The Pacific-Atlantic seesaw and the Bering Strait

Aixue Hu,[1] Gerald A. Meehl,[1] Weiqing Han,[2] Ayako Abe-Ouchi,[3] Carrie Morrill,[4,5] Yusuke Okazaki,[6] and Megume O. Chikamoto[6]

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[1] Paleo proxy data and previous modeling studies both indicate that the massive discharge of icebergs into the North Atlantic may have led to a (nearly) collapsed Atlantic meridional overturning circulation (AMOC), resulting in a seesaw-like climate change between the North Pacific and North Atlantic, with a warming in the former and a cooling in the latter. Here by using a fully coupled climate model, we show that this Pacific-Atlantic seesaw associated with changes of the AMOC can only occur when the Bering Strait is closed. As this strait is closed, the oceanic communication between the North Pacific and Atlantic is cut off. When AMOC collapses, the North Atlantic becomes cooler, but the North Pacific becomes warmer due to the buildup of the Pacific meridional overturning circulation which transports more warm and salty subtropical water into the North Pacific, leading to seesaw-like climate changes in the two ocean basins. **Citation:** Hu, A., G. A. Meehl, W. Han, A. Abe-Ouchi, C. Morrill, Y. Okazaki, and M. O. Chikamoto (2012), The Pacific-Atlantic seesaw and the Bering Strait, *Geophys. Res. Lett.*, *39*, L03702, doi:10.1029/2011GL050567.

1. Introduction

[2] Previous modeling study indicates that the changes of the Atlantic Meridional Overturning Circulation (AMOC) can cause seesaw-like climate changes between North Atlantic and North Pacific [*Saenko et al.*, 2004]. Saenko et al. used a standalone ocean model with a closed Bering Strait to show that, by adding freshwater forcing in the North Atlantic, the AMOC weakens, but the Pacific MOC (PMOC) strengthens. As a result, the North Atlantic becomes cooler due to the reduced northward meridional heat transport by the AMOC. But the North Pacific becomes warmer related to the setup of the PMOC which transports more tropical-sub-tropical warm water into the subpolar North Pacific. Additionally, if the surface freshwater forcing in the North Pacific reduces, the PMOC strengthens and the AMOC weakens. *Seidov and Haupt* [2003] using a coarse resolution ocean model found that the changes of the sea surface salinity (SSS) between the North Atlantic and North Pacific are opposite to each other when the AMOC changes, and proposed that SSS contrast between these two basins can be used as an indicator of the AMOC changes. However, *Hu et al.* [2008] indicate that the status of the Bering Strait can limit this relation between AMOC and SSS contrast.

[3] The Heinrich 1 (H1) event is a cold event in the North Atlantic that occurred at about 15–17.5 thousand years before present which can be identified by layers of ice-rafted debris found in North Atlantic sediment cores [*Heinrich*, 1988; *Hemming*, 2004]. This event has been associated with surging icebergs from the Laurentide ice sheet [*Alley and MacAyeal*, 1994]. During this event, it has been suggested that the AMOC collapsed or was seriously weakened [*McManus et al.*, 2004] (Figure 1a). Observationally based studies show that during this event, the eastern North Pacific was warmer and saltier [*Okazaki et al.*, 2010], and the North Atlantic was colder [*Waelbroeck et al.*, 2001] and fresher within proxy data dating uncertainty [*Chapman and Maslin*, 1999] (Figures 1c and 1e), consistent with the seesaw climate change suggested by modeling study [*Saenko et al.*, 2004]. By using an earth system model of intermediate complexity (EMIC), *Okazaki et al.* [2010] further suggested that this seesaw-like climate change during the H1 event was caused by the PMOC buildup, agreeing with the changes of the North Pacific water ventilation age inferred from proxies (Figure 1a). On the other hand, previous coupled climate modeling studies show that a collapse of the AMOC due to freshwater forcing in the North Atlantic induces a Northern Hemispheric scale cooling under modern day climate conditions [e.g., *Stouffer et al.*, 2006]. These somehow contradictory results raise an important question: is the climate response in the North Atlantic and the North Pacific to a collapsed or seriously weakened AMOC the same under modern conditions as that under glacial conditions? If the climate response in these two basins is different under these conditions, what are the underling mechanisms?

