GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L11703, doi:10.1029/2009GL038677, 2009



# Tropical Atlantic climate response to low-latitude and extratropical sea-surface temperature: A Little Ice Age perspective

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Received 13 April 2009; accepted 7 May 2009; published 5 June 2009.

[1] Proxy reconstructions and model simulations suggest that steeper interhemispheric sea surface temperature (SST) gradients lead to southerly Intertropical Convergence Zone (ITCZ) migrations during periods of North Atlantic cooling, the most recent of which was the Little Ice Age (LIA; ~100–450 yBP). Evidence suggesting low-latitude Atlantic cooling during the LIA was relatively small (<1°C) raises the possibility that the ITCZ may have responded to a hemispheric SST gradient originating in the extratropics. We use an atmospheric general circulation model (AGCM) to investigate the relative influence of low-latitude and extratropical SSTs on the meridional position of the ITCZ. Our results suggest that the ITCZ responds primarily to local, low-latitude SST anomalies and that small cool anomalies (<0.5°C) can reproduce the LIA precipitation pattern suggested by paleoclimate proxies. Conversely, even large extratropical cooling does not significantly impact low-latitude hydrology in the absence of ocean-atmosphere interaction. **Citation:** Saenger, C., P. Chang, L. Ji, D. W. Oppo, and A. L. Cohen (2009), Tropical Atlantic climate response to low-latitude and extratropical sea-surface temperature: A Little Ice Age perspective, *Geophys. Res. Lett.*, *36*, L11703, doi:10.1029/2009GL038677.

## 1. Introduction

[2] The Intertropical Convergence Zone (ITCZ) is a latitudinal band of intense precipitation with significant impacts on low-latitude Atlantic climate. Instrumental precipitation records suggest that the mean latitude of the ITCZ is strongly influenced by the sea surface temperature (SST) gradient between the relatively warm North Atlantic and the relatively cool South Atlantic [*Chiang et al.*, 2002]. Cool anomalies in the North tropical Atlantic reduce the interhemispheric SST gradient and drive enhanced cross-equatorial boundary layer flow into the Southern Hemisphere. Associated enhancement of northeasterly trade winds, and slackening of southeasterly trades, leads to a southerly displacement of the ITCZ.

[3] Proxy reconstructions of tropical Atlantic hydrology suggest that southerly ITCZ displacements coincide with high-latitude North Atlantic cooling on timescales ranging from hundreds to tens of thousands of years [*Peterson et al.*, 2000; *Haug et al.*, 2001]. One potential mechanism for these synchronous variations involves changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC). General circulation model simulations of freshwater induced weakening of the AMOC commonly exhibit North Atlantic cooling, a steeper interhemispheric SST gradient and a southerly displacement of the ITCZ [*Zhang and Delworth*, 2005; *Stouffer et al.*, 2006].

[4] The Little Ice Age (LIA; ~100–450 yBP) was a recent interval of prominent extratropical North Atlantic cooling that may have been associated with a weaker AMOC [*Broecker*, 2000]. Proxy records suggest that a 1–2°C cooling of extratropical Atlantic SSTs during the LIA [e.g., *Keigwin et al.*, 2003; *Jiang et al.*, 2005] was accompanied by stronger northeasterly trade winds [*Black et al.*, 1999] higher salinities [*Linsley et al.*, 1994; *Watanabe et al.*, 2001; *Lund and Curry*, 2006] and more arid conditions [*Hodell et al.*, 2005] at low latitudes (Figure 1). Combined with evidence for increased precipitation in the Southern Hemisphere [*Baker et al.*, 2001; *Thompson et al.*, 2006], these proxy records suggest that a southerly migration of the ITCZ was a robust response to cooler North Atlantic SSTs during the LIA.

[5] Although some proxy records indicate that low latitude North Atlantic SSTs cooled by approximately 3°C during the LIA [*Winter et al.*, 2000], recent research suggests that LIA cooling was more subtle and was often within the range of modern instrumental values [*Lund and Curry*, 2006; *Black et al.*, 2007]. The possibility that low latitude Atlantic SSTs were not markedly cooler during the LIA suggests that the ITCZ may have responded to extratropical cooling. Idealized simulations [*Broccoli et al.*, 2006] and climate models of the last glacial maximum [*Chiang and Bitz*, 2005] indicate that high-latitude climate can influence the meridional position of the ITCZ, but these coupled simulations make it difficult to determine if the ITCZ's response necessarily requires changes to low-latitude Atlantic SST. Recent work suggesting southerly ITCZ migrations can be understood as the atmospheric adjustment to increased poleward energy fluxes [*Kang et al.*, 2008] allows for the possibility that the ITCZ could respond to extratropical cooling alone.

