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Tina M. Niemi
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Kathleen Sullivan Sealey

ORGANIZER:

Troy A. Dexter

Executive Director
Gerace Research Centre
University of The Bahamas
San Salvador, The Bahamas

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Keynote Address

PALEOTEMPESTOLOGY OF THE CARIBBEAN AND GULF COAST REGION: EMERGING RESEARCH QUESTIONS AND METHODS

Kam-biu Liu

Department of Oceanography and Coastal Sciences
Louisiana State University
Baton Rouge, LA 70803 USA

ABSTRACT

The application of novel methods in paleotempestology has permitted the development of new insights into some key research questions fundamental to understanding the processes of storm sedimentation and the spatio-temporal dynamics of paleohurricane activities in the Caribbean and Gulf Coast region. This paper uses several examples from the Gulf Coast, the Dominican Republic, and Belize to illustrate this point. The application of X-ray florescence (XRF) analysis on sediment cores taken from coastal backbarrier lakes can reveal the chemical elemental composition of storm versus non-storm deposits, which can also provide a means to assess the relative contribution between freshwater and saltwater inputs to storm sedimentation. Coupled with palynological data, the results of XRF analysis from the sedimentary records of Bay Champagne, Louisiana, suggest that fluvial processes may have played a significant role in storm deposition from Hurricane Ike relative to that from Hurricane Gustav. Another example, based on oxygen isotopic analysis of coastal sediment cores from the Dominican Republic, suggests that freshwater input from fluvial processes may have played an even bigger role in the storm deposition in a hypersaline lake, which occurs commonly in the semi-arid areas of subtropical coasts. The application of stable isotopic techniques on a Belizean stalagmite has yielded a high-resolution, 450-year reconstruction of Caribbean hurricane activity. A remarkable change in hurricane activity after AD 1870 has been interpreted in terms of a shift in hurricane tracks caused by changes in the ITCZ, the Bermuda High, and the Hadley cell driven by global climate changes. The development of novel multi-proxy techniques, and their application to a variety of paleoenvironmental archives including coastal sediments and speleothems, have advanced the frontiers of paleotempestology by shedding new light on some key concepts such as the processes of storm deposition and the spatio-temporal patterns of Caribbean paleohurricane activity.

INTRODUCTION

The basic principle of paleotempestology involves the detection of hurricane events in the sedimentary record retrieved from coastal lakes and marshes. While the identification of overwash sand layers in sediment cores collected from backbarrier lakes and marshes remains the most widely used method in paleotempestology, new proxies and new archives have been added to the “tool box” at the disposal of paleotempestology researchers for the reconstruction of paleo-storm events in a variety of environmental settings. The application of these relatively new tools, in turn, have resulted in novel discoveries and findings that have led to the formulation of new research questions and hypotheses. In this review paper I will use a few examples from my work to illustrate these points.

THE ROLE OF FRESHWATER IN STORM DEPOSITION

The classical model of storm deposition in a backbarrier lake assumes that a clastic (usually sand) layer—taken as a proxy for a hurricane strike—is the product of seawater intrusion associated with overwash or storm surge processes (Liu, 2004, 2007). This assumption is undoubtedly true in many situations where storm surge is high (as in the case of a coastal site located close to the path of a landfalling intense hurricane) or where fluvial input to the site is low. However, there are increasing evidences to show that in many instances freshwater from fluvial flooding may play an important, yet under-appreciated, role in storm deposition. A case in point is Hurricane Harvey, a Category 4 hurricane that made landfall in coastal Texas in late-August 2017. While Harvey caused 0.3 to 3.0 m of storm surge to coastal Texas, extensive areas of southeastern Texas were flooded due to the 500-1539 mm precipitation that it brought, resulting in many rivers overflowing their banks (Blake and Zelinsky, 2017). Hurricane-generated fluvial flooding can have significant geological impacts on coastal landforms. An example comes from the Mosquitia (Mosquito Coast) of eastern Honduras (Cochran et al., 2009). During the extraordinarily active 2005 hurricane season, three late-season (October-November) tropical cyclones (Hurricanes Wilma and Beta, Tropical Storm Gamma) brought a combined total of 549 mm (21.6 inches) to this coastal region, causing major overbank flooding of the rivers. Freshwater outbursts from the overflowing rivers in turn led to the breaching of the barrier beaches along the Caribbean coast (Cochran et al., 2009) (Figure 1). It is therefore reasonable to expect that storm-generated fluvial flooding and freshwater outbursts must have changed the hydrology, chemistry, and sedimentary patterns in the backbarrier lagoons which the rivers emptied into.

