sv exiting through the conceptual Bering Strait (with a sill). Second, we shall specify 10 Sv of NADW formation that, with an open isthmus, correspond to 10 Sv entering the South Atlantic and less than 1 Sv entering through the Bering Strait.

Out of our 51 numerical experiments that we performed, 43 were with no NADW or any other upper-water removal. For such experiments, it has been repeatedly stressed in Nof (2000, 2002) that, even though the integration gives the transport as a function of the wind stress, this transport is also the transport that will be established in the presence of *modest* heating and cooling. This is so because heating and cooling enter the problem only through the pressure term, which integrates out of the problem. Physically, this means that the ocean will always adjust its temperature and salinity field in such a way that the heat exchange is satisfied and the transport required by the integration is achieved. In other words, modest thermodynamic processes are *included* in the model even though they are not explicitly specified. In the eight experiments with NADW the situation is, of course, quite different. Here, the cooling is severe (and not modest) so that the thermodynamics is represented by the specified sources and sinks.

d. 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 farther 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) argued that, in contrast to Munk and Palmén's analysis, the ACC form drag is more evenly distributed



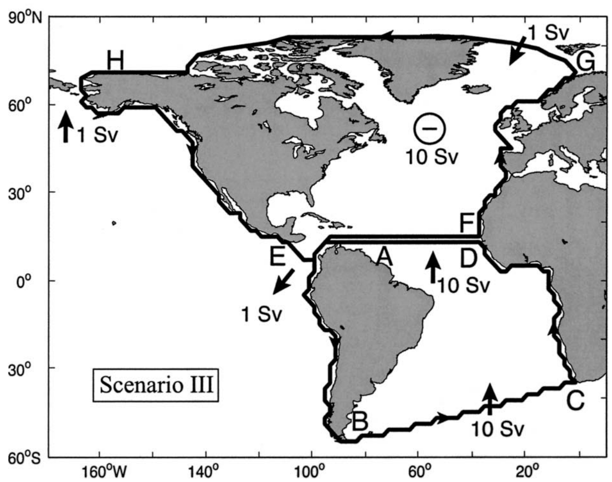


FIG. 1c. *Scenario III*: (top) Open Panama Isthmus, open Bering Strait, and 20 Sv of NADW (specified). Here, 2 Sv leave the North Atlantic to exit through the Bering Strait and 12 Sv enter the equatorial Atlantic via the open Panama Isthmus. As in scenario I, this is a hypothetical case corresponding 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 implicit but not 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. (bottom) Same as above except that 10 Sv of NADW are specified (instead of 20 Sv). In contrast to the 20-Sv case, this 10 Sv of NADW can be maintained because 1 Sv of Pacific water entering the Atlantic is not enough to collapse it.

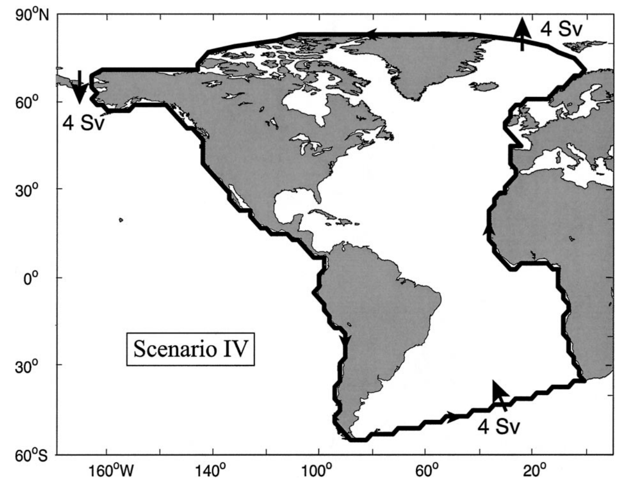


FIG. 1d. *Scenario IV*: Closed Panama gateway, open Bering Strait, no diapycnal mixing, and no deep-water formation. In this hypothetical case the wind would force 4 Sv in and out of the Atlantic. This scenario was already discussed in Nof (2000) and is presented here merely for completion. It shows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

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.

