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On the Interpretation of Caribbean Paleo-Temperature Reconstructions During the Younger Dryas

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On the interpretation of Caribbean paleo-temperature reconstructions during the Younger Dryas

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[1] A conundrum exists regarding whether the sea-surface temperatures decreased or increased over the southern Caribbean and the western Tropical Atlantic region during the Younger Dryas when the North Atlantic cooled substantially and the Atlantic thermohaline circulation was weakened significantly. Despite the proximity of core locations, some proxy reconstructions record a surface cooling, while others indicate a warming. We suggest that this seemingly paradoxical finding may, at least partially, be attributed to the competing physical processes that result in opposing signs of temperature change in the region in response to weakened North Atlantic meridional overturning circulation. Our coupled ocean-atmosphere model experiments indicate that the temperature response over the southern Caribbean and Western Tropical Atlantic regions is complex and can vary considerably in small spatial scales, depending on the nature of physical processes that dominate.

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1. Introduction

[2] Paleoceanographic proxy records indicate that Atlantic thermohaline circulation (ATHC) was substantially weakened during the Younger Dryas (12.8 and 11.5 cal. kyr BP) resulting in wide-spread surface cooling over the Northern Atlantic sector [*Zhao et al.*, 1995; *Bard et al.*, 2000; *Guilderson et al.*, 2001] and warming in the tropical South Atlantic [*Mulitza and Rühlemann*, 2000; *Arz et al.*, 1999; *Weldeab et al.*, 2006] (Figure 1). This dipole-like Sea Surface Temperature (SST) pattern is perceived as a robust response to a weakening in ATHC and is well simulated by a range of coupled climate models in the so-called water-hosing experiments where fresh water is hosed into the high latitude North Atlantic, mimicking melt water discharge [*Stouffer et al.*, 2006].

[3] Although the overall paleo-temperature reconstructions over a broad geographic scale are consistent with the occurrence of this SST dipole during the Younger Dryas, there are inconsistent findings about the temperature changes in the southern Caribbean region and in the western Tropical Atlantic. When an updated age model for ODP site 1002C (10°42.73′N, 65°10.18′W) [*Peterson et al.*, 2000] is applied to the alkenone unsaturation-based SST record from *Herbert and Schuffert* [2000], little or no temperature change is observed at the initiation of the Younger Dryas (temperatures remain about 24°C) and only a small warming of about 1°C is observed at the termination of the event at 11.5 kyr. In comparison, a Mg/Ca-SST record based on planktonic foraminifera in another Cariaco Basin core PL07-39PC (10°42′N, 64°56′W) suggests a 2–3°C cooling at the start of the Younger Dryas with an average temperature of about 24°C during the cold event [*Lea et al.*, 2003]. *Guilderson et al.* [2001] inferred an even larger amount of cooling off the coast of Barbados (13°N, 59°30′W) based on coral stable isotope values. In contrast, both alkenone-based [*Rühlemann et al.*, 1999] and faunal-based [*Hüls and Zahn*, 2000] SST reconstructions from a Tobago Basin core (12° 05′N, 61°15′W) in the western Tropical Atlantic indicated an opposite response — a surface warming during the Younger Dryas. In addition, a Mg/Ca-SST record from the southwestern Caribbean (11° 34′N, 78°25′W) also indicated ~1.2°C of surface warming during the Younger Dryas [*Schmidt et al.*, 2004] (Figure 1). Although these SST records are based on a variety of paleo-proxies, each with its own uncertainties which might be associated with seasonality, depth habitats or diagenesis etc., one wonders whether there is a physical explanation for the complex spatial structure of the reconstructed temperature change. The purpose of this short letter is to shed light on this issue by experimenting with a coupled ocean-atmosphere model.

