EOF ANALYSIS OF MORPHOLOGICAL RESPONSE TO HURRICANE IVAN

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Abstract: Hurricane Ivan, a Category-3 hurricane, came ashore near Gulf Shores, Alabama, on September 16, 2004. Santa Rosa Island, Florida, was within the Northeast quadrant of the storm and subject to surge heights in excess of 3 m. As a result the area suffered significant sediment loss (>200 m^3 m^{-1}) and widespread overwash and breaching. Morphological changes were quantified by comparing LIDAR images collected before and after landfall. In general, the morphological changes exhibited an alongshore variation at a range of scales (<1 km), consistent with the variation in foredune height prior to the storm. Using multivariate statistics it is found that this variation not only depends on the height of the foredune (relative to the surge elevation) but also on the alongshore extent of the dune and the presence and relative location of the secondary dunes. This alongshore variation will affect the recovery of the dunes, reinforcing the observed patterns.

INTRODUCTION

Hurricanes and tropical storms produce elevated water levels and large waves, capable of eroding the beachface and causing overwash and barrier breaching. In general, the impact of a storm on a barrier island depends on the elevation of the storm surge relative to the vertical geometry of the coast, which in turn depends on the extent and height of foredune development (Thieler and Young, 1991; Sallenger, 2000).

Alongshore variations in dune morphology can force alongshore patterns in overwash and breaching during storms (Morton and Sallenger, 2003). While dunes along Cape Hatteras are relatively continuous, variations in dune height (in excess of 8 m) have been noted at scales of kilometers to tens of kilometers (Elko *et al.*, 2002). Wetzell (2003) showed that the alongshore variation in storm impact was consistent with the variation in dune height and the Storm Impact Scale of Sallenger (2000). In areas where there is frequent and extensive overwash the dune field tends to develop as a mosaic of alongshore patches that vary in age and composition (Stallins and Parker, 2003). While the dunes will obstruct overwash penetration, surge water may be forced into the intervening areas of low elevation, which can become washover conduits (Morton, 2002). It is reasonable to expect that the concentrated flows within these conduits could impact adjacent foredunes through lateral erosion, which could increase overwash penetration where dune height is variable.

In recent years, Santa Rosa has been impacted by Hurricane Ivan (2004), Tropical Storm Arlene (2005), Hurricane Dennis (2005) and Hurricane Katrina (2005). During Hurricane Ivan, the dunes on Santa Rosa Island were again reduced in height through direct wave erosion and overwashing. It is hypothesized that the morphological response to Hurricane Ivan was conditioned by the alongshore variation in the height of the dunes that had recovered following Hurricane Opal (1995). The purpose of this study is to examine how the alongshore variation in dune height and extent affected the morphological response of Santa Rosa Island to Hurricane Ivan and the redistribution of dune and beachface sediment between the nearshore and overwash deposits.

STUDY SITE

Santa Rosa Island is a narrow sandy Holocene barrier island extending over 80 km in length, from East Pass near Destin in the east to Pensacola Pass in the west (Figure 1). The second-longest barrier island on the U.S. Gulf Coast, Santa Rosa Island is separated from the Pleistocene mainland coast by Santa Rosa Sound, a continuous lagoon 3 km wide in the west and tapering to less than 400 m in the east (Kwon, 1969). Although some scholars ascribe the origin of the island to erosion of a central Pleistocene "core" and longshore redistribution of sediments (Otvos, 1982), others (Stone, 1991; Stone *et al*., 1992; Stone & Stapor, 1996) attribute longshore sediments derived by bluff erosion east of Destin as contributing most to the island's formation. The island reached its present form by 3000 bp, and it has been characterized by overall transgression since then. On the basis of dated peat and tree stumps, Stone and Morgan (1993) estimated a landward shift of "one island width" over the past 800 years (cited in Otvos, 1997). This translates to a long-term shore retreat rate of about 2 ft/yr at the site of present-day Pensacola Beach.

Santa Rosa Island is microtidal, with an average tidal range of 0.43 m (Armbruster, 1997). In addition to strong wave action on the Gulf side, especially during tropical storms and hurricanes, the island experiences back-barrier shoreline erosion due to wind-driven waves generated by winter polar outbreaks. As a result, the roll-over effect commonly associated with transgressive island systems is largely absent, except following intense hurricanes that generate extensive overwash activity.