Figure 1. Satellite images showing the breaching of coastal sand barriers due to the outburst of fluvially-fed freshwater from Laguna Bacalar (square) and an adjacent meander bend of the Rio Tinto (circle) in the Mosquito Coast, eastern Honduras. This breaching and freshwater outburst event occurred as a result of the heavy precipitation and fluvial flooding caused by Tropical Storm Gamma in November 2005. See Cochran et al. (2009) for details.

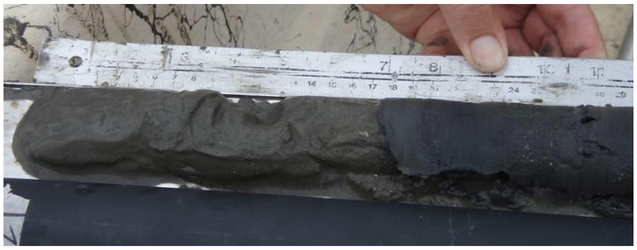

Figure 2. Core 21 from Bay Champagne, taken after Hurricanes Gustav and Ike, contains a 17 cm-thick layer of unconsolidated sandy clay at the top that represents a storm deposit caused by these hurricanes (From Liu et al., 2011).

FRESHWATER VERSUS SALTWATER INPUTS: A CASE STUDY FROM COASTAL LOUSIANA

Here I use a case study from coastal Louisiana to illustrate the importance of freshwater input in storm deposition, as well as its detection by means of X-ray fluorescence (XRF) techniques in the sedimentary record. Bay Champagne is a brackish water backbarrier lake near Port Fourchon, situated in a rapidly retreating part of the Louisiana coastal region that has experienced the highest rate of shoreline recession in the whole Gulf of Mexico (Dietz et al., 2018). In September 2008, coastal Louisiana was affected by two hurricanes consecutively within a two-week period. Hurricane Gustav made landfall in southern Louisiana as a high Category 2 hurricane, followed by Hurricane Ike which made landfall in southeastern Texas but its high storm surge caused significant coastal flooding in southern Louisiana. Cores taken after these two hurricane events from Bay Champagne contain a fresh sand layer at the top directly overlying finer sediments that are more consolidated and more clearly laminated (Liu et al., 2011). This sand layer has been interpreted to be the combined storm deposition attributed to Hurricanes Gustav and Ike (Liu et al., 2011). Accordingly, the lower part of this storm deposit was presumed to be caused by Hurricane Gustav, and the upper part by Hurricane Ike. In core 21, this storm deposit is 17 cm thick and contains a sloppy, unconsolidated section in the middle (8-13 cm) (Figure 2). We interpret this sloppy section to be the top of the Gustav deposit that was subsequently reworked by Ike. Loss-on-ignition (LOI) analysis of core 21 suggests that the Gustav-Ike sand layer at the top of each core contained low percentages of water and organic matter. In addition, it also reveals the presence of three thinner sand layers marked by low water and organic percentages in the lower part of the core, which were probably formed by older hurricanes prior to Gustav and Ike (Figure 3). X-ray fluorescence (XRF) analysis indicates that the storm deposits and the normal (non-storm) deposits have different elemental chemical characteristics. The storm deposits tend to have higher Cl/Br and Ca/Fe ratios than the finer-grained normal deposits, and typically contain lower Ti, Fe, and Mn concentrations (Liu et al., 2017). It is notable that Cl and Ca are typically enriched in seawater and the Cl/Br and Ca/Fe ratios have been used as indicators of marine incursions in coastal paleoenvironmental research, whereas Ti, Fe, and Mn are widely used as indicators of terrestrial sediment sources (Liu et al., 2014; Bianchette et al., 2016, 2017; Yao and Liu, 2018; McCloskey et al., 2015, 2018a, 2018b). Therefore, these elemental chemical characteristics suggest that the sandy storm deposits were formed by the incursion of seawater during storm surges, while the more organic, finer-grained sediments were deposited under less marine-dominated conditions.