2. Model Description and Numerical Experiments

[4] The coupled ocean-atmosphere model used in this study consists of a tropical-channel ocean general circulation model based on the Geophysical Fluid Dynamics Laboratory's (GFDL) Modular Ocean Model version 3 (MOM3) [*Pacanowski and Griffies*, 1999] and the Community Climate Model version 3.6.6 (CCM3) — a global atmospheric general circulation model developed at the National Center for Atmosphere Research (NCAR) [*Kiehl et al.*, 1998]. The CCM3 is coupled to the tropical-channel MOM3 through an anomaly coupling methodology [*Yeh et al.*, 2004]. Outside of the tropical ocean domain of 30°S and 30°N, no coupling is employed and the CCM3 is forced by specified SSTs. The strength of the ATHC can be altered by specifying lateral open boundary conditions that are derived from simulations of the global version of the MOM3. Hereafter, we refer this model to as the CCM3-trMOM3 model (see auxiliary material for more details).[1]

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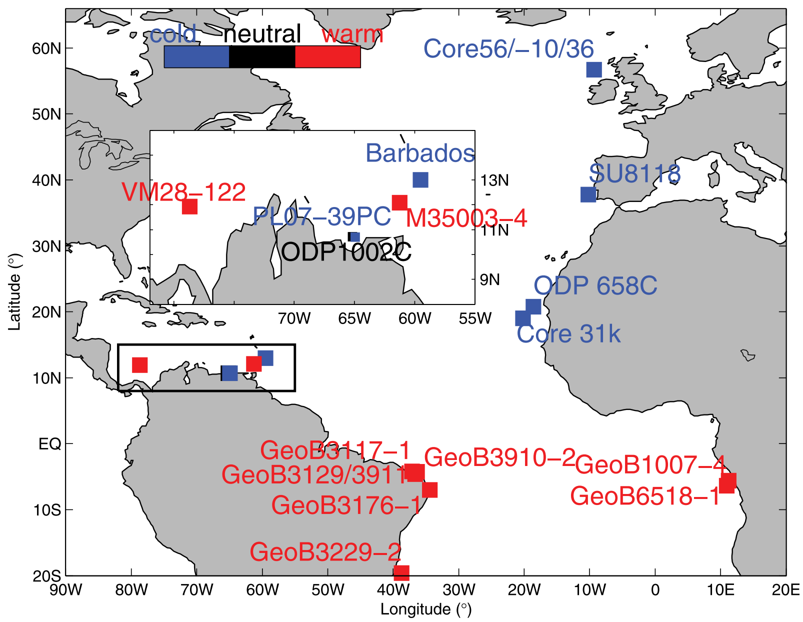

Figure 1. A summary diagram of paleo-SST reconstructions during the Younger Dryas over Atlantic Ocean: Core 56/-10/36 [*Kroon et al.*, 1997]; SU8118 [*Bard et al.*, 2000]; Core 31k, ODP658C [*Zhao et al.*, 1995]; Barbados [*Guilderson et al.*, 2001]; PL07-39PC [*Lea et al.*, 2003]; VM28-122 [*Schmidt et al.*, 2004]; M35003-4 [*Rühlemann et al.*, 1999; *Hüls and Zahn*, 2000]; ODP1002C [*Herbert and Schuffert*, 2000]; GeoB1007-4 [*Mulitza and Rühleman*, 2000]; GeoB3117-1, GeoB3176-1, GeoB3229-2 [*Arz et al.*, 1999]; GeoB3910-2 [*Jaeschke et al.*, 2007]; GeoB3129/3911 [*Weldeab et al.*, 2006]; GeoB6518-1 [*Weijers et al.*, 2007]. Blue denotes surface cooling and red denotes surface warming. The inset is an enlargement of black box in the southern Caribbean.

[5] As shown in recent studies, the cooling in the high-latitude North Atlantic produced by a weakening in ATHC can be transmitted into the tropical Atlantic via both atmospheric processes that involve interactions with ocean mixed layer [*Chiang et al.*, 2008] and oceanic processes that involve interactions between the wind-driven and thermohaline circulation [*Chang et al.*, 2008]. To isolate the contribution from each of these processes, we conducted the following experiments.

2.1. Control Experiment (CE)

[6] The atmospheric component of the CCM3-trMOM3 is forced with observed annual cycle of SST outside the tropical ocean domain and the oceanic component is forced with climatological inflow/outflow conditions at the open boundaries derived from a global MOM3 simulation forced by observed climatological winds with restoring to observed climatological surface temperature and surface salinity. This run provides a baseline for other perturbation experiments.

2.2. Boundary-Forcing Experiment (BFE)

[7] Same as CE except that the inflow/outflow conditions at the open boundaries are derived from a global MOM3 simulation with a fresh-water input at a rate of 1.0 Sv over northern North Atlantic, in addition to the observed climatological surface forcing. This run is designed to examine the effect of ocean circulation changes on tropical SSTs.

