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PERSPECTIVE

# Tropical cyclone frequency: turning paleoclimate into projections

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## Abstract

Future changes to tropical cyclone (TC) climate have the potential to dramatically impact the social and economic landscape of coastal communities. Paleoclimate modeling and paleohurricane proxy development offer exciting opportunities to understand how TC properties (like frequency) change in response to climate variability on long time scales. However, sampling biases in proxies make it difficult to ascertain whether signals in paleohurricane records are related to climate variability or just stochasticity. Short observations and simulation biases prevent TC models from capturing the full range of climate variability and TC characteristics. Integration of these two data types can help address these uncertainties. Robust data model comparison in paleotempestology will require (a) simulating TCs using new paleoclimate data assimilation products and climate model ensembles, (b) building a central repository of open access paleohurricane proxies, (c) compiling paleohurricane records, and (d) filling key gaps in the existing paleohurricane networks. Incorporating the combined information from both paleohurricane proxies and paleo TC simulations into risk assessments for coastal communities could help improve adaptation strategies.

## 1. Tropical cyclones (TCs): past, present, and future

TCs are costly natural disasters. In the US, TCs are by far the most destructive type of billion-dollar weather disaster. Since 1980, TCs have collectively caused over $1.1 trillion in damages (Smith 2021). Damages keep growing, alongside growing urgency to understand and predict how TCs will change with global warming. Some aspects of future TCs are well understood: observations and models agree that (a) storm *intensity* will increase globally, (b) storms will become *rainier*, and (c) sea level rise (SLR) will induce *higher storm surge* and subsequent *inundation*, increasing risk to coastal communities (Knutson *et al* 2020).

However, key uncertainties remain. TC frequency response to global warming is poorly understood, as there is no accepted theory surrounding climate controls on TC frequency (Sobel *et al* 2021). Due to the lack of theoretical/physical understanding, we do not know whether future TC numbers will increase or decrease (Sobel *et al* 2021). Biases and brevity of available observations complicate analyses of TC frequency trends and hinder efforts to use observations for model validation.

Paleoclimatology offers a promising avenue to address these uncertainties in TC projections. While observations from the last several decades span limited events and background climate states, paleohurricane data from the past 2000 yr can bolster our statistics and subsequent understanding of climatic controls on TCs. Paleotempestology uses signatures of TC landfall preserved in natural archives (e.g. tree rings, shallow marine/terrestrial sediments) to study how TC properties have changed over thousands of years (Wallace *et al* 2014). However, using paleohurricane data for model validation and TC theory requires robust strategies for data-model comparison.

Formal strategies for paleohurricane data-model comparison have not been established, and key barriers prevent seamless integration of paleoclimate information with climate model projections. To this end, this perspective piece presents future directions for the burgeoning field of paleohurricane data-model comparison. Such research in TC science is timely, as climate science has laid the groundwork for paleoclimate data-model comparison of fields such as temperature and modes of internal variability (PAGES2k Consortium 2017). Using advances in paleoclimate TC modeling and reconstruction, future work could improve understanding of TC frequency and thus projections of TC risk.

## 2. Paleoclimate archives of TCs

Most paleohurricane proxies fall into two categories: event-based records and statistical records (Burn 2021). Most records are 'event-based', meaning they identify and date distinct storm signatures in natural archives to reconstruct storm landfalls. A classic example of an event-based proxy is a sediment core collected from a coastal basin where fine-grained sediments dominate. During a TC, high winds and waves mobilize coarse grained sediments and transport them into the basin, leaving behind a distinct sandy signature (Figure 1). Dating these sandy layers provides clues surrounding when and how often TCs have hit the basin over time (Wallace *et al* 2014). Typically, event-based records reconstruct site-specific TC occurrence or frequency.

Similarly, statistical paleohurricane proxies reconstruct TC-related climate variables. These reconstructions quantitatively calibrate proxy archives with regional records of TC-related climate variables over the observational period (Burn 2021). For example, Maxwell *et al* (2021) calibrated the width of the latewood portion of tree rings from longleaf pine in the Carolinas to TC precipitation. The results showed that latewood width is strongly linked to the short duration and high-volume precipitation produced by TCs.

