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Influence of a spatially complex framework geology on barrier island geomorphology

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ABSTRACT

Barrier island response and recovery to storms, and island transgression with relative sea level rise, can be influenced by the framework geology. The influence of framework geology on barrier island geomorphology has previously been examined in areas where the framework is rhythmic alongshore or consists of an isolated paleo-channel or headland. The purpose of this paper is to examine the influence of framework geology on beach and dune geomorphology at Padre Island National Seashore (PAIS), Texas, USA, where the framework geology is variable alongshore. Alongshore beach and dune morphometrics and offshore bathymetric profiles were extracted from a combined topography and bathymetry digital elevation model (DEM) using an automated approach along the ~100 km study area, and an electromagnetic induction (EMI) survey was used to map the subsurface framework geology. Wavelet decomposition, Global Wavelet (GW), and bicoherence analyses were used to test for spatial relationships between and within the extracted alongshore metrics. GW trendlines demonstrate that beach and dune morphometrics are structurally controlled. Hotspots in wavelet coherence plots between framework geology and alongshore island morphometrics indicate that the paleo-channels dissecting the island influence beach and dune morphology, with large dunes found in the area directly landward of the paleochannels. Bicoherence analysis of alongshore beach and dune morphometrics indicates that low-frequency oscillations due to framework geology interact with higher-frequency oscillations, with greater small-scale variability in the dune line directly landward of the paleo-channels. These results suggest that the paleo-channels of PAIS non-linearly influence beach and dune morphology, which in turn alters the response of the island to storms and sea level rise. It is argued that an understanding of the framework geology is key to predicting island response to sea level rise and framework geology needs to be included in barrier island models. This paper demonstrates that an irregular framework geology influences small-scale coastal processes, and creates interactions across scales that influence beach and dune morphology and affects barrier island response to storms and sea level rise.

1. Introduction

Barrier island morphology is the product of modern processes (*e.g.* alongshore sediment transport, wave action) interacting with pre-existing topography and bathymetry formed by past processes or in response to past storms, changes in sediment supply and sea level rise. Improving our understanding of the role of subsurface geology on coastal development was recognized by Riggs et al. (1995), stating that "*it is imperative to incorporate the geologic framework into all models concerning the large-scale behavior of any coastal system*" (p. 215). Used here, framework geology is defined as any subsurface variation in geologic structure, where geologic structure can be defined by variations in sediment type (*i.e.* sand *vs.* silt *vs.* clay), differences in compaction, or significant changes in the subsurface organic content or mineralogy. Examples of framework geology features identified along the U.S. coast include relict infilled paleo-channels (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006), mud-core ridges (Houser and Mathew, 2011; Houser, 2012; Houser et al., 2015), shore-

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oblique gravel ridges (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006; Lazarus et al., 2011), and submerged outwash fan headlands (Schwab et al., 2013; Schwab et al., 2014; Warner et al., 2014). Studies of barrier islands along the U.S. Atlantic and Gulf of Mexico coasts demonstrate that subsurface geology can influence patterns of island development and transgression at broad geographic scales (Riggs et al., 1995; Lazarus et al., 2011; Lentz and Hapke, 2011; Houser, 2012; Schwab et al., 2013; Hapke et al., 2016), although these studies were focused on coasts with rhythmic geology, simple paleo-channels (*i.e.* limited bifurcation), or a single submerged headland. In many other environments, including the Outer Banks of North Carolina (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006) and parts of the Texas coast (Fisk, 1959; Anderson et al., 2014; Anderson et al., 2016), the framework geology is dominated by an irregular subsurface and offshore structure of varying size and sediment texture. The influence of framework geology on barrier island geomorphology is often overlooked or in some cases has been discounted as important when predicting future change and managing coastal resources (Duran and Moore, 2013; Murray et al., 2015; Goldstein and Moore, 2016; Goldstein et al., 2017).

The importance of modelling historical coastal morphology and predicting future coastal morphological changes and vulnerability is highlighted by recent work focused on: 1) improving our understanding and predictions of storm impacts (Stockdon et al., 2006; Plant and Stockdon, 2012; Gutierrez et al., 2015), 2) improving long-term coastal change assessments (Hapke et al., 2016), and 3) understanding coastal vulnerability to climate change and sea-level rise (Anderson et al., 2014; Wallace and Anderson, 2013; Dai et al., 2015). A Bayesian Network (BN) approach has recently been used to predict and assess the vulnerability of islands to sea level rise based on expert knowledge of hydrodynamic forcing, modern geomorphology and geologic constraints (Stockdon et al., 2006; Plant and Stockdon, 2012; Long et al., 2014; Wilson et al., 2015). The BN approach has been shown to be a valuable approach to predicting future changes, but there remains uncertainty about how the framework geology affects the hydrodynamic forcing, beach, and dune morphology. Improving model performance requires further study of how the framework geology influences beach and dune morphology through variations in wave energy or sediment supply and texture (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006; Houser, 2012; Schwab et al., 2013; Schwab et al., 2014; Warner et al., 2014).

As noted, the framework geology can range from rhythmic features to irregular and complex structures. Semi-regular offshore shore-oblique bar and trough structures have been documented at South Padre Island, Texas (Houser and Mathew, 2011), Santa Rosa Island, Florida (Houser et al., 2008; Houser, 2012; Houser et al., 2015), along the southeastern U.S. Atlantic coast (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006; Lazarus et al., 2011), and at Fire Island, New York (Lentz and Hapke, 2011; Schwab et al., 2013; Schwab et al., 2014; Warner et al., 2014). At South Padre Island, the origin of the bar and trough features is unclear, although it is plausible that they are formed from the ancestral Rio Grande paleo-river delta, which has been identified by Simms et al. (2007) and Anderson et al. (2016). Presumably, sediment from the delta has been reworked into the modern bar and trough sequences by waves approaching the coast at oblique angles. Troughs in the nearshore bathymetry correspond to narrow sections of the beach and taller dunes (Houser and Mathew, 2011). An opposite pattern is observed at Santa Rosa Island, where the ridge and swale bathymetry offshore of Santa Rosa Island creates quasi-regular littoral cells (Stone, 1991), and an alongshore variation in beach and dune morphology that determines island response to storms and island transgression (Hyne and Goodell, 1967; Stone, 1991; Houser, 2012). Similar structures are present along portions of the southeastern U.S. Atlantic coast and are related to irregular and non-repeating relict subsurface paleo-channels infilled during Holocene sea-level transgression (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006). Shoreface attached sand ridges also alter beach and dune processes at Fire Island, NY (Hapke et al., 2010; Lentz and Hapke, 2011; Schwab et al., 2013; Hapke et al., 2016), where they are believed to be formed and maintained by oceanographic processes reworking a sandy submerged headland (Schwab et al., 2014; Warner et al., 2014).

Regardless of how these different shore-oblique bar and trough features developed, their location and morphology can influence beach and dune morphology. Shoreline variability and erosional hotspots along the southeastern U.S. coast have also been linked to shore-oblique bars and infilled paleo-channels in the framework geology (McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006; Lazarus et al., 2011), where relict infilled paleo-channels are associated with areas exhibiting punctuated shoreline change. Lazarus et al. (2011) suggested that dominant driver of shoreline change varies over distinct spatial scales and that the dominant coastal processes will likely gradually transition along this continuum. For example, surf-zone currents are identified as the dominant driver of coastal geomorphology at alongshore length scales ranging from 30 m to 500 m, but that wave propagation over complicated bathymetry, as reflected by persistent kilometer-scale bedforms, begins to influence coastal geomorphology at an alongshore length scale of ~300 m. At the largest alongshore length scales analyzed, it was hypothesized that the dominant driver of coastal geomorphology are gradients in the wave-driven alongshore current associated with island curvature, although this hypothesis was not testable because the dataset did not extend far enough along the coast. The linear transition of dominant coastal processes with increasing alongshore length scales suggests that finer-scale processes cease to be a significant driver of coastal morphology at larger alongshore length scales and does not account for the influence of framework geology or interaction between broad- and fine-scale processes. Cross-scale interactions between framework geology and localized processes has been suggested in shoreline change studies (Hapke et al., 2016) and beach-dune morphology (see Houser, 2012) in areas where the framework geology exhibits a regular alongshore variation. While alongshore shoreline behavior may be dissipative, variations in the dune morphology are reinforced by washover (Houser, 2012; Weymer et al., 2015a), which occurs on shorter timescales than the recovery of the dune through the expansion of dune-building vegetation (Houser et al., 2015).Shoreline behavior may become disconnected from beach morphology and behavior, and beach morphology may become disconnected from dune morphology and behavior, a process referred to as 'process decoupling' (Houser, 2009; Hapke et al., 2016).

