Tempest in a tree ring: Paleotempestology and the record of past hurricanes

Claudia I. Mora and Dana L. Miller
Department of Earth and Planetary Sciences
University of Tennessee
Knoxville, TN 37996
cmora@utk.edu

Henri D. Grissino-Mayer
Department of Geography
University of Tennessee
Knoxville TN, 37996
grissino@utk.edu

ABSTRACT

Tropical cyclones can have devastating economic impact on U.S. coastal communities, yet the full range of their natural variability is not yet known. A more definitive understanding of tropical cyclone (i.e., hurricane) frequency, intensity and response to global climate change requires an understanding of their behavior over several millennia. The developing field of paleotempestology promises to add the perspective of time to current debate on the recent increase in tropical cyclone activity and intensity.

INTRODUCTION

North Atlantic tropical cyclone frequency and intensity have increased significantly since 1995 (e.g., Goldenberg et al., 2001; Elsner et al., 2000; Landsea et al., 1998), but the causes of these changes are fiercely debated. The increase in tropical cyclone *frequency* is thought to reflect natural, multidecadal scale variation governed by low frequency climate modes, such as the Atlantic Multidecadal Oscillation (AMO, low frequency changes in sea surface temperature; e.g., Elsner and Kara, 1999; Goldenberg et al., 2001; see Mann and Emanuel, 2006, for counterpoint). However, increased frequency may also be related to an increase in sea surface temperature (SST) over the past 35 years (Trenberth, 2005). Studies implicate global warming in the increased *intensity* of tropical cyclone events (Knutson and Tuleya 2004; Emanuel 2005; Webster et al. 2005), but definitive linkages between tropical cyclone frequency, changes in SST and rising greenhouse gas concentration are elusive (Pielke et al., 2005).

As they work towards resolution of these important questions, researchers are hampered by very short instrumental records of tropical cyclone activity. The highest quality instrumental records exist only since ~1940, and few extend past ~1850. In the absence of an instrumental record, the long-term physical, spatial and temporal patterns of tropical cyclone activity must be established by proxy. This is the essential challenge of the emerging field of ***paleotempestology***. Using geological, biological and written documentary (i.e., historical) evidence, scientists in this new field seek to develop records of past tropical cyclone activity over a large range of scales, from the day-by-day reconstruction of a single storm using historical documents to millennial-scale sediment records that define long periods of tropical cyclone activity or quiescence. Proxy-derived data are essential to develop a more complete understanding of natural, low-frequency trends and fluctuations in tropical cyclone activity, to deduce climate-tropical cyclone relationships operating over multidecadal or longer periods, and can be used to improve predictive modeling of tropical cyclone vulnerability and risk. Here we summarize the basis and application of paleotempestology proxies, with special attention to a newly-developed proxy based on stable oxygen isotope compositions in tree rings.

PALEOTEMPESTOLOGY

Historical proxies

The extreme nature of tropical cyclones has led to their documentation in a wide range of outlets, including newspapers, plantation diaries, government records and ship logs. These documents range from terse and qualitative reports to sometimes detailed accountings of storm phenomena or damage. Historical records are limited in time and geography by the requisite human observations. The reliability of the data is variable, and qualitative descriptions of events must be scaled and interpreted. Recent studies, such as those described below, seek to validate their methodology and results against instrumental records, with excellent results. Thus, with judicious and systematic interpretation, historical (written) documents can be exploited to reconstruct detailed records of past tropical cyclone activity (e.g., Mock, 2004).

The earliest known written reference and description of typhoons (Pacific tropical cyclones; called *jufeng*, or "wind that comes from four directions"), is found in an ancient Chinese text (A.D. 470; Louie and Liu, 2003). Voluminous archives of imperial government documents and semi-official local gazettes may yield very high-resolution records of western Pacific tropical cyclone occurrence, extending back many centuries. Liu et al. (2001) reconstructed a 935 year time series of typhoon landfalls for Guangdong province which suggests two periods of marked tropical cyclone activity in southern China which may have resulted from large, regional scale climate effects which steered western Pacific tropical cyclones towards more southerly landfalls.