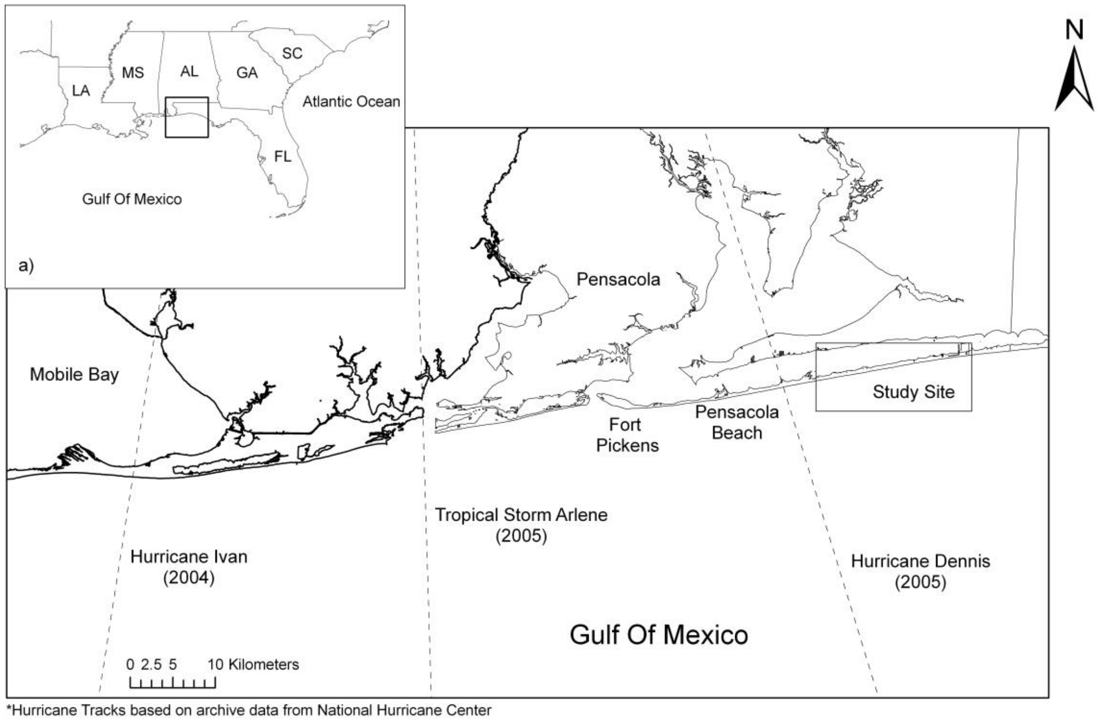

Fig. 1. Map of study site showing location relative to the tracks of Hurricanes Ivan and Dennis and Tropical Storm Arlene.

Historically, Santa Rosa Island has been been struck by relatively few hurricanes, especially throughout most of the 20th century. In spite of hurricanes in 1906, 1916,and 1926 (when Santa Rosa Island was unpopulated), the island's shoreline position remained relatively stable from 1920 to 1993 (Foster *et al.*, 1999; Stapor, 1975).

Short-term shoreline changes have, on the other hand, been rather dramatic since 1995 because of the passage of several hurricanes and tropical storms, e.g. Erin (1995), Opal (1995), Georges (1998), and various tropical storms. Such changes have been well documented (e.g. Leadon *et al*., 1998; Leadon *et al.*, 1999; Liebens, 2000, and unpublished analyses by Olsen & Associates).

METHODOLOGY

Changes to the barrier morphology were quantified by comparing LIDAR images collected immediately before and after landfall using cross-shore transects spaced 50 m alongshore. The cross-shore geometry of the island was examined using empirical orthogonal function (EOF) analysis to identify to reduce the topographic data into common forms. EOF analysis is similar to principal component analysis, except that the variability structure is examined through space rather through time. The relationship between the primary modes of the pre- and post-storm topographic data was examined through canonical correlation analysis (CCA). This test is used to investigate whether or not there are patterns that occur simultaneously in two different data sets and to describe the nature of those patterns.

RESULTS

A comparison of the pre- and post-storm alongshore variation in foredune elevation is provided in Figure 2. The foredune height exhibited considerable variability alongshore and was in some cases discontinuous with an average elevation above-sea-level of ~4.3 m prior to the storm. Through spectral analysis, it is found that the variation in dune height is periodic, with statistically significant spectral peaks at 9, 14, 31 and 76 transects. The average elevation within the foredune area was reduced to 2.3 m, with remnant dunes remaining only where relatively large continuous dunes had been present. The post-storm elevation data also exhibits an alongshore periodic variation at 31 and 76 transects and relatively muted variations at 9 and 14 transects.

