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Differentiating hurricane deposits in coastal sedimentary records: two storms, one layer, but different processes

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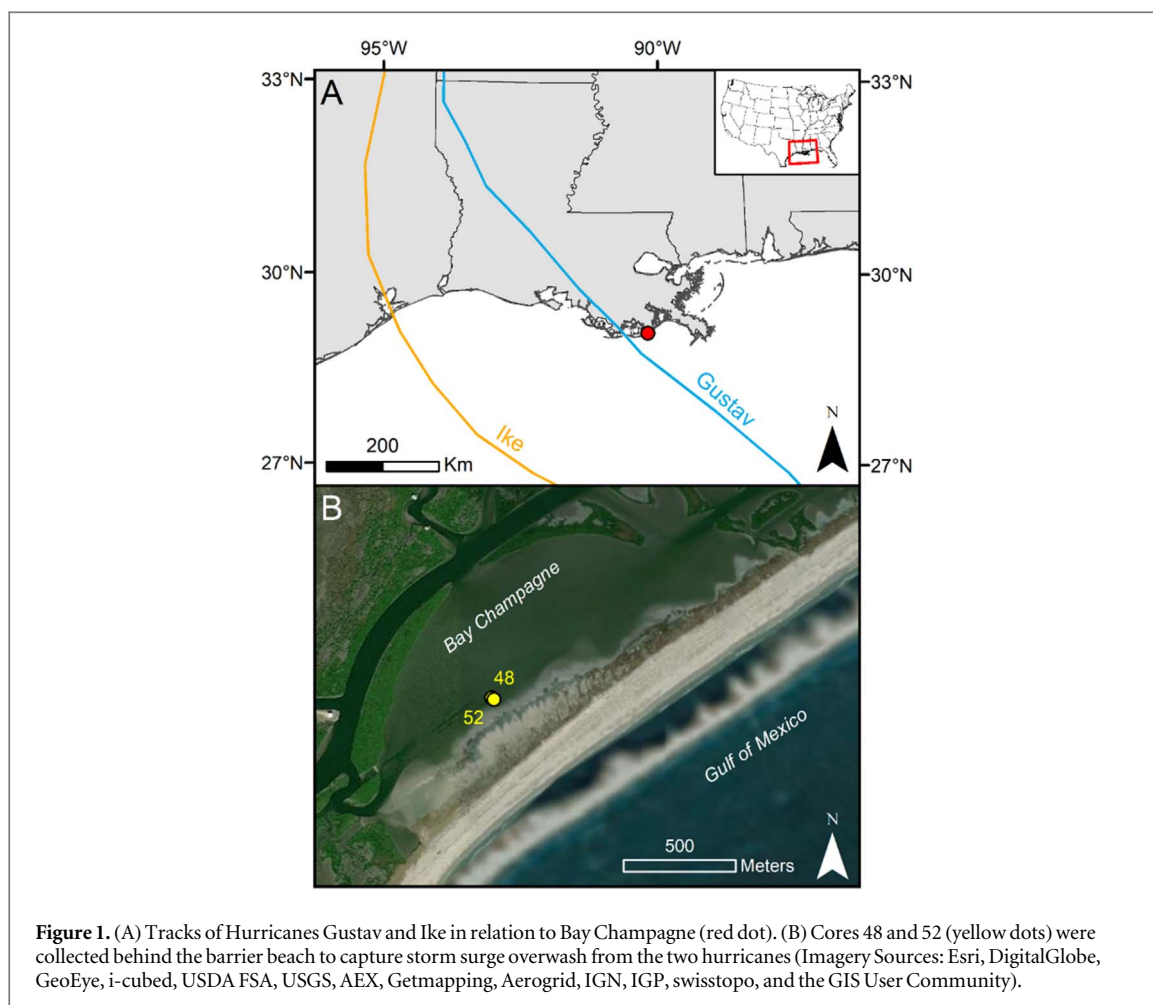
Marianne E Dietz¹ , Kam-biu Liu¹ , Thomas A Bianchette² and Denson Smith³ ¹ Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, United States of America² Department of Chemistry, Oakland University, Rochester, MI, 48309, United States of America³ Independent ResearcherE-mail: mdietz19@outlook.edu**Keywords:** hurricane, geochemistry, XRF, storm surgeSupplementary material for this article is available [online](#)**Abstract**

Hurricanes Gustav and Ike consecutively impacted coastal Louisiana in 2008. Two sediment cores taken from Bay Champagne, a coastal backbarrier lake near Port Fourchon, Louisiana, contain a depositional layer of clastic sediment up to 21 cm thick attributable to these two storms. X-ray fluorescence measurements and statistical analysis suggest the two storm events can be distinguished from one another based on contrasting geochemical profiles. The bottom portion of the layer, attributable to Gustav, contains high concentrations of marine-derived elements, suggesting a strong influence from storm surge. The top portion of the layer, attributed to Ike, contains higher concentrations of terrestrially-derived elements, indicative of contributions from fluvially-driven deposition. The elemental concentration profiles and corresponding environmental data suggest the storm deposits in each core were deposited through two distinct hydrological processes: a storm surge-driven marine intrusion event during Gustav, followed by a mixture of storm-surge and fluvial deposition resulting from Ike. Results show that hurricane-generated deposition in coastal environments is a bi-directional process in which the role of fluvial freshwater deposition cannot be ignored.

