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A role for North Pacific salinity in stabilizing North Atlantic climate

Lloyd D. Keigwin[1] and Mea S. Cook[1]

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[1] A simple ocean/atmosphere feedback may reduce the amplitude of climate variability in around the North Atlantic during interglacial compared to glacial states. When climate is warm in the North Atlantic region, the Intertropical Convergence Zone has a relatively northward position, and moisture is exported from the tropical Atlantic to the tropical Pacific. At the same time the east Asian summer monsoon is strong, which helps maintain a positive balance of precipitation over evaporation in the subpolar North Pacific. This is thought to account for lower salinity in the North Pacific relative to the North Atlantic, which, in turn, drives northward flow through the Bering Strait to the northern North Atlantic. Freshening in the North Atlantic by water of Pacific origin suppresses the meridional overturning circulation and reduces the heat flux. The opposite situation exists during cold climate. Thus the combination of atmospheric vapor transport and flow through Bering Strait tends to cool the North Atlantic region when warm and warm the region when cool.

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1. Introduction

[2] A first-order and unexplained phenomenon in climate during the last glacial cycle is the repeated occurrence of rapid changes in air temperature over Greenland, sea surface temperature and salinity in the North Atlantic, and ventilation of the North Atlantic. These and other climate changes, known as Dansgaard-Oeschger oscillations, are expressed in many kinds of proxy data at many locations and are thought to be transmitted around the Northern Hemisphere by the atmosphere [*Zhang and Delworth*, 2005; *Denton et al.*, 2005]. In contrast, climate of the past 11,000 years (the Holocene) has been unusually stable [*Dansgaard et al.*, 1993]. There is good evidence in marine records [*Keigwin and Jones*, 1989; *Bond et al.*, 1997] for the kind of millennial-scale variability on land that was first compiled by *Denton and Karlen* [1973], but the amplitude of Holocene climate variability around the North Atlantic was much lower than it was during the ice age [*Alley et al.*, 1997]. Tropical climate may not display this difference in amplitude. For example, the variability of planktonic foraminiferal δ^{18}O from the west equatorial Pacific doesn't change appreciably from the glacial [*Stott et al.*, 2002] to interglacial conditions [*Stott et al.*, 2004].

[3] Here we suggest that variability in the transport of relatively fresh water from the North Pacific to the North Atlantic through Bering Strait may help stabilize climate in the North Atlantic region when sea level is high and the strait is flooded. The annual average northward transport of $\sim$0.8 Sv [*Aagaard and Carmack*, 1989; *Woodgate and Aagaard*, 2005] is thought to be a consequence of the topography of the strait and the steric height difference between the North Atlantic and the North Pacific [*Stigebrandt*, 1984]. According to the most recent calculations with respect to an 800 m level of no motion, sea level in the Bering Sea is 70 cm above that on the Chukchi Slope, with about two thirds of this difference due to lower salinity in the Bering Sea [*Aagaard et al.*, 2006]. Northward flow through Bering Strait of low-salinity water accounts for about a third of the Arctic's freshwater budget [*Aagaard and Carmack*, 1989; *Serreze et al.*, 2006]. Low salinity in the North Pacific relative to the North Atlantic is probably maintained by some combination of the cooler surface waters there that evaporate less [*Warren*, 1983], by vapor flux from the Atlantic across Central American lowlands [*Weyl*, 1968; *Zaucker et al.*, 1994; *Benway et al.*, 2006], and by vapor flux and runoff from the Asian Monsoon that persists in the subpolar gyre because of the zonality of the subpolar-subtropical front [*Emile-Geay et al.*, 2003].

