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# Multi-Centennial Spatial Coherency Among Atlantic Tropical Cyclones From Simulated and Reconstructed Storm Records

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**Key Points:**

- Centennial tropical cyclone activity in the Caribbean is antiphased with activity over the eastern US, indicating an apparent storm dipole
- The dipole is a recurrent feature in model ensembles, supporting its presence in paleoreconstructions
- Storms derived from a climate model forced by Last Millennium Reanalysis sea surface temperatures share traits with proxy storm records

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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## Abstract

Proxy-based reconstructions of long-term Atlantic tropical cyclone (TC) variability reveal low-frequency oscillations in regional TC landfalls over the Common Era. However, the limited spatial coverage and increased uncertainty of the proxy records complicates assessments of this feature. Here we present a new multi-ensemble set of synthetic TCs downscaled from the Last Millennium Reanalysis project, which is based on sea surface temperatures that more accurately reflect past conditions. Throughout ensemble members, there are coherent multi-centennial shifts in landfalls with persistent intervals of increased (decreased) occurrence along the eastern US concurrent with inverse activity in the southwest Caribbean and Gulf of Mexico, associated with basin-scale redistributions of storm tracks. The emergent TC-dipole from modeled climate provides context and support for its presence within proxy-reconstructions. Furthermore, dipole recurrence across ensembles demonstrates that it arises from sea surface temperature-informed climate processes. However, timing differences between ensembles indicate that transient atmospheric variability influences dipole position.

## Plain Language Summary

Sedimentary evidence of past Atlantic tropical cyclone (TC) strikes suggest that intervals of prolonged increases in TC landfalls along the eastern US coast are concurrent with reduced landfalls in the southwestern Caribbean and Gulf of Mexico (and vice versa). However, the limited number of sediment records and their inherent uncertainty make it hard to confidently interpret these patterns. To address this, we used climate models that realistically reflect past sea surface temperatures to simulate a large data set of prehistoric TCs. These simulations consistently show a dipole-like pattern in storm activity. Additionally, the presence of the dipole across model runs and within sedimentary reconstructions means that this pattern is real and that long-term shifts in storm paths can be linked to background climate conditions. However, this work shows that multidecadal shifts in storm tracks are also influenced by weather variability in conjunction with the mean climate state.

## 1. Introduction

Tropical cyclones (TCs) are among the most destructive natural disaster to recurrently threaten North American coastlines (Pielke et al., 2008; Willoughby et al., 2024). Yet, these hazards are not uniformly distributed across the region. Between 1950 and 2020, 29 major TCs (≥ Category 3 on the Safir-Simpson scale) made landfall along the US Gulf Coast while only one, Hurricane Carol (1954), impacted the northeast over that same interval (Knapp et al., 2010). However, the susceptibility of the US East Coast to TC impacts is expected to change over the 21st century due to sea surface temperature (SST) driven shifts in storm characteristics (Murakami & Wang, 2010) and heightened flooding risks related to rising sea levels and rainfall amounts (Gori et al., 2022).

There remains substantial uncertainty in the sensitivity of TC genesis locations to warming. Some studies suggest a northward and eastward shift in genesis with rising SSTs, both in future projections (Colbert et al., 2013; Murakami & Wang, 2010) and 19th century reconstructions (e.g., Vecchi & Knutson, 2011), while others project increased cyclogenesis near the southeastern U.S. coast (Dailey et al., 2009; Weaver & Garner, 2023). In general, research shows that shifts in cyclogenesis locations are highly dependent on the specifics of future SST changes (e.g., Emanuel et al., 2008; Knutson et al., 2013). Beyond SST-driven changes in TC tracks, intrinsic atmospheric

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variability can also produce considerable multi-decadal fluctuations in storm tracks (e.g., Kortum et al., 2024; E. Wallace et al., 2020). Relatedly, the number of storms attaining major category strength at higher latitudes is expected to increase due to anthropogenic warming (Kossin et al., 2014; J. Lin et al., 2024; Studholme et al., 2022). However, our capacity to assess modern observations and contextualize future risk projections against long-term natural variability in TC dynamics is hampered by the brevity of the observational record (~1850 to present), which may obscure underlying secular trends. Moreover, restricting our focus to the most recent ~170 years complicates our understanding of naturally-forced TC variability, as contemporary observations reflect the impact of anthropogenic warming on tropical cyclogenesis (Knutson et al., 2010; Murakami et al., 2020).

To address these issues, proxy reconstructions of past TC landfalls, which can extend assessments of hurricane activity back by hundreds to thousands of years (Baldini et al., 2016; Liu & Fearn, 1993; R. M. Sullivan et al., 2022; E. J. Wallace et al., 2019; Winkler et al., 2023), have become a common method of identifying long-term patterns in TC frequency under an array of climate states. These reconstructions may be derived from speleothems (e.g., Frappier et al., 2007), tree-ring records (e.g., Maxwell et al., 2021), or sedimentary evidence of past TC impacts preserved in lacustrine (Lane et al., 2011), marsh (Boldt et al., 2010), or lagoonal (Peros et al., 2015) settings where the wind and wave energy induced by the proximal passage of a strong TC can remobilize existing coarse sedimentary reserves. Mobilized sediments then become stratigraphically preserved within the fine-grain background matrix of coastal depressions, providing a geologic record of TC activity.

Recently, distinct trends have begun to emerge from the growing network of sediment-derived paleostorm records along the northwest Atlantic and Caribbean region (Figure 1). At centennial-scales, storminess (i.e., storm activity) in the northeast US (NE) is often antiphased with activity over the Gulf of Mexico (GoM), southern Caribbean, and Yucatan Peninsula (SW hereafter), suggesting the existence of a TC-dipole that operates between the northwest and southwest regions of the North Atlantic (Biguenet et al., 2021; Donnelly, 2025; Elsner et al., 2000; Malaizé et al., 2011; R. M. Sullivan et al., 2025; van Hengstum et al., 2014; E. Wallace et al., 2021; Winkler et al., 2023; Y. Yang et al., 2020). Previous analyses have identified aspects of this dipole-like behavior at smaller scales over the modern era, such as shifts in landfall locations between the eastern US and GoM (Dailey et al., 2009; Kossin, 2017; Ting et al., 2019) or forecasted shifts in US storm strikes under different warming scenarios (Weaver & Garner, 2023). However, the broader spatiotemporal coverage of the proxy-reconstructions suggests characteristics of TC behavior unexplored by these regional modern studies. For example, proxy records from the Yucatan (R. M. Sullivan et al., 2025), The Bahamas (E. Wallace et al., 2021; Winkler et al., 2023), New England (Donnelly et al., 2015) and the Scotian Shelf (Y. Yang et al., 2020) indicate a shift in storminess away from the southwest and toward the northeast at ~1400 CE, an interval concurrent with the transition phase between the Medieval Climate Anomaly (MCA: ~850 to 1250 CE) and Little Ice Age (LIA; ~1500 to 1850). This pattern contrasts with modern observations, which show a poleward shift in TC tracks and intensification concomitant with anthropogenic warming (Kossin et al., 2014).

