Geo-Mar Lett (2012) 32:241–250
DOI 10.1007/s00367-011-0263-x

ORIGINAL

Can beach dune ridges of the Texas Gulf Coast preserve climate signals?

James R. Garrison Jr. · Alberto M. Mestas-Nuñez · Joshua R. Williams · Luz M. Lumb

Received: 27 March 2011 / Accepted: 17 October 2011 / Published online: 15 November 2011

Abstract A study of the evolution of North Padre Island (southern Texas Gulf Coast) dunes was carried out using LIDAR topographic data, dune vibracores through the center of the dunes, and grab samples of shoreface sand at four locations along a cross-shore profile. Grain-size analyses of the vibracores show vertical variations in shoreface sand deposition over decimeter depth intervals. A dune ridge growth model is introduced that describes the dune vertical accretion rate as a function of island progradation and freshwater lens expansion. This model allows indirect dating of the dune core samples based on a known island progradation rate (1 m/year), and height and spacing of the dunes calculated from the topographic data. A sand provenance model is also proposed that links the sand deposition in the dunes with sand sourced from various depths along the shoreface profile, depending on storm activity. We present evidence linking the changes in storm-sand deposition in the dune cores with yearly climatic fluctuations in the Gulf of Mexico associated with landfalling tropical storm activity in the period from 1942–1965. This record of storm-induced sand variability is negatively correlated with El Niño-Southern Oscillation (Pacific) sea surface temperature variability, and positively correlated with North Atlantic decadal sea surface temperature variability.

J. R. Garrison Jr. (✉)
Center for Lithospheric Studies, School of Natural Sciences and Mathematics, University of Texas at Dallas,
800 W Campbell Road,
Richardson, TX 75080, USA
e-mail: jxg116230@utdallas.edu

A. M. Mestas-Nuñez · L. M. Lumb
Department of Physical and Environmental Sciences, Texas A&M University–Corpus Christi,
6300 Ocean Drive,
Corpus Christi, TX 78412, USA

J. R. Williams
Coastal Geology Laboratory, Department of Marine Sciences, Texas A&M University at Galveston,
705 Sea Aggie Center, 1001 Texas Clipper Road,
Galveston, TX 77553, USA

Introduction

Climate variability can directly influence the dynamics of clastic shoreline depositional systems, resulting in variations in eustatic sea level, storm activity, and sediment budgets (e.g., Stone and Orford 2004; Keim et al. 2004; Schwarzer et al. 2004; Stone et al. 2004; Wanner et al. 2008). The sedimentologic and depositional facies patterns resulting from climatic fluctuations are commonly recorded in clastic shoreline deposits, and can be quantified using a variety of analytical techniques based on, for example, beach dune ridge granulometry and topography (e.g., Tanner et al. 1989; Tanner 1991, 1992 for the Gulf of Mexico), ground-penetrating radar (GPR; e.g., Buynevich et al. 2004 for Maine; Aagaard et al. 2007 for Denmark; Garrison et al. 2010 for the Gulf of Mexico), coring (e.g., Buynevich et al. 2004; Skilbeck et al. 2005 for eastern Australia), and a variety of geochemical analyses of sediments (Skilbeck et al. 2005; Aagaard et al. 2007).

The shoreface is extremely sensitive to variations in sediment supply, sea level, and hydrodynamic processes (e.g., Wright 1995; Schwarzer et al. 2004). Intense, short-time modifications of these parameters are possible during the passage of storms. During storm events, sediment transport rates increase by at least an order of magnitude, caused by high wave orbital velocities and strong wind-driven currents (e.g., Swift et al. 1985; Pepper and Stone

2004; Stone et al. 2004). A recent study of beach dune ridges at Skallingen Spit, Denmark, found that dune ridge topography and grain-size distributions were correlated with sea-level changes controlled by centennial climatic variations (Aagaard et al. 2007). The authors suggested that storm-transported sediment contributes to the formation of dunes, and showed that climatic variations were linked to variations in storm intensity (i.e., wave energy) and sediment availability.

Foredunes nucleate when vegetation becomes established on the backbeach, becoming a sediment trap for eolian-transported beach sand. As strand plain and barrier beaches grow seaward during progradation, the phreatic freshwater lenses also expand seaward, facilitating the establishment of a new line of vegetation, which is followed quickly by backbeach dune nucleation and the development of an incipient foredune ridge. The incipient foredune must survive storm surges until a critical survival height is reached, and vertical accretion becomes the dominant sedimentologic process. Even when incipient foredunes are destroyed by a major storm surge, the stable freshwater lens facilitates a rapid recovery of vegetation and the re-initiation of incipient dune growth.

This study evaluates a preserved beach dune ridge train on North Padre Island along the Texas Gulf of Mexico coast (Fig. 1). Shoreface and dune sand granulometric analyses are used to develop a model for the growth and propagation of beach dune ridges, document that beach dune ridges may contain storm-transported shoreface sand, and develop and test a methodology for detecting suspected inter-annual to decadal climatic signals in these beach dune ridges.

Study area

The barrier island system along the Texas Gulf Coast extends for over 500 km from the Bolivar Peninsula, on the southeast side of Galveston Bay, to South Padre Island at the international border with Mexico (Fig. 1). The longest island of this chain is Mustang Island/Padre Island, which is 200 km long and up to 3 km wide. This approximately 2,000-year-old barrier island (Garrison et al. 2010) was formed predominantly from northward longshore-drifted sediments derived from the Rio Grande River delta (Bullard 1942).

The prevailing winds in the region are from the southeast with monthly averaged wind speeds of about 25 km/h, maximum speeds normally reaching up to 40 km/h. Obviously, storm winds may reach speeds greater than 250 km/h during category 5 hurricanes. Northerly winds

Fig. 1 Map of the Texas Gulf Coast showing the location of the study areas (adapted from Morton et al. 2000)

associated with the passage of cold fronts occur periodically from October to March. The hydrodynamic conditions of the region are micro-tidal with a mean tidal range of 0.5 m, and a mean significant wave height between 0.8 and 1.0 m. During tropical storm conditions, significant wave heights and storm surge levels can range from 2 to 7 m.