1. Introduction

Global climate change is projected to cause more frequent tropical cyclone activity throughout the 21st century, including more major hurricanes (Bhatia *et al* 2018). Since stronger storms are typically responsible for a majority of the damage to coastal areas (Pielke *et al* 2008), assessing which areas are most at risk for major hurricane strikes is crucial. However, predictions about the probability of future hurricane strikes in a specific area largely rely on analyses of historic hurricane landfalls; these analyses are based upon instrumental records of hurricane observations and are typically insufficient to determine long-term activity trends. Such trends are typically reconstructed using environmental proxy records, specifically hurricane overwash deposits preserved in coastal areas. These deposits are the foundation for reconstructing pre-historic hurricane activity (Liu 2004, Donnelly and Woodruff 2007) and can be found in coastal lakes as clastic sediment layers created through storm surge deposition (Liu and Fearn 2000). The detection and quantification of these deposits in sediment cores have been used to reconstruct thousands of years of pre-historic hurricane activity in some areas (Braun *et al* 2017, Bregy *et al* 2018).

The reliability of such reconstructions depends upon accurate counts of hurricane deposit layers. These deposits typically manifest as anomalous sand layers in otherwise muddy coastal sediments and are assumed to be created from elevated storm surge events (Liu and Fearn 1993, Liu and Fearn 2000, Woodruff *et al* 2008). Individual deposits are commonly bound by fine-grained sediments deposited under normal, quiescent environmental conditions. This background deposition serves to separate individual hurricane layers which are



usually visually indistinguishable from one another (Scileppi and Donnelly 2007). If normally-deposited sediments are insufficient or missing (through erosion, bioturbation, decreased sedimentation rate, etc), differentiation between multiple hurricane deposits can be problematic. Hurricanes that impact the same area in rapid succession may not allow time for background sedimentation to be re-established, potentially resulting in multiple hurricane deposits combining to form a single layer. This type of occurrence could easily be misinterpreted in a sediment record as being caused by a single storm event, which would lead to inaccurate assessments of past hurricane activity.

A unique research opportunity was presented in 2008, when back-to-back hurricanes struck the Gulf Coast within a two-week timeframe. These consecutive events caused significant storm surge along the Louisiana coast and resulted in the deposition of a thick sand layer in a coastal lake located south of New Orleans (Liu *et al* 2011). The portions of this sand layer attributable to each respective storm were visually indistinguishable, and presented an ideal case study for investigating possible distinguishing features of successive storm surge deposition events. This study uses a novel combination of traditional geological, geochemical, statistical analyses of two sediment cores in order to differentiate between these consecutive hurricane deposits. The results of this study could be used as a modern analogue for analyzing older (pre-historic) hurricane deposits and improving paleo-hurricane reconstructions.

1.1. Hurricanes Gustav and Ike

In early September 2008, two hurricanes impacted the northern Gulf of Mexico coast in rapid succession (figure 1). Hurricane Gustav made landfall in Louisiana on September 1 as a strong category 2 event, causing a storm surge between 2.5–4 meters, heavy precipitation, and moderate localized flooding (Beven and Kimberlain 2009). Less than two weeks later, Hurricane Ike tracked through the Gulf of Mexico before making landfall in Texas on September 13, also as a category 2 storm. Ike was a much larger hurricane than Gustav, and affected much of the Gulf coast during its lifespan (Brown *et al* 2010). Ike caused storm surge of 1.5–5 meters and brought varying amounts of heavy rainfall to the entire Gulf coast (Berg 2009). The cumulative impacts of both hurricanes caused inundation and widespread flooding of low-lying coastal areas, particularly in coastal Louisiana (Morton and Barras 2011).

1.2. Study site

Bay Champagne, a shallow, semi-circular, and brackish coastal lake in eastern Louisiana that is an excellent repository for storm surge deposition (Liu *et al* 2011, Naquin *et al* 2014) was impacted by both Gustav and Ike. Freshwater input to the site is limited to streamflow from Bayou Lafourche and local precipitation. Bay Champagne is separated from the Gulf of Mexico by a low barrier beach that is overtopped by storm surge in excess of 1.2 meters (Penland and Ritchie 1979). This barrier can be breached during strong storms, creating connections to the Gulf of Mexico, although these connections are typically ephemeral (Dietz *et al* 2018, Whitehurst and Self 1974).