Written records of North Atlantic hurricanes include Spanish colonial records (by end 15th century) and British naval logs (by end 16th century). Those archives are of particular importance to developing tropical cyclone histories in the Caribbean and U.S. Gulf Coast.

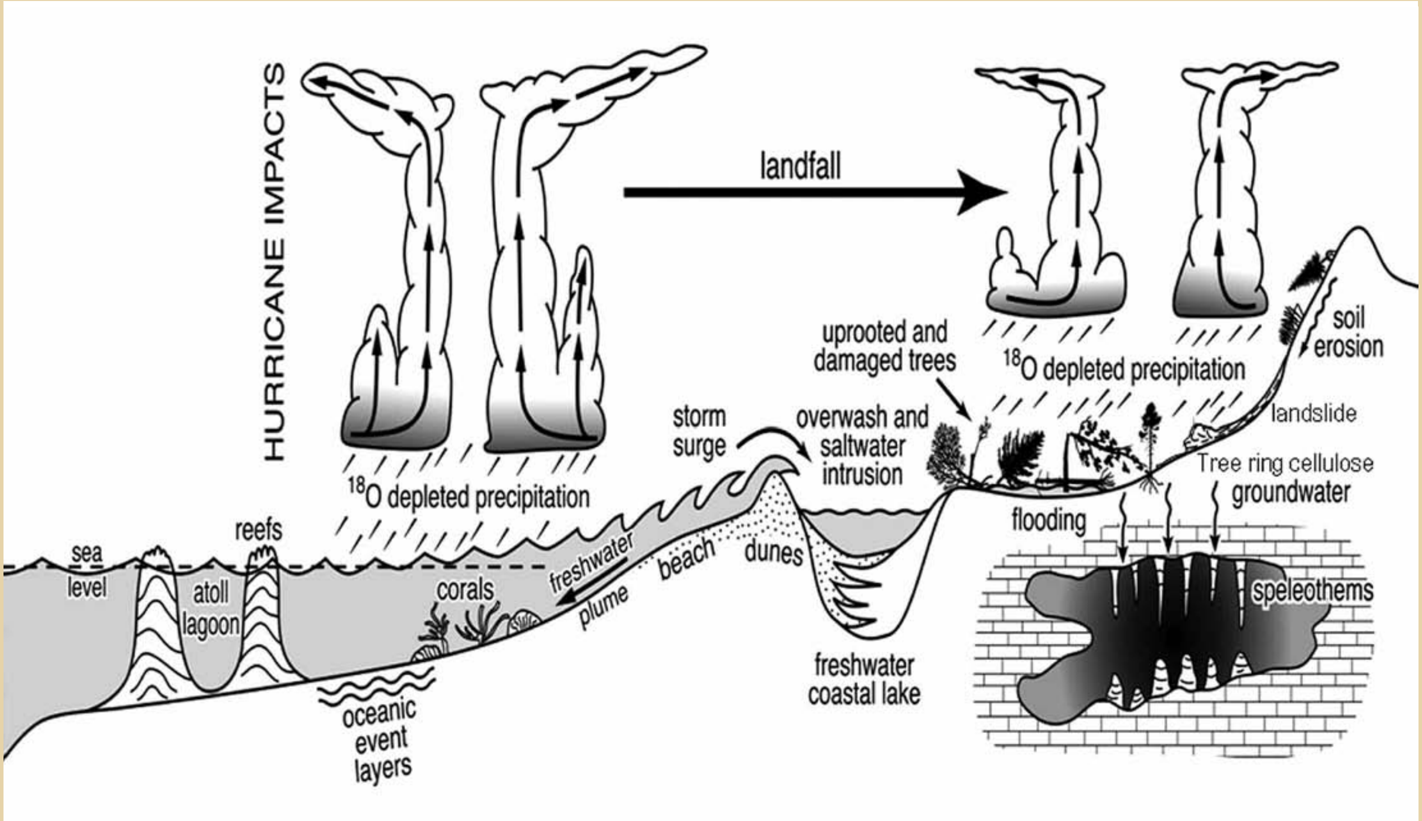

Figure 1. Geological and stable isotope proxies used in paleotempestology (after Liu, 2006). Geological proxies include storm deposits in coastal environments, oceanic event layers, and storm-induced landslides and erosional events. Stable isotope effects of tropical cyclones may be detected in tree rings, speleothems, and corals.

