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Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms

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Abstract

The response of a barrier island to an extreme storm depends in part on the surge elevation relative to the height and extent of the foredunes which can exhibit considerable variability alongshore. While it is recognized that alongshore variations in dune height and width direct barrier island response to storm surge, the underlying causes of the alongshore variation remain poorly understood. This study examines the alongshore variation in dune morphology along a 11 km stretch of Santa Rosa Island in northwest Florida and relates the variation in morphology to the response of the island during Hurricane Ivan and historic and storm-related rates of shoreline erosion. The morphology of the foredune and backbarrier dunes was characterized before and after Hurricane Ivan using Empirical Orthogonal Function (EOF) analysis and related through Canonical Correlation Analysis (CCA). The height and extent of the foredune, and the presence and relative location of the backbarrier dunes, varied alongshore at discrete length scales (of ~750, 1450 and 4550 m) that are statistically significant at the 95% confidence level. Cospectral analysis suggests that the variation in dune morphology is correlated with transverse ridges on the inner-shelf, the backbarrier cuspate headlands, and the historical and storm-related trends in shoreline change. Sections of the coast with little to no dune development before Hurricane Ivan were observed in the narrowest portions of the island (between headlands), west of the transverse ridges. Overwash penetration tended to be larger in these areas and island breaching was common, leaving the surface close to the watertable and covered by a lag of shell and gravel. In contrast, large foredunes and the backbarrier dunes were observed at the widest sections of the island (the cuspate headlands) and at crest of the transverse ridges. Due to the large dunes and the presence of the backbarrier dunes, these areas experienced less overwash penetration and most of the sediment from the beachface and dunes was deposited within the upper-shoreface. It is argued that this sediment is returned to the beachface through nearshore bar migration following the storm and that the areas with larger foredunes and backbarrier dunes have smaller rates of historical shoreline erosion compared to areas with smaller dunes and greater transfer of sediment to the washover terrace. Since the recovery of the dunes will vary depending on the availability of sediment from the washover and beachface, it is further argued that the alongshore pattern of dune morphology and the response of the island to the next extreme storm is forced by the transverse ridges and island width through alongshore variations in storm surge and overwash gradients respectively. These findings may be particularly important for coastal managers involved in the repair and rebuilding of coastal infrastructure that was damaged or destroyed during Hurricane Ivan.
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1. Introduction

The height and extent of foredune development, relative to the storm tide elevation, are primary controls on the response of a barrier island to extreme storms (Thieler and Young, 1991; Sallenger, 2000; Morton, 2002; Houser et al., 2007). The impact of Hurricane Alicia on Galveston Island, Texas was magnified by the absence of a protective foredune that had been eroded three years earlier during Hurricane Allen and had not had sufficient time to recover (Morton and Paine, 1985). The presence and relative location of backbarrier dunes also affect

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the impact of an extreme storm and the redistribution of sediment between overwash deposits and erosion offshore (Houser et al., 2007). Where the primary and backbarrier dunes are closely spaced, overwash penetration is reduced and eroded sediment is deposited in the upper-shoreface – a situation that is analogous to having a large wide foredune. As the separation distance between the primary and backbarrier dune increases, they no longer act like a large wide foredune and as a consequence, more sediment is deposited along the backbarrier by overwash. The ability of coastal dunes to recover and the morphological response to the next storm depends on the availability of sediment from the overwash (Leatherman 1976; Armon, 1980; Leatherman, 1979) and beachface (Psuty, 1992). Even if sediment is available from these sources, foredune recovery is only initiated when vegetation is able to re-establish with sufficient density and coverage to promote sediment deposition (Snyder and Boss, 2002).