The purpose of this paper is to test the hypothesis that an irregular framework geology influences fine-scale coastal processes (< 1000 m), and creates interactions across scales that influence beach and dune morphology and island response to storms and sea level rise. Previous studies of barrier island geomorphology have tended to focus on shoreline change at discrete alongshore length scales (Lazarus et al., 2011), but there is evidence that the framework geology influences broad-scale coastal processes, which in turn non-linearly influence filer-scale coastal processes responsible for changes in shoreline position, beach morphology, and dune morphology (Hapke et al., 2016). In this respect, the interaction between broad- and fine-scale coastal processes resembles a feedback mechanism, which is examined in the current study through wavelet decomposition, bicoherence analyses, and wavelet coherence. Wavelet decomposition provides valuable insight into structural patterns within a single morphological variable (see Lazarus et al., 2011), while bicoherence analyses help identify non-linear interactions (see Elsayed, 2006a, 2006b) between long-term (broad-scale) coastal processes (*i.e.* island transgression patterns and framework geology influences) and short-term (fine-scale) coastal processes (*i.e.* swash and surf zone processes). An extension of wavelet decomposition, wavelet coherence provides information about phase relationships between two variables. The analytical approaches used in this paper provide insight into process decoupling of shoreline, beach, and dune behavior at different spatial and temporal scales. Understanding and

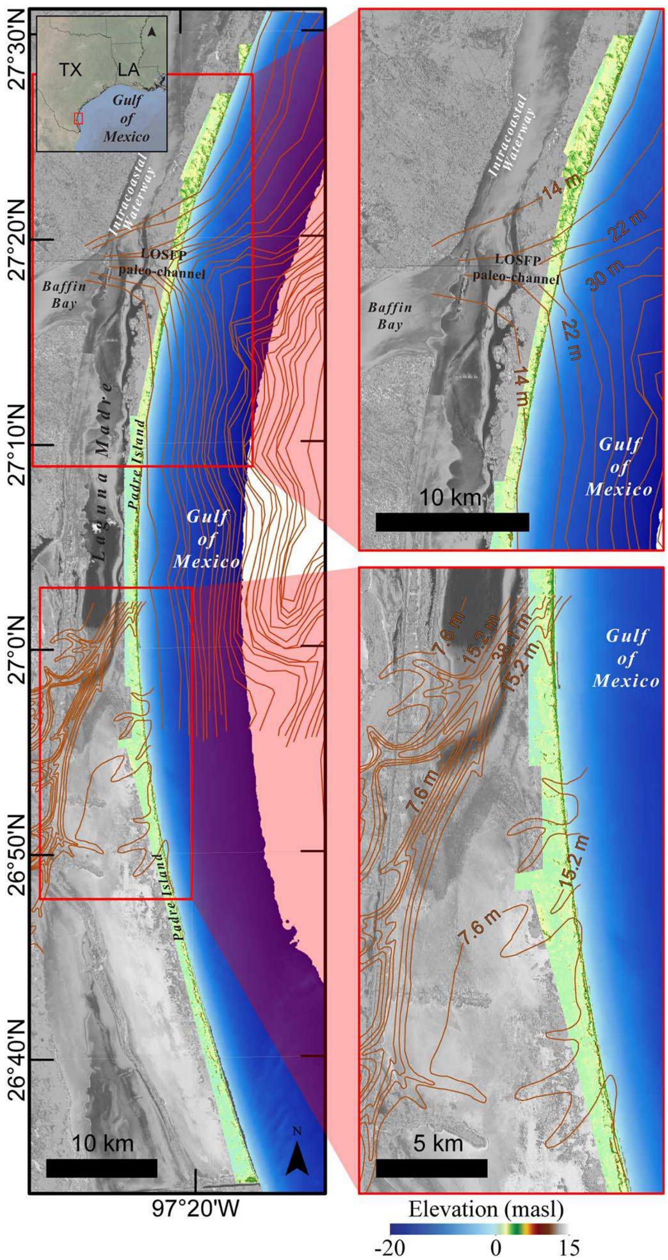

Fig. 1. Padre Island National Seashore topobathy DEM with MIS II subsurface contour lines from Fisk (1959) and Anderson et al. (2016).

quantifying the influence of framework geology as it interacts with shorter-term coastal processes is vital to managing coastal resources for short- and long-term sustainability.

2. Regional setting

This study was conducted within Padre Island National Seashore (PAIS), which forms a significant portion of North Padre Island, which is the longest continuous barrier island in the world. Located along the south Texas, USA coast, PAIS represents an ideal location to test for and quantify the influence of framework geology on long-term coastal morphology because it has documented geomorphic variability in the subsurface framework geology (Fig. 1; Fisk, 1959; Simms et al., 2007; Anderson et al., 2016). The central part of PAIS is characterized by large, relatively continuous dunes, compared to the elongated parabolic dunes in the north and the heavily scarped and dissected dunes in the south. The island is separated from the mainland by Laguna Madre, through which the Intracoastal Waterway (ICW) was dredged in the 1950s.

A previous study of the Laguna Madre and PAIS area used seismic surveys and sediment cores to demonstrate that there is significant variation in the underlying subsurface geology (Fig. 1; Fisk, 1959). While the study did not cover the entire length of Laguna Madre and PAIS, results suggest that there are multiple paleo-channels dissecting the central part of Laguna Madre and PAIS. These channels were hypothesized to have been incised into the Pleistocene mud surface and infilled with sands during Holocene sea-level transgression. This chronology is consistent with the prevailing theory of formation of PAIS proposed by Weise and White (1980), where the island was initially a series of disconnected barrier islands during the last glacial maximum (~18 ka). During this time, a series of channels were incised into the paleo-topographic surface. Rapid sea-level transgression during the late-Pleistocene and Holocene drowned the relict dunes and submerged other dunes located approximately 80 km inland, resulting in disconnected offshore shoals in the current location of PAIS. Sand from the relict Pleistocene dunes (~80 km offshore) and sediment discharged from rivers was reworked *via* alongshore currents around 2.8 ka, causing the disconnected shoals to coalesce into a more continuous shoal. It was hypothesized that sediment from the offshore relict dunes and river discharge eventually supplied enough sediment to cause the shoals to aggrade vertically enough to emerge as the modern barrier island (Weise and White, 1980).

Anderson et al. (2016) integrated offshore seismic surveys throughout the Gulf of Mexico to identify and extract the marine isotope stage (MIS) II paleo-surface (Fig. 1). Knick points in the MIS II surface offshore of PAIS indicate that the island is dissected by at least two substantial paleo-channels. The southern channel visible in the surface is in relative agreement with the location of the channel identified by Fisk (1959) in Laguna Madre and PAIS. This channel appears to make an abrupt bend to the north offshore of PAIS, and eventually intersects a large northern paleo-channel immediately adjacent to Baffin Bay. Simms et al. (2007) and Anderson et al. (2016) identified this paleo-channel as the ancestral Los Olmos, San Fernando, and Patronila Creeks (LOSFP) that were drowned during the most recent sea level transgression and eventually filled with sediment. The combination of relict infilled paleo-channels and complex modern island geomorphology make PAIS an ideal location to test the hypothesis that the framework geology influences barrier island geomorphology through interactions with higher-frequency processes.

3. Materials and methods

3.1. Subsurface framework geology

Information about the subsurface framework geologic structure was derived from a ~100 km long electromagnetic induction (EMI) survey. Subsurface apparent conductivity was measured every 10 m along the backbeach at 3 kHz, 10 kHz, and 15 kHz using a GSSI Profiler EMP-400 portable handheld device (Weymer et al., 2016; Weymer, 2016). Previous research demonstrates that EMI is a valuable tool for investigating subsurface geologic structure in a marine coastal environment (Seijmonsbergen et al., 2004; De Smedt et al., 2011; Weymer et al., 2015b; Weymer et al., 2016; Weymer, 2016). The current paper builds on previous work by utilizing an alongshore EMI survey as a proxy for subsurface framework geology. Since the depth of investigation is greatest for the 3 kHz frequency (~5 m) compared to 10 kHz and 15 kHz, the 3 kHz data was used for mapping the subsurface framework geology along the barrier island. Areas of lower apparent conductivity are interpreted as areas where the Pleistocene ravinement surface is deeper from the modern surface and the instrument is only measuring the conductivity of the Holocene sands overlying the Pleistocene paleo-surface. Conversely, a shallower Pleistocene ravinement surface is represented by areas of higher apparent conductivity because the finer sediment ravinement is more conductive than the overlying Holocene sands. This geologic interpretation of apparent conductivity is consistent with previous studies using EMI to identify and map subsurface geologic variations (see Seijmonsbergen et al., 2004 and De Smedt et al., 2011).