Both statistical and event-based paleohurricane records have transformed scientific understanding of long-term TC behavior. Most paleohurricane records indicate multi-decadal variability in TC properties over the past millennium with prolonged periods of substantially increased TC activity ('active intervals') followed by periods with lower TC activity ('quiescent intervals') (Wallace *et al* 2014). However, there is substantial spatial heterogeneity in the timing of these active intervals from record to record over the past 2000 yr (Wallace *et al* 2021b). As each new study attributes these spatially diverse active and quiescent intervals to different shifts in large-scale climate (e.g. the North Atlantic Subtropical High (Wallace *et al* 2021b)), it becomes difficult to reconcile the many different climatic interpretations.

Comparing proxies to models facilitates a quantitative assessment of uncertainties in paleohurricane records. Unfortunately, to-date, paleohurricane modeling and proxy generation efforts have been performed independently of one another. Most modeling studies examine TCs in global climate models (GCMs) using the following three approaches: (a) investigation of environmental variables related to TCs (e.g. genesis potential indices, as in Emanuel *et al* 2004), (b) direct simulation of TCs in high resolution GCMs or regional models (e.g. Zhao *et al* 2009), and (c) statistically downscaling of TCs (e.g. Lee *et al* 2018). Furthermore, most of these modeling studies focus on twentieth century climate (e.g. Klotzbach *et al* 2022) and future climate change scenarios (e.g. Zhao *et al* 2009).

By contrast, many studies using paleoclimate runs from GCMs to study TCs focus on distant past climates (i.e. the Pliocene (Fedorov *et al* 2010), Last Glacial Maximum (Korty *et al* 2012), or Holocene (Pausata *et al* 2017)), periods extending well beyond the past few millennia (the period covered by paleohurricane proxies). Recent studies (e.g. Garner *et al* 2021) have investigated climate forcing of millennial-scale TC simulations, but few integrate their findings with paleohurricane proxies.

New research (Wallace *et al* 2020, 2021a) has introduced techniques for merging existing TC models and proxies. These techniques could transform the field of paleotempestology, but have also introduced the following challenges:

- *Sampling biases complicate paleohurricane record applicability and consistency over large geographic scales.* TCs propagate according to large-scale climate (Emanuel 2008) and local randomly varying weather patterns (Zhang *et al* 2014). Paleohurricane records have prominent sampling biases—they only capture close moving storms (>200 km) with high intensity. Wallace *et al* (2020) generated pseudo sediment records from The Bahamas by applying sampling biases to synthetic TCs run over the past millennium and showed that much of the variability in TC frequency sampled at a single site in The Bahamas results from random variability, not climate. It is unclear whether all paleohurricane sites have a similarly low climate signal-to-noise ratio.
- *Climate models differ in their simulation of low-frequency climate variability.* The use of single models in most TC proxy-model comparison studies limits our ability to check the impacts of climate model biases. Several studies show that low-frequency climate variability is absent in current generation GCMs compared to paleoclimate records of sea surface temperatures (SST) (e.g. Laepple and Huybers 2014). This lack of low-frequency SST variance in climate models is problematic for capturing the full range of climate variability and TC characteristics that are plausible in the past and future.