To see that the neglect of the pressure force acting on the Bering Strait sill 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 with a variable sill depth. 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 (section 3). 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. In what immediately follows we present a brief description of these four scenarios. A detailed description will be given later.

First, we shall apply it to the situation shown in Fig. 1a in which the Bering Strait is closed and South America is an island (because of the open Panama Isthmus). In this hypothetical scenario (scenario I) both the South and North Atlantic do not contain any NADW so that no upper water is removed. We shall show that, under such conditions, 10 Sv are transported northward in the South Atlantic. These 10 Sv then flow westward from the Atlantic to the Pacific. Second (scenario II), we shall apply the island rule to the case in which North America is also taken to be an island (Fig. 1b). This is a reasonable scenario if we take into account that the Bering 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 water 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 analysis of proxy data mentioned earlier suggests that prior to the closure of the Panama Isthmus there was no NADW formation, we shall assume that in this second scenario all the water that enters through the Bering Strait must pass through cross section HG (Fig. 1b) and ultimately exit the North Atlantic via the upper layer. 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 very hypothetical case (Fig. 1c) in which there is a high rate of NADW formation (20 Sv) and the isthmus is open; that is, 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 America are taken to be islands but there is now a *specified* 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 enter 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 off the NADW formation, resulting in a transition of the system to the first scenario described above, namely, to the situation in which 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 1 Sv *exiting* the Atlantic via the Panama Gateway and 1 Sv entering the Atlantic via the Bering Strait. We shall see shortly that a 1-Sv inflow of Pacific water is not sufficient to collapse the NADW, which brings us to the conclusion that a formation rate of 10 Sv can be sustained even with an open Panama Isthmus.

This sensitivity demonstrates a critical point regarding general numerical simulations of multilayered oceans. Since diapycnal eddy diffusivity (which through cooling allows upper-water removal) is essentially analogous to NADW, the above results regarding the direction of the flow in the Panama Isthmus are extremely sensitive to the (specified) vertical eddy diffusivity and cooling in these models. It is suspected that the reason Maier-Reimer et al. (1990) and Mikolajewicz and Crowley (1997) obtained eastward rather than westward flow (through the open Panama Gateway) is their large volume of upper-layer removal through strong cooling and diffusivity.

Last, we shall discuss a fourth scenario (scenario IV shown in Fig. 1d) in which the Panama Isthmus is closed and 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 mentioned in Nof (2000) and is mentioned here (in passing) merely for completeness. In the next section we discuss these four scenarios in detail.

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 momentum equations (containing the present-day wind stress[1] along the contour shown in Fig. 1a, which passes along the western boundary of the island) in the same sense as done in Godfrey (1989) and Nof (2000, 2002), gives

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

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, l is the integration contour, and T is the transport. 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 (or other means of upper-water removal) in between.

It is important to realize that (2.1) is an approximation to the linearized equation because an exact integration along the slanted sections will also involve terms resulting from the variation of f with y (which are neglected here). This will lead to an error of approximately 15% becaue the slant is relatively small.

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-yr averages given by the National Centers for En-

[1] Note that the wind stress 3–4 million years ago could not have been that different from what it is today.

vironmental 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 proxy data interpretation that, prior to the emergence of the isthmus, there was no NADW formation, this situation corresponds 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 either 20 Sv of upper-water removal from the North Atlantic (Fig. 1c, top) or 10 Sv of removal (Fig. 1c, bottom). As mentioned, this is a hypothetical situation corresponding to what would happen if the Panama Isthmus were to be suddenly opened today while the NADW production rate of either 20 or 10 Sv is somehow (at least initially) maintained. We see that, in this 20-Sv 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 and 20 Sv of NADW, 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, it is impossible to say for certain what would be the *T–S* structure of the resulting mixture. However, for simplicity, we can

