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Tropical cyclone activity and western North Atlantic stratification over the last millennium: a comparative review with viable connections

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ABSTRACT: Tropical cyclones (TC) are recognized to modify the thermal structure of the upper ocean through the process of vertical mixing. Assessing the role this mixing plays in the overall stratification of the upper ocean is difficult, due to the relatively short and incomplete instrumental record. Proxy records for both TC landfalls and oceanographic stratification are preserved within the geological record and provide insight for how past changes in TC-induced mixing have potentially affected water column structure prior to the instrumental record. Here we provide the first comparison between previously published paleo-reconstructions of vertical ocean density and tropical cyclone activity from the western North Atlantic. A prominent lull in TC activity has been observed prior to approximately 1700 CE that extends back several centuries. This interval of low TC activity is shown to be concurrent with the timing of increased ocean stratification near Great Bahama Bank, potentially due in part to reduced TC-induced mixing. To test whether this relationship is feasible, we present numerical results from a coarse-resolution ocean general circulation model experiment isolating the effect of TC surface wind forcing on the upper ocean. An anomaly of roughly 0.12 $\mathrm{kg\,m^{-3}}$ in vertical stratification occurs above and below the mixed layer for model runs with and without TC mixing. This anomaly is roughly 25% of the entire paleo-density signal observed just prior to 1700 CE. These results suggest that TC mixing alone cannot completely explain the density anomaly observed prior to 1700 CE, but support TC variability as an important contributor to enhancing oceanic stratification during this interval. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: hurricanes; paleotempestology; paleoceanography; ocean; stratification; late Holocene.

Introduction

The relationship between tropical cyclone (TC) activity and climate variability continues to gain interest, largely because fundamental interactions remain poorly understood. Recent work has linked low-frequency variability in TC activity to changes in tropical sea surface temperature (Emanuel, 2005), and with observable increases in the number (Webster *et al.*, 2005) and strength (Elsner *et al.*, 2008) of the most intense storms since the onset of global satellite coverage around 1970 CE. However, model projections of future cyclone activity vary widely, and results suggest additional factors may be important within different climate change scenarios (Emanuel *et al.*, 2008, 2010; Knutson *et al.*, 2008). For example, new model results suggest that the annual number of Atlantic TCs is projected to decrease under continued anthropogenic warming, but the frequency of intense events (categories 4 and 5) may double (Bender *et al.*, 2010). While there is strong evidence for a response in TC activity to changes in large-scale climate properties, TCs also appear to actively contribute to the dynamics of the climate system through ocean mixing.

Ocean mixing is an important physical process that regulates the global oceanic transport of heat, mass, and nutrients. Past findings indicate that TCs are a significant source of upper-ocean mixing in the Tropics (Sriver and Huber, 2007; Sriver *et al.*, 2008). It has been hypothesized that this mixing is a major factor for maintaining the meridional overturning circulation and ocean heat transport (Emanuel, 2001), but recent modeling efforts suggest TCs play a more modest role for the present-day climate (e.g. Jansen and Ferrari, 2009; Sriver *et al.*, 2010; Sriver and Huber, 2010), though TCs may be more important for large-scale oceanic transports in climate scenarios with temperature patterns warmer than present day (Brierley *et al.*, 2009; Fedorov *et al.*, 2010; Korty *et al.*, 2008). Even though the impacts of TCs on high-latitude climate appear to be minimal, these events do appear to be important for tropical and subtropical ocean dynamics. New modeling results indicate that TC-induced ocean mixing influences upper ocean temperature and density patterns (Fedorov *et al.*, 2010; Jansen and Ferrari, 2009; Sriver and Huber, 2010), due in part to the response of shallow subtropical overturning circulation to enhanced mixing in tropical cyclone regions.

In order to understand the nature of TC variability within the context of future climate change it is useful to establish a long-term record of TC information extending back to periods with climate factors different from the present day. Currently the lack of such long-term records is a major limitation in the field of TC climate variability. In the Atlantic basin, an official dataset exists containing track information and maximum wind speeds dating back to 1851 CE (Landsea *et al.*, 2004), but the reliability of these data before the onset of satellite-based observations remains controversial (Landsea *et al.*, 2010; Mann *et al.*, 2007).