While proxy reconstructions provide valuable insights into past TC activity, concerns about their fidelity persist given the uncertainties and biases inherent in the data. Reconstructions are often highly site-specific, are biased toward intense proximal TCs (N. Lin et al., 2014; E. J. Wallace et al., 2021), may suffer from age-related uncertainties (Schmitt et al., 2020), or may be influenced by non-TC driven transport mechanisms, such as tsunamis (Biguenet et al., 2022). Additionally, individual reconstructions may insufficiently reflect low-frequency synoptic TC variability (E. J. Wallace et al., 2020). However, when TC records from multiple locations within a region are combined, the resulting composite record often reveals broader trends in regional storm activity (R. M. Sullivan et al., 2025; E. Wallace et al., 2021; Winkler et al., 2023). Considering that proper assessment of these trends is limited by the uncertainties inherent in the proxy-records, alternative methods are needed to more comprehensively interrogate past TC patterns.

Paleodata assimilation products, such as the Last Millennium Reanalysis project (LMR) (Hakim et al., 2016; Tardif et al., 2019) offer an alternate method of investigating past TC activity. The LMR project employs an offline paleodata assimilation approach, which connects proxy records from the 2017 PAGES 2k collection (PAGES2k Consortium et al., 2017) with pre-industrial climate simulations from the Community Climate System Model version 4 (CCSM4) (Gent et al., 2011) via a linear proxy system model. Assimilating these proxies with the CCSM4 outputs, using a Kalman filter to update the prior state vector with new proxy data, produces annually resolved reconstructions of thermodynamic and hydroclimate variables. This approach ensures that the temporal

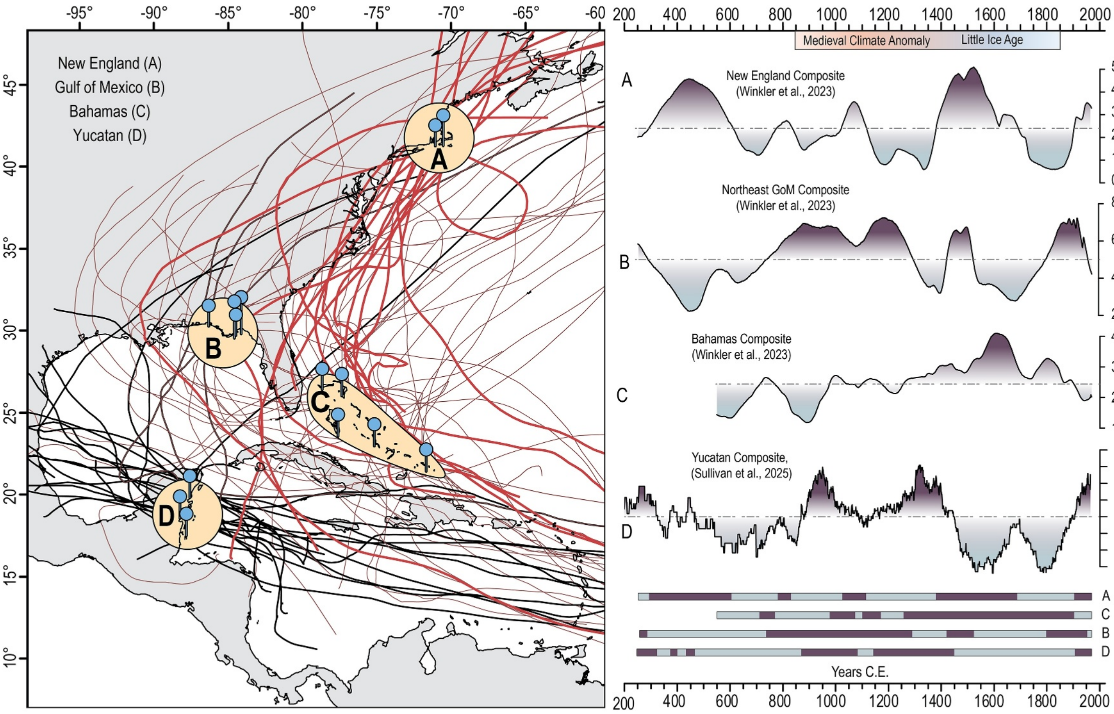


**Figure 1.** (left) The locations of the four paleo-proxy compilations discussed in this work. Lines represent all storm tracks (TS and above) that impacted each location since 1850 within the IBTrACS database (Knapp et al., 2010). Lines in red are storms that impacted New England (a); black, the Yucatan (d); brown tracks are storms that impacted either the Bahamas (c) or northeastern Gulf of Mexico (b). (right) Composite paleorecords referenced in this study presented north to south. Mauve (gray) shading indicates intervals where storminess exceeded (fell below) the regional mean for the Common Era. (lower right) Simplified representation of above but organized east to west highlighting zonal synchronicity.

variability within the outputs is derived from the proxies themselves, potentially offering a more accurate depiction of Common Era climate conditions than would be derived solely from the CCSM4 simulation. The utility of using LMR outputs to interrogate past TC activity was recently demonstrated by W. Yang et al. (2024) who used SST data from the LMR to develop a statistical model of Atlantic hurricane activity. That work found agreement between the emulated storms and basin-wide compilations of Atlantic TC proxy-reconstructions, demonstrating that LMR SSTs could be leveraged for explorations of naturally-forced TC dynamics.

To further investigate the TC-dipole pattern found in the proxy records we use a large set (>500 k) of Atlantic TCs, downscaled from 1150 years (850–1999 CE) of global atmospheric general circulation model (GFDL AM2.1) (Anderson et al., 2004) simulations forced by SST data from the LMRv2.1. This data set allows us to consider a wider range of spatiotemporally continuous TC variability than is possible with proxy-based reconstructions alone. Our synthetic storm data set reveals coherent patterns in storm track behavior and landfalls, showing that, at multidecadal-to-centennial scales TC impacts along the eastern US are antiphased with those in the Caribbean and GoM. Importantly, our LMR simulated centennial TC frequency counts share some similarities with existing proxy composites. These similarities suggest (a) that climate-driven environmental changes inform the trajectory of TCs at multi-decadal to centennial scales, and (b) LMR environments more realistically simulate low-frequency TC activity at both basin and regional resolutions. Ultimately, faithful simulations of long-term, basin-wide TC dynamics will be crucial for ensuring that TC risk mitigation strategies and coastal defenses remain viable over the 21st century.

## 2. Data and Methods

We employed multiple analytical techniques to investigate low-frequency spatiotemporal variability in last millennium TC dynamics and conduct comparisons between synthetic and reconstructed storm events. We downscaled TCs from a climate model forced by LMRv2.1 SSTs using the statistical dynamical downscaling method described by Emanuel (2006) and Emanuel et al. (2008). Coastal regions were analyzed for time-dependent changes in landfall occurrence, enabling the identification of coastlines with coetaneous TC risks. We then divided the Northwest Atlantic into regions that exhibit similar variability in TC occurrences. In each region, we generated a timeseries of centennial storm frequency over the past millennium and compared these with proxy reconstructions. Specific methods are detailed below.