2. Salt Oscillators and Climate

[4] Many authors have described mechanisms of climate change that rely on transport of fresh water in the climate system. *Broecker et al.* [1990] proposed that a "salt oscillator" operated in the glacial North Atlantic, and that this mechanism could affect the meridional overturning circulation (MOC). This model involved variable export of North Atlantic Deep Water (NADW) as a means of removing salt from the North Atlantic, ice melt as a source of fresh water in the North Atlantic, and atmospheric export of water across Central America. (The role of Central American vapor transport was first emphasized by *Weyl* [1968].) One could argue that the salt oscillator has not operated the same way (or at all) during the Holocene because there is no evidence of climate change similar to the D-O oscillations of the glacial epoch. However, the Broecker et al. salt oscillator mechanism did not consider Bering Strait because for most of the last glacial cycle, when sea level was below -50 m, the strait was dry land.

[1] Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.

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[5] *Shaffer and Bendtsen* [1994] used a three-box model of ocean MOC to evaluate the response of the North Atlantic and North Pacific Oceans to changes in temperature and freshwater fluxes. They showed that increased flow of relatively fresh water through Bering Strait could lower the salinity of surface water in the northern North Atlantic and cause a reduction in the MOC. The sense of this result is supported by general circulation models (GCMs). *Goosse et al.* [1997] reported that with an open Bering Strait the throughflow induces freshening of the North Atlantic and a 6% reduction in the intensity of NADW production relative to a scenario with Bering Strait closed. They criticized the earlier contrary result of *Reason and Power* [1994] because the strong surface salinity restoring in their GCM offset the effect of salinity feedback in Bering Strait. Using a free surface ocean GCM, *Hasumi* [2002] found that the difference between an open and closed Bering Strait accounts for a 17% difference in Atlantic Ocean deep circulation. *Wadley and Bigg* [2002] used an ocean GCM specially designed to evaluate the role of Bering Strait and the Canadian Archipelago on North Atlantic overturning. Their analysis showed overturning increased as much as a factor of 2 when both straits are closed, with most of the difference due to convection in the Labrador Sea.

[6] On the other hand, it has been suggested that feedbacks through Bering Strait could help maintain the stability of present-day climate. For example, *DeBoer and Nof* [2004] discuss the intriguing idea that an open Bering Strait helps stabilize the MOC through reversals in the flow direction. Using the modified "Island Rule" [*Godfrey*, 1989], they argue that strong zonal winds in the Southern Ocean push ~4 Sv of water into the South Atlantic, which today is eventually exported via NADW production. In the case of a flux of fresh water to the North Atlantic large enough to shut down the MOC, *DeBoer and Nof* [2004] contend that this 4 Sv must exit the Atlantic via the Arctic, carrying the anomaly with it through Bering Strait. This could restore the salinity of the North Atlantic within several years. In the case of a small freshwater flux that might suppress but not shut down the MOC, *DeBoer and Nof* [2004] conclude the anomaly would be removed from the surface ocean by deep convection in the North Atlantic within a decade with no flow reversal through Bering Strait. At present, there is no strong multiproxy evidence for complete shut down of NADW since flooding of Bering Strait at ~12 ka [*Keigwin et al.*, 2006], although low $\delta^{18}O$ evidence for surface ocean freshening during the largest Holocene climate event, at 8.2 ka [*Keigwin et al.*, 2005; *Came et al.*, 2007], and coarsening sediments in a North Atlantic piston core [*Ellison et al.*, 2006] raise the possibility that the MOC was affected at that time.

3. Ocean/Atmosphere Feedbacks and Flow Through Bering Strait

[7] We propose a simple conceptual model with feedbacks both at Bering Strait and in the low-latitude atmosphere that combined may account for the relative stability of Holocene climate compared to glacial climate (Figure 1). Assume the modern situation, with a warm North Atlantic, a strong MOC, and lowering salinity in intermediate and deep water [*Dickson et al.*, 2002; *Curry et al.*, 2003]. (By making this assumption we do not suggest that lowering salinity over recent decades is related to Bering Strait or global warming.) If North Atlantic salinity were to continue to decline, the MOC might eventually weaken, the northward heat flux would decrease, and the North Atlantic region would cool. A colder North Atlantic would drive the Intertropical Convergence Zone (ITCZ) southward [*Chiang and Bitz*, 2005; *Broccoli et al.*, 2006]. This diverts moisture that is transported at present across Central America to the Pacific, making it saltier. In addition, a weaker east Asian monsoon would deliver less freshwater to the subpolar gyre [*Emile-Geay et al.*, 2003]. North Pacific salinity would increase, and this would cause decreased flow through Bering Strait, and increased salinity in the North Atlantic. The MOC would increase and the cycle would continue.

