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Increased hurricane frequency near Florida during Younger Dryas Atlantic Meridional Overturning Circulation slowdown

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ABSTRACT

The risk posed by intensification of North Atlantic hurricane activity remains controversial, in part due to a lack of available storm proxy records that extend beyond the relatively stable climates of the late Holocene. Here we present a record of storm-triggered turbidite deposition offshore the Dry Tortugas, south Florida, USA, that spans abrupt transitions in North Atlantic sea-surface temperature and Atlantic Meridional Overturning Circulation (AMOC) during the Younger Dryas (12.9–11.7 ka). Despite potentially hostile conditions for cyclogenesis in the tropical North Atlantic at that time, our record and numerical experiments suggest that strong hurricanes may have regularly affected Florida. Less severe surface cooling at mid-latitudes (~20°–40°N) than across much of the tropical North Atlantic (~10°–20°N) in response to AMOC reduction may best explain strong hurricane activity during the Younger Dryas near the Dry Tortugas and possibly along the entire southeastern coast of the United States.

INTRODUCTION

Reduction in Atlantic Meridional Overturning Circulation (AMOC) during the Younger Dryas (YD), most often attributed to meltwater release during drainage of glacial Lake Agassiz (e.g., Clark et al., 2001, and references therein), may have lowered sea-surface temperatures (SSTs) in the North Atlantic (e.g. Schmidt and Lynch-Stieglitz, 2011) and therefore, possibly the intensity of tropical cyclones (TCs) as well. However, the environmental controls on TC activity (genesis, track, intensity) are complex, responding not only to changes in local SST but also vertical wind shear and humidity. For example, a globally heterogeneous response of TC activity to universally colder temperatures in PMIP2 (Paleoclimate Modeling Intercomparison Project; http://pmip2.lsce.ipsl.fr/) simulations of the Last Glacial Maximum (21 ka) was shown by Korty et al. (2012). Future multimodel mean (CMIP5, Coupled Model Intercomparison Project; http://cmip-pcmdi.llnl.gov/index.html) projections, assuming a high greenhouse-gas emissions scenario, anticipate increased TC potential intensity across much of the tropical North Atlantic by the end of the 21st century (Sobel et al., 2016), but it remains unclear if this would translate into more landfalling intense hurricanes along the basin margins. Historic observations (1947–2015 CE) demonstrate that warm SSTs and low vertical wind shear in the Main Development Region (MDR) (Fig. 1A) have often fostered increased basin-wide TC activity while coinciding with less favorable conditions for storm intensification along the Eastern Seaboard (Kossin, 2017). No proxy records or comparable modeling experiments of TC activity currently exist for the YD that could be used to test if severe changes in MDR thermodynamic structure, likely to affect cyclone intensity, were counterbalanced by more favorable conditions elsewhere in the basin.

Proxy-based reconstruction of past TC activity using coarse-grained overwash deposits in lower energy back-barrier marshes or lagoons (e.g., Donnelly et al., 2001) has typically been limited to the mid-late Holocene