The average pre- and post-storm cross-island profiles are presented in Figure 3. The net change in sediment volume ranged from an erosion of 238 to 43 m^3 per unit width of beach. The largest net losses of sediment (>150 m^3 per unit width of beach) were coincident with the location of breaches, which were observed where the dune crest elevation (based on a 9-point moving average) is at a minimum and close to the surge elevation (Figure 2). The crest of the dune at these locations would have been overtopped early in the storm and would have focused overwash that would eventually precipitate a breach. The breaches were reactivated during Hurricane Katrina (2005) and are activated during frontal storms that coincide with high tide.

The amount of sediment removed per unit width of beach exceeded 45% at the breach sites and ~20% on average. The loss of sediment is considerably larger than the volumetric changes presented by Stone *et al.*, (2004) for Hurricane Opal, although sediment volumes in that study were considered to a depth of 1.5 m on both the Gulf and Sound side of the island. Except for the breach areas, the amount of sediment lost from the profile does not exhibit a clear relationship with the pre-storm elevation of the foredune. This suggests that the height of the foredune is not the only control on the redistribution of sediment between overwash and erosion offshore.

Empirical Orthogonal Function (EOF) Analysis

In both the pre- and post-storm data, the first 5 modes were found to be statistically significant (ρ<0.05), with the percent of the total variance explained being 65 and 75% respectively. The primary eigenmode (E1) for the pre-storm morphology explains 21% of the variance and shows a secondary dune (positive factor weightings) ~170 m landward of the average primary dune (Figure 4a). Secondary dunes are also indicated by positive factor weightings for E3 and E5, at 67 and 117 m landward of the primary dune respectively. The second eigenmode (E2) explains 14% of the variance and exhibits negative factor weightings in the vicinity of the beachface and positive factor weightings on the landward slope of the primary dune.

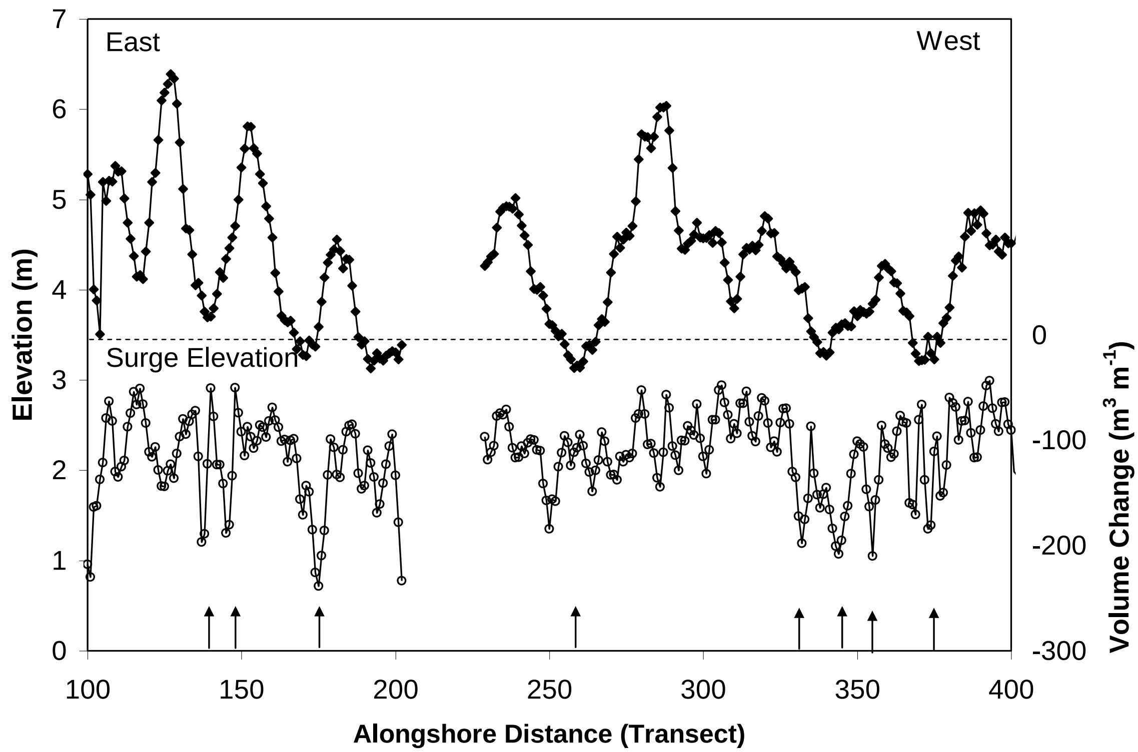

Fig. 2. Alongshore variation in dune height modelled using a 9-point moving average and the volume change between the pre- and post-storm profiles. Also shown with the arrows are the locations where breaches were observed.

