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Perspective: coordinating paleoclimate research on tropical cyclones with hurricane-climate theory and modelling

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ABSTRACT

Extending the meteorological record back in time can offer critical data for assessing tropical cyclone-climate links. While paleotempestology, the study of ancient storms, can provide a more realistic view of past 'worst case scenarios', future environmental conditions may have no analogues in the paleoclimate record. The primary value in paleotempestology proxy records arises from their ability to quantify climate–tropical cyclone interactions by sampling tropical cyclone activity during pre-historic periods with a wider range of different climates. New paleotempestology proxies are just beginning to be applied, encouraging new collaboration between the paleo and tropical cyclone dynamics communities. The aim of this paper is to point out some paths toward closer coordination by outlining target needs of the tropical cyclone theory and modelling community and potential contributions of the paleotempestology community. We review recent advances in paleotempestology, summarize the range of types and quality of paleodata generation, and identify future research opportunities for paleotempestology, tropical cyclone dynamics and climate change impacts and attribution communities.

1. Introduction

Recent advances in the field of tropical cylone (TC) dynamics have raised new questions about the importance of anthropogenic climate change for future hurricane hazards in the near and long term (Elsner and Liu, 2003; Emanuel, 2001, 2002, 2003; Camargo and Sobel, 2004; De et al., 2004; Elsner et al., 2004; Emanuel and Nolan, 2004; Emanuel et al., 2004; Free et al., 2004; Murnane, 2004; Walsh, 2004; Wu and Wang, 2004; Emanuel, 2005; Pielke et al., 2005; Trenberth, 2005; Webster et al., 2005). Reanalysis and documentary-based TC reconstructions can overcome some of the limitations inherent in historical meteorological data sets of TC activity (Liu et al., 2001; Chenoweth, 2003; Landsea et al., 2004; García-Herrera et al., 2005; Landsea et al., 2006; Kossin et al., 2007; Mock, 2004). Yet, regional gaps and the brevity of meteorological records remain problematic. Paleotempestology aims to extend the meteorological record back in time by exploiting documentary and geological/biological proxy archives of TC activity (Liu, 2004; Nott, 2004; Liu, 2007).

Paleotempestology records provide a better estimate of the 'worst case scenario' than conventional historical hurricane databases because very long records are more likely to sample very rare, catastrophic events with long recurrence intervals of hundreds to thousands of years (Liu and Fearn, 1993; Liu and Fearn, 2000; Nott and Hayne, 2001; Nott, 2003a). For example, Liu (2004) documented a Gulf Coast 'hyperactive period' about 3800 to 1000 yr ago during which catastrophic hurricanes struck 3 to 5 times more frequently than during the most recent millennium. Because, the 'best case' scenario—no major landfalls in populated areas—plays itself out regularly, paleotempestology is often the only source of data regarding very large/rare events in the tail of the distribution. While 'hyperactive' and 'inactive' periods are of similar interest for studying TC dynamics, the climatology of extreme catastrophic cases is of far greater interest to society, which must bear the costs mainly when TCs strike occupied locales. Brief meteorological data sets sometimes grossly undersample the landfall probability of catastrophic TCs (Liu, 2004, 2007; Nott, 2003a; Nott et al.,

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2007). Still, the concept of 'recurrence interval' assumes an invariant probability field. To the extent that TCs are a manifestation of shifting climatic conditions, the spectrum of recurrence interval risk is also non-stationary. Yet, expected future climate conditions forced by anthropogenic greenhouse gases lack close paleoclimatic analogues (e.g. Crowley, 1990; Mitchell, 1990; Covey et al., 1996;). For example, the Holocene Climatic Optimum (∼6000–9000 y.b.p.), a warm period when many climatic boundary conditions were similar to today, was characterized by seasonal rather than mean annual warming (Crowley, 1990). Paleotempestology data alone are unlikely to provide an accurate estimate of the future probability of extreme events. On the other hand, paleotempestology records that have been produced from more recent intervals provide better analogues to present and future climates. Thus, the most valuable contribution of paleotempestology will likely be as a unique source of observations critical for assessing tropical cyclone–climate interactions across a range of climatic conditions (Cronin, 1999).

