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Key Points:

- The current network of paleohurricane proxies captures annual to multi-decadal scale variability in Atlantic tropical cyclone (TC) frequency
- Paleohurricane records predominantly capture storms that impact the U.S. Gulf Coast and Caribbean Sea
- More paleohurricane records, especially from the U.S. Southeast, are needed to reconstruct recurving TCs

Supporting Information:

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

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Resolving Long-Term Variations in North Atlantic Tropical Cyclone Activity Using a Pseudo Proxy Paleotempestology Network Approach

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Abstract Paleohurricane reconstructions extend the observational record of tropical cyclones (TCs) back thousands of years. However, these records are subject to biases–capturing only close-moving intense storms at varying resolutions. We devise two pseudo proxy networks drawing from the full suite of published paleohurricane studies in the North Atlantic. We run synthetic storms forced with two global climate model simulations of the past millennium through each pseudo network to assess the theoretical skill of paleohurricane proxies at capturing low-frequency variability in North Atlantic basin-wide and intrabasin TCs. We find that basin-wide and paleohurricane compiled TC counts are significantly correlated with one another for the past millennium on annual to multi-decadal timescales, but compilation skill is limited by proxy temporal resolution. Current paleohurricane proxy networks predominantly capture storms moving in the Caribbean/Gulf of Mexico. Increasing the quantity of paleohurricane records from the North American coastline substantially improves reconstruction skill.

Plain Language Summary As our climate warms, we need to understand how the statistics of Atlantic hurricanes will change. Scientists use natural archives, such as sediment and tree cores, to reconstruct Atlantic hurricane frequency over the past couple of thousand years. These natural archives, also known as paleohurricane proxies, are biased; they only record storms that move close to the coring site at a high intensity. Over the past few decades, scientists have amassed large networks of paleohurricane proxies from coastlines in the western North Atlantic. Here, we use two different sets of synthetic hurricanes to test if a compilation of the current network of paleohurricane proxies will smooth out the biases of each individual site and provide an accurate representation of Atlantic basin-wide hurricane frequency over the past 1,000 years. We find that current network of paleohurricane records can be used to reconstruct past Atlantic hurricanes, but most of the current sites only capture storms that form/move through the Caribbean Sea and the Gulf of Mexico. We can improve our estimates of past hurricanes in future work by adding more sites from the U.S. Southeast and Central America.

1. Introduction

Climate change has the potential to dramatically change future tropical cyclone (TC) hazards in the near and long term. While most studies predict that global warming will lead to a global increase in TC precipitation (e.g., Patricola & Wehner, 2018; Wright et al., 2015) and intensity (e.g., Bhatia et al., 2018; Korty et al., 2017), models disagree about the sign of future TC frequency change (Knutson et al., 2020).

The divergence in model projections of TC frequency arises from a lack of clear theoretical understanding and observational evidence to support the relationship between TC frequency and recent global warming (Knutson et al., 2020). Most TC modeling studies only use ~50 years of observations from the satellite era (1970–present) for validation. With such a short dataset, it is difficult to improve future projections of TC activity. To contextualize recent changes and model projections in TC frequency against a pre-Industrial baseline, extended statistics on TC track, intensity, and landfall geography are needed.

To this end, paleohurricane records are employed to extend TC statistics thousands of years beyond the instrumental era. Paleohurricane records include both documentary records (e.g., Boose et al., 2001; Chenoweth & Divine, 2008) and geological and biological archives of hurricane activity (e.g., Altman et al., 2018; Boldt et al., 2010; Frappier, Sahagian, et al., 2007; Wallace et al., 2019). The vast majority of these paleohurricane records are event-based, meaning that they reconstruct TC histories through identifying and dating indicator layers (e.g., coarse-grained overwash deposits, lower $\delta^{18}O$ values of tree-ring cellulose) (Burn, 2021). These indicator layers often date within uncertainties to historical TCs of a known intensity that passed close to a site (<200 km). These modern analogs allow researchers to provide an estimate of the storm intensity required for leaving an indicator layer at the site.

However, there are complications in using these individual paleohurricane records to constrain changes in intrabasin and/or basin-wide TC climate. Low-frequency variations captured in single paleohurricane records do not necessarily define a regional TC climate signal. Specifically, pseudo proxies created for paleohurricane sites in The Bahamas demonstrate that the majority of the signal captured in the single event-based record from this region is due to random variability in TC tracks (e.g., local weather, moist processes) not large-scale climate variability (Wallace et al., 2020). Therefore, we must turn to wider-scale compilations of records to investigate long-term TC climate (Burn, 2021).

Mann et al. (2009) presented the first compilation of sediment-based paleohurricane records from the North Atlantic and found that it was statistically consistent with an independent statistical model prediction of past millennium hurricane activity. Idealized millennial-scale TC simulations (Kozar et al., 2013; Reed et al., 2015) indicate that counts of landfalling TCs over the past millennium match with basin-wide TC activity in the Atlantic. Unfortunately, compilation efforts are impeded by the widely varying temporal resolutions, sensitivities, durations, and interpretations across paleohurricane reconstructions (Oliva, Viau, et al., 2018).

Here, we use a TC model forced with two global climate model (GCM) simulations spanning the last millennium to evaluate the viability of paleohurricane proxy networks to capture annual to multi-decadal variations in North Atlantic basin-wide and intrabasin TC frequency. Specifically, we perform a proof-of-concept with two pseudo proxy networks designed based on existing paleohurricane record locations, resolutions, and sensitivities. Drawing from paleoclimate sensor-placement literature (Comboul et al., 2015), we investigate whether broadening the network of proxy sites improves our ability to capture the simulated TC statistics.

