coas 25-05-13 13sn --- Thursday Apr 09 2009 04:30 PM

This manuscript/text has been typeset from the submitted material. Please check this proof carefully to make sure there have been no font conversion errors or inadvertent formatting errors. Allen Press

AUTHORS: THE FOLLOWING QUERIES/COMMENTS ARE FOR EDITORIAL STAFF FROM PROOFREADERS. The editorial staff will contact you if they have any questions regarding these queries and comments.

EDITORIAL STAFF: Query markers appear in boxes in the margins as a question mark followed by a number. Please respond to each query in the margin of the corresponding proof page. Comment markers are suggested corrections that will also appear in the margin, but as a "C" followed by a number. If you wish to implement the suggested correction, please transfer the correction to the margin and text of the corresponding proof page.

C1: Replace italic colon with a roman colon after "In".
C2: Replace italic colon with a roman colon after "In".

Journal of Coastal Research | 00 | 0 | 000–000 | West Palm Beach, Florida | Month 0000

Effect of Hurricane Ivan on Coastal Dunes of Santa Rosa Barrier Island, Florida: Characterized on the Basis of Pre- and Poststorm LIDAR Surveys

Vanda Claudino-Sales†, Ping Wang‡, Mark H. Horwitz§

†Department of Geography
Federal University of Ceará. Bloco 911
Campus do Pici
Fortaleza, Ceará 60.000 Brazil

‡Department of Geology
University of South Florida
4202 E Fowler Avenue
Tampa, FL 33620, U.S.A.
pwang@cas.usf.edu

§BCI Engineers and Scientists Inc.
Lakeland, FL 33803, U.S.A.

ABSTRACT

CLAUDINO-SALES, V.; WANG, P., and HORWITZ, M.H., 2009. Effect of Hurricane Ivan on coastal dunes of Santa Rosa Barrier Island, Florida: characterized on the basis of pre- and poststorm LIDAR surveys. *Journal of Coastal Research,* 00(0), 000–000. West Palm Beach (Florida), ISSN 0749-0208.

Santa Rosa Island, situated along the northwestern Florida coast facing the Gulf of Mexico, is an 85-km-long wave-dominated low-lying barrier island with well-developed incipient and established dunes. In this paper, we examine the regional-scale effect on coastal dunes by a strong category 3 hurricane, Ivan, through comparison of pre- and poststorm airborne LIDAR (light detecting and ranging) surveys. On the basis of pre-Ivan LIDAR survey data, the elevation of the berm and back beach is typically 2.0 m above MSL (mean sea level). Incipient dunes range from 2.5 to 10 m above MSL, or 0.5 to 8.0 m above the surrounding beach. The hummocky dunes that developed over relic washover platforms are typically less than 4.0 m above MSL. The densely vegetated, established dune fields are composed of dunes less than 7.0 m high and intradune wetlands lying at less than 1.0 m above MSL. The entire island was severely affected by Ivan, which made landfall about 45 km to the west in September 2004. The landscape was substantially changed by Ivan. Over 70% of the incipient and hummocky dunes were destroyed, and a large portion of the low-lying wetlands was covered by washover. The degree of storm-induced morphology change depends not only on the intensity and duration of the storm but also on the antecedent morphological characteristics of the barrier island. Comparison of pre- and post-Ivan cross-island LIDAR profiles indicates that at most locations, more sand was eroded from the subaerial portion of the barrier island (*e.g.,* beach and dune) than was deposited as washover terraces and lobes. This suggests a net sand loss to the offshore region. Evidence of sand moving alongshore related to the oblique orientation of the dunes was also identified. Under inundation regime, the subaerial sediment deficit could be accounted for by subaqueous sedimentation into the back-barrier bay.

ADDITIONAL INDEX WORDS: *Barrier islands, hurricanes, coastal morphology, coastal dunes, storm overwash, tropical storms, Gulf of Mexico, Florida.*

INTRODUCTION

The 85-km-long Santa Rosa Island, Florida, was severely affected by Ivan, a large, slow-moving strong category 3 hurricane that made landfall about 45 km to the west in September 2004. The hurricane induced regional-scale morphology change (Claudino-Sales, Wang, and Horwitz, 2008; Wang and Horwitz, 2007; Wang *et al.,* 2006). Owing to the recent improvements in remote sensing technology, the morphological changes can be quantified at a regional scale. Specifically, airborne LIDAR (light detecting and ranging) surveys were conducted in conjunction with aerial photography shortly before and after the passage of the hurricane.

Dunes on Santa Rosa Island are generally lower than 8 m (Kurz, 1942). The primary reasons for the relatively low dunes are the lack of sand-sized sediment supply and persistent onshore winds (Davis, 1994). In addition, the modest width of the island does not offer adequate accommodation space for wind-blown sand accumulation. The overall low dune elevations make the barrier islands particularly vulnerable to storm overwash. Various interactive factors controlling the destruction or survival of coastal dunes induced by Hurricanes Ivan (2004) and Dennis (2005) were examined qualitatively by Claudino-Sales, Wang, and Horwitz (2008) by comparison of pre- and poststorm aerial photographs. They found that the degree of storm-induced morphology changes depends not only on the characteristics of the storm but also on the antecedent morphological properties of the barrier island. In contrast to many previous studies emphasizing dune height as the dominating morphological factor (*e.g.,* Sallenger, 2000), the survival or destruction of dune fields on low-lying barrier islands is controlled by a range of interactive factors. Specifically, the chances of dune survival increase with increasing distance from the hurricane landfall, width of the barrier island, distance to the ocean, overall elevation, vegetation density, presence of woody vegetation,

DOI: 10.2112/08-1105.1 received 2 August 2008; accepted in revision 4 January 2009.

This research is partly funded by the National Science Foundation's Geography and Regional Science Program. V. Claudino-Sales is supported by CAPES—Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brasília, Brazil.

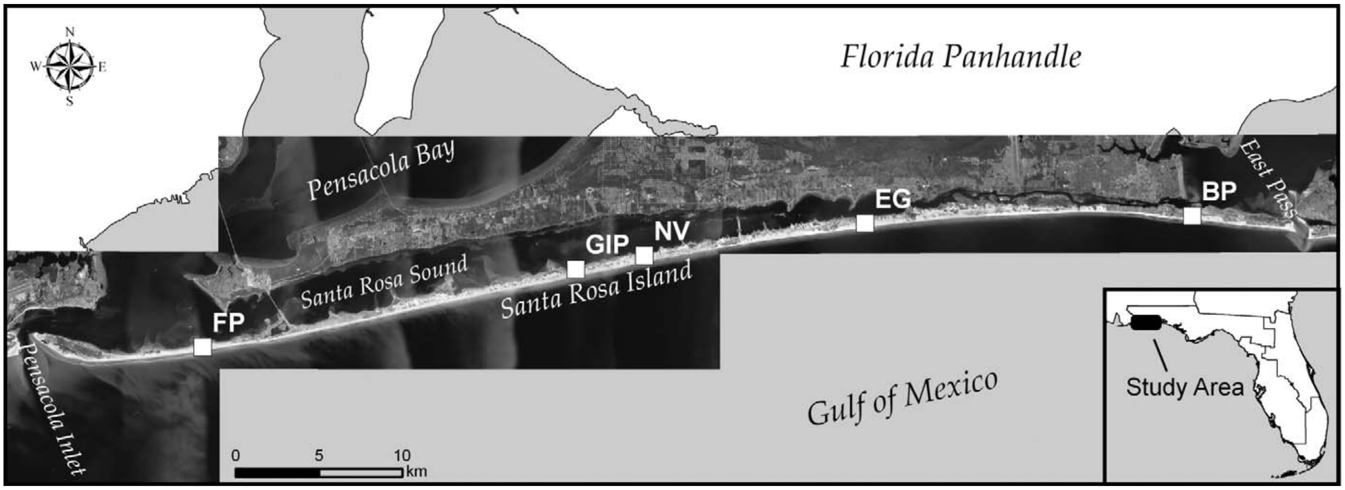

Figure 1. Pre-Ivan aerial photo mosaic of Santa Rosa Island showing the location of the five study sites: FP = Fort Pickens State Park, GIP = Gulf Island National Sea Shore, NV = Navarre Beach, EG = Eglin Air Force Base, BP = Beasley Park. The Ivan landfall is about 45 km west of the FP site.

and continuity and width of the dune field. Conversely, the chances of dune survival decrease with increasing site-specific storm intensity, duration, and frequency, and the presence of relic washover terraces.

In this paper, we expand on the qualitative study by Claudino-Sales, Wang, and Horwitz (2008). The extensive pre- and post-Ivan LIDAR data were analysed and compared to quantify the regional-scale dune erosion and washover deposits. The LIDAR data were compared with some pre- and post-Ivan land survey data for ground truthing. The goals of this paper are to (1) quantify the pre- and poststorm elevation characteristics of the various barrier island subenvironments, (2) calculate the volume of sand eroded and deposited by the storm, and (3) verify and further improve the conceptual model proposed by Claudino-Sales, Wang, and Horwitz (2008) with the use of regional-scale LIDAR survey data. More information on the study area and a more detailed literature review can be found in Claudino-Sales, Wang, and Horwitz (2008).

STUDY AREA

Located along the northwestern Florida Gulf of Mexico coast, Santa Rosa Island extends 85 km from Pensacola Inlet at its western end to East Pass at its eastern end, with the relatively narrow Santa Rosa Sound separating the barrier island from the mainland (Figure 1). Parallel to the general trend of the northern Gulf of Mexico coast, the barrier island is oriented roughly east-west, ranging in width from 1050 to 160 m, with an average width of approximately 500 m. Santa Rosa Island is a late Holocene wave-dominated barrier island (Davis, 1997) that was built over a Pleistocene core (Otvos, 1981). It has relatively well-developed beaches and dunes, composing some of the largest dune fields in the state of Florida (Davis, 1997).