Proxies for both TC occurrences (e.g. Frappier *et al.*, 2007a; Nott, 2004), and ocean stratification (e.g. Lund *et al.*, 2006) exist within natural geological archives, and provide an additional resource for evaluating potential connections between TC activity and oceanic properties. To this end we provide a brief review of the state of knowledge with respect to both TC variability and ocean stratification in the western North Atlantic over the last millennium, framed in the context of potential interactions. Further, recent global climate modeling results by Sriver and Huber (2010) are presented to assess the sensitivity of vertical stratification in the western North Atlantic to TC mixing, and to provide a quantitative evaluation for the feasibility of TC variability as a driver for observed changes in paleo-stratification.

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Tropical cyclone proxies

Proxies for reconstructing TCs prior to the best-track dataset come from a diverse array of sources. Current compilations from ship logs, newspapers, government records and diaries extend back for several centuries both in the western North Atlantic (Boose *et al.*, 2001, 2004; Chenoweth, 2006; Chenoweth and Divine, 2008; Garcia-Herrera *et al.*, 2005; Ludlum, 1963; Mock, 2004, 2008), and western North Pacific (Chan and Shi, 2000; Fogarty *et al.*, 2006; Garcia-Herrera *et al.*, 2007; Grossman and Zaiki, 2007; Liu *et al.*, 2001). Negative $\delta^{18}O$ anomalies associated with TC precipitation are preserved in annually resolved speleothems and tree rings (Frappier *et al.*, 2007b; Malmquist, 1997; Miller *et al.*, 2006; Nott *et al.*, 2007), and high terrestrial run-off by TCs also affecting the annual growth rate and luminescence of coral (Lough, 2007; Nyberg *et al.*, 2007). TC-induced freshwater flooding events are also preserved within sedimentary archives (Grossman, 2001; Noren *et al.*, 2002), with varved lacustrine chronologies allowing for annually resolved reconstructions of intense precipitation (Besonen *et al.*, 2008). Additional to these historic and precipitation-based proxies, evidence of coastal inundation by TCs is often preserved within the geological record, including storm-induced beach ridges and scarps (Brooke *et al.*, 2008; Buynevich *et al.*, 2007; Nott, 2011; Nott *et al.*, 2007, 2009; Nott and Hayne, 2001), cyclone-transported boulder deposits (Scheffers and Scheffers, 2006; Spiske *et al.*, 2008; Suzuki *et al.*, 2008; Yu *et al.*, 2009; Zhao *et al.*, 2009), and the existence of marine foraminifera within inland sediments (Hippensteel and Martin, 1999; Scott *et al.*, 2003; Williams, 2010).

Along with the above-mentioned proxies, storm-induced overwash deposits preserved in coastal lagoons and salt marshes have proven to be an especially effective method for developing millennial-scale records of TC occurrences. Bottom sediments collected from these ordinarily sheltered areas are typically composed of fine-grained organic material. In contrast, during intense TC activity, associated storm surge and waves carry coarser sediment and marine material from the beach and near-shore into these back-barrier environments and deposit them as an anomalous event layer. Over time these storm layers are covered by accumulating fine-grained organic matter until the next high-energy storm event forms another anomalous deposit. The result is a preserved sedimentary record of TC-induced flooding at a site, identified typically from sediment cores using grain size analysis (e.g. Donnelly and Woodruff, 2007), percent inorganic content (e.g. Liu and Fearn, 2000), and/or the relative abundance of marine sourced material (e.g. Woodruff *et al.*, 2009). Regions where overwash reconstructions currently exist for the western North Atlantic include the US east coast (Boldt *et al.*, 2010; Donnelly *et al.*, 2001a,b, 2004; Donnelly and Webb, 2004; Scileppi and Donnelly, 2007), the Gulf of Mexico (Liu and Fearn, 1993, 2000; McCloskey and Keller, 2009; Wallace and Anderson, 2010; Lane *et al.*, 2011), and the Caribbean (Donnelly and Woodruff, 2007; Woodruff *et al.*, 2008b). Although still limited in number, statistically significant trends in TC activity are beginning to emerge from these western North Atlantic paleo-TC overwash records (Mann *et al.*, 2009; Woodruff *et al.*, 2008a). More specifically, prior to approximately 1700 CE evidence exists for a period of decreased TC activity in the western North Atlantic extending back for several centuries. This lull in activity is roughly concurrent with the Little Ice Age (LIA), when independent climate proxies suggest more prevalent El Niño like conditions, and reduced tropical North Atlantic sea surface temperatures (Donnelly and Woodruff, 2007; Mann *et al.*, 2009), with both of these climatic trends generally serving to hinder TC activity in the western North Atlantic (e.g. Bove *et al.*, 1998; Emanuel, 2005; Goldenberg *et al.*, 2001; Gray, 1984). Prior to the LIA a period of increased TC activity similar to present levels occurs around roughly 1000 CE during an interval known as the Medieval Climate Anomaly (MCA), with this local maximum in TC activity likely driven by an increase in both sea surface temperature and a shift towards more La Niña-like conditions (Mann *et al.*, 2009).

