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Cooling of Northwest Atlantic slope waters during the Holocene

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[1] Climate of the last 11,000 years, the Holocene, is usually described as warm and stable. Benchmark temperature records from central Greenland ice cores show none of the large, abrupt variations that characterized the prior 100,000 years of glacial climate. Nor do they show any substantial trend, indicating at most 1°–3°C of cooling. Here we show that the slope waters east of the United States and Canada cooled 4°–10°C during the Holocene. Declining insolation, increasing convection in the Labrador Sea, and equatorward shifting of the Gulf Stream path may have caused the cooling. **Citation:** Sachs, J. P. (2007), Cooling of Northwest Atlantic slope waters during the Holocene, *Geophys. Res. Lett.*, *34*, L03609, doi:10.1029/2006GL028495.

[2] Greenland ice cores depict a Holocene climate that was warm and stable compared to the preceding 100 kyr. Yet most elements of the climate system were undergoing large secular changes during the last 11 kyr. Summer insolation in the northern hemisphere declined to Last Glacial Maximum (LGM) levels. Atmospheric CO_2 increased 20 ppmv and the carbonate ion concentration of the deep sea decreased 5–10 μmol/kg [*Broecker et al.*, 1999], signaling a large shift in the global carbon cycle. The oxygen isotope composition of atmospheric O_2, an indicator of global productivity and hydrology, increased 0.5‰, retracing roughly 50% of the non-ice-volume deglacial decrease [*Bender et al.*, 1999]. The monsoons of Asia and Africa weakened, the inter-tropical convergence zone (ITCZ) migrated southward, the frequency of El Niño events increased, and North Africa became a desert, indicative of substantial changes in tropical climate [*Fleitmann et al.*, 2003; *Moy et al.*, 2002]. Here we show that the Northwest Atlantic Ocean between Virginia and Newfoundland cooled by 4°–10°C during the last 11 kyr, providing additional evidence that the Holocene was a time of profound secular changes in the climate system.

[3] SSTs were determined by alkenone paleothermometry [*Brassell et al.*, 1986; *Sachs and Lehman*, 1999] using the temperature calibration of *Prahl et al.* [1988]. One core was from the continental slope east of Virginia (37°N, 75°W, 1049 m; core CH07-98-GGC19). A second core was from the margin east of Nova Scotia (44°N, 63°W, 250 m; core OCE326-GGC30). The third core was from abyssal depths of the Laurentian Fan (43°N, 55°W, 3975 m; core OCE326-GGC26) (Figure 1). Age control is from radiocarbon dates on planktonic foraminifera. Linear interpolation of time between calibrated ^{14}C ages provides a chronology for each core (Figure 2a).

[4] Cooling of 4°–10°C occurred at each location more or less continuously throughout the Holocene (Figure 2b). Warmest SSTs of 19°C off Virginia, 18°C on the Laurentian Fan, and 15°C on the Scotian Margin occurred at the beginning of the Holocene (Figure 2b). Coldest SSTs of 14.5°C, 8.5°C, and 8°C, respectively, occurred within the last few centuries (Figure 2b). Core-top alkenone temperatures at each site are 1°–2°C below measured mean annual SSTs [*Conkright et al.*, 2002] (Figure 2a), close to the 1.5°C standard error of the technique [*Müller et al.*, 1998].

[5] Radiocarbon ages of alkenones several thousand years greater than those of coeval planktonic foraminifera have been observed in some sediments and attributed to an input of older, laterally advected alkenones [*Mollenhauer et al.*, 2005]. Seven lines of evidence argue against distortion of our paleotemperature records by non-local alkenones. (1) The severe and continuous cooling is observed in three cores from diverse depositional environments (shelf, slope and abyssal fan). (2) Comparable cooling was inferred from dinoflagellate cyst assemblages on the Scotian Margin [*Levac*, 2001] and the southwestern Labrador Sea [*de Vernal et al.*, 2000]. (3) ^{14}C ages of alkenones in early and late Holocene sections of the Laurentian Fan core (OCE326-26GGC) are less than 1.2 kyr greater than for coeval planktonic foraminifera [*Keigwin et al.*, 2005]. (4) A maximum in the abundance of sand-sized (non-advectible) polar planktonic foraminifera (*N. pachyderma* s.) coincides with an abrupt decrease in alkenone SSTs 8.5–7.8 kyr ago in the Laurentian Fan core [*Keigwin et al.*, 2005]. (5) Core top alkenone SSTs are within 1°–2°C of modern mean annual SSTs. (6) For anomalous early Holocene warmth in all three cores to have been caused by lateral transport of warm-water alkenones the predominant flow of abyssal currents and sediment, presently from the north and east, would have had to have been from warmer water to the south and west. (7) Alkenones produced for ca. 100 kyr prior to the start of our records would have been uniformly less saturated, reflecting the colder glacial climate, so their transport and deposition at the three core sites would be even less likely to cause the anomalous warmth indicated for the early Holocene. The most parsimonious conclusion from this disparate set of evidence is that the alkenone records reflect local SST above the core sites.