3.2. Surface morphology

Surface morphology for PAIS is derived from 2009 LiDAR data accessible from NOAA's Digital Coast. Raw point cloud data was processed into a digital elevation model (DEM) using System for Automated Geoscientific Analyses (SAGA) GIS software. A semi-variogram was fit to the raw point cloud elevation values to account for spatial structure in the point cloud. An ordinary kriging algorithm was used with the semi-variogram parameters to interpolate the point cloud to a continuous 1 m resolution DEM (± 15 cm vertical and horizontal accuracy). The LiDAR data available was acquired using a sensor operating in the red portion of the electromagnetic spectrum, and, as a result, does not capture subaqueous surfaces. Since the LiDAR-derived DEM does not include the bathymetric surface, depth to water bottom was obtained from a National Geophysical Data Center (NGDC) coastal relief model (CRM) with a 10 m resolution and accurate to 1 m vertically (NOAA National Centers for Environmental Information, 2017). To facilitate comparison between the LiDAR-derived DEM and CRM, the CRM was resampled using a spline interpolation to a resolution of 1 m, based on the DEM grid. Since the LiDAR was collected in the red portion of the electromagnetic spectrum and does not contain bathymetry, the DEM includes the water surface. This means that there are a series of breaking waves visible at the shoreline and within the surf zone in the original DEM. The shoreline location was extracted as 0.2 m above sea level (masl), which is slightly above the tallest breaking wave present in the DEM. Beach width, beach volume, dune height, dune volume, island width, and island volume were extracted every 1 m along ~100 km of PAIS a multi-resolution automated approach based on relative relief (Wernette et al., 2016), resulting in a series of continuous alongshore data series. Each data series can be treated as a 'signal'. The shoreline extracted from the topobathy DEM was offset seaward in 1 km intervals up to 7 km offshore to obtain bathymetric depth profiles along the entire island.

3.3. Shoreline change

Monitoring patterns of long- and short-term shoreline change is a continuing focus of the Texas Bureau of Economic Geology (BEG). Historical shoreline position along much of the Texas Gulf of Mexico coast was derived from a combination of historical maps, aerial imagery, and LiDAR. The provided BEG shoreline change values were computed using intermittent shoreline position data from 1937 to 2007. Shoreline change analysis was conducted by the BEG using the digital shoreline analysis system (DSAS), which employs a series of traditional shore-orthogonal transects extending from a baseline. To assess long-term patterns of shoreline change, we utilize both end-point rate (EPR) and linear regression (LRR) approach. The EPR change estimate is a simple linear distance between the locations along a transect where the shoreline in 1937–38 and shoreline in 2007 intersect the transect. These intersecting points represent the sum of short-term processes to influence long-term shoreline change.

LRR shoreline change rates are based on the linear regression rate for a series of shorelines from 1937–38 to 2007 intersecting a series of transects, while the exact years varies by county. All EPR and LRR change estimates are derived from publicly available shoreline change data from the Texas Bureau of Economic Geology. Change estimates for Kelberg County are based on shoreline position information from 1937–38, 1956–59, 1974 (partial coverage), 1995, 2000, and 2007. Estimates for Kenedy County are based on shoreline positions from 1937–38, 1969, 1974, 1995, 2000, and 2007. Rate estimates for Willacy County are based on shoreline information from 1937, 1960, 1975, 1995, 2000, and 2007.

3.4. Statistical analyses

The extracted island metrics and bathymetric profiles are analogous to time-series, where space (*i.e.* geographic latitude) was substituted for time. Each of the alongshore metrics was decomposed using a continuous wavelet transformations (CWT) with a complex Morlet (Gabor) wavelet, which provides a balanced trade-off between frequency and spatial resolution. CWT plots provide insight into data structure at a range of frequencies. All wavelet decomposition analysis was conducted using the *biwavelet* package in R (Gouhier et al., 2016). Statistically significant areas of the wavelet plots were identified using Chi-square analysis by comparing the extracted waveform to a simulated red-noise signal. Wavelets serve as a valuable approach to extract detailed information about the spatial structure at all length scales along the entire length of PAIS by fitting a waveform to data at different locations and frequencies in the data series. Global Wavelet (GW) was subsequently extracted from the CWT transformation at multiple spatial scales using AutoSignal©, signal processing software. Plotting the computed GW variance against the alongshore scales (*i.e.* wavelength) provides useful information about the spatial structure of the alongshore data. To improve interpretation of the GW plots, a logarithmic stretch was applied to both variance and alongshore wavelength axes.

Power trendlines (*i.e.* trendlines fit using a power function) were fitted to each of the GW morphometrics to examine whether the extracted signal was white noise, structurally controlled (*i.e.* pink noise), or dissipative red noise (*i.e.* Brownian motion). A trendline with slope approaching 0 is considered white noise because variance does not change with spatial scale. Therefore, data at a given location is scale invariant and does not have any broader structural control. Metrics with slopes approaching 1 are considered pink noise, and represent patterns that are structurally controlled. Steeper sloping trendlines approaching 2 or greater are considered red noise (*i.e.* Brownian motion). Red noise signals are dissipative and tend to lack significant small-scale variability, as observed with long-term shoreline change where alongshore variations in bathymetry create alongshore transport gradients that tend towards a straight coast (Lazarus et al., 2011; Lazarus and Armstrong, 2015; Lazarus, 2016). In this respect, GW trendlines provide useful insight into the degree to which a signal exhibits structural control across a range of spatial scales.

3.5. Bispectrum and bicoherence

It is feasible that some metrics may exhibit an interaction between small-scale variations and the larger-scale variations on which they are super-imposed. One useful approach to examine and test for these non-linear interactions is by computing the bispectrum of a signal. Bispectrum works by measuring the degree of phase coupling between two different wavelet scales. Although bispectrum is often computed using Fourier transform, we computed bispectrum using CWT information extracted from each metric because CWT provides more continuous information about the data structure. The bispectrum of a given signal was computed in R using:

$$B_{yxx}(a1, a2) = \int W_y^*(a, \tau) W_x(a1, \tau) W_x(a2, \tau),\ d\tau \qquad (1)$$

where $a1$ and $a2$ are wavelet components of different scale lengths of $x(t)$ and a is a wavelet component of $y(t)$ (Elsayed, 2006a). The wavelet transform of signal y is represented by W_y and the wavelet transform of signal x is represented by W_x. ${W_y}^*$ represents the complex conjugate of W_y. This computation assumes that the frequency sum rule is satisfied such that $1/a = 1/a1 + 1/a2$.

The bicoherence (*i.e.* bispectral coherency) is useful for quantifying frequency coupling by squaring and normalizing the computed

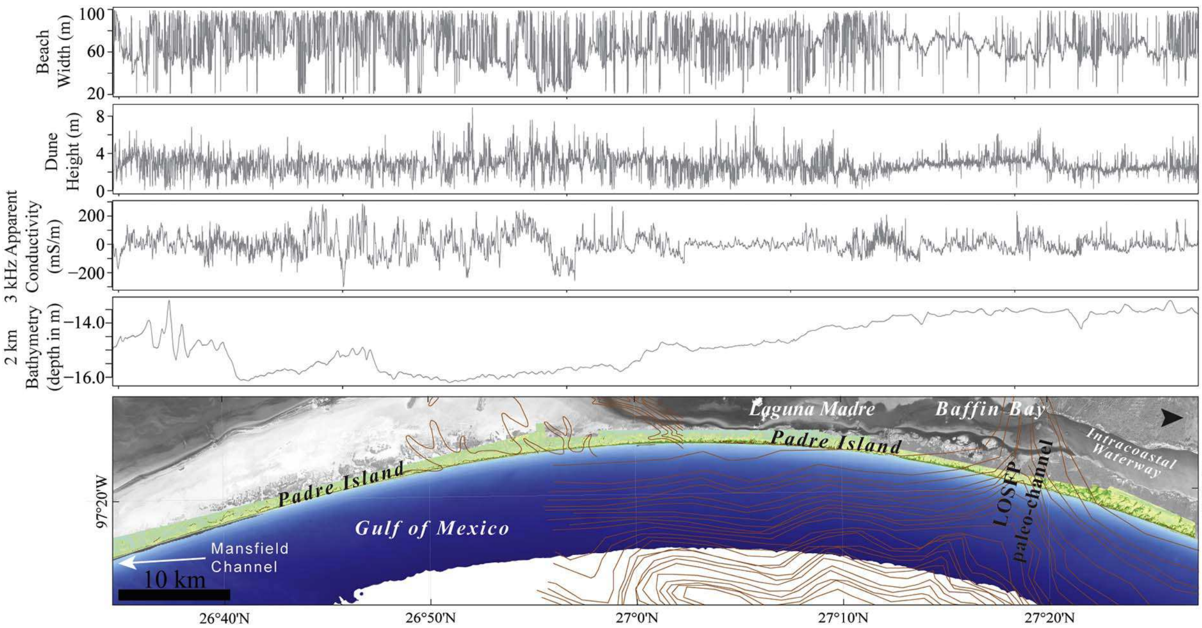

Fig. 2. Sample alongshore spatial data series for barrier island surface, subsurface, and bathymetric morphology. From top to bottom, the alongshore spatial data series are: beach width, dune height, apparent conductivity, and 4 km offshore bathymetric depth profile.