[8] Paleodata and modeling [*Chiang and Bitz*, 2005; *Broccoli et al.*, 2006] support the connection between climate and ITCZ movement. The ITCZ has shifted southward by about 10° throughout the Holocene in association with long-term cooling [*Haug et al.*, 2001]. That trend is orbitally driven and is presumably insensitive to processes related to Bering Strait. In an extreme example of southward ITCZ shift, presently arid NE Brazil (Figure 1) became humid, as evidenced by cave deposits that occur only during the Younger Dryas, Heinrich events, and other abrupt coolings of the past 200 ka [*Wang et al.*, 2004]. Geochemical data from the same cold events indicate elevated salinity in the east equatorial Pacific [*Leduc et al.*, 2007]. Models of less extreme behavior show that reduced export of Atlantic water vapor across Central American lowlands could lower North Atlantic salinity, and hence reduce the MOC, if it were to persist on the order of decades [*Schmittner et al.*, 2000]. *Stigebrandt* [1984] estimated that the residence time for fresh water in the upper 1100 m of the North Pacific is about 1000 years, and from that he estimated the Atlantic-Pacific salinity difference should be stable for periods of the order hundreds of years.

[9] Although vapor flow across Central America has traditionally been thought of as the source of lower salinity in the North Pacific [*Weyl*, 1968; *Zaucker et al.*, 1994], *Warren* [1983] and *Emile-Geay et al.* [2003] show that the zonality of the wind stress in the North Pacific isolates the subpolar gyre from the subtropics which allows it to remain cold and fresh. Whereas low salinity of eastern subtropical Pacific origin may eventually mix northward, given as much as 1000 years, vapor flux from the tropical Atlantic may not actually contribute to the salinity feedback on shorter timescales as proposed above. The reason is that as the eastern Pacific freshens from this transport, the tropical Atlantic gets saltier (opposite to the *Schmittner et al.* [2000] situation), and that would tend to compensate for local warming and freshening [*Latif et al.*, 2000].

[10] Another source of moisture to the subpolar North Pacific may be the west tropical Pacific. Recently, *Emile-Geay et al.* [2003] suggested that salinity in the North Pacific is lower than in the North Atlantic not because of lower SSTs and reduced evaporation, as suggested by *Warren* [1983], but because of the influence of atmospheric