Regional records for the northern Caribbean at Vieques, Puerto Rico (Fig. 1), exhibit trends similar to those observed within the TC composite proxy record constructed for the entire western North Atlantic (Mann *et al.*, 2009). More specifically, a period of reduced TC activity is observed between roughly 1700 and 1000 CE, bracketed between two periods of relatively higher TC activity both between 1700 CE and present, and for an extended period of time prior to 1000 CE (Fig. 2A). A pattern of increased TC activity before 1000 CE, followed by reduced activity, is also observed both in overwash reconstructions from the northern Gulf Coast and from the New York region (Fig. 2A), together suggesting a concurrent shift to decreased TC activity following the MCA (Mann *et al.*, 2009; Woodruff *et al.*, 2008a). The most recent transition to increased activity following 1700 CE is less evident in Gulf Coast records, but observed both at the Vieques and New York sites (Fig. 2A), potentially suggesting a digression between TC activity in the Gulf of Mexico and that in the open western North Atlantic (Liu and Fearn, 2000).

Reconstructions of TC wind damage from Puerto Rico also exhibit a marked increase in severe TC wind damage of F2 and F3 magnitude on the Fujita Scale (equivalent to approximately hurricane categories 3–5 intensity), beginning around 1700 CE (Boose *et al.*, 2004), and at roughly the same time when overwash reconstructions for storms of similar intensity at the Vieques site show a concurrent increase in TC counts (Fig. 2B). This historical-based reconstruction for Puerto Rico is almost certainly biased towards a gradual decrease in storm counts when extended toward the beginning of the record due to a decline in the number of historical documents available and a

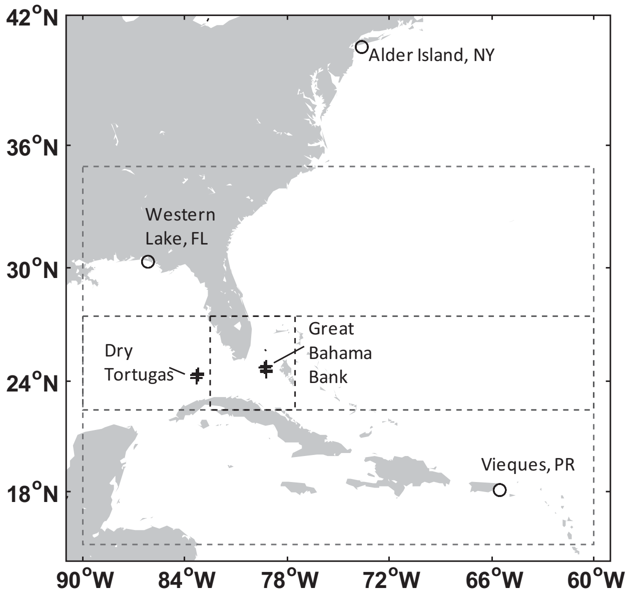


Figure 1. Site map with locations for presented paleo-TC (circles) and paleo-density (plus signs) reconstructions presented in Fig. 2. Dashed lines identify the boundaries of spatial averaging for model results presented in Fig. 3C, including the grid point enclosing Great Bahama Bank (black), the Gulf Stream region at the Bahaman latitude (dark gray), and the larger western boundary region (light gray).