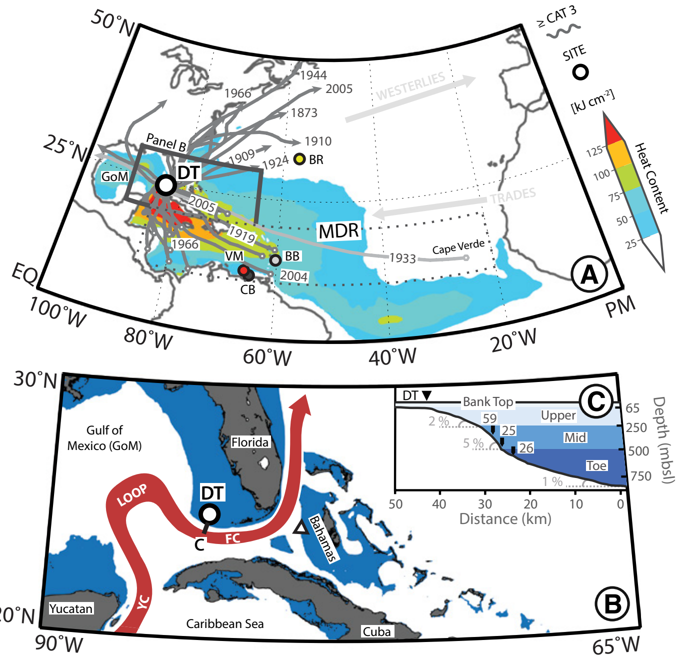

Figure 1. Site maps. A: Historic North Atlantic hurricane tracks passing within 65 nm of our site at major hurricane strength (96 kn, 1 min maximum sustained wind) since 1848 CE (Knapp et al., 2010). White circle pinpoints the Dry Tortugas (DT). Location used in Figure 2 proxy reconstructions by dots: red—Vema 12–107 (VM); yellow—Bermuda Rise (BR); light gray—Barbados (BB); dark gray—Cariaco Basin (CB). Tracks of major hurricanes that formed in the Caribbean (dark gray) versus one from the eastern North Atlantic (light gray) are noted. Background color map was compiled from National Oceanic and Atmospheric Administration (NOAA) monthly satellite-derived ocean heat content data for the 2013–2015 CE storm seasons (Data Repository [see footnote 1]). MDR—main development region; GoM—Gulf of Mexico; CAT—category; EQ—equator; PM—prime meridian. B: Regional map of southern Florida, northern Caribbean, and Gulf of Mexico. Red arrow shows the generalized path of the Yucatan (YC), Loop, and Florida Currents (FC). Location of transect (shown in inset C) is given by black line from DT to c (in inset C). Bahamas hurricane reconstruction sites from Toomey et al. (2013) are indicated by triangle. Blue shading indicates shallow water areas (<120 m below sea level, mbsl). C: Schematic profile across offbank core transect. Jumbo piston core (JPC) 59 is located ~15 km west of JPC25 and JPC26 and projected into line DT-c. Maps were created using Matlab M_map function suite (created by Pawlowicz et al., https://www.eoas.ubc.ca/~rich/map.html).

due to shoreward transgression of these environs in response to deglacial sea-level rise (Bard et al., 2010). However, resuspension of sediment on continental shelves by storm-induced currents, its subsequent transport offshore, and deposition within continental margin sedimentary sequences

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could potentially yield much longer records of past TC landfalls. Shanmugam (2008) reviewed observations from modern storms that document bottom-water velocities regularly in excess of 1 m s^{-1} on continental shelves and offshore sediment transport. Toomey et al. (2013) found that deposition of coarse-grained layers in an offbank transect of multicores (~200–500 m below sea level, mbsl) from the Bahamas (Fig. 1B) closely tracked the passage of 10 major hurricanes between ca. 1915 and 1965 CE. Older deposits at that site, thought to reflect increased mid-late Holocene hurricane activity, are consistent with published Caribbean back-barrier overwash records (Toomey et al., 2013, and references therein).

Here we use jumbo piston cores (JPCs) from offshore the Dry Tortugas, Florida, that span the YD and early Holocene (EH) (Lynch-Stieglitz et al., 2011) to extend the Bahamas paleohurricane reconstruction (located ~400 km east) in Toomey et al. (2013). Florida is in the path of storms tracking out of the eastern Atlantic, western Caribbean, and Gulf of Mexico; sedimentary archives there are well positioned to capture changes in North Atlantic cyclogenesis. Together with analysis of general circulation model experiments, we address two main questions. (1) How do cooler SSTs and/or AMOC slowdown affect North Atlantic TC activity? (2) Are model-simulated changes in storminess consistent with our proxy-based record of TC landfalls near Florida?