### 2.1. Storm Synthesis

The TC downscaling approach used in this work requires daily wind data at the 250 and 850 mb pressure levels, monthly mean temperature and specific humidity at all pressure levels, and monthly mean SSTs and sea level pressure. These variables were produced from the GFDL atmospheric general circulation model AM2.1 over the period 850–1999 CE. The AM2.1 simulations were forced by SSTs from LMRv2.1 while direct radiative forcings were fixed at a pre-industrial level. To estimate and correct for the bias of AM2.1 in simulating the atmospheric circulation and thermal state, we regressed the daily or monthly climatologies from the European Center for Medium-Range Weather Forecasts' fifth reanalysis product (Hersbach et al., 2020) over the 20-year period 1980–1999 onto the input SSTs. Daily climatologies are used for daily zonal and meridional winds.

We generated a database of 575,000 synthetic TCs spanning 850 to 1999 CE. Five model ensembles (115,000 storms per ensemble at a rate of 100 storms per year) were run by randomly varying the initial conditions, which were drawn from a set of pre-industrial simulations. These five ensembles share the same SST-forcing and differ only in initial conditions to allow assessment of internal variability within the atmosphere. This means that parameters such as surface temperature, pressure, wind (e.g.) varied owing to the internal physics of the atmospheric model.

Synthetic storms were randomly initiated (i.e., seeded) within the time-evolving coarse-scale climate states of the modeled Atlantic during each simulation year. These proto-TCs consisted of weak, dry, warm-core vortices with initial peak wind speeds of 12 m/s. Storm trajectories were then calculated from the model's winds (Marks, 1992), and intensities were computed using a purely deterministic, coupled ocean-atmosphere TC model (Emanuel et al., 2004). The majority of these seeded vortices dissipated; however, those that intensified beyond 21 m/s were retained and used to estimate the modeled TC climatology. The seeding process continued until 100 storms developed each simulation year. We chose 100 storms per year instead of a more realistic number to allow for capturing the full range of TC variability under various climate conditions.

It should be noted that biases within underlying GCMs can impact downscaled TCs. For example, there is an underrepresentation of intense Atlantic TCs possibly due to how models handle ocean heat transport (Emanual, 2025). Moreover, certain biases are known to arise using these downscaling methods, as revealed by comparing TCs downscaled from modern reanalyzes with observations. For example, while the random seeding method does not impact overall basin activity, it does produce a westward bias in storm genesis (Danso et al., 2022) (Figures S1 and S2 in Supporting Information S1). See Emanual (2025) for a more robust evaluation of this downscaling approach and see Text S1 in Supporting Information S1 for further discussion of biases within the synthetic storm-set.

### 2.2. Coastal Correlation

To explore landfall patterns in our synthetic storms, we divided the North American coastline into 30 segments, or gates, 500 km in length spanning from 10°N to 45°N latitude. This partitioning ensured that, throughout the 1150-year duration of our simulation, a statistically representative sample of storms impacted each gate. A landfall was defined as a storm passing within 50 km of a gate. While each storm was counted only once per gate, it was possible for the same storm to make landfall over multiple gates, reflecting the real-world scenario where TCs can affect distant coastal areas during their lifespan. To analyze long-term trends, we produced a time series of landfalls at each gate and applied a 101-year moving average to minimize high-frequency variability and focus on centennial patterns.

### 2.3. Hierarchical Cluster Analysis (HCA)

While the coastal correlation focused on the contiguous North American coast, we utilized an Hierarchical Cluster Analysis (HCA) (Ward, 1963) approach to analyze spatiotemporal patterns (Ramos, 2001) of storm activity across the western Atlantic, Caribbean, and GoM more broadly (Text S2 in Supporting Information S1). To

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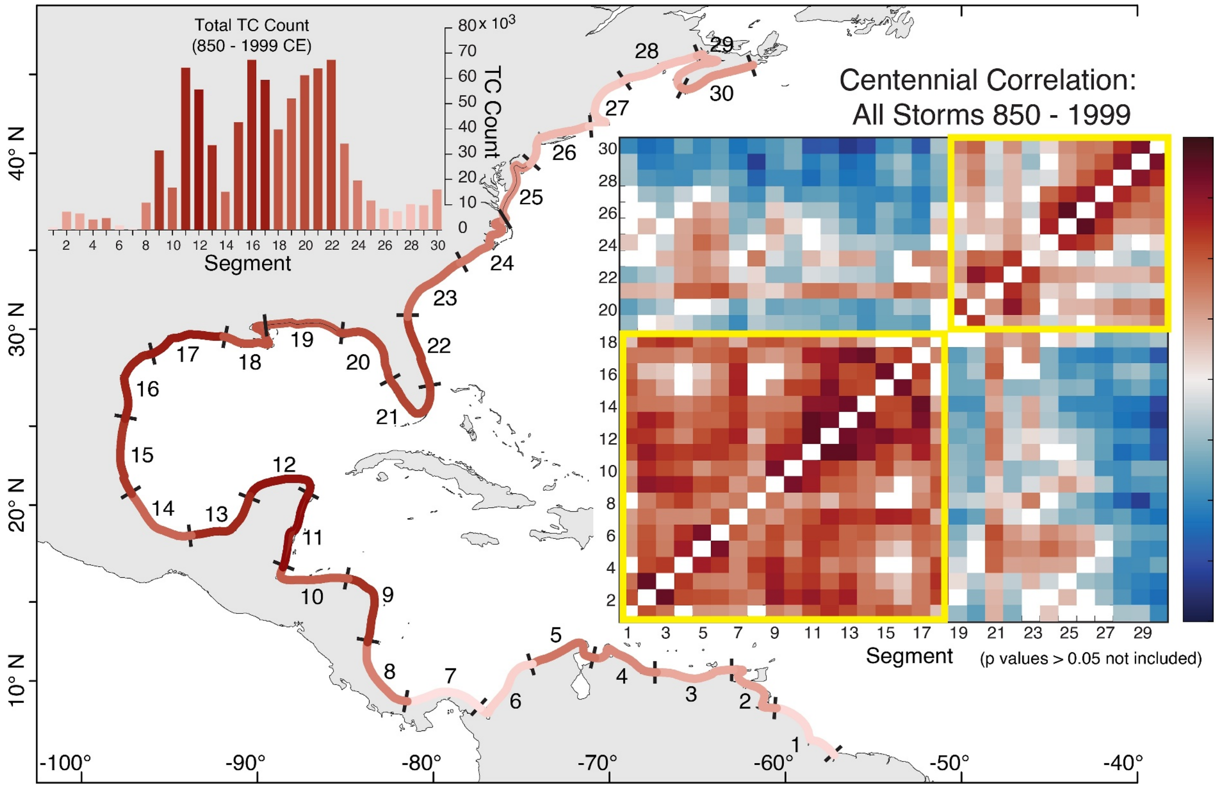


**Figure 2.** The location of the 30 coastal gates used in this study. Also shown is the correlation plot depicting how centennial-scale storm activity correlates between each of the 30 coastal gates for all 575,000 storms. The inset shows the total number of events that impacted each gate over the entirely of the simulation. Darker gate/bar plot colors denote more impacts.

generate the timeseries for our HCA analysis we divided the area between 100°W and 60°W and 12°N to 46°N into a grid of 2° × 2° cells. We then tallied the annual number of storms impacting each cell. Only the first intersection of a storm with an individual cell was counted, but intersections by a single event with multiple grid cells were permitted. To minimize biases related to terrestrial interference we excluded any cell from our analysis where less than 50% of its area fell over water. Additionally, given the scarcity of landfall events south of 12°N, cells located beneath this latitude were omitted. Finally, we smoothed each time series using a 101-year moving window to highlight centennial variability.