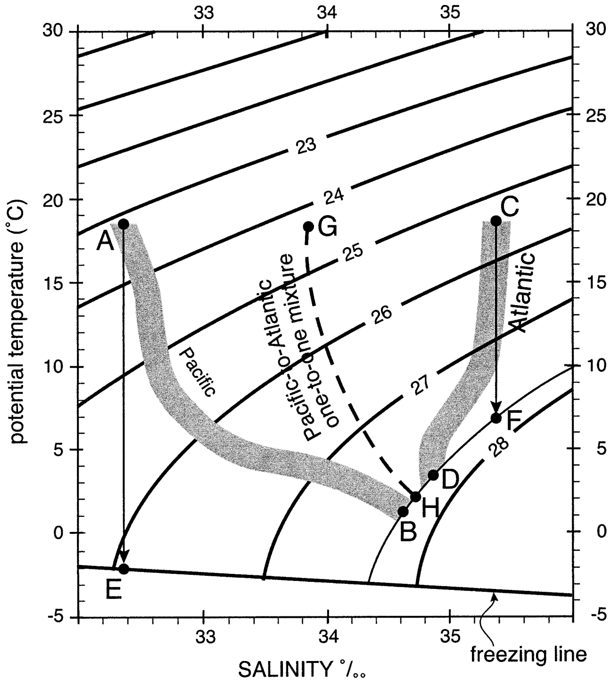
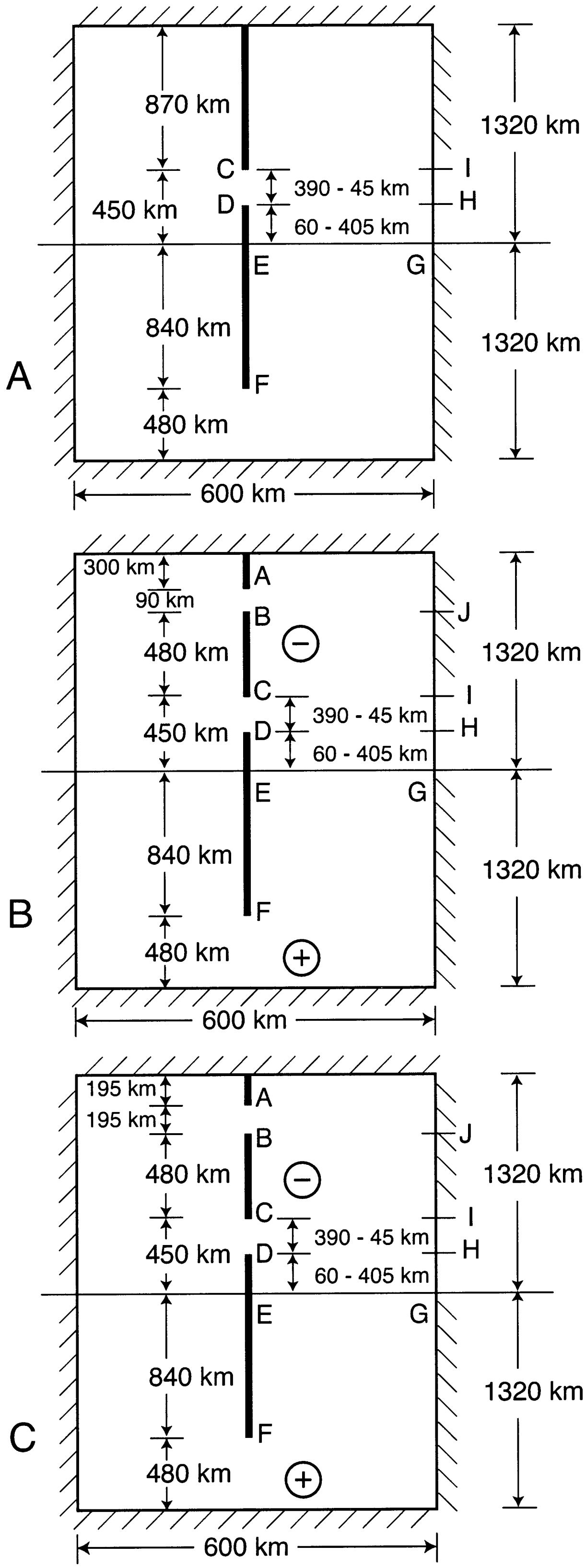


FIG. 2. *T–S* diagram of North Pacific (AB) and North Atlantic (CD) water [all values are from Emery and Dewar (1982)] as well as the interpolated values for mixed water that would be formed in the North Atlantic had the Panama Isthmus been opened today (GH). A comparison of AB and CD vividly shows why 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 with 20 Sv of NADW (Fig. 1c, upper panel) corresponds to an approximately 1:1 mixture of Atlantic and Pacific surface water (dashed line). Linear interpolation implies 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 density.

