Jennifer M. Collins · Kevin Walsh *Editors*

Hurricanes and Climate Change

Volume 3

Aegean conferences

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Preface

This book was inspired by the 5th International Summit on Hurricanes and Climate Change, held in Chania, Greece, in June 2015. This ongoing series of conferences brings together leading experts from around the world to discuss work on the relationship between hurricanes, climate, and the assessment of hurricane risk. Hurricanes are among nature's most powerful and destructive phenomena. They have captured the interest of atmospheric researchers for more than 75 years, as before satellite observations became routinely available, they often struck with little or no warning. Tropical cyclones cause physical and economic disruption not only to societies in the tropics and subtropics but to the mid-latitude regions as well. Their destructive power comes not only from high winds and heavy rains but from storm surge and the potential to spawn tornadoes as they make landfall. The impacts of tropical cyclones fall most heavily on less developed nations, but developed nations have also suffered extreme hardship.

Early research established an understanding of the climatological and dynamic character of tropical cyclones, as well as their evolution and lifecycle. These advances led to an increase in forecast skill. The development of technologies, such as radar and satellite techniques, along with better monitoring methods, has led to a reduction in error for track and intensity forecasts. Additionally, studies have examined changes and variability in the occurrence of tropical cyclones. By understanding the interannual and interdecadal variability in tropical cyclone occurrence, societies can be better prepared and can position resources better for aiding impacted areas.

Today we understand that there is an intimate relationship and cooperation between atmospheric and oceanic conditions and processes leading to the development of tropical cyclones. Changes in climate will influence the occurrence and intensity of tropical cyclones in the future, even though the nature of these changes is not yet entirely clear. This book is comprised of ten chapters that present cutting-edge research which attempts to answer outstanding questions that remain in our understanding of tropical cyclones, whether this research endeavors to uncover their historical character, dynamics, societal impacts, and what the future may bring.

The first and second chapters discuss the climatological history of tropical cyclones. The first reviews research from the last decade in the subject of paleotempestology. This field endeavors to piece together the occurrence of tropical cyclones on the timescale of centuries and millennia or the climatological behavior of tropical cyclones before the observational record (about 160 years). These studies find that long-period behavior in the El Niño and Southern Oscillation phenomenon, the North Atlantic Oscillation, and location of the ITCZ are some factors that control periodicity on the century and millennial timescales. This work also reveals that tropical cyclone activity today is not at an historical high level going back to the mid-Holocene. The second chapter focuses on tropical cyclone landfalls along the southeast US coast, and the authors find that the locus of landfalls has shifted about 1° latitude further north. Thus, this study provides critical guidance for policy makers and those whose responsibility includes disaster preparedness.

The dynamic, thermodynamic, and kinematic behavior of tropical cyclones is another topic of wide interest, and Chaps. 3, 4, and 5 explore various aspects of tropical cyclone lifecycles. Chapter 3 examines the relationship between sea surface temperatures and tropical cyclone intensity in the eastern North Pacific, an area that has not been studied as extensively as other tropical cyclone basins. Using statistical methods, the authors find generally that sea surface temperatures exert a greater influence on tropical cyclone intensity than in other basins, in particular when compared with the North Atlantic.

The next chapter reviews both in situ and remote sensing methods that have been developed for estimating tropical cyclone winds. Better estimates will lead to better forecasts, which is of benefit to societies exposed to tropical cyclone risks. The authors note that each method has their strengths and weaknesses, but the use of different methodologies could, for example, lead to differing conclusions about trends in tropical storm intensity. They recommend the continued improvement of satellite-based techniques in order to improve the current state of the art.

The fifth study examines a new concept impacting tropical cyclone genesis over land called the "Brown Ocean." In recent years, there have been a few notable cases of tropical cyclones intensifying over land. Conventional wisdom holds that these storms should decay once over land. However, if enough surface moisture is present, then tropical cyclones can actually strengthen over land if the latent heat flux is sufficient.

The techniques of risk management have become increasingly important in tropical cyclone studies, and the next chapter proposes a novel statistical analysis of tropical cyclone risk, both in the Atlantic basin and along the coast of China. The authors conclude that standard methods of risk assessment may underestimate tropical cyclone risk factors such as storm surge and wave height.

The topic of the final four chapters is the ability of models to project aspects of tropical cyclone occurrence on the timescales of decades or longer. Decadal projection of various phenomena in atmospheric science has been a topic of considerable interest in the last 5 years. The first of these chapters studies the use of the next generation general circulation models in assessing tropical cyclone risk in a warmer world. The authors propose that these models, with increased resolution, will be able to reveal smaller-scale structures in future events, as well as provide the basis for the study of topics such as teleconnectivity between tropical cyclone basins and occurrence-to-landfall rates. The second of these chapters examines multidecadal simulations of tropical cyclone occurrences by basin. However, the authors also discuss the limitations of the models and tracking algorithms, the influence of model physics, and an overview of our current understanding and future direction of tropical cyclone activity research.

Forecasting the frequency of landfalling storms in the Atlantic basin on the seasonal and decadal timescales is the subject of the third modeling chapter. The authors use the UK Met Office's seasonal forecasting algorithm and demonstrate that there is significant skill in some regions due to the strong El Niño and Southern Oscillation signal, but lower skill in other places where this signal is not strong. The Met Office algorithm does produce successful multi-year forecasts of landfalling storms, and the authors point out that their methodology will identify decadal-scale active and inactive regimes for subregions within the Atlantic basin. The final chapter studies future changes in rainfall intensities associated with tropical cyclones, with a focus on landfalling storms. The authors performed a model sensitivity study to examine the relative impact of warmer sea surface temperatures only versus a doubling of atmospheric carbon dioxide concentration only and compare these to a control run. They found that tropical cyclone precipitation is more intense when sea surface temperatures increase. When atmospheric carbon dioxide concentration is doubled, tropical cyclone rainfall actually decreased slightly. Lastly, the study found that rainfall accompanying landfalling tropical cyclones increases and that the greater uplift of moist low-level air forced by landfall plays a significant role in increased vulnerability of coastal regions to tropical cyclone impacts.