Hurricanes Gustav and Ike caused local storm surges of 2.7 m and 1.3 m at Bay Champagne, respectively (Liu *et al* 2011). Gustav, which made landfall less than 50 km away from the site, caused barrier breaching, beach erosion, and extensive overwash deposition at the site (Morton and Barras, 2011). Though Ike made landfall more than 450 km to the west of Bay Champagne (Berg 2009), the storm's size and track was such that Bay Champagne was within the radius of tropical-storm force winds.

2. Methods

To examine overwash deposits at Bay Champagne, two sediment cores were collected in 2012 just after Hurricane Isaac, a category 1 storm that had minimal discernible geomorphic impact on the site (see Supplemental Information (available online at stacks.iop.org/ERC/3/101001/mmedia)). The core sites are located approximately 300 meters behind the dune crest of the barrier beach to optimally capture hurricane overwash (figure 1). Water depth at the core sites was 1.5 m. BC-48 (46 cm long) was extracted via Russian peat borer, and BC-52 (62 cm long) was extracted with an aluminum push corer. Cores were capped and wrapped in plastic foil to minimize sediment disturbance and water loss during transport. Sediment chronology was established for the top portion of each core through comparison with the stratigraphy of other cores collected in prior years from the same location (see Supplemental Information).

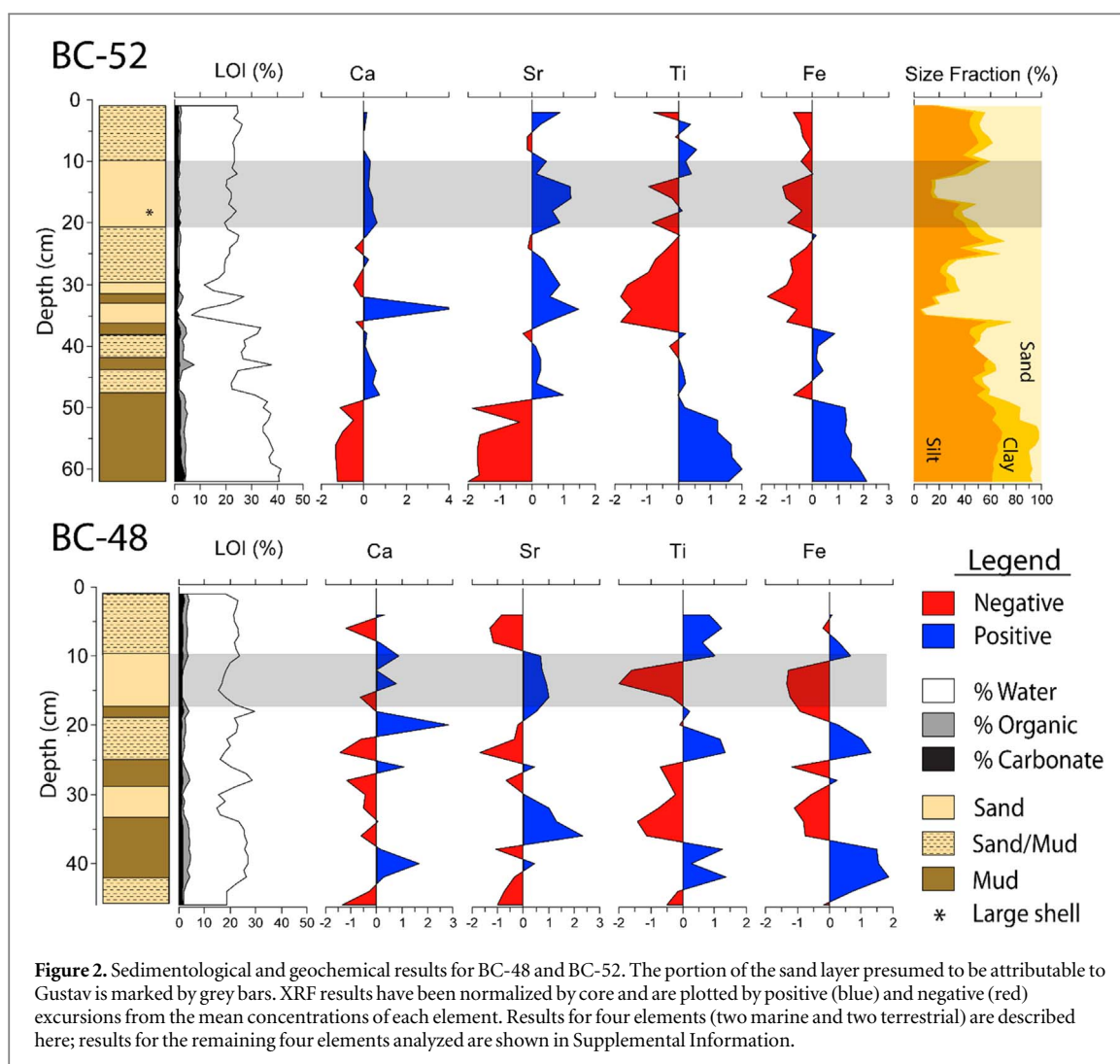
Loss-on-ignition (LOI) was performed at 1-cm intervals to determine water, organic, and carbonate contents; samples were burned at 105 °C, 550 °C, and 1000 °C, respectively, according to standard LOI procedures (Liu and Fearn 2000). Sediment water content can be influenced by factors such as organic matter content, dry density, and particle size, and can be utilized as a proxy for grain size (Menounos 1997). Sand deposits tend to have a lower water content, whereas sediments dominated by finer grain sizes tend to contain more water (McCloskey and Liu 2012). Grain-size analysis was conducted on core BC-52 at 1-cm intervals using a Beckman-Coulter laser particle analyzer (model LS 13-320). Organic matter was removed from samples prior to analysis. Sufficient quantities of sediment were not available to test BC-48.