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 1 Sv 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 1:1 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 (no matter what the cooling is) because the freezing point is again 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 or at least reduced because of an invasion of Pacific water.

As alluded to earlier, it turns out that the above result is fairly sensitive to the (specified) rate of NADW for-



mation. A specification of 10 Sv instead of 20 Sv would correspond to 1 Sv exiting the equatorial Atlantic (via the Panama Gateway) and 1 Sv entering the North Atlantic (via the Bering Strait). This situation (Fig. 1c, lower panel) is very different from that corresponding to the earlier 20 Sv of NADW formation (Fig. 1c, upper panel). 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) because the Atlantic density profile will be very close to what it is today (with an inflow of 1 Sv through the Bering Strait). Hence, 10 Sv of NADW formation can be maintained even with an open isthmus. Equivalently, it is quite possible that prior to the closure of the isthmus there was merely a reduced rate of NADW.

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. This shows that the strong southern winds push water northward into the South Atlantic. Without NADW or cooling and diapycnal mixing to remove it, this water would exit 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 (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. A continuously stratified upper layer with variable density would have been better, but, since the ocean will always adjust its temperature and salinity field (according to the buoyancy exchange with the atmosphere) so that (2.1) is satisfied, this is not an issue.

We performed three sets of experiments (sets A, B, and C) totaling 51 experiments (Table 1). Out of the 51 experiments, 43 were without NADW or diapycnal mixing. To examine the relationship between the numerical

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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, and $\Delta t = 360$ s.

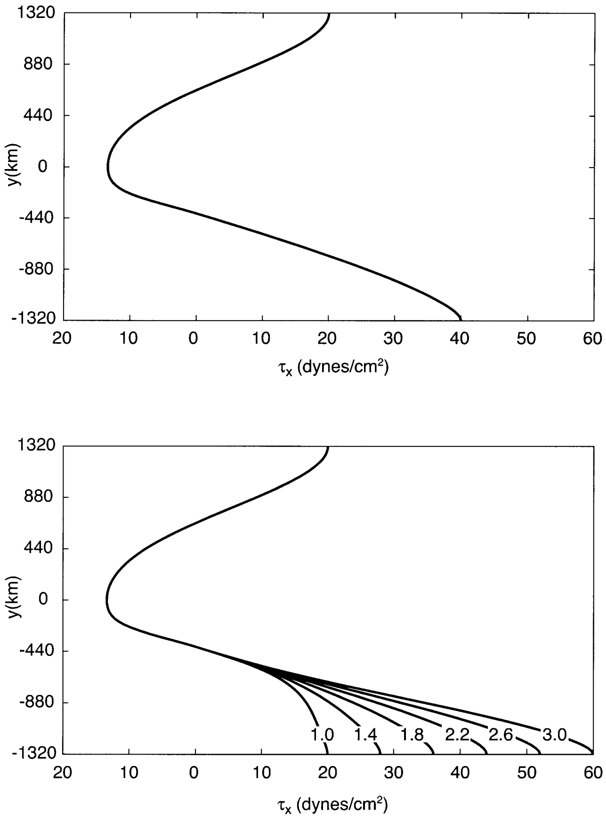

FIG. 4. The magnified (and simplified) zonal wind stress as a function of latitude (adapted from Hellerman and Rosenstein 1983). The upper panel shows the wind profile used for all subsets for which the wind is not varied (sets AI, BI, BIII, CI, CIII, and CIV). The lower panel shows the six wind profiles 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.

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, CII, and CIII)]. 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.

As in Nof (2000, 2002), to make our runs more economical we used a magnified β, a magnified wind stress τ, and a reduced basin size. Figures 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. Figure 7, which shows the effects of a sill, displays 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 one-half of the fluid thickness. Note, however, that a shallow sill does not alter the direction of the flow.

