Bering Strait throughflow and the thermohaline circulation

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[1] In this study, we employ a global coupled climate model to show that the Bering Strait is important to the variations of the thermohaline circulation. Three experiments are analyzed, a present day control run, and two freshwater hosing runs. Results show that as the thermohaline circulation weakens due to freshwater forcing in the northern North Atlantic, the Bering Strait throughflow weakens, and even reverses its direction, and the export of the Arctic freshwater into the northern North Atlantic is reduced, or the Arctic even takes freshwater from the latter, thus helping the thermohaline circulation to recover relatively quickly after the end of the freshwater hosing. Citation: Hu, A., and G. A. Meehl (2005), Bering Strait throughflow and the thermohaline circulation, Geophys. Res. Lett., 32, L24610, doi:10.1029/2005GL024424.

1. Introduction

[2] The Bering Strait is a narrow and shallow pathway connecting the Pacific and Atlantic through the Arctic with an average mean throughflow about 0.8 Sv (1 Sv ≡ 10^6 m^3 s^-1) northward. This throughflow transports a significant amount of freshwater to the Arctic and the Atlantic [Aagaard and Carmack, 1989; Woodgate et al., 2005]. Previous studies indicate that the transport from the Pacific to the Arctic through the Bering Strait plays an important role in the freshwater budget of the world oceans [e.g., Wijffels et al., 1992]. This throughflow can also affect the strength of the thermohaline circulation (THC) [Reason and Power, 1994; Goosse et al., 1997; Wadley and Bigg, 2002], the deep western boundary currents in the Atlantic, the separation point of the Gulf Stream from the eastern coast of America [Huang and Schmitt, 1993], and consequently may also influence global climate [DeBoer and Nof, 2004a, 2004b].

[3] The THC is a global scale ocean circulation involving a transformation of the warmer, saltier upper water into dense deep water in the northern North Atlantic and around the periphery of the Antarctic through atmospheric cooling processes. Under current climate conditions, the THC transports about 1.2 × 10^15 W of heat northward in the Atlantic at 24°N [Rahmstorf, 1999]. Altering the strength of this circulation could induce significant regional and global climate change [e.g., Stouffer et al., 2005]. Paleo climate records indicate that abrupt climate change occurred during the last glacial period, such as the Younger Dryas or the Dansgaard/Oeschger events [Bard, 2002]. The cause of these millennium timescale climate changes is mainly attributed to the collapse or re-establishment of the THC [Committee on Abrupt Climate Change, Ocean Studies Board, Polar Research Board, Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies, National Research Council, 2002]. The collapse of the THC was possibly related to a flush of glacier melt-water into the Atlantic [e.g., Clark et al., 2002].

[4] A recent multi-coupled-model inter-comparison study shows that the THC gradually declines by 10 to 50% in 11 different climate models in a 140-year period during which the atmospheric CO_2 increases 1% per year compound, and quadruples at year 140, but none of the models produces a total collapse of the THC [Gregory et al., 2005]. At quadrupled CO_2, a large percentage of the Arctic sea ice would melt, particularly in the summer season. If a significant amount of the melt-ice water, plus the increased precipitation and river runoff in the Arctic, is transported into the northern North Atlantic marginal seas, would we see a collapsed or a strongly declined THC? Evidently, only a portion or a small portion of the available anomalous freshwater in the Arctic is transported into the northern North Atlantic marginal seas. As concluded by Gregory et al. [2005], the THC weakening in all models is caused more by changes in surface heating than by changes in surface freshwater input.

[5] The questions we will address in this paper are what prevents the available freshwater from exiting the Arctic into northern North Atlantic, and what role does the Bering Strait play? We find that as the THC slows down due to a freshening in the North Atlantic, the flow from the Pacific into Arctic through the Bering Strait weakens, and even reverses its direction. In other words, instead of a freshwater source to the Arctic and Atlantic, the Bering Strait throughflow could become a freshwater sink when the THC declines significantly, consistent with the theoretical studies of De Boer and Nof [2004a, 2004b]. This is the first study of the relationship of THC and Bering Strait throughflow using a global coupled model which highlights the importance of the Bering Strait on global climate.