The response and recovery of a barrier island are further complicated by alongshore variations in dune height (Morton, 2002; Gares and White, 2005; Stockdon et al., 2007) and island width (Morton, 2002), which can influence overwash and localize breaching. For example, dunes along Cape Hatteras are relatively continuous, but variations in dune height (in excess of 8 m) have been noted at scales of kilometers to tens of kilometers (Elko et al., 2002). Similar variations in shoreline response (erosion and deposition) have also been documented (Terwindt and Battjes, 1990; Morton et al., 1995), but the mechanisms responsible for this variability remain poorly understood. Several studies suggest that localized coastal response can be forced by the geologic framework and offshore bathymetry (Demarest and Leatherman, 1985; Kraft et al., 1987; Pilkey et al., 1993; Riggs et al., 1995; Schwab et al., 2000; McNinch, 2004; Browder and McNinch, 2006; Schupp et al., 2006; Stockdon et al., 2007). For example, “hotspots” of shoreline change can develop in response to gradients in alongshore transport as a result of wave refraction/diffraction around bathymetric highs or lows (*e.g.* O’Reilly and Guza, 1993; Bender and Dean, 2003; Schupp et al., 2006). Schupp et al. (2006) have shown that shoreline variability is highly correlated (but with a lag) to shore-oblique ridges, which in turn are correlated with Pleistocene gravel outcrops. Since beach width and budget affect the availability of sediment to the foredune (Psuty, 1992; Bauer and Davidson-Arnott, 2003), it is reasonable to expect that these local-scale variations in beach morphology and width will be mirrored in the dune morphology.

Spatial variation in island response to a storm can lead to similar variations in the supply of sediment and vegetation growth. In breached areas, the recovery of the dune system can be limited by the presence of moisture (Belly, 1964; Hotta et al., 1984; Sherman et al., 1998; Cornelis et al., 2004; Wiggs et al., 2004; Davidson-Arnott et al., 2005) and lag deposits (Nickling and McKenna-Neuman, 1995; McKenna-Neuman, 1998). Burial tolerant vegetation is preferentially selected within overwash and breach areas (Stallins and Parker, 2003), which promotes the development of dunes with limited relief (Stallins, 2005). As noted, surge water may be forced into the intervening areas of low-elevation, which can become washover conduits (Morton, 2002; Gares and White, 2005), such that the dune field tends to develop as a mosaic of alongshore patches that vary in age and composition (Stallins and Parker, 2003). In this respect, the dunes can reinforce alongshore patterns in overwash and breaching during subsequent storms (Stockdon et al., 2007; Morton and Sallenger, 2003). Due to the importance of vegetation to topographic development, Stallins (2005) describes this biogeomorphic feedback as an adaptive system. However, this classification does not account for geologic controls on storm impact and dune development/recovery, which can create a forced variation in dune morphology and vegetation.

While alongshore variations in coastal dune morphology have been described (Elko et al., 2002; Stallins and Parker, 2003), the controls on this variations are not well understood. In recent years, Santa Rosa Island in northwest Florida has been impacted by Hurricane Ivan (2004), Tropical Storm Arlene (2005), Hurricane Dennis (2005) and Hurricane Katrina (2005). During Hurricane Ivan, Santa Rosa Island was within the northeast quadrant of the storm (Fig. 1) and subject to surge heights in excess of 3 m. The island morphology changed from a discontinuous foredune backed by hummocky backbarrier dunes and maritime forest (at the cuspate headlands), to washover terraces at the headlands and washover corridors between headlands (Fig. 2). Claudino-Sales et al. (2008) provide a qualitative assessment of hurricane impact along Santa Rosa Island and conclude that dune survival is controlled by the characteristics of the storm and dune morphology. However, the authors do not explain why the island response (and impact to infrastructure) exhibited considerable variability alongshore at length scales that appear to depend on the spacing of the backbarrier cuspate headlands (Houser et al., 2007). The aim of the present study is to describe the statistical relationship between dune morphology, the historic and storm-related rates of shoreline retreat (hotspots), island width and bathymetric features alongshore Santa Rosa Island. As noted above, the relationships between offshore bathymetry and storm impact (including shoreline erosion) have been established in general (McNinch and Leuttich, 2000; Cooper and Navas, 2004; McNinch, 2004; Schupp et al., 2006), but the relationships have not been described along the Central Gulf Coast or in relation to dune morphology.

2. Study site

The focus of this study is an approximately 11 km stretch of Santa Rosa Island in Northwest Florida that was impacted by Hurricane Ivan (2004). Santa Rosa Island is a narrow sandy Holocene barrier island extending 96 km from East Pass near Destin to Pensacola Pass in the west. It is the second-longest barrier island on the U.S. Gulf Coast, and is separated from a higher standing barrier complex of late Pleistocene origin by Santa Rosa Sound. While the origin of the island has been attributed to the erosion of a central Pleistocene “core” and longshore redistribution of sediments (Otvos, 1982), others attribute longshore sediments derived by bluff erosion east of Destin as contributing most to the island’s formation (Kwon, 1969; Stone, 1991; Stone et al., 1992; Stone and Stapor, 1996).

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