It should be pointed out that similar results would have been obtained with periodic rather than solid boundaries. Namely, the analytical results remain unaltered for experiments where the easternmost and westernmost boundaries shown in Fig. 3 are periodic. Note, however, that the detailed numerical procedure needs to be different in the periodic case because, under such conditions, there will also be a net meridional flow in the western basin implying that sources and sinks must be placed there (see Nof 2003). It is also important to realize that our analytical results will be altered when there are viscous eastern boundary currents because the integrated pressure variations along those boundaries will no longer be given by the meridional wind stress (see, e.g., Spall 2000).

4. Summary and discussion

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

The analysis takes into account that, with a Panama Gateway (i.e., open isthmus), both 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 analytical and numerical calculations show that, if there were indeed no NADW formation because of the in-

TABLE 1. A description of the three sets (A, B, and C) of numerical experiments (employing a 1½-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' is the reduced gravity (0.15 m^2 s^{-1}), H is the undisturbed thickness (600 m), ν is the eddy viscosity (2000 m^2 s^{-1}), K is the linear drag (20×10^{-7} s^{-1}), $\bar{f}$ is the average Coriolis parameter in the basin, R_{dg} is the radius [$(g'H)^{1/2}/\bar{f}$ = 39.53 km], T is the transport, $\Delta x = \Delta y$ = 15 km, and Δt = 360 s.

Set	Description		Expt. No.	Panama gap width (km)	W/R_{dg}	R_{dg} (km)	No. grid cells in Panama gap	Southern wind factor	Upper water removal (Sv)	$T/(g'H^2/2\bar{f})$	Sill depth (m)	D/H	Shown in Fig.	
A	Bering	Varying	1	390	3.81	102	26	2	0	0	NA	NA	5	
	Strait	Panama	2	315	3.53	89	21							
	closed	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	Varying	13	390	3.81	102	26	2	0	0	NA	NA	6	
	Strait	Panama	14	315	3.53	89	21							
	fully open	gap	15	240	3.04	79	16							
		I	16	165	2.32	71	11							
	Six grid		17	90	1.4	64	6							
	in Bering		18	45	0.74	61	3							
	Strait		19	165	2.32	71	11	1	0	0	NA	NA		
	(90 km);	Varying	20					1.4						
	R_{dg} = 26.75	wind	21					1.8						
		II	22					2.2						
			23					2.6						
			24					3						
		Varying	25	165	2.32	71	11	2	0	0	NA	NA		
		upper 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	I	32	165	2.32	71	11							
	cells		33	90	1.4	64	6							
	in Bering		34	45	0.74	61	3							
	Strait		35	165	2.32	71	11	1	0	0	60	0.1		
	(195 km)	Varying	36					1.4						
	R_{dg} = 25.39	wind	37					1.8						
		II	38					2.2						
			39					2.6						
			40					3						
		Varying	41	165	2.32	71	11	2	0	0	60	0.1		10
		upper	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		

vasion 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); that is, there is no invasion of Pacific water. The second scenario (Fig.