2.3. Surface-Forcing Experiment (SFE)

[8] Same as CE except that in the North Atlantic basin (north of 20°N) a cold SST anomaly derived from an ensemble of GFDL fully coupled climate model (GFDL CM2.1) water hosing runs [*Zhang*, 2007] are superimposed onto the observed SST climatology to force the atmosphere. This run is designed to examine the effect of atmospheric processes on tropical SSTs.

2.4. Combined-Forcing Experiment (CFE)

[9] The CCM3-trMOM3 is forced at both the surface of the North Atlantic Ocean and the open boundaries of the ocean model, as described in SFE and BFE, respectively. This run is designed to examine the combined effect of the atmospheric and oceanic processes on tropical SSTs.

[10] Each of these experiments consists of 100-year integrations. The analyses presented below are based on averages of the last 40 years of the simulations.

3. Analyses and Results

[11] Figure 2a shows the SST difference between CFE and CE over tropical Atlantic basin. Consistent with other model water hosing experiments [*Stouffer et al.*, 2006], the combined effect of the surface cooling in the North Atlantic and the ocean circulation change is to produce an SST dipole with strong cooling in excess of 1°C over the north tropical Atlantic, and a moderate warming over much of the equatorial and south tropical Atlantic. Interestingly, a narrow strip of warmer surface water also appears off the northern coast of South America, extending into the Southern Caribbean. This warming is surrounded by wide-spread surface cooling of the North Atlantic, giving rise to a complex SST response pattern in the region where many proxy reconstructions took place. The question is what physical processes are responsible for this SST response.