A growing suite of high-resolution paleotempestology data has the potential to shed light on problems with which the broader TC dynamics community is wrestling (Cohen, 2001; Miller, 2005; Miller et al., 2006; Frappier et al, 2007; Nott, 2007). The aim of this paper is to point out some ways toward closer coordination between the TC dynamics and paleotempestology communities by outlining target needs of the former and potential contributions of the latter. We review recent advances in paleotempestology, summarize the potential types and quality of paleodata generation and identify opportunities for collaboration.

2. Tropical cyclone theory and modelling efforts: potential contributions from paleotempestology

2.1. *Substantial regional coverage of long-time records of tropical cyclone activity*

Attempts to reconstruct paleo-temperature from various proxy measures at a limited number of locations, analogous to meteorological stations (e.g. Mann et al. 1999), are made more feasible by the relatively large spatial correlation scales of long timescale temperature anomalies. For global paleotempestology reconstructions, spatial correlations must also be considered, as modern TC activity increases in one region are sometimes offset by decreases in another basin (c.f., Atlantic vs. Eastern Pacific). Therefore, obtaining a reliable picture of past global TC occurrence might require extensive geographically dispersed sampling in order to distinguish between regional and global (tropics-wide) changes, and to detect any shifts in the areas of TC occurrence.

Geographically dispersed sample sites would return quasi-independent samples of past activity, and the number of sites required will vary according to the research question of interest. For example, probability theory could be applied to estimate the likelihood of a given number or fraction of independent sites showing changes of a given sign in global TC frequency, resulting in adaptive estimates of sampling requirements needed to obtain certain confidence levels for changes in global TC frequency. Scenarios in which inferred TC changes relatively large might be addressed sooner, as fewer sites would be sufficient to determine first-order sensitivity as a function of past climate conditions.

2.2. *Sampling of tropical cyclone behaviour from very different climates*

Each proxy type has a different applicable time frame (Table 1). Very long TC records (e.g. thousands of years) provide better sampling of rare extreme events. If we assume that the TC climate is stationary during the period, this allows investigators to better estimate the underlying (stationary) probability density function. This information, useful for documenting the amount of past variability in the real world, is necessary for assessing the degree to which any secular trend (e.g. warming during the instrumental era) is unusual with respect to past variations, as has been done by several groups for the case of Northern Hemisphere mean temperatures over the past millennium (e.g. Mann et al., 1999; Jones et al., 2001; Mann et al., 2003; Jones and Mann, 2004; Rutherford et al., 2005). Analogously, climate change detection and attribution studies for TCs stand to benefit from further development and analysis of paleotempestology data sets. Paleotempestology data can also define rates of change in storm activity parameters (e.g. Liu et al., 2001; Elsner et al, 2004; Zhao and Chu, 2006).

Paleoclimatic variability provides a series of natural experiments from which valuable observational constraints regarding TC-climate sensitivity can be derived by sampling TC behaviour during very different climates. Independent proxy reconstructions of paleo-TCs, paleoclimate boundary conditions and forcing factors can provide well-grounded estimates of climate change and therefore climate sensitivity, assuming the climate forcing can be estimated well enough. For TCs, the Last Glacial Maximum may provide a sufficiently large climate change signal that a robust TC response can be detected in proxy records. With sufficient regional coverage, this finding could serve as a key evaluation point for models that are being used to simulate TC-climate connections with respect to global-scale changes in climate (Hamilton and Hemler, 1997; Henderson-Sellers et al.,1998; Knutson et al, 1998; Knutson et al., 2001; Jagger et al. 2002; Camargo and Sobel, 2004; Knutson and Tuleya, 2004; 1999; Webster et al., 2005). Although previously not available, this potential avenue of research has become more possible by advances in paleotempestology techniques (Frappier et al, 2007; Nott et al., 2007). The failure of a modelling system to simulate the proxy-derived behaviour of paleo-TCs could be attributable to either problems with the TC simulations or to