bispectrum. The advantage of bicoherence over bispectrum is that bicoherence values range from 0 (*i.e.* random phase coupling) to 1 (*i.e.* perfect phase coupling); therefore, bicoherence is easier to interpret than the bispectrum. Bicoherence ($[b_{yxx}(a1, a2)]^2$) was computed using Eq. (2):

$$[b_{yxx}(a1, a2)]^2 = \frac{|B_{yxx}(a1, a2)|^2}{[\int |W_x(a1, \tau)W_x(a2, \tau)|^2 d\tau][\int |W_y^*(a, \tau)|^2 d\tau]} \quad (2)$$

where $B_{yxx}(a1, a2)$ is the bispectrum of the signal at frequencies $a1$ and $a2$. Bispectrum and bicoherence analysis have been applied to analyzing the statistical correlation between oceanographic wind-wave and wave-wave interactions (Elsayed, 2006a, 2006b). In the current paper, bicoherence is utilized to assess the degree of phase coupling within a given signal to examine how fine-scale patterns and processes are coupled with broader-scale patterns and processes to influence coastal geomorphology.

4. Results

The ~100 km long spatial series of island morphometrics, shoreline change, and apparent conductivity are presented in Fig. 2, and the wavelet plots for the spatial series are presented in Fig. 3. All island morphometrics exhibit considerable variability alongshore (Fig. 2), but have distinct spatial patterns across spatial scales (Fig. 3). While CWT plots are useful to examine spatial variation in the dataset at multiple alongshore length scales, Fig. 4 presents GW information, which is useful to infer the degree to which a given spatial data series is structurally controlled. Variance is plotted as a function of alongshore length scale and trendlines were fit to the alongshore spatial series. As previously mentioned, trendlines with slopes approaching 0 are white noise where the variance is scale-independent, while trendline slopes approaching 2 or greater are dissipative (*i.e.* trend towards a homogenous value). Trendline slopes approaching 1 are structurally controlled since the variance increases with increasing alongshore length scale. Non-linear interactions between broad-scale structural controls and finer-scale coastal processes (*i.e.* wave refraction) are presented in Fig. 5, where areas of red represent non-linear interaction between oscillations at the x-axis frequency and oscillations at the y-axis frequency. Hotspots evident in the bicoherence plots (as indicated by the red hues in Fig. 5) suggest that the island morphometrics have non-linear interactions with broader-scale structure and finer-scale oscillations. To discern the nature of the relationships between infilled paleo-channels and alongshore variations in beach and dune morphology, wavelet coherence analyses are presented in Figs. 6, 7, and 8. Black arrows in red areas of the WTC plots (Figs. 6, 7, and 8) are used to illustrate whether the two variables in a plot are anti-phase (arrows pointing left), in-phase (arrows pointing right), or some degree of phase shift (arrows generally pointing up or down). If two variables are in-phase, then an increase in one metric corresponds to an increase in the second metric. Conversely for anti-phase, an increase in one metric corresponds to a decrease in the second variable.

4.1. Framework geology

The alongshore EMI survey and offshore bathymetric profiles represent the framework geology along the coast. Framework geology is highly variable alongshore and across spatial scales (Figs. 2 and 3c). Since apparent conductivity is essentially a spatial averaging of physical properties that are directly related to the geology (*i.e.* mineralogy, porosity, grain size), variations in the EMI survey serve as a proxy for the subsurface framework geology. The EMI survey is highly variable alongshore at scales smaller than ~250 m (Fig. 3c). This variability is considerable along the length of PAIS, with the lowest powers being immediately north of the large paleo-channel identified by Fisk (1959) in the central part of the island. While the EMI survey provides valuable information about the onshore framework geology, it is feasible that channels in the framework geology extend offshore at oblique angles from the shoreline.

Offshore bathymetric profiles representing the modern bathymetric surface are used as proxies for variations in the framework geology extending into the Gulf of Mexico. A series of ridges and swales are visible in the southern portion of PAIS bathymetry as oblique ridges extending northeast from the shoreline (Figs. 1, 3, and 9). While these features are present in the southern part of the island, they are absent in the northern roughly two-thirds of the island (Figs. 1 and 3). The presence of these features was confirmed using CWT decomposition, where these features appear as statistically significant hotspots at approximately 1000 m alongshore length scales (Fig. 3f and g). Upon closer examination of the CRM, these oblique ridges are visible in the southern

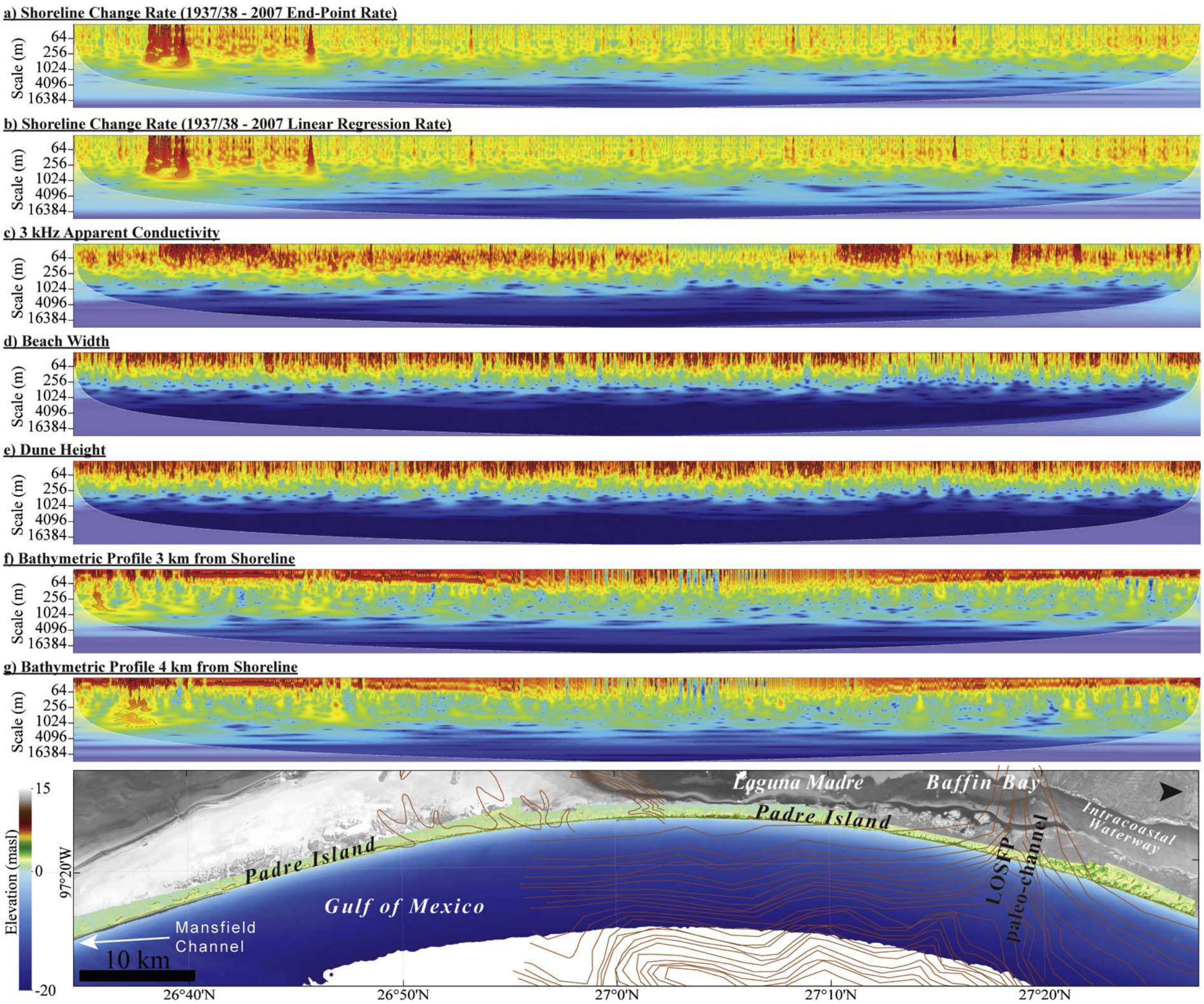

Fig. 3. Continuous wavelet transformations (CWT) for individual spatial series. Plots are aligned spatially with the map at the bottom based on latitude. Warmer colors are more significant, with statistically significant areas outlined in black. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

portion of PAIS (Fig. 9). These hotspots migrate to the north with increasing distance from the shoreline (from Fig. 3f to g), indicating that the ridges and swales extend to the northeast, oblique to the overall shoreline orientation.