[4] From reconstructed global mean sea level data [*Lambeck and Chappell*, 2001], the H1 event occurred at a time when the global mean sea level was more than 50 meters below the present-day level. This led to a closure of the Bering Strait, a shallow and narrow strait connecting the North Pacific and Arctic [*Hu et al.*, 2010]. Presently this strait transports about 0.8 Sv (Sv ≡ 10^6 m^3 s^{-1}) of relatively fresh North Pacific water into the Arctic [*Woodgate and Aagaard*, 2005], and then onto the North Atlantic. Previous studies suggest that the status of the Bering Strait can affect the AMOC's response to freshwater forcing in the North Atlantic [*Shaffer and Bendtsen*, 1994; *De Boer and Nof*, 2004; *Hu et al.*, 2008], and it potentially also could influence the stability of the ice sheet [*Hu et al.*, 2010]. Here we use a fully coupled state-of-the-art climate model with a reasonably high resolution for this application to show for

[1] Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado, USA.
[2] Department of Atmospheric and Oceanic Sciences, University of Colorado at Boulder, Boulder, Colorado, USA.
[3] Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Japan.
[4] Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, Colorado, USA.
[5] National Climatic Data Center, NOAA, Boulder, Colorado, USA.
[6] Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan.

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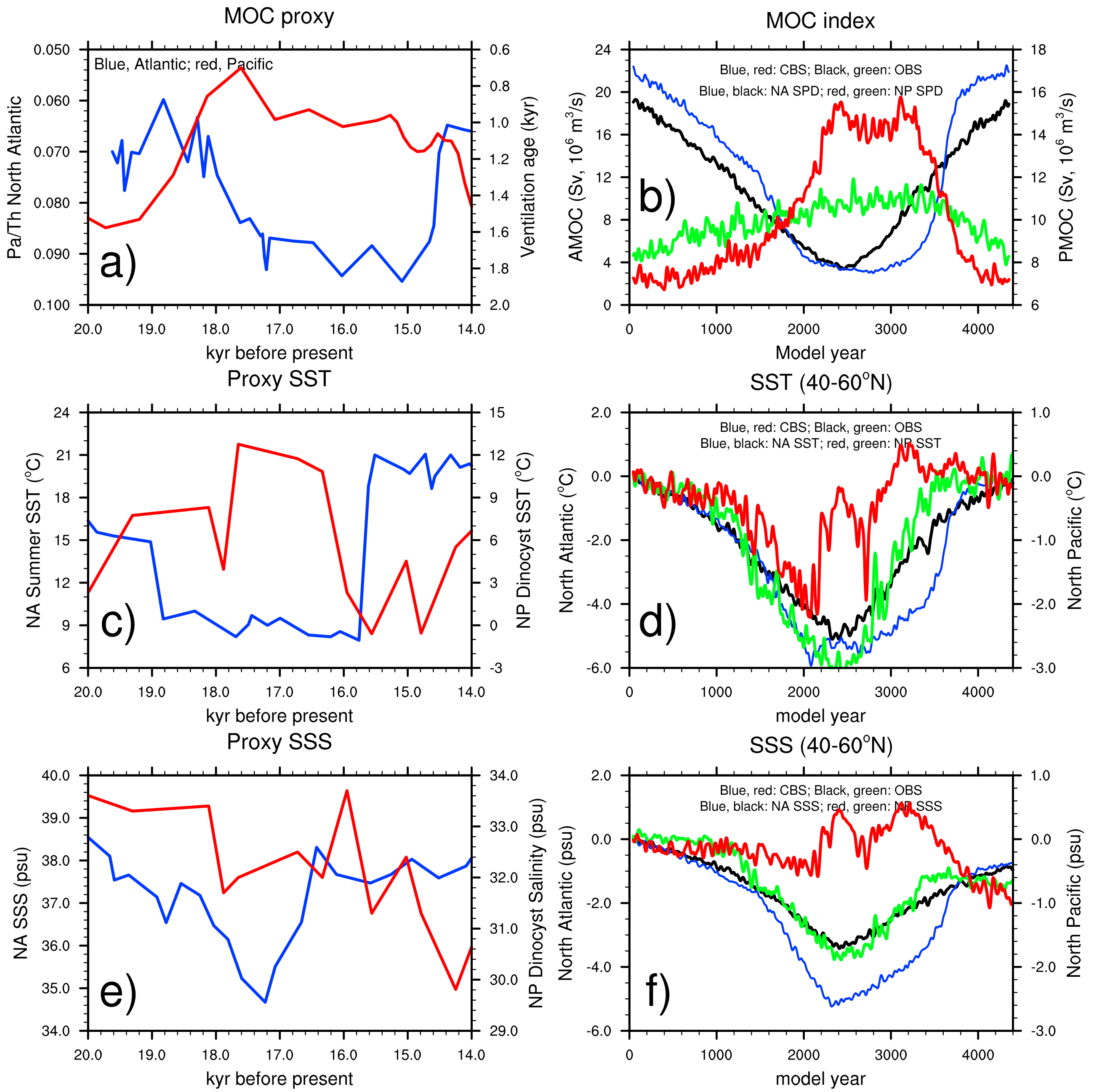