[6] In this paper, we explore the relative influence of low-latitude and extratropical North Atlantic SSTs on tropical precipitation within the context of the LIA. Using an atmospheric general circulation model (AGCM), we examine the potential for extratropical Atlantic cooling to alter tropical precipitation in the absence of low-latitude SST anomalies. In contrast to coupled model simulations, our approach isolates the specific influence of SST on Atlantic ITCZ variability. Our results indicate that without ocean-atmosphere coupling, cooler extratropical SSTs alone cannot force southerly Atlantic ITCZ migrations, suggesting

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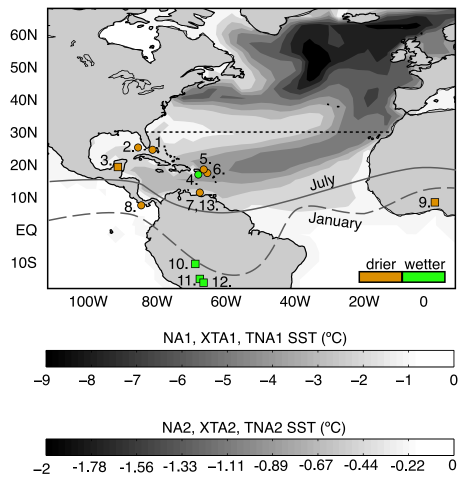


**Figure 1.** Imposed SST anomaly pattern (shading) for CAM3 simulations (note separate scales). XTA simulations applied SSTs only north of 30°N (dotted line). TNA simulations applied SSTs only south of 30°N. Marine (circles) and terrestrial (squares) proxy records indicating wetter (open/orange) and drier (filled/green) LIA conditions. Numbers correspond to Table 1. Modern seasonal ITCZ extremes are also shown.

that LIA ITCZ displacements were likely accompanied by some degree of low-latitude cooling.

## 2. Model Description and Methods

[7] We performed six simulations using the National Center for Atmospheric Research (NCAR) Community Atmosphere Model version 3 (CAM3) at T42 resolution (2.8° by 2.8° latitude-longitude, 26 vertical levels) [*Collins et al.*, 2006]. In general, CAM3 reproduces the pattern and amplitude of mean annual low-latitude Atlantic climate variability, as well as interannual migrations of tropical convergence zones [*Hack et al.*, 2006, *Hurrell et al.*, 2006] suggesting that it is appropriate for investigating the mean state of the ITCZ during the LIA. However, as in other AGCMs, CAM3 tends to overestimate Caribbean precipitation, particularly in boreal summer and autumn [*Hack et al.*, 2006; *Biasutti et al.*, 2006].

[8] Given the possibility that LIA SST and ITCZ variability was associated with a weaker AMOC, all simulations were forced using the North Atlantic SST pattern from the "hosing" experiment of *Zhang and Delworth* [2005] (hereinafter referred to as ZD05). Briefly, ZD05 applied a 0.6 Sv freshwater forcing to the high-latitude North Atlantic (55°–75°N, 63°W–4°E) for 60 years in an ocean-atmosphere global general circulation model. In response to this forcing, the entire North Atlantic cooled, with some SST anomalies reaching −9°C.

[9] Our first two simulations (NA1, NA2) prescribe the ZD05 SST pattern in the Atlantic north of the equator and use climatological SSTs elsewhere (Figure 1). NA1 uses the full magnitude of cooling, which reaches 9°C in the extratropical North Atlantic. NA2 is identical to NA1, but uniformly reduces SST anomalies by 78% such that extratropical Atlantic cooling does not exceed 2°C. NA1 is intended to be an idealized simulation that will yield a clear ITCZ response, while NA2 is designed to reflect the subtle cooling that may have characterized the LIA. Our second two simulations (XTA1, XTA2) are identical to NA1 and NA2, respectively, but apply ZD05 SSTs only north of 30°N. Our final two simulations (TNA1, TNA2) apply ZD05 SSTs only from the equator to 30°N. All simulations were run for 18 years, of which the final 14 years were analyzed. We assumed pre-industrial carbon dioxide concentrations, and assessed significant anomalies (95%) using a two-tailed t-test.