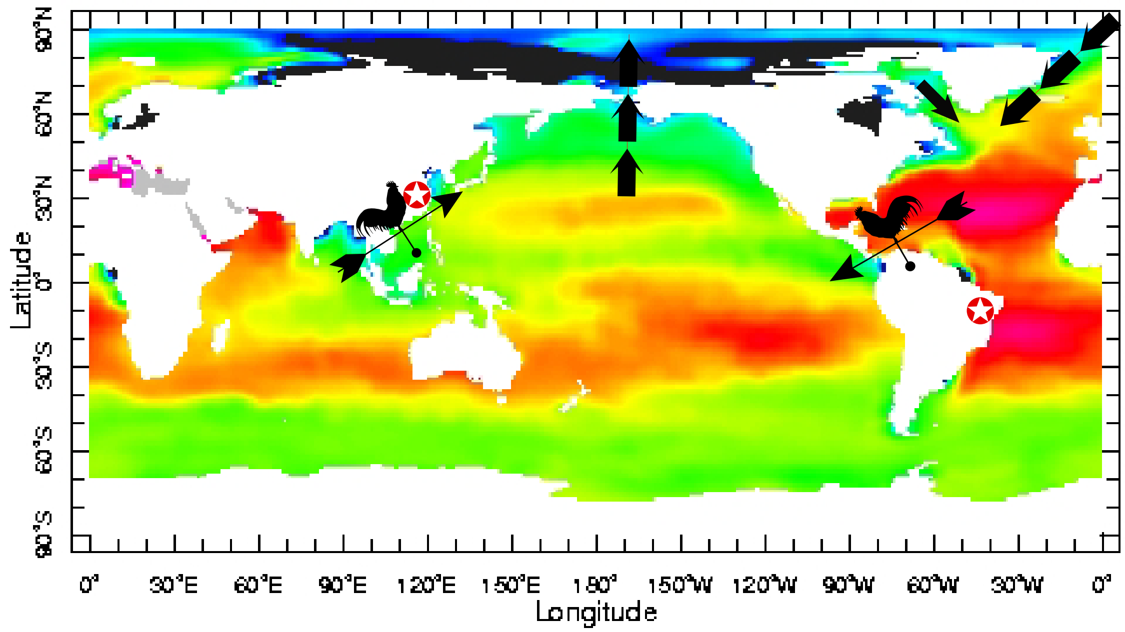

Figure 1. Some important paths of atmospheric (weather vane) and oceanic (arrows) water transport in the climate system. Dark blue marks annual average sea surface salinity <30 psu, and magenta marks salinity of 38 psu. It is proposed here that cold climate episodes in the Holocene would tend to increase the salinity of the North Pacific. This would occur because during cold events vapor export from the Caribbean is reduced as the Intertropical Convergence Zone (ITCZ) shifts to the south, and vapor transport to the North Pacific subpolar gyre is reduced as the Asian summer monsoon weakens. These two atmospheric effects are well documented by cave deposits in northeastern Brazil and eastern Asia (stars). Such changes in moisture transport would increase the steric height of the North Pacific relative to the North Atlantic, and that would decrease the transport of fresh water through Bering Strait to the North Atlantic. Buildup of salt in the northern North Atlantic would lead to increased export of North Atlantic Deep Water, warmer climate in the North Atlantic region and perhaps beyond, and northward movement of the ITCZ.

circulation. Their analysis shows that in the summertime the Asian monsoon transports moisture from the west Pacific warm pool to the subpolar gyre along the western margin of the northern North Pacific, and that in the wintertime moisture is driven farther to the east over the Gulf of Alaska by cold dry winds that originate over the Asian continent. The oxygen isotope record from Hulu Cave indicates cooler and drier climate (less intense Asian monsoon) during all the cold episodes of the last glaciation [*Wang et al.*, 2001], and results from Dongge Cave [*Wang et al.*, 2005] show that the same millennial-scale process continued through the Holocene, but with a reduced amplitude. Thus salinity in the North Pacific could increase during cold epochs because of reduced moisture transport on both the eastern tropical and western mid latitude margins.

[11] Although the east Asian monsoon mechanism may affect subpolar North Pacific salinity more directly (and rapidly) than vapor flux across Central America, these two processes are complementary in their ability to increase North Pacific salinity during cold climate events. Therefore it is plausible that climate cooling could have decreased the Atlantic-Pacific sea level difference, and decreased the northward flow through Bering Strait. This, of course, coupled with the mechanisms discussed by *Broecker et al.* [1990], would lead to increased salinity in the North Atlantic, increased MOC, increased warming, and northward movement of the ITCZ.

4. Summary and Discussion

[12] In summary, various studies have attempted to explain both the Holocene climate stability and glacial climate variability using either atmospheric moisture transport from the tropics or freshwater transport through Bering Strait. However, in reality, the stability of Holocene climate, at least in the North Atlantic region, probably involves both types of transport and their negative feedbacks. This hypothesis is consistent with the available Holocene paleoclimate data on land, and will be testable with high-resolution paleosalinity data in the subpolar North Atlantic and North Pacific Oceans. It should also be amenable to modeling by coupled ocean-atmosphere GCMs, provided that transport through the 85 km wide Bering Strait is enabled. At present, the *Hasumi* [2002] and *Wadley and Bigg* [2002] treatments of the effects of Bering Strait throughflow on North Atlantic MOC are the most sophisticated, but their models do not explicitly consider changes in vapor transport by the Asian Monsoon or by movement of the ITCZ. Because our proposed climate oscillator depends on a flooded Bering Strait, it may account for the

observation that large climate variability on millennial timescales throughout the late Pleistocene was restricted to the long intervals when the ice volume effect on seawater δ^{18}O was at least -0.30‰ (=sea level lowering of at least 30 m) [*McManus et al.*, 1999].