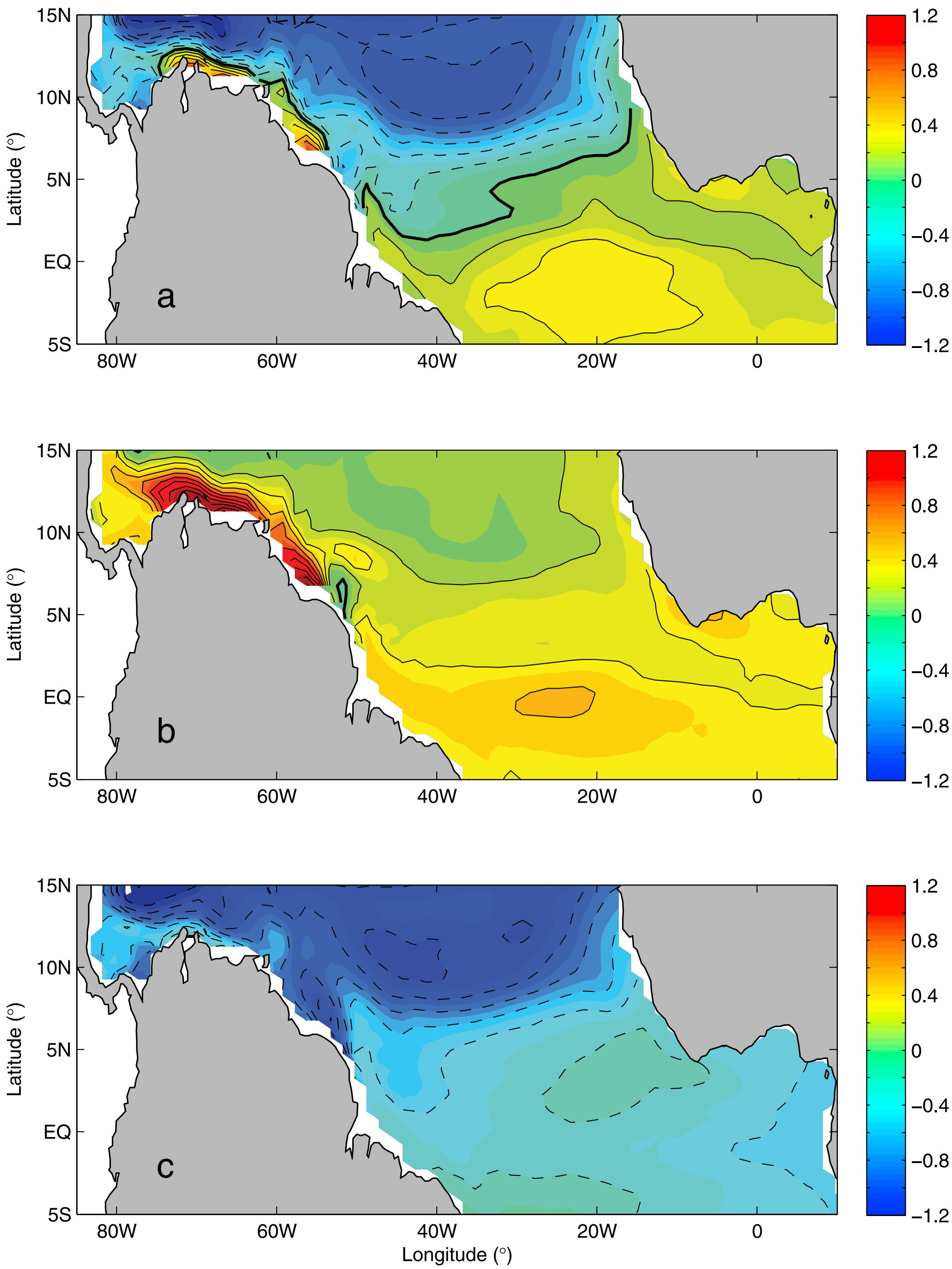

Figure 2. CCM3-trMOM3 simulated SST differences between (a) CFE and CE, (b) BFE and CE, (c) SFE and CE, respectively. Experiment details are given in the text. The interval of contour line is 0.2°C.

[12] To shed light on this issue, we turn first to the BFE where the SST change can only be attributed to ocean circulation changes. As shown in Figure 2b, in the absence of the surface cooling in the North Atlantic, the weakened ATHC produces surface warming in the entire tropical Atlantic basin with a strong warming along the northern coast of South America extending into the equatorial wave guide. This surface warming originates from the strong subsurface temperature gradient zone that separates the warmer and saltier subtropical water from the colder and fresher tropical gyre water along the boundary between the subtropical gyre and tropical gyre. As explained by *Chang et al.* [2008], the weakening of the ATHC causes the northward western boundary current to decrease. The weakened western boundary current then produces a strong subsurface temperature warming near the strong temperature gradient zone due to horizontal heat advection by anomalous currents. Figure 3a shows that under the present climate condition there is roughly 12 Sv of cross-hemisphere flow in the upper 500 m of the tropical Atlantic Ocean. In the BFE, this flow is reduced to less-than 4 Sv accompanied with a subsurface warming of 2.5°C centered