Sediment on this low-profile barrier island is composed of 99% quartz sand, 75% of which lies within the 0.2–0.4-mm grain size fractions (Stone and Stapor, 1996). The remaining 1% of sediment is mostly heavy minerals such as kyanite, illmenite, and rutile (Stone *et al.,* 2004). This textually and compositionally mature sediment can be attributed to an overall lack of significant and active terrestrial sediment sources. The morphodynamics of Santa Rosa Island is largely controlled by redistribution of sediment from the inner continental shelf, intertidal zone, back beach, dune field, and back-barrier bay. Extreme storms play an essential role in the sediment redistribution.

Portions of Santa Rosa Island are heavily developed (*e.g.,* the areas in the vicinities of Pensacola Beach, Navarre Beach, and Fort Walton Beach); however, a large portion of the island remains pristine. In this paper, only the nondeveloped portions of the island are analysed. Five study areas spanning the entire length of the barrier island are examined (Figure 1), including, from west to east, Fort Pickens State Park (FP), Gulf Island National Seashore (GIP), the nondeveloped western end of Navarre beach (NV), Eglin Air Force base (EG), and Beasley Park (BP).

Locations similar to those examined in the Claudino-Sales, Wang, and Horwitz (2008) study are investigated further here. Whereas the previous study visually evaluated the destruction and survival of the incipient and established dunes via pre- and poststorm aerial and ground photographs, this study quantifies the changes on the basis of pre- and poststorm LIDAR surveys. Similar dune definitions are used: the incipient dunes are defined as those with grassy type of vegetations or no vegetation at all; the established dunes are defined as those with woody/shrub type of vegetations.

METEOROLOGICAL AND OCEANOGRAPHIC CHARACTERISTICS OF HURRICANE IVAN

The 2004 Atlantic and Gulf of Mexico hurricane season was extremely active and had a tremendous effect on the Florida coasts (Stone *et al.,* 2005; Wang and Horwitz, 2007; Wang *et* *al.,* 2005, 2006). One of the major hurricanes, Ivan, affected the study areas directly. Ivan was a large sustained category 4 hurricane that weakened to a strong category 3 at landfall (Figure 2), with extreme wind, wave, and surge. Figure 2 also shows the measured wave and surge conditions as the hurricane approached the coastline. At landfall, sustained hurricane force winds extended 170 km from the storm centre. Sustained tropical storm strength winds extended 475 km from the centre. The entire study area was affected by sustained onshore-directed hurricane-strength wind, with the wind-wave-surge forcing decreasing from west to east as the distance from the hurricane eye increased.

Extremely high waves were measured at the National Data Buoy Center (NDBC) wave buoys. Shortly before Ivan landfall, 16-m waves were measured offshore at westernmost buoy 42040 (Figure 2), which damaged the buoy. At buoy 42039, 220 km to the east, the highest wave recorded was 12 m. Further east at buoy 42036, the highest wave was 6.4 m. The highest waves at all three buoys were recorded shortly before landfall. These extreme offshore wave conditions persisted through the landfall. The high waves generated by Hurricane Ivan offshore of Pensacola exceeded historical records (Stone *et al.,* 2005). Wang *et al.* (2005) measured higher waves than those reported by the NBCD buoys, with maximum wave height (H_{max} component) reaching 30 m near the Ivan centre. These extreme wave conditions are nearly one order of magnitude greater than average conditions. The monthly averaged significant wave heights (from 1995 to 2001) at NDBC buoy 42039 (Figure 2), at a water depth of 290 m, are around 1.2 m during the winter months and 0.8 m during the summer months (O'Neal-Caldwell *et al.,* 2005).

Sustained high surge was measured over a large area during the passage of Ivan (Figure 2). At the Pensacola tide gauge, the highest surge recorded was 2.1 m above mean lower low water (MLLW). The capacity of the gauge was exceeded at Ivan landfall. Many qualitative pieces of evidence indicate that the water level along the open beach substantially exceeded 2.1 m (Wang *et al.,* 2006). At Panama City Beach, near the east boundary of the study area, the tide gauge is located along the Gulf beach. The highest surge measured was 2.0 m above MLLW during Ivan, nearly four times the typical tidal range. Surge levels above 1.5 m (MLLW) persisted for more than 10 hours (Figure 2).

The measured surge levels do not include contributions by wave set-up and swash run-up that occurs along open beaches (Roberts, Wang, and Kraus, 2009). On the basis of measured pre- and poststorm beach profile changes, Wang *et al.* (2006) found that the highest elevation of beach erosion extended well above the measured storm surge level, indicating that storm wave set-up and swash run-up played substantial roles in controlling the elevation of beach and dune erosion. Wang *et al.* (2006) suggested that the wave set-up and swash run-up accounted for 50% of the total elevated water level along the beach during Ivan landfall. Therefore, wave set-up and swash run-up should contribute significantly to overwash processes and dune erosion.

MATERIALS AND METHODS

LIDAR survey data were collected along the entire northwestern Florida coast before and after Hurricane Ivan. The data used in this study were obtained from the National Oceanic and Atmospheric Administration (NOAA, 2009) Topographic Change Mapping LIDAR database. These were "first return" data and therefore include bare earth elevations as well as vegetation and buildings where present. These data have been shown to yield accuracies on the order of 1 m in the horizontal and 0.15 m in the vertical over bare earth (Sallenger *et al.,* 2003). The tall tree features on the established dunes are apparent in the LIDAR data. In contrast, the grassy vegetation that dominates the incipient dunes and wetlands cannot be distinguished. The prestorm LIDAR survey was conducted in April 2004, roughly 5 months before Ivan landfall. The poststorm LIDAR survey was conducted in November 2004, about 2 months after landfall. Overall, the LIDAR coverage of Santa Rosa Island is nearly complete, except at the wide western end and a few places along the bayside shoreline. The LIDAR data organization, illustration, and analysis were conducted with the use of ESRI Arc-GIS v. 9.2.

The same areas examined in Claudino-Sales, Wang, and Horwitz (2008) were further quantified here on the basis of the LIDAR survey data. Rectified aerial photos used in the previous study were used here as background information, as well as an overall visual evaluation of the LIDAR data. The datum used in the LIDAR survey is NAVD88. On the basis of NOAA National Geodetic Survey Data sheets, zero NAVD88 is 0.04 m above mean sea level (MSL) in the study area (Wozencraft, 2000). In the following discussion, MSL is taken to be roughly the same as zero NAVD88. The 4 cm difference is well within the LIDAR uncertainty.

The main goal of this study is to quantify the regional-scale effects on the dune systems by Hurricane Ivan through comparison of pre- and poststorm LIDAR surveys. As a first step, point cloud LIDAR data were interpolated with Triangulate Irregular Network (TIN) and contoured at 0.5-m elevation intervals. In addition, the data were compared with the rectified photos to ensure that there are no apparent mismatches between the photos and the LIDAR data. For example, large flat-topped buildings should match well. It is difficult to illustrate the elevation contours, especially because of the overall small and complicated variations. After various comparisons, three-dimensional (3D) LIDAR images with a 1.5 times vertical exaggeration were determined to be the most effective and were used in the illustrations. The 3D images allowed for an overall assessment of erosional and depositional patterns. Cross-island profiles at locations of interest were then created from the LIDAR TIN database. The storm-induced erosion and deposition, which quantify the redistribution of sand by the extreme energy, were computed by RMAP (Regional Morphology Analysis Package) software developed by the U.S. Army Engineer Research and Development Center. To ensure accurate comparison of the LIDAR-generated pre- and poststorm cross-island profiles, a common fixed point was identified on each profile. The most frequently used common point is the road. It is assumed here that the location and elevation of the road did not change substantially before and after the storm. Although many sections of the road were buried during passage of the storm, the sand had been removed from most sections by 2 months poststorm,