2. Data and Methods

2.1. Basin-Wide Atlantic Synthetic Storms

We use a single full forcing simulation of last millennium climate from two GCMs: the Max Planck Institute Earth System Model (MPI-ESM; Taylor et al., 2012) and Community Earth System Model-Last Millennium Ensemble (CESM-LME #7; Otto-Bliesner et al., 2016). Both GCMs are run with similar external forcing (Schmidt et al., 2011); therefore, differences in simulated climate from each GCM arise from structural differences between the models. We provide an overview of the model experiments and their biases in Section S1 (Supporting Information S1). Both models were selected based on the availability of necessary thermodynamic (e.g., SSTs, vertical temperature/humidity profiles) and kinematic (e.g., daily winds) state variables from 850 to 2005 CE.

We generate a database of synthetic TCs in the Atlantic from 850–2005 CE using a statistical deterministic TC model (Emanuel et al., 2006, 2008) run with initial and boundary conditions taken from the GCMs (Section S2 in Supporting Information S1). Our MPI-ESM and CESM-LME storm databases include 100 storms per year of modeled climate (~115,600 synthetic TCs). We chose 100 storms/year as opposed to a more realistic number (i.e., 10–20) to sample the full distribution of TC characteristics (i.e., intensity, track shape, landfall) that can be produced under each year's climate. We compare the genesis, track, and intensity properties of our synthetic storms with observations (IBTrACS, Knapp et al., 2010; Figures S1 and S2). Despite biases in all three datasets (Section S3 in Supporting Information S1), the statistics of the synthetic storms broadly match observations.

2.2. Intrabasin Atlantic Synthetic Storms

To analyze intrabasin patterns of Atlantic hurricanes, we separated each whole Atlantic dataset (MPI-ESM, CESM-LME) into spatial clusters using regression mixture models (Gaffney et al., 2007) fit to the geographic shape of the TCs. The method builds a mixture of quadratic regression curves of storm position against time

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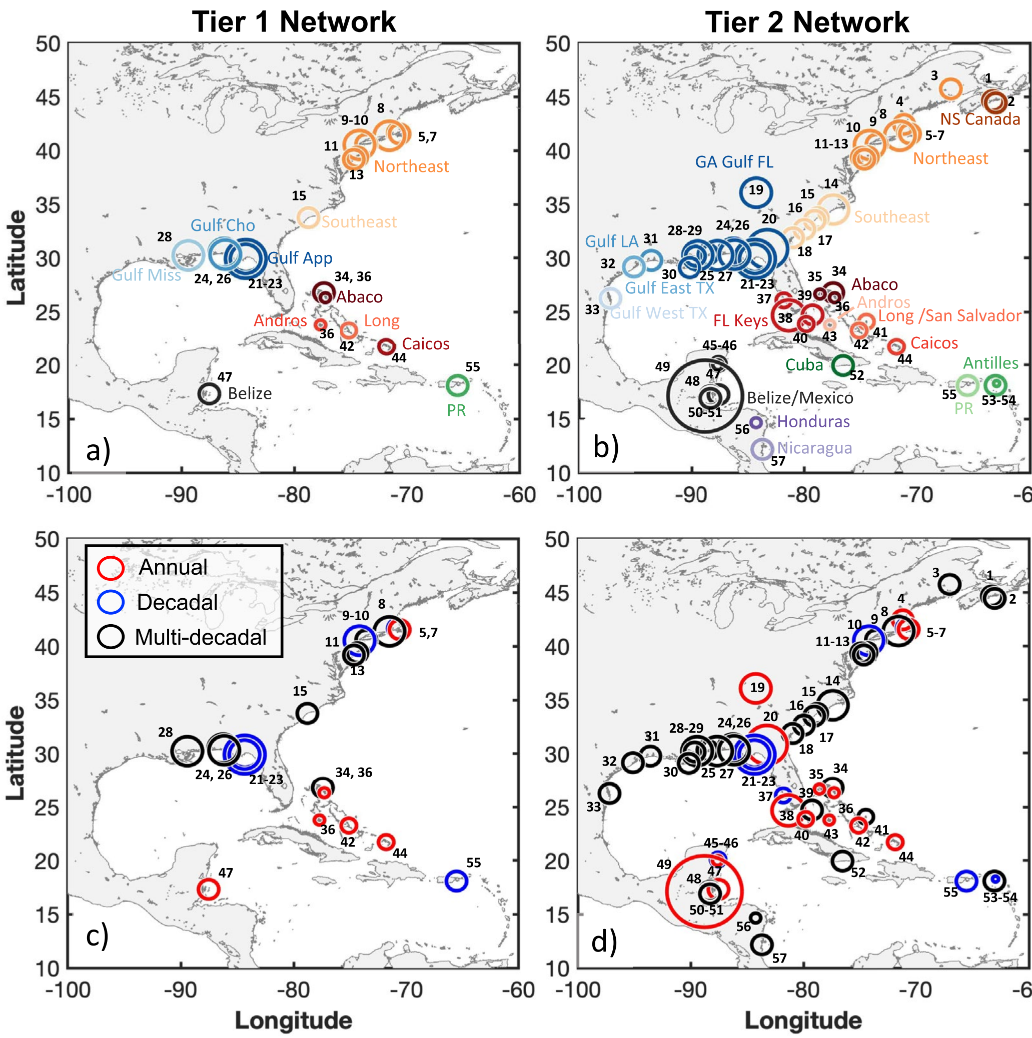

Figure 1. Tier 1 (a and c) and tier 2 (b and d) proxy networks. Sites are colored by region (a and b) and by temporal resolution (c and d). Circles show the sensitivity radii. Publication information, region categories, and sensitivity criteria are listed in Table 1.

from which TC tracks might have been generated. Each storm is assigned to one of K different regression models with each model including its own shape parameters expressed as regression coefficients and noise. Clustering considers both shape and position of each storm by including the genesis location in the analysis. This approach is advantageous for using different types of storms (synthetic vs. observational) because it accommodates tracks of different length. Following Kossin et al. (2010), we set the number of clusters to four and assigned a cluster (#1–4) to every synthetic storm in our two datasets.