Figure 1. (a) Proxies for AMOC (Ph/Th, blue line [*McManus et al.*, 2004]) and PMOC (ventilation age based on ^{14}C, red line [*Okazaki et al.*, 2010]) during Heinrich 1 event, both axes oriented such that stronger MOC plotted towards the top of the chart. North Atlantic and North Pacific (c) sea surface temperature from foram [*Waelbroeck et al.*, 2001] and dinocyst assemblages [*de Vernal and Pedersen*, 1997], and (e) sea surface salinity from foram assemblages and δ^{18}O [*Chapman and Maslin*, 1999] and dinocyst assemblages [*de Vernal and Pedersen*, 1997]. (b) Time evolving AMOC, PMOC, (d) sea surface temperature and (f) salinity of the North Pacific and North Atlantic basins between 40 and 60°N from our model.

the first time that the seesaw-like climate change between the North Pacific and North Atlantic associated with the reorganization of the global ocean circulation can occur only during glacial times when the Bering Strait is closed.

2. Model and Experiments

[5] The state-of-the-art coupled climate model used in this study is the National Center for Atmospheric Research (NCAR) Community Climate System Model version 3 (CCSM3) [*Collins et al.*, 2006]. The atmospheric component in this version of CCSM3 is the Community Atmospheric Model version 3 (CAM3) using spectral dynamics at T42 resolution (grid points roughly every 240 km) 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 (1/3°) in the equatorial tropics and the North Atlantic and with 40 vertical levels. The sea ice model is the Community Sea Ice Model version 5 (CSIM5) with

elastic-viscous-plastic dynamics, a subgrid-scale thickness distribution, and energy conserving thermodynamics. The land model is the Community Land Model version 3 (CLM3).

[6] Two sensitivity experiments are carried out here in which everything is identical except in one experiment there is an open Bering Strait (OBS), and the other has a closed Bering Strait (CBS). These two simulations are branched from an OBS control run (OBSctrl) and a CBS control run (CBSctrl) respectively. To isolate the effect of the Bering Strait closure on the AMOC and PMOC, the same present-day background climate boundary conditions are used in both simulations. Following *Rahmstorf et al.* [2005], additional freshwater forcing is uniformly distributed in the North Atlantic between 20 and 50°N with an initial value of 200 m^3/s. This freshwater forcing increases linearly every year by 200 m^3/s until AMOC shuts down. Afterwards this additional freshwater forcing decreases linearly by 200 m^3/s per year until reduced to zero. This initial additional freshwater flux is very small and the rate of increment/decrement later on is also very slow, such that it takes 500 model years for the added freshwater forcing to increase by 0.1 Sv. This should be sufficient to keep AMOC in a quasi-equilibrium state throughout our simulation.

3. Results

[7] Figure 1b illustrates the time evolving AMOC and PMOC index, defined as the maximum meridional streamfunction below a depth of 500 meters. In the OBS simulation, the AMOC (black line) collapses after 2200 years with a peak freshwater forcing of 0.44 Sv, then restarts again at year 2400, 200 years after the added freshwater flux begins to reduce. In the CBS simulation, the AMOC (blue line) collapses at year 2100 with a peak freshwater forcing of 0.42 Sv, and restarts at about year 3400 with a freshwater forcing of 0.14 Sv. Thus, the AMOC is off for more than 1000 years in this simulation, but only two hundred years in the OBS simulation, suggesting the CBS simulation represents the H1 event better than the OBS one.