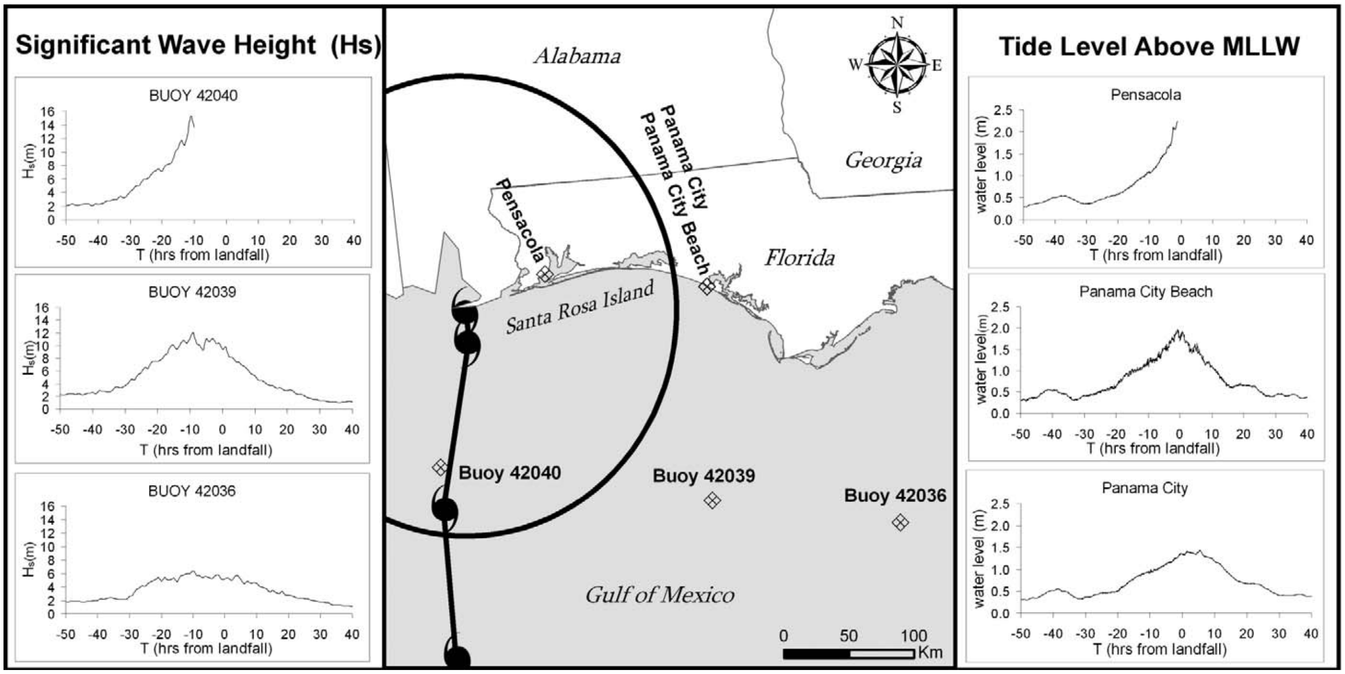

Figure 2. Map of the northwestern Florida coast (centre panel) showing the locations of tide gauges and offshore wave buoys (diamonds), and the track of Hurricane Ivan. The left and right panels show significant wave heights and water levels, respectively, measured during the passage of Ivan. Wave buoy 42040 was damaged by the storm. Zero hour on the horizontal axis represents the time of landfall. The circle indicates the extent of hurricane-force winds.

the time of the LIDAR survey. For most cases, the common fixed point compared well, with an average elevation differential of 0.15 m. In this paper, only those profiles that compared well were used to assess the amount of erosion and deposition.

Several LIDAR profiles were compared with ground surveys following the traditional level-and-transit procedures. As shown in Figure 3, the common point (*i.e.,* Highway 98) matched well on the pre- and post-Ivan LIDAR profiles. Also,

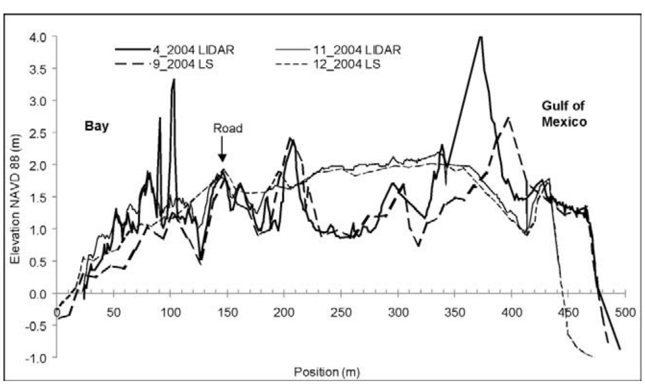

Figure 3. Comparison of LIDAR and ground survey (LS) profiles at the BP site. The relatively flat portion of the topography matches well. The mismatch at the highly 3D dunes is caused by the slight differences in the LIDAR and LS profile locations.

the LIDAR profiles compared well in overall shape with the ground survey data, especially over the washover platform where the elevation is relatively consistent and in the foreshore areas where the longshore elevation change is small. The land survey was conducted with the use of local coordinates, with several control points for line reoccupation. The geographical locations of the control points were obtained with a hand-held GPS with a horizontal accuracy of about 2 m. Given the highly 3D nature of the dunes, it is not expected that individual dune features should match exactly; however, the overall shape and trend should be similar. It is not the purpose of this paper to evaluate the absolute accuracy of airborne LIDAR surveys. The above precautions were taken to ensure accurate comparison between pre- and poststorm LIDAR profiles. Airborne survey data are now broadly used to quantify regional-scale coastal morphology. Recent examples include Finkl and Andrews (2008), Sallenger *et al.* (2003), and Stockdon *et al.* (2002).

RESULTS: IVAN-INDUCED DUNE EROSION AND OVERWASH DEPOSITION

Hurricane Ivan induced dramatic regional-scale morphological changes to the dune systems on Santa Rosa Island. Three processes, in part based on the impact scales of Sallenger (2000), are distinguished as: *inundation regime, overwash regime,* and *collision regime with dune scarping*. Wang and Horwitz (2007) investigated the sedimentary characteristics of washover deposits using trenching and ground-pen-

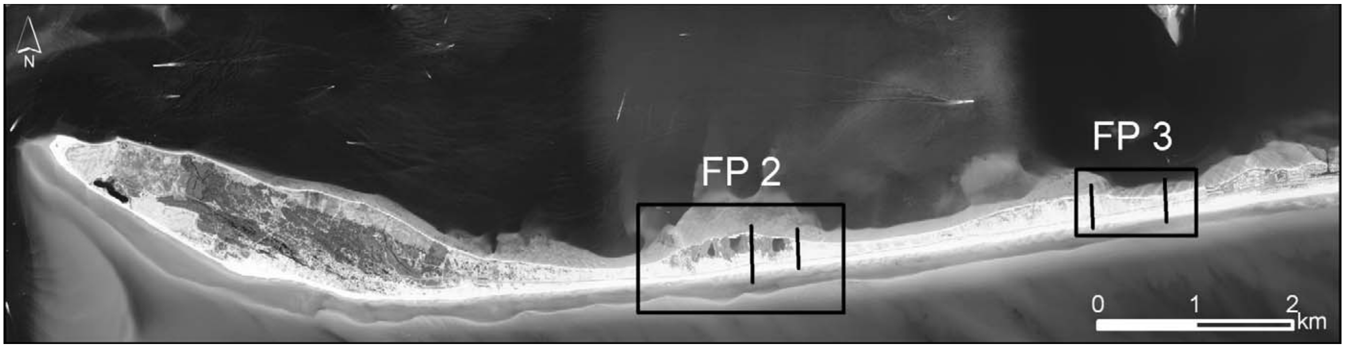

Figure 4. Pre-Ivan aerial photo of the FP study site. Two segments, as outlined, were examined in detail. The middle segment, FP2 (Figure 5), is characterized by three ponds near the bayside shoreline, and the eastern segment, FP3 (Figure 6), is relatively narrow with no established dunes.

etrating radar. Claudino-Sales, Wang, and Horwitz (2008) examined qualitatively various factors controlling dune survival and destruction through time series aerial photos. In the following sections, the study of Claudino-Sales, Wang, and Horwitz (2008) is expanded with the use of pre- and post-Ivan LIDAR data over similar sites.

Fort Pickens State Park (FP)

The FP study site is located at the western end of Santa Rosa Island about 45 km east of Ivan's landfall position (Figure 4). This segment illustrates the greatest variation in width over the entire island (Figure 2). The western end of the island is roughly 1.05 km wide and represents the widest portion of the island. The width of the island decreases to about 220 m at the eastern portion of the FP site. Two segments are examined along this section of the island: FP2 and FP3 (Figure 4). The wide western end, FP1, as examined in Claudino-Sales, Wang, and Horwitz (2008), is not included in this study because of incomplete LIDAR coverage over the wide established dune field.

Section FP2 represents the central segment of the FP study site. It is a rather unique section, with three ponds near the bayside shoreline. The extensive incipient dunes, as identified from aerial photos, are relatively low, generally less than 3 m MSL (Figure 5). Established dunes surrounding the ponds are higher than the incipient dunes, with elevations reaching nearly 5 m. The narrow spikes near the northern bay side (Figure 5C) appear to be caused by tall trees. The established dune field is characterized by the presence of a considerable amount of intradune wetlands, with elevations of about 1.0 m or less. Comparing the pre- and post-Ivan LIDAR images (Figures 5A and 5B), the complete erosion of the incipient foredunes and hummocky dunes is apparent.

Two cross-island pre- and poststorm profiles were obtained from the LIDAR TIN database. At FP2-West, an extensive washover platform nearly 150 m wide was deposited over the prestorm incipient dune field (Figure 5C). The elevation of the washover platform is 1.5–2.0 m above MSL. Comparing the pre- and poststorm LIDAR profiles, a volume of about 90 m^3/m was eroded from the beach and incipient dune system, with 50 m^3/m deposited on the washover platform. This indicates that a profile volume of 40 m^3/m was lost from the subaerial barrier island along this profile. It is worth emphasizing that all the profile volume calculations discussed in this paper did not extend into the portions of the established dune fields with trees, an example of which is shown in Figure 5C between 80 and 250 m. It is also noted that, because of elevation uncertainties attributable to the grassy type of vegetation that dominates the incipient and hummocky dunes, the volume calculations should be considered first-order estimations. Given that the prestorm LIDAR data were obtained at the end of the winter season, the uncertainty associated with grass vegetation should be minimized. The FP2-east location was inundated with the complete erosion of the low incipient dunes (Figure 5D). The road was also destroyed at this location. A profile volume of 200 m^3/m was eroded from the beach and incipient dune. The elevation of the inundated surface was about 1.0 m above MSL, substantially lower than the elevation of the washover platform. A large amount of washover was deposited into the back-barrier bay. The volume of sand deposition in the back-barrier bay could not be quantified because of lack of LIDAR data below zero NAVD88. However, the volume of sand deposited above zero NAVD88 was approximately 100 m^3/m. Thus, a net profile volume of 100 m^3/m was lost from the subaerial barrier island along this profile.