2.3. Producing Pseudo Paleohurricane Compilations

We create two pseudo paleohurricane proxy networks (Figure 1 and Table 1). The tier 1 network includes records used in previous compilation efforts (Mann et al., 2009; Wallace, Donnelly, vanHengstum, Winkler, Dizon, et al., 2021) and is the "current state" of paleohurricane research. The tier 2 network represents an idealized network and adds additional studies from the Oliva, Viau, et al. (2018) paleohurricane database. The tier 1 and tier 2 proxy networks are divided into 11 and 18 regions, respectively, according to their geographic location (Figure 1 and Table 1).

Using our TC datasets, we create pseudo paleohurricane compilations including the storms sensed by the study locations in each proxy network. The first step is to generate 1,000 records of storm occurrence in the Atlantic

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Table 1
List of Tier 2 Proxy Network Sites

	Publication	Lat.	Long.	Region	Radius (km)	Intensity (m/s)
1	Oliva, Peros, et al. (2018)	44.65	−63.28	NS_Canada	100	43
2	Yang et al. (2020)	44.43	−63.03	NS_Canada	100	43
3	Patterson et al. (2020)	45.73	−67.01	Northeast	100	18
4	Besonen et al. (2008)	42.43	−71.15	Northeast	100	43
5	**Boldt et al. (2010)**	**41.65**	**−70.79**	**Northeast**	**100**	**43**
6	Buynevich and Donnelly (2006)	41.57	−70.64	Northeast	100	50
7	**Donnelly et al. (2015)**	**41.54**	**−70.63**	**Northeast**	**100**	**43**
8	**Donnelly, Bryant, et al. (2001)**	**41.38**	**−71.52**	**Northeast**	**150**	**43**
9	**Scileppi and Donnelly (2007)**	**40.60**	**−73.58**	**Northeast**	**100**	**43**
10	**Brandon et al. (2016)**	**40.52**	**−74.19**	**Northeast**	**150**	**33**
11	**Donnelly et al. (2004)**	**39.41**	**−74.36**	**Northeast**	**100**	**50**
12	Nikitina et al. (2014)	39.37	−74.89	Northeast	100	50
13	**Donnelly, Roll, et al. (2001)**	**39.19**	**−74.66**	**Northeast**	**100**	**50**
14	Hippensteel and Garcia (2014)	34.52	−77.41	Southeast	150	58
15	**Scott et al. (2003)**	**33.76**	**−78.79**	**Southeast**	**100**	**50**
16	Collins et al. (1999)	33.51	−79.05	Southeast	100	50
17	Hippensteel (2008)	32.67	−79.97	Southeast	100	58
18	Kiage et al. (2011)	31.89	−80.97	Southeast	100	43
19	Li and Sriver (2018)	36.08	−84.23	GA_Gulf_FL	150	18
20	Miller et al. (2006)	30.84	−83.25	GA_Gulf_FL	200	18
21	**Brandon et al. (2013)**	**30.10**	**−84.34**	**GA_Gulf_FL**	**150**	**33**
22	**Rodysill et al. (2020)**	**29.93**	**−84.36**	**GA_Gulf_FL**	**150**	**33**
23	**Lane et al. (2011)**	**29.93**	**−84.34**	**GA_Gulf_FL**	**200**	**43**
24	**Rodysill et al. (2020)**	**30.49**	**−86.25**	**GA_Gulf_FL**	**150**	**50**
25	Horton et al. (2009)	30.34	−88.52	GA_Gulf_FL	100	50
26	**Liu and Fearn (2000)**	**30.32**	**−86.15**	**GA_Gulf_FL**	**150**	**58**
27	Liu and Fearn (1993)	30.26	−87.66	GA_Gulf_FL	150	58
28	**Bregy et al. (2018)**	**30.25**	**−89.43**	**GA_Gulf_FL**	**150**	**50**
29	Reese et al. (2008)	30.18	−89.65	GA_Gulf_FL	100	50
30	Liu et al. (2011)	29.11	−90.17	GA_Gulf_FL	100	50
31	Williams (2013)	29.79	−93.58	Gulf_LA	100	50
32	Hawkes and Horton (2012)	29.17	−95.12	Gulf_EastTX	100	50
33	Wallace and Anderson (2010)	26.25	−97.20	Gulf_WestTX	100	50
34	**van Hengstum et al. (2016)**	**26.79**	**−77.42**	**Abaco**	**100**	**50**
35	Lane's Delight Blue Hole*	26.66	−78.59	Abaco	50	43
36	**Winkler et al. (2020)**	**26.32**	**−77.29**	**Abaco**	**50**	**43**
37	Ercolani et al. (2015)	26.07	−81.79	FLKeys_BhaBank	75	50
38	Trouet et al. (2016)	24.67	−81.35	FLKeys_BhaBank	160	33
39	Toomey et al. (2013)	24.71	−79.24	FLKeys_BhaBank	100	50
40	Cay Sal Bank Blue Hole*	23.87	−79.81	FLKeys_BhaBank	75	33
41	Mattheus and Fowler (2015)	24.08	−74.48	Long_SanSalv	75	50
42	**Wallace, Donnaelly, Winkler, Mckeon, et al. (2021)**	**23.27**	**−75.12**	**Long_SanSalv**	**75**	**43**
43	**Wallace et al. (2019)**	**23.78**	**−77.72**	**Andros**	**50**	**50**