MATERIALS AND METHODS

The Florida margin (Fig. 1) near the Dry Tortugas Islands (25°N, 83°W) can be divided into four general bathymetric zones: bank top (~0–60 mbsl), upper slope (~60–250 mbsl, 2% grade), mid-slope (250–500 mbsl, 5% grade), and toe of slope (500–1000 mbsl, 1% grade). An offbank depth transect of cores (JPC25, 494 mbsl; JPC26, 546 mbsl; JPC59, 358 mbsl) extending from the upper slope into the Florida Straits was collected aboard the R/V *Knorr* in January 2002 (cruise KNR166-02). Grain size was measured at ~1 cm intervals in these cores, using a Beckman-Coulter (LS13320) laser particle size analyzer. Bulk mean grain-size data from JPC25, presented in Figure 2A, are archived in the GSA Data Repository[1]. Existing radiocarbon chronology and *Globigerinoides ruber* $\delta^{18}O$ from JPC26 (Lynch-Stieglitz et al., 2011) were stratigraphically correlated to JPC25 and JPC59 using X-ray fluorescence (ITRAX; http://www.boscorf.org/instruments/itrax-high-resolution-xrf-analysis-sediment-cores) ln(Ca/Fe), defining the YD and EH boundaries in each core (Fig. DR1). We note, however, that this approach is not aimed at differentiating events occurring in rapid succession and/or short-term changes in local sedimentation rate within the YD or EH.

We also analyzed environmental conditions known to favor TC development and intensification in two segments of the Transient Climate Evolution Experiment (TraCE), a globally coupled ocean-atmosphere-land model simulation performed with Community Climate System Model version 3.0 (CCSM3; e.g., Liu et al., 2009). TraCE captures much of the YD SST cooling seen in comparable North Atlantic proxy reconstructions (see Table DR1). We computed TC potential intensity, absolute vorticity, and tropospheric wind shear, which is a measure of tropospheric saturation deficits (see the Data Repository). These metrics can be combined into a genesis potential index (Korty et al., 2012) that measures the combined effects of wind shear, moist thermodynamics, and convection in producing favorable conditions for TCs to form and intensify.

We calculated these variables using monthly TraCE output spanning the middle of the YD (12.5–12.0 ka), during which the North Atlantic was subject to freshwater hosing, and during a later 600 yr segment (10.8–10.2 ka) following establishment of reduced EH meltwater fluxes. Genesis potential was calculated for each month and then summed over June to November of each year; the seasonal totals were averaged over both the YD and EH segments.

[1]GSA Data Repository item 2017358, grain-size data, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