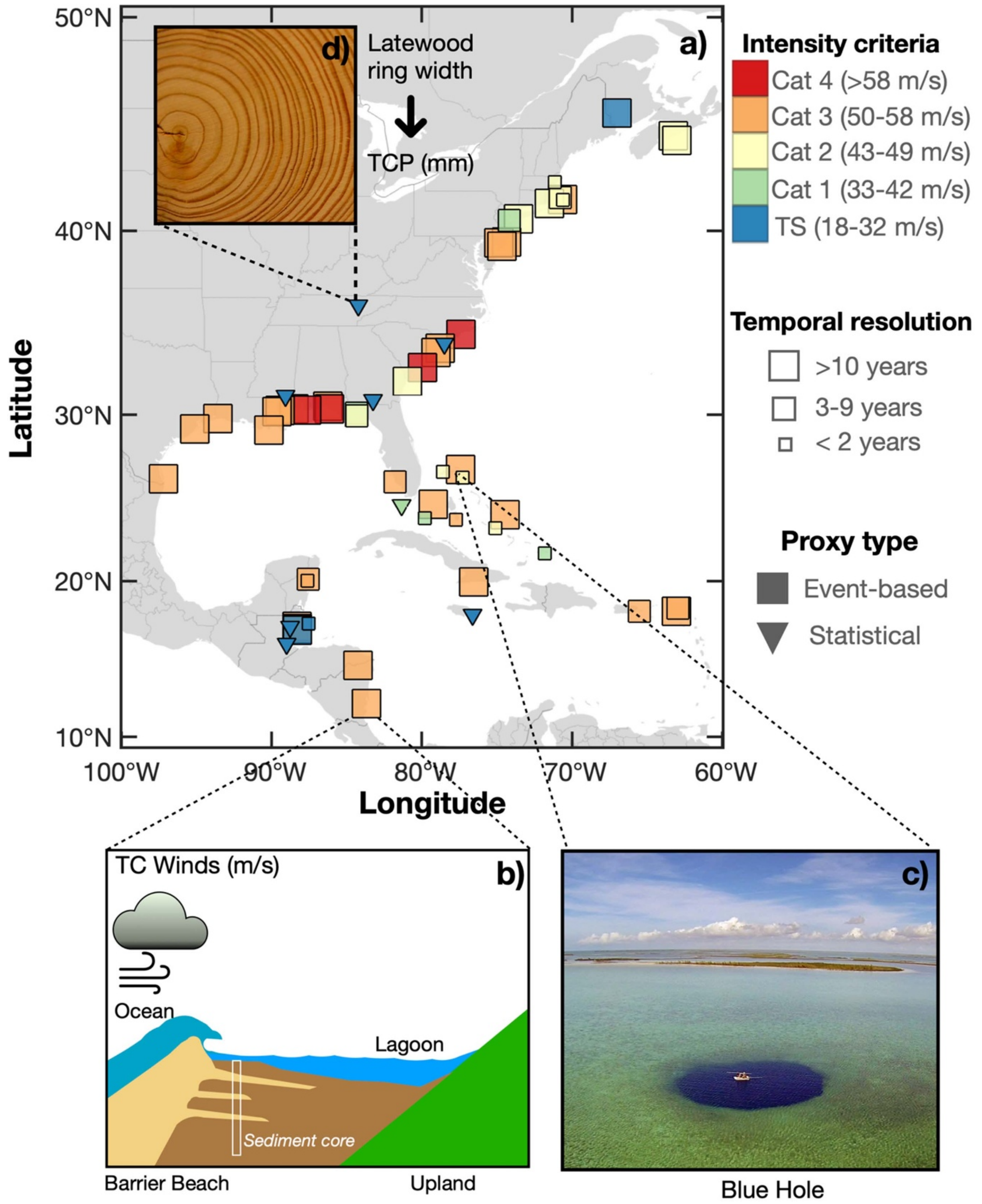


**Figure 1.** Locations of paleohurricane studies in the North Atlantic. (a) Paleohurricane networks span proxy types (shapes), intensity criteria (colors), and temporal resolutions (size). Event-based proxies reconstruct TC frequency and are sourced from coastal basins (e.g. (b) ponds, (c) blue holes (Reproduced from Winkler *et al* 2020, with permission from Springer Nature. CC BY 4.0). Many statistical proxies that reconstruct TC signals, including precipitation, are sourced from other archives. (e.g. (d) tree-rings (Reproduced from https://rawpixel.com.CC01.0), speleothems, corals).