Section FP3 is the easternmost segment of the FP site (Figure 6) and represents a relatively narrow section of the island. The incipient dunes that developed over the relic washover platform were low, mostly less than 3.0 m above MSL or about 0.5–1.5 m above the general back beach elevation. The low incipient foredune ridge extended relatively continuously seaward of the road (Figure 6A). The thin line of established dunes along the bayside shoreline is of relatively low elevation, mostly lower than 3.5 m. All the incipient and established dunes were eroded by Hurricane Ivan, leaving a flat inundation surface. The road was also almost completely destroyed. An extensive scour channel was developed along the landward side of the road.

Two cross-island profiles, one extending across the widest

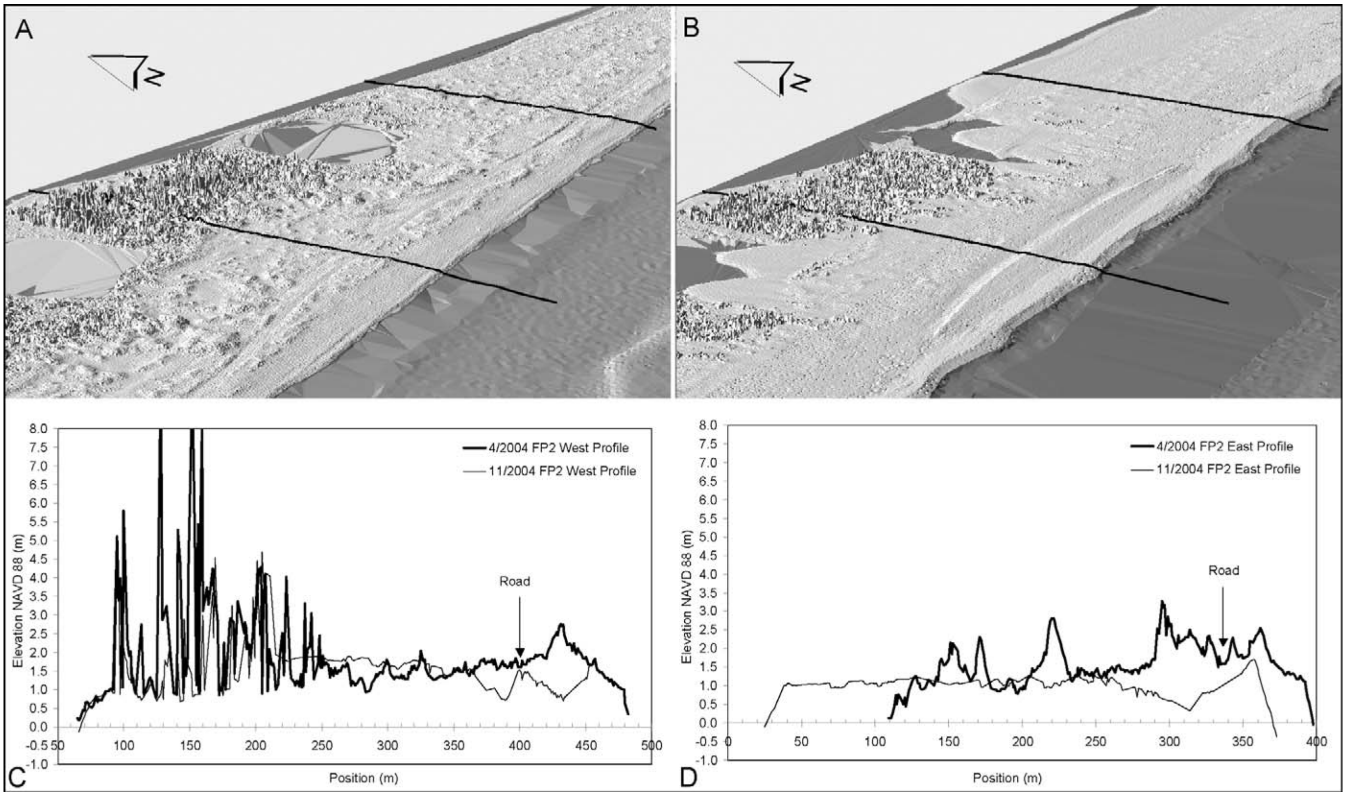

Figure 5. The FP2 study site (Figure 4) and the locations of the two cross-island profiles. (A) Pre-Ivan LIDAR image with 1.5 times vertical exaggeration. (B) Post-Ivan LIDAR image with 1.5 times vertical exaggeration. Note the complete destruction of all incipient dunes. (C) FP2-West profile. (D) FP2-East profile. Note that the road at this location is completely eroded and the bayside shoreline propagated nearly 100 m landward.

portion of this segment and one across the narrowest portion, were examined at the FP3 location. All the low-lying incipient dunes along the FP3-West line were eroded with a profile volume loss of 120 m^3/m from the dry beach and dunes (Figure 6C). The elevation of the fairly flat inundation platform is about 1 m above MSL, similar to that at the FP2-East location. The volume gain along the bayside shoreline above zero NAVD88 was 70 m^3/m, with a landward shoreline propagation of about 50 m. Overall, 40 m^3/m of sand was lost from the subaerial barrier island along this profile. The FP3-East profile extends through the portion with complicated scour features. A profile volume loss of 170 m^3/m from the beach and dune system was measured (Figure 6D). The volume gain along the bayside shoreline above zero NAVD88 was 80 m^3/m, with a net loss of 90 m^3/m of sand from the prestorm subaerial barrier island. Although no permanent breach channels were developed, a scour channel up to 1 m deep formed along the bay side of the road, a common poststorm feature found along much of Santa Rosa Island. The overall elevation of the inundation surface is mostly less than 1.0 m MSL, with numerous scour holes and channels. This contrasts with the rather flat inundation surface at other locations (*e.g.,* FP3-West). The bayside shoreline propagated landward for up to 110 m along this narrow section of the island.

Gulf Island National Seashore (GIP) and Navarre Beach (NV)

These two study sites represent a 9-km-long stretch of Santa Rosa Island and illustrate rather uniform widths (Figure 7). Most of this stretch is 400–500 m wide, with a maximum width of about 750 m. The bayside shoreline shows rhythmic features with several sandy headlands separated by gentle embayments. This bayside shoreline configuration could be the result of the reworking of previous washover lobes. The headlands tend to be covered by established dunes (Figure 7). The GIP and NV sites are located approximately 70 and 77 km east of Ivan landfall, respectively.

The well-developed incipient dunes seaward of the road were fairly continuous at both study sites, with elevations ranging from 4 to 6 m above MSL (Figures 8 and 9). Extensive hummocky dunes developed over the relic washover platforms in the barrier island interiors. These dunes are typically less than 3 m MSL. The established dunes identified on the basis of dense tree-type vegetation by Claudino-Sales, Wang, and Horwitz (2008) are in fact mostly wetlands with scattered dunes of typically less than 4 m MSL. The elevation of the wetlands is between 0.5 and 1.0 m MSL.

Nearly all the incipient dunes, including both the semicon-

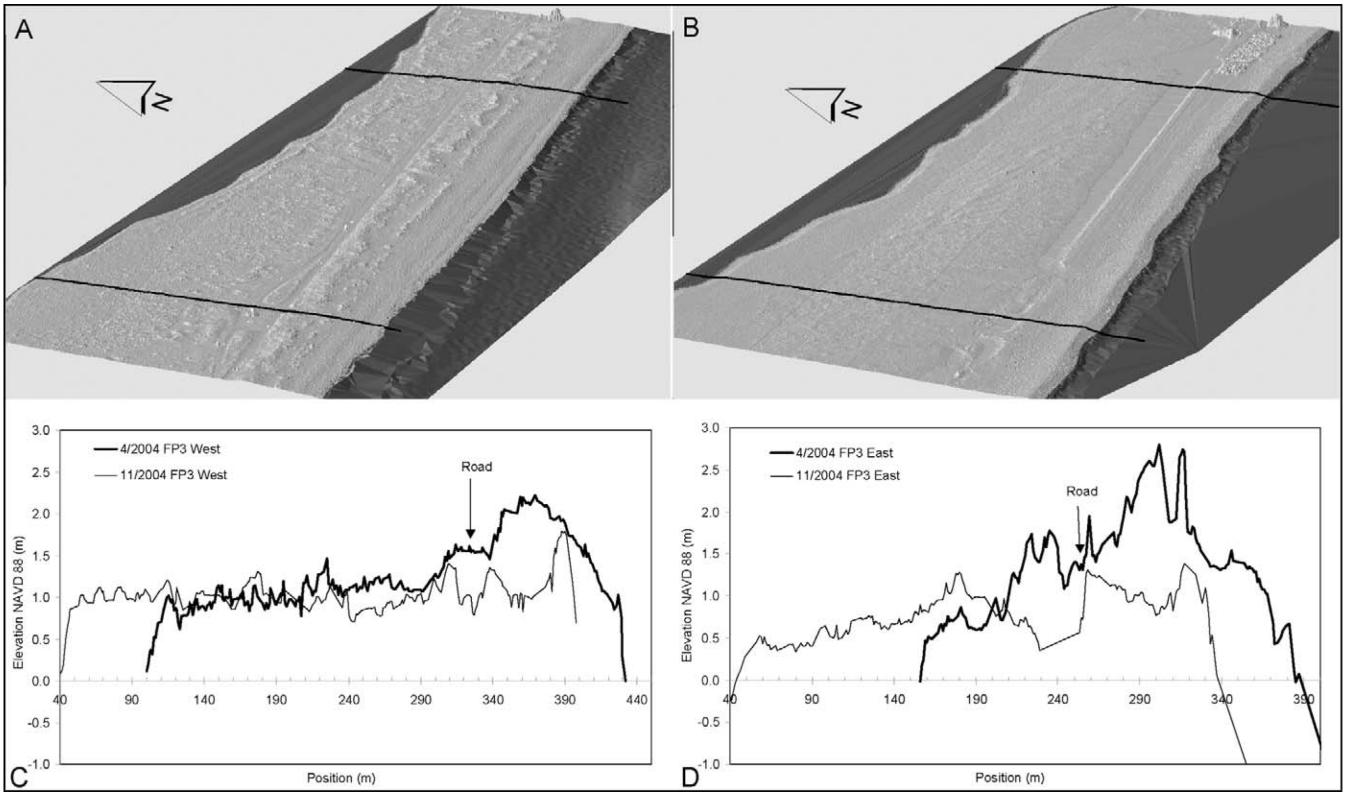

Figure 6. The FP3 study site (Figure 4) and the locations of the two cross-island profiles. (A) Pre-Ivan LIDAR image with 1.5 times vertical exaggeration. (B) Post-Ivan LIDAR image with 1.5 times vertical exaggeration. Note the complete destruction of all incipient dunes. (C) FP3-West profile. (D) FP3-East profile. Note the scour hole along the destroyed road at both profile locations and the landward propagation of the bayside shoreline. The rectangular topographic features at the top of panel 6B are piles of road debris.

