North Atlantic salinity oscillations linked to atmospheric and ocean circulation changes over the last glacial cycle

MATTHEW SCHMIDT* AND HOWARD SPERO

Department of Geology, University of California Davis, USA

*Now at Department of Oceanography, Texas A&M University, USA; schmidt@ocean.tamu.edu

Evaporation, precipitation and atmospheric water vapor transport play an important role in maintaining North Atlantic Meridional Overturning Circulation (AMOC) through their influence on salinity (Broecker, 1989; Broecker et al., 1990; Zaucker and Broecker, 1992). Net evaporation exceeds precipitation in both the Caribbean and western North Atlantic subtropical gyre, elevating Gulf Stream sea surface salinity (SSS) as waters circulate northward through the subtropics (Broecker et al., 1990; Curry et al., 2003). The excess salt advected to the North Atlantic is critical in maintaining modern AMOC (Broecker, 1991).

It is generally agreed that the abrupt climatic shifts that characterized Dansgaard-Oeschger (D-O) cycles in the Greenland ice cores were triggered by changes in North Atlantic surface water density at the sites of overturning circulation (Boyle, 2000; Oppo and Lehman, 1995; Rasmussen and Thomsen, 2004). While warm interstadials are characterized by a circulation pattern similar to today (Fig. 1), the northward flow of warm, salty surface waters into the sub-polar North Atlantic may have been reduced and/or subducted below a cold, fresh surface layer during stadials. A better understanding of past surface temperature and salinity distributions is needed to determine the role of density-driven changes in ocean circulation.

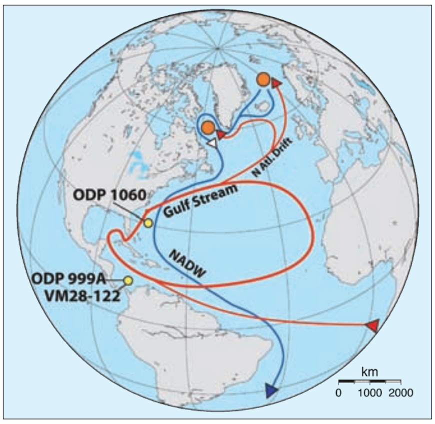

*Figure 1: Modern N. Atlantic surface (**red**) and deep water (**blue**) circulation and location of Caribbean cores ODP 999A (12°45'N, 78°44'W; 2,827 m; 4 cm/kyr sed. rate) and VM28-122 (11.56°N, 78.41°W; 3,623 m; 4-15 cm/kyr sed. rate) and N. Atlantic subtropical gyre core ODP 1060 (30°46'N, 74°28'W; 3480 m; 20-53 cm/kyr sed. rate). Orange circles indicate sites of deepwater formation in N. Atlantic.*

Reconstructing past surface-salinity change

The oxygen isotopic composition of foraminiferal calcite ($\delta^{18}O_c$) is a function of both temperature and the isotopic composition of the seawater ($\delta^{18}O_{SW}$) in which an individual precipitates its shell. Because $\delta^{18}O_{SW}$ covaries linearly with SSS (Charles and Fairbanks, 1990), shell $\delta^{18}O_c$ can be used to estimate past SSS change if $\delta^{18}O_{SW}$ and temperature can be deconvolved. Based on this approach, Schmidt