2. Model and Experiments

[6] To answer the questions posed above, we investigate the relationship of the THC and the transport of the Bering Strait throughflow by artificially adding freshwater flux into the northern North Atlantic to force the THC to weaken. We use the Community Climate System Model version 2 (CCSM2.0) [Kiehl and Gent, 2004]. Its atmospheric component is the NCAR Community Atmospheric Model (CAM2) at T42 resolution and 26 hybrid levels in the vertical. The ocean model is a version of the Parallel Ocean Program (POP) developed at Los Alamos National Lab with 1° horizontal resolution and enhanced meridional resolution (1/2°) in the equatorial tropics, and with 40 vertical levels. The sea ice model is the Community Sea Ice Model.
Table 1. Changes of the THC, Bering Strait Transports

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>0.1 Sv Hosing</th>
<th>1 Sv Hosing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>590–599</td>
<td>740–749</td>
</tr>
<tr>
<td>THC Sv</td>
<td>15.7</td>
<td>15.4</td>
<td>15.7</td>
</tr>
<tr>
<td>BS Vol Sv</td>
<td>0.808</td>
<td>0.806</td>
<td>0.836</td>
</tr>
<tr>
<td>BS FWF Sv</td>
<td>0.0617</td>
<td>0.0488</td>
<td>0.0622</td>
</tr>
</tbody>
</table>

*THC represents thermohaline circulation, BS Vol is Bering Strait volume transport, and BS FWF is the Bering Strait freshwater transport. For the Bering Strait transport, positive (negative) values indicate a transport from the Pacific (Arctic) to Arctic (Pacific). Units for all value are Sv (Sv = 10⁶ m³ s⁻¹). Values for the control run are a 300-year average, those for others are decadal mean.

(CSIM4) with Elastic-viscous-plastic dynamics, a subgrid-scale thickness distribution, and energy conserving thermodynamics. The land model is the Community Land Model (CLM).

The experiments analyzed in this study include the CCSM2 millennial present day control run from year 500 to 799, and two freshwater hosing runs. In the first hosing experiment, a 0.1 Sv additional freshwater flux is uniformly distributed in the northern North Atlantic between 50°N and 10°S (H0.1SV), which could be viewed as comparable to a freshwater pulse during the last deglaciation. This additional freshwater flux represents a 50% increase in net freshwater input into this region relative to the control experiment. The second hosing experiment (H1SV) is the same as the first one except that the rate of freshwater input is 10 times higher, 1 Sv, close to the current global river runoff. A freshwater flux this large is extremely unlikely in the near future under realistic greenhouse gas projections, though it could have occurred during last deglaciation with a much shorter duration [Clarke et al., 2003]. In any case, this flux is on the high side of paleo-records [e.g., Sarnthein et al., 1995], and a forcing weaker than this could have shut down the THC in some models [e.g., Seidov et al., 1996]. These two experiments are branched from the control run at year 500. The hosing runs are integrated with the additional freshwater flux for a century, and that flux is then switched off for another century and half.

3. Results

In the Atlantic, the THC dominates the meridional overturning circulation, therefore we use the maximum value of the Atlantic meridional stream function below 200 meters as an index to represent the THC. The mean strength of the THC in the control run is 15.7 Sv (Table 1), agreeing well with observed estimates [e.g., McCartney and Talley, 1984]. As shown in Figure 1a, the THC is stable in the control run with almost no trend. In both hosing experiments, the THC weakens dramatically during the first 10 years. After that, the rate of the THC decrease becomes slower. At the end of the hosing period, the THC has weakened by 4.3 Sv (or 27%) in the H0.1SV run, and 9.7 Sv (or 62%) in the H1SV run. When the additional freshwater flux is switched off, the THC recovers to its full strength (as in the control run) in a hundred-years in the H0.1SV run, but is still about 4.6 Sv (or 29%) weaker than the control value 150 years after the switch-off in the H1SV run (Table 1).

Figure 1b shows the time-evolving Bering Strait transport in the three experiments. The mean strength of this transport in the control run is 0.808 Sv (Table 1) from the Pacific into the Arctic, in good agreement with observations (e.g., 0.8 Sv [Aagaard and Carmack, 1989]). In the H0.1SV run, as the THC weakens due to the freshening of the northern North Atlantic, this transport also weakens, and reduces to about 0.561 Sv (or a 30% reduction) by the end of the hosing. After the hosing, it returns to its original strength as in the control run in about 70 years, similar to the timescale of recovery of the THC. However, this transport in the H1SV run reduces to zero in the first 10 years of hosing along with a dramatic decrease in THC, and then becomes negative (southward) thereafter. By the end of the hosing, there is about 0.872 Sv of Arctic water flowing into the Pacific. Then this reversed transport gradually becomes weaker, and reverses its direction again about 80 years after the end of hosing. By the end of the integration, the Bering Strait transport only returns to about 30% of the control value in this run (Table 1).