The dune ridge study area is located on Mustang Island, approximately 23 km south of Port Aransas, within the southern portion of Mustang Island State Park, and 1 km north of Corpus Christi Pass (northern white box in Fig. 1). This area was chosen because it is one of the few areas at the northern end of North Padre Island that contains a preserved beach ridge dune train across the entire island. The ephemeral washover pass, Corpus Christi Pass, lies to the south of this location, and an ancient washover plain lies to the north. The beach gradient of North Padre Island is about 0.008 (1 m/128 m), estimated from data by Williams et al. (2005).

The study area for the analysis of the shoreface nucleation and development of foredunes is located on the Padre Island National Seashore (southern white box in Fig. 1) at Malaquite Beach (Fig. 2a). This section of beach was chosen for this study because it is a protected beach, not altered by anthropogenic activity.

Materials and methods

Calibration of dune ridge age and vertical accretion rate

Foredune beach ridges (Fig. 2a) have been well documented in the literature, but the nature of the processes

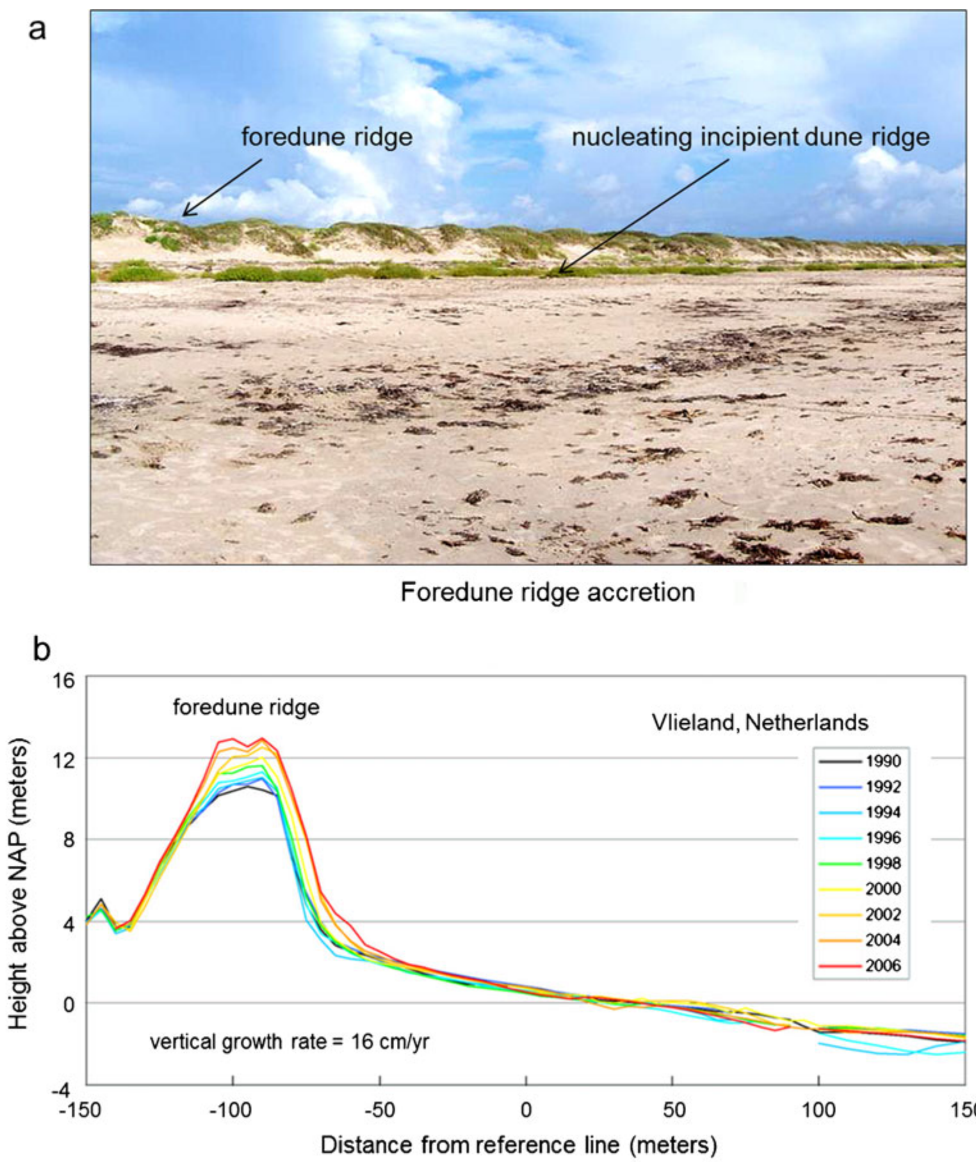

Fig. 2 a Photograph of the foredune ridge and row of incipient foredunes (vegetation line) at Malaquite beach on the Padre Island National Seashore. **b** Yearly dune topographic profiles from the Wadden Sea island of Vlieland (The Netherlands), illustrating the vertical accretion growth of foredunes (modified from Arens et al. 2007) resulting in their nucleation and subsequent growth is only beginning to be understood (e.g., Nordstrom et al. 1990; Tanner 1991; Otvos 2000; Aagaard et al. 2007; Arens et al. 2007; Lindhorst et al. 2008). Arens (1996) suggested that vegetated foredunes grow by vertical accretion, and that very little saltating sand reaches the leeward side of the foredune. Arens and co-workers estimated that the vertical accretion rate in modern vegetated foredunes is about 15–20 cm/year on the Wadden Sea island of Vlieland in the southern North Sea (Fig. 2b; Arens and Wiersma 1994; Arens et al. 2007), whereas Aagaard et al. (2007) reported dune vertical accretion rates of 13–18 cm/year at Skallingen Spit, Denmark.

Based on this knowledge, a novel conceptual model describing the progressive development of beach dune ridges has been developed for this study (Fig. 3). The model assumes that a given dune, $n=1$, at location x_0 will grow vertically from time T_0 to time T_1 to reach a height h_1 at a rate $R_1=h_1/(T_1–T_0)$, and then stop. At that same time, T_1, a new dune, $n=2$, will start developing at location x_1, and in turn grow to reach a height h_2 at time T_2 at a rate $R_2 = h_2/(T_2 - T_1)$. In this model, x_1 coincides with the leading edge of the subsurface freshwater lens expanding at rate E_{0-1}, which is assumed to be equal to the island progradation rate $P_{0-1} = \Delta x_{0-1}/\Delta T_{0-1} = (x_1 - x_0)/(T_1 - T_0)$. Therefore, in this model, vertical dune accretion is controlled not only by wind energy and sediment availability, but also by beach progradation rate, which in part controls the rate of freshwater lens expansion. If the beach progradation rate is known or can be estimated, this model can be used to estimate the vertical accretion rates of older beach ridges.