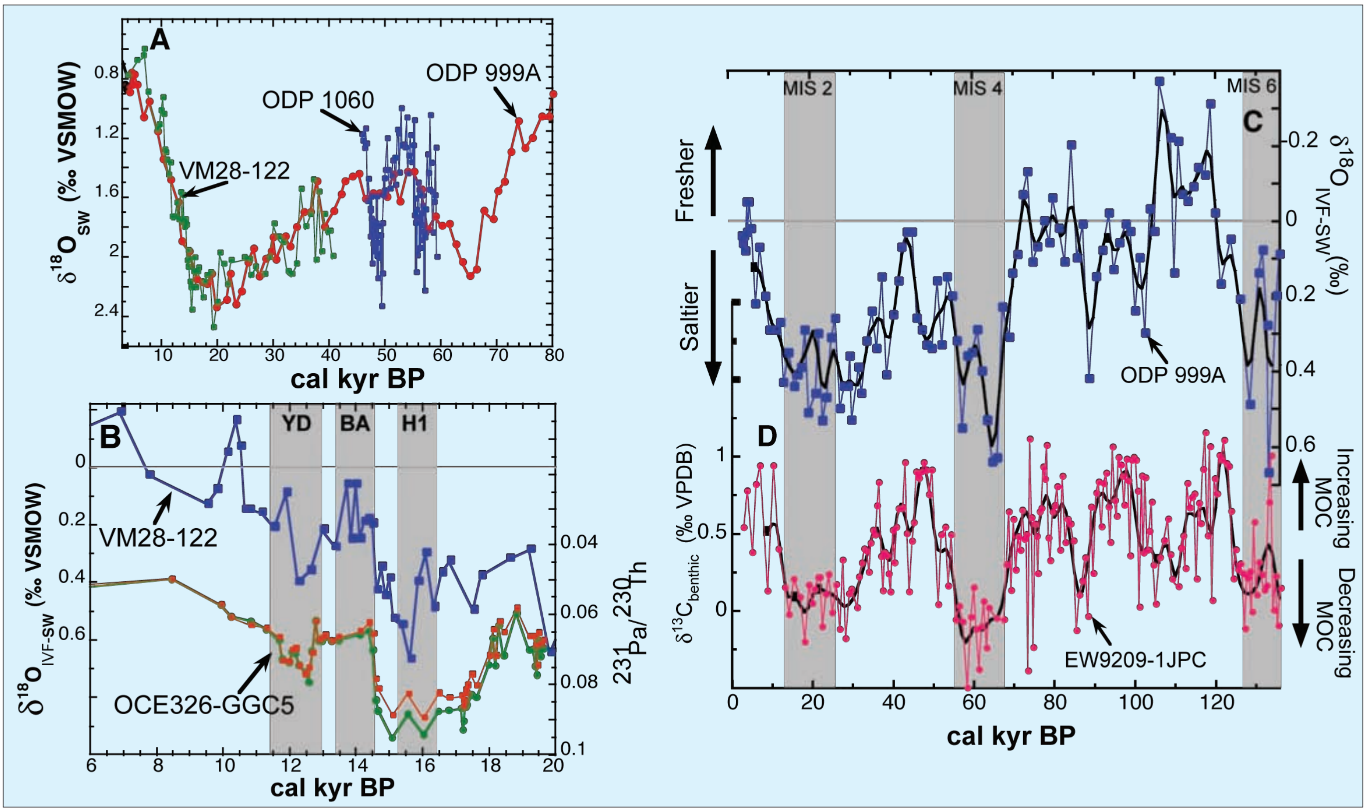

*Figure 2: **A**) Computed $\delta^{18}O_{SW}$ records from the Caribbean at sites ODP 999A (red line) and VM28-122 (green line) and in the North Atlantic gyre at ODP 1060 (blue line) during the last glacial cycle. $\delta^{18}O_{SW}$ values calculated from Mg/Ca-derived SST and $\delta^{18}O_c$ in planktic foraminifer G. ruber. To compare regional $\delta^{18}O_{SW}$ change between Caribbean and gyre site 1060, modern $\delta^{18}O_{SW}$ difference between the two sites (0.3‰) was subtracted from ODP 1060 values to account for additional evaporation that occurs as waters transit between the tropics and subtropics. After removing global $\delta^{18}O_{SW}$ change due to continental ice volume (Waelbroeck et al., 2002), local $\delta^{18}O_{SW}$ records were normalized to modern regional value, resulting in ice volume free $\Delta\delta^{18}O_{IVF-SW}$ record from VM28-122 (**B;** blue line) and 999A (**C;** blue line) during the last glacial cycle. Note the rapid salinity decrease recorded in the Caribbean at VM28-122 at 14.6 cal kyr BP corresponds to a decrease in $^{231}Pa/^{230}Th$ ratios in Bermuda Rise core OCE 326-GGC5 (**B;** red line) (McManus et al., 2004), indicating a strengthening of AMOC at the beginning of BA. Shaded bars also illustrate Heinrich Event 1 (H1) and Younger Dryas (YD). **C**) $\Delta\delta^{18}O_{IVF-SW}$ from ODP 999A (black line is a low-pass (5 kyr) filter with 5-point filter weight running through raw data (blue line)). Benthic $\delta^{13}C$ record (**D**) (black line is a low-pass (5 kyr) filter with 10-point filter weight) from Ceara Rise core EW9209-1JPC (5°N, 43°W; 4,056 m; pink line) indicates times of reduced AMOC (lower $\delta^{13}C$)(Curry and Oppo, 1997) when $\Delta\delta^{18}O_{IVF-SW}$ in ODP 999A are enriched.*

et al. (2004; 2006a, 2006b) combined Mg/Ca-paleothermometry with $\delta^{18}O_C$ measurements on the surface-dwelling foraminifers *Globigerinoides ruber* (white variety) from western Caribbean cores ODP 999A and VM28-122, and from the western North Atlantic gyre site ODP 1060 to reconstruct past variation in tropical/subtropical $\delta^{18}O_{SW}$ (Figs. 1 and 2A).