## 3. Modeled Precipitation and Wind Stress

[10] NA1 exhibits decreased annual average precipitation throughout the North Atlantic in response to cooler SSTs (Figure 2a). Negative precipitation anomalies extend in a zonal band from the eastern North Pacific to West Africa and can exceed −4 mm day$^{-1}$. Consistent with previous studies [*Zhang and Delworth*, 2005; Stouffer et al. 2006; *Sutton and Hodson*, 2007], increased precipitation immediately south of this zonal band can be interpreted as a southerly displacement of the Atlantic ITCZ. Cooler NA1 SSTs also lead to positive sea-level pressure (SLP) anomalies throughout the North Atlantic (not shown) that strengthen northeasterly wind stress at low-latitudes (Figure 2a). Enhanced northeasterly wind stress is most prominent along the northern coast of South America and in the southern Caribbean where anomalies extend across the Central American isthmus.

[11] Annual average results from NA2 are similar to those of NA1, suggesting an approximately linear response to the downscaled SST forcing (Figure 2b). A linear regression of NA1 and NA2 precipitation anomalies has a slope of 0.25 ± 0.1 that is close to the 0.22 expected for a perfectly linear response. As in NA1, NA2 precipitation anomalies exhibit a zonal band of increased aridity just north of the equator, although opposing positive precipitation anomalies to the south of this band are more subtle.

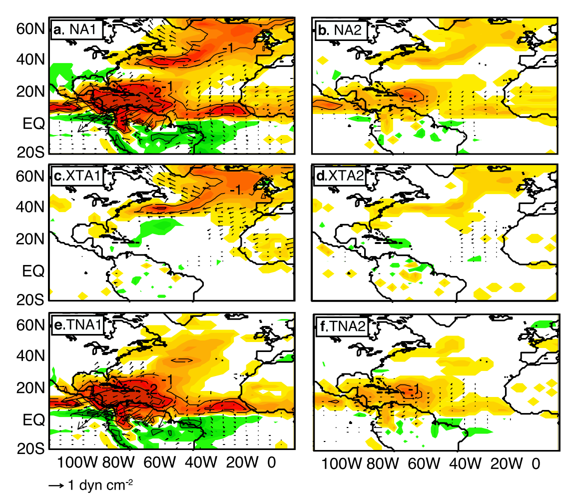


**Figure 2.** Significant mean annual precipitation (contours, mm day$^{-1}$) and wind stress (vectors, dyn cm$^{-1}$) anomalies for (a) NA1, (b) NA2, (c) XTA1, (d) XTA2, (e) TNA1, and (f) TNA2. Shading highlights positive (dark/green) and negative (light/orange) precipitation anomalies that are significant at 95%.

**Table 1.** Comparison of LIA Hydrologic and Trade Wind Proxies With Model Simulations[a]

| Map | Location | LIA Conditions (Proxy) | Modelled Precip. Anomaly (mm day$^{-1}$) NA1/NA2 | XTA1/XTA2 | Reference |
|---|---|---|---|---|---|
| 1 | West Atlantic (Bahamas) | more saline (foram. $\delta^{18}$O) | −1.78/−0.22 | insig/+0.19 | *Lund and Curry* [2006] |
| 2 | Florida, USA | more saline (foram. $\delta^{18}$O) | −1.22/−0.22 | insig/insig | *Lund and Curry* [2006] |
| 3 | Central America (Yucatan) | drier (ostracode $\delta^{18}$O) | −1.41/insig | insig/insig | *Hodell et al.* [2005] |
| 4 | Caribbean (Puerto Rico) | less saline (foram. $\delta^{18}$O) | −3.23/−0.79 | +0.34/+0.32 | *Nyberg et al.* [2002] |
| 5 | Caribbean (Puerto Rico) | more saline (coral $\delta^{18}$O) | −3.23/−0.79 | +0.34/+0.32 | *Watanabe et al.* [2001] |
| 6 | Caribbean (St. Croix) | more saline (coral $\delta^{18}$O) | −3.37/−1.41 | +0.30/+0.23 | *Saenger et al.* [2008] |
| 7 | Caribbean (Cariaco) | drier (%Ti) | −3.19/−0.65 | insig/insig | *Haug et al.* [2001] |
| 8 | Tropical Pacific (Panama) | more saline (coral $\delta^{18}$O) | −1.86/−0.47 | insig/insig | *Linsley et al.* [1994] |
| 9 | West Africa | drier (lake level, model) | −0.97/−0.27 | −0.25/insig | *Shanahan et al.* [2009] |
| 10 | South America (Andes) | wetter (mass accumulation) | insig/insig | insig/insig | *Thompson et al.* [2006] |
| 11 | South America (Andes) | wetter (multiproxy) | +0.40/insig | insig/insig | *Baker et al.* [2001] |
| 12 | South America (Andes) | wetter (mass accumulation) | +0.40/insig | insig/insig | *Liu et al.* [2005] |
| Map | Location | LIA Conditions (Proxy) | Modelled Wind Stress Anomaly (dyn cm$^{-2}$) NA1/NA2 | XTA1/XTA2 | Reference |
| 13 | Caribbean (Caricao) | strong NE trades (# *G. bulloides*) | 0.14/0.41 | insig/insig | *Black et al.* [1999] |