## 3. Results

### 3.1. Coastal Correlation

From all 575,000 LMR TCs spanning our five ensembles, 64% made landfall on the continental coastline of the Northwest Atlantic. Most landfalls, 75%, occurred between Nicaragua and Florida (Figure 2; gates 9 and 22, respectively) with high concentrations of TCs found in the Yucatan Peninsula, the northwest GoM, and Florida. Interannual variability of landfalls along these coastlines was not uniform. A correlation matrix for the timeseries of landfalls across all gates revealed distinct patterns of co-variability (Figure 2). Specifically, gates 1 to 18 (northern South America to Louisiana/Mississippi) are positively correlated, suggesting that increased storm activity in the southern Caribbean is often linked to more landfalls in the western Caribbean and the northwestern GoM. From the Florida panhandle to Nova Scotia (gates 20 to 30), there is also notable spatial coherence in storm activity (Figure 2). However, these correlations are not as consistently strong as those further south, likely due to lower incidence of landfalls at higher latitudes (Figure S1 in Supporting Information S1).

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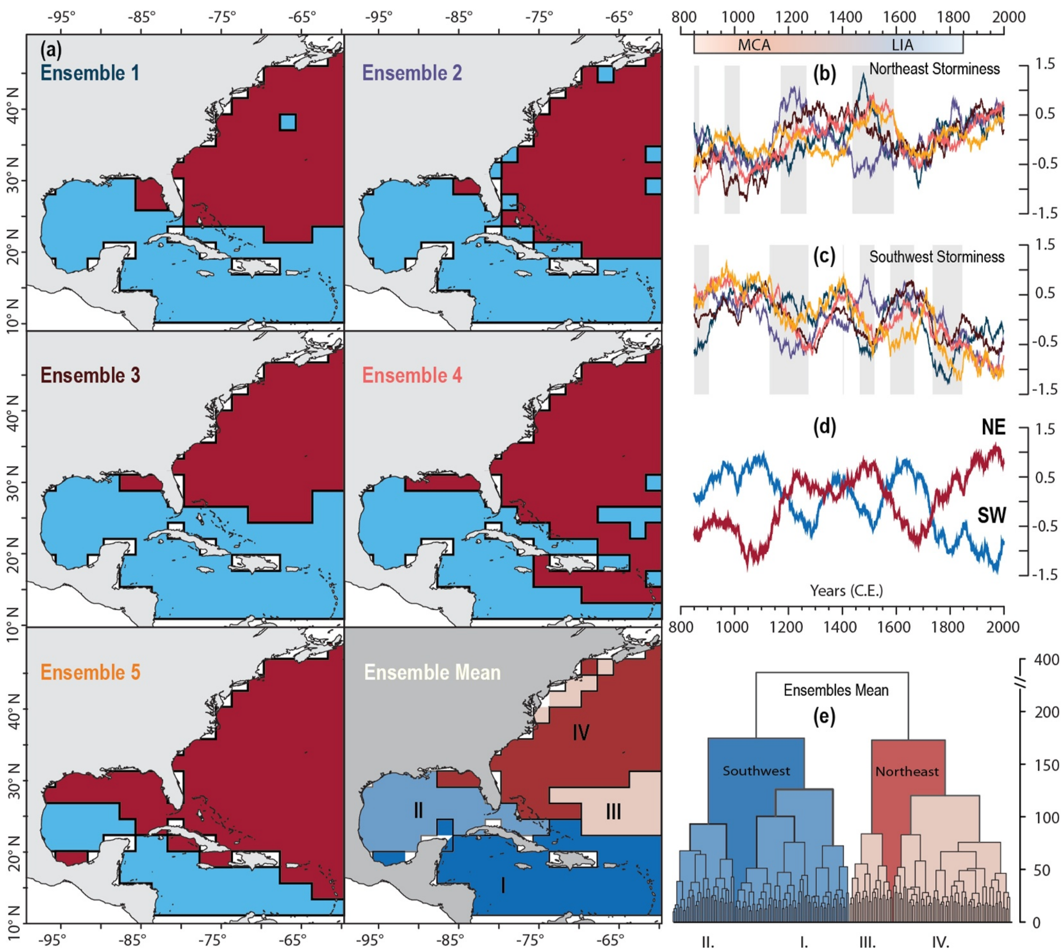


**Figure 3.** Hierarchical Cluster Analysis results for each of the five ensemble runs and the ensemble mean. (a) Maps show the locations of the NE and SW clusters for each ensemble. The ensemble mean includes the locations of the four subclusters identified within the mean. (right) Standardized timeseries demonstrating how storm activity varied within the NE (b) and SW (c) clusters for each ensemble (colors correspond to ensemble labels in (a)) and the mean (d). Gray bars highlight intervals where the spread between ensembles exceeded 1$\sigma$. (e) Dendrogram showing how each grid cell within the ensemble mean was grouped into the parent clusters and four subclusters.

### 3.2. Hierarchical Cluster Analysis (HCA)

Our HCA results (Figure 3, Figure S3 in Supporting Information S1) largely match our correlation analyses. We delineate two primary clusters of TC activity, a SW region consisting of the GoM and the Caribbean (Figure 3a, areas in blue), and a NE region containing the subtropical Atlantic, eastern US, and northern Bahamas (Figure 3a, areas in red). The HCA results were not identical between ensembles. The NE cluster in Ensemble 5 encompasses nearly all the Lesser and Greater Antilles and most of the GoM; by contrast, the SW cluster in Ensemble 3 contains most islands of the Caribbean region and portions of the subtropical western Atlantic. Despite these differences, all depict a dipole pattern in Atlantic TC impacts, demonstrating that storminess in the southern Caribbean and GoM is distinct from storminess along the eastern US and subtropical Atlantic.

HCA timeseries (Figures 3b–3d) show consistent antiphased behavior between the SW and NE clusters over the past millennium. Across ensembles, NE (SW) storminess reached its minimum (maximum) ~1100 CE and was typically above (below) the millennial mean from ~1150 to 1550 CE (with a slight reversal ~1400 CE). All ensembles show a lull (increase) in NE (SW) storminess during the late 17th century followed by an increase (decrease) into the present. However, there is notable internal variability between the ensembles. Differences between ensembles are highlighted in gray (Figures 3b and 3c) with ensemble two deviating substantially from the others during the late 15th/early 16th century.

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To better explore ensemble variance, Pearson correlation coefficients were calculated between each ensemble and a corresponding leave-one-out ensemble mean (e.g., correlating ensemble 1 with the mean of ensembles 2–5), highlighting both inter-ensemble agreement and the magnitude of internal variability (Figure S4 in Supporting Information S1). Averaging TC activity timeseries across ensembles for each cluster emphasizes the common climate-driven signal while reducing internal model variability. Correlation coefficients indicate how closely individual ensembles reflect this shared climate signal, with values ranging widely (Figure S4 in Supporting Information S1). Specifically, climate forcing accounts for 27%–76% of variance in the NE cluster and 52%–86% in the SW cluster across ensemble members.