Table 1. Paleotempestology Proxy Overview. Abbreviations are as follows: δ^{18}O values (stable oxygen isotope ratios), ^{14}C (radiocarbon dating), optical spin luminescence (OSL) dating (OSL establishes time elapsed since last exposure of quartz or feldspar mineral grains to sunlight, based on post-burial accumulation of crystal lattice damage from ionizing radiation), mass sedimentation rate (MSR) dating (age determination based on MSR), U-series dating (application based on radioisotope ratio disequilibrium in the Uranium to Lead decay series)

Proxy archive	General location	Dating methods	Typical record length (years)	Earliest likely applicable time interval (year before present)	storm activity temporal resolution max	storm activity temporal resolution min	Principle tropical cyclone parameters	Notes	Example References
Coral aragonite δ^{18}O values	Offshore and nearshore reefs	^{14}C; schle-rochronology	100	10^5+	Hourly	Weekly	Storm frequency	Storm signal duration is brief (days); very high-resolution analyses required; seasonality of storm strike can be identified.	Cohen, 2001
Offshore shell deposits; tempestites	Offshore shallows	^{14}C	Unknown	Unknown	Unknown	Unknown	Storm frequency, intensity?	Coarse offshore sediment deposits from deep wave action by strong storms.	Keen and Slingerland, 1993
Ridge – coral rubble	Carbonate shorelines	^{14}C	5000	6000 +	Decadal	Millennial	Storm frequency/ intensity; storm surge height	Bathtub-ring style record of wave heights.	Nott and Hayne, 2001
Ridge – Chenier	Beaches	^{14}C	5000	6000 +	Decadal	Millennial	Storm frequency/ intensity; storm surge height	Bathtub-ring style record of wave heights. Pre-Holocene record (>10 ky b.p.)?	Reviewed in Nott, 2004
Ridge – beach sand	clastic beaches	^{14}C; MSR dating	1000	6000 +	Seasonal	Millennial	Storm surge height; recurrence interval spectrum	Bathtub-ring style record of wave heights.	Nott, 2004
Sand dune morphology	Coastal dunes	^{14}C; MSR dating	500	6,000 +	Decadal	Millennial	Storm surge height; windspeed	Sand splays and heavy mineral lag deposits indicate dune destruc-tion/construction.	Nott, 2004
Coastal lagoon sediment	Coastal lagoons	^{14}C	5000	6000 +	Seasonal	Millennial	Storm frequency/ intensity; storm surge height	Millennial-scale records are routine; storm surge direction of approach can be identified with spatial coring	See multiple papers by Liu et al., Donnelly et al.

Table 1. cont'd

Proxy archive	**General location**	**Dating methods**	**Typical record length** (years)	**Earliest likely applicable time interval** (year before present)	**storm activity temporal resolution** max	min	**Principle tropical cyclone parameters**	**Notes**	**Example References**
Coastal marsh sediment	Coastal marshes	^{14}C	4000	6000 +	Decadal	Millennial	Storm frequency/ intensity; storm surge height	Millennial-scale records are routine.	See multiple papers by Donnelly et al.
Lacustrine microfossil assemblages	Freshwater lakes	^{14}C	5000+	10^4+	Seasonal	Millennial	Storm frequency, intensity	Multi-proxy records e.g. foraminifera, diatoms, dinoflagellates, phytoliths, pollen.	Lu and Liu, 2005; Scott et al. 2003; Lambert et al. 2005
Tree-ring cellulose $\delta^{18}O$ values	Terrestrial forests; high to low elevation	^{14}C; dendrochronology	100	10^4+	Monthly	Seasonal	Storm frequency, precipitation amount (possibly intensity)	Calendar year dating precision; two samples per year returns an annual storm/non-storm record; higher resolution is possible.	Miller et al., 2006
Speleothem $\delta^{18}O$ values	Terrestrial caves	U-series, ^{14}C, layer counting	1000	10^6+	Weekly	Seasonal or decadal	Storm frequency, intensity (possibly precipitation amount)	Very high-resolution analyses required; can resolve storm strikes spaced months to weeks apart; decadal storm activity is possible.	Frappier et al. 2007; Nott et al., 2007
Speleothem trace elements	Coastal caves	U-series, ^{14}C, layer counting	1000	10^6+	Weekly	Seasonal or decadal	Storm frequency, integrated wind intensity indicator	Storm intensity and translation speed control sea salt flux to caves; high temporal resolution is possible	Murgulet and Aharon, 2006