[a]Results from TNA simulations were nearly identical to those of NA simulations. Map numbers 1 – 12 are for hydrologic proxies, and map number 13 is for a trade wind proxy.

Negative low-latitude precipitation anomalies are accompanied by enhanced northeasterly wind stress anomalies that are consistent with NA1.

[12] Neither XTA1 nor XTA2 exhibit significant low latitude precipitation or wind stress anomalies (Figures 2c and 2d). Even the idealized XTA1 exhibits precipitation anomalies that are generally heterogeneous with little evidence for robust patterns of change. Neither simulation exhibits significant northeasterly wind stress anomalies in the Caribbean or deep tropics. In contrast, low-latitude precipitation and wind stress anomalies in TNA1 and TNA2 (Figures 2e and 2f) are nearly indistinguishable from those in NA1 and NA2.

[13] Low-latitude precipitation and wind stress anomalies in NA and TNA simulations are clearly more similar to LIA proxy records than either XTA simulation (Figures 1 and 2 and Table 1). Considering that proxy records estimate the sign of hydrologic variability more accurately than its magnitude, we compare their spatial patterns with model results. Negative low-latitude North Atlantic annual average precipitation anomalies in NA and TNA simulations agree well with nearly unanimous proxy evidence for drier LIA conditions. In contrast, precipitation anomalies in XTA simulations are either insignificant or suggest increased precipitation that is at odds with proxy evidence. Furthermore, enhanced northeasterly wind stress in NA and TNA simulations agrees well with proxy evidence for greater wind-induced LIA upwelling [*Black et al.*, 1999], while insignificant wind stress anomalies in XTA simulations do not. In the Southern Hemisphere, only NA1 and TNA1 show significant precipitation increases as suggested by proxy records [*Baker et al.*, 2001; *Thompson et al.*, 2006], although similar precipitation anomaly patterns in NA2 and TNA2 agree qualitatively with proxy data.

## 4. Discussion

[14] Our results support suggestions that low latitude North Atlantic precipitation patterns during the LIA can be explained by a southerly displacement of the mean ITCZ. However, XTA simulations suggest this displacement was not forced by high-latitude SSTs alone, but must have been accompanied by some degree of low-latitude Atlantic cooling. Consistent with previous work illustrating the ITCZ's sensitivity to small SST gradients [*Chiang et al.*, 2002], NA2 and TNA2 simulations suggest that enhanced northeast trades and a southerly ITCZ displacement can occur in response to a mean low-latitude North Atlantic cooling anomaly of less than 0.5°C. The magnitude of this anomaly is at the upper detection limit of many commonly used paleotemperature proxies.

[15] The insensitivity of low-latitude precipitation to extratropical cooling is supported by an AGCM forced by 20th century multidecadal SST variability, which also shows that tropical precipitation is primarily driven by low-latitude SSTs [*Sutton and Hodson*, 2007]. Furthermore, the work of *Sutton and Hodson* [2007] suggests our results are insensitive to the exact pattern of SST forcing, and that they are likely to be relevant even if mechanisms other than a weakened AMOC caused LIA cooling.