Performing HCA on the ensemble mean highlights dominant broader trends (Figure 3d). Unsurprisingly, the ensemble mean also displays distinct, antiphased, spatiotemporal variability between the SW and NE regions. These two clusters can be further subdivided into four distinct subclusters located in the south, west, east, and north of the study area (Subclusters I, II, III, and IV in Figures 3a and 3e respectively). Unlike the two parent clusters these subclusters were less consistently defined across the constituent ensembles (Figure S3 in Supporting Information S1).

## 4. Discussion

Decades of proxy-based paleotempestological reconstructions revealed a distinct pattern of low-frequency dipole-like Atlantic TC variability. However, it remained unclear until now whether this pattern arose from uncertainties within the proxy network or is a genuine climate-driven signal discernible in numerical simulations. Our analysis of a large multi-ensemble set of synthetic TCs, derived from LMR environmental constraints, demonstrates that this spatially coherent behavior indeed emerges from modeled climates. This result strongly supports the interpretation of this dipole as an intrinsic feature of the Atlantic climate system rather than merely an artifact of proxy uncertainty.

At centennial scales, synthetic TC landfalls cluster into two dominant regions with inverse periods of activity. When landfalls increase in the Caribbean and western GoM (SW), they tend to decrease along the US East Coast and Florida panhandle (NE), and vice versa. Our analyses highlight the coastlines between Louisiana and Florida as the inflection point between these clusters (though the southern extent of Florida often aligns with the SW cluster). While the HCA frequently groups the northeastern GoM with the eastern US, due in part to TCs that cross the SE US impacting both the GoM and Atlantic coasts (e.g., historical events such as Kate in 1985 or Elsa in 2021), the boundary between the SW and NE clusters varies somewhat across ensembles (Figure 3a), indicating that the mean climate state exerts less of an impact on TC landfalls at finer spatial scales. Nonetheless, the emergence of the SW and NE clusters across ensembles (which differ only from random perturbations to their initial climate conditions), and different analytical approaches indicate that the dipole's presence is informed by the underlying SST patterns that remain consistent across ensembles.

However, variability in the timing and expression of the dominant clusters across ensemble members (Figures 3b and 3c) demonstrates that SST conditions alone cannot fully explain dipole behavior. While climate forcing accounts for 27%–76% of variance in the NE cluster and 52%–86% in the SW cluster (Figure S4 in Supporting Information S1), the remaining variance arises from intrinsic atmospheric variability within each model run. This means that while the TC dipole does respond to changes to the mean climate state, weather-scale variability also influences dipole orientation at multidecadal scales. These findings are consistent with Kortum et al. (2024) who noted that weather, in addition to climate, drove spatial shifts in modern multidecadal-TC tracks and genesis.

Using our synthetic storm data, we can explore how properties like genesis play a role in generating this dipole pattern. The partitioning of storms into NE and SW clusters aligns with the dominant genesis locations within the synthetic TCs (Figure S1 in Supporting Information S1). This can be seen more clearly by looking at genesis density anomalies associated with the positive phases of each dipole orientation. Positive genesis anomalies in the Caribbean and tropical Atlantic are concurrent with increased SW activity, while NE activity is primarily associated with genesis over the northeast Caribbean region, GoM, and subtropical Atlantic (Figure S5 in Supporting Information S1). Storms forming between 10°N and 15°N, typically west of 55°W, are more likely to enter the Caribbean and impact the Yucatán and western GoM; northern-forming storms are unlikely to track south into the Caribbean and instead pose greater hazards to Florida and the eastern US. This interpretation is consistent with the work of Donnelly et al. (2015), which proposed shifts in genesis favorability over The

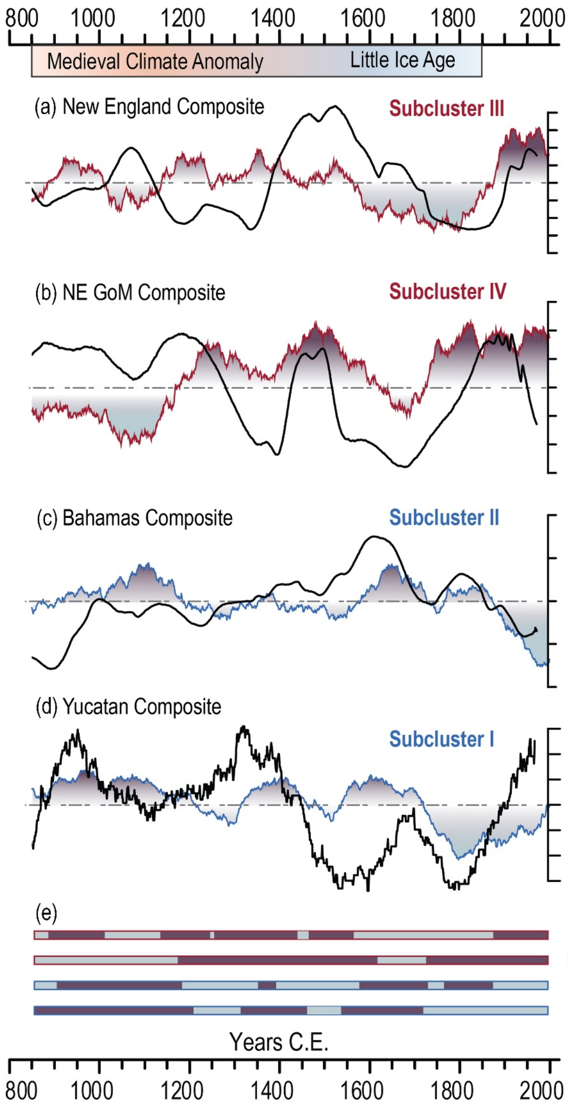


**Figure 4.** (a–d) Paleoproxy tropical cyclone reconstructions (black lines) for each of the four regions plotted against storm frequency indices for the most proximal Hierarchical Cluster Analysis (HCA) subcluster. Red (blue) lines indicate subclusters that fall within the larger NE (SW) clusters. All graphs are standardized to represent deviations in storminess above/below the mean. (e) Simplified representation of when storminess in each HCA subcluster is above (mauve) or below (gray) the mean.

Bahamas as a mechanism mediating New England TC activity. Our work lends credence to that hypothesis, showing that shifting genesis domains are critical factors in dipole orientation and landfall susceptibility.

This further highlights the significance of this work; using statistically downscaled TCs, we are identifying large-scale patterns in TC behavior that had previously only been observed in paleoreconstructions. Not only is this the first example of the dipole pattern emerging from modeled climate, thus validating proxy-based paleohurricane research, but our work shows promise for future climate and TC modeling and integrating proxy analyses with modeled data. The annual resolution and spatial continuity of the synthetic TC records reveal how the dominance of these divergent populations evolves over time to a degree that the lower-resolution proxy-reconstructions are unable. Moreover, while previous work has shown that, at a basin scale, proxy data and modeled results compare favorably (W. Yang et al., 2024), the storms presented here provide the opportunity for regional data-model comparisons.