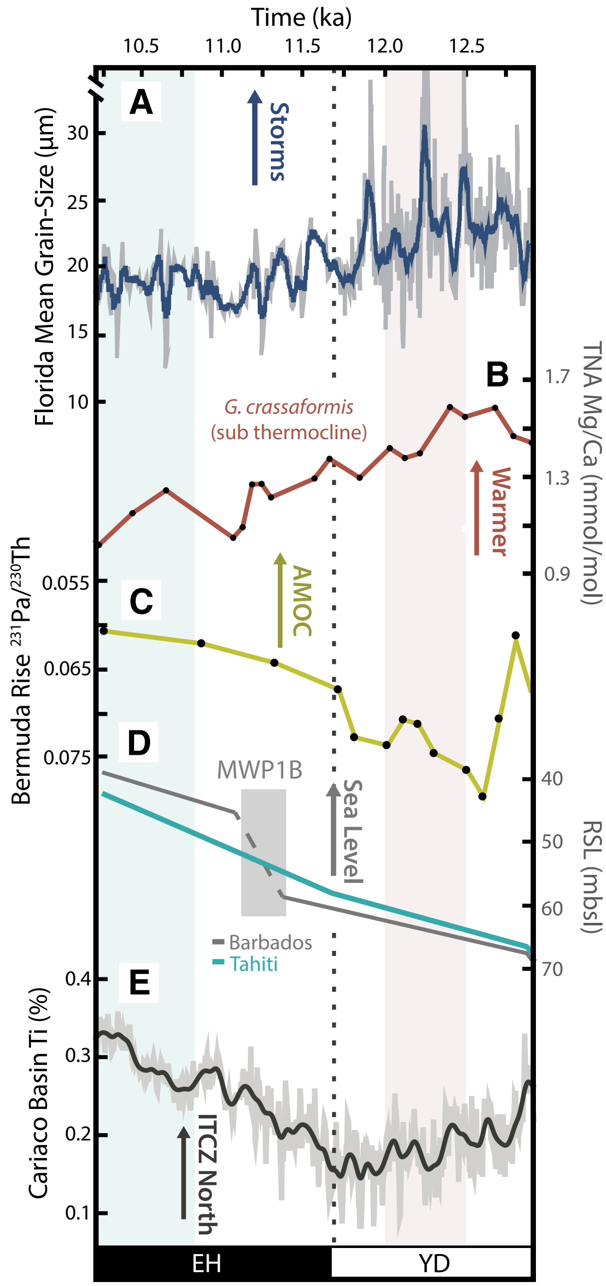

Figure 2. Climatic variability across the Younger Dryas–early Holocene (YD-EH) transition. A: Grain-size record from Florida Straits core KNR166–2 JPC25. Raw data are shown in gray with 50 yr moving average filtered time series given by blue line. Note broken y axis. B: Mg/Ca paleotemperature proxy data (red) from core VM12–107 (Schmidt et al., 2012). TNA—Tropical North Atlantic; *G.—Globorotalia*. C: Bermuda Rise (core OCE326-GGC5) $^{231}Pa/^{230}Th$ record of Atlantic Meridional Overturning Circulation (AMOC) (McManus et al., 2004) (yellow). D: Subsidence corrected relative sea-level (RSL; mbsl—m below sea level) records from Barbados (gray) and Tahiti (light blue) adapted from Bard et al. (2010, and references therein). MWP—meltwater pulse. E: Cariaco Basin, Venezuela (Ocean Drilling Program Site 1002), %Ti (Haug et al., 2001) (dark gray). Blue and pink shading highlights EH and YD Transient Climate Evolution Experiment (TraCE; see text) segments, respectively. ITCZ—Intertropical Convergence Zone.

RESULTS AND DISCUSSION

A matrix composed largely of carbonate mud and trace quantities of iron-bearing fines supports coarser grained biogenic grains in JPC25, JPC26, and JPC 59. Despite relatively uniform composition, downcore changes in color and iron abundance versus calcium-rich sediments derived from the bank top (Fig. DR1) define tie points between cores coincident with deglacial flooding of the bank top (ca. 13 ka), the YD-EH transition (ca.11.7 ka), and platform submergence (ca.10 ka). In general, the sediments appear largely structureless; however, there is sporadic evidence of low-density turbidite deposition, such as parallel laminae (millimeter scale) and sand lenses. Burrows, avoided during sampling, were also occasionally identified by visible changes in sediment structure and/or color. The >63 µm sediment fraction is dominated by benthic foraminifera (primarily miliolids and rotalids), planktonic foraminifera, and occasional pelycopod shell fragments. While we caution that no benthic foraminifera diagnostic of shallow-water origin were observed in the coarsest layers, most of the pelycopod shells were fractured and angular, suggesting that their taphonomic history included breakage during transport from elsewhere.