The bathymetric depth profile GW series are best fit by power trendlines with slopes between 1.63 and 1.93 (Fig. 4b). The average power trendline slope for all bathymetric depth profiles (1.76 ± 0.12) is trending towards 2.00. While the ridges and swales in the southern part of PAIS may affect the degree to which the bathymetric depth profiles GW trendlines exhibit structural control (Fig. 4b), these ridges and swales do not cover a large enough part of PAIS to pull the bathymetric depth profiles data series GW trendline slopes low enough for them to be considered structurally controlled. Smoothing the bathymetric depth profiles for the southern part of PAIS results in a similar trendline slope, suggesting that the ridges and swales in the southern part of PAIS are do not dominate the degree to which the entire data series are structurally controlled. The power trendline slopes do not exhibit any pattern with the distance to shoreline that would suggest structural control is strongest closer or farther from the coast.

4.2. Long-term shoreline change behavior

There is no significant difference between the EPR and LRR shoreline change wavelet plots at PAIS (Fig. 3a and b), which suggests that it does not make a difference which metric is used in subsequent analysis with framework geology, beach, and dune morphometrics. Shoreline change exhibits statistically significant hotspots in the southern part of PAIS, between approximately 5 km to 23 km north of Mansfield Channel (Fig. 3a and b). The red areas in Fig. 3a and b outlined by black lines represent statistically significant areas of the CWT plots. This area of the island is also statistically significant in the EMI data, suggesting that there is a relationship between the subsurface framework geology and shoreline change at PAIS. The significant shoreline change hotspot between approximately 5 km to 10 km north of Mansfield Channel corresponds spatially to shore-oblique bars evident in the coastal relief model. Similarly, it follows that shoreline change is greater along southern PAIS where waves refract around ridges and dissipate energy in the swales. This imbalance in energy results in a variable shoreline position, depending on variations in the approaching waves.

The long-term EPR shoreline change is fit by a power trendline with slope ~2.26 (Fig. 4a). The high trendline slope value for long-term shoreline change indicates that variance is dominated at large alongshore length scales and that there is relatively little variance at small alongshore length scales. Variance focused at the large alongshore length scales (*i.e.* > 1000 m alongshore) suggests that the long-term shoreline change is trending towards a homogenous value and that the long-term shoreline change is dissipative along PAIS. The high r^2 value in both parts of the curve (> 0.88) indicates that long-term shoreline change is appropriately fit by a power law trendline. No significant hotspots (*i.e.* areas of bright red) are present in the shoreline change bicoherence plot (Fig. 5a) that would suggest non-linear interactions are influencing the overall shoreline change rates.

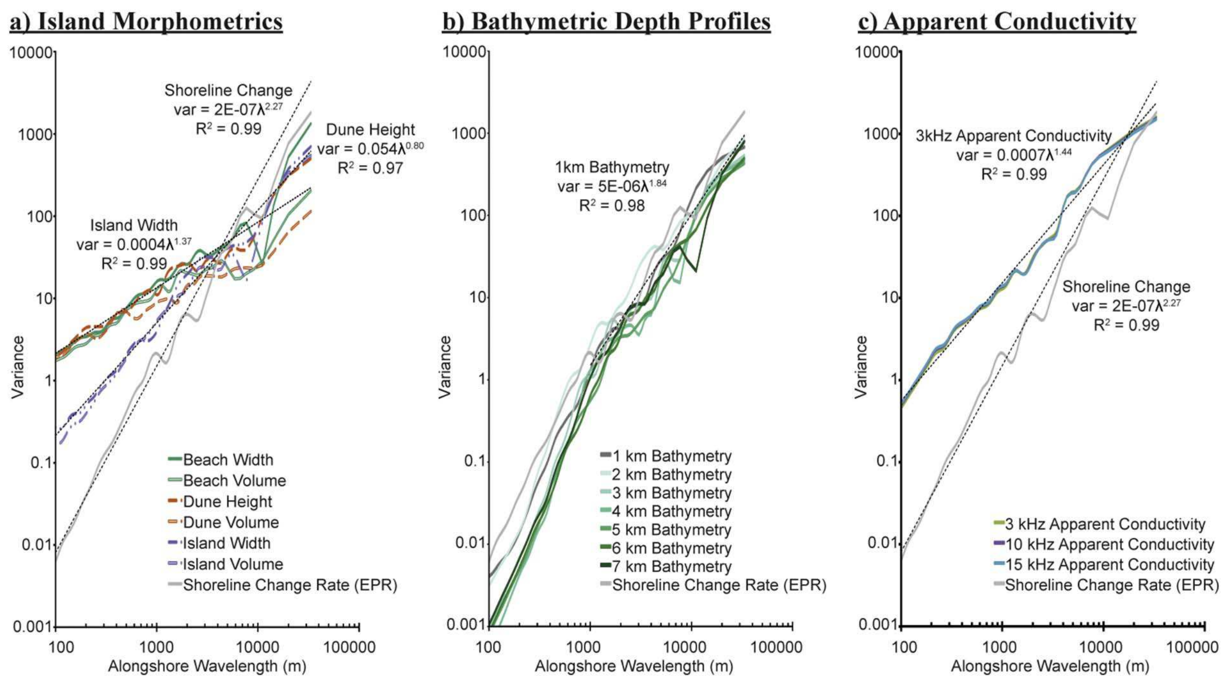

Fig. 4. Global Wavelet (GW) plots of decomposed spatial series: (a) island morphometrics, (b) 1–7 km bathymetric depth profiles, and (c) 3, 10, and 15 kHz EMI apparent conductivity. Long-term shoreline change rate is plotted on a, b, and c to facilitate comparison of the different plots and their relationship to the observed shoreline behavior. Trendline slopes provide valuable information about the degree to which the spatial series is white noise (slope ~ 0), structurally controlled (slope ~ 1), or dissipative (slope ~ < 2).

4.3. Barrier island morphology

Beach width exhibits substantial alongshore variability, with the greatest variability concentrated at scales smaller than ~250 m (Fig. 3d). Approximately 70 km from the Mansfield Channel there is less statistically significant structure and the overall strength of the wavelet decreases. Also, around 70 km from Mansfield Channel, the dune height wavelet plot becomes less statistically significant than in the central part of the island, as displayed by more cooler colors around 70 km north of the Mansfield Channel. The most significant change in significance and wavelet transformation is the abrupt decrease in island width significance around 70 km.

The island morphometrics are best fit by power trendlines with slopes ranging from ~0.79 to ~1.37 (Fig. 4a). The R^2 value is very high for all trendlines, indicating that the power trendlines are an appropriate measure of the data structure. All island metrics can be characterized as pink noise (slope ~ 1; Fig. 4a), which suggests that the signal is structurally controlled. While island width and island volume have slightly steeper trendlines than the other metrics, both trendlines are still approximately 1. Based on the GW trendline slopes, all alongshore island metrics (Fig. 4a) are structurally controlled at a range of alongshore length scales. Because none of these trendline slopes deviate substantially from ~1, it follows that the barrier island morphometrics may be controlled by a single common factor along the entire island, such as structure in the framework geology.

Several of the island morphometric bicoherence plots indicate significant non-linear interactions occur at distinct scales. Beach width (Fig. 5c) and beach volume (Fig. 5d) both exhibit non-linear interaction between oscillations at ~1200 m and ~280 m, as indicated by the red hotspots in Fig. 5c and d. Oscillations at 280 m interact non-linearly with signals between ~380 m and 800 m in the dune height (Fig. 5e), dune crest elevation (Fig. 5f), and dune volume (Fig. 5g). Island width (Fig. 5h) and island volume (Fig. 5i) spatial series appear to be influenced by the interaction between 1200 m and 380 m.