Although previous investigations have been fruitful, there is still much unexploited material (García Herrera et al., 2004). Additional records such as plantation logs and newspapers were added with settlement and economic development of the U.S. southern and eastern coasts, and Mock (2004) reports the most complete historical tropical cyclone reconstruction for the U.S.: a 222 year record (1778-2000), for the Charleston, South Carolina, area.

Geological proxies

Geological proxies for tropical cyclone activity provide an independent tool to assess tropical cyclone frequency and to constrain the relationship between tropical cyclones and climate on a much longer time scale than historical proxies. Geological proxies predominantly derive from coastal sedimentary records (Fig. 1). Other proxies include storm-triggered landslides and erosional events, and hurricane event layers in marine sediments and atoll lagoons (e.g., Bentley et al., 2002). The storm surge and high wave energy associated with landfalling tropical cyclones may leave distinct storm deposits in coastal ponds, backbarrier lagoons and marshes. These deposits are typically sandy overwash deposits, thickest towards the barrier and thinning towards the center of the pond or lagoon, that are embedded in fine-grained, organic-rich sediments typical of backbarrier lagoons and coastal ponds. Each sandy layer is interpreted to record a single hurricane event. Radiocarbon dating of the enclosing mud layers permit time resolution of the events. Applications of coastal sediment proxies are reported by Liu and Fearn (1993, 2000), Donnelly et al. (2001a, 2001b, 2004), Scott et al. (2003), and others (additional references in Liu, 2004).

Challenges inherent to coastal sediment proxies are the unique identification of the sand layer as the result of a tropical cyclone, the variability of the overwash deposits as a function of storm energy and trajectory, and the superimposed effects of long term changes in sea level. Storm deposits are most confidently interpreted in combination with studies of microfossils (foraminifera, diatom, etc.; Collins et al., 1999; Hippensteel and Martin, 1999; Scott et al., 2001) to establish the provenance of the sand, employing local sea level curves (Scott et al., 2003), and by comparison to the documentary record, where storm events fall within the timeframe of historical records (Scott et al., 2003). Using these approaches, studies along the Gulf and Atlantic coasts (references below) have demonstrated the particular association of these deposits with major tropical cyclones (~Category 3-5, Saffir-Simpson scale).

A suite of studies (Liu and Fearn, 1993, 2000; Donnelly et al., 2001a, 2001b, 2004; Scott et al., 2003) utilizing the coastal sediment proxy has yielded a millennial-scale record of North Atlantic tropical cyclone activity along the U.S. Gulf and Atlantic coasts. Coastal pond records from sites along the Gulf Coast from Louisiana to Florida record few catastrophic (major hurricanes; see above) hurricane strikes from 0 to 1000 B.P., but three to five times greater landfall frequency of catastrophic storms between 1000 and 3500 yr B.P. A very different record is noted at Atlantic seaboard sites, which indicate major hurricane activity in the period 0 to 1000 B.P. and relative quiescence from 1000 to 3500 yr. B.P. This complementary record has been interpreted to reflect control of low frequency climate modes, in particular the North Atlantic Oscillation (NAO, a large scale fluctuation in atmospheric pressure between the polar low and subtropical high) on the frequency, intensity and track of North Atlantic hurricanes (Elsner et al., 2000; Scott et al, 2003). The "Bermuda High" hypothesis suggests that a southerly position of the Bermuda High (i.e., negative phase of NAO) favors tropical cyclone tracks resulting in landfall along the Gulf Coast, whereas northerly positions of the Bermuda High (i.e., positive phase of the NAO) results in greater recurvature of the storm tracks, with landfall along the Atlantic seaboard (Liu and Fearn, 2000; Elsner et al., 2000). Fluctuation of the NAO occurs on a much shorter time frame than millennial, thus the geological proxy is inferred to record the *dominant* position of the high over centuries to millennia. These studies demonstrate the promise of geological proxies to better document low frequency variation in hurricane frequency and to define hurricane-climate relations preceding significant anthropogenic impacts on the atmosphere.