Table 1. cont'd

Proxy archive	**General location**	**Dating methods**	**Typical record length** (years)	**Earliest likely applicable time interval** (year before present)	**storm activity temporal resolution** max	min	**Principle tropical cyclone parameters**	**Notes**	**Example References**
Potential proxy archives					**Likely temporal resolution** max	min	**Potential tropical cyclone parameters**		
A toll blue hole sediments	Offshore atolls	^{14}C; U-series	Unknown	10^5+ ?	Unknown	Unknown	Storm frequency, intensity	Sensitivity not yet quantified	n/a
Coral aragonite trace elements	Coral reefs near rivers	^{14}C; schle-rochronology	100	10^5+	Daily	Decadal	Terrestrial runoff (land-use interactions)	Low salinity water can temporarily impede coral growth	Lawrence, 1998
Fish otolith $\delta^{18}O$ values	Aquatic basins (marine basins and rivers?)	^{14}C; layer counting	10	10^6+	Daily	Decadal	Storm frequency (precipitation amount, storm intensity?)	Short, high-resolution records possible	Patterson, 1998
Bivalve $\delta^{18}O$ values	Aquatic basins (marine basins and rivers?)	^{14}C; layer counting	20	10^4+	Daily	Decadal	Storm frequency (precipitation amount, storm intensity?)	Short, high-resolution records possible	Lawrence and Gedzelman, 1998
Lacustrine sediments	Freshwater lakes	^{14}C	5000+	10^4+	Seasonal	Centennial	Storm frequency, intensity	Multiple storm impacts within years to decades may not be distinguishable	n/a

shortcomings in the simulations of large-scale environmental conditions, such as sea surface temperatures (SST). A wider range of TC proxy records is available to assess TC activity sensitivity to more recent climate intervals, such as the Medieval Warm Period or Little Ice Age (c.f. Liu et al., 2001; Miller et al., 2006). As new paleotempestology data sets are developed, more valuable multi-proxy regional TC archives are being compiled from single site records (Mann, 2002). In past work of this type, the understanding of aspects of climate system dynamics was successfully advanced when the community set as a priority the development of paleo-records during key time intervals of interest, producing time-slice maps and gridded data sets (e.g. CLIMAP, 1984; Jagger et al., 2002).

How has the paleotempestology work to date addressed these issues? Established proxies – coastal sedimentary records of TC storm surges – have generated testable hypotheses regarding controls on storm track locations (Elsner et al., 2000; Liu and Fearn, 2000). Paleotempestology has revealed times of rapid change in some TC basins (e.g. compare storm frequency stability between the Atlantic and Pacific: Liu et al., 2001; Nott 2003b; Liu, 2004). Establishing the timing and sign of regime shifts within and between basins (Donnelly and Woodruff, 2007) can together help test potential climate system links and forcing factors. Recent advances in paleotempestology include emerging new proxies (addressed below), more quantitative approaches to traditional proxies and more detailed documentary data sets (Liu, 2007).

Coastal proxies, applied across the last 7000 yr in limited locations, rely on storm-surge and wave-driven deposits, including clastic washover deposits, beach ridges composed of coral, shell and/or sand, and dune geomorphic changes (Liu and Fearn, 1993; Nott, 1997; Elsner et al., 2000; Liu and Fearn, 2000; Donnelly et al., Nott and Hayne, 2001; 2001a; Donnelly et al., 2001b; Elsner and Liu, 2003; Nott, 2003a; Nott, 2003b; Nott, 2004;Donnelly and Webb, 2004; Donnelly, 2005; Liu, 2007). High-resolution sediment core analysis promises to capture a larger fraction of lower-intensity storm surge events, through time-series analysis. Since the end of the last glaciation, sea level rise has overrun earlier storm deposits, making it difficult to use these deposits to assess TC activity prior to the last ∼5000 yr in most locations (see also Nott, 1997; Elsner et al., 2000; Liu and Fearn, 2000).