We propose that the most likely mechanism for emplacement of coarse-grained material in these cores is entrainment of sediment on the bank top and deposition offshore by turbidites during storms. Grain size increases downslope (Fig. DR2), and the coarsest beds are poorly sorted relative to background sediments; these observations are inconsistent with winnowing by the Florida Current. Preferential contourite formation during the YD is also unlikely given evidence for greatly reduced AMOC strength at that time (Lynch-Stieglitz et al., 2011; McManus et al., 2004; Fig. 2). Extensive seismic surveying of the southwest Florida margin by Brooks and Holmes (1989) shows that depositional units are oriented offbank, not along the path of the Florida Current. We also note higher sedimentation rates during the YD than the ensuing EH, suggesting that coarse-grained beds in the YD unit are net depositional rather than erosional. General agreement between grain-size records from JPC25, JPC26, and JPC59, the latter located ~15 km west along bank, likely excludes local mass wasting as a viable alternative mechanism for emplacement of coarser grained units. These sites do not face active margins likely to produce frequent large tsunamis, nor do they occupy the type of steep continental margin thought to be susceptible to slope failures triggered by distant earthquakes (e.g., Johnson et al., 2017). While there are no comparable TC records with which to definitively rule out other local sediment transport mechanisms, given (1) little evidence for contourite formation or tsunami-triggered mass wasting, (2) widespread observations of sediment entrainment on continental shelves during modern storms (Shanmugam, 2008), and (3) sedimentary evidence of density current deposition offbank the Bahamas from historic major hurricanes (Toomey et al., 2013), we argue that coarse-grained material in cores JPC25, JPC26, and JPC59 is largely derived from storm-triggered turbidites.

Grain-size variability in our cores suggests relatively more frequent high-energy events during the YD with an abrupt transition to finer grained deposition moving into the EH (Fig. 2A; Fig. DR2). For example, mean grain size in JPC25 is 23 ± 4 µm through the YD, but drops to 19 ± 2 µm in the EH section (11.7–10.2 ka). Transgressive drowning of the Florida Bank during Meltwater Pulse 1B (MWP1B), ca. 11.4–11.1 ka, limiting entrainment of sediment by storm waves, could provide another explanation for the lack of coarse-grained deposits during the EH; however, recent drilling of drowned reefs offshore Tahiti (Bard et al., 2010, and references therein) indicates a relatively gradual change in the rate of sea-level rise from the YD (~8 mm/yr) to the EH (12 mm/yr), calling into question the existence of MWP1B. Instead, we propose that sustained AMOC reduction during the YD (McManus et al., 2004) produced environmental conditions that were more hostile to storms across much of the tropical North Atlantic, but locally more favorable near the southeastern United States.

The spatial pattern of changes in potential intensity during the YD (Fig. DR3) shows that it was much lower where SSTs fell most dramatically across low latitudes of the tropical Atlantic, but potential intensity was little changed or sometimes higher where SSTs were warmer relative to the remainder of the basin. Near Florida, the seasonal (June–November) maximum potential intensity remained high enough to support category 5 storms throughout the YD and EH (Fig. 3C; YD = 70 m s^{-1}, EH = 74 m s^{-1}). Vecchi and Soden (2007) showed that potential intensity is strongly related to relative SST rather than to absolute SST. Potential intensity is the highest where waters are locally warmer than the regional average. On average, storm season wind shear was higher during the YD than EH across the tropical Atlantic (Fig. DR3), but lower near Florida ($\Delta = -0.3$ m s^{-1}) and in the subtropics. In colder atmospheres, a smaller quantity of water vapor is required to saturate an air column. This, in combination with lower shear, yields higher genesis potential (GP in Fig. 3B) with conditions more favorable for TCs near the Dry Tortugas, outweighing lower absolute local SST (TraCE: YD = 25 °C, EH = 26 °C, comparable to Mg/Ca proxy SST from JPC26; Schmidt and Lynch-Stieglitz, 2011).

In addition to the potential for increased storm activity in the western subtropics, genesis potential appears largely unchanged (YD versus EH) in the southern Caribbean (Fig. 3B), the source region for most major storms tracking near the Dry Tortugas today. Since 1848 CE, 11 of the 12 storms passing the JPC25 core site (≤65 nm radius) as major hurricanes (≥category 3) formed within or proximal to the Caribbean Sea (Fig. 1A; Knapp et al., 2010), often steered by late season westerlies north-northwest over deep, warm waters on their way toward Florida. A more southern mean position of the Intertropical Convergence Zone (Haug et al., 2001) and westerlies during the YD could have shifted hurricane tracks toward Florida in late summer when warm Caribbean waters often reach their maximum extent.