## 3. A roadmap for data-model comparison in TC science

We offer key scientific targets (Figure 2) to solve paleohurricane challenges and promote data model comparison:

### 3.1. Capitalize on paleoclimate data assimilation (DA) products and climate model ensembles for the past millennium

Paleoclimate Modelling Intercomparison Project (PMIP4) simulations are now publicly available providing multi-model ensembles of atmospheric and ocean fields spanning the past 1000 years. While the output from PMIP4 simulations is not high enough resolution to directly simulate TCs, both TC genesis indices and

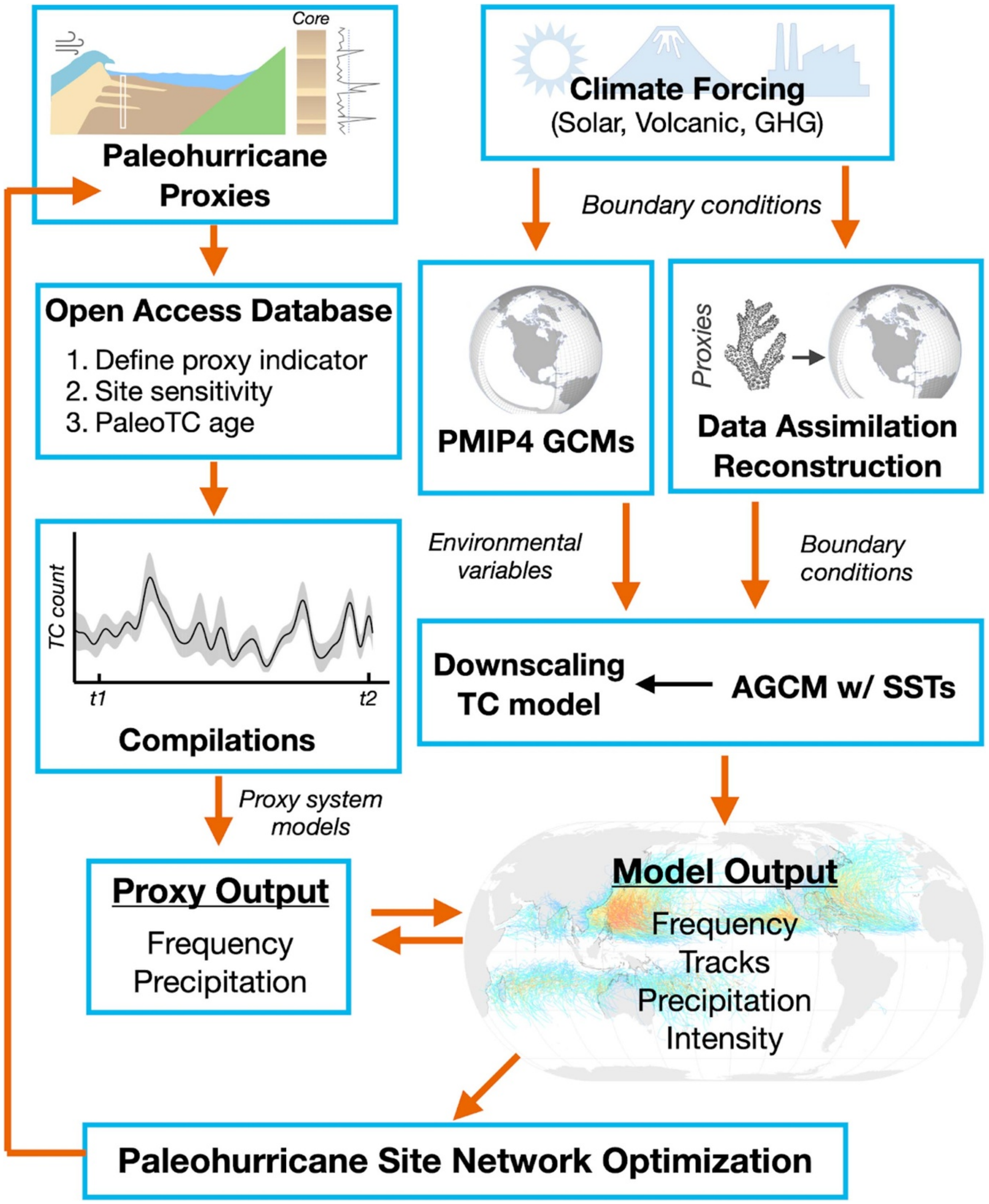


**Figure 2.** A roadmap for paleohurricane data-model comparison.

statistical downscaling approaches can be readily applied to these new last millennium simulations. In particular, statistically downscaled models (Emanuel 2006, Lee *et al* 2018) can generate large numbers of synthetic TCs with realistic intensity using monthly to daily-resolved boundary conditions. Approaches are already in place for using these synthetic storms to assess uncertainties in paleohurricane proxies (Wallace *et al* 2020) and to investigate long-term response of TC properties to climate feedbacks (Garner *et al* 2021, Wallace *et al* 2021a).

The advent of paleoclimate DA (Figure 2), which fuses paleoclimate archives with the dynamics of GCMs (e.g. Hakim *et al* 2016), has led to the generation of multiple climate state reconstructions spanning the past 2000 years, such as the Last Millennium Reanalysis (Hakim *et al* 2016). These DA reconstructions include fields critical for the simulation of TCs, specifically SSTs, spanning thousands of years. High resolution (25–50 km) SST-forced atmospheric models (e.g. Zhao *et al* 2009) can successfully simulate many aspects of TC climatology. More research is needed to explore the differences between TCs simulated using DA products and TCs spun up using PMIP-style models. Critically, DA techniques use reconstructed internal variability in SST, and are thus most likely to capture 'real world' low frequency variability in SST patterns.