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Chapter 1
Recent Advances in the Emerging Field of Paleotempestology

Joanne Muller, Jennifer M. Collins, Samantha Gibson, and Leilani Paxton

Abstract Roughly 35 % of the world's 7.4 billion people are in the path of tropical cyclones, and coastal populations are expected to increase in the coming century. To understand the future damage that tropical cyclones could impose on an ever-growing coastal population, it is critically important to better understand the relationships between tropical cyclones and climate. Large-scale features of the climate system have been shown to affect tropical cyclone activity, for example, the El Niño Southern Oscillation (ENSO) has been shown to influence tropical cyclone frequency in all oceanic basins on seasonal, yearly, and decadal timescales. However, the relatively short observational record (<160 years) is inadequate for identifying the climatic influences on tropical cyclones over centennial to millennial timescales. Paleotempestology, a relatively new science, helps to resolve this issue by extending the instrumental record back several thousands of years. Over the past two decades, the number of paleotempestology records has increased substantially for sites along the Northwest Atlantic Ocean, Gulf of Mexico and Caribbean Sea, the South Pacific Ocean, and the Northwest Pacific and Indian Ocean regions. The most obvious characteristic of these records is that they reveal extended alternating periods of either greater or lesser tropical cyclone activity over centennial and millennial timescales. In these studies, researchers have shown that large-scale climatic features such as ENSO, sea surface temperatures (SSTs), the latitudinal position of the intertropical convergence zone (ITCZ), and the North Atlantic Oscillation (NAO) are likely driving the alternating long-term behavior of tropical cyclones in global oceanic basins. This review paper will focus on recent paleotempestology studies from multiple global sites and endeavor to synthesize the results and interpretations.

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1 Introduction

The North Atlantic Basin provides the longest observational record of tropical cyclone activities spanning the past 160 years (Landsea et al. 2012). Examination of this record reveals significant interannual and interdecadal variability in tropical cyclone activity, which can be related to regional- and global-scale climatic phenomena such as sub-Saharan drought, El Niño Southern Oscillation (ENSO) events, and changes in sea surface temperatures (SSTs) in the Main Development Region (MDR; Gray 1990; Landsea et al. 1996; Elsner and Kara 1999). However, due to the brevity of the historical record, it is impossible to assess whether such variability occurs at longer centennial to millennial timescales. This question can be addressed by means of paleotempestology, a relatively new research field that utilizes geological, biological, and written documentary techniques to study past tropical cyclone activity (Liu and Fearn 1993; Donnelly et al. 2001a; Hippensteel 2011; among others).

Paleotempestology seeks to develop tropical cyclone activities over a large range of timescales, from day-by-day reconstructions to millennial-scale reconstructions. Since the early 1990s significant progress has been made in the field of paleotempestology with new developments in research theory, methodology, and understanding. As a result, paleotempestology has become an important component of quaternary paleoclimatology (Liu 2004; Nott 2004; Fan and Liu 2008) not only in its basic scientific research application but also in its practical application to society. This research has allowed for tropical cyclone return period calculations that extend back beyond the historical record for selected coastal areas, potentially providing empirical data for risk assessments by insurance companies, civil planners, and emergency management officials (Liu 2004).

In 2008, Fan and Liu (2008) published a comprehensive review on the development of paleotempestology proxy techniques, methodologies, and research achievements at the global scale. The review outlined all potential paleotempestology archives and their relevant proxies, in addition to the widely accepted climatic interpretations in the field of paleotempestology in 2008. Since the publication of this review paper, there have been a number of advances in the field. This review chapter presents recent paleotempestology advances that have contributed important information to our understanding of paleotempestology dynamics. We will summarize these studies and their findings in the following pages.

2 Recent Developments in Paleotempestology Proxies

As discussed in Fan and Liu (2008), there are a number of archives that provide information on past tropical cyclone activity. The more commonly used archives include (1) historical documentary records; (2) speleothem, coral-ring, and tree-ring archives; (3) beach ridges and cheniers; and (4) coastal lacustrine, lagoonal, and marsh overwash facies, while less common archives include (5) shallow-marine storm sequences, (6) estuarine storm-related rhythmites, and (7) storm deposits in atoll lagoons and inner reef flats. Since Fan and Liu's review paper publication in 2008, advances in the field are mostly confined to the more commonly used archives outlined above and coastal karst basins, a relatively new type of paleotempestology archive. Therefore, this review chapter will focus on these paleotempestology archives and the climatological interpretations from these recent works. In addition we will provide some information on the potential difficulties facing the field of paleotempestology.

2.1 Historical Documentary Records

Tropical cyclones are often catastrophic disasters to society as they pose hazards to humans such as high winds, heavy rain, storm surge, powerful waves, potential tornadoes, coastal flooding, landslides, etc. These societal impacts are often recorded in historical written records after the beginning of literal history. Documentary records of tropical cyclones are sometimes archived in official histories, gazettes, newspapers, and civilian writings such as travel logbooks, diaries, poems, etc. (Fan and Liu 2008). Since 2008, few studies have been published that utilize historical documentary records. However, in 2016, Trouet et al. used documented Spanish shipwrecks to look at tropical cyclone variability in the Caribbean during the Maunder Minimum (MM; 1645–1715 CE), a period defined by the most severe reduction in solar irradiance in documented history (1610–present). This research utilizes a combined documentary time series of Spanish shipwrecks in the Caribbean (1495–1825 CE) and a tree-growth suppression chronology from the Florida Keys (1707–2009 CE). Trouet et al. (2016) found a 75 % reduction in decadal-scale Caribbean tropical cyclone activity during the MM that also correlates with cool North Atlantic SSTs, El Niño-like conditions, and a negative phase of the North Atlantic Oscillation (NAO). It is suggested that these conditions are primarily modulated by reduced solar irradiance during the MM time period. The study also highlights the need for a better understanding of oceanic and atmospheric responses to radiative forcing in order to improve our future tropical cyclone projection skills.