Coarse discretization of the TraCE ocean domain (25 vertical levels and ~200–400 km horizontal resolution at these latitudes), however, may limit its sensitivity to thermocline structure and therefore subsurface warming during episodes of sustained AMOC reduction and/or migrations of the Florida Current (~100 km wide), which may have further

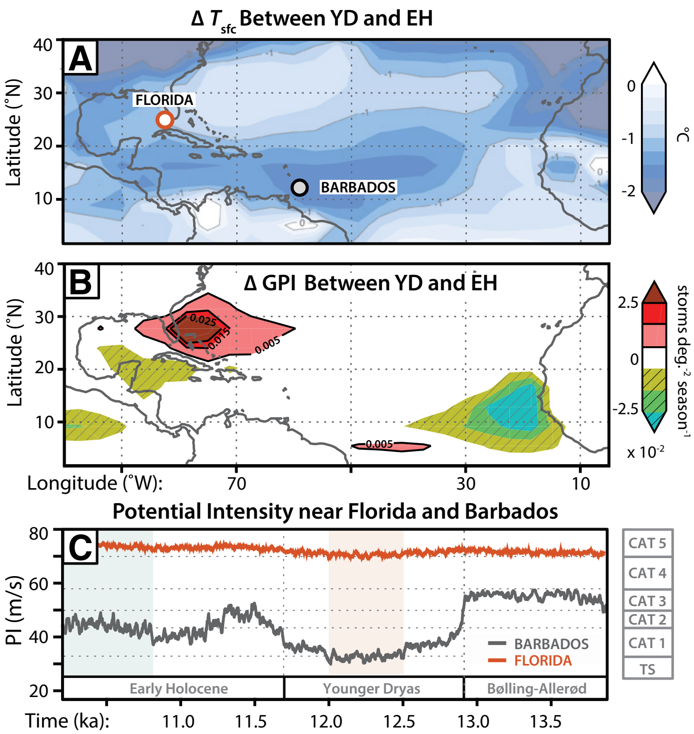

Figure 3. Simulated changes in climatic controls on hurricane activity between the Younger Dryas (YD, 12.0–12.5 ka) and early Holocene (EH, 10.2–10.8 ka). A: Spatial difference in storm season surface temperature (T_{sfc}). B: Spatial difference in genesis potential index (GPI), averaged for each Transient Climate Evolution Experiment (TraCE) interval (see text). C: Filtered (20 yr) time series of maximum potential intensity (PI) near the Dry Tortugas (red) and Barbados (gray) from 13,850 yr ago through the EH. CAT—category; TS—tropical storm.

augmented favorable TC conditions near our site. Tropical North Atlantic subsurface temperature is thought to be anticorrelated with AMOC strength (Zhang, 2007), and Mg/Ca temperature estimates from southern Caribbean indicate substantial warming (~3–4 °C) at intermediate depths during the YD (Schmidt et al., 2012). Entrainment of cold water from the thermocline into the surface mixed layer by hurricane-force winds brings colder water to the surface, working as a negative feedback on storm intensity by reducing the transfer of heat to the atmosphere (e.g., Price, 1981). In turn, however, increased hurricane mixing is thought to enhance poleward heat flux (Emanuel, 2001), and could have acted as negative feedback on YD high-latitude cooling.

CONCLUSIONS

Despite cooler local surface temperatures, reconstructed hurricane strikes and general circulation model experiments suggest relatively strong storm activity along the coast of Florida during the YD. While YD conditions for TC development appear unfavorable across much of the North Atlantic, the large-scale environment was more conducive for TC genesis and intensification near the southeastern U.S. coast, where SST cooling was less than elsewhere in the basin. Subsurface warming may also have contributed to strong hurricane development near the Dry Tortugas during the YD, motivating future modeling experiments that can better resolve changes in thermocline depth. Complementary storm records along the Eastern Seaboard are also needed to isolate the impact of deglacial sea-level rise on site sensitivity and establish whether increased western North Atlantic hurricane activity is a robust feature of other Pleistocene cold events (i.e., Heinrich) or, possibly, periods of slower AMOC in general.

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