Figure 4 plots the four proxy composites presented in Figure 1 with the simulated TC frequency timeseries from the nearest HCA subcluster (identified from the ensemble mean) to compare centennial variability. There is agreement between (a) the Bahamas Composite and Subcluster II, which encompasses portions of The Bahamas and much of the GoM and (b) the NE GoM composite and Subcluster IV (covering the SE US, Florida panhandle, northwest Atlantic, and northern Bahamas). Both the Bahamas composite and Subcluster II show increased activity ~1600 and ~1800 CE followed by a general declining trend into the present. Similarly, the NE GoM composite and Subcluster IV feature concurrent lulls in activity ~1100, 1400, and 1700 CE. Furthermore, Subclusters II and IV fall within different ends of the dipole and have antiphased storm records, which is a pattern also observed in the Bahamas and NE GoM paleorecords. Lastly, the Bahamas (NE GoM) composite is consistently anticorrelated with the synthetic records from the NE (SW) subclusters (Figure S6 in Supporting Information S1) indicating an agreement between the paleo and synthetic records regarding dipole inflection.

There is substantially less agreement between the composites from New England and the Yucatan and their subcluster counterparts. The sign of TC frequency change in each subcluster does not consistently correspond to the sign of the change in the compiled records. For example, the increase in New England storms near the start of the LIA (~1500–1850 CE) is not reflected in the synthetic data. These disagreements may arise from a bias in the synthetic storms that permits few events poleward of 35°N (Figure S1 in Supporting Information S1). Thus, the LMR TCs likely underestimate the risk of storm strikes to New England, complicating comparisons with the sediment record. It is easier to make these comparisons in the GoM and Bahamas where synthetic storm passage is greater. Additionally, the Yucatan (R. M. Sullivan et al., 2025) and New England (E. Wallace et al., 2021) sediment core composites include few paleoreconstructions (three and two, respectively), while the Bahamas (Winkler et al., 2023) and NE GoM (E. Wallace et al., 2021) composites include substantially more (i.e., eight and four). Our work suggests that increasing the number of reconstructions contributing to compilations improves our ability for model comparisons. Additionally, it may be that the role weather-variability exerts relative to underlying climatic conditions is more pronounced at the higher and lower latitudes, which would continue to complicate our efforts to model dipole behavior at the extrema.

Another potential source of uncertainty for paleohurricane data model comparison arises from the current placement of North Atlantic proxy sites. Most existing reconstructions are located on subcluster boundaries. For example, we correlated the GoM proxy reconstructions with synthetic TC activity in Subcluster IV, but the proxy records are situated on the Florida panhandle along Subcluster IV's boundary. The Bahamas sediment reconstruction correlates with Subcluster II, but the individual proxy sites fall along the boundary between Subclusters II and IV (Figure 1). To improve future data model comparison efforts, we must expand proxy-networks within subclusters, for example, along the SE US and Bermuda (Subcluster VI), the coasts of Texas and northeast Mexico (Subcluster II), and Jamaica and the Lesser Antilles (Subcluster I). Additionally, more high latitude reconstructions from Atlantic coasts along the Canadian Maritimes (Subcluster IV) may clarify how these locations compare to the New England reconstructions, which is grouped within Subcluster III. The coastal correlations show that more TCs pass within 50 km of Nova Scotia than New England (Figure 2). This may result from the bias against high latitude storms in the model (Figure S1 in Supporting Information S1) or could be attributed to Nova Scotia's further eastward location and greater coastal exposure that makes it more prone to encountering recurving TCs than the sheltered coasts of northern Massachusetts and Maine (gates 27 and 28). Paleoreconstructions from the Maritime coasts can potentially ground-truth these findings and resolve this ambiguity.

Given the uncertainties in both the simulated storms and proxy records, it is exciting that any matches can be made between these two independent storm data sets. Our work demonstrates that as improvements are made to models (e.g., through incorporating realistic SSTs) and proxies (e.g., compiling more sites) we will see stronger agreement between data sets and hopefully more accurate portrayals of past storm climate. Ultimately, these refinements will let us more thoroughly investigate dipole dynamics and drivers improving long-term TC risk assessment under different climate configurations.

## 5. Conclusion

Our work uses a variety of different statistical tests (e.g., coastal gate correlations, HCA) to identify a North Atlantic TC dipole pattern in LMR synthetic storms that shifted on multi-centennial scales throughout the past millennium. The presence of the dipole pattern in both LMR SST-driven TC simulations and independent sedimentological reconstructions indicates that secular changes in storm trajectories reflect underlying climate processes rather than random atmospheric variability alone. Consequently, coherent multi-decadal variations in TC landfalls appear tied to synoptic-scale climate patterns, suggesting a significant and potentially predictable climate influence on regional storm activity. Thus, future analyses will more thoroughly explore the background climate conditions and potential inter-basin teleconnections associated with each dipole state to better understand what drives these low-frequency shifts in TC landfalls. Moreover, the spatiotemporal similarities between the simulated and reconstructed storms highlight recent advancements in simulating historical TC climates. Lastly, the analyses presented here are only possible due to the growing database of proxy records that permitted the development of the LMR climate products and allowed us to examine the results of this work in the context of independent TC reconstructions, bridging a critical gap between numerical simulations and paleoreconstructions.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

Synthetic storms and MATLAB scripts are available on Zenodo (R. Sullivan et al., 2025). Paleodatasets used in this work can be found on Paleohurdat: https://paleohurdat.whoi.edu/.

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## References

Anderson, J., Balaji, V., Broccoli, A. J., Cooke, W. F., Delworth, T. L., Dixon, K. W., et al. (2004). The new GFDL global atmosphere and land model AM2–LM2: Evaluation with prescribed SST simulations. *Journal of Climate*, *17*(24), 4641–4673. https://doi.org/10.1175/JCLI-3223.1

Baldini, L. M., Baldini, J. U., McElwaine, J. N., Frappier, A. B., Asmerom, Y., Liu, K., et al. (2016). Persistent northward North Atlantic tropical cyclone track migration over the past five centuries. *Scientific Reports*, *6*(1), 37522. https://doi.org/10.1038/srep37522

Biguenet, M., Chaumillon, E., Sabatier, P., Paris, R., Vacher, P., & Feuillet, N. (2022). Discriminating between tsunamis and tropical cyclones in the sedimentary record using X-ray tomography. *Marine Geology*, *450*, 106864. https://doi.org/10.1016/j.margeo.2022.106864

Biguenet, M., Sabatier, P., Chaumillon, E., Chagué, C., Arnaud, F., Jorissen, F., et al. (2021). A 1600 year-long sedimentary record of tsunamis and hurricanes in the Lesser Antilles (Scrub Island, Anguilla). *Sedimentary Geology*, *412*, 105806. https://doi.org/10.1016/j.sedgeo.2020.105806

Boldt, K. V., Lane, P., Woodruff, J. D., & Donnelly, J. P. (2010). Calibrating a sedimentary record of overwash from Southeastern New England using modeled historic hurricane surges. *Marine Geology*, *275*(1–4), 127–139. https://doi.org/10.1016/j.margeo.2010.05.002

Colbert, A. J., Soden, B. J., Vecchi, G. A., & Kirtman, B. P. (2013). The impact of anthropogenic climate change on North Atlantic tropical cyclone tracks. *Journal of Climate*, *26*(12), 4088–4095. https://doi.org/10.1175/jcli-d-12-00342.1

Dailey, P. S., Zuba, G., Ljung, G., Dima, I. M., & Guin, J. (2009). On the relationship between North Atlantic sea surface temperatures and US hurricane landfall risk. *Journal of Applied Meteorology and Climatology*, *48*(1), 111–129. https://doi.org/10.1175/2008jamc1871x.1