After removing the influence of continental ice volume on global $\delta^{18}O_{SW}$ (reported as $\Delta\delta^{18}O_{IVF-SW}$; ice volume free seawater), Schmidt et al. (2004) showed that $\Delta\delta^{18}O_{IVF-SW}$ values were more positive than modern seawater by ~0.5 to 0.6‰ during glacial marine isotope stages (MIS) 2, 4 and 6 in the western Caribbean (Fig. 2C). Positive values indicate elevated SSS due to the removal of excess $H_2^{16}O$ through evaporation. In contrast, ice volume corrected interglacial $\delta^{18}O_{SW}$ values were indistinguishable from modern values. If the freshwater $\delta^{18}O$ value of Caribbean rainfall during the Last Glacial Maximum (LGM) was similar to the modern value, as some models suggest (Jouzel et al., 2000), the $\delta^{18}O_{SW}$ shifts indicate that Caribbean SSS was ~2.5 psu higher during glacial phases.

Schmidt et al. (2006a) examined the question of whether subtropical North Atlantic SSS varied on millennial timescales using a $\delta^{18}O_{SW}$ record from ODP Site 1060 (Fig. 3A). $\delta^{18}O_{SW}$ showed that abrupt D-O warming events (Fig. 3C) coincided with rapid SSS reductions in the North Atlantic gyre, while gyre salinity increased substantially during cold stadials. Using modern relationships, the average stadial-interstadial $\delta^{18}O_{SW}$ values indicate millennial-scale SSS enrichments of 0.7 to 1.5 psu during stadials. Importantly, absolute reconstructed $\delta^{18}O_{SW}$ from the gyre agree with reconstructed $\delta^{18}O_{SW}$ from Caribbean site 999A during the overlapping MIS 3 time period when the modern $\delta^{18}O_{SW}$ difference between these locations is accounted for (Fig. 2A). This comparison provides internal consistency, indicating that the reconstructed tropical/subtropical salinity shifts are robust. We note that the large amplitude SSS variability observed in the gyre during MIS 3, but absent in the Caribbean, is a result of sedimentation rates that are 8-15 times higher at site 1060 than at 999A.