In 2014 Bossak et al. undertook a study of historic Georgia tropical cyclones. They analyzed the frequency trends, intensity over time, seasonality, zone of formation, time from formation to landfall, and spatial distribution for Georgia's 14 recorded tropical cyclone landfalls in HURDAT2. They noted a declining number of tropical cyclones, both in Georgia and immediately neighboring coasts, since 1851. In each successive 50-year interval, the frequency of tropical cyclones that make landfall in Northeast Florida, Georgia, and South Carolina has decreased. As of 2017, Welford et al. (this volume, Chap. 2) extended this Georgia record through the examination of temporal and spatial tropical cyclone landfall trends along the Georgia coast from 1750 to 2012. Since 1750, 18 of the 24 recorded tropical cyclones that made landfall along the Georgia coast occurred between 1801 and 1900, yet the tropical cyclone intensities have declined since 1851. This study also demonstrates that the mean location of landfall along the Georgia coast has shifted 60 km north and hence closer to Savannah. Whether this change represents a movement due to anthropogenically enhanced global radiative forcing and Atlantic SSTs or a change in tracks due to NAO forcing or a statistical anomaly is impossible to establish. Certainly, +NAO or −NAO indices affect the location of the subtropical high and the resultant track of tropical cyclones around the periphery of the high pressure (Welford et al. this volume, Chap. 2).

2.2 Speleothem, Coral-, and Tree-Ring Archives

2.2.1 Speleothems

Tropical cyclones produce large amounts of precipitation with distinctly lower $\delta^{18}O$ values than typical low-latitude thunderstorms. This isotopic signal of tropical cyclones can thus be incorporated into the calcium carbonate of stalagmites in limestone caves, in tropical cyclone prone regions.

In 2008, Frappier published a four-step screening method used to select stalagmites with the goal of developing a proxy record of individual tropical cyclone rainfall events (Frappier 2008). Field and laboratory criteria were combined to develop a process for pre-screening speleothem samples to screen out candidate stalagmites whose characteristics indicated lower sensitivity to storm–water infiltration. The approach was designed to increase the likelihood that selected stalagmites would increase the signal to noise ratio of the target phenomenon in the resulting proxy records. Hallmarks of this approach include (1) establishing a priori scientific targets, (2) applying sample criteria in the form of contraindicators, and (3) organizing the sample screening protocol into a series of practical stages. The overall approach to stalagmite selection presented here supports cave conservation and can be adapted readily by others in support of different scientific goals.

In 2014, Haig et al. published research that used a new tropical cyclone activity index (CAI) which is the average accumulated energy expended over the tropical cyclone season within range of the site, accounting for the number of days since genesis and the intensity and size of the storm relative to its distance from the site at each point along its track. The CAI allows for a direct comparison between the modern instrumental record and long-term paleotempestology (prehistoric tropical cyclone) records derived from the $\delta^{18}O$ of seasonally accreting carbonate layers of actively growing stalagmites. The CAI showed that the low levels of storm activity which have occurred on the mid west and northeast coasts of Australia are unprecedented over the past 550–1500 years (Fig. 1.1). Their results also revealed a repeated multi-centennial cycle of tropical cyclone activity, the most recent of which commenced around AD 1700. The present cycle includes a sharp decrease in activity after 1960 in Western Australia. This is in contrast to the increasing frequency and destructiveness of Northern Hemisphere tropical cyclones since 1970 in the North Atlantic Ocean and the western North Pacific Ocean (e.g., Emanuel 2005).

2.2.2 Corals

Corals in stormwash deposits have previously been used as an indicator of tropical cyclone activity (Fan and Liu 2008); however, new research is being conducted to determine if corals themselves may be used as a direct proxy. Corals are sensitive to, and can record, the $\delta^{18}O$ values of the waters in which they grow and should thus be able to record the changes in precipitation associated with a tropical cyclone.

In 2011, Kilbourne et al. published a study that investigated the usefulness of coral skeletal $\delta^{18}O$ as a means of reconstructing past tropical cyclone events. Isotopic modeling of rainfall mixing with seawater shows that detecting an isotopic signal from a tropical cyclone in a coral requires a salinity of $\sim$33 psu at the time of coral growth, but this threshold is dependent on the isotopic composition of both fresh and saline end-members. Unfortunately, a comparison between coral $\delta^{18}O$ and historical records of tropical cyclone activity, river discharge, and precipitation from multiple sites in Puerto Rico showed that tropical cyclones are not distinguishable in the coral record from normal rainfall using this approach at these sites.

In 2008, Hetzinger et al. presented a $\delta^{18}O$ record from a brain coral situated in the Atlantic tropical cyclone domain. This record showed equal sensitivity to SST and seawater $\delta^{18}O$ variations, with the latter being strongly linked to precipitation. The authors demonstrate that this coral-based proxy record ($\delta^{18}O$) captures the multidecadal variations associated with the Atlantic Multidecadal Oscillation (AMO) and the tropical cyclone activity (Fig. 1.2) that interestingly exhibits a long-term increase over the last century. This study raises new possibilities in extending the limited AMO observational record using corals and therefore the ability to gain new insights into the mechanisms underlying the AMO and its effects on long-term tropical cyclone variations.

2.2.3 Tree Rings

Tropical cyclones impact trees in a variety of ways, which can then be measured through an analysis of the annual growth bands, $\delta^{18}O$ and $\delta^{13}C$ values within the α-cellulose, and even statistical correlations between the rings and isotopic values. The recognition of tree rings as a valuable proxy for tropical cyclones has increased the need for refinement of the methodologies by which tree cores are extracted and the data are analyzed.