Danso, D. K., Patricola, C. M., & Bercos-Hickey, E. (2022). Influence of African easterly wave suppression on Atlantic tropical cyclone activity in a convection-permitting model. *Geophysical Research Letters*, *49*(22), e2022GL100590. https://doi.org/10.1029/2022gl100590

Donnelly, J. P. (2025). Reconstructing tropical cyclone activity from sedimentary archives. *Annual Review of Earth and Planetary Sciences*, *53*(1), 251–281. https://doi.org/10.1146/annurev-earth-040523-021619

Donnelly, J. P., Hawkes, A. D., Lane, P., MacDonald, D., Shuman, B. N., Toomey, M. R., et al. (2015). Climate forcing of unprecedented intense-hurricane activity in the last 2000 years. *Earth's Future*, *3*(2), 49–65. https://doi.org/10.1002/2014ef000274

Elsner, J. B., Liu, K., & Kocher, B. (2000). Spatial variations in major US hurricane activity: Statistics and a physical mechanism. *Journal of Climate*, *13*(13), 2293–2305. https://doi.org/10.1175/1520-0442(2000)013<2293:svimus>2.0.co;2

Emanuel, K. (2006). Climate and tropical cyclone activity: A new model downscaling approach. *Journal of Climate*, *19*(19), 4797–4802. https://doi.org/10.1175/JCLI3908.1

Emanuel, K. (2025). A framework for testing tropical cyclone hazard models. *Environmental Research: Climate*, *4*(2), 025011. https://doi.org/10.1088/2752-5295/add9ba

Emanuel, K., DesAutels, C., Holloway, C., & Korty, R. (2004). Environmental control of tropical cyclone intensity. *Journal of the Atmospheric Sciences*, *61*(7), 843–858. https://doi.org/10.1175/1520-0469(2004)061<0843:ECOTCI>2.0.CO;2

Emanuel, K., Sundararajan, R., & Williams, J. (2008). Hurricanes and global warming: Results from downscaling IPCC AR4 simulations. *Bulletin of the American Meteorological Society*, *89*(3), 347–368. https://doi.org/10.1175/BAMS-89-3-347

Frappier, A. B., Sahagian, D., Carpenter, S. J., González, L. A., & Frappier, B. R. (2007). Stalagmite stable isotope record of recent tropical cyclone events. *Geology*, *35*(2), 111–114. https://doi.org/10.1130/g23145a.1

Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C., Jayne, S. R., et al. (2011). The community climate system model version 4. *Journal of Climate*, *24*(19), 4973–4991. https://doi.org/10.1175/2011JCLI4083.1

Gori, A., Lin, N., Xi, D., & Emanuel, K. (2022). Tropical cyclone climatology change greatly exacerbates US extreme rainfall–surge hazard. *Nature Climate Change*, *12*(2), 171–178. https://doi.org/10.1038/s41558-021-01272-7

Hakim, G. J., Emile-Geay, J., Steig, E. J., Noone, D., Anderson, D. M., Tardif, R., et al. (2016). The last millennium climate reanalysis project: Framework and first results. *Journal of Geophysical Research: Atmospheres*, *121*(12), 6745–6764. https://doi.org/10.1002/2016JD024751

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Knapp, K. R., Kruk, M. C., Levinson, D. H., Diamond, H. J., & Neumann, C. J. (2010). The international best track archive for climate stewardship (IBTrACS) unifying tropical cyclone data. *Bulletin of the American Meteorological Society*, *91*(3), 363–376. https://doi.org/10.1175/2009bams2755.1

Knutson, T. R., McBride, J. L., Chan, J., Emanuel, K., Holland, G., Landsea, C., et al. (2010). Tropical cyclones and climate change. *Nature Geoscience*, *3*(3), 157–163. https://doi.org/10.1038/ngeo779

Knutson, T. R., Sirutis, J. J., Vecchi, G. A., Garner, S., Zhao, M., Kim, H.-S., et al. (2013). Dynamical downscaling projections of twenty-first-century Atlantic hurricane activity: CMIP3 and CMIP5 model-based scenarios. *Journal of Climate*, *26*(17), 6591–6617. https://doi.org/10.1175/JCLI-D-12-00539.1

Kortum, G., Vecchi, G. A., Hsieh, T.-L., & Yang, W. (2024). Influence of weather and climate on multidecadal trends in Atlantic hurricane genesis and tracks. *Journal of Climate*, *37*(5), 1501–1522. https://doi.org/10.1175/JCLI-D-23-0088.1

Kossin, J. P. (2017). Hurricane intensification along United States coast suppressed during active hurricane periods. *Nature*, *541*(7637), 390–393. https://doi.org/10.1038/nature20783

Kossin, J. P., Emanuel, K. A., & Vecchi, G. A. (2014). The poleward migration of the location of tropical cyclone maximum intensity. *Nature*, *509*(7500), 349–352. https://doi.org/10.1038/nature13278

Lane, P., Donnelly, J. P., Woodruff, J. D., & Hawkes, A. D. (2011). A decadally-resolved paleohurricane record archived in the late Holocene sediments of a Florida sinkhole. *Marine Geology*, *287*(1–4), 14–30. https://doi.org/10.1016/j.margeo.2011.07.001

Lin, J., Lee, C.-Y., Camargo, S. J., & Sobel, A. (2024). Poleward migration of the latitude of maximum tropical cyclone intensity—Forced or natural? *Journal of Climate*, *37*(21), 5453–5463. https://doi.org/10.1175/JCLI-D-23-0705.1

Lin, N., Lane, P., Emanuel, K. A., Sullivan, R. M., & Donnelly, J. P. (2014). Heightened hurricane surge risk in northwest Florida revealed from climatological-hydrodynamic modeling and paleorecord reconstruction. *Journal of Geophysical Research: Atmospheres*, *119*(14), 8606–8623. https://doi.org/10.1002/2014jd021584

Liu, K., & Fearn, M. L. (1993). Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology*, *21*(9), 793–796. https://doi.org/10.1130/0091-7613(1993)021<0793:lsrolh>2.3.co;2

Malaizé, B., Bertran, P., Carbonel, P., Bonnissent, D., Charlier, K., Galop, D., et al. (2011). Hurricanes and climate in the Caribbean during the past 3700 years BP. *The Holocene*, *21*(6), 911–924. https://doi.org/10.1177/0959683611400198

Marks, D. G. (1992). *The beta and advection model for hurricane track forecasting*. NOAA NWS. Retrieved from https://repository.library.noaa.gov/view/noaa/7184/noaa_7184_DS1.pdf

Maxwell, J. T., Bregy, J. C., Robeson, S. M., Knapp, P. A., Soulé, P. T., & Trouet, V. (2021). Recent increases in tropical cyclone precipitation extremes over the US east coast. *Proceedings of the National Academy of Sciences*, *118*(41), e2105636118. https://doi.org/10.1073/pnas.2105636118

Murakami, H., Delworth, T. L., Cooke, W. F., Zhao, M., Xiang, B., & Hsu, P.-C. (2020). Detected climatic change in global distribution of tropical cyclones. *Proceedings of the National Academy of Sciences*, *117*(20), 10706–10714. https://doi.org/10.1073/pnas.1922500117