tinuous foredune ridge and the hummocky dunes, were eroded by Ivan at both the GIP and NV sites (Figures 8 and 9). Almost no hummocky dunes survived the storm impact. A few dunes along the foredune ridge survived. The height of the foredune ridge does not seem to be the dominant factor controlling its survival, whereas the width of the dune appears to play a more important role (Figures 8 and 9). The dunes that survived tended to occur at places where dune

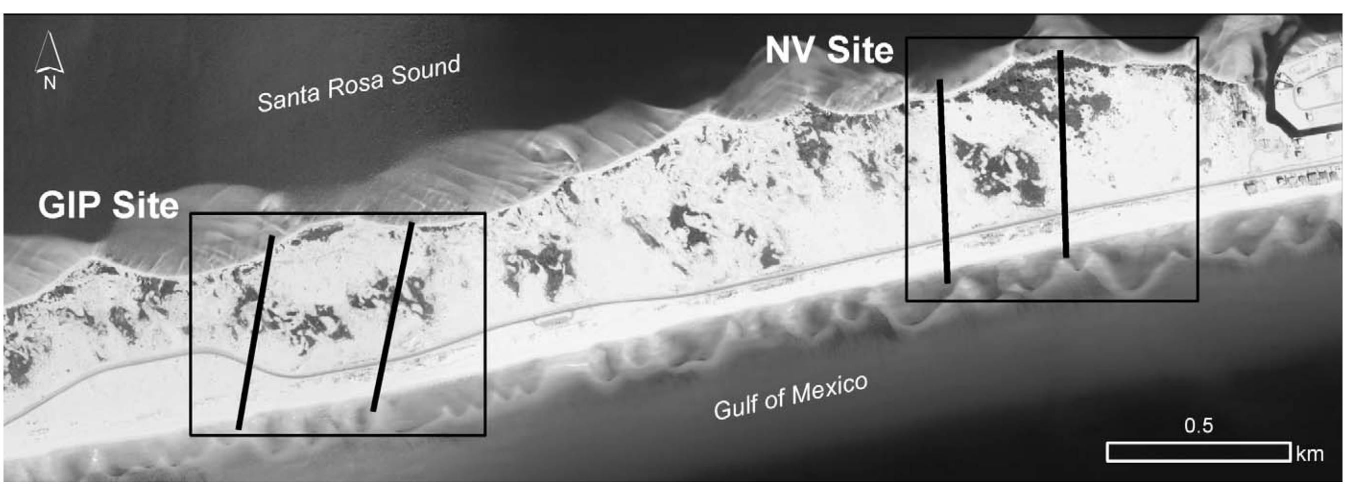

Figure 7. Pre-Ivan aerial photo of the GIP and NV study sites.

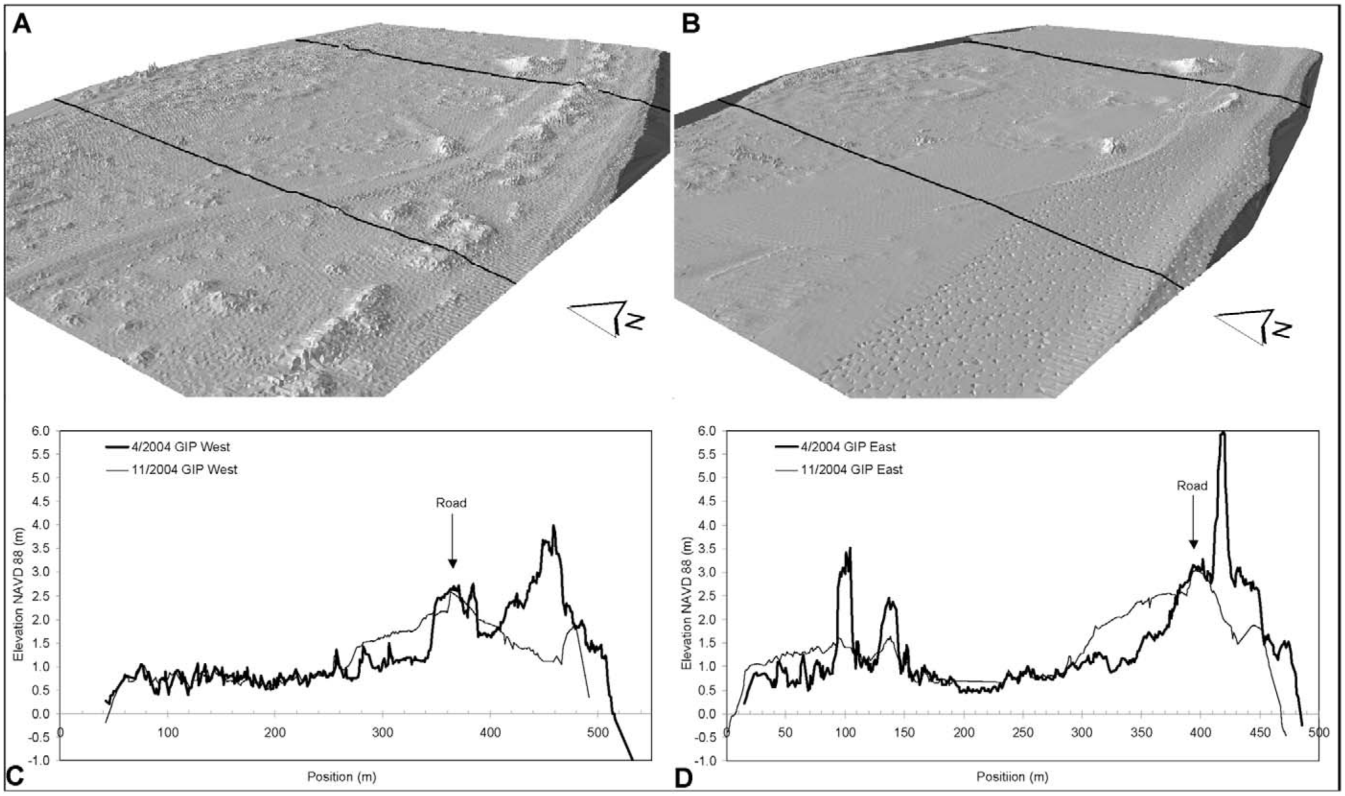

Figure 8. The GIP study site (Figure 7) and the locations of the two cross-island profiles. (A) Pre-Ivan LIDAR image with 1.5 times vertical exaggeration. (B) Post-Ivan LIDAR image with 1.5 times vertical exaggeration. Note the nearly complete destruction of all incipient dunes and the formation of extensive washover platforms. (C) GIP-West profile. (D) GIP-East profile.

widths were greatest. It is worth noting that many times, wider dunes also tended to be higher.

Extensive washover lobes into the interior wetlands were formed. The landward extents of the washover lobes seem to be controlled by sediment supply (Figure 8), as well as the blockage of established dune features (Figure 9). Compared with visual estimation from aerial photos, the LIDAR survey allowed distinctions between low-lying heavily vegetated intradune wetlands and established dune features. Under most circumstances, the washover lobes extended into the wetlands until the sediment supply was depleted (Figure 8). At places in which the established dunes were relatively close to the Gulf shoreline, they blocked the landward propagation of washover deposition (Figure 9). Overall, most of the established dune features survived Ivan with various amounts of erosion along the seaward flank.

Two cross-island profiles were examined at the GIP site. Nearly complete foredune erosion was observed at all the profiles regardless of the height of the dunes (Figure 8C and 8D). Along the GIP-West profile, a profile volume loss of 130 m^3/m was measured along the back beach and dune system. A volume of 50 m^3/m sand was deposited as the washover platform just landward of the eroded foredune (Figure 8C), resulting in a subaerial profile volume loss of 80 m^3/m. A wide portion of the wetlands did not receive washover deposits, limited by sediment supply. At GIP-East, the foredune was much higher than at GIP-West, 6 *vs.* 4 m MSL. Despite the higher elevation, the entire dune was eroded, along with two smaller established dunes farther landward. Approximately 90 and 30 m^3/m of sand were eroded from the incipient and established dunes, respectively. A large portion of the 120 m^3/m eroded sand was deposited directly landward as washover with a volume gain of 100 m^3/m, including 70 m^3/m landward of the foredune and 30 m^3/m landward of the established dunes. Approximately 20 m^3/m of subaerial sand was lost along this profile. The washover platforms directly landward of the eroded foredune have a relatively high elevation of 1.5–2.5 m MSL. The washover platforms farther landward are lower, between 1.0 and 1.5 m MSL, influenced by the depleting sediment supply.