Of the total Bering Strait transport, the mean freshwater flux through Bering Strait is 0.0617 Sv (Table 1) in the control run, close to the observed estimate (e.g., 0.053 Sv [Aagaard and Carmack, 1989]). In the H0.1SV run (Figure 1c), the freshwater flux through Bering Strait reduces to 0.0488 Sv (or a 21% reduction) at the end of hosing, then gradually recovers to its control strength. In the H1SV run, freshwater transport through Bering Strait reduces to zero by year 10 of the hosing, then freshwater is transported from the Arctic into the Pacific. At the end of hosing, the rate of freshwater transported southward through the Bering Strait is 0.1777 Sv from the Arctic to the Pacific. After the hosing ends, the freshwater flux towards the Pacific reduces, and reverses to its normal direction (from the Pacific to the Arctic) 80 years later, but is still lower than its control value a century and half later.

The freshwater directly exiting through the Bering Strait into the Pacific is about 14.5% of the total additional freshwater input in the northern North Atlantic in the H1SV run during 170 years when the Bering Strait transport...
reverses its direction. If we take the difference of Bering Strait freshwater flux between the hosing runs and the control run, the Pacific obtains an equivalent about 26% of the total additional freshwater input in the North Atlantic via the Bering Strait in about 200 years in the H1SV run, and about 22% of that in the H0.1SV experiment through indirect and/or direct means. The effect of this freshwater removal from the Atlantic to the Pacific is two fold: a, it reduces the strength of the freshwater forcing in the Atlantic; b, it slows the reduction rate of the sea surface salinity (SSS) contrast between the North Atlantic and the North Pacific by lowering the SSS in the latter. As indicated by Seidov and Haupt [2003], a higher/lower SSS contrast between these two basins would strengthen/weaken the THC. Thus the net effect of this freshwater removal would slow the rate of the THC weakening during hosing and help the THC to recover quicker after the hosing.

[12] To help understand why these changes in circulation occur, we first examine the horizontal distribution of the decadal-mean SSS anomalies for the 1 Sv hosing experiment relative to the control run. As illustrated in Figure 2a, after 10 years of hosing, a freshwater plume flows out of the Arctic into the North Pacific and circulates with the subpolar gyre there, consistent with the reversal of the Bering Strait throughflow. When the hosing continues, the freshwater plume becomes stronger, and peaks at the end of the hosing, indicating a strengthened freshwater export from the Arctic into the North Pacific (Figures 2b and 2c). This freshwater flux originates in the northern North Atlantic hosing zone, is transported by the North Atlantic current, then the Norwegian current into the Arctic via Barents Sea, then towards the Bering Strait mainly along the Eurasian side of the Arctic. After the hosing ends, the SSS anomalies weaken dramatically in about 10 years, and almost totally disappear 40 years later (Figure 2d).

[13] Further insight into why these circulation anomalies develop in the hosing experiments is provided by the theoretical study of De Boer and Nof [2004a, 2004b]. They show that without North Atlantic deep water (NADW) formation, the 4 Sv of upper ocean water forced into the South Atlantic by strong Southern Ocean winds will exit to the Pacific through the open Bering Strait, instead of returning to the Southern Oceans via the lower branch of the THC as NADW under present conditions. This implies that any strong freshwater flux into the North Atlantic which could sufficiently shut down the NADW formation (or THC) would be quickly flushed out of the North Atlantic into the North Pacific via Bering Strait by that 4 Sv upper Southern Ocean water. Consequently, the THC (or NADW formation) would be re-established fairly quickly.

[14] By checking for these processes in the CCSM2, we find that in the control run, the Southern Ocean winds also force about 4 Sv upper ocean water into the Atlantic at 30°S, consistent with the estimation of De Boer and Nof [2004a, 2004b]. In the H1SV run, only 3.15 Sv of the NADW cross 30°S averaged over the last decade of hosing. At the same time, about 0.872 Sv water exits the Bering Strait into the Pacific as mentioned previously. Since the THC is not completely shut down in this run, the freshwater anomaly is not flushed out of the North Atlantic as quick as in the case of De Boer and Nof, resulting in a slower recovery of the THC in our experiments.