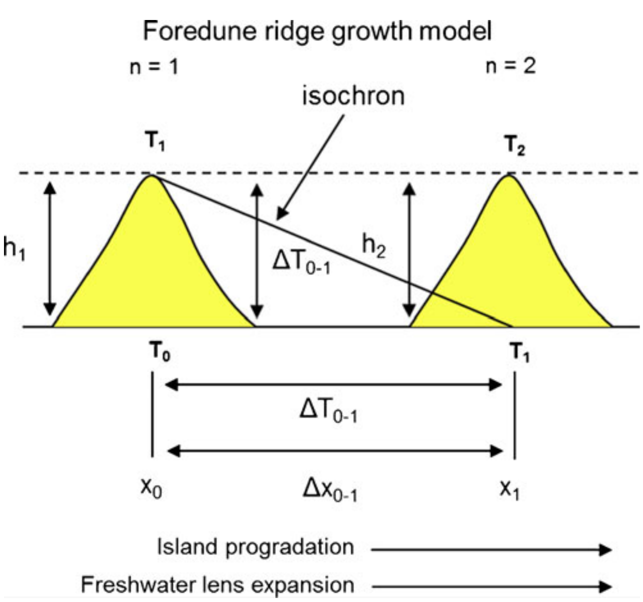

Fig. 3 Conceptual geochronological model for the growth of foredune ridges as a function of island progradation rate and freshwater lens expansion rate. An isochron illustrates the timing of progradation and expansion

Garrison et al. (2010) concluded that the spatial distribution of the seaward-dipping reflectors in a Padre Island cross-island GPR profile indicated approximately 2 km of seaward progradation of the barrier island over the past 2,000 years, corresponding to an average progradation rate of 1 m/year for that time period. Morton and Pieper (1977) identified that, over a period of 115 years prior to 1977 AD, most of North Padre Island experienced seaward progradation at a rate reaching 1 m/year. This progradation rate is consistent with the time-averaged progradation rate estimated from the North Padre Island GPR data. Based on these two studies, cross-island distance (in meters) is assumed to be a reasonable indicator of dune ridge age (in years). Using the model for dune ridge growth shown in Fig. 3 and dune ridge ages, vertical accretion rates were calculated from dune topography (i.e., spacing and height).

Topographic analysis

The topographic analysis of the beach ridge dune train was conducted utilizing a portion of a geo-referenced 2005 University of Texas Bureau of Economic Geology LIDAR survey conducted at the northern end of North Padre Island. The LIDAR topographic data have an estimated horizontal error of <0.5 m and an estimated vertical error of <0.25 m. The elevation of the top of each dune along the sampling transect was calculated from the LIDAR dataset by means of ArcGIS software. The distance of each dune to the beach was also determined using the LIDAR data, and defined as the perpendicular distance from the top of the dune to the seaward toe of the youngest foredune ridge.

Dune vertical granulometry

Vibracores 7.6 cm in diameter were collected through the center of selected North Padre Island dunes along a cross-island transect using a modified Dreyer vibrator system. The data included a 4.2 m core in a dune located on the seaward side of the island at a distance of 41 m from the beach (MI-3), a 1.4 m core in a dune in the center of the island at a distance of 642 m from the beach, and a 1.3 m core in a dune on the landward side of the island at a distance of 1,396 m from the beach. These vibracores were used for vertical grain-size profile analysis by dividing them into 10 cm intervals.

The grain-size analysis of these samples was done using standard sieve techniques. Briefly, samples were dried in an oven at 40°C for 48 h. The entire sample was then homogenized and a split for grain-size analysis was taken. The grain size was characterized using the phi (φ) scale. A sub-sample of each interval was sieved through a set of 0.25 phi increment brass sieves using a Ro-Tap machine. The proportion of each size fraction was determined according to the procedures outlined by Folk (1974).

Replicate analyses of splits demonstrated an excellent reproducibility in each case.

Grain-size distributions of the samples were constructed using the method of moments. Those distributions determined to be polymodal were subsequently unmixed into discrete end-member distributions using a simple mixing algorithm developed in Excel. End-member grain-size distributions were determined from selected unimodal and bimodal grain-size samples where the distribution peaks could be clearly defined. The abundance of these end-members was used to calculate the relative proportions of coarser (2.5 phi) and finer (3.25–3.5 phi) sand populations in each sample. This paper focuses on the granulometric results from the longer MI-3 core.

Shoreface granulometry

The data for the shoreface analysis come mainly from samples taken during the monitoring program for the construction of the Packery Channel, Corpus Christi, Texas (Williams et al. 2005). These data are grab samples of the upper 10 cm of sediment collected at four depths along a cross-shore profile, namely, 0 m (foreshore), 0.5 m (upper shoreface), 4 m (middle shoreface), and 8 m (lower shoreface) with respect to mean sea level. The grain-size distributions of these samples were constructed using the same procedure as applied to the dune sediments (see above).

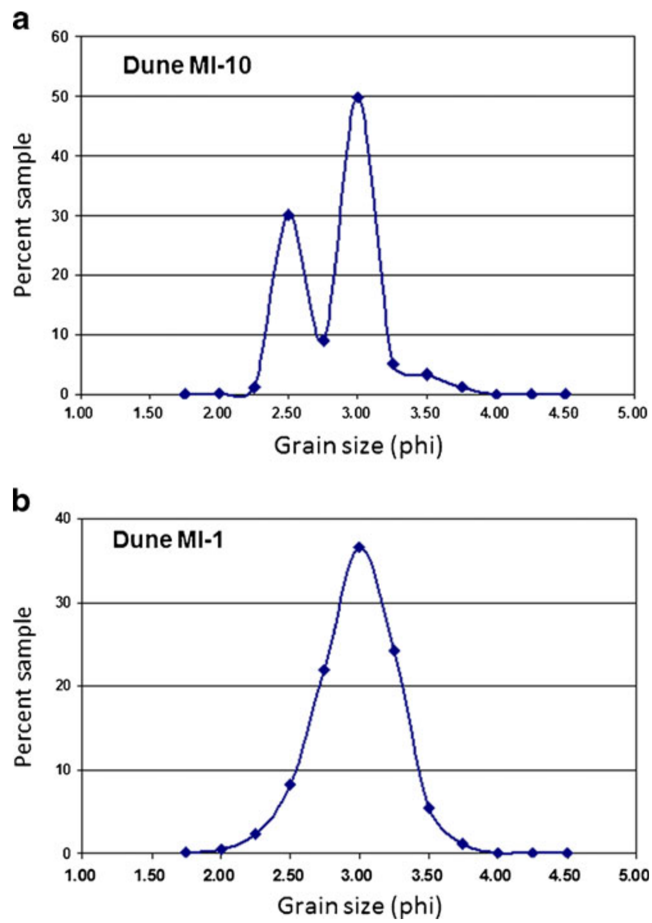

Fig. 4 Grain-size distributions of two selected dune samples (**a**, **b**) taken at 30 cm depth and characterizing North Padre Island dunes