[6] Such severe and continuous cooling of the slope water system from Virginia to Nova Scotia and offshore to the Laurentian Fan is enigmatic in light of the multitude of proxy air and sea temperature records from throughout the western Arctic (> 60°N) and eastern Atlantic Ocean that typically indicate no more than 1°–3°C of cooling during the Holocene [*Kaufman et al.*, 2004], including ice-isotopic temperature records from Greenland [*Grootes and Stuiver*,

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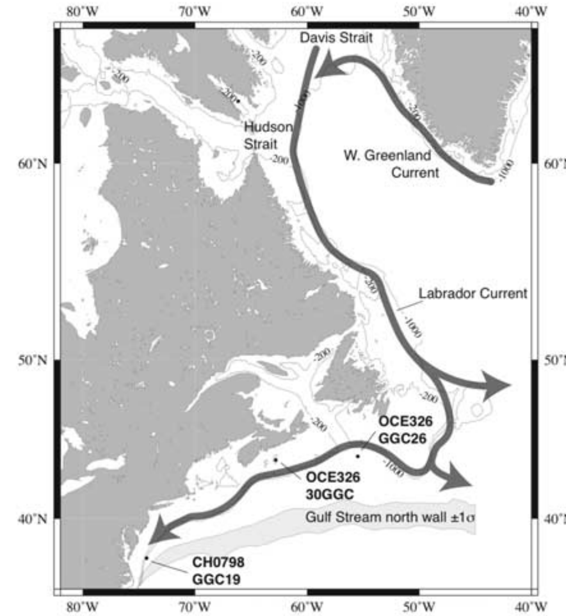

Figure 1. Map of the slope water region showing the location of cores used in this study, in addition to major surface currents and bathymetric features.

1997] and alkenone SST records from the eastern North Atlantic [*Marchal et al.*, 2002].

[7] A decline in summer and mean annual insolation at middle and high northern latitudes during the last 11 kyr (e.g., by 48, 40 & 36 W/m^2 at 65°, 45° & 20°N, respectively, during summer, and by 9, 8 & 7% in the annual mean [*Berger*, 1978]) to levels last reached during the LGM provides a direct radiative mechanism for cooling North Atlantic surface waters (Figure 2c) [*Renssen et al.*, 2005]. A concurrent increase in the winter (9%) and mean annual (2%) meridional gradients of insolation (20°–65°N) during the Holocene could account for the increased zonal and meridional gradients of SST across the North Atlantic and along its western margin (from ~0°C 11 ka to 6°C today, Figure 2b) by intensifying westerly winds (owing to the thermal wind balance), a response supported by some models [*Renssen et al.*, 2005] and data [*Forman et al.*, 1995; *Zdanowicz et al.*, 2000].

[8] Intensified Westerlies preferentially cool the slope waters by increasing convection in the Labrador Sea and the export of cold water via the Labrador Current, strengthening the subpolar gyre, and creating opposing sea ice anomalies in the Labrador and Greenland Seas [*Curry and McCartney*, 2001; *Marshall et al.*, 2001]. Initiation of deep convection in the Labrador Sea ~8 ka [*Hillaire-Marcel et al.*, 2001]—close to the time of precipitous cooling on the Scotian Margin, the Laurentian Fan and the southwest Labrador Sea [*de Vernal et al.*, 2000] (Figures 2b and 2c)—and its subsequent intensification [*Marchitto and deMenocal*, 2003] support a causal link between slope water cooling and Labrador Sea convection. Moreover, a coupled ocean-atmosphere model forced with Holocene insolation changes produced monotonic cooling and increased convection in the Labrador Sea over the last 9 kyr [*Renssen et al.*, 2005].