[16] An idealized experiment that investigates the tropical response to extratropical heat anomalies describes the ITCZ in terms of a constraint imposed by atmospheric energy transport [*Kang et al.*, 2008]. Following a Northern Hemisphere cooling, *Kang et al.* [2008] suggest eddy energy transport can export heat from the northern tropics toward the northern pole, thus forcing the ITCZ toward the warmer Southern Hemisphere. Although the interhemispheric SST gradient steepens in these simulations, the mechanism for ITCZ variability does not explicitly require SST to change. In contrast, our results suggest cooler low-latitude North Atlantic SSTs were probably a necessary condition for southerly ITCZ migrations during the LIA.

[17] Coupled simulations often support the importance of tropical SST anomalies in determining the ITCZ's meridional position, but they suggest that these anomalies can propagate from high latitudes [*Chiang and Bitz*, 2005; *Broccoli et al.*, 2006]. A simulation in which the ITCZ was displaced southward by imposing high-latitude sea ice identified wind-evaporation-SST (WES) feedbacks as a

potential mechanism for communicating extratropical cooling to the tropics [*Chiang and Bitz*, 2005], although recent studies suggest that other atmospheric mechanisms are also important (S. Mahajan et al., The wind-evaporation-sea surface temperature (WES) feedback as a thermodynamic pathway for the equatorward propagation of high latitude sea-ice induced cold anomalies, submitted to *Journal of Climate,* 2009). Alternative mechanisms suggest high latitude signals may be transmitted to the tropics relatively rapidly via coastal Kelvin waves [*Yang*, 1999] and that interactions between a weakened AMOC and the wind-driven circulation may lead to changes in tropical Atlantic SST [*Chang et al.*, 2008].

[18] Ocean-atmosphere interactions, not captured by our uncoupled simulations, were likely important in shaping LIA climate. Such processes could enhance or dampen the precipitation and wind anomalies seen in our results. The stronger northeasterly trades in NA and TNA simulations would likely cause a positive WES feedback that could enhance or prolong cool SST anomalies. However, if cooler LIA SSTs were caused by a weaker AMOC, subsequent weakening of the low-latitude western boundary current would likely cause subsurface warming in the Caribbean and western tropical Atlantic leading to warmer SSTs in upwelling regions [*Wan et al.*, 2009]. The degree to which our simulations are realistic depends on the relative influences of these feedbacks. If the WES mechanism dominates, amplification of the small cooling imposed in NA2 and TNA2 may lead to a more pronounced tropical response. If the subsurface ocean warming has a larger influence, the imposed cooling would decay quickly, leading to a more subtle response [*Wan et al.*, 2009].

[19] Finally, some proxy evidence suggests that a southerly ITCZ migration during the LIA was a global phenomenon [*Newton et al.*, 2006] that may reflect remote climatic impacts of Atlantic SST anomalies. ZD05 suggest the cooler Atlantic SSTs and enhanced cross-isthmus winds seen in NA and TNA simulations could induce an El Niño-like tropical Pacific circulation capable of weakening the Indian and Asian monsoons. This mechanism is in agreement with evidence for weaker monsoons [e.g., *Gupta et al.*, 2003] and El Niño-like conditions [e.g., *Mann et al.*, 2005] during the LIA. However, without ocean feedbacks, our simulation exhibits an enhanced southwest Asian monsoon circulation (not shown) that further illustrates the important role of coupled atmosphere-ocean interactions in global climate teleconnections.

## 5. Summary and Conclusions

[20] We have identified a clear role for low-latitude Atlantic SST anomalies in forcing southerly ITCZ displacement. Low-latitude cooling within the range of recent LIA SST proxy estimates generates precipitation and wind stress anomalies that agree with available reconstructions. Conversely, without ocean-atmosphere interaction, even very large extratropical cooling cannot reproduce LIA precipitation and trade wind patterns. Additional highly-resolved and well-dated proxy reconstructions are clearly needed to better constrain the spatial and temporal evolution of Atlantic SST and hydrology during the LIA. Furthermore, additional simulations with both coupled and atmospheric GCMs that better resolve small-scale circulation features will help elucidate the important processes related to regional and remote influences of Atlantic SST on tropical hydrology.