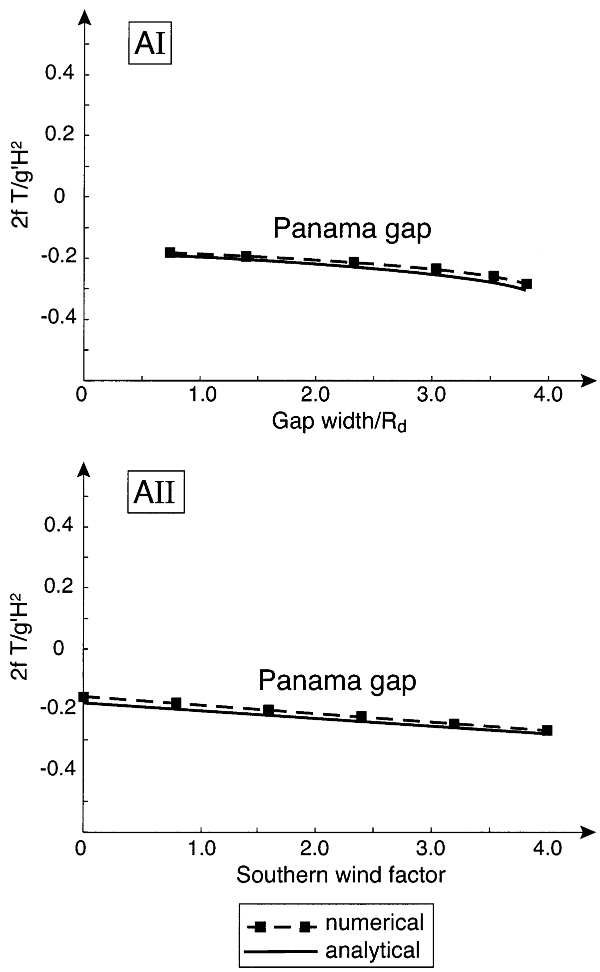

FIG. 5. A comparison of the numerical experiments of set A (Bering Strait closed; see Table 1) with the analytical theory. In the upper panel (set AI, varying Panama gap) the solid line shows the theoretical solution for the nondimensional transport through the Panama gap (CD in Fig. 3) as a function of the nondimensional Panama gap width. The gap width is scaled with the local Rd at the gap and the transport with $g'H^2/2\overline{f}$ (see Table 1). The dashed line with squares shows the results of the six numerical 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).

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) that is essentially the same as the second scenario except that we added either 20 or 10 Sv of NADW (specified). In the 20-Sv case, an invasion can indeed take place via the open isthmus. However, because this invasion would collapse the NADW, the eastward flow in the Panama Gateway could not be sustained and the system would either revert to that described in the second scenario or be reduced to the 10-Sv case.

a. *Results*

Overall, we can say that how much of an invasion took place and where it had originated (Bering Strait or Panama Gateway) depends on whether or not there was NADW in the Atlantic and how strong it was. 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 3 (but not 10: 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, upper panel). 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) 1:1 mixture of Pacific and South Atlantic water because the 20 Sv sinking in the North Atlantic would contain 10 Sv of South Atlantic water and 12 Sv of Pacific water. (Two Sv do not sink, but exit through the Bering Strait.)

The *T–S* diagram for present-day Pacific and present-day Atlantic water (Fig. 2) suggests 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-Sv NADW cell would collapse.

Repetition of the above analysis with 10 Sv of NADW formation instead of 20 Sv gives an entirely different result (Fig. 2a, lower panel). In this case, 1 Sv would exit the Atlantic via the Panama Gateway and 1 Sv would enter the Atlantic via the Bering Strait, implying that no total 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 cooling and 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