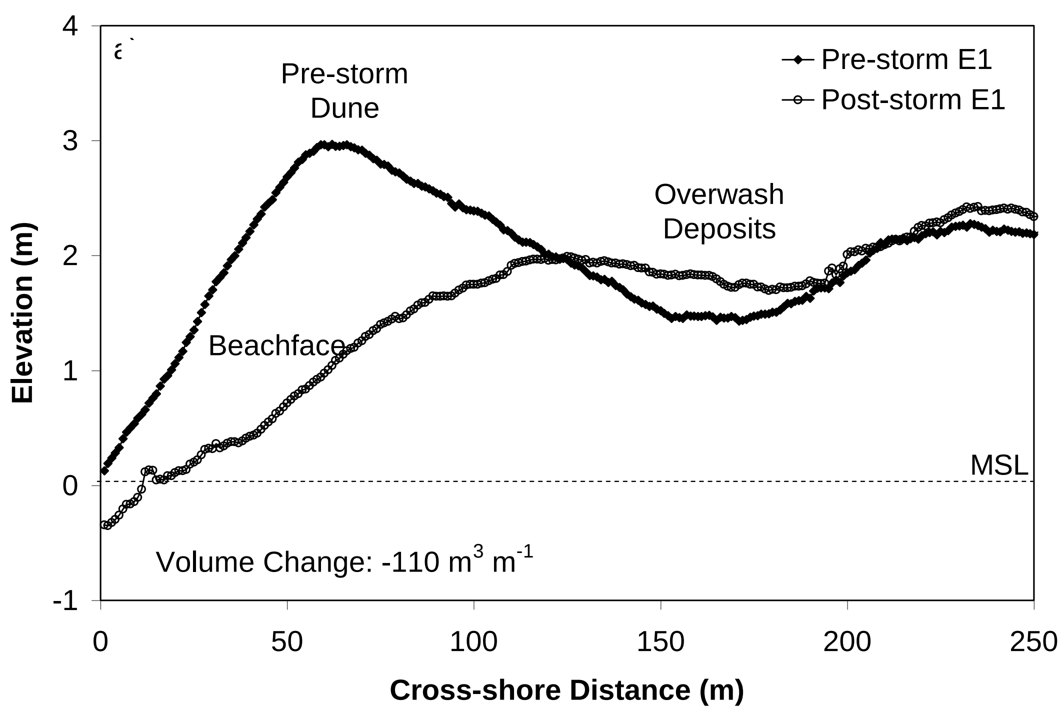

Fig. 3. Pre- and post-storm average cross-island profiles with major morphological features identified.