Murakami, H., & Wang, B. (2010). Future change of North Atlantic tropical cyclone tracks: Projection by a 20-km-Mesh global atmospheric model. *Journal of Climate*, *23*(10), 2699–2721. https://doi.org/10.1175/2010JCLI3338.1

PAGES2k Consortium, Emile-Geay, J., McKay, N. P., Kaufman, D. S., Von Gunten, L., Wang, J., et al. (2017). A global multiproxy database for temperature reconstructions of the Common Era. *Scientific Data*, *4*(1), 170088. https://doi.org/10.1038/sdata.2017.88

Peros, M., Gregory, B., Matos, F., Reinhardt, E., & Desloges, J. (2015). Late-Holocene record of lagoon evolution, climate change, and hurricane activity from southeastern Cuba. *The Holocene*, *25*(9), 1483–1497. https://doi.org/10.1177/0959683615585844

Pielke, R. A., Gratz, J., Landsea, C. W., Collins, D., Saunders, M. A., & Musulin, R. (2008). Normalized hurricane Damage in the United States: 1900–2005. *Natural Hazards Review*, *9*(1), 29–42. https://doi.org/10.1061/(ASCE)1527-6988(2008)9:1(29)

Ramos, M. C. (2001). Divisive and hierarchical clustering techniques to analyse variability of rainfall distribution patterns in a Mediterranean region. *Atmospheric Research*, *57*(2), 123–138. https://doi.org/10.1016/S0169-8095(01)00065-5
Schmitt, D., Gischler, E., Anselmetti, F. S., & Vogel, H. (2020). Caribbean cyclone activity: An annually-resolved Common Era record. *Scientific Reports*, *10*(1), 1–17. https://doi.org/10.1038/s41598-020-68633-8
Studholme, J., Fedorov, A. V., Gulev, S. K., Emanuel, K., & Hodges, K. (2022). Poleward expansion of tropical cyclone latitudes in warming climates. *Nature Geoscience*, *15*(1), 14–28. https://doi.org/10.1038/s41561-021-00859-1
Sullivan, R., Wallace, E., Dee, S., Vecchi, G., Yang, W., & Kerry, E. (2025). Multi-centennial spatial coherency among Atlantic tropical cyclones from simulated and reconstructed storm records—Storm dataset and code [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.15262056
Sullivan, R. M., van Hengstum, P. J., Donnelly, J. P., Tamalavage, A. E., Winkler, T. S., Little, S. N., et al. (2022). Northeast Yucatan hurricane activity during the Maya Classic and Postclassic periods. *Scientific Reports*, *12*(1), 20107. https://doi.org/10.1038/s41598-022-22756-2
Sullivan, R. M., van Hengstum, P. J., Wallace, E. J., Coats, S., Donnelly, J. P., Korty, R., et al. (2025). Yucatan hurricane activity highlights Common Era tropical cyclone dipole. *Geophysical Research Letters*, *52*, e2024GL113940. https://doi.org/10.1029/2024GL113940
Tardif, R., Hakim, G. J., Perkins, W. A., Horlick, K. A., Erb, M. P., Emile-Geay, J., et al. (2019). Last Millennium Reanalysis with an expanded proxy database and seasonal proxy modeling. *Climate of the Past*, *15*(4), 1251–1273. https://doi.org/10.5194/cp-15-1251-2019
Ting, M., Kossin, J. P., Camargo, S. J., & Li, C. (2019). Past and future hurricane intensity change along the U.S. East coast. *Scientific Reports*, *9*(1), 7795. https://doi.org/10.1038/s41598-019-44252-w
van Hengstum, P. J., Donnelly, J. P., Toomey, M. R., Albury, N. A., Lane, P., & Kakuk, B. (2014). Heightened hurricane activity on the little Bahama bank from 1350 to 1650 AD. *Continental Shelf Research*, *86*, 103–115. https://doi.org/10.1016/j.csr.2013.04.032
Vecchi, G. A., & Knutson, T. R. (2011). Estimating annual numbers of Atlantic hurricanes Missing from the HURDAT database (1878–1965) using Ship track density. *Journal of Climate*, *24*(6), 1736–1746. https://doi.org/10.1175/2010JCLI3810.1
Wallace, E., Donnelly, J., van Hengstum, P., Winkler, T., Dizon, C., LaBella, A., et al. (2021). Regional shifts in paleohurricane activity over the last 1500 years derived from blue hole sediments offshore of Middle Caicos Island. *Quaternary Science Reviews*, *268*, 107126. https://doi.org/10.1016/j.quascirev.2021.107126
Wallace, E. J., Coats, S., Emanuel, K., & Donnelly, J. P. (2020). Centennial-scale shifts in storm frequency captured in paleohurricane records from the Bahamas arise predominantly from random variability. *Geophysical Research Letters*, *48*(1), e2020GL091145. https://doi.org/10.1029/2020gl091145
Wallace, E. J., Dee, S. G., & Emanuel, K. A. (2021). Resolving long-term variations in North Atlantic tropical cyclone activity using a Pseudo proxy Paleotempestology network approach. *Geophysical Research Letters*, *48*(18), e2021GL094891. https://doi.org/10.1029/2021gl094891
Wallace, E. J., Donnelly, J. P., van Hengstum, P. J., Wiman, C., Sullivan, R. M., Winkler, T. S., et al. (2019). Intense hurricane activity over the past 1500 years at south Andros island, the Bahamas. *Paleoceanography and Paleoclimatology*, *34*(11), 1761–1783. https://doi.org/10.1029/2019pa003665
Ward, J. H., Jr. (1963). Hierarchical grouping to optimize an objective function. *Journal of the American Statistical Association*, *58*(301), 236–244. https://doi.org/10.1080/01621459.1963.10500845
Weaver, M. M., & Garner, A. J. (2023). Varying genesis and landfall locations for North Atlantic tropical cyclones in a warmer climate. *Scientific Reports*, *13*(1), 5482. https://doi.org/10.1038/s41598-023-31545-4
Willoughby, H. E., Hernandez, J. I., & Pinnock, A. (2024). Trends in U.S. Atlantic tropical cyclone Damage, 1900–2022. *Journal of Applied Meteorology and Climatology*, *63*(12), 1499–1510. https://doi.org/10.1175/JAMC-D-24-0047.1
Winkler, T. S., van Hengstum, P. J., Donnelly, J. P., Wallace, E. J., Albury, N. A., D'Entremont, N., et al. (2023). More frequent Hurricane passage across the Bahamian Archipelago during the little ice age. *Paleoceanography and Paleoclimatology*, *38*(11), e2023PA004623. https://doi.org/10.1029/2023pa004623
Yang, W., Wallace, E., Vecchi, G. A., Donnelly, J. P., Emile-Geay, J., Hakim, G. J., et al. (2024). Last millennium hurricane activity linked to endogenous climate variability. *Nature Communications*, *15*(1), 816. https://doi.org/10.1038/s41467-024-45112-6
Yang, Y., Maselli, V., Normandeau, A., Piper, D. J. W., Li, M. Z., Campbell, D. C., et al. (2020). Latitudinal response of storm activity to abrupt climate change during the last 6,500 years. *Geophysical Research Letters*, *47*(19), e2020GL089859. https://doi.org/10.1029/2020GL089859