Results

Dune and shoreface granulometry

The grain-size distributions of the shallower sediment samples in two selected Mustang Island dunes are shown in Fig. 4. These distributions and other similar ones from other dunes are characterized by the presence of different grain-size components (populations), suggesting that the dune ridge sediment is of mixed origin. Furthermore, the relative abundance of the different grain-size components varies with depth at decimeter scales in all cores.

The grain-size distributions of the four beach shoreface sediment samples are shown as insets on the beach profile in Fig. 5. Overall, coarser sand (mode: ~2.5 phi) abounds at shallower depths and finer sand (mode: 3.25–3.5 phi) at the deeper end of the beach cross-section. Significant amounts of intermediate-size sand grains (mode: ~3 phi) are found at all depths along the shoreface profile.

Storm-sand transport model

Based on the results of the shoreface grain-size analyses, a conceptual storm-sand transport model is proposed here (Fig. 6). Storm sands are here defined as shoreface sands with unique grain-size distributions, upper shoreface sands being characterized by a grain-size mode of ~2.5 phi, and middle to lower shoreface sands by modal diameters of 3.25–3.5 phi. These two sand provenance zones represent two distinctly different depths of local storm wave bases, which correlate with different storm intensities. The upper shoreface sand occurs in shallow water (<3 m), and is easily transported onto the beach by less intense storms. This is due to the fact that less intense storms have smaller waves that break in shallower water. Lower to middle shoreface sand occurs in deeper water (4–10 m), and is transported by more intense storms that have larger waves that break in deeper water. The ~3.0 phi grain-size mode is ubiquitous in all samples, and therefore not considered to be diagnostic as a provenance indicator. It represents the most commonly transported eolian component.

Dune vertical granulometry and tropical storms

To investigate the possible associations between the vertical variations in dune sand deposition and climatic variability, the total amount of storm sands was calculated for the

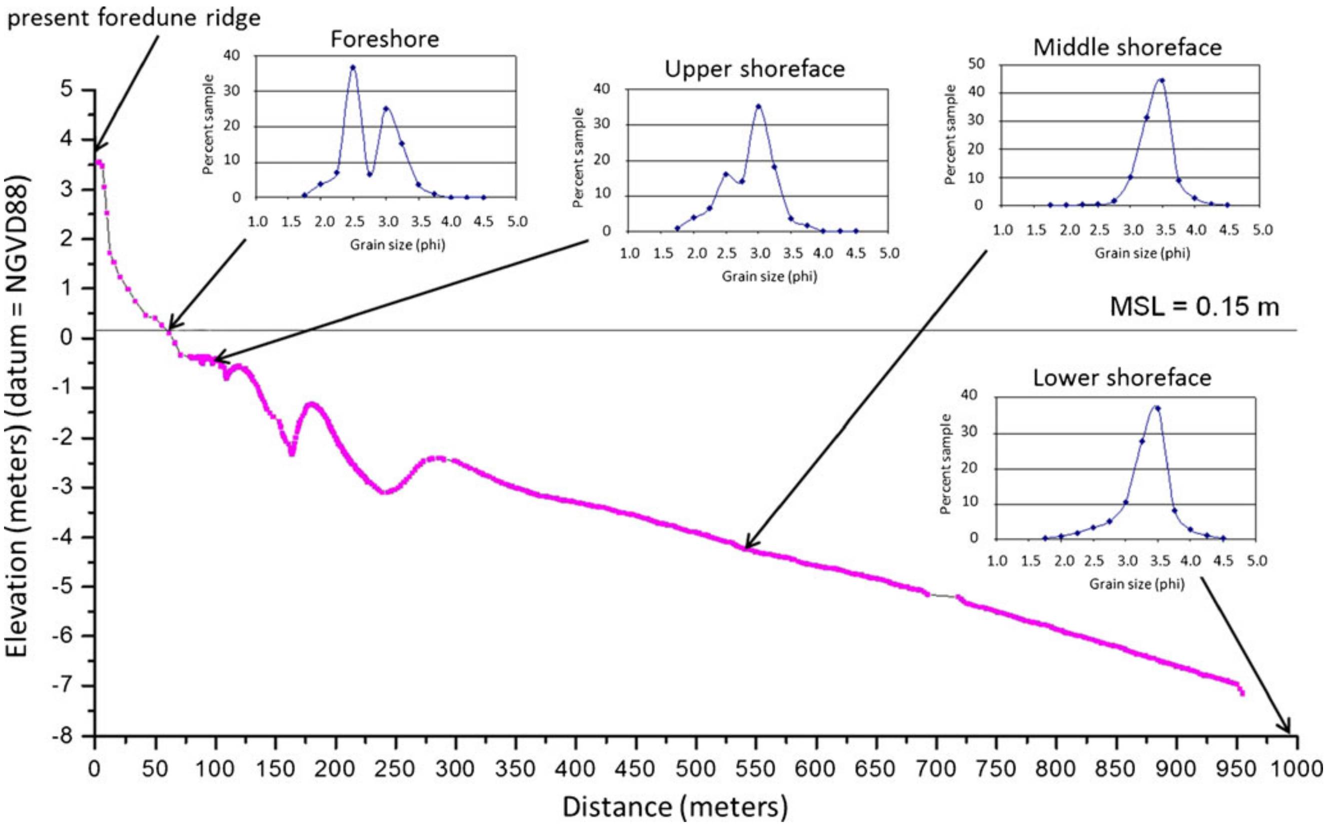

Fig. 5 Beach profile and grain-size distributions of beach shoreface samples from four different water depths along the shoreface profile