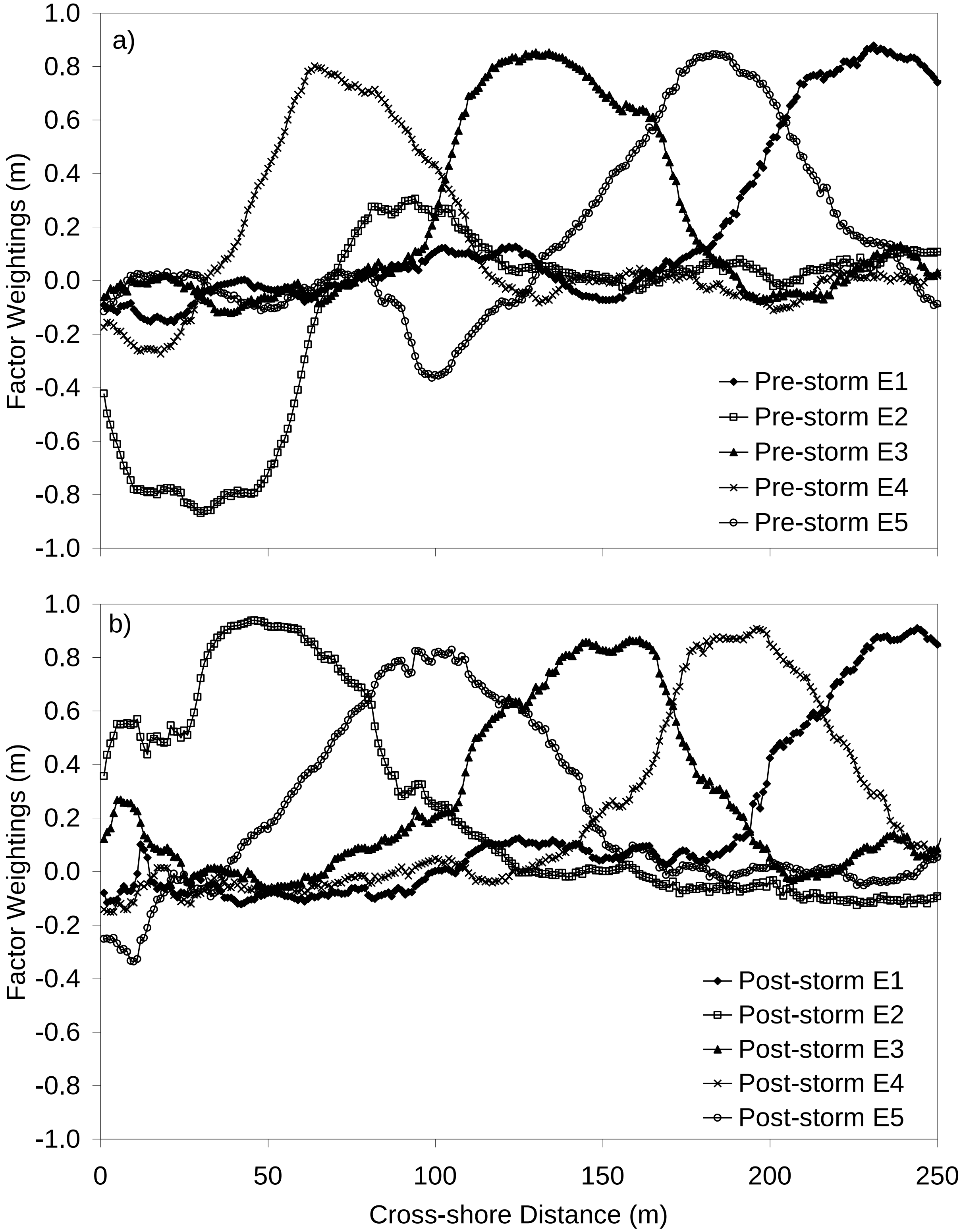

Fig. 4. Factor weightings for the first 5 eigenmodes of the (a) pre-storm morphology and (b) the post-storm morphology.

This profile is characterized by a single foredune that is ~20 m landward of the average foredune position and a relatively extensive foreshore and backshore. The fourth eigenmode (E4) has positive factor weightings at the crest of the foredune and is characteristic of a foredune that is ~0.80 m larger than the average dune (Figure 3).

In the post-storm morphology, 26% of the total variance is explained by E1and 25% of the variance is explained by E2. The primary eigenmode (E1) for the post-storm morphology exhibits positive factor weightings in the backbarrier similar in position and amplitude to the primary eigenmode for the pre-storm morphology (Figure 4b). Remnant secondary dunes are also apparent, to varying degrees, in the profiles for E3 and E4. The location and amplitude of these dunes is consistent with E3 and E5 for the pre-storm morphology. The second eigenmode exhibits positive factor weightings and accretion in the vicinity of the beachface, characteristic of either less beachface erosion or accretion relative to the average post-storm profile (Figure 3).

Canonical Correlation Analysis

As observed in the EOF analysis, there are similarities in the factor weightings of the pre- and post-storm morphology. Canonical correlation analysis between the factor scores for the pre- and post-storm morphology yields a correlation of 0.73 ($\rho<0.05$). Results of the analysis are presented in Table 1. The negative correlation (-0.79) between the pre-storm E2 and post-storm E2 is a reflection of how overwash penetration is inversely related to dune height and that significant overwash penetration and even breaching are observed in areas of low dune height (areas with a negative pre-storm E2). The positive correlation between pre-storm E4 and post-storm E5 is a reflection of increased beachface erosion and sediment loss to the offshore with increasing dune height. Overwash penetration is relatively small and in some cases absent where there is a strong positive pre-storm E4 (large dunes). The additional correlation between pre-storm E4 and post-storm E2 suggests that large dunes adjacent to smaller dunes (or areas where dune are absent) can be eroded through lateral erosion.