4.4. Wavelet coherence

Cross-wavelet coherence analysis of the 3 kHz EMI and dune height signals demonstrate that the relatively minor shore-perpendicular paleo-channels identified by Fisk (1959) are out of phase with dune height at approximately 1000 m to 3500 m alongshore length scales, as indicated by the arrows pointing left in Figs. 7 and 8. In other words, taller dunes are present in these areas of lower apparent conductivity, which is indicative of and inverse relationship between shallower subsurface paleo-channels and taller dunes in the south-central part of the island. Conversely, apparent conductivity and dune height are in-phase where the paleo-channel forming modern Baffin Bay dissects PAIS (Figs. 7 and 9).

The WTC plot between the 2 km bathymetric depth profile and dune height exhibits statistically significant relationships, as indicated by the red hotspots and arrows in Figs. 7b and 8b. The 2 km–dune height coherence has the greatest overall statistical significance at hotspots between ~1000 m and 3500 m alongshore length scales (Figs. 7b and 8b). Many of the largest alongshore statistically significant hotspots where the bathymetry and dune height are anti-phase, indicated by arrows pointing to the left, are adjacent to previously identified paleo-channels, such as ~30 to 45 km from Mansfield Channel.

5. Discussion

Wavelet decomposition of framework geology (Figs. 3c, f, g, 6, 7, and 8) and modern island morphometrics (Figs. 3d, e, 6, 7, and 8) suggests that the geomorphology of PAIS is influenced by paleo-channels in the central and northern sections of the island (Figs. 7 and 8), and shore-oblique ridges present in the southern part of the island (Fig. 9). Given the proximity of southern PAIS is to South Padre Island, it is likely that the ridge and swale complex in south PAIS (Fig. 9) represents a northern extension of the South Padre Island ridge and swale complex identified by Houser and Mathew (2011). Since the oblique ridges are only present overlying the ancestral Rio Grande River paleo-delta, it is feasible that the modern ridges are formed from deltaic sediments reworked by waves. While it remains unclear why these ridges

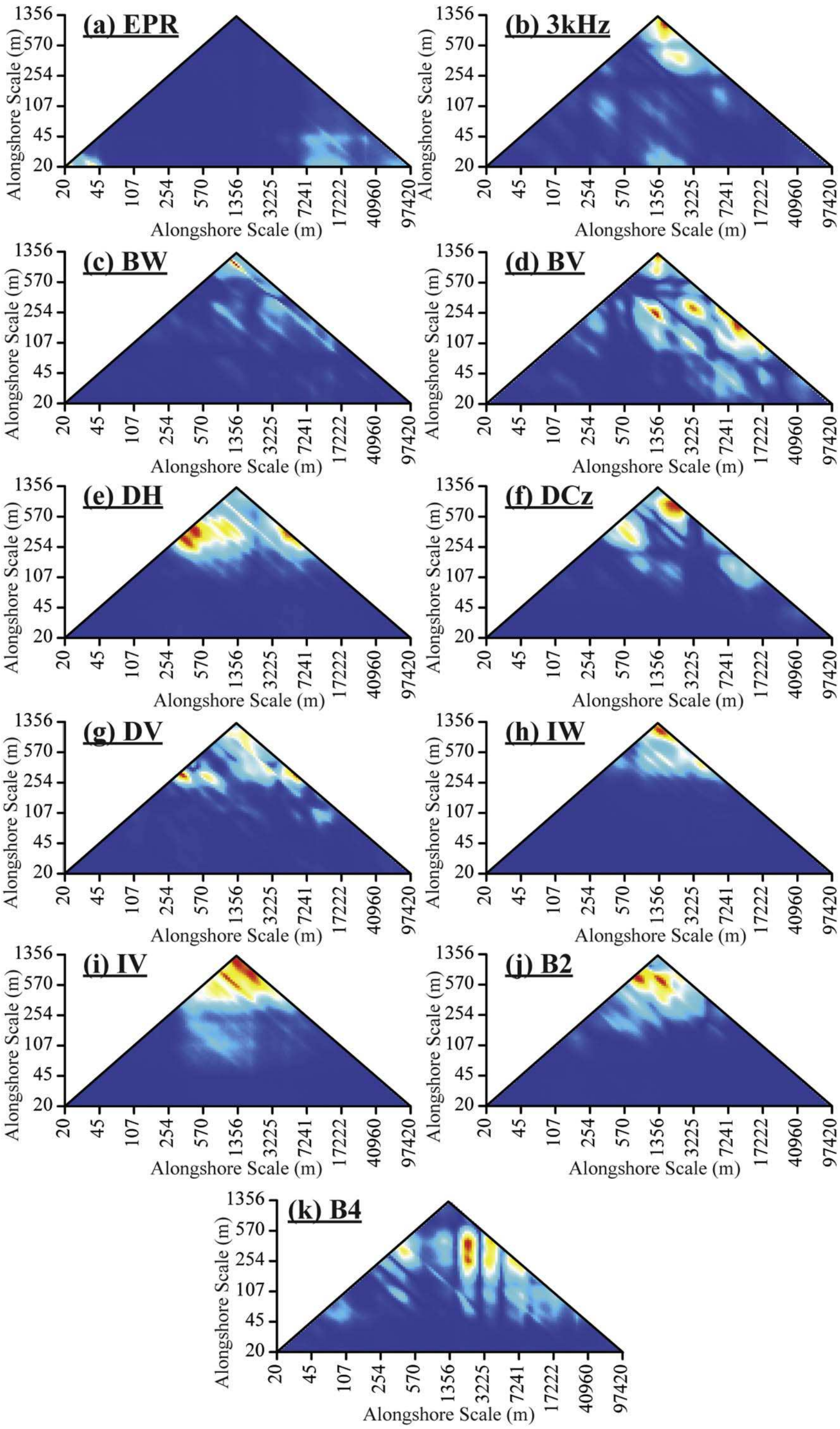

Fig. 5. Bicoherence plots provide insight into the scales interacting non-linearly for each spatial data set. Both axes refer to oscillations at a given spatial scale within the data series. In this way, the bicoherence plots can highlight non-linear interactions between oscillations at two different frequencies. Spatial series represented are: (a) long-term shoreline change (EPR), (b) 3 kHz apparent conductivity, (c) beach width, (d) beach volume, (e) dune height, (f) dune crest elevation, (g) dune volume, (h) island width, (i) island volume, (j) 2 km bathymetric depth profile, and (k) 4 km bathymetric depth profile. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

are relatively consistently spaced at ~1000 m at PAIS, it is plausible that this spacing is the result of oceanographic forcing or a result of past island transgression (Hapke et al., 2010; Schwab et al., 2013; Schwab et al., 2014; Warner et al., 2014; Hapke et al., 2016). Ridges in the southern PAIS nearshore bathymetry are aligned with lower dunes and more frequent dune gaps, while swales are aligned with more continuous dunes (Figs. 6b, d, and 9). Increased shoreline variability coincident to these shore-oblique features is consistent with shoreline change data from Santa Rosa Island (see Houser et al., 2008; Houser and Barrett, 2010; Houser, 2012) and the eastern US coast (Schupp et al., 2006; Lazarus et al., 2011). The bathymetry alters the alongshore pattern of wave refraction that also influences beach and dune morphology through variations in the availability of sediment to be deposited on the beach and in the dunes. At Padre Island the largest dunes are found landward of the swales where the beach is less-dissipative and more sediment is emplaced on the beach for dune growth (see Houser and Mathew, 2011). This is unlike the pattern observed at Santa Rosa Island, where the largest dunes are located landward of the ridges where the beach is relatively more dissipative (compared to the swales) and aeolian transport is promoted.