Remarkably, within the thick sandy storm deposit at the top of the core, the upper half—attributed to Hurricane Ike—is characterized by a lower Cl/Br ratio and higher concentrations of Ti, Fe, and Mn than the Gustav-deposited lower layer (Liu et al., 2017) (Figure 3). This implies that while the coastal impacts by Hurricane Gustav were dominated by storm surge-generated marine incursion processes, the Hurricane Ike impacts were characterized by a greater contribution from freshwater influx. In addition to direct atmospheric input from heavy precipitation during Hurricane Ike, a likely source of freshwater input was from the bayou at the back of the lake, which drains the extensive wetlands in the Port Fourchon area. Hydrological data from the Bay Champagne water-

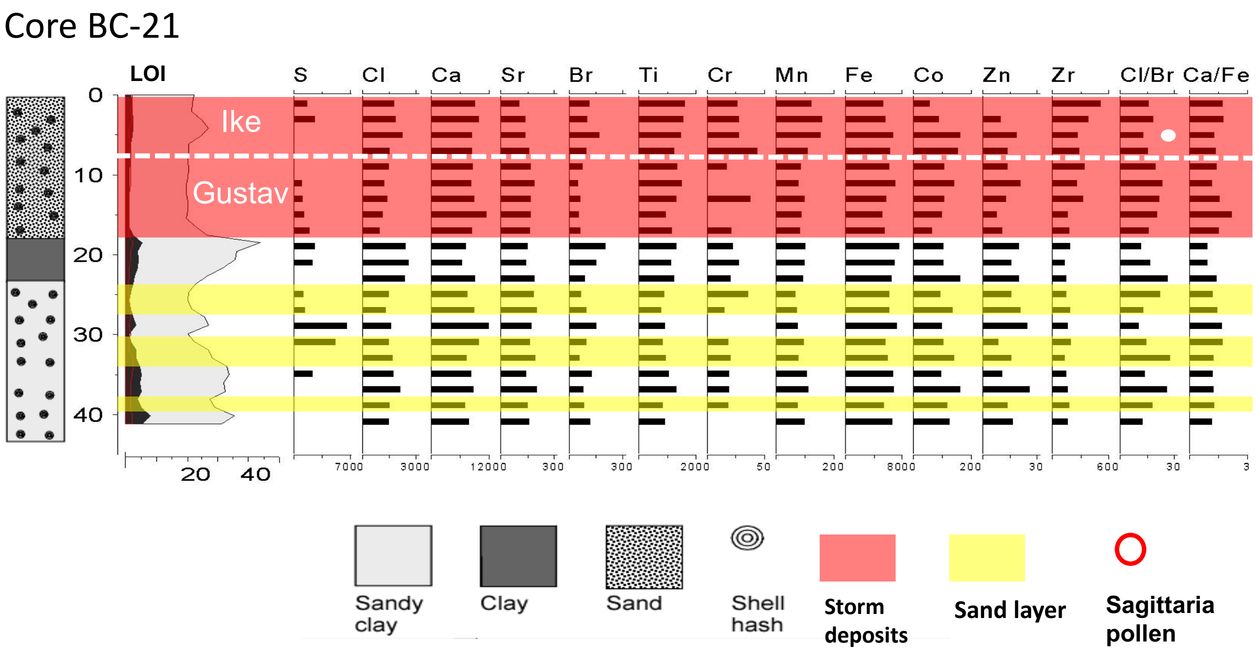

Figure 3. Loss-on-ignition (LOI) and X-ray flouresence curves of 12 chemical elements and the Cl/Br and Ca/Fe ratios from core 21 in Bay Champagne.

shed support the notion that Hurricane Ike was a wetter storm and delivered more freshwater runoff to the wetlands surrounding the lake (Dietz et al., 2016). Additional support for the higher freshwater input to Bay Champagne comes from palynological data in core 21. The pollen of *Sagittaria* (duck potato or bulltongue arrowhead), a common plant of fresh marshes, was found in the Hurricane Ike sediment layer but not in the underlying Gustav layer (Liu et al., 2011). The convergence of the geochemical, palynological, and environmental data therefore suggests that freshwater input from fluvial processes can play a significant role in hurricane-generated storm sedimentation in coastal lakes and marshes.