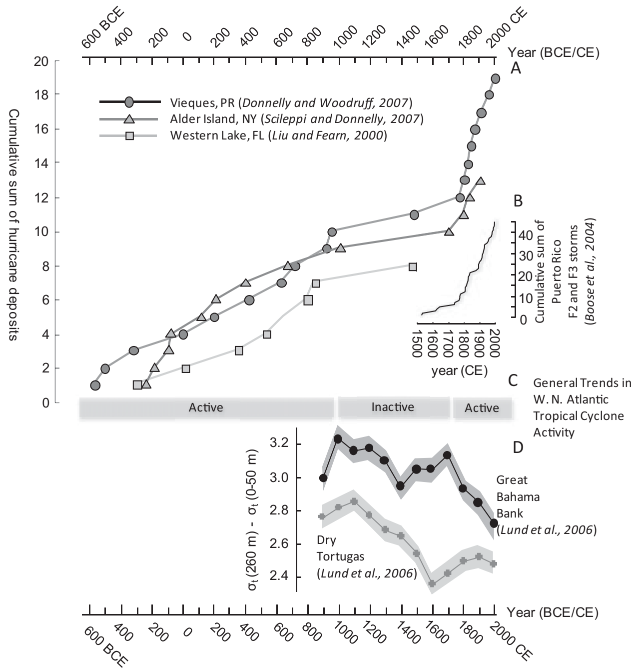


Figure 2. (A) Cumulative number of TC-induced overwash layers since 600 BCE identified at: Vieques, PR, Alder Island, NY, and Western Lake, FL with sources for each individual record cited in figure. (B) Cumulative sum of F2 and F3 storms for Puerto Rico (Boose *et al.*, 2004), referenced to the Fujita scale (Fujita, 1971, 1987), and roughly equivalent to category 3 or greater storm TC intensity. (C) General trends in western North Atlantic TC activity based on results presented in A and B. (D) Stratification for Great Bahama Bank (black circles) and Dry Tortugas (gray plus signs) expressed as thermocline density (at 260 m water depth) minus surface mixed layer density (0–50 m). Error bars are plus and minus 1σ. For clarity, 0.5 density units have been subtracted from the Dry Tortugas time series.

resultant decrease in the density of observations. However, these biases notwithstanding, the sharp increase in historical accounts at Puerto Rico around 1700 CE is still of potential significance, given that it is concurrent with a similar increase in storm counts from the entirely independent sediment-based reconstructions at the Vieques site (Fig. 2B).

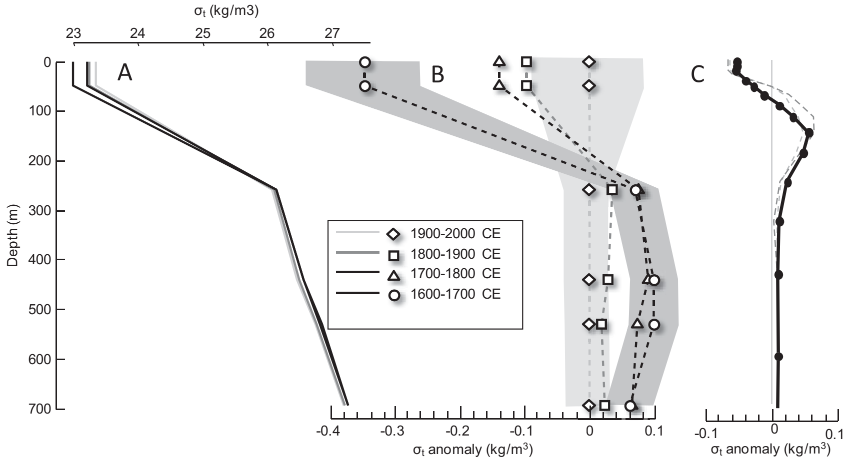
Paleo-density reconstructions

To assess the potential impacts of reduced TC-related mixing prior to 1700 CE on upper ocean stratification we employ results from Lund *et al.* (2006), who present millennial-scale paleo-density reconstructions based on benthic foraminifera from five separate water depths at Great Bahama Bank (i.e. 700 m, 530 m, 440 m, 260 m, and the surface mixed layer from 0 to 50 m). A complete description of the sediment processing, stable isotope, and chronological methods is given in Lund *et al.* (2006). Here we provide an abbreviated methodology.