Two cross-island profiles were examined at the NV site (Figure 9). Overall, similar erosional and depositional trends compared with those at the GIP site were observed. At the NV-West profile, the foredune ridge had two dune features of about 5 m MSL. Both dunes were completely eroded. However, the washover deposits were stopped by a tall incipient dune more than 7 m high (Figure 9C). This dune is oriented at about 30° from the shoreline (Figure 9A and 9B). A profile volume loss of 110 m^3/m was measured at the dry beach and foredune. The amount of sand deposited over the narrow

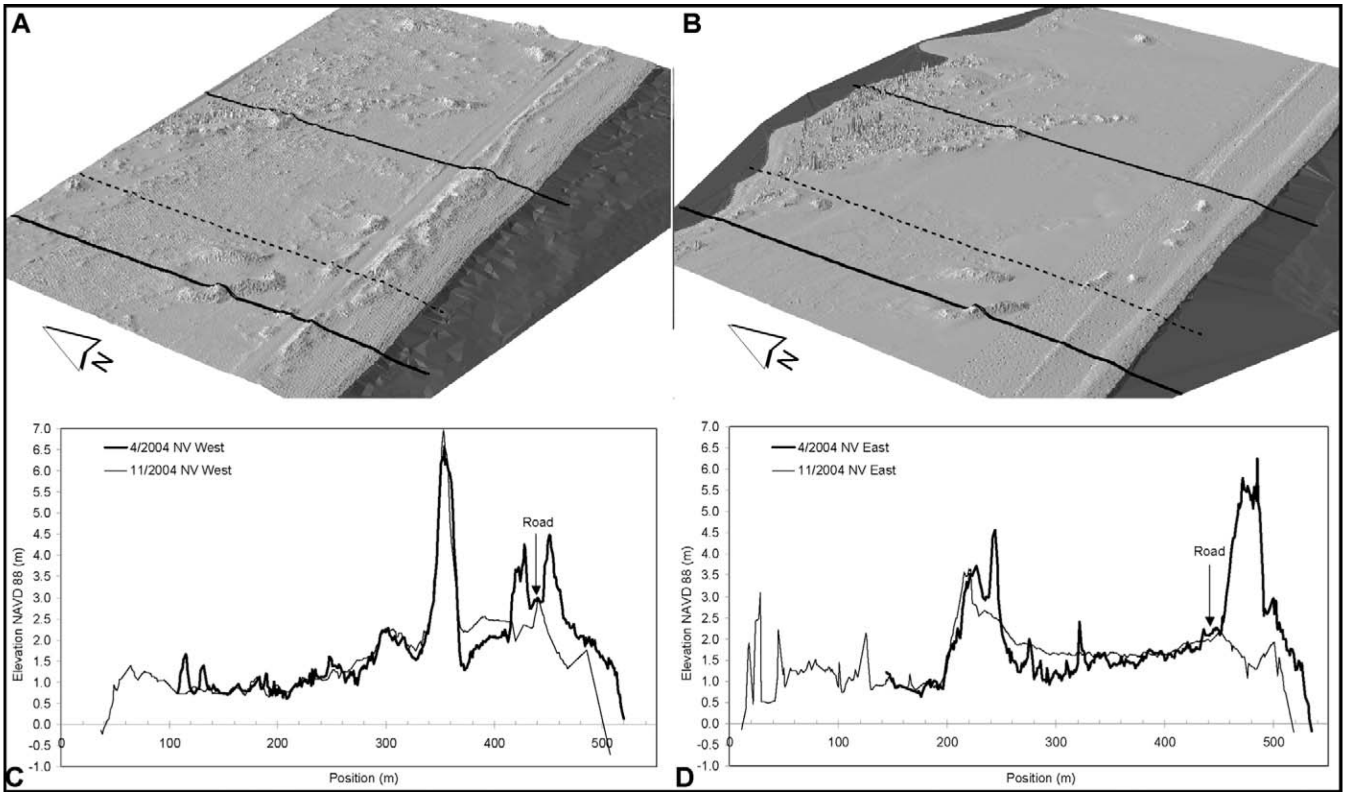

Figure 9. The NV study site (Figure 7) and locations of the two cross-island profiles (solid lines). An additional profile (dashed line), referred to as NV intermediate profile, is also examined and shown in Figure 10. (A) Pre-Ivan LIDAR image with 1.5 times vertical exaggeration. (B) Post-Ivan LIDAR image with 1.5 times vertical exaggeration. Note the nearly complete destruction of all the semicontinuous incipient dunes. The orientation of the washover lobes tends to be parallel to the orientation of the preserved dune field. (C) NV-West profile. (D) NV-East profile.

washover platform, 20 m^3/m, is much smaller than the eroded amount, resulting in a sand deficit of nearly 90 m^3/m. The low hummocky dunes landward of the tall surviving dune were partially eroded, leaving a flat terrace at about 1 m elevation. Profile NV-East extends across a well-developed established dune ridge, oriented also at about 30° from the shoreline. This orientation could be related to the dominant southeast wind in this area (Davis, 1997). The tall and wide foredune was completely eroded. A washover platform at about 1.5 m MSL was formed. The overwash was apparently blocked by the established dune ridge (Figure 9D). The seaward flank of the established dune experienced some erosion. Morphology change in the low-lying wetlands landward of the established dune ridge is minimal. A volume loss of 150 m^3/m was measured at the dry beach and foredune. A volume of 40 m^3/m sand was deposited on the washover platform. As shown in Figure 9B, the orientation of the washover lobes is apparently influenced by the oblique orientation of the established dune ridge. This could account for the significant imbalance between the profile volume loss and gain, as discussed above. An additional profile (Figure 9A and 9B, dashed line) is cut between the west and east lines, shown in Figure 10. Substantial erosion occurred at the foredune and back beach, with a profile volume loss of 110 m^3/m. A large washover lobe was deposited landward of the surviving part of the wide (~100 m) prestorm foredune system, with a profile volume of 60 m^3/m. It is apparent that this deposit is not directly the result of sand washed over the preserved dune. Instead, longshore sand transport, probably influenced by the obliquely oriented dunes, contributed to the development of this "washover" lobe. As shown in Figure 9B, several wash-

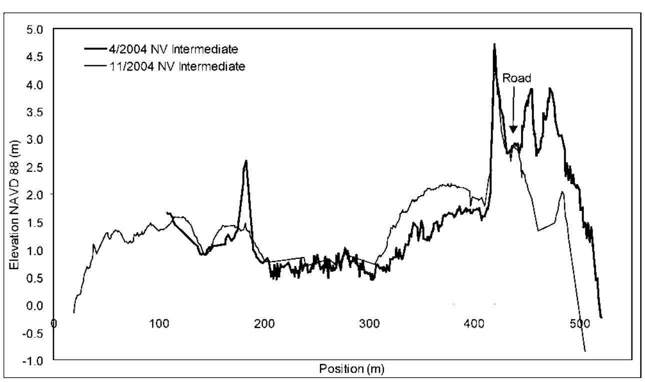

Figure 10. The NV intermediate profile. Note the "washover" deposit landward of the surviving dune. Location of the profile is shown in Figure 9 as the dashed line.

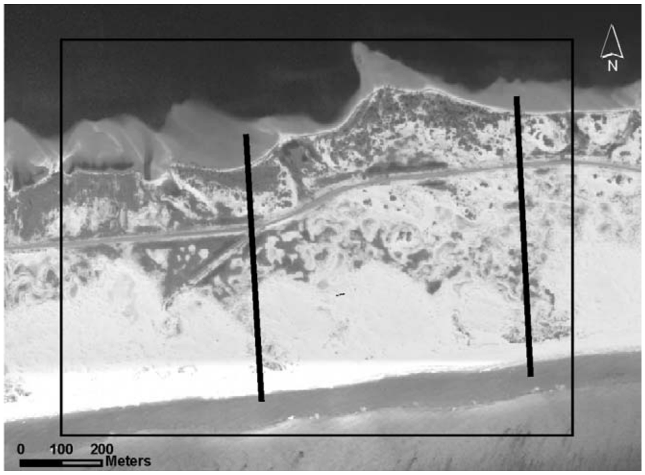

Figure 11. Pre-Ivan aerial photo of the EG study site.

over lobes demonstrated an oblique orientation parallel to the established dune ridge. This indicates that dune orientation, especially that of large continuous dunes, might influence the trend of sediment transport and deposition.

Because of the greater island width and increased distance from the storm centre, limited inundation occurred at GIP and NV sites compared with the FP site. Washover deposition was largely confined to the island interior—either blocked by preserved dunes, limited by the depleted sediment supply, or both. GIP and NV sites are located along the transition from inundation to overwash regimes.

Eglin Force Air Base Site (EG)

The EG site is located along a stretch of the barrier island that is considerably wider, ranging from 550 to 750 m in width. The bayside shoreline also displays rhythmic features, with sandy headlands separated by broad embayments (Figure 11). The Gulf-side shoreline is generally straight. The EG site lies about 85 km east of Ivan landfall.

In contrast to the GIP and NV sites, the EG site does not have a continuous foredune ridge (Figure 12A), likely because of the effects of Hurricane Opal in 1995 (Dean, 1999; Dean and Suter, 1999). Numerous hummocky dunes were scattered over the Opal washover platform, representing post-Opal dune recovery over a 10-year period. The established dune system, including both dunes and intradune wetlands, were better developed along this wider section of the barrier island (Figure 11). Some of the highest incipient and established dunes are identified along this section of the island, reaching 7 m MSL (Figure 12C).