X-ray fluorescence (XRF) is a commonly used tool to investigate variability of the chemical composition of marine sediments (Rothwell and Croudace 2015) and has been increasingly used to detect past hurricane deposits (Woodruff *et al* 2009, Van Soelen *et al* 2012, McCloskey and Liu 2013, Bianchette *et al* 2017, Yao *et al* 2020a, 2020b, Williams and Liu 2021). While some site-specific variability in elemental provenance likely exists, previous studies along the Gulf of Mexico coast have identified elements that are representative of the marine (S, Cl, Ca, and Sr) and terrestrial (Ti, Fe, Zn, and Zr) environments (Liu *et al* 2014, Naquin *et al* 2014, Yao *et al* 2018). These eight elements were measured at 2-cm intervals along each core using a handheld Innov-X Delta XRF unit. The XRF results were normalized by core to provide a difference from the mean concentration for each element, to facilitate comparisons between the two cores, and to provide a baseline for anomaly detection.

A standard scalar was used to transform both the LOI and XRF data from each core to facilitate comparisons. Principal Component Analysis (PCA) was used to reduce the eleven variables (8 elements, 3 LOI) to two components (Pedregosa *et al* 2011). K-means analysis, a non-deterministic clustering technique (Jain 2010), was then used to assign each sample to a group based on the PCA output. Three groups were specified in an attempt to identify sediment sample provenance (i.e., marine-derived, terrestrially-derived, or mixed).

3. Results

Cores BC-48 and BC-52 exhibit similar stratigraphy (figure 2). Thick sandy layers are present at the top of both cores (17 cm in BC-48, 21 cm in BC-52). In BC-48, a sharp contact exists between the bottom of the surficial sand layer and the darker, finer-grained sediment beneath it. Mud layers are present at 17–19 cm, 25–28 cm, and 34–42 cm, with sand layers interspersed between them. The sediment between 34–43 cm is comprised of stiff gray mud with little to no sand present. In core BC-52, thin (1–2 cm thick), distinctive sand layers are present at 30–32 cm and 34–37 cm, respectively. Interspersed between these layers are deposits comprised of dark, fine-grained sediment containing little to no sand to about 48 cm depth. Sharp boundaries exist between each of these