The oxygen stable isotopic ratio of foraminifera, expressed as $\delta^{18}O$, depends on the temperature and $\delta^{18}O$ of seawater ($\delta^{18}O_w$) in which they live. Because $\delta^{18}O_w$ is linearly related to salinity, and the difference between foraminiferal $\delta^{18}O$ and $\delta^{18}O_w$ is thermodynamically controlled, seawater density (σ_t) can be estimated using $\delta^{18}O$ (Lynch-Stieglitz *et al.*, 1999). Sediments collected from a given water depth contain both benthic (sea-floor-dwelling) and planktonic (surface-ocean-dwelling) foraminifera. Planktonic foraminiferal $\delta^{18}O$ can therefore be used to constrain σ_t for the surface mixed layer, while benthic species provide σ_t constraints at thermocline depths. Where sloping bathymetry permits, paleo-density profiles can be created using the $\delta^{18}O$ from benthic formanifera collected at targeted depths in combination with mixed-layer $\delta^{18}O$ values derived from planktonic foraminifera.

A relatively good agreement has been shown between direct water column measurements of seawater density (σ_t) off of Great Bahamas Bank and $\delta^{18}O$-derived σ_t values reconstructed from modern foraminifera in recently deposited sediments from the western slope of Great Bahama Bank (Lund *et al.*, 2006). Supported by this correlation Lund *et al.* (2006) presents a time series of stratification from Great Bahama Bank extending back to 800 CE, and expressed as the difference between σ_t values just below the mixed layer at 260 m and σ_t values in the mixed layer (Fig. 2D). Further, a subset of vertical profiles from Lund *et al.* (2006) of foraminiferal-derived seawater density progressing back into the LIA is presented in Fig. 3(A). Theoretical age resolutions for each sediment sample is 15–50 years, but biological mixing of the sediments degrades the resolution such that each represents a multidecadal to century-scale average. As expected, the vertical density profiles in Fig. 3(A) show that density increases with water depth for each time interval. These profiles also reveal more subtle changes in water column stratification when expressed as the σ_t anomaly relative to present (Fig. 3B). For example, the surface layer σ_t anomaly exhibits a clear monotonic drop to $-0.3\ \mathrm{kg\,m^{-3}}$ when extended to 1600–1700 CE, while the σ_t anomaly below the mixed layer at a water depth of 260 m during this same period increases to approximately $+0.1\ \mathrm{kg\,m^{-3}}$ (Fig. 3B). This decrease in surface water density towards the LIA combined with the increase in densities below the mixed layer implies that water column stratification at Great Bahama Bank was greater prior to 1700 CE (Fig. 2D). Variability in vertical stratification at Great Bahama Bank is broadly consistent with changes in TC frequency inferred from overwash deposits, particularly with respect to reconstructions obtained just to the east of the site at Vieques, PR (Fig. 2A and B). Specifically, the general shift towards reduced TC frequency prior to 1700 CE (Fig. 2C) occurs contemporaneously with an increase in vertical stratification at Great Bahama Bank (Fig. 2D).

The only other available record of centennial-scale changes in vertical stratification in the North Atlantic is from near Dry Tortugas (Lund *et al.*, 2006). Like the Great Bahama Bank site, this location is subject to vertical mixing from TCs and displays a prolonged interval of anomalously high vertical stratification relative to present during a pronounced drop in TC activity between 1000 CE and 1500 CE (Fig. 2D). Unlike Great Bahama Bank, however, the Dry Tortugas record displays a minimum in water column stratification around 1600 CE, followed by a gradual increase towards present levels of stratification. The discrepancy between the Great Bahama Bank and Dry Tortugas sites after 1600 CE is approximately coeval with the discrepancy in overwash records from the western North Atlantic and Gulf of Mexico, where the New York and Vieques records exhibit an anomalous increase in activity, while the Western Lake, FL record (Fig. 2A) and recent results by Lane *et al.* (2011) both support relatively quiescent conditions in the northern Gulf of Mexico. Increased TC-induced mixing in the western North Atlantic relative to the Gulf of Mexico following roughly 1600 CE may therefore help to explain observed discrepancies in stratification between the Great Bahama Bank and Dry Tortugas sites. Further, the reduced stratification during 1600 CE at the Dry Tortugas site is due primarily to anomalously high surface salinity, rather than a decrease in salinity at depth due to an increase in vertical mixing. This observation suggests that factors other than TC variability could also be responsible for the 1600 CE minimum in stratification at Dry Tortugas, such as previously cited mechanisms associated with a southward migration of the