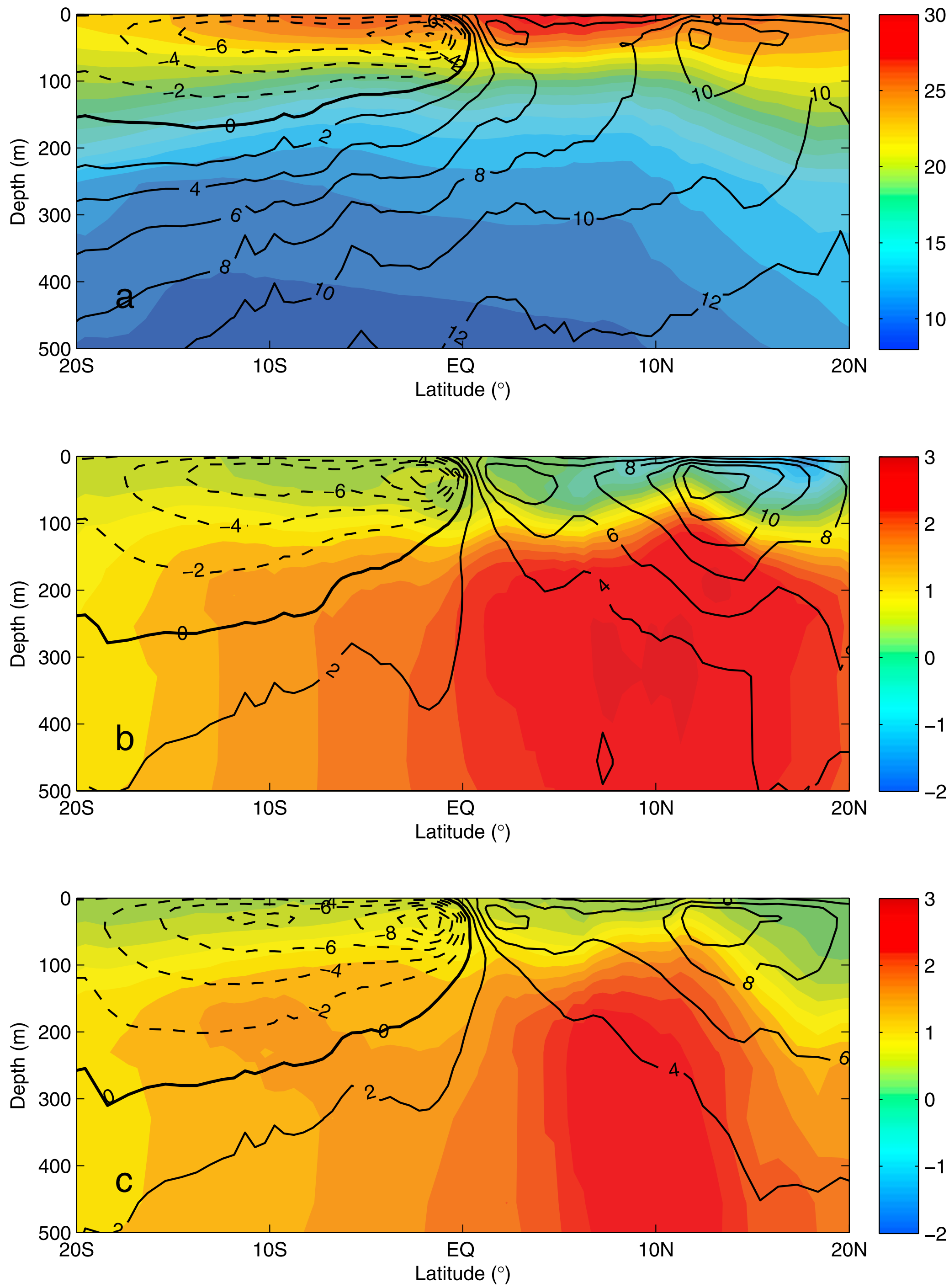

Figure 3. Upper Atlantic Ocean meridional overturning circulation streamfunction (contour) in (a) CE, (b) CFE and (c) BFE, superimposed on zonally averaged temperature (color) in CE (Figure 3a), zonally averaged temperature difference (color) between CFE and CE (Figure 3b) and between BFE and CE (Figure 3c). The color bars indicate the temperature changes in °C and the streamfunction contour interval is 2 Sv, where 1 Sv = 10^6 m^3 s^{-1}.

around 8°N and 300 m (Figure 3b). The warming extends into the surface mixed layer along the Atlantic coast of northern South America due to coastal upwelling (Figure 2b). Meanwhile, the subsurface warming also spreads southeastward along the western boundary and then along the equatorial wave guide, because the substantially weakened ATHC causes the subsurface North Brazil Current (NBC) to reverse direction and enable warmer and saltier subtropical gyre water to penetrate into the equatorial zone [*Chang et al.*, 2008] (Figure 2b). Equatorial upwelling subsequently brings the warming to the ocean surface and surface currents then spread the warm water over much of the tropical Atlantic. Therefore, the ocean circulation changes alone tend to warm the tropical Atlantic Ocean.

[13] In contrast, if we only permit North Atlantic surface cooling to occur without changing the ocean circulation, as

in the SFE, then surface cooling prevails everywhere in the tropical Atlantic basin (Figure 2c). The cooling spreads into the tropics from the North Atlantic through a series of atmospheric processes and interactions with the ocean mixed layer. *Chiang et al.* [2008] argue that the wind-evaporation-SST (WES) feedback, which involves interactions between the wind-induced latent heat flux and SST changes [*Chang et al.*, 1997], is particularly effective in transmitting the high-latitude SST changes to the tropics. The process sets in quickly and can transmit the cooling into the tropics within a decade. The cooling over the North Atlantic also enhances the northeasterly trade wind, which in turn strengthens the wind-driven STC. A comparison between the STCs in the CFE (Figure 3b) and the BFE (Figure 3c) shows that the surface cooling causes the maximum strength of the northern STC to increase from 10 Sv in the BFE to 14 Sv in the CFE. Therefore, the complex SST response pattern in the southern Caribbean is attributable to the interplay between atmospheric process induced surface cooling and oceanic process induced subsurface warming. The relative strength of these processes determines the occurrence and strength of the opposing temperature changes in the region.