Table *1*
Continued

	Publication	Lat.	Long.	Region	Radius (km)	Intensity (m/s)
44	**Wallace, Donnelly, Van Hengstum, Winkler, Dizon, et al. (2021)**	**21.72**	**−71.81**	**Caicos**	**75**	**33**
45	Brown et al. (2014)	20.10	−87.58	Belize_Mex	75	50
46	Muyil Sinkhole, Mexico*	20.01	−87.62	Belize_Mex	50	50
47	**Schmitt et al. (2020)**	**17.32**	**−87.53**	**Belize_Mex**	**100**	**18**
48	McCloskey and Keller (2009)	17.14	−88.30	Belize_Mex	100	50
49	Frappier, Sahagian, et al. (2007)	17.12	−88.78	Belize_Mex	370	18
50	Adomat et al. (2015)	16.99	−88.28	Belize_Mex	100	50
51	McCloskey and Liu (2012a)	16.90	−88.29	Belize_Mex	100	18
52	Peros et al. (2015)	19.95	−76.54	Cuba	100	50
53	Biguenet et al. (2021)	18.28	−62.96	LessAntilles	30	50
54	Bertran et al. (2004)	18.10	−63.05	LessAntilles	100	50
55	**Donnelly and Woodruff (2007)**	**18.09**	**−65.52**	**PR**	**100**	**50**
56	Cochran et al. (2009)	14.65	−84.24	Honduras	50	50
57	McCloskey and Liu (2012b)	12.16	−83.69	Nicaragua	100	50

Note. Each record was sorted into a region and given a radius and intensity sensing criteria based on the original publication. Bolded records make up the tier 1 network. * denote sites from fortcoming work by Tyler Winkler and Richard Sullivan.

from 850 to 2005 CE for each synthetic storm dataset (i.e., MPI, CESM) using a Poisson process-based random draw (Wallace et al., 2020) from the 100 TCs available each year (Section S4 in Supporting Information S1).

We build pseudo paleohurricane compilations moving from a site to a regional level to the final basin-wide estimate. From site to site, we record which storms would leave an indicator layer based on two criteria: (a) sensing radius only and (b) sensing radius + storm intensity (expressed as maximum ground-relative wind speed at the site) (Table 1). For each site, we can create a time series of TC counts from 850 to 2005 CE for both criteria (Figure S3). Details on the sensing criteria are provided in Section S5 in Supporting Information S1.

To create a regional compilation, we add the storms sensed by all sites in a region together. Any storms captured in multiple records from a region are only counted once. Finally, all regional compilations are summed together to create a basin-wide compilation. To account for age uncertainties, we smooth our annually resolved pseudo paleohurricane compilations on decadal (10-year) and multi-decadal (40-year) timescales. These methods are repeated to build intrabasin compilations by only running storms belonging to one of the four TC clusters through our proxy networks at a time. We also test the robustness of the compilations with a jackknife analysis wherein we eliminate regions one at a time and create compilations using the remaining regions. Finally, we analyze how inhomogeneous temporal resolutions across records affects compilation skill by limiting the number of storms recorded at each site based on the accumulation rate of the archive (Section S6 in Supporting Information S1).

We calculate the Pearson correlation coefficients between the detrended TC frequency time series generated from the 1,000 Atlantic records of storm occurrence and their corresponding detrended TC frequency time series as sensed by each network/sensing criteria. Higher correlation coefficients indicate greater skill for each proxy network in capturing North Atlantic TC frequency.

3. Results

3.1. Basin-Wide Network Reconstruction Skill

Both the tier 1 and tier 2 pseudo paleohurricane compilations capture a substantial fraction of the variance in basin-wide TC activity (Figure 2). Assuming multi-decadal resolution and radius only sensing criteria, tier 1 (currently available) paleohurricane compilations significantly correlate with model-simulated North