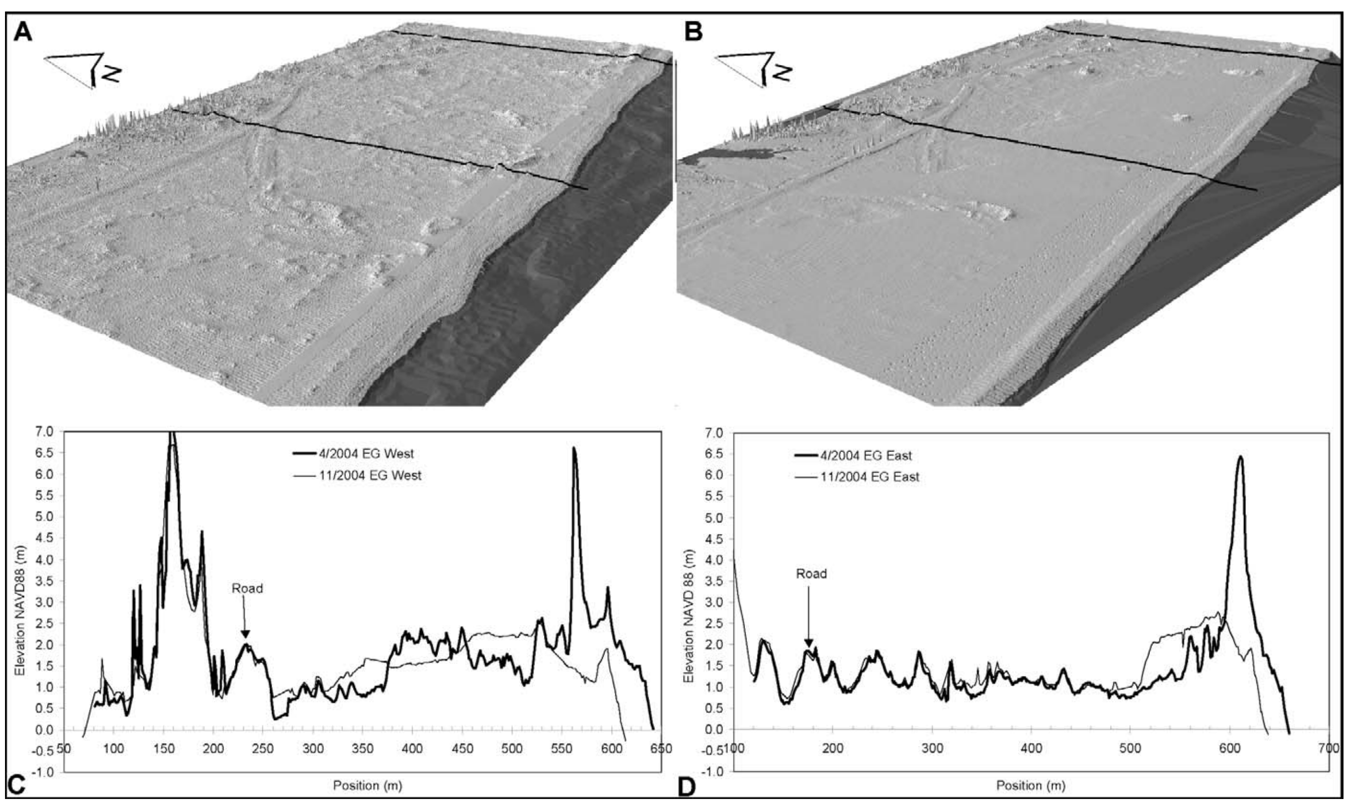

Figure 12. The EG study site (Figure 11) and locations of the two cross-island profiles. (A) Pre-Ivan LIDAR image with 1.5 times vertical exaggeration. (B) Post-Ivan LIDAR image with 1.5 times vertical exaggeration. Note the nearly complete destruction of all incipient dunes and the formations of extensive washover platforms. (C) EG-West profile. (D) EG-East profile.

Compared with the study sites to the west, the landward extent of washover deposits was reduced because of decreased storm forcing. Most of the dunes along the landward half of the barrier island survived the Ivan impact, whereas most of the dunes along the Gulf-ward half were eroded. Remnants of just a few wide incipient dunes were preserved. Like the sites farther to the west, widths of the discontinuous dunes seem to be a more determining factor for dune survival than heights. It is reasonable to assume that the width of the dune is proportional to its ability to endure prolonged storm attack. The EG site is in the region dominated by the overwash regime.

Profile EG-West extends across an isolated incipient foredune nearly 7 m high and lying seaward of a well-developed established dune (Figure 12). The high foredune and several low dunes both landward and seaward were completely eroded, resulting in an extensive washover platform more than 200 m wide (Figure 12C). The elevation of the washover platform is roughly 1.5–2.5 m MSL, as in the other sites. The landward decreasing elevation is caused by depleting sediment supply. Nearly no change occurred at the established dunes that lie more than 300 m from the Gulf shoreline. A profile volume loss of 180 m^3/m was measured over the dry beach and the foredune, accompanied by a 90 m^3/m volume gain on the washover platform. A net profile volume of 80 m^3/m was lost from the subaerial barrier island. Profile EG-East extends across a tall isolated incipient dune 7 m high with extensive low-lying wetlands landward. The incipient dune was completely eroded despite its height. The washover platform of 2.0–2.5 m MSL extends about 100 m into the wetlands (Figure 12D). Little change was measured over a large portion of the wetlands because of depleted sediment supply. A profile volume loss of 120 m^3/m was measured over the dry beach and the foredune, accompanied by a 70 m^3/m volume gain in the washover platform, indicating a net subaerial loss of 50 m^3/m.

Beasley Park (BP)

The BP study site is located at the eastern end of Santa Rosa Island (Figure 1), roughly 110 km east of Ivan's landfall position. Because of the longer distance from the landfall, the overall effect at this site is not as severe compared with the four western sites. In addition, east of the BP site, the effects associated with Ivan were dominated by a collision regime, with extensive dune scarping (Wang *et al.,* 2006). Limited overwash occurred east of the BP site.

The BP site is located at the eastern end of a heavily developed stretch of the barrier island (Figure 13). The western half of the BP site has a rather wide and continuous series of established dunes (Figure 14A). Along the eastern half, scattered established dunes of low elevations dominated the region north of Highway 98 (Figures 13 and 14). A narrow and nearly continuous foredune ridge up to 4 m high existed seaward of the established dunes. Scattered hummocky dunes were developed over the relic washover platform (Figure 14A). The narrow incipient dune ridge was mostly eroded by Ivan, along with nearly complete destruction of the hummocky dunes in the eastern half (Figure 14B). The storm effect on the well-developed, established dunes along the western half was minimal.

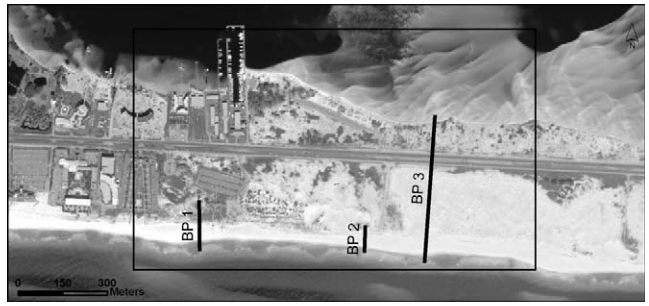

Figure 13. Pre-Ivan aerial photo of the BP study site and locations of the profiles BP1, BP2, and BP3.

Three profiles were surveyed at the BP site pre- and post-Ivan following standard level-and-transit procedures with the use of an electronic total survey station, similar to the procedure used by Wang and Davis (1998). The measured profile changes, along with short-term poststorm recovery, were discussed in Wang *et al.* (2006). Here, three LIDAR profiles from similar locations (estimated to be within 3–5 m on the basis of the accuracy of a hand-held GPS) were examined. Profile BP1, located at the west end of the study area, is a dune-beach profile extending from the top of an established dune seaward to the Gulf shoreline (Figure 14C). Profile BP2, located in the central portion of the study area, is also a dune-beach profile, which extends seaward from the top of a high isolated incipient dune (Figure 14D). The third and easternmost profile, BP3, is a cross-island profile that extends across a relic washover platform (Figure 3).

At the BP1 profile, the established dune largely survived Ivan impact (Figure 14C). The small incipient dune seaward of the established dune was eroded. Substantial beach erosion was measured. A profile volume loss of 30 m^3/m was measured from the beach and foredune. Along profile BP2, the isolated incipient dune of more than 10 m high survived, although substantial dune face and beach erosion occurred (Figure 14D). A volume loss of 100 m^3/m was measured. Immediately west of BP2, overwash associated with Ivan penetrated landward through a gap between the high incipient foredunes, forming a washover lobe, overlying a relic Opal washover lobe (Wang and Horwitz, 2007). The washover destroyed most of the small hummocky dunes. The BP3 site was overwashed by Hurricane Ivan. Nearly all the low incipient and hummocky dunes over the Opal washover were destroyed, leaving a flat platform 2 m above MSL. A profile volume loss of 110 m^3/m was measured from the beach, foredune, and hummocky dunes. An equal volume of 110 m^3/m was deposited as washover. This is in contrast to the consistent net subaerial losses found at all the other cross-island profiles. The volume calculation included only the portion seaward of Highway 98.