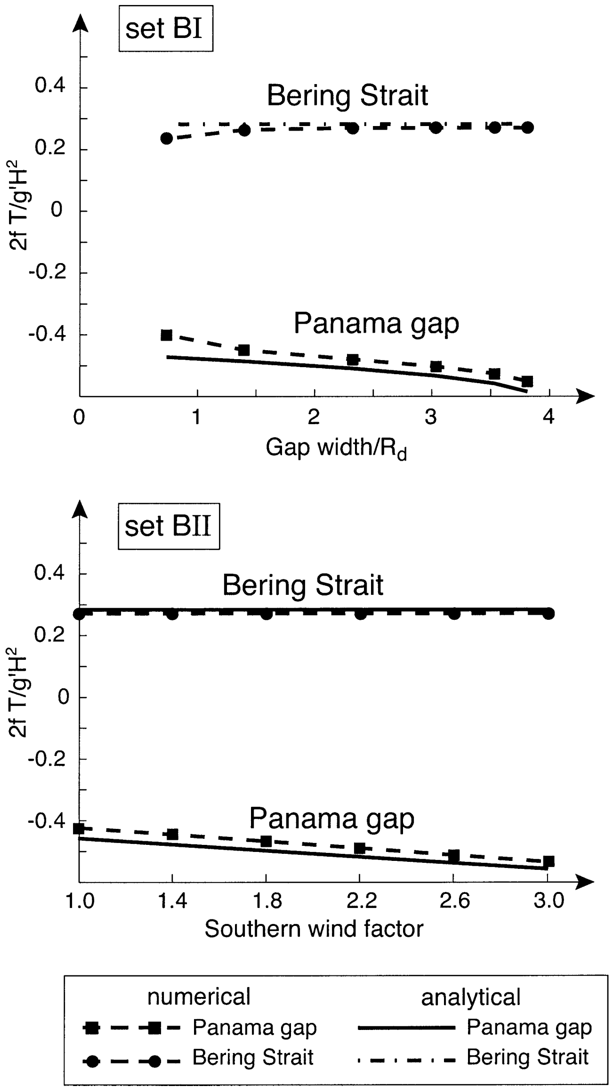

FIG. 6a. As in Fig. 5, a comparison of the numerical experiments in set B (Bering Strait fully open; see Table 1) with the analytical theory. In the upper panel (set BI, varying Panama gap) the dashed–dotted line and the dashed line with circles show the analytical and numerical transports, respectively, 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.

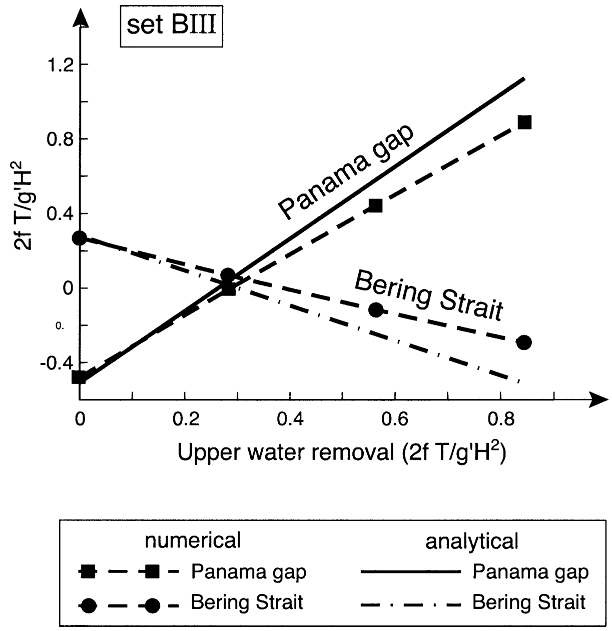

FIG. 6b. The numerical experiments in set BIII (varying upper-water removal). These transports are plotted as a function of the nondimensional transport associated with the upper-water removal. The solid line is the analytical transport through the Panama gap, and the dashed line with squares is the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

wind, varying upper-water removal, and varying Bering Strait sill depth (Table 1, Figs. 5–7). All experiments show reasonable 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.

Last, it should be pointed out that 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 not neglected here. Note also that the traditional calculations usually take the integration lines east of the island to be zonal; this cannot be done in our problem [because of 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). 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.

b. Key conclusions

The first key conclusion of our study is that, without NADW, the flow through the open Panama Isthmus is from the Atlantic to the Pacific rather than the other way around (scenario II, Fig. 1b). This contradicts the argument put forward by earlier studies (Maier-Raimer et al. 1990; Mikolajewicz and Crowley 1997) that, using