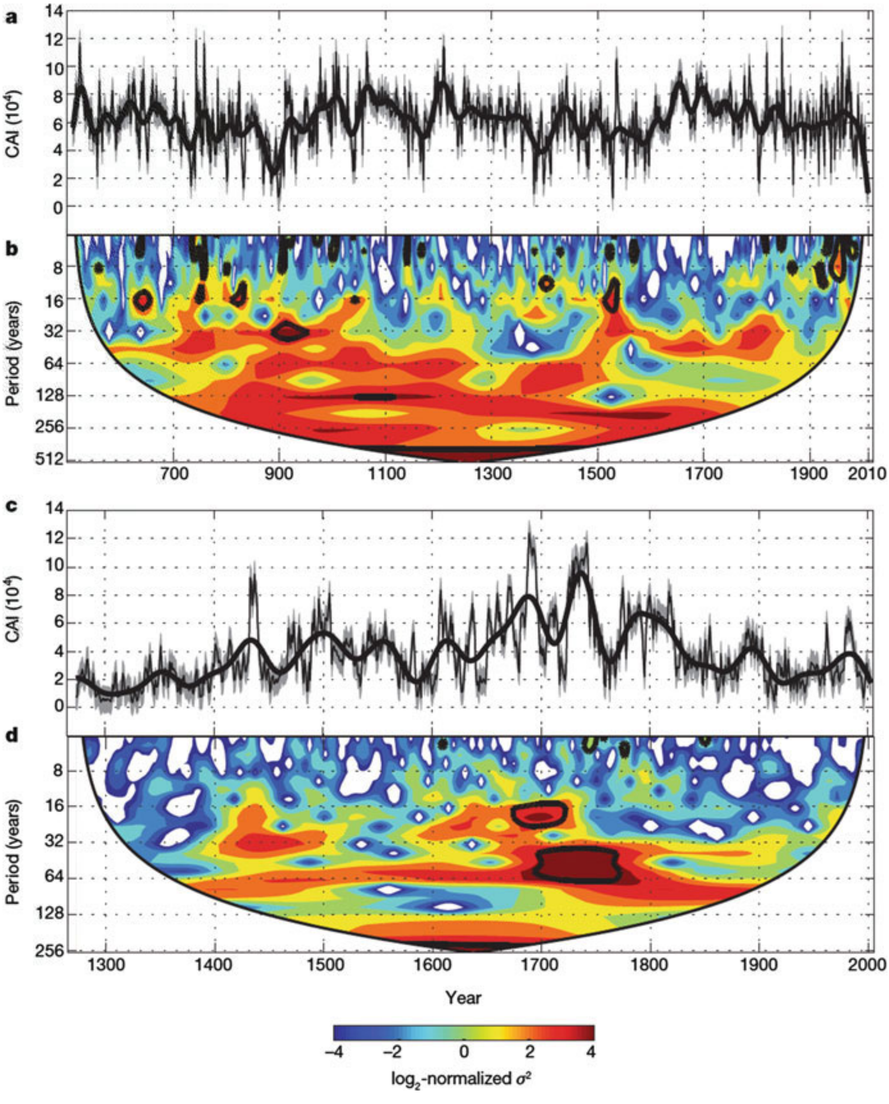

Fig. 1.1 Cyclone activity index (CAI) over the last 1500 and 700 years (Modified from ref. Haig et al. 2014). **a**, **c**, Cape Range (**a**) and Chillagoe (**c**); *black line* indicates smoothing of the series (smoothed data were not used in the statistical analysis). *Gray shading* indicates the r.m.s.e. of the model. **b**, **d**, Wavelet power spectra (Morlet wavelet) of Cape Range (**b**) and Chillagoe (**d**). Power increases from *blue* to *red*, *black* contours indicate regions above the 1 % significance level, and the *white* areas are regions subject to edge effects. The spectra have lag-autocorrelation coefficients of 0.75 (Cape Range) and 0.78 (Chillagoe) (Software provided by C. Torrence and G. Compo (http://atoc.colorado.edu/research/wavelets/))