4. Discussion

[14] The competing nature of the atmospheric and oceanic processes that tend to cancel each other may contribute to the difficulty in interpreting paleo proxy records over the Caribbean region during the Younger Dryas event and may explain some of the inconsistencies of surface temperature paleo reconstructions in the region. Our results suggest it is possible that the surface temperature change may have different signs within short spatial scales, as the published paleo records suggest. In general, a substantially weakened ATHC should produce surface cooling through atmospheric processes in much of the open ocean of the North Atlantic, except along the coast of northern South America and along the equatorial wave guide where surface warming may prevail due to the combined effects of subsurface ocean temperature change and upwelling. Faunal studies from the Colombian Basin [*Kameo et al.*, 2004] and the Tobago Basin [*Hüls and Zahn*, 2000] do indeed suggested a shallower thermocline existed in the southwestern Caribbean during glacial times due to increased coastal upwelling in this region. Therefore, whether a proxy reconstruction records a warming or a cooling response depends critically on whether the temperature change at the site is dominated by surface atmospheric processes or subsurface oceanic processes. Unfortunately, a direct comparison of the simulated and reconstructed temperature change would not be meaningful at this stage, because 1) the current model resolutions are inadequate to fully resolve the complexity of bottom topography and coastline geometry in the Caribbean region, and 2) the past climate boundary conditions should be used in order to fully simulate changes in past climatic events. Based on previous modeling studies [e.g., *Chiang et al.*, 2003], we speculate that if Younger Dyras or glacial boundary conditions were used, the ice sheet build-up over the Northern Hemisphere would enhance surface cooling in the North Atlantic via atmospheric processes, acting to weaken the ocean- induced warming over the Caribbean.

[15] The Mg/Ca-SST record from *Lea et al.* [2003] indicates a strong cooling in the Cariaco Basin of 2–3°C at a time when the CFE minus CE results indicate a strong subsurface warming at 10°N in the western tropical Atlantic (Figure 3b). Although this may appear as a discrepancy between the proxy data and our model results, the contradictory temperature trends can be explained by local dynamical responses within the Cariaco Basin. Today, the deepest sill in the Cariaco Basin is <146 m, restricting the horizontal flow of waters between the open Caribbean and the Basin. During the Younger Dryas, sea level was about 60 m lower, restricting mixing between the Cariaco Basin and the open Caribbean even further. The CFE minus CE results clearly show that the subsurface warming is below 100 m at 10°N, with a maximum warming at about 300 m water depth (Figure 3b). Therefore, it is unlikely the subsurface warming in the Caribbean mixed into the isolated Cariaco Basin during the Younger Dryas. Although upwelling in the Cariaco Basin was enhanced during the Younger Dryas [*Peterson et al.*, 2000; *Haug et al.*, 2001], the source of the upwelled waters must have remained cold relative to the open Caribbean, resulting in the 2–3°C of cooling recorded in the Mg/Ca-SSTs [*Lea et al.*, 2003].

[16] Nevertheless, these modeling results suggest that a strong temperature gradient developed between the subtropical gyre and the western boundary current off the Venezuela and Guyana coast in response to reduced ATHC (Figure 2a). This region may be of particular importance in terms of understanding the temperature response of the tropical Atlantic to ATHC changes, as much of the tropical Atlantic surface warming appears to originate in this region.

[17] Given the robust and unambiguous subsurface temperature change simulated by the models, it may be desirable to extend the paleo proxy reconstruction of temperature change to include the subsurface in this region. The only regional subsurface temperature record was generated by *Rühlemann et al.* [2004] using stable oxygen isotope values in benthic foraminiferal. These researchers estimated a rapid, 1–3°C temperature increase at ~1300 m water depth in the Tobago Basin during the Younger Dryas, suggesting the magnitude of subsurface warming may have exceed that of the surface by as much as 2°C at this location [*Rühlemann et al.*, 1999]. Clearly, an expanded proxy data base in this region can help to address the role of oceanic processes in abrupt climate change in the tropical Atlantic sector. Furthermore, climate models need to enhance spatial resolutions in simulations of past abrupt climate changes to fully resolve regional-scale circulation features and ocean-atmosphere interactions in the Caribbean and Western Tropical Atlantic.

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