Stable Isotope Proxies

Stable isotopic records of biological and geological materials which grow incrementally through time, such as tree rings (Miller et al., in press), speleothems (Frappier, 2002), and coral skeletons (Cohen, 2001), potentially provide much higher resolution (annual or better) than other geological proxies (Fig. 1). Tropical cyclones are well organized, long-lived mesoscale convective systems whose remarkably high precipitation efficiency, large size, high and thick clouds, and longevity lead to extreme ^{18}O depletions and $\delta^{18}O$ values of precipitation that may approach the $\delta^{18}O$ of the source water vapor (Lawrence and Gedzelman, 1996). Thus, the $\delta^{18}O$ value of tropical cyclone rain is markedly lower (by as much as 10‰) than rain generated by a typical thunderstorm in the tropics (Lawrence et al., 2002) and isotope depletions may be significant even several hundreds of km from the storm center. The basis of these isotope proxies is the incorporation, during growth of carbonate or cellulose, of oxygen from water bearing the characteristically ^{18}O depleted isotope values of precipitation generated by tropical cyclones (Lawrence 1998).

A TREE RING ISOTOPE PROXY FOR TROPICAL CYCLONES

Oxygen isotopes in tree-ring cellulose mainly reflect the isotopic composition of biophysiological effects, including biosynthesis, xylem water–sucrose exchange, and leaf water evaporative enrichment (Saurer et al., 1997; Anderson et al., 2002; Weiguo et al., 2004), but a significant proportion of oxygen is also derived from source water (precipitation), taken up through the roots, without isotopic fractionation, as soil water. The magnitude of the biophysiological effects is large (~30‰), but tends to be similar for a given species grown in the same environment (Anderson et al., 2002). Thus, inter- and intra-annual variability on the order of a few permil in the oxygen isotope value of cellulose from an individual tree, or like species from a given field area, most likely reflects changes in source water (precipitation) compositions. The magnitude of tropical cyclone-related isotopic depletions observed into cellulose will depend on many factors, including the size and proximity of the storm, soil type, and preexisting soil moisture conditions, and is therefore useful only as an indicator of tropical cyclone occurrence, but cannot be used as a measure of tropical cyclone intensity.