[8] It is clear that when the AMOC collapses in the CBS simulation, the PMOC (red line) significantly strengthens from about 7 Sv to about 15 Sv (Figure 1b). As the AMOC restarts after the freshwater forcing becomes significantly small, the PMOC weakens quickly. This seesaw-like variation of the AMOC and PMOC is similar to that during the H1 event (Figure 1a), agreeing well with a previous observationally-based study [*Okazaki et al.*, 2010] and the standalone ocean model study [*Saenko et al.*, 2004]. However, as AMOC weakens in the OBS simulation, the PMOC (green line) strengthens only slightly from about 8 Sv to 11 Sv. Corresponding to these MOC changes, the meridional heat transport in these two basins varies in a similar way as the MOCs (Figure S1 in the auxiliary material).[1] Therefore, with an open Bering Strait, our simulations suggest a seesaw-like AMOC-PMOC variation is unlikely.

[9] Changes of North Pacific and North Atlantic sea surface temperature (SST) and SSS with the AMOC (Figures 1d and 1e) show more significant differences between the CBS and OBS simulations. In the CBS simulation, initially the North Pacific SST (red line) varies in a similar way as the North Atlantic SST, with both cooling. However, once the AMOC collapses and the PMOC strengthens, the North Pacific SST rises by about 2°C in a short time period despite a continuously North Atlantic cooling (blue line), thus showing a clear seesaw-like climate change as that in the proxy data (Figure 1c). Eventually, the North Pacific SST is about 0.5°C warmer than that in the control simulation. When the AMOC restarts, the North Pacific SST cools to the prehosing level. In the North Atlantic, the SST is cooler/warmer as the AMOC is weaker/stronger. In the OBS simulation, the SST in both North Pacific (green line) and North Atlantic (black line) varies similarly—cooling/warming as the AMOC weakens/strengthens. Thus the SST changes in these two basins in this OBS simulation do not oppose to each other.

[10] In the CBS simulation, the North Pacific SSS (red line) slightly decreases initially as the AMOC weakens, then starts to increase when the AMOC collapses and PMOC strengthens (Figure 1f), agreeing with proxy data (Figure 1e). This higher SSS persists until the AMOC starts to intensify. In the North Atlantic, the SSS (blue line) decreases/increases continuously as the added freshwater forcing becomes greater/weaker. In the OBS simulation, the surface ocean becomes fresher/saltier in both ocean basins as the freshwater forcing strengthens/reduces. Therefore, the resulting surface climate changes in these two ocean basins, which agree with proxy data and previous modeling studies, are only realized in the CBS simulation.

[11] This significantly different response of the AMOC and PMOC, and the associated surface climate changes to the freshwater forcing in the North Atlantic, can be attributed to the change of the mass and freshwater transport at the Bering Strait. As shown in Figures 2a and 2b, when the AMOC weakens in the OBS simulation, the Bering Strait mass and freshwater transports decrease, thus reducing the freshwater convergence in the North Atlantic, and keeping more freshwater in the North Pacific. This freshwater gain in the North Pacific leads to a fresher and more stably stratified upper ocean which prevents the occurrence of deep convection there (Figure S2). At the same time, the surface freshwater input (Figure 2c) in the North Pacific also increases. This is primarily induced by reduced evaporation and increased sea ice melting (Figures 2d–2f) associated with the cooler climate (Figure 1d). Note in this cooler climate, the increase of the winter sea ice production leads to an increased ice melt back in summer. However, the magnitude of this increased surface freshwater input is only about 50% of the anomalous freshwater transport at the Bering Strait. At 40°N, the southward freshwater water transport increases/decreases in a delayed mode with the changes of the Bering Strait freshwater transport (Figure S3). Therefore our results suggest that this anomalous freshwater transport at Bering Strait has played the major role in preventing the PMOC setup in this simulation.

[12] On the other hand, in the CBS simulation (Figures 2c–2f), the surface freshwater input in the North Pacific increases only slightly because of the reduced evaporation and increased sea ice melting related to the initial cooling (Figure 1b) as the AMOC weakens. Once the AMOC collapses, the evaporation increases significantly. This overcomes the effect of the increased precipitation, leading to a more saline North Pacific, resulting in an elevated surface water density (Figure S1), which makes the deep convection to occur in this basin and the PMOC setup. On the other hand, once the AMOC starts to spin

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL050567.