[9] An increase in the gradient of SST across the North Atlantic and along the slope waters, as observed to occur through the Holocene, is associated with the positive state of the North Atlantic Oscillation (NAO), during which time the Westerlies, the subpolar gyre circulation, and Labrador-Nordic Sea ice anomalies all increase [*Marshall et al.*, 2001]. Although the NAO is an inter-annual mode of climate variability it has been proposed as a model for North Atlantic climate evolution during the Holocene

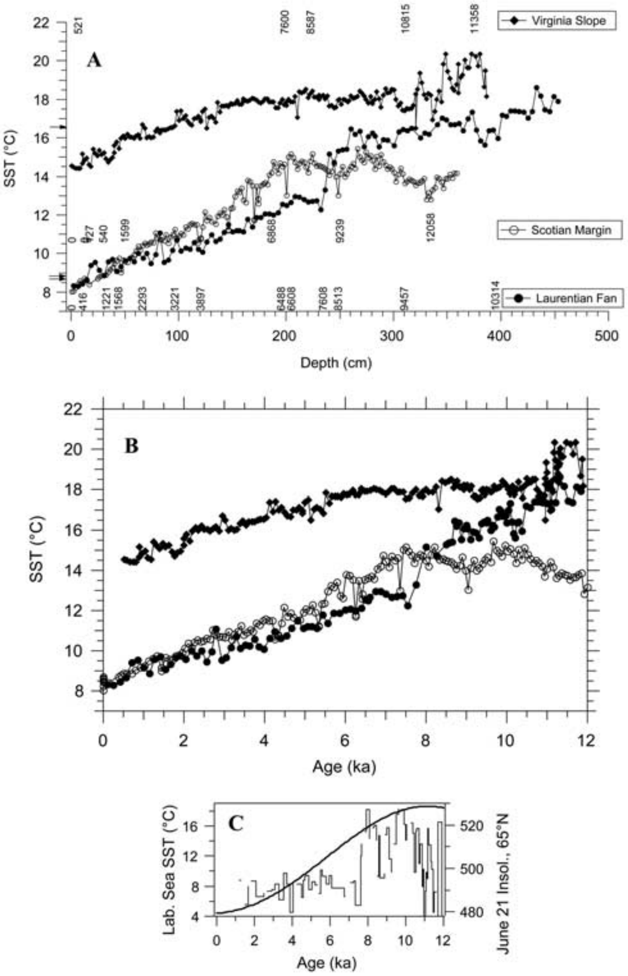

Figure 2. Alkenone-derived SSTs in three slope water cores. (a) Alkenone SSTs on a depth scale in Virginia Slope core CH07-98-GGC19 (36°52′N, 74°34′W, 1049 m) (diamonds), Scotian Margin core OCE326-GGC30 from the Emerald Basin (43°53′N, 62°48′W, 250 m) (open circles), and Laurentian Fan core OCE326-GGC26 (43°29′N, 54°52′W, 3975 m) (solid circles). Calendar ages from ^{14}C measurements on planktonic foraminifera are shown for each core. Arrows on the SST axis indicate mean annual SSTs at each site [*Conkright et al.*, 2002]. (b) Alkenone SSTs in the three slope water cores plotted on an age scale. Linear interpolation of time between the ^{14}C-derived ages shown in Figure 2a provided the chronology. (c) Summer SSTs in the southwest Labrador Sea derived from dinoflagellate cysts [*de Vernal et al.*, 2000] (broken line) and June 21 insolation at 65°N [*Berger*, 1978] (solid line).

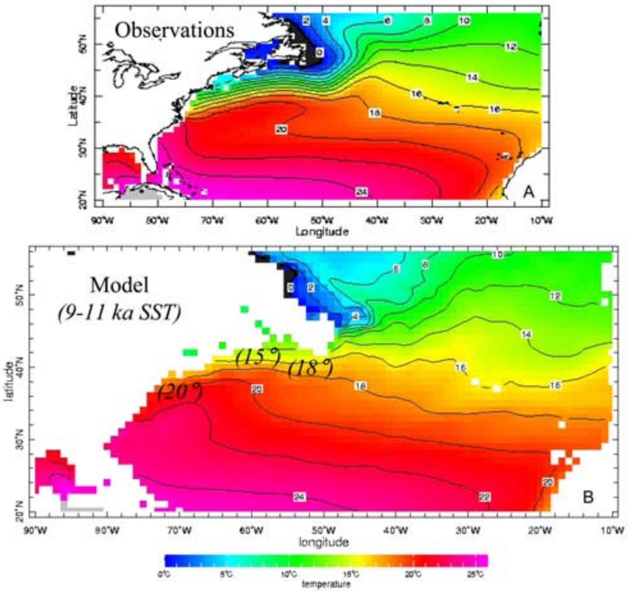

Figure 3. Model temperatures match early Holocene SSTs when the Gulf Stream separates east of Newfoundland. (a) Mean annual temperature at 75 m [*Conkright et al.*, 2002]. (b) Mean annual temperature at 95 m from the MITgcm [*Marshall et al.*, 1997; *Menemenlis et al.*, 2005]. Alkenone SSTs were averaged over the period 9–11 ka from the Scotian Margin (15°C), the Laurentian Fan (18°C), and the Virginia slope (20°C); and plotted in parentheses.