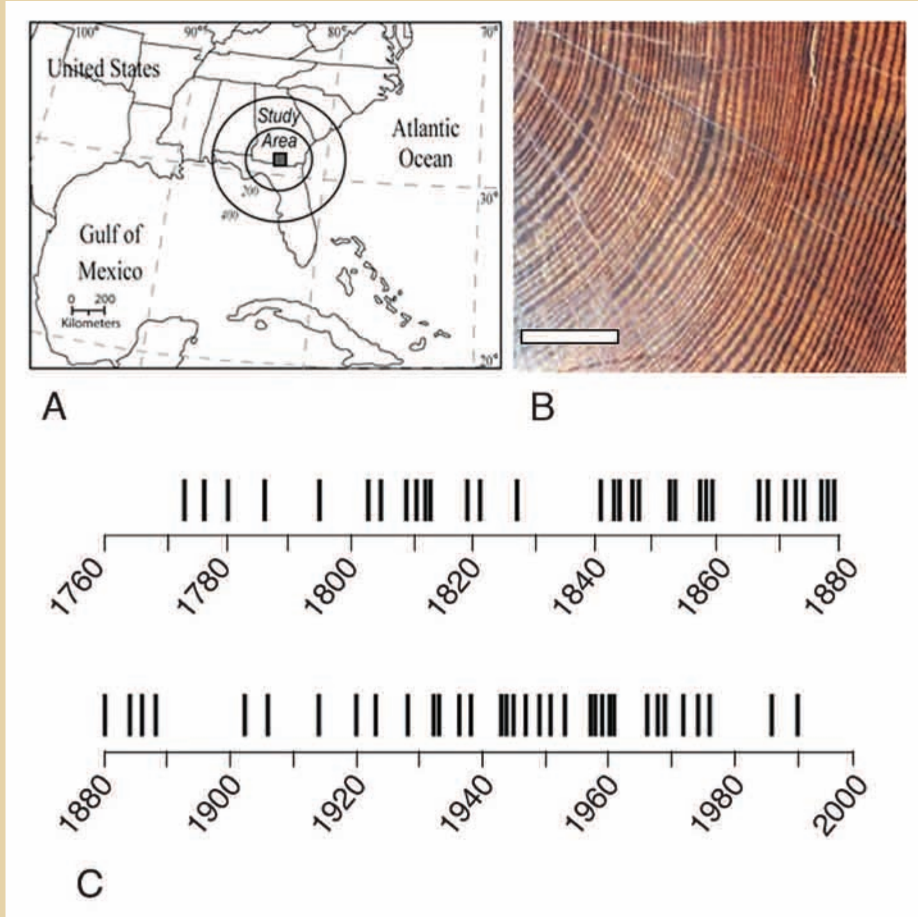

Figure 2. (a) The study site near Valdosta, Georgia, and radius of tropical storm impact examined in tree ring isotopes (~400 km; outer circle). (b) Oxygen isotope depletions related to tropical cyclones are noted almost exclusively in latewood portions of tree rings (dark ring portions) from longleaf pines. Scale bar 1 cm. (c) A record of tropical cyclone events preserved in tree rings in study site for 1770-1990. The record shows multidecadal periods of relative activity or quiescence of tropical cyclones affecting the study area.

Low ^{18}O precipitation derived from tropical cyclones may persist in soil water for several weeks after a large event, until the isotopic signal is ameliorated as the result of soil water evaporation (Lawrence, 1998; Tang and Feng, 2001). The ephemeral nature of tropical cyclone-related soil water suggests it is captured only in cellulose produced in the weeks following a storm event. This typically is only a small proportion of annual cellulose production, and the isotopic anomaly is not readily detected in cellulose from averaged annual rings. Tree rings preserve distinct earlywood (EW; growth in the early portion of the growing season) and latewood (LW; growth in the later portion of the growing season) components that can be separately analyzed (Fig. 2). Because more than 90% of tropical cyclones impact the southeastern U.S. during LW growth months of July through October (especially, August and September; Landsea 1993), isotopic evidence of tropical cyclone activity is expected to be prevalent only in LW cellulose.

A tree-ring oxygen isotope proxy record of tropical cyclone events impacting an area within ~400 km of Valdosta, Georgia (Fig. 2) was determined by Miller et al. (in press) and the record of tropical cyclones is shown in Figure 2. The reliability of the proxy-derived data for 1940-1990 was tested by comparison with (1) "best track" data for all tropical cyclones tracking within the defined study area (HURDAT; http://www.nhc.noaa.gov/pastall.shtml; Jarvinen et al. 1984; Landsea et al., 2004), and; (2) local precipitation records on days the storm made closest approach. Only one "false positive" (i.e., a storm detected by proxy for which there is no instrumental evidence) was noted and only three storms known to have tracked and near the study site were "missed" over the period 1855 to 1990.

Additional climate relations can be determined by comparison of tree ring isotope compositions (earlywood and latewood) and various climate indices. An example is shown in Figure 3. Earlywood oxygen isotope compositions correspond to climate factors affecting precipitation, without the complication of a superimposed tropical cyclone record. Earlywood $\delta^{18}O$ values correlate well with a smoothed (10 yr running average), January to May, AMO index (Enfield et al. 2001). From 1876 to 1950, the relationship is inverse ($r=-0.66$, $p<0.001$). From 1965 to 1990, the correlation is weaker, and positive. A similar comparison of latewood isotope compositions compared to AMO indices showed a negative correlation from 1876 to 1950 ($r = -0.35$, $p<0.001$), but no significant correlation post-1950.