FRESHWATER INPUT TO COASTAL HYPERSALINE LAKES: AN EXAMPLE FROM THE DOMINICAN REPUBLIC

Coastal hypersaline lakes are common in certain arid, semi-arid, or seasonally dry environments. In these lakes hurricane rainfall may be a major source of freshwater input to an otherwise hypersaline aquatic environment. Thus, freshwater input from fluvial processes can play a significant role in storm deposition. Stable isotopic techniques have been used to detect the occurrence of hurricane-generated freshwater input events in the sedimentary record of hypersaline lakes. An example from Laguna Alejandro, a hypersaline lake on the southern coast of the Dominican Republic, illustrates this application (LeBlanc et al., 2017; Lane et al., 2017). A core (ALEJ08-5) taken from the lake contains three coarse-grained layers with allochthonous leaf litter in the lower part that were interpreted to be deposited under hurricane-generated high-energy conditions based on the sedimentary evidence. All three storm deposits were marked by significant negative excursions consistent with freshwater input derived from strongly isotopically depleted hurricane rainfall (Lane et al., 2017; Lawrence and Gedzelman, 1996). The isotopic signature of these sedimentologically-defined storm deposits allowed the detection of two more storm layers above them, even though the latter lacked any diagnostic sedimentary evidence to support their identification (Figure 4). This case study provides another example to show that freshwater input—either from direct atmospheric precipitation or from fluvial processes, or both—can play an important role in paleotempestology.

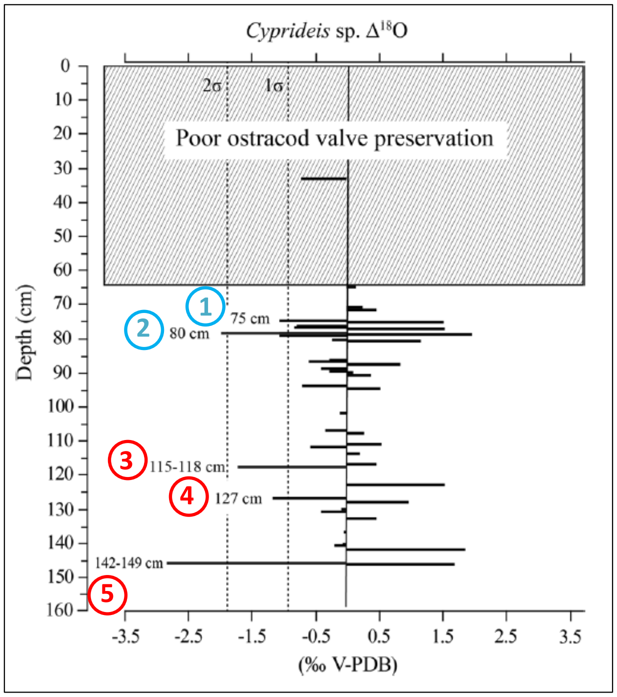

Figure 4. Results of oxygen isotopic analysis of ostracod valves from a sediment core from hypersaline Laguna Alejandro, Dominican Republic. Ostracods at 5 stratigraphic levels contained strongly negative $\delta^{18}O$ values that are typically associated with hurricane rainfall. Three of these levels (labelled as 3 – 5) in the lower part of the core correspond with hurricane events identified by sedimentary proxies. Despite the lack of sedimentary evidence, two higher levels (labelled as 1 and 2) were inferred to be hurricane deposits based on their isotopic signatures. This study shows that the detection of freshwater input into hypersaline lakes by means of oxygen isotopic analysis can provide a more complete reconstruction of paleohurricane events. (From: Lane et al., 2017).