[13] It is not clear how the relatively slow mechanism we describe could reduce the amplitude of climate oscillations in the Holocene compared to glacial times. It might require a complementary process with a faster response time. To begin with, the residence time of North Pacific surface waters may be somewhat less than the $\sim$1000 year estimate of *Stigebrandt* [1984]. As noted above, he assumed the North Pacific surface layer was 1100 m thick, but *Aagaard et al.* [2006] show that the deepest continuous pressure surface connecting the North Pacific and the Arctic lies at about 800 m. *Aagaard et al.* [2006] also describe a connection between interannual variability in flow through the strait and steric height. Moorings in Bering Strait show evidence for a small decrease in transport between 1994 and 2002, which may have been forced by a coeval decrease in steric height difference between the Bering Sea and the nearby Arctic Ocean of $\sim$20%. At the same time there was a small decrease in the salinity of Bering Strait waters [*Woodgate and Aagaard*, 2005]. In addition, it is now known that some Bering Strait water takes a shortcut to the North Atlantic. A shelf break jet has recently been described in the Chukchi and Beaufort Seas with a mean transport of 0.39 Sv [*Pickart*, 2004; *Pickart et al.*, 2005]. This current transports a significant fraction of Bering Strait water eastward toward the Canadian Archipelago (the remainder is advected offshore in eddies and is thought to maintain the Arctic halocline). Using nitrate to phosphate ratios as a tracer for North Pacific water, *Jones et al.* [2003] showed that the various passages in the Canadian Archipelago contain upper halocline water that is dominantly of Pacific origin. These recent observations suggest the system is capable of fast response to remote forcing by freshwater sources along the Bering shelf and the Gulf of Alaska.

[14] A final question comes to mind: Are there mechanisms that rapidly deliver Pacific water to the coastal currents that feed into Bering Strait? The answer is yes. Figure 6 of *Emile-Geay et al.* [2003] shows that the greatest wintertime moisture convergence in the subpolar Pacific occurs in the Alaskan Gyre, and especially along the west coast of North America. Some of this moisture must condense and fall as snow on the western cordillera, only to run off in the summer. *Weingartner et al.* [2005] showed that most of this freshwater entering the coastal Gulf of Alaska is transported poleward in the Alaska Coastal Current and does not mix offshore. This water is a first-order quantity in the Bering Sea freshwater budget [*Weingartner et al.*, 2005]. However, significant water vapor must make it over the cordillera at high altitude because the Mackenzie drainage basin is dominated by North Pacific moisture. In autumn, winter, and spring, moisture is transported from the subtropical and mid latitude Pacific Ocean by extratropical cyclones in what is known as an atmospheric river [*Smirnov and Moore*, 2001]. This transport is probably part of the wintertime flow described by *Emile-Geay et al.* [2003]. Although the Mackenzie is the fourth largest river draining into the Arctic Ocean, its transport ($\sim$0.01 Sv) is small compared to the $\sim$0.3 Sv estimated by *Emile-Geay et al.* [2003] for the excess of precipitation over evaporation for the North Pacific. Nevertheless, at least some of that fresh water probably joins the shelf break current and heads directly for the passages to the Atlantic in the Canadian Archipelago with little dilution [*Jones et al.*, 2003]. These two sources of low-salinity Pacific water may provide the rapid feedback necessary to prevent Holocene climate variability from reaching Dansgaard-Oeschger proportions.

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M. S. Cook and L. D. Keigwin, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA. (lkeigwin@whoi.edu)