The abrupt change in the relationship between the AMO and isotopic compositions coincides with a change in the predominant type of tropical cyclones, i.e., tropical or baroclinically-enhanced tropical cyclones of extra-tropical origin. These types of tropical cyclones form by fundamentally different mechanisms. (Elsner and Kara, 1999). The 1965-1990 period, in which baroclinically-enhanced tropical cyclones were dominant, was one of relative quiescence for major tropical cyclones impacting the US coast. Since the mid 1990s, tropical cyclones have returned to dominance (Elsner and Kara, 1999), with a greater number and greater intensity than in the previous 30 years. Our isotope time series unfortunately does not extend to present day, however, we note an apparent divergence in the isotopic data between 1990 and 1997 (data from a different tree species and not shown here). Thus, on the basis of the isotope record, we hypothesize a return to the inverse relationship between tree-ring isotope compositions and AMO indices, similar to the relationship dominant earlier in the 20th century. We suggest that the AMO was less influential on southeastern climate during 1965 to 1990, and other climate modes, such as the Pacific Decadal Oscillation or the El Niño Southern Oscillation, had greater influence on the southeastern U.S. climate and tropical cyclone formation.

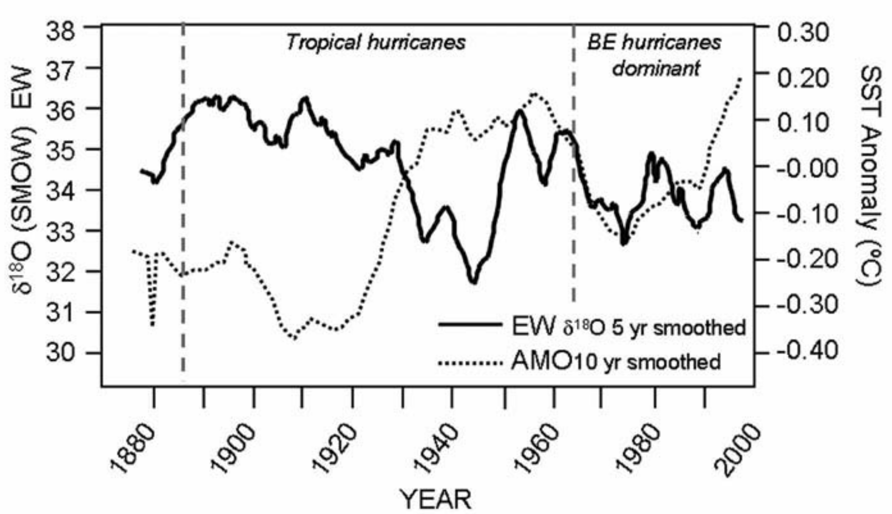

Figure 3. Inverse relationship between earlywood (light portion of rings in Figure 2b) oxygen isotope compositions and indices of the Atlantic Multidecadal Oscillation, a low frequency variation in North Atlantic sea surface temperature. The magnitude of tree ring isotope compositions is largely controlled by biophysiological effects (~30‰), but variations in the time series (1 to 6‰) are affected by climate. A similar relationship is noted in latewood compositions. The relationship changes significantly as the climate system shifts to support the predominance of tropical cyclones formed by a different mechanism (baroclinically-enhanced versus tropical; see text). The results suggest remote climate controls on hurricane occurrence may operate in time frames that can be studied by paleotempestology.

CONCLUSIONS

Many questions remain about the frequency and climatology of tropical cyclones and whether global climate change portends critical changes in their frequency or intensity. Geological, historical and stable isotope proxies extend the instrumental record of tropical cyclone activity and may yield a rich archive of information on their long term, natural variability on a variety of time scales, from annual to millennial. Proxy-derived data may better inform our understanding of tropical cyclone climatology, our possible complicity in forcing significant and potentially dangerous changes in their behavior, and also inform predictions of vulnerability and risk along the U.S. Gulf and Atlantic coasts.

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