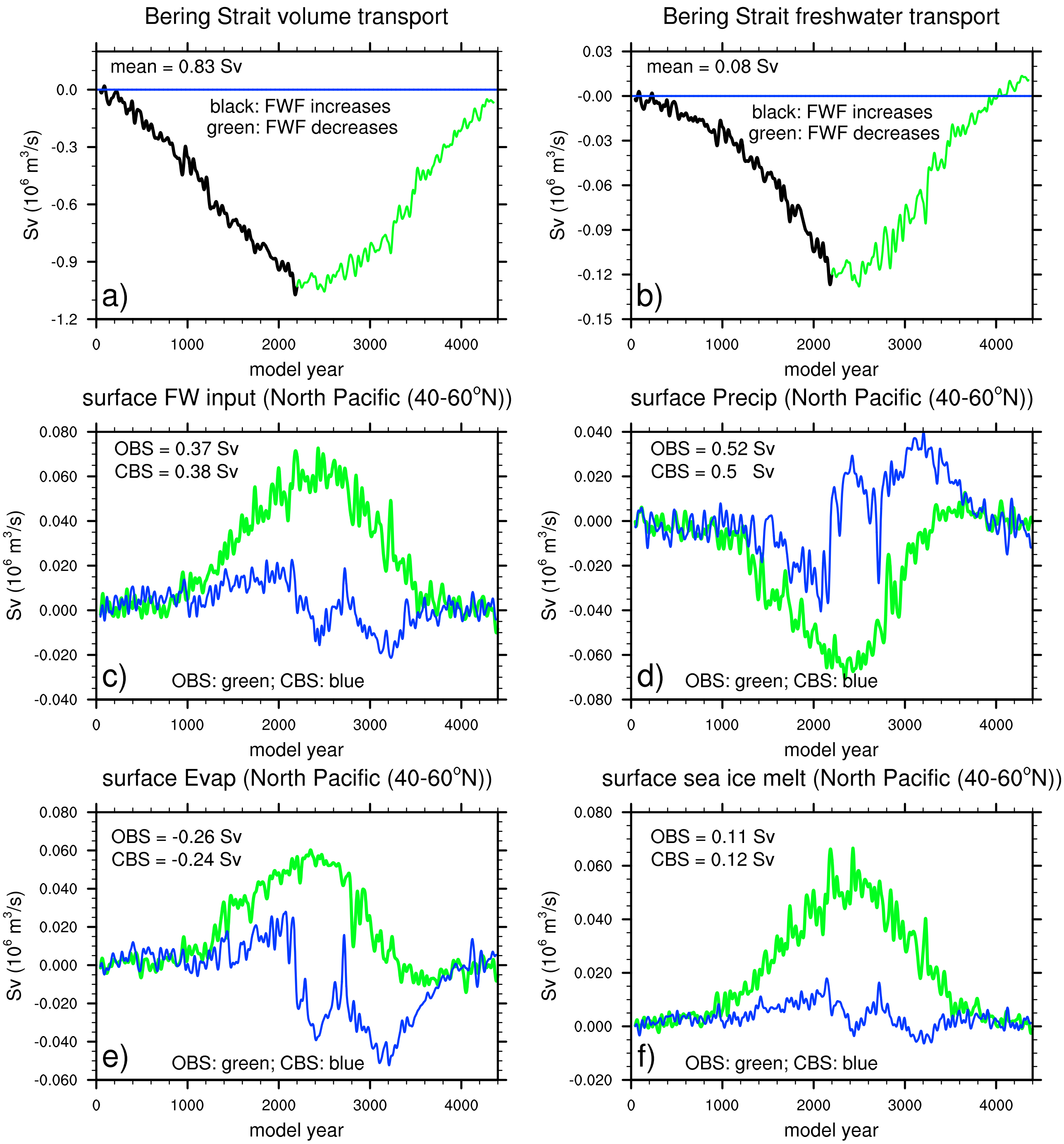

Figure 2. Anomalous Bering Strait (a) mass, (b) freshwater transports (black line indicate freshwater forcing increasing phase, and green line decreasing phase); anomalous total surface (c) freshwater input, (d) precipitation, (e) evaporation, and (f) sea ice melt in the North Pacific between 40 and 60°N. Control mean values for these variables are inserted in the related panels.

up when the freshwater forcing becomes sufficiently small in the North Atlantic, this stronger AMOC pulls more heat from the Pacific into the North Atlantic, leading to a cooling effect and reduced evaporation in the North Pacific. As a result, the oceanic stratification strengthens and the deep convection weakens there, inducing a collapse of the PMOC.