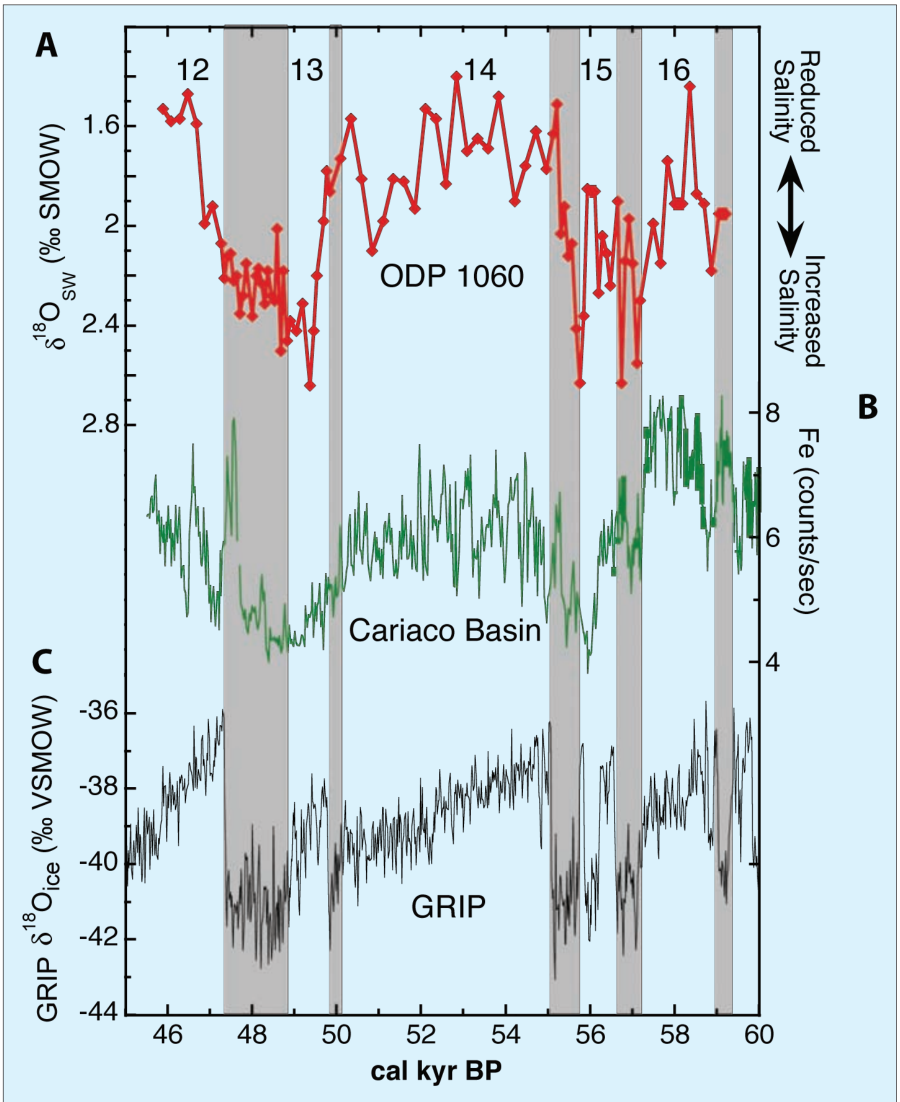

Figure 3: Salinity variation at ODP site 1060 during MIS 3. ***A)*** *Computed $\delta^{18}O_{SW}$ from site 1060;* ***B)*** *Fe content (counts/sec) from Cariaco Basin core ODP 1002 (Peterson et. al., 2000), adjusted to the GRIP age model;* ***C)*** *GRIP $\delta^{18}O_{ICE}$ record (Johnsen et al., 2001). Cold stadials in the GRIP record are marked by more arid conditions in the western tropical Atlantic (lower Fe concentrations) and elevated gyre salinities (increased $\delta^{18}O_{SW}$ values at site 1060). Note the salinity increases (as $\delta^{18}O_{SW}$) associated with the shaded stadial events and the reduced salinities associated with the numbered interstadials 12-16.*

North Atlantic SSS and ocean circulation

It is generally accepted that cold periods in the North Atlantic are associated with reduced AMOC. Benthic foraminiferal $\delta^{13}C$ oscillations from the deep western tropical Atlantic reflect the relative strength of North Atlantic Deep Water (NADW) (high $\delta^{13}C$) and Antarctic Bottom Water (low $\delta^{13}C$) production. $\Delta\delta^{18}O_{IVF-SW}$ values from ODP 999A show that the positive salinity shifts that characterize cold glacial periods occur when western tropical Atlantic benthic $\delta^{13}C$ is reduced and AMOC is weak (Curry and Oppo, 1997) (Fig. 2D). As AMOC results in the export of cold, salty NADW, reduced AMOC during glacial intervals may contribute to the accumulation of salt in the north Atlantic.

Comparison of VM28-122 $\Delta\delta^{18}O_{IVF-SW}$ values with the Bermuda rise record of sedimentary $^{231}Pa/^{230}Th$ ratios (a proxy for the strength of AMOC) (McManus et al., 2004) over the last deglacial reveals that Caribbean SSS decreased rapidly at the onset of the Bølling-Allerød (BA), just as the $^{231}Pa/^{230}Th$ record suggests that AMOC resumed (Fig. 2B). During the brief period of BA warmth in the North Atlantic, Caribbean salinity reduced significantly, reaching a minimum between 14.5-13.7 cal kyr BP. Given the saline conditions that existed in the Caribbean during the early deglaciation, it has been proposed that excess salt advecting from the Caribbean at ~14.6 cal kyr BP (Fig. 2B) may have helped offset the low-salinity conditions that existed in the North Atlantic as a result of Heinrich Event 1 (Schmidt et al., 2004).

Tropical atmospheric circulation changes were also a major contributor to shifts in glacial/stadial-interglacial/interstadial SSS. Fe and Ti concentrations in Cariaco Basin core ODP 1002 suggest the Intertropical Convergence Zone (ITCZ) migrated southward during cold stadial and northward during warm interstadial events, resulting in reduced (southward) or elevated (northward) freshwater flux over northern South America and into the North Atlantic (Peterson et al., 2000) (Fig. 3B). Wet/dry oscillations in the ODP 1002 Fe record covary with fresher/saltier conditions at site 1060 (Fig. 3A). Furthermore, general circulation model simulations predict increased northeast Trade Wind strength during periods of high-latitude cooling, associated with an intensification of the subtropical high pressure over the North Atlantic gyre (Lohmann, 2003; Vellinga and Wood, 2002; Vellinga and Wu, 2004). These conditions result in a precipitation deficit in the tropical/subtropical North Atlantic, coupled with a freshening of the tropical/subtropical South Atlantic. Covariation between shifts in the Atlantic ITCZ, as inferred from the Cariaco Basin Fe record, and changes in North Atlantic gyre salinity suggest that a similar oscillation may have operated in the Atlantic during MIS 3 on millennial timescales, resulting in elevated North Atlantic gyre SSS during stadials.