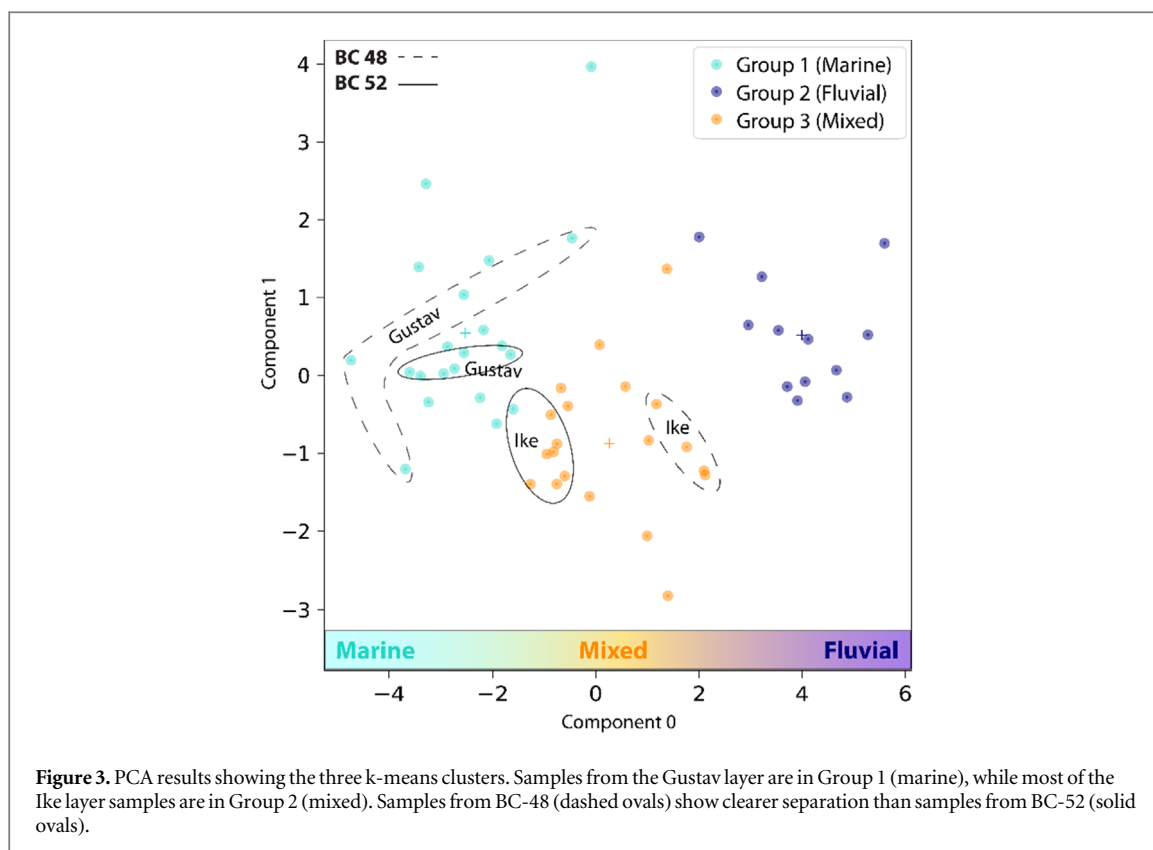


layers. The bottom of the core is comprised of a stiff gray mud, similar to the lower portion of BC-48. Notably, a large shell is located at the bottom of the 21 cm thick sand layer (at 20 cm depth).

Variations in water content in both cores correspond to changes in stratigraphy. The average water content of BC-48 remains the same throughout core, with several notable decreases in sand-rich sections at 10–17, 24–25, and 28–34 cm. The highest water percentages corresponded with clay-rich sections at 17–19 and 25–28 cm depth. The uppermost 10 cm of the core contains a higher water content than the sand layer directly beneath. BC-52 shows a slightly different trend in water content than BC-48. The bottom half of the core has much higher water content than top of the core, and the overall water content decreases towards the top. Notable sharp decreases in water content are observed in sand deposits at 30–32, 34–37, 39–42, and 44–47 cm. A slight decrease in water percentage is observed at 10–21 cm; the very top of the core contains a slightly higher percentage.

Grain size analysis shows that BC-52 is comprised mostly of varying concentrations of silt and sand. A small fraction of clay is also present throughout the core and is highest at the bottom where sand percentage is at a minimum. The grain size data highlight the sand-rich layers at two depths where percent sand maxima occur: 13–16 and 32–35 cm. The very top of the core is a relatively even mix between sand and silt with a small percentage of clay.

For simplicity, XRF results for four elements (two marine-derived and two terrestrially-derived) are described here; results for the remaining four elements analyzed are included in Supplemental Information. Positive and negative excursions from the mean are observed in all elements in both cores. Most of these excursions are within 1–2 standard deviations from the mean values. Notably, an anomalous positive Ca excursion is present in each core, with values 3–4 standard deviations from the mean. For BC-52, positive excursions exist in Ca and Sr at the top of the core; both of these elements have negative excursions at the bottom of the core. The opposite trend is observed in both Ti and Fe concentrations in this core; values for both elements show more negative excursions at the top of the core and positive excursions at the bottom of the core. The marine-derived elements (Ca and Sr) are mostly positive throughout the top three-quarters of the core and are



strongly negative in the bottommost portion of the core. This trend is nearly the opposite in the terrestrially-derived elements (Ti and Fe). BC-48 exhibits more variability in the XRF results for each of the four elements. Positive and negative excursions appear to alternate for each element throughout the core. However, in almost all samples, the marine- and terrestrial-element trends are opposite: where marine elemental concentrations are higher (positive excursion), terrestrial elemental concentrations are low (negative excursion).