ISOTOPIC RECORD FROM BELEZEAN SPELEOTHEM SHED NEW LIGHTS ON CARIBBEAN PALEOHURRICANE ACTIVITY

In addition to their application to paleo-hurricane detection in coastal sedimentary records as illustrated above, stable isotopic techniques have been successfully used to develop high-resolution paleo-hurricane reconstructions from speleothem records (e.g., Frappier et al., 2007), which has shed new light on the spatial and temporal patterns of Holocene hurricane activities in the Caribbean region. A recent study, based on a new index of coupled carbon and oxygen isotope ratio derived from an annually-resolved stalagmite proxy record from Belize, yields a 450-year reconstruction of tropical cyclone activity for the western Caribbean region (Baldini et al., 2016). The results suggest that during the past five centuries Atlantic tropical cyclone (TC) tracks responded sensitively to latitudinal shifts in the positons of the Intertropical Convergence Zone (ITCZ) and NH Hadley Cell driven by anthropogenic greenhouse gas and sulphate aerosol emissions. Specifically, the study postulates that since AD 1870 more TCs have followed recurving tracks in response to a southward shift of the ITCZ and an expanded Hadley Cell and Bermuda High, therefore resulting in reduced TC risks for the western Caribbean but increased risks for the Northeast Atlantic coast (Baldini et al., 2016) (Figure 5). This new model is consistent with the premises of the Bermuda High Hypothesis, which suggests that proxy-based reconstructions of hurricane activity patterns from the Caribbean to the Northeast Atlantic coast should show an out-of-phase or anti-phase relationship between the south and north as a function of long-term shifts in the predominant storm tracks in response to latitudinal migrations of the ITCZ and the Bermuda High (Liu and Fearn, 2000; Liu, 2004).

CONCLUSIONS

The application of relatively new research techniques such as XRF analysis and stable iso-

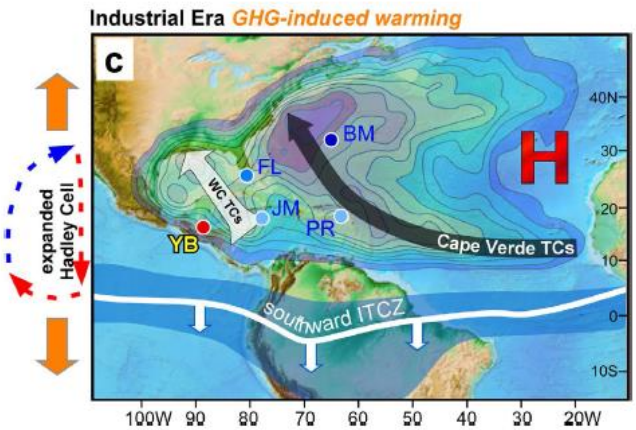

Figure 5. Inferred predominant hurricane tracks after AD 1870 based on a stable isotopic record derived from a Belizean stalagmite. Anthropogenic warming resulted in an expanded Hadley Cell and Bermuda High, while increased aerosols caused a southward shift of the ITCZ. These mechanisms combined has led to the prevalence of more recurving storm tracks, bringing higher risks to the northeastern U.S. coasts (From Baldini et al., 2016).

topic analysis to speleothems and sedimentary archives has advanced the frontiers of paleotempestology. Although XRF techniques have been applied to coastal paleoenvironmental research in the northern Gulf of Mexico (e.g., van Soelen et al., 2012; Yao et al., 2015), its application to paleotempestology—especially to distinguishing between the freshwater and saltwater inputs to storm deposition—has been limited (Liu et al., 2014). This paper shows the potential of using the XRF-derived chemical elemental signatures of different storm deposits to assess the relative contributions between saltwater intrusion and freshwater flooding associated with different hurricane events. These results help to shed new light on the potentially important role of freshwater input and fluvial processes in storm deposition in coastal environments. The role of freshwater input derived from hurricane precipitation is even more significant in hypersaline lakes in semi-arid tropical coastal environments, as the oxygen isotopic record from Laguna Alejandro in the Dominican Republic demonstrates (Lane et al., 2017). In another example of novel methodological development, the application of stable isotopic techniques on a Belizean stalagmite has resulted in an annually-resolved reconstruction of Caribbean hurricane activity that has offered new insights into the dynamic interactions between the ITCZ, Bermuda High, and hurricane tracks over the last 450 years (Baldini et al., 2016). In a nutshell, the development of novel multi-proxy techniques and their application to new environmental archives have opened new doors to enhance our understanding of past hurricane activities in the Caribbean and Gulf Coast region, and advanced the frontiers of paleotempestology.

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