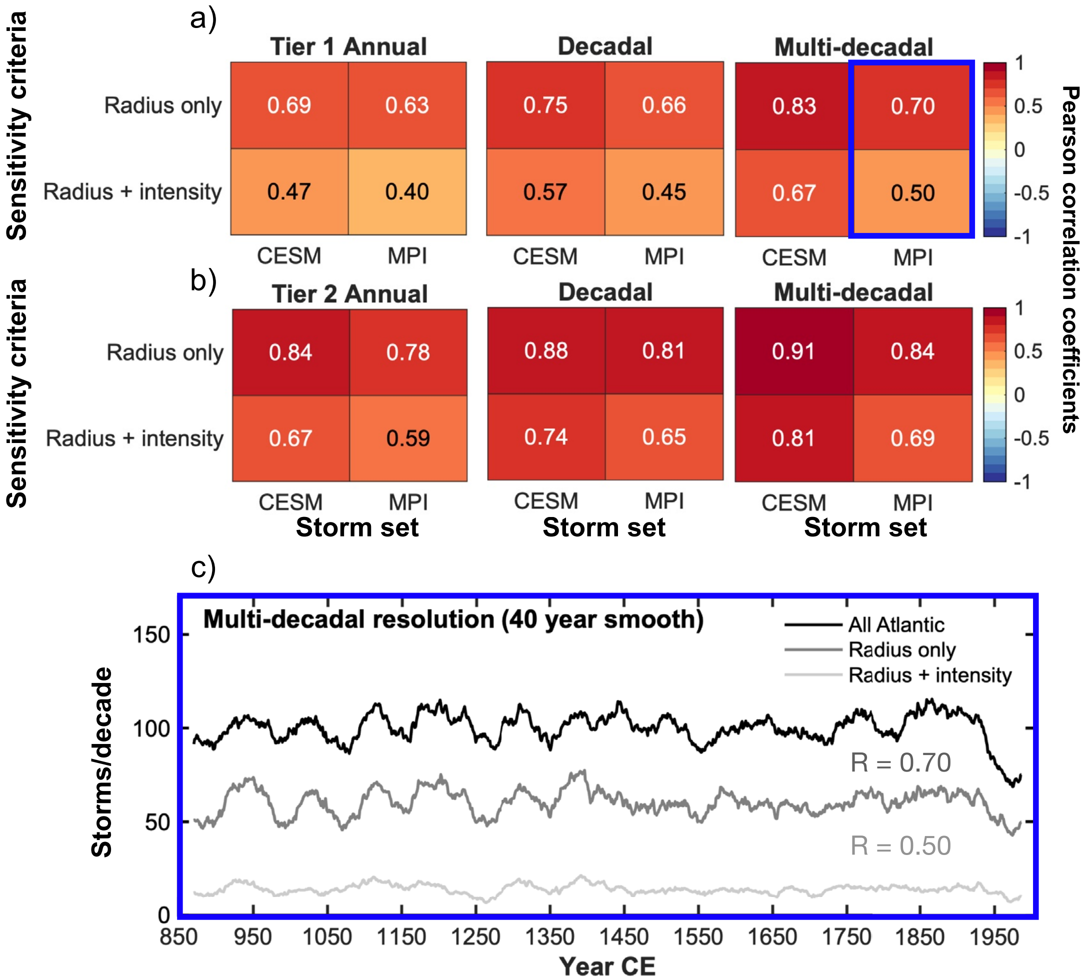

Figure 2. Heatmap of median correlation coefficients between basin-wide Atlantic TC frequency and paleohurricane compilation TC frequency from 1000 different records of storm occurrence from 850 to 2005 CE. MPI and CESM TCs for the tier 1 (a) and tier 2 (b) proxy networks are sensed by radius only and radius + intensity. Annual, decadal, and multi-decadal results come from correlating unsmoothed (left), 10-year smoothed (middle), and 40-year smoothed (right) time series. All correlation coefficients are significant at a 95% confidence level. (c) Example 40-year smoothed (multi-decadal) time series of MPI basin-wide TC frequency (black) and tier 1 paleohurricane compilation TC frequency sensed by radius only (dark gray) and by radius + intensity (light gray).

Atlantic storm frequency from 850 to 2005 CE ($r = 0.7$–0.83, corresponding to 49%–69% shared variance). Correlations are stronger ($r = 0.84$–0.91%, 70%–83% shared variance) as we increase site density in the idealized tier 2 compilations.

These correlations degrade with more realistic sensing criteria (i.e., radius + intensity) for the tier 1 ($r = 0.5$–0.67) and tier 2 ($r = 0.69$–0.81) networks. Since the majority of paleohurricane sites in both the tier 1 (16 of 21) and tier 2 (45 of 57) networks capture ≥Category 2 storms, adding the intensity criterion limits each network's ability to capture variation in lower intensity TC frequency (Table 1). These correlations do not substantially improve when comparing the paleohurricane compilations to basin-wide ≥ Category 2 TC frequency (Figure S4).

Correlation coefficients for CESM storms are higher by approximately 0.1 than their MPI counterparts (Figure 2). These stronger correlations are an artifact of larger range and variance in the number of TCs occurring on average each year in the CESM records of storm occurrence (Figure S5). Years with more CESM storms in the Atlantic result in more opportunities for those storms to be sensed and thus a stronger relationship between paleohurricane-sensed and basin-wide storms. Similarly, synthetic TCs are better cap-