Paleo-Density Reconstructions (Data from Lund et al., 2006)

Model Output
(Data from Sriver and Huber, 2010)

Figure 3. (A) Centennial averaged vertical ocean density profiles near Great Bahama Bank since 1600 CE (solid lines) from Lund *et al.* (2006), and (B) respective density profile anomalies relative to the 20th century (dashed lines with markers). Error estimates for the mixed layer and thermocline anomalies are ± 0.10 kg m^{-3} and ± 0.06 kg m^{-3}, respectively (1σ), and are presented for reference as gray shading on anomaly profiles for the 17th and 20th centuries. (C) Density anomaly depth profiles from idealized ocean model simulations for control scenario (without TCs), relative to simulations that includes TC forcing closest to present-day levels. Anomaly profile for the grid point closest to Great Bahama Bank is shown in black. Spatially averaged profiles across the Gulf Stream at the Bahaman latitude and the larger western boundary region are shown as dashed dark gray and light gray lines, respectively (see Fig. 1 for averaging boundaries).

Atlantic Intertropical Convergence Zone (ITCZ) (Lund and Curry, 2006).

It is also possible that changes in the $\delta^{18}O_w$-salinity relationship account for density anomalies during the last millennium; however, the evidence available does not support this interpretation. For example, multiple paleoclimate reconstructions from the North Atlantic suggest surface temperatures were about 1°C cooler during the Little Ice Age (e.g. Dahl-Jensen *et al.*, 1998; Marchitto and deMenocal, 2003). Based on the spatial relationship between temperature and the $\delta^{18}O$ of precipitation (Dansgaard, 1964), this would imply a ~1‰ decrease in the fresh end-member, and a steeper $\delta^{18}O_w$-salinity slope. The net effect of this change would be to increase thermocline density during the LIA and therefore amplify the reconstructed density anomaly rather than decrease it. The LIA thermocline anomalies could also be eliminated if the fresh end-member were 3‰ more enriched than today but this scenario is unlikely given cooler high latitude temperatures. Even if the greater thermocline $\delta^{18}O$ (and hence σ_t could be accounted for with a different $\delta^{18}O_w$-S relationship, we are left to explain $\delta^{18}O$ in the surface mixed layer whece the signal is the reverse of that at depth. Therefore, the simplest interpretation is that the presented $\delta^{18}O$ time series reflect real changes in seawater density. Further, the reconstructed thermocline anomalies are likely minimum estimates given plausible changes in $\delta^{18}O_w$ during the LIA.

Model sensitivity experiments

Comparisons between proxy records for oceanographic stratification at Great Bahama Bank and TC landfalls at the nearby Vieques, PR site present a qualitative connection between a prolonged period of reduced regional TC activity prior to 1700 CE and a concurrent increase in water column stratification (Fig. 2). To further assess whether this relationship is feasible, we present numerical results initially run by Sriver and Huber (2010) to quantify differences in ocean density structure for simulations with and without TC surface wind forcing. Simulations were performed using the ocean component of the Community Climate System Model (CCSM3) (Collins *et al.*, 2006), using the low-resolution configuration (100 zonal and 116 meridional grid points, with 25 vertical levels). Current-day levels of TC activity are simulated using globally gridded TC wind fields, derived from NASA's Quick Scatterometer (QuickScat), and blended into a standard bulk forcing surface input dataset (Large and Yeager, 2004). TC model runs include all cyclone events from 2000 to 2006, as defined by the Best Track datasets (Landsea *et al.*, 2004), with simulations run for 1000 years, which is sufficiently long to achieve near-equilibrium conditions within the uppermost 1000 m.