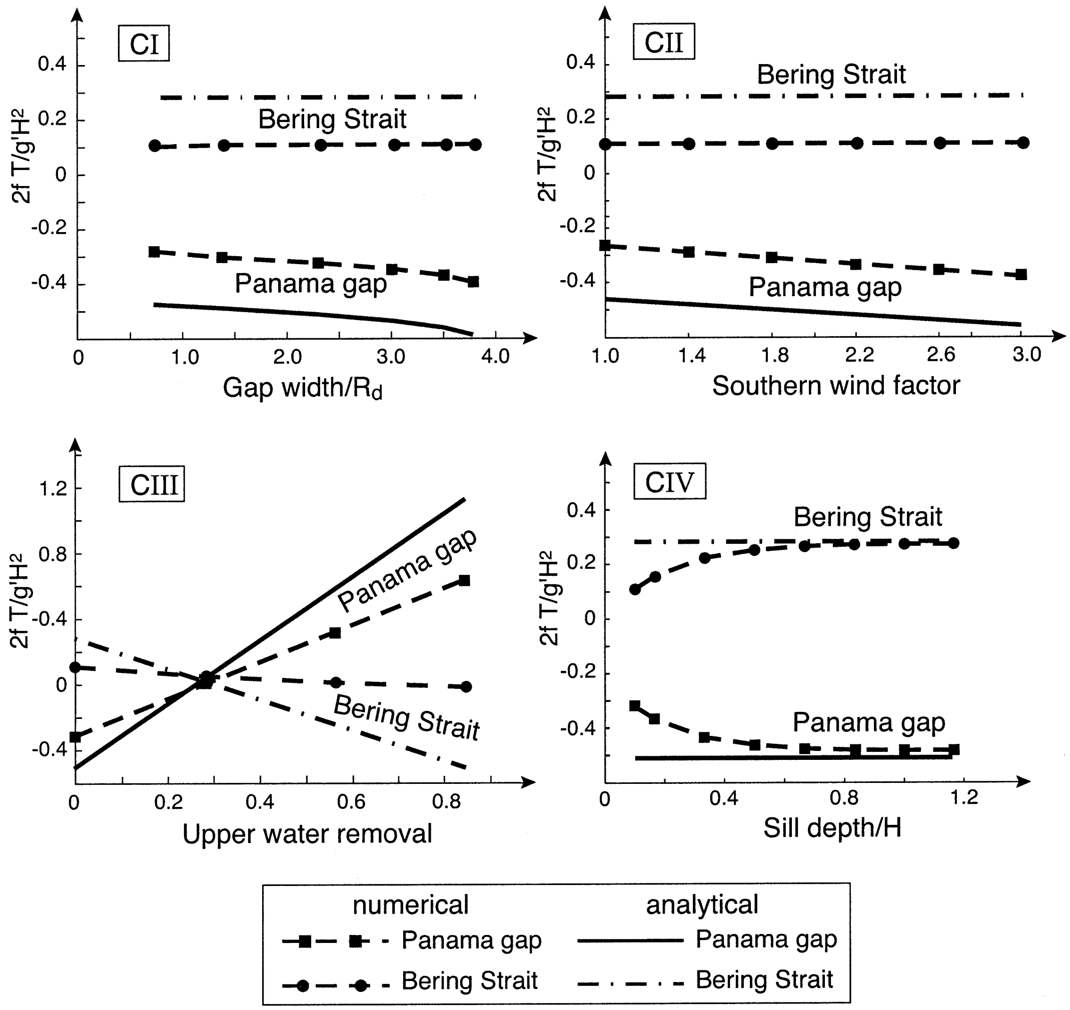

FIG. 7. As in Figs. 5 and 6, a comparison of the numerical experiments in set C (sill at Bering Strait; see Table 1) to the analytical (no-sill) theory. In the upper-left panel (set CI, varying Panama gap), the dashed–dotted line and the dashed line with circles show the transport through the Bering 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.

GCMs, suggest there was a flow from the Pacific to the Atlantic prior to the closure of the isthmus and the initiation of NADW. It is suggested that the combination of cooling and high vertical diffusivities (relative to the observed 0.1 cm^2 s^{-1}) caused a reversal of the flow in their modeled passage (scenario III, Fig. 1c). This conclusion is based on a simple model that allows for both wind and density variations in the field. Our study also points out that the invasion of Pacific water into the Atlantic must have occurred through the Bering Strait rather than through an open Panama Isthmus (scenario II, Fig. 1b).

The second key conclusion is that, even with an open Panama Isthmus, NADW is still possible although it can only be present at a reduced rate (~10 Sv). This is because 1 Sv of low-salinity water entering the Atlantic via the Bering Strait is insufficient to dilute the salinity of the Atlantic to the degree that completely shuts off the NADW formation.

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APPENDIX

List of Symbols

f_1	Average Coriolis parameter along the northernmost boundary of integration
f_2	Average Coriolis parameter along the southernmost boundary of integration
$\overline{f}$	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, $(g'H)^{1/2}/\overline{f}$
T	Transport
β	Linear variation of the Coriolis parameter with latitude (11.5×10^{-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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