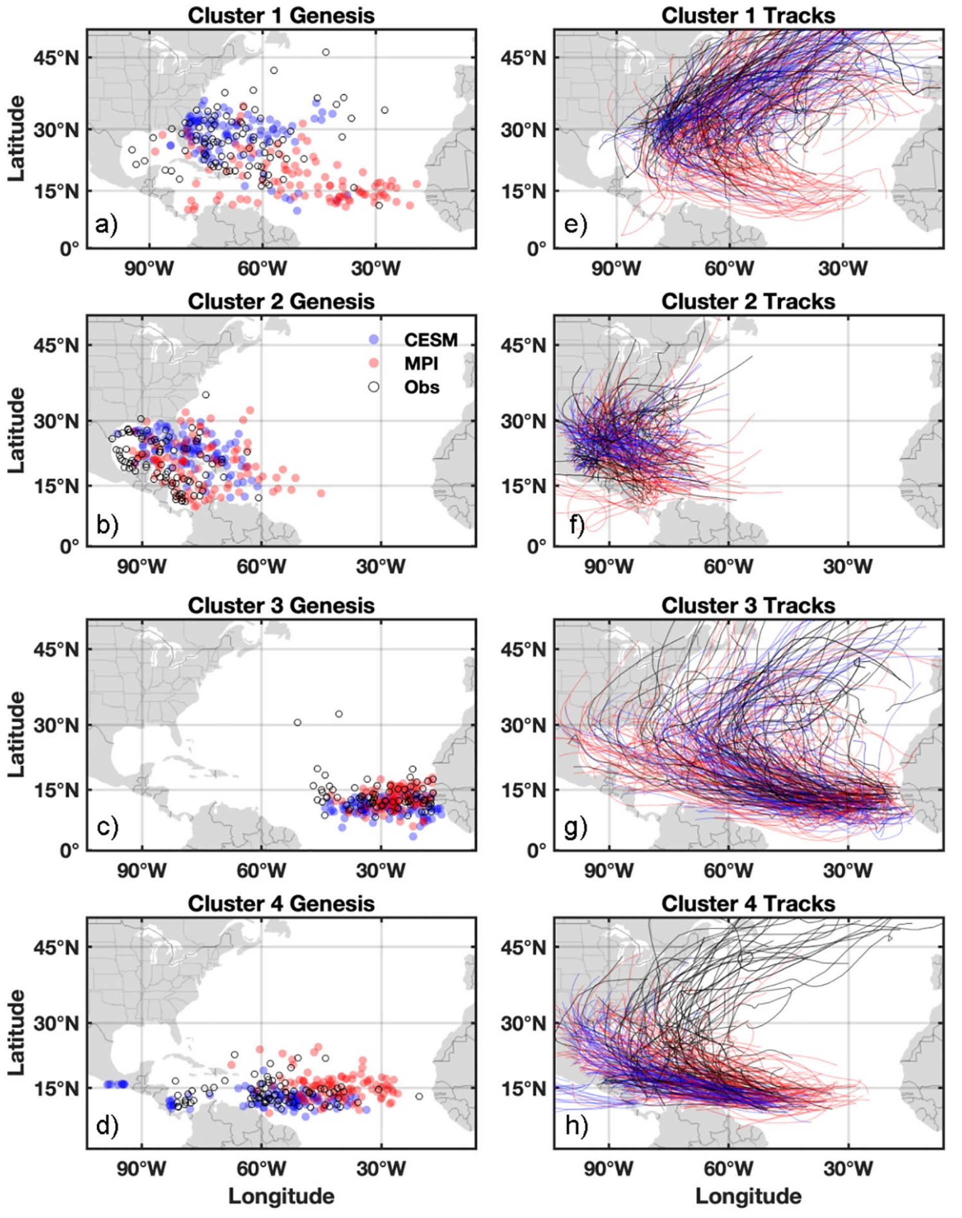

Figure 3. (a–d) Genesis points and (e–h) tracks for observed (black) and synthetic (CESM-blue; MPI-red) Atlantic tropical cyclones from 1851 to 2005 CE as separated by cluster analysis. A randomly chosen set of 200 of each type of storm are plotted.

tured by the proxy networks than the observations (Figure S6). Biases in the observational record toward fewer TCs (e.g., Vecchi & Knutson, 2008; Villarini et al., 2011) make the dataset more difficult to sense with proxy networks.

3.2. Intrabasin Network Reconstruction Skill

We also measure the skill of paleohurricane proxy networks in capturing intrabasin TC frequency by testing their ability to capture different TC clusters. We reproduced the four storm clusters of Kossin et al. (2010) using observational (1851–2019 CE) and synthetic storms (850–2005 CE) (Figure 3). In the observations, cluster 1 storms form northward and eastward either recurving out into the open Atlantic or striking the US East Coast. Cluster 2 storms form almost exclusively in the Gulf of Mexico/western Caribbean Sea and make landfall in the Gulf/Caribbean islands. Cluster 3 storms form at low latitudes off the west coast of