High-resolution TC proxies, often containing annual layers, are poised to contribute important new tools to paleotempestology, by extending records of storm frequency much further into the past and developing decadally to seasonally resolved records. Precipitation-based proxies exploit the characteristically low stable oxygen and hydrogen isotopic values of TC rainfall (see Lawrence and Gedzelman, 1996; Lawrence, 1998; Gedzelman et al., 2003; Pedersen et al., 2005). This rainfall proxy is unlikely to be much affected by sea level change, and has been explored in corals (Cohen, 2001), otoliths (Patterson, 1998), tree rings (Miller, 2005; Miller et al., 2006;), and cave stalagmites (Malmquist, 1997; Schwehr, 1998; Frappier et al., 2007, Nott et al., 2007). Additional proxies are on the horizon, for example. a stalagmite proxy record of sea-spray found in a Pacific coastal atoll cave (Murgulet and Aharon, 2006, unpublished data).

Proxy records, documentary sources and oral histories often record post-storm impacts from TC events (including saltwater intrusion, rainfall-induced flooding, salt spray, fire, forest disturbance and mass movements) and associated cultural responses (Liu et al., 2007; Lu and Liu, 2005, Cohen, personal communication, 2003). Some regions of China are already demonstrated sources of centuries-long documentary records (Liu et al., 2001) of impacts to community infrastructure and homes, sanitation, nutrition and health, forestry and agriculture and commerce. Records of paleotempest impacts on urban and rural communities would support local and regional climate change impact mitigation efforts by tracking the resilience and capacity of different modes of development. Critical economic and insurance-related questions could be addressed: for example, when a major storm strikes, how does the maize crop fare compared to coffee? Storm impacts data are also of interest to specialists including archaeologists, ecologists, water resource managers and foresters in TC regions (e.g. McDowell et al., 1996; McDowell, 2001). The positive effects of TC activity in different regions are also of interest, including their roles in breaking drought, delivering scarce moisture to desert regions and replenishing aquifers (e.g. DRBC, 2000; Gutzler and Ritchie, 2004).

The broader field of paleoclimatology stands to contribute substantially to TC research by developing records of environmental factors that have been implicated as TC forcing factors in the modern observational record (e.g. Klotzbach and Gray, 2004; Goldenberg and Shapiro, 1996). Potentially reconstructable factors include SSTs in the Main Development Regions, El Niño – Southern Oscillation (ENSO) variability, thermocline depth, evaporative fluxes and tropical atmospheric organization. Regional parameters of primary interest for the Atlantic basin include West African monsoon rainfall, Saharan dust fluxes, position of the North Atlantic high-pressure cell and Gulf Stream flow rates. Unfortunately, existing paleo-records of most of these agents are low-resolution and/or very widely spaced in space and time. Only a handful of SST proxy records are available in the tropical Atlantic region for the last several thousand years, with temporal resolution of a ∼100–500 yr (e.g. Rühlemann et al. 1999; deMenocal et al. 2000, Winter et al. 2000; Nyberg et al. 2002). For the Pacific and Indian oceans, multi-century SST proxy records are available (Wilson et al. 2006). Concomitant development of additional high-quality tropical and subtropical paleoclimate records will support quantitative studies of paleotempest–climate interactions.

3. Conclusions

The demand for greater fundamental understanding of TC–climate interactions is converging from several corners, including TC dynamics, climate change detection and attribution, climate change impact research, as well as from society at large. Paleotempestology provides a unique source of data regarding TC landfall events across a wide range of past climate boundary conditions. New TC proxies are increasing in temporal resolution, dating precision, and the accuracy of intensity estimates, in addition to expanding the range of times and places where the historical record can be extended back in time. The main limitations of paleotempestology to address fundamental questions regarding climate–TC interactions are the present lack of (1) spatially distributed networks of long TC activity records, (2) detailed paleoclimate records of agents or conditions that have affected TC activity in historical times and (3) exact climate system analogues in the past for climate conditions expected in the future. Paleotempestology can play critical roles in testing hypotheses regarding climate–TC activity interactions, in reshaping our understanding of how the climate system works, and in support of paleodata-model intercomparison efforts.

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