[21] **Acknowledgments.** This work was supported by NSF grants OCE 0623364 and ATM 033746 as well as the student research fund of MIT's Department of Earth, Atmospheric and Planetary Science.

## References

Baker, P. A., G. O. Seltzer, S. C. Fritz, R. B. Dunbar, M. J. Grove, P. M. Tapia, S. L. Cross, H. D. Rowe, and J. P. Broda (2001), The history of South American tropical precipitation for the past 25,000 years, *Science*, *291*, 640–643.

Biasutti, M., A. H. Sobel, and Y. Kushnir (2006), AGCM precipitation biases in the tropical Atlantic, *J. Clim.*, *19*, 935–958.

Black, D. E., L. C. Peterson, J. T. Overpeck, A. Kaplan, M. N. Evans, and M. Kashgarian (1999), Eight centuries of North Atlantic Ocean atmosphere variability, *Science*, *286*, 1709–1713.

Black, D. E., M. A. Abahazi, R. C. Thunell, A. Kaplan, E. J. Tappa, and L. C. Peterson (2007), An 8-century tropical Atlantic SST record from the Cariaco Basin: Baseline variability, twentieth-century warming, and Atlantic hurricane frequency, *Paleoceanography*, *22*, PA4204, doi:10.1029/2007PA001427.

Broccoli, A. J., K. A. Dahl, and R. J. Stouffer (2006), Response of the ITCZ to Northern Hemisphere cooling, *Geophys. Res. Lett.*, *33*, L01702, doi:10.1029/2005GL024546.

Broecker, W. S. (2000), Was a change in thermohaline circulation responsible for the Little Ice Age?, *Proc. Nat. Acad. Sci. U. S. A.*, *97*, 1339–1342.

Chang, P., R. Zhang, W. Hazeleger, C. Wen, X. Wan, L. Ji, R. J. Haarsma, W. P. Breugem, and H. Seidel (2008), Oceanic link between abrupt changes in the North Atlantic Ocean and the African monsoon, *Nat. Geosci.*, *1*, 444–448.

Chiang, J. C. H., and C. M. Bitz (2005), Influence of high latitude ice cover on the marine Intertropical Convergence Zone, *Clim. Dyn.*, *25*, 477–496.

Chiang, J. C. H., Y. Kushnir, and A. Giannini (2002), Deconstructing Atlantic Intertropical Convergence Zone variability: Influence of the local cross-equatorial sea surface temperature gradient and remote forcing from the eastern equatorial Pacific, *J. Geophys. Res.*, *107*(D1), 4004, doi:10.1029/2000JD000307.

Collins, W. D., P. J. Rasch, B. A. Boville, J. J. Hack, J. R. McCaa, D. L. Williamson, and B. P. Briegleb (2006), The formulation and atmospheric simulation of the Community Atmosphere Model version 3 (CAM3), *J. Clim.*, *19*, 2144–2161.

Gupta, A. K., D. M. Anderson, and J. T. Overpeck (2003), Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean, *Nature*, *421*, 354–357.

Hack, J. J., J. M. Caron, S. G. Yeager, K. W. Oleson, M. M. Holland, J. E. Truesdale, and P. J. Rasch (2006), Simulation of the global hydrological cycle in the CCSM Community Atmosphere Model version 3 (CAM3) mean features, *J. Clim.*, *19*, 2199–2221.

Haug, G. H., K. A. Hughen, D. M. Sigman, L. C. Peterson, and U. Rohl (2001), Southward migration of the Intertropical Convergence Zone through the Holocene, *Science*, *293*, 1304–1308.

Hodell, D. A., M. Brenner, J. H. Curtis, R. Medina-Gonzalez, E. I. Can, A. Albornaz-Pat, and T. P. Guilderson (2005), Climate change on the Yucatan Peninsula during the Little Ice Age, *Quat. Res.*, *63*, 109–121.

Hurrell, J. W., J. J. Hack, A. S. Phillips, J. Caron, and J. Yin (2006), The dynamical simulation of the Community Atmosphere Model version 3 (CAM3), *J. Clim.*, *19*, 2162–2183.

Jiang, H., J. Eiriksson, M. Schulz, K. L. Knudsen, and M. S. Seidenkrantz (2005), Evidence for solar forcing of sea-surface temperature on the North Icelandic Shelf during the late Holocene, *Geology*, *33*, 73–76.