It is feasible that the lack of a clear structurally controlled signal in the bathymetric depth profiles (Fig. 3b) may be caused by the cumulative wave refraction and reflection patterns in conjunction with the amount of time (~ > 20 years) between hurricanes. Similar to shoreline

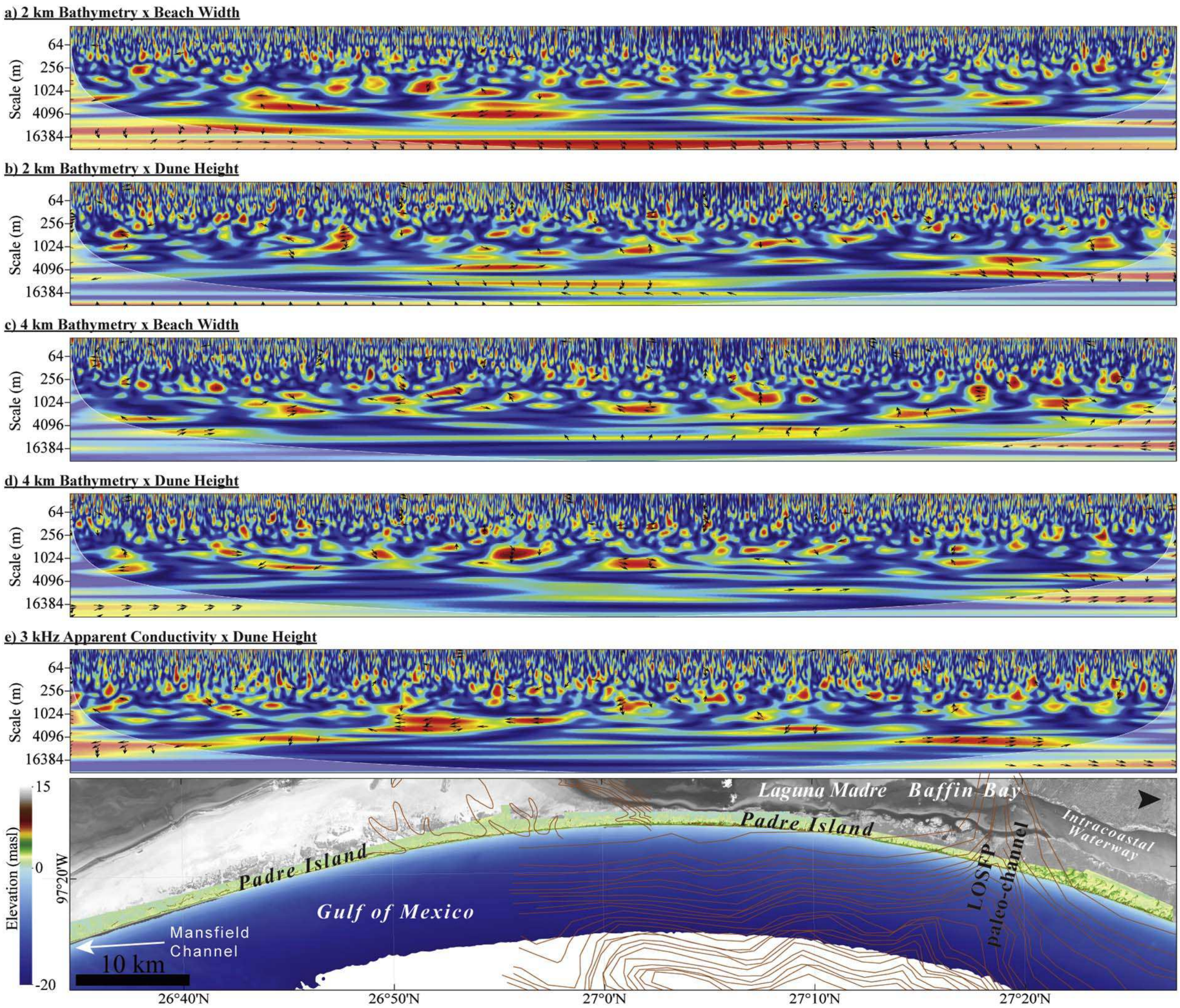

Fig. 6. Wavelet coherence (WTC) of different combinations of two alongshore spatial series. Plots are aligned spatially with the map at the bottom based on latitude. Warmer colors are more significant, with statistically significant areas outlined in black. Arrows pointing to the left indicate anti-phase relationships, while arrows pointing to the right indicate in-phase relationships. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

change behavior, where short-term perturbations and undulations in the shoreline change rates are smoothed out over longer time scales, it is reasonable to assume that initial variations in the nearshore bathymetry, such as large-scale ridges and swales may be smeared over with modern, possibly re-worked, sediments. This 'smearing' may cause the GW power trendline slopes to appear dissipative. Given enough time, we would expect the GW power trendlines to continue to trend towards dissipative, similar to shoreline change behavior along the Eastern U.S. coast (Lazarus et al., 2011).

Results of the bicoherence analysis suggest that there is a non-linear interaction across scales in which the framework geology determines (to varying degrees) the small-scale processes responsible for beach and dune morphology. Specifically, beach width and volume exhibit significant non-linear interaction (Fig. 5c and d) that suggests small-scale processes (*i.e.* daily wave refraction patterns) are influenced by the large-scale framework geology (*i.e.* paleo-channels; shore-oblique ridges and swales) despite the overall dissipative nature of shoreline change, as indicated by the shoreline change GW trendline slope exceeding 2 (Fig. 4) and the identical EPR and LRR shoreline change wavelet coherence plots (Fig. 3a and b). Whereas the alongshore pattern of historical shoreline change is dissipative (Fig. 4), suggesting that it is dominated by large-scale patterns associated with island curvature, as suggested along the Eastern U.S. coast (see Lazarus et al., 2011).

The non-linear interaction for beach and dune morphology (Fig. 5c, d, e, f, and g) suggests that both small- and large-scale processes are responsible for the observed patterns and that the small-scale processes are slaved to the framework geology. For example, the red hotspots in Fig. 5e, f, and g demonstrate that the variation in dune morphology at scales between 300 and 380 m interacts with the variations in dune morphology at alongshore length scales of 800 to 1500 m. This large-scale variation (800 to 1500 m) is also present as statistically significant hotspots in the beach and dune morphology–framework geology wavelet coherence plots (Fig. 6) and is consistent with the average spacing of the shore-oblique ridges in southern PAIS (Fig. 9), and suggests that the ridges in the southern part of PAIS control the small-scale processes through wave refraction similar to what has been observed at Santa Rosa Island (see Houser et al., 2008). Together, the bicoherence and wavelet coherence plots suggest that the irregular framework geology influences small-scale coastal processes, and creates interactions across scales that influence beach and dune morphology at PAIS and will likely affect future island response to storms and sea level rise.

The paleo-channels in the central and northern parts of the island are associated with larger and more continuous dunes compared to the southern part of the island. Several areas of the EMI and dune height wavelet coherence plot exhibit a statistically significant coherence at alongshore length scales of between 1000 and 3500 m (Fig. 7a and b). Many of the paleo-channels south of the ancestral LOSFP channel (which form modern day Baffin Bay) are statistically out-of-phase with

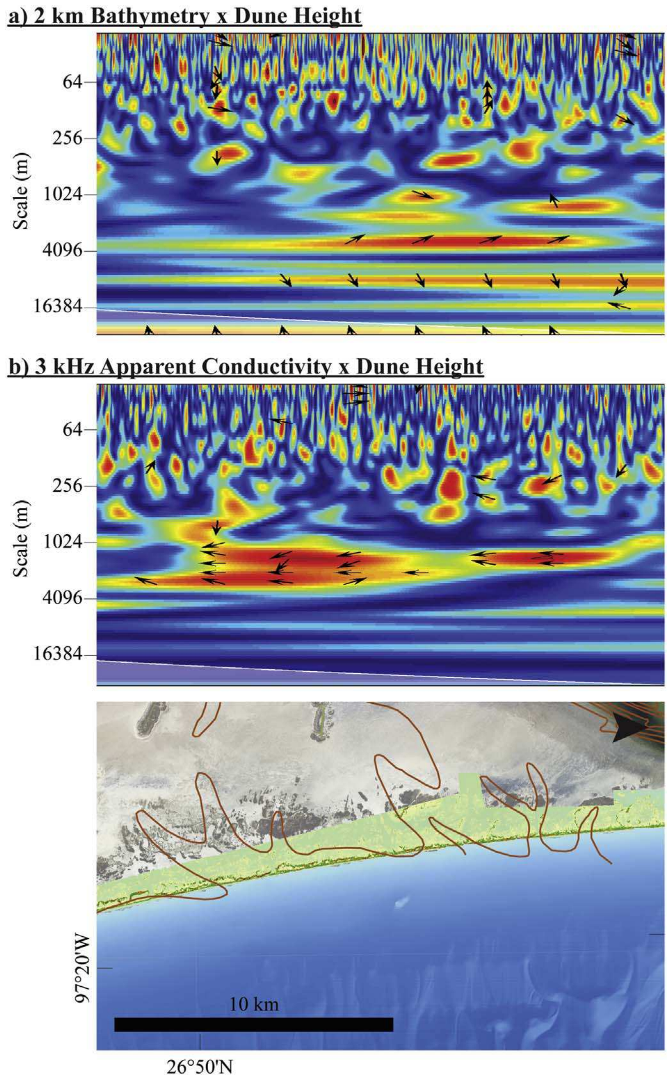

Fig. 7. Wavelet coherence of dune height and framework geology parameters along central PAIS, where Fisk (1959) previously identified paleo-channels in the MIS II surface. There is a statistically significant in-phase relationship between dune height and the 2 km offshore bathymetric profile at ~4000 m alongshore length scales, and a statistically significant anti-phase relationship between dune height and the 3 kHz EMI survey at ~1000 m to ~3500 m alongshore length scales.