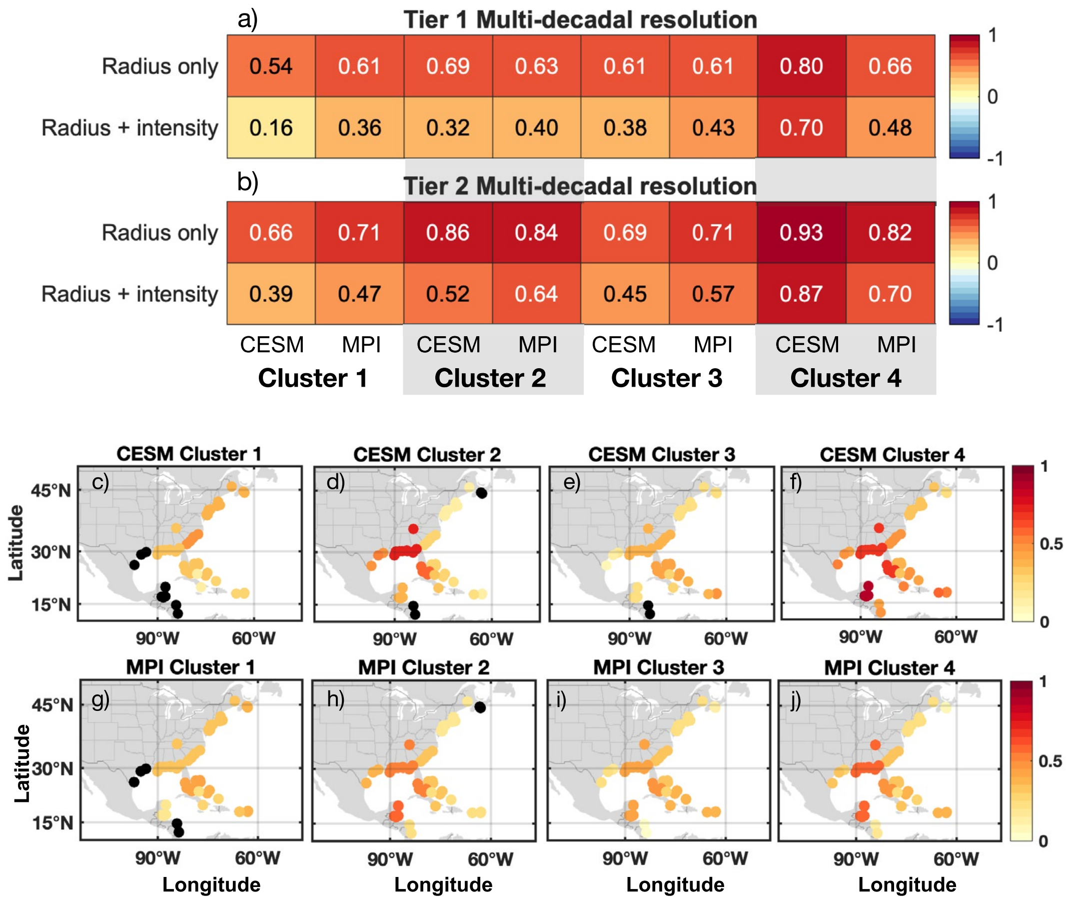

Figure 4. Heatmap of correlation coefficients between multi-decadal (40-year smooth) cluster 1–4 TC frequency and paleohurricane compilation clustered TC frequency. MPI and CESM TCs for the tier 1 (a) and tier 2 (b) proxy networks are sensed by radius only and radius + intensity. Correlation coefficients between multi-decadal cluster TC frequency and paleohurricane compilation cluster TC frequency mapped by tier 2 regions for the CESM (c–f) and MPI (g–j) datasets. Black circles indicate sites that sensed no storms in that cluster. All values are the median of 1000 different records of storm occurrence and are significant (95% confidence).

Africa and recurve north and west. Cluster 4 storms also form at low latitudes but much further westward and often strike in the Gulf of Mexico/Central America (Kossin et al., 2010).

Comparing synthetic storm clusters to the observations highlights the spatial biases in the MPI and CESM models. MPI climate captures storm genesis in the tropical Atlantic and western Caribbean well (Figures 3a–3d) but creates noticeable fewer storms with a pronounced northward component to their track. Therefore, MPI fails to produce the archetype cluster 1 and 3 storms that recurve out into the Atlantic/along the US East Coast (Figures 3e and 3g). Instead, more MPI storms make landfall in the Gulf of Mexico. CESM is successful at producing synthetic TCs with similar geometry to the observed clusters (Figure 3). However, CESM storms feature a southward and eastward bias in genesis (Figures 3a–3d) due to higher vertical wind shear across the North Atlantic basin during the hurricane season (June–November) in the CESM atmospheric model (Done et al., 2015).

Biases in the models affect the skill of the networks in capturing changes in cluster TC frequency. For CESM, pseudo paleohurricane compilations, both current (tier 1) and idealized (tier 2), have stronger correlations with cluster 2 and 4 TC frequency (Figure 4). For MPI, all storm clusters are captured equally well by the tier 1 proxy network (Figure 4, $r = \sim 0.6$). Biases in the MPI cluster 1 and 3 storms make them less likely to recurve northward and thus more likely to be sensed by existing paleohurricane networks.

Within proxy networks, some regional compilations play a more important role in capturing storms in each cluster type. Proxy sites in the Gulf of Mexico, Central America, and The Bahamas are more sensitive (more highly correlated) to cluster 2 and 4 TCs (Figure 4). The mapped correlation values are in general agreement with the geographic distribution of cluster tracks: cluster 2, which is heavily skewed toward Gulf of Mexico storms, is more highly correlated with Gulf proxy sites (Figure 4).

Ultimately, storm tracking in the North Atlantic is a function of weather-scale variability and the modulation of tracks in response to large-scale slowly varying climate factors (e.g., El Niño Southern Oscillation, North Atlantic Oscillation). On annual timescales and intra-basin spatial scales, we might expect random variability to dominate, but on longer time scales and basin-wide spatial scales, randomness may filter out. The strong relationships between basin-wide and paleohurricane-compiled storm frequency on multi-decadal timescales suggests that these two quantities are changing in response to the same underlying drivers (i.e., climate factors). This interpretation is supported by greater correlations between the decadal and multi-decadal smoothed time series than the unsmoothed time series (annual resolution) (Figures 2 and 4) and the greater correlations between basin-wide time series (Figure 2) versus intrabasin (i.e., storm cluster) time series (Figure 4).

4. Discussion

We investigated the fidelity of paleohurricane proxy networks to reconstruct North Atlantic basin-wide and intrabasin TC statistics for the past millennium. We find that the current generation of paleohurricane proxies (tier 1 radius + intensity) captures 25%–45% of the variance in basin-wide TC frequency on multi-decadal timescales (Figure 2). This is substantially improved from previous idealized paleohurricane compilations that captured only 15% of the variance on multi-decadal ($r = 0.41$) timescales (Kozar et al., 2013). Recent advances in paleohurricane research in the North Atlantic including the introduction of high resolution records from coastal karst basins in the Caribbean (e.g., Schmitt et al., 2020; Wallace et al., 2019; Winkler et al., 2020) and along the Gulf Coast of Florida (e.g., Lane et al., 2011; Rodysill et al., 2020) have improved our ability to resolve changes in North Atlantic TC frequency.