Limitations associated with the TC simulations by Sriver and Huber (2010) include: (i) use of a coarse-resolution ocean model; (ii) lack of ocean–atmosphere coupling; and (iii) incomplete equilibration of the deep ocean. It is also highly unlikely that TC activity was completely quiescent prior to 1700 CE; thus the model control scenario that excludes TC activity completely represents a more extreme case than TC conditions during the LIA. Keeping these caveats in mind, the sensitivity experiments by Sriver and Huber (2010) still serves as a useful exercise to explore how general changes in transient TC mixing processes can influence the mean state of the upper ocean. Comparisons between these model runs and the paleo-reconstructions by Lund *et al.* (2006) therefore provide a means to evaluate the rough order of magnitude in which reduced TC mixing is capable of affecting variability observed within paleo-density reconstructions.

Figure 3(C) illustrates the modeled time–mean anomalous density profile at the grid point closest to the Great Bahama Bank location for no TC mixing (i.e. the control scenario), relative to simulations that best represent present day TC activity. To first test whether density effects from TC-induced mixing at the Great Bahama Bank location is a robust representation for the region, we compare modeled stratification at the site with spatially averaged values for larger regions of the northwestern Atlantic. The same general range of variability between simulations with and without TC winds (i.e. control minus the TC case) is observed for expanding spatial scales, including when spatially averaged both across the Gulf Stream at the Bahama latitude, and the larger western boundary region. Thus the marked agreement between model profiles at Great Bahama Bank and the larger spatial averages support the robustness of the anomalous TC-induced density signal at Great Bahama Bank in indicating large-scale properties of the western North Atlantic, rather than a local regional bias in the model.

In addition to more direct impacts of TC mixing on vertical stratification, it is possible that TC variability may also indirectly influence density at the Great Bahama Bank site through modification of Gulf Stream properties. However, our modeling results do not support this mechanism as a primary driver for

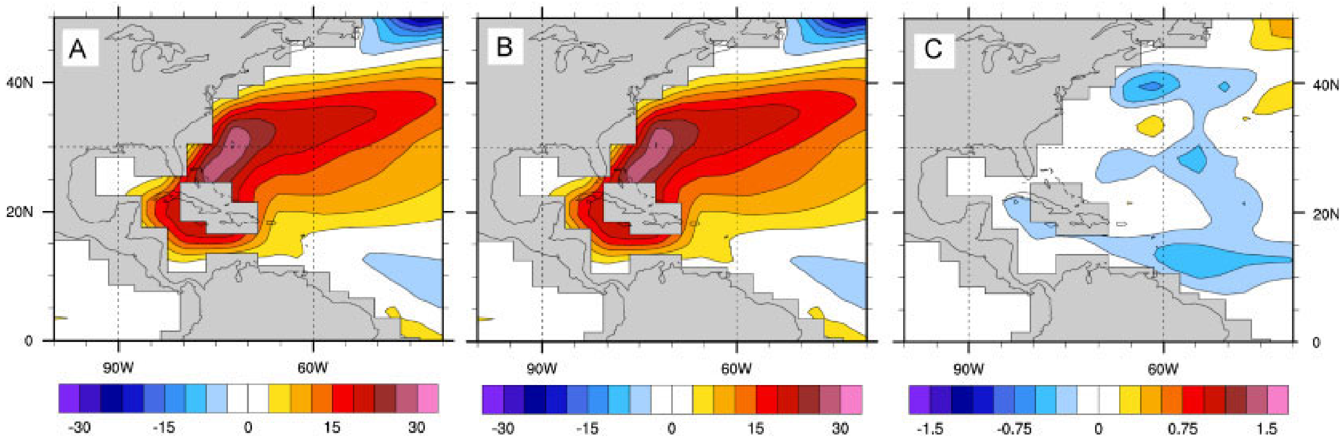


Figure 4. Modeled barotropic stream functions for the North Atlantic region for model simulations performed by Sriver and Huber (2010). (A) Case with TC winds. Units are in sverdrups (1 Sv = 10^6 m^3 s^{-1}). (B) Same as A, but for control scenario without TC winds. (C) Difference between the cases shown in A and B. Very little change is observed between the two scenarios.

changes in density structure, with no significant difference in the mean characteristics of the Gulf Stream between model cases with and without TC wind forcing (Fig. 4). Thus TC mixing in the model does not appear to alter the mean strength or location of the wind-driven subtropical gyre.