PCA results show clear separation between the three k-means clusters (figure 3). Sediment samples that are sand-rich are classified in Group 1; samples that are clay- and silt-rich (bottom of BC-52) are in Group 2. Samples comprised of both sand and silt/clay are classified in Group 3. Based on this observation, the three groups are labeled based on likely sediment provenance. For statistical purposes, we consider the sand layers to be hurricane overwash deposition. Additionally, Component 0 is used as a spectrum of sediment provenance; lower values represent marine-derived sediments, while higher values indicate terrestrially-derived, fluvially-deposited sediments.

4. Discussion

4.1. Identification of Hurricane layers

Sand layers present at the top of both cores are presumed to have been deposited by the cumulative impacts of Gustav and Ike. These layers are approximately the equivalent thickness of a sand layer observed in cores collected from the same site directly after Ike's landfall in 2008 (Liu *et al* 2011). Based on limited pollen and sediment evidence from a single core, Liu *et al* (2011) hypothesized that the 17 cm sand layer at the core top was the cumulative product of the two hurricane events. Based on stratigraphy, the bottom portion of the sandy layers in each core is attributed to Gustav (gray bar in figure 2), while the top portion was likely deposited by the more recent Ike. However, no clear visual distinction is apparent between the presumed-Gustav and -Ike layers in any core collected at this site. The top of each sand layer contains more fine-grained sediment that was slightly darker in color than the lower portion of the layer, which is comprised of coarse-grained sand.

The sand layer between 13 and 16 cm in BC-52 contains one of the highest mean grain sizes (~3 phi; fine sand) and is located at the same depth of the layer presumed to be attributed to Gustav. The presence of coarser grains (sand) indicates high energy sediment transport in the form of storm surge overwash. The layer overlying this section (presumably from Ike), while sand-dominant, exhibits a smaller mean grain size of 4–5 phi (silt/very fine sand), indicating it contains a larger component of fine-grained sediment. Since fine-grained sediments are

typically indicative of low-energy deposition, this increase suggests a larger fluvial influence during the creation of this layer.

LOI results for BC-48 show the presumed Gustav and Ike sand layers contain contrasting water contents. A notable decrease in water occurs at 10–17 cm depth, corresponding with the portion of the sand layer attributed to Gustav. The portion of the layer above 10 cm (attributable to Ike) has a higher water percentage, suggesting an increase in fine sediment and a decrease in sand content. The water curve for BC-52 is less informative, but grain size analysis provides a direct measure of sediment composition and indicates that BC-52 is comprised mostly of varying silt and sand contents.

4.2. Geochemical characteristics of Marine and Fluvial sediments

Geochemical variations exist between the upper and lower portions of the sand layer in both cores (figure 2). In both cores, the presumed Gustav layer showed negative excursions in terrestrially-derived elements Ti and Fe, and positive excursions in Ca and Sr, suggesting a strong marine influence. The trend is less clear for the presumed Ike layer, which shows lower concentrations of marine elements than the Gustav layer along with moderate increases in terrestrial elements. Core sections that exhibit increases in water content correspond with elevated percentages of silt and clay, and increases in terrestrially-sourced elements. These fine-grained sediments rich in terrestrially-sourced elements are presumed to be terrestrial (Bianchette *et al* 2016), and likely represent normal fluvial deposition under quiescent conditions. Conversely, core sections that show decreases in water content, an increased percentage of sand, and increases in marine-derived elements were probably deposited via storm surge.

The sediment and chemical composition of the Gustav layer in both cores is indicative of a strong marine influence and suggests that this layer was formed through storm surge depositional processes. The Ike layer, however, displays a distinctly different geochemical pattern than the Gustav layer, and appears to exhibit evidence of both marine and fluvial depositional processes. These results indicate the Gustav and Ike layers can be distinguished based on their geochemical makeup.