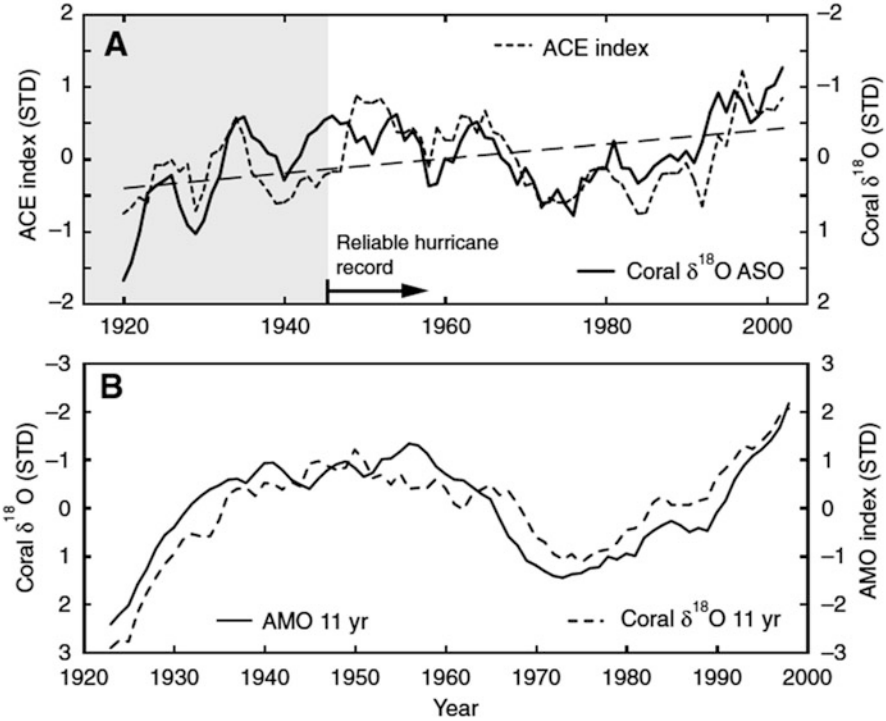

Fig. 1.2 (**a**) Comparison between coral $\delta^{18}O$ and the index of accumulated cyclone energy (ACE) for the North Atlantic (Modified from ref. Hetzinger et al. 2008). Data shown are for the peak months of the Atlantic tropical cyclone season, August-September-October (ASO), and were averaged using a 5-year running filter. The correlation is high ($r = -0.66$) and significant at the 1 % level, assuming 14 degrees of freedom (1920–2002); $r = -0.52$ for unsmoothed ASO data (not shown), 1918–2004. The correlation is also stable for detrended values ($r = -0.50$ for unsmoothed ASO data and $r = -0.67$ for 5 years means, the same time intervals as above). *Dashed line* represents the upward trend seen in coral $\delta^{18}O$ over the 1920–2002 time period. The trend is statistically significant at the 0.1 % level, assuming 9 degrees of freedom. (**b**) Comparison between coral $\delta^{18}O$ and the AMO index (North Atlantic SST averaged between 0 and 70°N; Enfield et al. 2001). Seasonal mean values were removed from the monthly data before averaging to annual resolution. Then an 11-year running filter was applied. The correlation is high ($r = -0.86$) and statistically significant at the 5 % level, even with only four effective degrees of freedom. *AMO* Atlantic Multidecadal Oscillation, *ASO* August-September-October, *STD* standard deviation

Both Li et al. (2011) and Kagawa et al. (2015) have determined ways by which the process of extracting α-cellulose can be hastened without losing, if not gaining, accuracy in the stable isotope analysis. Li et al. (2011) took advantage of the unique ability of tree rings, among other paleotempestite archives, to retain intra-annual climate signals by extracting the α-cellulose directly from the whole wood spline and foregoing both the peeling and grinding methods. Kagawa et al. (2015) increased the versatility of single-batch processing of tree rings through the creation and evaluation of the "cross-section method" whereby they created a prototype polytetrafluoroethylene (PTFE) case, choosing PTFE due to its nonreactive nature, which could entirely house the tree-ring lath throughout the chemical and drying processes. Freeze-drying the α-cellulose laths showed to be the optimal method of drying with minimum splitting and shrinkage of the α-cellulose and left minimal contamination, and the process then follows standard methods. Both processes provide statistically similar measures in $\delta^{13}C$ and $\delta^{18}O$ integrity; however, the new process presented by Li et al. (2011) and expanded upon by Kagawa et al. (2015) is quicker and more cost-effective which allows for the processing of more samples.

Because dendrochronology relies upon the way that trees respond to their environment, different environments and tree species may pose different kinds of problems when interpreting tree-ring patterns. In 2011, Lewis et al. utilized a multi-tree approach to interpreting tree-ring response to a known climatic driver within a Texas preserve. Through a composite analysis of the $\delta^{18}O$ values, they discovered that sometimes individual trees within a stand would record false positives whereas other times they would not record the storm event at all. By comparing the tree-ring $\delta^{18}O$ values within this study to known climatic trends, Lewis et al. were able to determine that climatic trends such as seasonally uncharacteristic high or low precipitation, drought, and a strong El Niño event could lead to either of these issues. In extending the range of dendrochronological studies, Harley et al. (2011) determined that the South Florida slash pine, the pine species with the southernmost range, is a suitable candidate for tree-ring dating. As a tree species that reliably produces only one growth band per year in a subtropical environment and is most heavily influenced through rainwater, the South Florida slash pine can be used to determine tropical cyclone activity as far south as the Florida Keys. In 2012, Knapp and Hadley also addressed the issue of expanding dendrochronological research but in the Pacific Northwest portion of the United States where high wind events were correlated with extratropical and tropical cyclones. Through this study, Knapp and Hadley were able to provide a 300-year analysis of windstorms within the Pacific Northwest, spanning the time frame between the Little Ice Age and the current climate regime while also identifying the major correlation between the high wind events within the context of the ENSO and non-ENSO phases and the Pacific Decadal Oscillation.

2.3 Beach Ridges

Beach ridges are parallel ridges that form on sandy coastlines and largely consist of coarse sand and shell fragments. Nott and other researchers have found that the cliffy coarse-grained beach ridges in Northeastern, Northern, and Western Australia have been deposited by the wave action usually associated with intense tropical cyclones (Rhodes et al. 1980; Nott et al. 2009; Forsyth et al. 2010; Nott 2011a; Nott and Forsyth 2012). Each ridge in the plain is initially deposited at the rear of the beach. Over time a sequence of ridges develops to form a plain of between 10 and 30 shore parallel ridges. The addition of each new ridge causes the plain to prograde seaward.

The developing ridge at the rear of the beach increases in elevation over time with successive tropical cyclone-generated marine inundation events. Progressively higher marine inundations are required to continue depositing sediment onto the sand ridge as it increases in height (Nott and Forsyth 2012). The ridges generally attain a maximum elevation of 4–6 m above mean sea level. Therefore only the largest marine inundations can deposit sediment onto the crests of ridges at this height; hence, the final sedimentary unit on each ridge crest registers the largest marine inundation responsible for depositing the ridge (Nott and Forsyth 2012). The geology has been supported by meteorological and oceanographic models to determine the origin of a sequence of 29 shore parallel sand beach ridges in Northeastern Australia (Nott et al. 2009). The results suggest that the ridges were constructed by waves and that the final form or height of the ridges is a function of high-energy tropical cyclone-generated waves plus storm tides (Nott and Forsyth 2012).