Table 1. Canonical correlation coefficients (*r*) between the pre- and post-storm profiles, with the largest coefficients (strongest relationships) highlighted.

		Post-storm Profiles				
		E1	**E2**	**E3**	**E4**	**E5**
Pre-Storm Profiles	**E1**	0.66	-0.06	0.16	0.18	0.14
	E2	0.13	-0.79	-0.07	0.10	0.02
	E3	0.08	-0.06	0.63	0.24	-0.05
	E4	-0.03	0.21	0.23	0.07	0.72
	E5	0.20	0.03	0.04	0.52	-0.24

DISCUSSION

It has been well demonstrated in previous studies that the response of a barrier island to an extreme storm depends not only the local magnitude of the storm but also the pre-storm morphology (e.g. Sallenger, 2000; Morton, 2002). The models developed in these studies provide reasonable estimates of storm impact (see Wetzell, 2003), but the models only provide a first approximation based largely on foredune height and there is a need for verification in the prototype. In the present study, LIDAR data is used to examine how the response of Santa Rosa Island to Hurricane Ivan was directed by the pre-storm geometry. Results suggest that (to the first order) the morphological response partly varies with the height of the foredune relative to the elevation of the storm surge, which supports the storm impact model of Sallenger (2000).

The pre-storm height of the foredune exhibited considerable variation alongshore and the variation in the morphological response and profile volume exhibited a similar variation. Prior to the storm, the alongshore variation in the foredune height exhibited periodic variations at 76, 31, 14 and 9 transects. The larger-scale variations remained strong following the storm while the smaller-scale variations were significantly weaker following the storm. If the impact of this storm depended only on the relative elevations of the dune and storm surge, then these small-scale variations would have been maintained and potentially reinforced with larger and sustained impacts where there were small dunes. It is reasonable to expect that the absence of these small-scale variations following the storm is a result of lateral dune erosion and that the scale of variation that is removed (or weakened) by the storm depends on the magnitude and duration of the storm. As noted in a number of studies, surge water can be forced into areas with low dune heights (Morton, 2002) and the fast flowing water within these conduits is capable of eroding the dunes laterally.

The morphological response and redistribution of dune sediment was also found to depend on the cross-island geometry. Where there were no secondary dunes overwash and sediment erosion offshore were primarily dependent on the height of the foredune (Sallenger, 2000), which was the general case in the eastern section of the study site (transects 115 through 181). Numerous secondary dunes were observed in the western section of the study site (transects 229 to 400) with a periodicity of 38 transects. Where the primary and secondary dunes were closely spaced overwash was restricted and sediment erosion offshore was increased. This situation was analogous to having a large wide foredune (Thieler and Young, 1991). As the separation between the primary and secondary dune increased, overwash penetration was not restricted and the amount of sediment eroded offshore was reduced.

While the island appears to be uniformly covered an overwash terrace the results of this study have shown there to be considerable alongshore variability in the morphological response and redistribution of dune sediment. This variation will ultimately affect the recovery of the dune system, such that there will be alongshore variation in the height and extent of the next foredune. If the frequency of extreme storms increases the alongshore variation will be reinforced and the dunes will develop a mosaic of alongshore patches that have a cross-island orientation (Stallins and Parker, 2003). The secondary dunes on Santa Rosa Island are remnant features that not only survived Hurricane Ivan but had also survived Hurricane Opal in 1995. The alongshore periodicity of these features (~30 transects) is consistent with the alongshore periodicity in the height of the foredune, suggesting that the alongshore response of the island is directed by a persistent variation in the island geometry that is a reflection of the storm frequency (Stallins and Parker, 2003).

CONCLUSIONS

While it has been well demonstrated in previous studies that the response of a barrier island to an extreme storm depends on the pre-storm morphology, these models only provide a first approximation based on foredune height. Results from the present study suggest that the morphological response not only depends on the foredune height but also on the presence and relative location of secondary dunes and breaks in the crest. Where there were no secondary dunes, overwash and sediment erosion offshore were primarily dependent on the height of the foredune. Where the primary and secondary dunes were closely spaced, overwash was restricted and sediment erosion offshore increased, analogous to having a large wide foredune. As the separation between the primary and secondary dune increases, overwash is not restricted and the amount of sediment eroded offshore is reduced. The alongshore variation in morphological response will ultimately control the recovery of the dune system, such that the alongshore variation in dune height and extent may redevelop and direct the response to the next extreme storm.

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