4.2 m core taken from dune MI-3. Using the conceptual model for beach ridge growth presented in Fig. 3, the dune ridge was calculated to be about 41 years old with an average vertical growth rate of 17 cm/year. The MI-3 dune age and vertical accretion rate were then used to convert the core depths of grain-size samples into time. The resulting

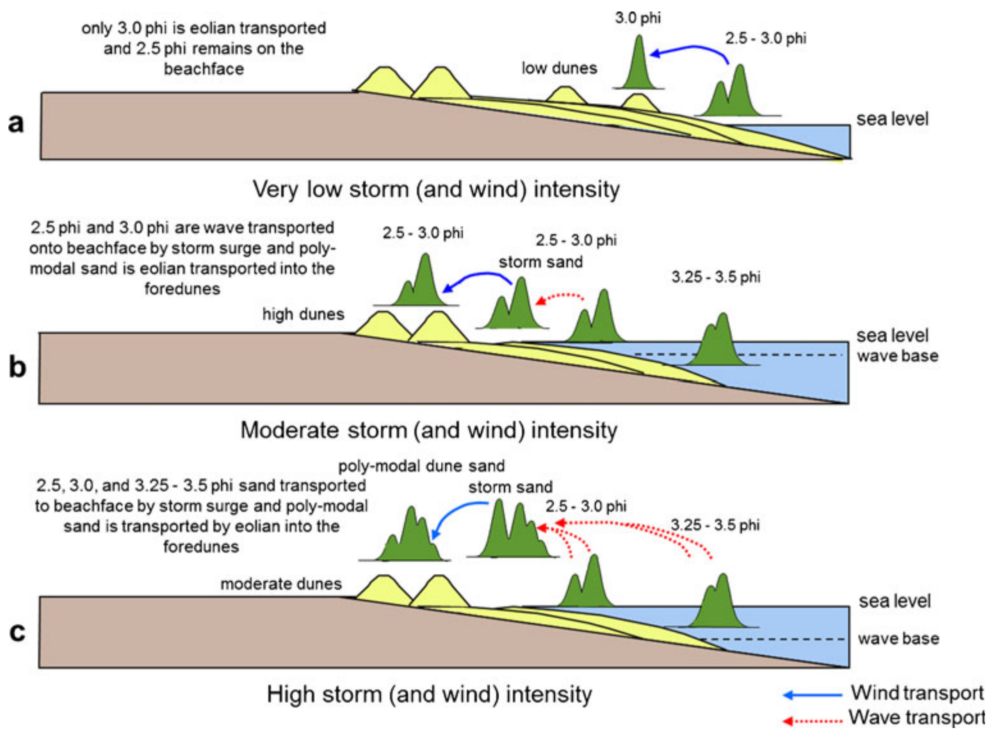

Fig. 6 Conceptual model for the introduction of storm-transported sand into beach dune ridges as a function of sea level and wave energy

temporal record of storm-sand abundance extracted from the dune core reveals year-to-year temporal variability at inter-annual to decadal timescales.

Discussion

Dune vertical granulometry and tropical storms

The vertical accretion rate for dune MI-3 of 17 cm/year estimated in this study is consistent with the 15–20 cm/year accretion rates reported by Arens and Wiersma (1994) and Arens et al. (2007), and the 13–18 cm/year rate reported by Aagaard et al. (2007).

To verify that the variability in the storm sands in the MI-3 dune is indeed associated with tropical cyclone variability, the National Hurricane Center North Atlantic hurricane database, also known as HURDAT or "best tracks" (Landsea et al. 2004), was used. This dataset allowed constructing a record of the number of Gulf of Mexico storms and hurricanes that made landfall west of the Louisiana–Alabama border during 1941–1966. When this time series was compared to the time series of proportion of storm sand, a statistically significant positive correlation of about 0.45 was obtained (Fig. 7a). This supports the hypothesis that increases (decreases) in thickness of storm-sand layers in the dunes may be associated with enhanced (diminished) sand transport