Based on these results, it appears that surface waters in the Caribbean and the subtropical gyre became exceptionally salty during glacial/stadial intervals over the last 136 kyr. Correlations between tropical/subtropical SSS change, inferred AMOC variability and meridional shifts in the ITCZ suggest that changes in ocean circulation and the tropical hydrological cycle combined to alter the glacial/stadial Atlantic salinity budget. Results indicate that as the ITCZ migrated southward during stadials, water vapor supply to the North Atlantic decreased and/or water vapor removal increased (Xie et al., 2007). This lead to the accumulation of salt in the tropical/subtropical North Atlantic, which was not advected out of the basin due to reduced AMOC. Therefore, the hydrological cycle may act as a negative feedback during weak phases of AMOC, increasing North Atlantic surface water density and preconditioning the system for a return to an interstadial mode of strong AMOC. More intriguing is the possibility that these elevated stadial gyre salinities played a critical role in maintaining North Atlantic SSS high enough to allow for the rapid resumption of North AMOC, in spite of increased freshwater input associated with interstadial warming events.

Note

All data are archived at the NOAA Paleoclimatology Database: www.ncdc.noaa.gov/paleo/

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The bipolar seesaw on the Iberian margin stretching over the past 420,000 years

Joan O. Grimalt[1] and Belen Martrat[2]

[1]Department of Environmental Chemistry, Institute of Chemical and Environmental Research, Barcelona, Spain; jgoqam@cid.csic.es

[2]Spanish National Research Council, Barcelona

Continuous cores of ancient ice recovered from Greenland and Antarctica contain unique records of changes related to the air temperature. While several ice age cycles have been recovered for Antarctica (Jouzel et al., 2007), only one climate cycle (i.e., interglacial followed by a glacial period) has been recovered from Greenland (NGRIP members, 2004). This fact presents a challenge if we are to estimate the climate variability at European latitudes, as past temperatures in Antarctica rose and fell gradually, whereas sudden transitions occurred in the Greenland record. A possible explanation for this interhemispheric climate pattern is thresholds and nonlinear hysteresis behavior (i.e., the state of the dynamic system depends on its history) in the climate system (Stocker and Wright, 1991).

The Iberian Margin is a real laboratory for describing hydrological conditions from surface and deepwater masses, from the northern Atlantic and Antarctic regions, respectively. At this location, the surface temperature record very closely resembled the temperature record over Greenland, whereas the deep-temperature estimates were in line with Antarctica, hence providing the opportunity for further testing on the seesaw connection between hemispheres (Blunier and Brook, 2001; Shackleton, 2001; Stocker and Johnsen, 2003).

To contribute to this knowledge of the northern hemisphere climate, a recent study (Martrat et al., 2007) worked on new Iberian sites (Marion Dufresne sediment cores MD01-2443 and MD01-2444). Two questions were posed: Firstly, what were interglacial-to-glacial cycles like, prior to the last one? Secondly, which climatic processes were providing the link between Mediterranean centennial variability and the polar regions? It must be emphasized that conclusions were mainly based on the temporal changes and relative phasing between different indicators measured along each of the two cores. The conclusions were consequently irrespective of the absolute timescale chosen.

In this study at the Iberian Margin, Dansgaard-Oeschger saw-tooth-type variability and associated interhemispheric linkage were both common robust features over the past four climate cycles (420 kyr). Iberian sea surface temperature (SST) variability and stable isotope ratios in ice-water molecules from Greenland had correlation coefficients of up to 0.92 (Martrat et al., 2007). Correlation coefficients for Iberian deep-ocean temperature variability and stable isotope ratios of Antarctic ice-water molecules were similarly high (Martrat et al., 2007). None of the climate cycles studied was an exact reproduction of another (Figs. 1-4). This fact was not surprising, as the governing factors of ice-age dynamics were never identical in the past. One point of interest—both in variable glacials and in the warm, relatively stable preceding periods—was that the SST variability increased while the Pleistocene progressed to the present (annual mean $U^{k'}_{37}$-SST; Figs. 1-4A). Warming stages of limited duration were designated as Iberian Margin Interstadials (IMI) and short-term cooling stages as Iberian Margin Stadials (IMS), with the number of the climate cycle to which they belong always shown immediately before.

Glacial periods were recognized by frequent incursions of extremely cold surface waters traced by the distribution of coccolith-synthesized alkenones, very likely associated with generations of icebergs in the northern Atlantic (increased per-