4.3. Statistical signature of the Gustav and Ike deposits

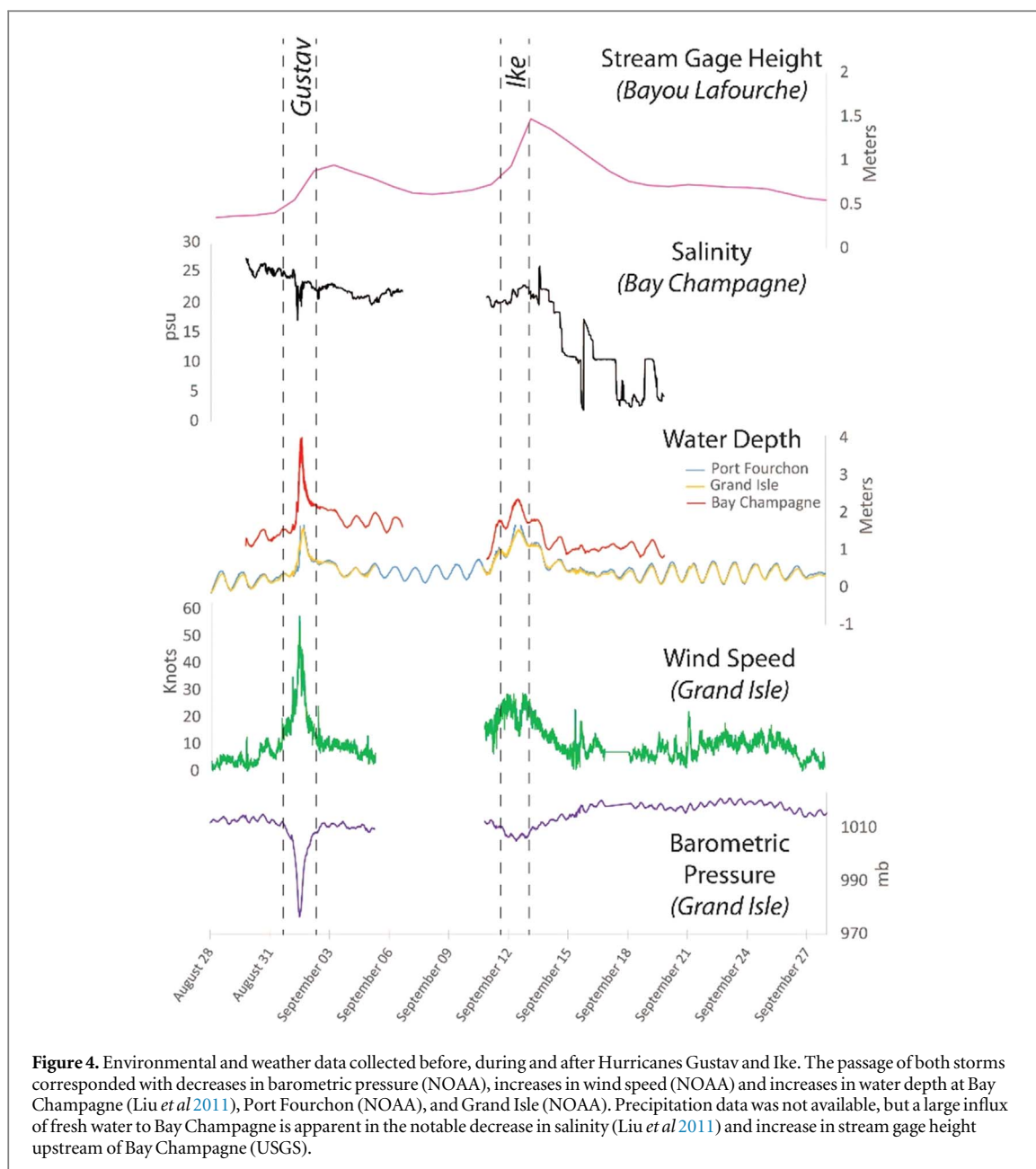
The Gustav layers for both cores are sand-rich and clearly classified in Group 1 (marine), consistent with the sedimentological and geochemical results. The Ike layers in both cores are mostly contained within Group 3, which represents a mixture of marine- and fluvial-derived sediments. These results reinforce that the Gustav and Ike layers are sedimentologically and geochemically distinct from one another, and statistically different from normal fluvial deposition (Group 2).

Samples from BC-48 (figure 3, gray ovals) are clearly separated by the Component 0 spectrum. The samples from the Gustav layer are at the lowest end of the spectrum, while the Ike layer samples are much closer to Group 2 (fluvial) samples. There is less distinction between the Gustav and Ike samples from BC-52 (figure 3, pink ovals). The Gustav layer is clearly marine (Group 1), but the Ike layer, while mostly contained within the mixed group (Group 3) also contains a sample from the marine group (Group 1). This suggests that the sharp definition between the Gustav and Ike layers displayed in BC-48 may not exist as definitively in other cores.

4.4. Environmental impacts of Gustav and Ike

Environmental and meteorological data collected at and around Bay Champagne provides insight to the local conditions before, during and after the passages of Gustav and Ike (figure 4; figure S4 Supplemental Info). Meteorological data from nearby Grand Isle, LA recorded the arrival of each storm, indicative of increased wind speeds and a corresponding decrease in barometric pressure. The period of maximum local impact from each hurricane is shown in figure 4 with dotted lines. It is clear from these data that Gustav tracked much closer to this area than Ike and thus had a much greater local impact. Storm surge generated by each hurricane is evident at Bay Champagne by changes in water depth measurements at Bay Champagne and two nearby locations (see supplemental figure S4). The storm surge caused by both storms was high enough to overtop the barrier beach at Bay Champagne, but the surge caused by Gustav (2.7 m) was more than twice as high than the surge during Ike (1.3 m) (Liu *et al* 2011). Additionally, Gustav's storm surge quickly peaked and retreated, while the surge produced by Ike occurred more gradually.