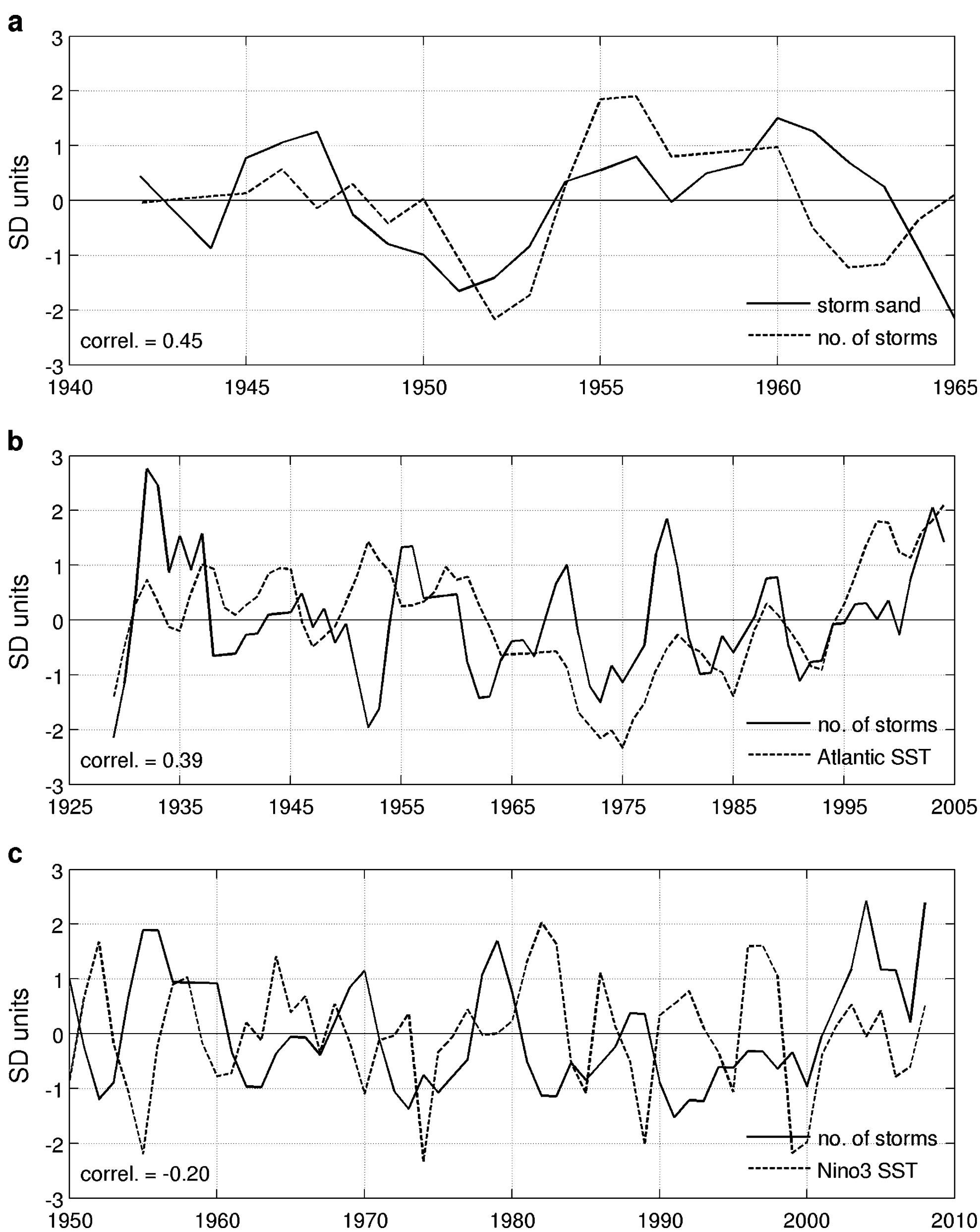

Fig. 7 **a** Yearly proportion of storm sand in dune MI-3 (*solid*) and number of Atlantic tropical cyclones landfalling at the Gulf of Mexico coast west of the Louisiana–Alabama border in 1942–1965 (*dashed*). **b** Same as the dashed curve in **a** but for 1930–2002 (*solid*) and SST averaged over the North Atlantic (the latter data from Kaplan et al. 1998, *dashed*). **c** Same as dashed curve in **a** and solid curve in **b** but for 1950–2007 (*solid*) and summer Niño-3 SST (*dashed*). All time series have been detrended, normalized (i.e., divided by their respective standard deviations, SD), and smoothed with a 3-point running mean

during periods of more (less) storm activity in the western Gulf of Mexico.

Drivers of climate variability in tropical storm activity

On multidecadal timescales, Atlantic major hurricane activity (category 3–5) is positively correlated with North Atlantic sea surface temperature (SST) through the Atlantic Multidecadal Oscillation (AMO; Goldenberg et al. 2001). The AMO is a quasi-periodic climate mode of variability with multidecadal periodicities (~60–80 years) manifested by anomalous warming and cooling of North Atlantic SSTs, with climate impacts in and around the North Atlantic basin and beyond (Mestas-Nuñez and Enfield 1999; Enfield et al. 2001). In the Gulf of Mexico, the AMO may involve shorter (~30–60 years) periodicities (Poore et al. 2009). There is also some evidence of positive decadal correlations between Atlantic tropical storm and hurricane activity and Atlantic SSTs (e.g., Molinari and Mestas-Nuñez 2003).

In contrast, Atlantic tropical cyclone activity is negatively correlated with tropical Pacific SSTs associated with the El Niño-Southern Oscillation (ENSO) phenomenon on inter-annual timescales (Gray 1984). During the warm phase of ENSO (El Niño), the anomalous atmospheric circulation results in an increase in wind shear over the Atlantic, which is unfavorable for the formation of tropical storms (e.g., Shapiro and Goldenberg 1998).

To see if the decadal to multidecadal relationships between Atlantic tropical cyclone activity and climate variability apply to tropical cyclone activity in the western Gulf of Mexico, a climatic index of North Atlantic SST was compared with the number of Gulf of Mexico tropical cyclones landfalling west of the Louisiana–Alabama border. The North Atlantic SST index used here follows the Enfield et al. (2001) AMO index definition based on the Kaplan et al. (1998) dataset, but without applying the 10-year running mean. It was found that the North Atlantic SSTs indeed modulate the storm variability (Fig. 7b) with somewhat