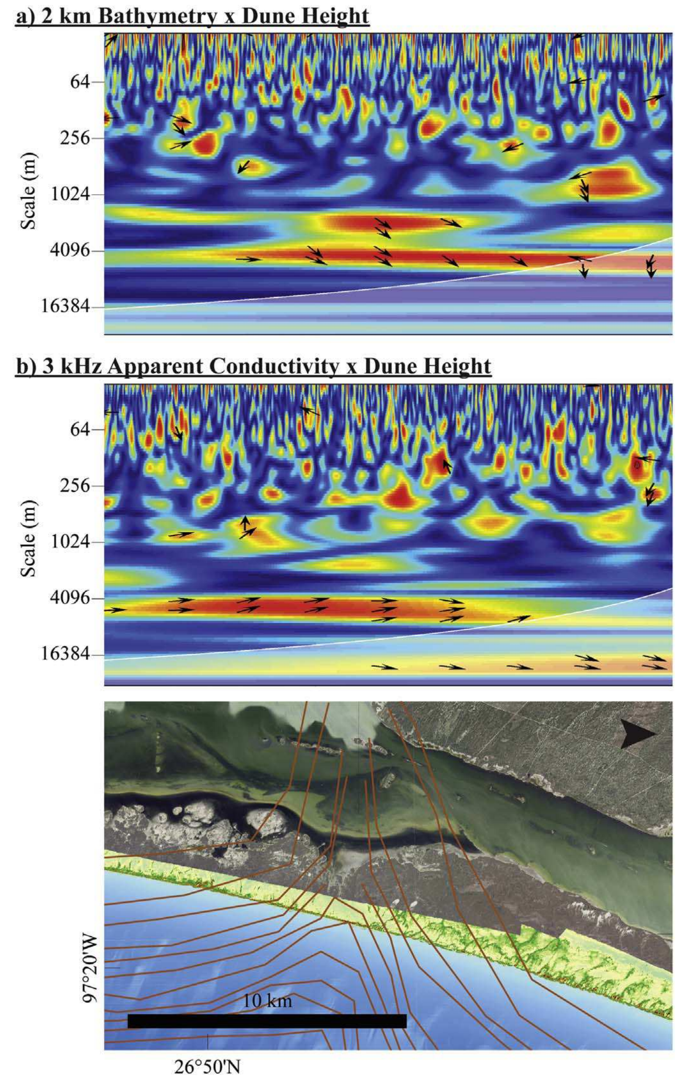

Fig. 8. Wavelet coherence of dune height and framework geology parameters of PAIS adjacent to the paleo-channel forming modern-day Baffin Bay. Both wavelet coherence plots exhibit in-phase relationship between wavelet coefficients of the two spatial series. Dune height and the 2 km offshore bathymetry are statistically in-phase at ~1500 m to 4500 m alongshore length scales, while dune height and the 3 kHz EMI survey are in-phase at alongshore length scales from ~4000 m to ~5500 m.

the dune height (indicated by black arrows pointing left in Fig. 7a and b), indicating that dunes are taller within the paleo-channels. Conversely, subsurface framework geology and dune height are in-phase where the ancestral LOSFP channel crosses PAIS. While the exact mechanism for the different influence of various paleo-channels is unclear, it is possible that the out-of-phase relationship south of the ancestral LOSFP channel is a direct result of the relatively small distance between channels, in which the signal from one channel is likely to overlap with the signal of an adjacent channel, resulting in an apparent continuous signal. Conversely, the larger ancestral LOSFP channel, which is both deeper and wider than the channels to the south, would appear statistically significant at larger alongshore length scales in the CWT and WTC plots. The ancestral LOSFP channel is an excellent example of this, where the influence of the channel is evident at larger alongshore length scales (~4000 m), but is not present at smaller length scales (Fig. 7). The large paleo-channel dissecting PAIS at an oblique angle south of the ancestral LOSFP channel also appears statistically significant at very large alongshore length scales (~4000 m to 10,000 m). While large and small paleo-channels appear to have different influences on the beach and dune morphology, the channels influence island morphology and that small-scale beach and dune interaction is dependent on larger-scale patterns in wave refraction and/or sediment supply and texture.

This paper presents evidence that the framework geology influences barrier island geomorphology by creating alongshore variations in either oceanographic forcing and or sediment supply and texture that influences the smaller-scale processes responsible for local beach and dune interaction. Results of the present study suggest that even a variable framework geology provides a structural control on beach and dune morphology similar to what has been observed on islands with a semi-regular framework geology (*e.g.* Santa Rosa Island, South Padre Island and Fire Island). While the shoreline may be dissipative through the alongshore redistribution of sediment, there is no effective process that redistributes sediment alongshore along the dune, and gaps in the dune can only fill in through the lateral expansion of vegetation. Gaps in the dune are maintained/reinforced through lateral erosion by washover (Weymer et al., 2015a) and blowouts (Jewell et al., 2014, 2017), resulting in the observed pink noise signal for the dune morphology. Areas where framework geology allows for the formation of relatively large dunes, as observed in the relict infilled paleo-channels

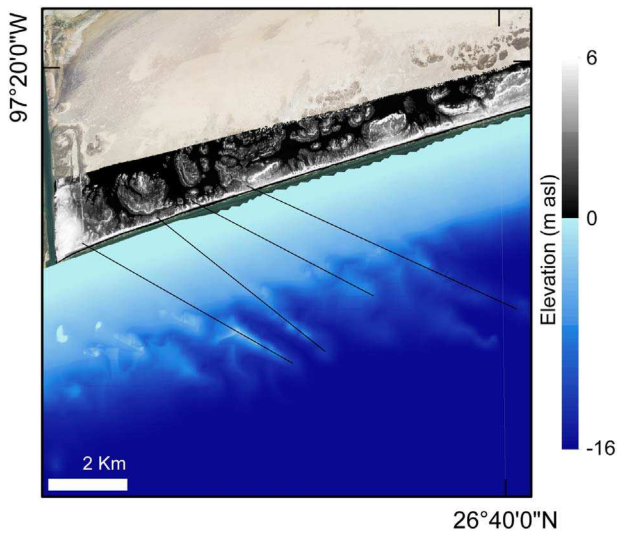

Fig. 9. Southern PAIS framework geology likely represents a northern extension of ridges and swales from South Padre Island. Ridges in the nearshore (represented by black shore-oblique lines) align with areas of smaller dunes with frequent dune gaps.

south of the ancestral LOSFP, are more likely to withstand a storm and less likely to be overwashed, compared to the smaller dunes outside the paleo-channels. Areas with greater washover will experience a net loss of sediment landward and localized erosion, but the dissipative nature of shoreline change means that those losses are distributed alongshore over time. In this respect, the variation in dune height alongshore in response to the framework geology influences the rate of historical shoreline retreat and island transgression. This suggests that models of island response to sea level rise in the future should not assume that island morphology or framework is uniform alongshore without explicit evidence that this is appropriate.

6. Conclusions

This paper suggests that the geomorphology of PAIS is dependent on the subsurface and offshore framework geology, and that framework geology constrains small-scale (< 1000 m) processes responsible for beach and dune morphology at distinct spatial scales. Unlike historical change, the processes responsible for beach and dune morphology are dissipative across scales. Rather, localized variations in beach and dune morphology are dependent on larger-scale patterns driven by alongshore variations in wave energy or sediment supply and texture. Dune height and volume are significantly distinct from wavelet plots exhibit adjacent to subsurface paleo-channels and shore-oblique ridges, which suggests that the modern island morphology is dependent on the Pleistocene paleo-topography. The interaction of low-frequency (*i.e.* millennial scale) and high-frequency (*i.e.* daily through decadal scale) coastal processes represents a significant challenge in geomorphological research, although quantifying this interaction through wavelets and bicoherence provides valuable insight into how the coast is likely to change in response to future storms and sea level rise. Furthermore, the methods utilized in this paper can help bridge the gap between shoreline change modelling and geophysical/geomorphological studies by providing an approach to examine how spatial variations in multiple variables are linearly and non-linearly related. An irregular framework geology at PAIS influences small-scale coastal processes and creates interactions across scales that influence beach and dune morphology. These setup variations in beach and dune morphology, in turn, affect future island response to storms and sea level rise. This paper demonstrates that, despite the non-linear interaction of large-scale coastal processes with smaller-scale coastal processes, variations in the framework geology can significantly influence alongshore variations in modern barrier island morphology. These variations persist through time, despite the temporal disconnect between when the island developed (~2.8 ka, Weise and White, 1980) and today. Understanding how the pre-existing geology affected and continues to affect barrier island formation is vital to effective long-term management of coastal resources, given the growing pressure of climate change and sea-level rise.

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