Model data comparison

The influence of TC-induced mixing is readily observable in the modeled density anomaly profiles (Fig. 3C), with trends similar to those observed within the paleo-density reconstructions by Lund *et al.* (2006) (Fig. 3B), although moderately smaller in size. Reducing TC wind forcing decreases ocean density within the top 100 m while increasing ocean density beneath 100 m, thus shallowing the mixed layer and increasing stratification for the control case. This effect is caused primarily by reduced wind-induced vertical mixing, which diminishes the entrainment of cold water through the base of the mixed layer while decreasing warm surface water mixing down into the thermocline.

Both numerically simulated and proxy profiles for vertical density at Great Bahama Bank under reduced TC activity exhibit negative anomalies in the mixed layer and positive anomalies below. An anomaly of roughly 0.12 kg m^{-3} in vertical stratification occurs above and below the mixed layer for model runs with and without TC mixing, which is roughly 25% of the entire paleo-density anomaly observed just prior to 1700 CE relative to present (Figs 2D and 3B). The modeled seawater density anomaly directly below the mixed layer for the control case relative to current TC activity (roughly 0.06 kg m^{-3}, Fig. 3C), is also similar to anomalies observed in the paleo-record below the mixed layer during the LIA (roughly 0.10 ± 0.06 kg m^{-3}, Fig. 3B). Profiles for the control simulation without TC-induced mixing and proxy records during the LIA also both exhibit a negative density anomaly at the surface (Fig. 3B and C); however, proxy-based LIA anomalies of approximately -0.35 ± 0.10 kg m^{-3} are observed in the surface mixed layer compared to a significantly smaller modeled anomaly of roughly -0.06 kg m^{-3} for the control simulation.

Vertical changes in density for model simulations without TC-induced mixing are structured somewhat differently from paleo-observations during the LIA. First, the transition from negative surface anomalies to deeper positive density anomalies occurs at a water depth of ~100 m in the model, compared to a depth of ~200 m in the paleo-density data. However, the observed depth of 200 m is based on a linear interpolation of sampling depths at 50 m and 260 m, with the lack of observations between these two points potentially helping to explain this particular model/data discrepancy. Model results also indicate that mixing associated with TCs primarily affect the upper 300–400 m of the water column, while higher LIA density anomalies are observed to exist well below this depth, although error estimates for benthic anomalies (± 0.06 kg m^{-3}) suggest results at a water depth of 700 m are not statistically different from zero (Fig. 3B).

TC-induced mixing is naturally one of several factors that can influence seawater density at the Great Bahama Bank site, with model/data discrepancies suggesting an ensemble of processes contributing to increased stratification during the LIA. Indeed, Lund and Curry (2006) hypothesize that the reduced influence of saline water from the North Atlantic subtropical gyre due to a southward shift of the ITCZ likely served to decrease surface salinity at Great Bahama Bank during the LIA.

Additionally, density could also respond to altered vertical mixing or varying boundary conditions in the ventilated thermocline region. Our intention here is not to exclude other mechanisms as potential drivers for observed variability in ocean paleo-stratification, but rather to put forth TC mixing as an additional contributor capable of forcing density changes at roughly the same order of magnitude as variability observed during the past millennium.

Conclusion

Foraminiferal records provide observational evidence that upper ocean density structure near Great Bahama Bank has changed during the past millennium. Specifically, this region exhibited stronger stratification between roughly 1000 and 1700 CE, which is roughly concurrent with the LIA. A general decrease in the number of TCs affecting the western North Atlantic relative to present also occurs during this same time interval. On the basis of this correlation we present a potential link between reduced TC mixing and observed centennial changes to the vertical structure of the tropical western North Atlantic. A coarse-resolution ocean model sensitivity experiment provides a further assessment of this potential connection. The model can explain roughly 25% of the total anomaly in vertical paleo-density when driven without TC surface wind forcing. Modeling results therefore suggest that TC mixing alone cannot completely explain the entire density anomaly observed during the LIA, but do support TC variability as an important and feasible contributor to enhancing oceanic stratification during this interval.

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Abbreviations. ITCZ, Intertropical Convergence Zone; LIA, Little Ice Age; MCA, Medieval Climate Anomaly; TC, tropical cyclone.

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