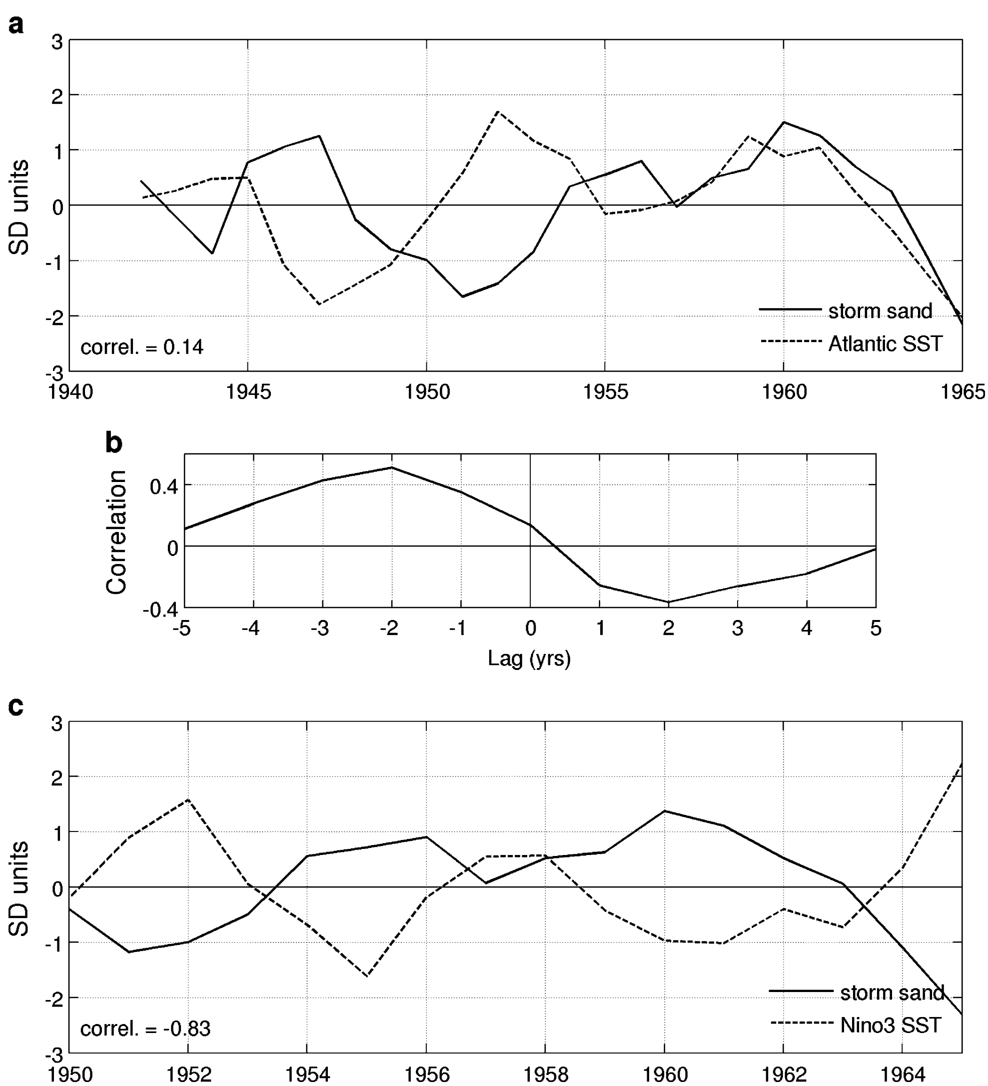

Fig. 8 **a** Yearly proportion of storm sand as shown in Fig. 7a (*solid*) and North Atlantic SST as shown in Fig. 7b (*dashed*) but for 1942–1965. **b** Lagged correlations between the two time series in **a** with SST leading for negative lags. **c** Yearly proportion of storm sand as shown in **a** (*solid*) and Niño-3 SST as shown in Fig. 7c but for 1950–1965 (*dashed*). For more information, see caption of Fig. 7

better correlations after a 3-point smoother is applied. Evidence of both decadal and multidecadal fluctuations is found in these time series.

To verify the inter-annual inverse associations between western Gulf of Mexico tropical storm activity and ENSO, a Niño-3 SST index for 1950–2008 extracted from the NOAA Climate Prediction Center website (www.cpc.ncep.noaa.gov/data/indices) was used. The negative correlation shown in Fig. 7c is consistent with El Niño (La Niña) having unfavorable (favorable) influences in the formation of Atlantic tropical cyclones.

Dune vertical granulometry and climate variability

This study has shown that the dune sand time series is a good proxy for western Gulf of Mexico tropical cyclone activity, and that the tropical cyclone activity is in turn directly associated with Atlantic SSTs for decadal to multidecadal timescales, and inversely related to Pacific SSTs (ENSO) for inter-annual timescales. It remains to be verified that these climatic signals are also present in the sand dune time series.

A comparison of the proportion of storm sand in dune MI-3 (Fig. 7a) with the Atlantic SST index for 1942–1965 (Fig. 7b) reveals a positive correlation (Fig. 8a), although there appears to be a 2-year time lag between changes in the Atlantic SST index and the subsequent change in storm frequency in the Gulf of Mexico (Fig. 8b). Examination of the Fig. 8a time series indicates that this lag varies over time, with a larger value of about 4 years in the earlier part of the records and nearly zero during the last part. The 4-year lag could be due to errors in the estimation of the dune age and accretion rates for the earlier part of the record.

In Fig. 8c, the proportion of storm-sand time series is compared with the ENSO SST index to show that the storm-sand data are consistent with the associations between tropical cyclone activity and ENSO. During warm (cold) ENSO events there is a decrease (increase) of sand transported and deposited in the dunes, which is consistent with the corresponding ENSO modulation of Atlantic tropical cyclone activity.

Conclusions

Two conceptual models are presented in this study of North Padre Island dunes, one that describes the cross-shore evolution of the barrier island, and another that identifies the sources and transport routes of sand from the shoreface to the coastal dune. The results suggest that dune ridge cores may preserve a record of past climate variability. Expanding the analysis to subsequent older dunes of the dune train would allow extending the record of storm-sand variability back in time to more than a millennium. A century or longer record of storminess would allow studying the potential signature of the AMO. On the other hand, if this study can be extended back in time and validated, it may provide a useful tool for studying the future evolution of North Padre Island under different climate change scenarios. A weak part of the analysis is the indirect dating of the dune profiles, and direct dating of the dune sediment samples is therefore recommended for future studies.

Acknowledgements The beach shoreface data were provided by D. Williams from the Division of Nearshore Research of the Conrad Blucher Institute for Surveying and Science, the LIDAR data by J. Gibeaut of the Harte Research Institute, and the Wadden Sea island dune topographic data by B. Arens. Mustang Island State Park samples were collected with permission of Texas Parks and Wildlife. This study was conducted under Padre Island National Seashore research permits PAIS-2008-SCI-0002 and PAIS-2009-SCI-0001 to J. Garrison. K. Deppe, J. Hardell, and J. Polasek assisted with vibracore acquisition, K. Deppe and E. Weber with grain-size analyses, and R. Hay with LIDAR data analysis. L. Lumb was supported in part by NSF Undergraduate Mentoring in Environmental Biology grant #0602783, TAMUCC, and A. Mestas-Nuñez by NSF grant ATM-0631677. Two anonymous reviewers and the journal editors B.W. Flemming and M.T. Delafontaine provided valuable comments. This paper is Contribution No. 1222 from the Department of Geosciences at the University of Texas at Dallas.

References

Aagaard T, Orford J, Murray AS (2007) Environmental controls on coastal dune formation; Skallingen Spit, Denmark. Geomorphology 83:29–47. doi:10.1016/j.geomorph.2006.06.007

Arens SM (1996) Rates of aeolian transport on a beach in a temperate humid climate. Geomorphology 17:3–18. doi:10.1016/0169-555X(95)00089-N

Arens SM, Wiersma J (1994) The Dutch foredunes: inventory and classification. J Coast Res 10:189–202

Arens SM, Loffler MAM, Nuijen EM (2007) Evaluatie Dynamisch Kustbeheer Friese Waddeneilanden RAP2006.04. Commissioned by North-Netherland National Public Works. Bureau for Beach and Dune Research, Land Guide Office, Amsterdam

Bullard F (1942) Source of beach and river sands on the Gulf Coast of Texas. Geol Soc Am Bull 53:1021–1044

Buynevich IV, FitzGerald DM, van Heteren S (2004) Sedimentary records of intense storms in Holocene barrier sequences, Maine, USA. Mar Geol 210:135–148. doi:10.1016/j.margeo.2004.05.007

Enfield DB, Mestas-Nuñez AM, Trimble PJ (2001) The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. Geophys Res Lett 28:2077–2080