### 3.2. Apply F.A.I.R. (findability, accessibility, interoperability, and reuse) data standards to paleotempestology

There is no standard format for paleohurricane data and metadata and no central repository to store and share data. As a result, many invaluable paleohurricane records cannot be incorporated into compilations or risk assessments. Building such a database of published records will require buy-in from the entire paleohurricane community. Paleohurricane studies, at minimum, should provide the following information on their archive:

- Clearly defined criteria for what constitutes a storm indicator *(e.g. grain size cutoff).*
- Site sensitivity (typically as radius + intensity criteria) defined by attribution/calibration to modern TCs *(e.g. Middle Caicos sediment cores capture > Category 1 storms within a 75 km radius (*Wallace *et al* 2021b)).
- The age of each paleoTC or the start/end years of the event bound, including age model information (software used for generation, e.g. BACON (Blaauw and Christen 2011)).

Whenever possible, published studies that did not provide this information should be revised to meet the above guidelines.

### 3.3. Compile paleohurricane records to produce TC climate variables

Compilations of paleohurricane records are required to make robust regional comparisons with paleoclimate simulations and DA reconstructions, and recent work has produced new methods for regional compilations of high resolution records from the circum-Caribbean and North Atlantic coastline (Wallace *et al* 2021b). We need to apply these methods to reconstruct storms on a basin-scale. The North Atlantic basin is a perfect testing ground for compilations with a dense network of readily-available paleohurricane sites (Oliva *et al* 2018).

Existing networks of paleohurricane sites (Figure 1) span different temporal resolutions and sensitivities, which complicate compilation efforts (Wallace *et al* 2021a). For example, older records (e.g. Liu and Fearn 1993) from terrestrial back barrier environments capture only Cat 4–5 storms at low resolution (multi-decadal). New studies (e.g. Winkler *et al* 2020) from shallow marine environments capture lower intensity storms at annual resolution. Given varying temporal resolutions, we could choose only to combine high resolution reconstructions, but this choice would reduce the geographic coverage of paleohurricane networks. Alternatively, we could smooth our compilation to the resolution of the coarsest record, but then we lose new high-resolution data. More research is needed to explore how different compilation methods affect the underlying reconstruction.