Direct measurements of precipitation were not available at Bay Champagne during this time period, likely because weather stations were destroyed or disabled by Gustav prior to landfall. However, the presence of freshwater inputs from hurricane-driven precipitation is indirectly evident in measurements of salinity of Bay Champagne and stream gage height measurements (an indication of freshwater flow) of Bayou Lafourche (figure 4), the primary freshwater source for Bay Champagne and the surrounding region. Gustav caused a gradual decrease in salinity at Bay Champagne and a gradual increase and decrease in stream height at Bayou Lafourche (figure 4), suggesting a moderate freshwater input. In contrast, salinity values plummeted to near zero



and stream height quickly rose more than a meter during and after Ike's passage. This large influx of freshwater was likely caused by hurricane-derived precipitation, since Ike brought a significant amount of precipitation to this region (Berg, 2009). It is also worth noting that stream height at Bayou Lafourche had not yet returned to pre-Gustav levels prior to Ike's arrival, suggesting that flood conditions were likely still present before the addition of Ike-induced precipitation. Stream height also appeared to be slow to return to normal after both storms, which probably indicates prolonged, widespread flooding in the area.

4.5. Hurricane-driven, bi-modal depositional process

Deposition for each hurricane appears to have occurred through different hydrologic processes. The Gustav layer was likely deposited through storm surge processes, while the layer attributed to Ike was seemingly formed through a combination of storm surge and fluvial processes. However, both storm deposits appear to contain some component of each process; neither deposit was created by a single (directional) process. This indicates that hurricane deposits can be created not only through storm-surge processes but also fluvial processes resulting from hurricane-induced flooding, and their relative contributions can vary from one storm to another and from one site to another. Other recent studies have highlighted the importance of fluvial input in hurricane-induced deposition. Wang *et al* (2019) analyzed diatoms to understand marine and fluvial contributions in a sand layer deposited by the historic Bernard Romans hurricane of 1772, ravaging southern Alabama. Yao *et al* (2019) implemented sedimentological and geochemical proxies to capture a fluvial signal in Hurricane Harvey

deposits located in the San Bernard National Wildlife Refuge in southeast Texas. Williams and Liu (2019, 2021) characterized Hurricane Harvey's fluvial flood deposit and Hurricane Ike's washover deposit in the McFaddin National Wildlife Refuge in eastern Texas based on their sediment texture, XRF measurements, and foraminifera contents.

The creation of hurricane storm deposits at Bay Champagne appears to be driven by a bi-modal depositional mechanism corresponding of two distinct parts. First, storm-surge transports marine-derived sediment into interior areas. Second, heavy hurricane-induced precipitation causes localized freshwater flooding during and after the storm's passage. Terrestrially-derived sediments are deposited in coastal areas as floodwaters recede seaward. These bi-directional landward and seaward processes occur in concert, but would likely depend on hurricane characteristics (e.g., size, intensity, landfall location, trajectory) as well as the geologic situation of the coastal study site. The relative importance of marine and fluvial processes in the creation and preservation of hurricane deposits most likely varies among storm events, even at the same location, as evident by the Gustav and Ike data.

5. Conclusions

Our study demonstrates that successive coastal deposits created from hurricanes Gustav and Ike in 2008 at Bay Champagne can be differentiated through sedimentary and geochemical analysis. While both hurricanes impacted the same site, each storm caused varying environmental effects which were recorded and preserved in the sediment record. The Gustav layer was likely deposited via storm surge while the Ike layer was seemingly formed through a combination of storm surge and fluvial processes. The findings from this study contribute to coastal sedimentology in two principal ways: by utilizing geochemical, sedimentological and statistical proxies to delineate distinct hurricane-induced marine and terrestrial processes in a dynamic coastal backbarrier setting, and by identifying and separating the hydrological impacts of specific recent hurricanes within thick clastic deposits. The bi-modal depositional mechanism documented in this study suggests that the role of freshwater flooding requires additional attention, especially in determining if additional proxies can identify and separate marine and fluvial processes, and if these processes can be clearly delineated in older, paleo-deposits. In addition, thick, hurricane-derived clastic layers should be analyzed with multiple proxies to avoid undercounting, thereby underestimating local risk assessments.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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