The beach ridges of sand, shell, and a mixture of sand and shell in Australia show a variable tropical cyclone history throughout the late Holocene. Forsyth et al. (2010) identified two periods of tropical cyclone inactivity between 3380 and 2480 years and between 1440 and 440 CE in a coarse-grained beach ridge sequence near Tully Heads in North Queensland. They also identified periods of activity here between 5000 and 4500 CE and a very active period between 4100 and 3400 CE. At Wonga Beach, several hundred kilometers to the north, Forsyth et al. (2010) recognized a 1200-year period of heightened tropical cyclone activity between 2100 and 900 CE, while prior to this a 1700-year period of tropical cyclone inactivity occurred between 3800 and 2100 CE (Fig. 1.3). Nott (2011a) also identified a 1700-year period of tropical cyclone inactivity between 5400 and 3700 CE from a pure shell beach ridge record at Shark Bay, Western Australia. Nott et al. (2009) identified a 1000-year period of tropical cyclone inactivity between 1820 and 850 years in a sand beach ridge sequence south of Cairns, North Queensland (Fig. 1.3). Nott et al.'s 6000 year-long record of intense tropical cyclones (Nott et al. 2009) implies that extreme tropical cyclones occurred considerably more frequently than that suggested by the short historical record for this region (Fig. 1.3).

On a sidenote, in 2009, Donnelly et al. published an article that addressed the use of beach ridges in sea-level reconstructions. Some authors have argued that the beach ridges along the Gulf of Mexico represent sea-level highstands in the past. They argue that beach ridges cannot be built by storms because storms are typically erosional and the rate of beach ridge formation is considerably slower than the recurrence rate of storms at any one location (Tanner 1995; Morton et al. 2000). This is obviously not the case for beach ridges formed along the NE Australian coast, as discussed by Nott and Forsyth above (Nott and Forsyth 2012). Furthermore, Donnelly argues that for every direct strike many more tropical cyclones would traverse the Gulf of Mexico, significantly increasing the overall wave climate during tropical cyclone seasons and potentially leading to an increase in the frequency of constructional swells (Otvos 1995, 2000). Increases in "fair-weather" swell frequency and height during periods of more tropical cyclone activity in the Gulf of Mexico may provide an alternative explanation for beach ridges developing a few meters above their contemporaneous sea level.

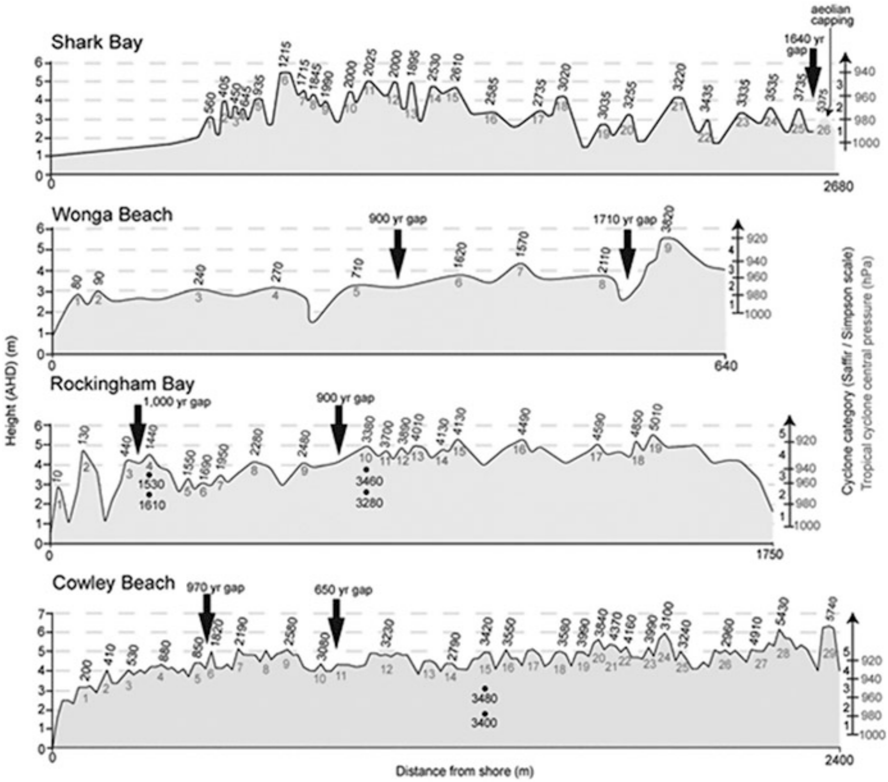

Fig. 1.3 Beach ridge cross-sections and chronologies (Shark Bay is dated using radiocarbon, and remainder using OSL) (Modified from ref. Nott and Forsyth 2012)

2.4 Coastal Lacustrine, Lagoon, and Marsh Overwash Deposits

Most long-term paleotempestological records are created using preserved tropical cyclone overwash signatures. As a tropical cyclone nears the coast, it produces strong winds and storm surge. The storm surge will often breach the barrier island and/or dune system, depositing foreshore, offshore, and dune sediments into back-barrier lagoons, coastal lakes, or marshes. Due to close coastal proximity and their significantly different geomorphological and sedimentological depositional characteristics, coastal lacustrine, lagoon, and marsh deposits are ideal locations for recording high-energy storm surge associated with tropical cyclone events. In this case, tropical cyclone-deposited marine sediments differ from back-barrier lagoon or lake sediments in a number of ways, such as grain size, diatom faunal and foraminifera composition, and percent $CaCO_3$ and organics. By obtaining radiometrically determined age-control points throughout a core and using the abovementioned proxies to analyze overwash layers, it is possible to generate a much longer tropical cyclone record than the short-term instrumental/historical record. In recent years, a number of paleotempestology studies have been published that utilize coastal lacustrine and lagoonal deposits. These studies can largely be divided up into short-term (or modern) records and longer-term records.