[13] It is worth mentioning that with a Bering Strait closure, the freshwater anomaly in the North Atlantic cannot be transported into the North Pacific as quickly as in the OBS simulation. As a result, the overall temperature and salinity anomalies in the North Atlantic are larger in the CBS run than in the OBS run, especially the salinity. This larger salinity anomaly contributes to a much slower recovery of the deep convection in the North Atlantic in the CBS run after the added freshwater forcing starts to decrease, and a much delayed recovery of the AMOC.

[14] The zonal mean salinity and the meridional streamfunction (MSF) of the Pacific in the control run and their anomalies when AMOC is off in both simulations are shown in Figure 3. In the control simulations, the deep overturning

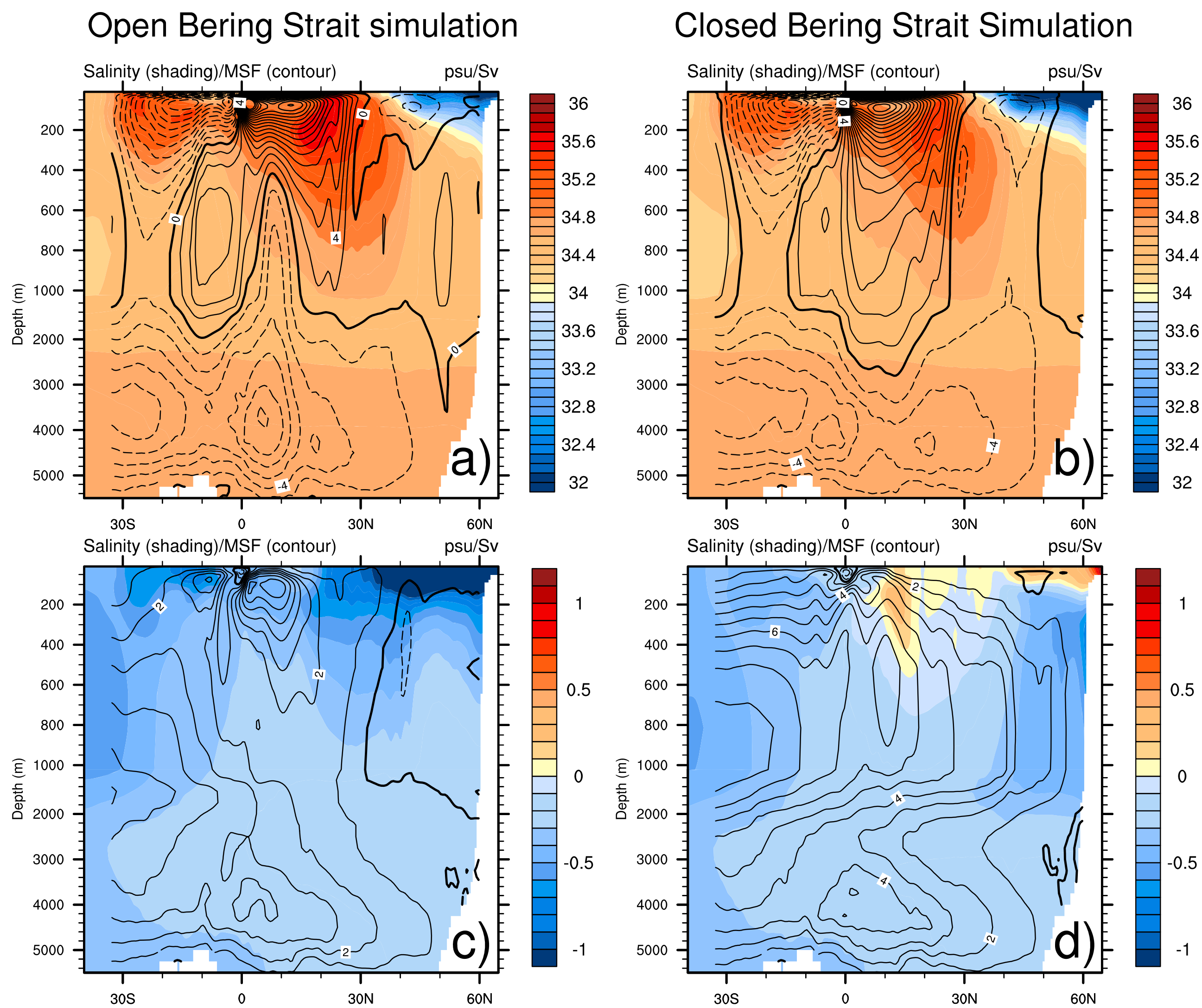

Figure 3. Pacific zonal mean salinity (shading) and meridional streamfuction (contour) in the (a) OBS and (b) CBS control simulations when AMOC is on. (c and d) The zonal mean salinity (shading) and meridional streamfuction (contour) anomaly when AMOC is off. The contour interval is 0.1 psu for salinity, 2 Sv for the meridional streamfunction, and 1 Sv for the meridional streamfunction anomaly.