[15] In the H0.1SV run, the total freshwater transport from the Arctic into the northern North Atlantic marginal seas reduces by 26%, about 0.048 Sv after the first decade of hosing. This reduction is equivalent to 48% of the 0.1 Sv additional freshwater we put into the hosing region. In the H1SV run, the freshwater transport between the Arctic and the North Atlantic reverses direction after the first decade of hosing. Instead of a flow of 0.186 Sv freshwater into the North Atlantic, about 0.201 Sv freshwater flows from the Atlantic into the Arctic between the hosing year 11 and 100. This is equivalent to the Arctic obtaining a total of 0.387 Sv (or 39%) of that 1 Sv hosing water. If this freshwater would remain in the Arctic and gradually release to the Atlantic after the end of hosing, it would postpone the recovery of the THC. As mentioned previously, a significant portion of this Arctic freshwater gain is directly or indirectly transported into the North Pacific via the Bering Strait. This weakens the freshwater forcing added in the hosing zone. Once the additional freshwater flux is terminated, the THC can quickly recover on interdecadal timescales as shown in Figure 1.

4. Conclusion and Discussion

[16] A global coupled climate model (CCSM2) is used to study, for the first time, the relationship between the THC and the Bering Strait throughflow. When the THC is reduced by an artificial freshwater flux added to the northern North Atlantic between 50 and 70°N, the Bering Strait throughflow from the North Pacific into the Arctic weakens, and even reverses its direction when that artificial freshwater flux is strong. This is associated in a similar way to changes in the freshwater transport from the North Pacific to the Arctic. At the same time, the freshwater exported from
the Arctic into the North Atlantic marginal seas is reduced also. This reduction is comparable to a large portion of the artificial freshwater flux added in the northern North Atlantic. Thus the removal of this freshwater from the North Atlantic by this process means that there is less anomalous freshwater in that region. If it could have remained, it could have weakened the THC even further. When the artificial freshwater flux is terminated, the freshwater flux from the Arctic into the North Atlantic is still lower than that in control run, which helps the THC to recover more quickly than without this process.

[17] If the Bering Strait is closed due to a lowering of the sea level, such as during last glaciation, there would be no Pacific water flowing into the Arctic and the Atlantic. The lack of the fresher Pacific water flowing into the Arctic and Atlantic would induce a saltier Atlantic surface layer, stronger deep convection, and a stronger THC, as shown by Goosse et al. [1997] and Wadley and Bigg [2002]. On the other hand, when a pulse of freshwater flux is applied into the northern North Atlantic, a closed Bering Strait would not allow the transport of the freshwater anomaly out of the Atlantic into the Pacific. If the freshwater pulse is strong enough to significantly weaken the THC, it would take much longer to transport the freshwater anomaly out of the Atlantic. Thus the recovery of the THC would take much longer with a closed Bering Strait.

[18] With an open Bering Strait, when the atmospheric CO$_2$ level increases, the global mean temperature increases, which leads to a melting of the Arctic sea ice. Initially, the melt-water would be transported out of the Arctic, contributing to a stabilization of the northern North Atlantic ocean by lowering the surface density, in addition to the contributions to the surface density reduction from CO$_2$-induced local warming effect. When the THC slows down, the strength of the Bering Strait throughput weakens. Less water is exported out of the Arctic into the northern North Atlantic. This may not immediately produce a net reduction of the freshwater export out of the Arctic since the Arctic water becomes fresher due to ice melting. However, if the Bering Strait throughput did not weaken, we would expect more freshwater to be exported into the northern North Atlantic, and that would produce a more dramatic weakening of the THC. Although this throughput may only passively respond to the THC changes in our experiments, the net effect of the open Bering Strait is to help maintain a stable SSS contrast between the North Atlantic and the North Pacific, and thus a stable THC. When the THC is strong, more freshwater is transported from the Pacific to the Atlantic to moderate the strength of the THC. When the THC is weak, less freshwater flows into the Atlantic, thus strengthening the THC.

[19] In this paper, we have emphasized the importance of the Bering Strait to the THC variations. But to further isolate the effect of the Bering Strait on the THC, we need to run a series experiments with the same setup as those studied here but with a closed Bering Strait, and these experiments are in progress.

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