Paleohurricane proxy networks (Figure 1) also span different proxy types (Wallace *et al* 2021a). To-date, there is no work integrating event-based proxies with statistical proxies. For example, combining estimates of direct TC occurrence (from sediment proxies) with TC-related climate properties (e.g. precipitation from tree cores) is not straightforward. It is unclear how TC precipitation and TC frequency relate at a single location. Presumably, years with more frequent TCs will result in larger amounts of TC rainfall. Unfortunately, this relationship can be confounded by other storm properties that affect rainfall (e.g. translational velocity (Lai *et al* 2020)). Creating physically-based proxy system models (PSMs, e.g. Dee *et al* 2015) for paleohurricane records may help with these integration efforts by improving event attribution in paleohurricane archives, and by bringing model variables (e.g. wind, precipitation) closer to the proxy units (e.g. coarse-grained sediment, tree ring width). Sediment event-based proxies could benefit from the development of PSMs with a hydrodynamic modeling component (Lin *et al* 2014) that simulates sediment mobilization due to TC-related storm surge. Ultimately, compilation efforts should seek to reconstruct TC properties produced by models (i.e. precipitation, frequency) at relevant spatial scales (regional to basin) (Figure 2).

### 3.4. Fill critical gaps in networks through targeted field campaigns

Data-model comparison work will also help inform future paleohurricane field campaigns. Field expeditions are expensive and time consuming. Traditional approaches to choosing field sites rely heavily on the presence of suitable archives for capturing storm signatures, but some sites have a greater potential for capturing climate signals simply based on geographic location. For example, Bramante *et al* (2020) collected sediment cores from the Marshall Islands, close to a primary genesis site of Northwest Pacific TCs. As a result, the paleorecord of storms from this island isolated climate controls on TC genesis in this region. Considering storm climate in addition to geologic suitability allows for more records that maximize climate signal relative to local noise.

Running model TC tracks through existing networks of paleo-proxies can allow us to identify gaps in a network's ability to capture TC climate signals. Wallace *et al* (2021a) presents an approach for developing pseudo networks of paleohurricane sites. Using simplified sensitivity criteria for each site, we can evaluate how many TCs are captured by a network and where we need more data to fill in gaps. This study highlights that the current network of paleohurricane sites in the North Atlantic does not resolve recurving TCs. To capture this key population of storms, we need more archives from the Southeast U.S. These pseudo network techniques will be especially useful when expanding paleohurricane networks in larger and more active ocean basins like the Northwest Pacific.

## 4. Implications of paleohurricane research for society

Flooding caused by future shifts in storms, SLR, and shoreline change is one of the largest threats facing coastal communities today. Projected changes in TC climate are the biggest contributor to future flood hazards (precipitation and storm surge), bigger than SLR (Gori *et al* 2022). The viability of coastal urban centers will require coordinated adaptation strategies to future risks, but planning is inhibited by large uncertainties in flooding projections for the future (Woodruff *et al* 2013). There is a critical need to consider future TC risk in long term planning and decision-making, such as how and where infrastructure is developed. Decisions made today are based on modern climate, which could lock in substantial future exposure and vulnerability in a changed climate.

Paleohurricane research can help develop realistic risk estimates for coastal communities. Approaches for using paleohurricane data in return period calculations for extreme storms already exist (Lin *et al* 2014). This work has shown, in some cases, that current methods for calculating storm return periods are underestimating risks in coastal areas. Along the Gulf Coast of Florida, for example, return periods of extreme TCs are an order of magnitude shorter (40 vs. 400 years) when calculated using paleoclimate data instead of observations (Lin *et al* 2014). As we make paleohurricane proxy information publicly available and develop techniques to merge this data with climate and TC simulations, we must work to translate this information into risk assessments for coastal communities.

Imagine it is 2050. Sea levels are rising and TCs are more intense. U.S. coastal communities are facing chronic, disruptive flooding that directly affects people's lives. How will we have changed the way we develop our coastline? Most coastal communities are not prepared for the SLR and storm climate that they will see in the future. Growing populations and developments along the coast will enhance damages due to TCs. Communities will need to make tough decisions, including plans for managed retreat to higher elevations (Woodruff *et al* 2013). Expanded storm statistics afforded by the paleoclimate record can improve our risk calculations and reduce uncertainty, which will hopefully streamline adaptation and mitigation. We need to capitalize on this knowledge now.

## Data availability statement

No new data were created or analysed in this study.

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