associated with the Antarctic bottom water is weaker in the CBSctrl run than in the OBSctrl run, but the Pacific subtropical cell in the CBSctrl run is stronger and penetrates deeper than in the OBSctrl run (Figures 3a and 3b). In general, the upper 1000-meters of the Pacific are a bit fresher in the CBSctrl simulation than in the OBSctrl. This is associated with the blocking of the Bering Strait flow in the former simulation.

[15] In the anomalous zonal mean salinity field when AMOC is off, the upper Pacific is much fresher in the OBS run than in the CBS run due to the reduced, or even reversed Bering Strait flow that leads to a freshwater convergence in the North Pacific (Figures 3c and 3d). On the other hand, the upper North Pacific is saltier in the CBS run due to the increased evaporation, which has helped the setup of the PMOC initially, and also helps to maintain the PMOC later on. The freshening signal from the south Pacific is associated with the freshwater divergence from the North Atlantic via the southern oceans in both CBS and OBS simulations. From the anomalous MSF field, it is obvious that the deep cell related to the Antarctic bottom water is significantly reduced in both hosing simulations. In the CBS run, the anomalous MSF shows an overturning cell which is just like that in the Atlantic when AMOC is on. This represents the PMOC where the upper limb transports warmer and saltier water into the subpolar North Pacific. This leads to a warmer and saltier North Pacific, and a seesaw-like climate change between the North Pacific and North Atlantic. However, in the OBS simulation, the slightly strengthened PMOC shown in Figure 1b is mostly due to the strengthening of the Pacific subtropical cell which penetrates deeper than 500 meters when the AMOC is off (Figure 3d). Thus there is no real PMOC setup in this simulation, which leads to the absent of the seesaw-like climate change.

4. Conclusion

[16] Our simulations suggest that the seesaw-like climate change between the North Atlantic and the North Pacific when AMOC severely weakens as identified from paleo-proxy

record [*Okazaki et al.*, 2010] can occur only when the Bering Strait is closed, such as during glacial times. This closed Bering Strait prevents the freshwater anomaly in the North Atlantic to be transported into the North Pacific. As a result, the North Pacific becomes saltier due to changes in the hydrological cycle. This makes the deep convection to occur in the North Pacific, and a PMOC setup. Then, more warm and salty tropical-subtropical water is transported into the North Pacific. The more saline water further enhances deep convection in the North Pacific. On the other hand, with an open Bering Strait, the freshwater anomaly in the North Atlantic is transported into the North Pacific via this Strait, making the upper North Pacific much fresher, and preventing the deep convection to happen in the North Pacific and the PMOC setup. Thus, there are no seesaw-like AMOC and PMOC variations, and seesaw-like climate changes.

[17] In summary, our results suggest that the setup of the PMOC when AMOC collapses may be the crucial condition for a seesaw-like climate change between the North Pacific and the North Atlantic. Moreover, this PMOC setup can only occur when the Bering Strait is closed in our simulations, suggesting that the climate system's response to a major reorganization of the oceanic circulation would be different depending on the status of the Bering Strait. Therefore, the Bering Strait may have played an important role in the past climate changes, and may also influence significantly on the future climate response to greenhouse-gas induced warming [*Hu et al.*, 2011].

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A. Abe-Ouchi, Atmosphere and Ocean Research Institute, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8568, Japan.

M. O. Chikamoto and Y. Okazaki, Japan Agency for Marine-Earth Science and Technology, 2-15 Natsushima-cho, Yokosuka 237-0061, Japan.

W. Han, Department of Atmospheric and Oceanic Sciences, University of Colorado at Boulder, Boulder, CO 80301, USA.

A. Hu and G. A. Meehl, Climate and Global Dynamics Division, National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80305, USA. (ahu@ucar.edu)

C. Morrill, National Climatic Data Center, NOAA, 325 Broadway, Boulder, CO 80305, USA.