2.4.1 Modern Records

Before 2008 few studies have assessed the sedimentary mechanism or distribution pattern of storm deposits in back-barrier lakes, lagoons, and marshes attributed to the overwash processes of recent known tropical cyclones. In recent years, Williams (2009, 2010, 2011a, b, 2012) has published multiple studies that focus on the better understanding of modern overwash deposits. Both Williams (2009) and Williams and Flanagan (2009) studied overwash deposits associated with Hurricane Rita along the southwest Louisiana coast. Rita's storm surge and accompanying waves transported sand and mud into woodland and freshwater marsh environments leaving a sedimentary deposit that is up to 0.5 m thick and extends at least 500 m inland. Analysis suggests two distinct phases of deposition: a thin layer of finer sand and mud and an overlying thicker layer of coarser sand. These findings suggest deposition from suspension of offshore sand and mud in an early stage of storm surge inundation. This layer is overlain by coarser sand with an abrupt termination 100–150 m inland that was likely deposited as a traction load, formed at a later stage of storm surge inundation. Williams (2010) documents similar storm surge sedimentation for Hurricane Ike on the McFaddin National Wildlife Refuge. Again two distinct styles of sedimentation are found: a thick, sandy washover fan, extending about 150 m inland, deposited as traction load, and an underlying thinner, finer, more organic-rich blanket of sediments extending more than 2.7 km inland, deposited from suspension. This specific study also shows that storm surge sedimentation can extend a considerable distance inland, with the implication that paleotempestology studies could potentially be conducted farther inland. Williams also studied shell bed tempestites in part of southwest Louisiana's Chenier Plain (2011a). The shell bed tempestites are predominantly composed of disarticulated bivalves, probably reworked and transported landward from skeletal remains offshore. The shell bed has an erosional base, is bioclast supported, normally graded, and has common mud rip-up clasts. Williams demonstrates that the Hurricane Ike shell bed is a valuable analog for older palaeotempestological investigations and that tropical cyclones have likely contributed to the construction of both modern berm ridges and paleo-beach ridges on this Louisiana coastal plain. Another study from the southwest Louisiana Chenier Plain (Williams 2013) denotes overwash layers as storm-surge-deposited sand enclosed by marsh sediments. The sand layers have sharp basal contacts, extend hundreds of meters into the marsh, and contrast in lithology and microfossil assemblages with enclosing marsh deposits (Fig. 1.4). Based on the modern analogs of Hurricanes Audrey (1957), Rita (2005) and Ike (2008), and consideration of nearby landfalling tropical cyclones in the

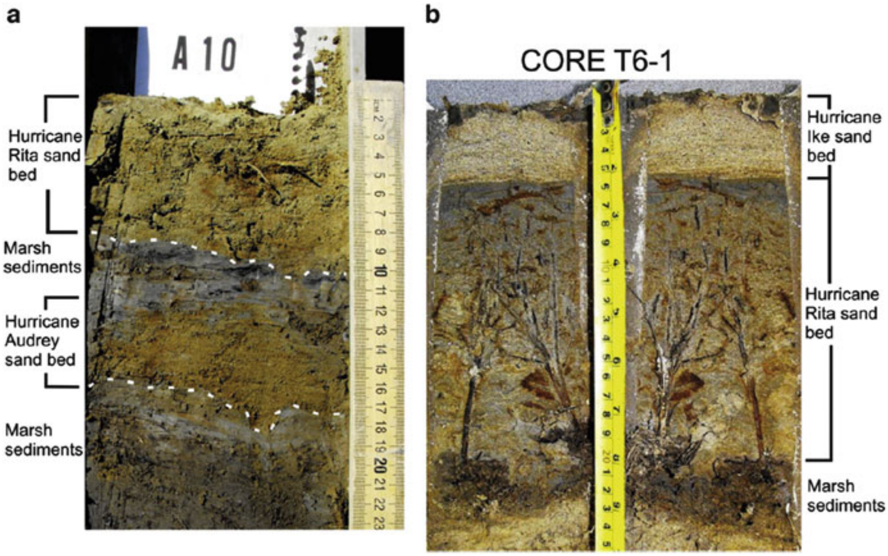

Fig. 1.4 (**a**) Wedge core A10 showing sand beds of Hurricanes Audrey and Rita, separated by a few centimeters of muddy organic-rich marsh sediment (Modified from ref. Williams 2013). *Dashed lines* indicate sharp basal contact of each Sand Bed. (**b**) Core T6-1 showing the sharp contact between sand beds of Hurricanes Ike and Rita. Marsh plants, in growth position and rooted in the buried marsh surface, are encased in Tropical Cyclone Rita's sand bed. Photograph taken approximately 8 months after landfall of Hurricane Ike; by 20 months after landfall, Hurricane Ike's deposit was no longer recognizable having been obscured by bioturbation

historical record, it was determined that the storm intensity threshold of the study site is equivalent to a category 3 hurricane. In many of these studies, Williams (2009, 2010, 2011a, b, 2012) shows that the characteristics of the storm surge deposits, including texture, thickness, inland penetration, and preservation, reflect the intensity and proximity of the landfalling tropical cyclones.