Kang, S. M., I. M. Held, D. M. W. Frierson, and M. Zhao (2008), The response of the ITCZ to extratropical thermal forcing: Idealized slab-ocean experiments with a GCM, *J. Clim.*, *21*, 3521–3532, doi:10.1175/2007JCLI2146.1.

Keigwin, L. D., J. P. Sachs, and Y. Rosenthal (2003), A 1600-year history of the Labrador Current off Nova Scotia, *Clim. Dyn.*, *21*, 53–62.

Linsley, B. K., R. B. Dunbar, G. M. Wellington, and D. A. Mucciarone (1994), A coral-based reconstruction of Intertropical Convergence Zone variability over Central-America since 1707, *J. Geophys. Res.*, *99*, 9977–9994.

Liu, K. B., C. A. Reese, and L. G. Thompson (2005), Ice-core pollen record of climatic changes in the central Andes during the last 400 yr, *Quat. Res.*, *64*, 272–278.

Lund, D. C., and W. Curry (2006), Florida Current surface temperature and salinity variability during the last millennium, *Paleoceanography*, *21*, PA2009, doi:10.1029/2005PA001218.

Mann, M. E., M. A. Cane, S. E. Zebiak, and A. Clement (2005), Volcanic and solar forcing of the tropical Pacific over the past 1000 years, *J. Clim.*, *18*, 447–456.

Newton, A., R. Thunell, and L. Stott (2006), Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium, *Geophys. Res. Lett.*, *33*, L19710, doi:10.1029/2006GL027234.

Nyberg, J., B. A. Malmgren, A. Kuijpers, and A. Winter (2002), A centennial-scale variability of tropical North Atlantic surface hydrography during the late Holocene, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *183*, 25–41.

Peterson, L. C., G. H. Haug, K. A. Hughen, and U. Rohl (2000), Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial, *Science*, *290*, 1947–1951.

Saenger, C., A. L. Cohen, D. W. Oppo, and D. Hubbard (2008), Interpreting sea surface temperature from strontium/calcium ratios in Montastrea corals: Link with growth rate and implications for proxy reconstructions, *Paleoceanography*, *23*, PA3102, doi:10.1029/2007PA001572.

Shanahan, T. M., J. T. Overpeck, K. J. Anchukaitis, J. W. Beck, J. E. Cole, D. L. Dettman, J. A. Peck, C. A. Scholz, and J. W. King (2009), Atlantic forcing of persistent drought in West Africa, *Science*, *324*, 377–380.

Stouffer, R. J., et al. (2006), Investigating the causes of the response of the thermohaline circulation to past and future climate changes, *J. Clim.*, *19*, 1365–1387.

Sutton, R. T., and D. L. R. Hodson (2007), Climate response to basin-scale warming and cooling of the North Atlantic Ocean, *J. Clim.*, *20*, 891–907.

Thompson, L. G., E. Mosley-Thompson, H. Brecher, M. Davis, B. León, D. Les, P. Lin, T. Mashiotta, and K. Mountain (2006), Abrupt tropical climate change: Past and present, *Proc. Nat. Acad. Sci. U. S. A.*, *103*, 10,536–10,543.

Wan, X. Q., P. Chang, R. Saravanan, R. Zhang, and M. W. Schmidt (2009), On the interpretation of Caribbean paleo-temperature reconstructions during the Younger Dryas, *Geophys. Res. Lett.*, *36*, L02701, doi:10.1029/2008GL035805.

Watanabe, T., A. Winter, and T. Oba (2001), Seasonal changes in sea surface temperature and salinity during the Little Ice Age in the Caribbean Sea deduced from Mg/Ca and $^{18}O/^{16}O$ ratios in corals, *Mar. Geol.*, *173*, 21–35.

Winter, A., H. Ishioroshi, T. Watanabe, T. Oba, and J. Christy (2000), Caribbean sea surface temperatures: Two-to-three degrees cooler than present during the Little Ice Age, *Geophys. Res. Lett.*, *27*, 3365–3368.

Yang, J. Y. (1999), A linkage between decadal climate variations in the Labrador Sea and the tropical Atlantic Ocean, *Geophys. Res. Lett.*, *26*, 1023–1026.

Zhang, R., and T. L. Delworth (2005), Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation, *J. Clim.*, *18*, 1853–1860.

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