[*Tremblay et al.*, 1997]. Driftwood accumulations on the Arctic margin [*Tremblay et al.*, 1997], dinoflagellate cysts in Labrador and Nordic Sea sediments [*Solignac et al.*, 2006], the increased meridional SST gradient we document (Figure 2b), and the increased meridional SST gradient implied by 1°–3°C cooling in the eastern North Atlantic through the Holocene [*Marchal et al.*, 2002] relative to 4°–10°C of cooling in the western North Atlantic that we document (Figure 2b) support the notion of a mean North Atlantic climate pattern similar to that observed during the negative phase of the NAO in the early Holocene and the positive phase of the NAO in the late Holocene.

[10] An alternative mechanism for cooling the slope waters is a southward migration of the Gulf Stream (GS) path. As shown in Figure 2 the abruptness of the cooling increased with increasing latitude, being nearly monotonic in the Mid-Atlantic Bight (37°N, 75°W) (Figure 2b) and a step function in the SW Labrador Sea (50°N, 45°W) (Figure 2c) [*de Vernal et al.*, 2000]. In between those locations, at the Laurentian Fan (43°N, 55°W), about half of the cooling occurred abruptly 8.5–7.5 ka, with the remainder occurring gradually before and after that time (Figure 2b). This pattern of temperature change—large and step-like to the north, moderate and gradual to the south–would be expected from a steady equator-ward migration of an oceanographic front, such as the GS, from near 50°N in the early Holocene to near 40°N today. A comparable GS shift was previously inferred from foraminifera assemblages [*Balsam*, 1981; *Balsam and Huesser*, 1976].

[11] This speculative interpretation is stimulated, ironically, by a failure of modern ocean general circulation models (GCMs) to produce a Gulf Stream that separates from the continental shelf at the observed location east of Cape Hatteras [*Kiss*, 2002; *McWilliams*, 1996; *Schmeits and Dijkstra*, 2001]. Most GCMs instead produce Gulf Streams that follow the shelf break 2,000 km beyond Cape Hatteras before leaving the continental shelf east of Newfoundland. Though some very high resolution (e.g., 0.1° × 0.1°) models can be tuned to produce Gulf Streams that separate at or near Cape Hatteras, suggesting that convergence on the correct solution may occur once adequate model resolution is achieved, multiple steady states are dynamically possible [*Schmeits and Dijkstra*, 2001] and there remains no accepted theory for western boundary current separation. A substantial change in the GS path cannot therefore be ruled out.

[12] When the GS follows the shelf break to the Flemish Cap, modeled SSTs are much closer to those from the early Holocene than they are to modern values (Figure 3). In one such model, the MITgcm [*Marshall et al.*, 1997; *Menemenlis et al.*, 2005], temperatures of 15°–20°C characterize the slope waters from the Mid-Atlantic Bight to the Grand Banks (Figure 3b). As shown in Figure 3b, early Holocene (9–11 ka average) alkenone SSTs at our three core sites are nearly identical to those in the surface mixed layer of the model.

[13] Another argument favoring the plausibility of a substantial shift in the GS path is the modern-day behavior of the Kuroshio. The western boundary current in the North Pacific Ocean exhibits a bimodal behavior, fluctuating up to 5° of latitude between "straight" and "meandering" paths over several months, and remaining in the altered state for as long as a decade [*Schmeits and Dijkstra*, 2001]. Though the cause of this behavior is unknown it demonstrates that western boundary currents need not remain fixed, that they can exist in more than one stable state for years, and that a shift can occur in the absence of substantial external forcing.

[14] The lack of an accepted theory for western boundary current separation and their poor representation in models make causal mechanisms of a GS shift difficult to evaluate. Some possibilities are changes in: (1) the wind field caused by lower insolation, (2) the extent of sea and land ice, (3) the strength of the Deep Western Boundary Current caused by altered Labrador Sea convection and/or freshwater fluxes out of the Arctic, and (4) changes in coastline geometry and shelf bathymetry caused by rising global sea level and regional isostatic adjustment.

[15] Evaluating the causes for a 4°–10°C decline in SSTs off the eastern seaboard of the United States and Canada during the Holocene will presumably require a fully coupled ocean-atmosphere-ice model and a better understanding of the controls on western boundary current separation. What is clear is that the Holocene, often considered a time of climatic stability, was characterized by large secular changes throughout the climate system. Perhaps cooling of the northwest Atlantic slope waters is a harbinger of climate deterioration preceding the next glacial period.

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