Liu et al. (2011) investigated the patterns and processes of recent storm deposition in coastal lakes by conducting sediment coring, coupled with hydrodynamic measurements, before and after Hurricane Gustav and Ike in Bay Champagne, Lafourche Parish, LA. Two-bottom-mounted conductivity, temperature, and depth sensors (CTDs) deployed on August 29, 2008, 3 days before Hurricane Gustav's landfall, recorded a maximum storm surge of ∼2.7 m. A segment of loose sediment, occurring in the middle of this storm deposit, was probably formed by the reworking of the upper part of the Gustav storm deposit by Hurricane Ike, 12 days later. In 2014, Naquin et al. also published a study that looked at geological processes induced by tropical cyclones in Bay Champagne. Within each marine incursion layer, terrestrial elemental concentrations, as determined by XRF, display large depletions. Grain size analysis of a portion of the core (30–86 cm) indicates the presence of two series of sequential high-energy storm deposits followed by intense fluvial flooding within Bay Champagne. These events are attributed to Hurricane

Katrina/Rita in 2005 and Gustav/Ike in 2008. The studies of Liu et al. (2011) and Naquin et al. (2014) highlight the difficulty in differentiating overwash deposits laid down in the same year. This impacts the field of paleotempestology, where, for example, going back through time two overwash layers may be interpreted as one thick overwash layer.

Horton et al. (2009) also studied Hurricane Katrina and Rita's overwash layers in Mississippi and Alabama salt marshes. Horton et al. noted a three-dimensional sediment distribution of tropical cyclone-induced storm surge deposits that tapered landward, overlying salt marsh sediment. A sharp erosional boundary between the pre-storm surge and storm surge sedimentary units was observed by a change in color and lithology. The overlying storm surge sediment unit was coarser than the pre-storm surge unit with a lower organic content. Foraminiferal analyses revealed a virtual absence of tests within the storm surge sediments, whereas abundant agglutinated foraminifera were found in the underlying salt marsh deposits.

2.4.2 Difficulties in Using Tropical Cyclone Overwash Records

As demonstrated above, by better understanding the depositional characteristics of the modern-day tropical cyclone record, in different geographical regions, researchers can progress the field of paleotempestology. However, the study of the modern-day record has also identified potential weaknesses in the research field, and paleotempestology has become more contentious in recent years because the exact nature of storm deposition and preservation is somewhat unclear. The general consensus is that overwash sand layers occurring in coastal lakes and marshes are a reliable proxy for major tropical cyclones, rather than minor tropical cyclones or winter storms (Liu and Fearn 1993, 2000; Liu 2004; Liu et al. 2008; Donnelly et al. 2001a, b, 2004; Donnelly and Webb 2004; Scileppi and Donnelly 2007; Donnelly 2005; Donnelly and Woodruff 2007). There are a number of factors that contribute to the deposition and preservation of overwash archives. In general, overwash is an artifact of storm surge, and storm surge varies with tropical cyclone intensity (decreasing tropical cyclone central pressure), speed of forward storm movement, radius of maximum winds, bathymetry, and coastal configuration. In addition, one must consider the site and its preservational integrity, including overwash sediment source; postdepositional erosion; postdepositional lagoonal productivity, including bioturbation and sediment reworking; and lagoonal sediment accumulation rates. Finally, the physical characteristics and geomorphology of the lagoonal barrier and its vulnerability to being breached by storm surge must be considered. Many of the below studies find that at certain geographic locations, not all tropical cyclones are recorded in the geologic record. Why certain storm events are recorded, and others are not, is generally a combination of the above factors.

Using Hurricane Ivan as a modern analog, Liu et al. (2011) demonstrate that the storm surge associated with this category 3 hurricane caused sand deposition in the southern basins of Little Lake and Middle Lake but not in the center of the larger Lake Shelby site (Bianchette 2007) confirming that the proxy record from the center of Lake Shelby is sensitive to direct hits by catastrophic hurricanes of categories 4 and 5 only. This research has been advanced by modeling efforts such as those of Elsner et al. (2008) who developed a statistical model that quantitatively links the tropical cyclone return period (frequency) with the tropical cyclone return levels (intensities) for the Lake Shelby area using information derived from both the historical record (AD 1851–2005) and the proxy record. Their study also confirmed that it takes landfalling intense tropical cyclones with wind speeds of at least 64 m s^{1} (i.e., middle of the category 4 range) to deposit an overwash sand layer in the center of this particular site. Another modeling study by Woodruff et al. (2008) applied a simple advective-settling model to constrain the coastal flooding intensities required to transport clastic overwash deposits to various distances behind the barrier. They found that the topmost overwash deposits in the core could be attributed to four or five most intense tropical cyclones that have struck Puerto Rico since ca. AD 1820.

In 2011, Hippensteel pointed out inconsistencies in overwash signatures from the back-Folly Island barrier marshes in South Carolina. Sedimentological and micropaleontological analysis of 15 gouge-auger cores revealed a lack of spatio-lateral continuity for paleotempestology deposits. The offshore-indicative calcareous microfossil content of some storm deposits was taphonomically altered or destroyed, and in many cases cores taken 10 m apart provided significantly different storm records. Hippensteel cautions that the combination of bioturbation, erosion, and taphonomic degradation of the foraminifera and sedimentary signatures leaves the comprehensive and complete character of the storm record from the Southeastern Atlantic in doubt. In 2011, Otvos also pointed out some of the same inconsistencies in paleotempestology records where the diversity of topographic, hydrodynamic, and sedimentological settings and factors as well as postdepositional settings account for major difficulties in correlating individual sand layers with specific prehistoric tropical cyclone events. This complicated or prevented identification of discrete tropical cyclones, their velocity categories, calculations of recurrence interval probabilities, and accurate risk assessment. Otvos (2011) recommended that the stable isotope method be used in organic-enriched limnic and brackish muds of paralic basins; which may further refine, detail, quantify, and supplement sand layer-based storm proxy signals for improved storm archiving and correlation on the interregional-to-hemispheric scale. Numerous researchers have embarked on a scrutiny of carefully collected detailed data from several worldwide localities. In time, these studies will elucidate the highly variable prehistoric record of tropical cyclone intensities and frequencies on a global scale.

2.4.3 Long-Term Records

Most of the recent long-term lacustrine, lagoon, and marsh overwash studies are constrained to sites along the North Atlantic Basin coastlines, with a few studies from the Western Pacific margins.