While previous work (Kozar et al., 2013) suggests that paleohurricane records might not be appropriate for resolving higher frequency TC variability, our work suggests the opposite. Using only six annually resolved records from our tier 1 network, we capture 11%–26% of the variance in basin-wide TC frequency ($r = 0.33$–0.42) (Figure S7). Many North Atlantic storms pass through the Caribbean in their lifetimes, underscoring the importance of new paleohurricane records from this region. Indeed, the jackknife sensitivity analysis (Figure S8) suggests newer, high-resolution records from Belize and Mexico play an important role in both networks for resolving basin-wide TC frequency changes.

While the current network of paleohurricane records captures a substantial amount of the variance in basin-wide TC frequency, more records are needed. Reconstruction skill is restricted by proxy temporal resolution. When we apply realistic temporal resolutions to each site in our networks (Figure S9), we find that the current generation of paleohurricane reconstructions can only capture 13%–27% of the variance in basin-wide TC frequency on multi-decadal timescales. Expanding the paleohurricane network helps to improve reconstruction skill even with inhomogeneous temporal resolutions across records. If we create long records that are accessible to the community at all the tier 2 sites, we could capture 28%–46% of the variance in past millennium basin-wide TC frequency even with resolution-restricted proxies (Figure S9). However, at present, many tier 2 network proxies include previously published papers with currently inaccessible data. As a community, it is essential to publish data in a machine-readable format.

Analysis of intrabasin TC statistics suggests both paleohurricane networks capture more of the variability in TCs that impact the Gulf Coast and Caribbean islands (clusters 2 and 4) than recurving TCs (clusters 1 and 3) that impact the U.S. East Coast. Indeed, our tier 2 proxy network captures ~80% of all cluster 2 and 4 storms in both synthetic TC datasets, but only 30%–40% of cluster 1 and 3 storms. This follows given that the cluster 2 and 4 populations contain the most landfalling storms (Kossin et al., 2010), but it also highlights an important bias in using paleohurricane networks to estimate climatic drivers of Atlantic basin-wide TC activity. Different modes of climate variability modulate the cluster members in differing ways (Kossin et al., 2010). For example, the Madden Julian Oscillation strongly modulates Gulf of Mexico forming storms (cluster 2) (Kossin et al., 2010). Thus, if we use the current set of proxy networks to reconstruct TC frequency, we will likely find a disproportionate influence from climate factors that modulate these cluster 2/4 TCs.

The current network of paleohurricane sites (tier 1) must be expanded to resolve changes in recurving storms that impact the densely populated U.S. eastern seaboard. More sites from the Southeast United States are critical for resolving cluster 1/3 TCs (Figure 4). Unfortunately, there are no high-resolution, long paleohurricane records from the Southeast United States. Most existing sediment records from this region (e.g., Hippensteel, 2008; Hippensteel & Garcia, 2014; Scott et al., 2003) document only the highest intensity events (Categories 4–5) at a very low resolution with sparse geochronology (Hippensteel, 2010). Tree ring records offer a potential solution, providing monthly to annually resolved records extending back hundreds of years. Building new paleohurricane tree ring records and comparing them to existing sedimentary proxies could help build a reliable and high-resolution paleohurricane record from the US Southeast.

This work has important implications for paleohurricane field campaign design. Our analysis of past millennium storms identifies key sites with stronger correlations to intrabasin TC frequency (i.e., Belize/Mexico). Field expeditions to create paleoclimate proxies are time-consuming and expensive. Instead of choosing field sites based only on the presence of suitable natural archives, we can use the framework presented here to select sites that capture TC statistics that are more representative of the basin-wide/intrabasin pattern and not dominated by local noise or micro-climatic effects.

We acknowledge several caveats of this work related to the idealized nature of climate simulations and our downscaling approach to TCs. We only use two GCMs (MPI; CESM) due to the lack of daily wind data archived for other GCM simulations spanning the past millennium. Neither model reproduces an exact replica of real-world climate due to inherent biases in GCMs and uncertainties in the properties and imposition of past external forcing (e.g., Brohan et al., 2012; Fernandez-Donado et al., 2013; PAGES 2k-PMIP3 group, 2015). There are well-documented biases in CESM Atlantic climate including enhanced vertical wind shear resulting in fewer and less intense TCs in the western North Atlantic (Done et al., 2015). While MPI climate produces a realistic number of intense TCs, it also generates spatial biases in TC genesis and trajectories compared to the observations (Figures 3 and S1). However, spatial biases in each model's synthetic storms did not dramatically impact the ability of our proxy networks to resolve variability in basin-wide and intrabasin TC statistics. In fact, the different model biases further illustrate the robustness of our proxy networks in capturing storm populations of different shapes and trajectories.

We also make simplifying assumptions in the design of our proxy networks. We assume that the sensitivity criteria (i.e., radius, intensity) for each paleohurricane proxy accurately capture the real-world processes that generate storm indicator layers in natural archives. Other storm properties (e.g., translational velocity, track orientation, radius of maximum winds) play an important role in event deposition particularly in sedimentary records (Lin et al., 2014). In forthcoming work, we will explicitly model physical processes that generate storm layers in natural archives; additional sensing criteria can then be applied to each proxy site in our networks.

As we accelerate into a warmer mean climate state, it is critical to constrain how TC statistics will change. This work expands those statistics with a broader array of paleoclimate data and provides promising estimates of the degree to which networks of proxies can enhance our understanding of the past. Such expanded constraints on Atlantic TC activity are needed to (1) improve understanding of forced shifts in TC activity, (2) compare modern and future anthropogenic storm statistics to a last millennium baseline to understand the rates and magnitude of climate change impacts on TCs, and (3) inform policy decisions surrounding adaptation and mitigation to future changes in landfalling TCs.

Data Availability Statement

The data and code are available on Zenodo (http://doi.org/10.5281/zenodo.5244421).

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