Folk RL (1974) Petrology of sedimentary rocks. Hemphill, Austin

Garrison JR Jr, Williams J, Potter Miller S, Weber ET II, McMechan G, Zeng X (2010) Ground-penetrating radar study of North Padre Island: implications for barrier island internal architecture, model for growth of progradational microtidal barrier islands, and Gulf of Mexico sea-level cyclicity. J Sediment Res 80:303–319. doi:10.2110/jsr.2010.034

Goldenberg SB, Landsea CW, Mestas-Nuñez AM, Gray WM (2001) The recent increase in Atlantic hurricane activity: causes and implications. Science 293:474–479

Gray WM (1984) Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. Mon Weather Rev 112:1649–1668

Kaplan A, Cane MA, Kushnir Y, Clement AC, Blumenthal MB, Rajagopalan B (1998) Analyses of global sea surface temperature 1856–1991. J Geophys Res 103:18,567–18,589. doi:10.1029/97JC01736

Keim BD, Muller RA, Stone GW (2004) Spatial and temporal variability of coastal storms in the North Atlantic Basin. Mar Geol 210:7–15. doi:10.1016/j.margeo.2003.12.006

Landsea CW, Anderson C, Charles N, Clark G, Dunion J, Fernandez-Partagas J, Hungerford P, Neumann C, Zimmer M (2004) The Atlantic hurricane database re-analysis project: documentation for the 1851–1910 alterations and additions to the HURDAT database. In: Murnane RJ, Liu K-B (eds) Hurricanes and typhoons: past, present and future. Columbia University Press, New York, pp 177–221

Lindhorst S, Betzler C, Hass HC (2008) The sedimentary architecture of a Holocene barrier spit (Sylt, German Bight): swash-bar accretion and storm erosion. Sediment Geol 206:1–16. doi:10.1016/j.sedgeo.2008.02.008

Mestas-Nuñez AM, Enfield DB (1999) Rotated global modes of non-ENSO sea surface temperature variability. J Climate 12:2734–2746

Molinari RL, Mestas-Nuñez AM (2003) North Atlantic decadal variability and the formation of tropical storms and hurricanes. Geophys Res Lett 30:1541. doi:10.1029/2002GL016462

Morton RA, Pieper MJ (1977) Shoreline changes on Mustang Island and North Padre Island (Aransas Pass to Yarborough Pass); an analysis of historical changes of the Texas Gulf shoreline. University of Texas at Austin, Bureau of Economic Geology, Geological Circular 77-1

Morton RA, Paine JG, Blum MD (2000) Responses of stable bay-margin and barrier-island systems to Holocene sea-level high-stands, western Gulf of Mexico. J Sediment Res 70:478–490. doi:10.1306/2DC40921-0E47-11D7-8643000102C1865D

Nordstrom KF, Psuty N, Carter B (1990) Coastal dunes: form and process. Wiley, Chichester

Otvos EG (2000) Beach ridges—definitions and significance. Geomorphology 32:83–108

Pepper DA, Stone GW (2004) Hydrodynamic and sedimentary responses to two contrasting winter storms on the inner shelf of the northern Gulf of Mexico. Mar Geol 210:43–62. doi:10.1016/j.margeo.2004.05.004

Poore RZ, DeLong KL, Richey JN, Quinn TM (2009) Evidence of multidecadal climate variability and the Atlantic Multidecadal Oscillation from a Gulf of Mexico sea-surface temperature-proxy record. Geo-Mar Lett 29:477–484. doi:10.1007/s00367-009-0154-6

Schwarzer K, Diesing M, Larson M, Niedermeyer R-O, Schumacher W, Furmanczyk K (2004) Coastline evolution at different time scales – examples from the Pomeranian Bight, southern Baltic Sea. Mar Geol 194:79–101. doi:10.1016/S0025-3227(02)00700-4

Shapiro LJ, Goldenberg SB (1998) Atlantic sea surface temperatures and tropical cyclone formation. J Climate 11:578–590

Skilbeck CG, Rolph TC, Hill N, Woods J, Wilkens RH (2005) Holocene millennial/centennial-scale multiproxy cyclicity in temperate eastern Australian estuary sediments. J Quat Sci 20:327–347. doi:10.1002/jqs.920

Stone GW, Orford JD (2004) Storms and their significance in coastal morpho-sedimentary dynamics. Mar Geol 210:1–5. doi:10.1016/j.margeo.2004.05.003

Stone GW, Liu B, Pepper DA, Wang P (2004) The importance of extratropical and tropical cyclones on the short-term evolution of barrier islands along the northern Gulf of Mexico, USA. Mar Geol 210:63–78. doi:10.1016/j.margeo.2004.05.021

Swift DJP, Niederoda AW, Vincent CE, Hopkins TS (1985) Barrier island evolution, middle Atlantic shelf, U.S.A. Part I: shoreface dynamics. Mar Geol 63:331–361. doi:10.1016/0025-3227(85)90089-1

Tanner WF (1991) The "Gulf of Mexico" Late Holocene sea level curve and river delta history. Gulf Coast Assoc Geol Soc Trans 41:583–589

Tanner WF (1992) Late Holocene sea-level changes from grain-size data: evidence from the Gulf of Mexico. Holocene 2:249–254. doi:10.1306/A1ADDD3F-0DFE-11D7-8641000102C1865D

Tanner WF, Demirpolat S, Stapor FW, Alvarez L (1989) The "Gulf of Mexico" Late Holocene sea level curve. Gulf Coast Assoc Geol Soc Trans 39:553–562. doi:10.1306/A1ADDC78-0DFE-11D7-8641000102C1865D

Wanner H, Beer J, Bütikofer J, Crowley TJ, Cubasch U, Flückiger J, Goosse H, Grosjean M, Joos F, Kaplan JO, Küttel M, Müller SA, Prentice IC, Solomina O, Stocker TF, Tarasov P, Wagner M, Widmann M (2008) Mid- to Late Holocene climate change: an overview. Quat Sci Rev 27:1791–1828. doi:10.1016/j.quascirev.2008.06.013

Williams DD, Kraus NC, Kelly FJ, Smith AN, Anderson CM (2005) Baseline and construction monitoring of Packery Channel, Corpus Christi, Texas. In: Proc Florida Shore and Beach Preservation Association. http://www.fsbpa.com/05Proceedings/13-Deidre%20Williams.pdf (accessed 1 May 2009)

Wright LD (1995) Morphodynamics of inner continental shelves. CRC Press, Boca Raton