At the western FP and GIP sites, inundation was the dominant process during Ivan, except along the wide, western end of Santa Rosa Island. This inundation resulted in nearly com-

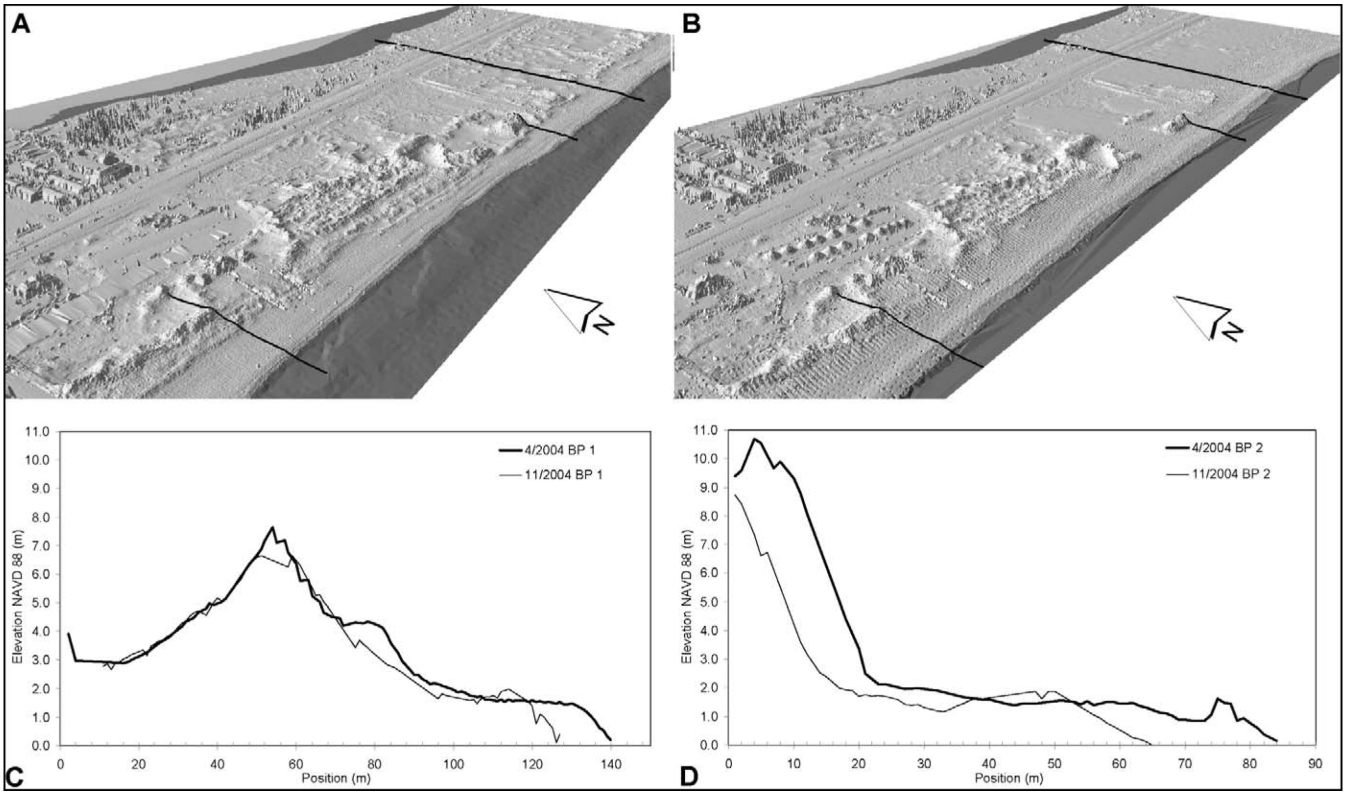

Figure 14. The BP study site (Figure 13) and locations of the cross-island profiles. (A) Pre-Ivan LIDAR image with 1.5 times vertical exaggeration. (B) Post-Ivan LIDAR image with 1.5 times vertical exaggeration. Note the survival of most of the established dunes and the erosion of the small incipient dunes seaward. (C) BP1 profile (west). (D) BP2 profile (middle). The westernmost profile, BP3, is shown in Figure 3. The two rows of sand piles appearing on the post-Ivan LIDAR is related to the poststorm repair of Highway 98 and cleanup of the parking lot.

plete destruction of both established and incipient dunes and sedimentation in the back-barrier bay resulting in landward migration of the bayside shoreline. At the NV and EG sites, the major morphological effect was regional-scale overwash. The severe overwash destroyed most incipient dunes, whereas most of the established dunes and wetlands along the bayside shoreline survived. The easternmost BP site illustrates the transition from overwash to collision regime.

DISCUSSION: FACTORS CONTROLLING THE SURVIVAL OF THE COASTAL DUNES

The survival of incipient as well as established dunes on Santa Rosa Island during the passage of Hurricane Ivan is controlled by a number of interactive factors that can be divided into two categories, including (1) the intensity and duration of the storm and (2) the morphological characteristics of the dune field and the barrier island. These factors were discussed qualitatively in Claudino-Sales, Wang, and Horwitz (2008) on the basis of pre- and poststorm aerial photos. In the following, each of these factors and their interactions are discussed further on the basis of pre- and post-Ivan LIDAR surveys. The morphological characteristics can be quantified more accurately with the LIDAR data. A recent literature review on overwash processes is provided by Donnelly, Kraus, and Larson (2006).

Elevation Characteristics of Santa Rosa Barrier Island

Five barrier island subenvironments were identified, including, berm and back beach, incipient dunes, established dunes, interior wetlands, and relic washover platforms. Hurricane Ivan induced substantial erosion of the berm and back beach along nearly the entire northwestern Florida coast (Wang *et al.,* 2006). Interior wetlands provide important accommodation space for washover deposition.

The general elevation characteristics obtained from the pre-Ivan LIDAR survey are summarized here. All the elevations are referenced to MSL, unless otherwise specified. Generally, the elevation of the berm and back beach is lower than 2.5 m. A typical elevation of the flat part of the back beach is about 2.0 m. The elevation of the incipient foredune crest varies substantially, ranging from 2.5 to 10.0 m, or between 0.5 and 8.0 m above the beach. Most of the dunes are less than 7 m MSL, with the highest dune of about 10 m measured at the BP2 site. The higher incipient foredunes tend to distribute near the Gulf of Mexico shoreline. This is attributed to the relatively abundant sand supply from the beach.

The foredunes were significantly affected by Ivan, to the extent that most of the dunes along the western portion of the island were completely eroded. The hummocky dunes that develop on relic washover platforms are typically lower than 4 m MSL, or 2 m above the beach level. Because the last effects of a major hurricane were from Opal in 1995 (Dean, 1999), these hummocky dunes likely represent 10 years of dune growth.

The crests of established dunes typically range from 4 to 7 m, with the highest, at 7 m, identified at the EG site. It is worth noting that established dunes on Santa Rosa Island tend to occur near the bayside shoreline, especially along the wider segments of the island (*e.g.,* the western end of the FP site). As discussed earlier, because of the dense woody vegetation that characterises the established dunes, LIDAR elevations include some level of uncertainty.

The elevation of the interior marsh and wetlands is typically between 0.5 and 1.0 m; however, it is not clear whether these elevations were measured at the top of the vegetation or at the sediment surface. A large portion of the densely vegetated areas, identified by Claudino-Sales, Wang, and Horwitz (2008) as established dunes, is composed of these low-lying wetlands.

Hurricane Ivan induced regional-scale inundation and overwash along the entire length of Santa Rosa Island. Inundation occurred mostly along the western part of the island, and resulted in the destruction of nearly all the dunes. Concomitant washover deposition into the back-barrier bay yielded landward propagation of the bayside shoreline. A typical elevation of the inundated surface is around 1.0 m (Figures 5D, 6C, and 6D).

Extensive overwash occurred along a large portion of the island. The morphology of the washover is controlled by several interactive factors, including accommodation space, sediment supply, and antecedent dune morphology. Extensive washover platforms tend to develop where an adequate sediment supply is available (Figures 3, 8C, 8D, and 10). Washover platform elevations decrease landward, reflecting the trend of decreasing sediment supply. Regardless of its distance to the storm centre, washover platform elevations tend to range from 1.5 to 2.5 m. The highest elevation at the seaward end of the washover lobes is typically about 2–2.5 m. This elevation is similar or slightly higher than that of the berm crest and back beach or the toe of the foredune (Figures 3, 8C, 8D, 9C, 12C, and 12D). Exactly what controls this washover elevation is not apparent. It is reasonable to believe that the storm surge, as well as the storm wave energy, should be considerably higher at the western sites compared with the eastern sites. This however did not result in an eastward decrease in washover-platform elevations. In addition, the washover-platform elevation is 0.5 to 1.0 m higher than the inundation surface elevation.

Storm Intensity and Duration at the Specific Site

The intensity and duration of the storm are probably the most important factors controlling the destruction or survival of dunes on low-lying barrier islands. The site-specific storm intensity and duration are controlled by a range of factors, including the maximum wind speed, size of the storm, forward speed, and distance of the particular study site to the storm centre. Nearshore bathymetry might also influence the development of a storm surge.

Claudino-Sales, Wang, and Horwitz (2008) compared the effects of the large, slow-moving Ivan and the smaller, fast-moving Dennis (2005). Although recorded peak wind speeds were similar for both storms, the slow-moving Ivan induced more morphological changes than the fast-moving Dennis. The width of the dune appears to play a more important role than dune height in controlling dune survival, indicating storm duration is a crucial factor (Figures 8–10 and 12).

Barrier Island Width and Distance from the Ocean

The LIDAR survey allowed the distinction between dune features and wetlands, which could not be distinguished in the earlier analysis of aerial photos by Claudino-Sales, Wang, and Horwitz (2008). Wider sections of the island provide more space for dune development, especially the more storm-resistant established dune systems. In addition, interior wetlands tend to develop more extensively over wider sections of the barrier island. The low-lying wetlands provide accommodation space for washover deposition. Therefore, a wider barrier island not only hosts more erosion-resistant established dunes but also provides more accommodation space, a factor necessary for the development of washover terraces. In addition, greater island widths generally correspond with increased distances between the dunes and the sea. Accordingly, more energy dissipation would be expected, therefore favouring reduced effects on the more distal established dune fields (Figures 8D, 9C, 9D, and 12C).

The distance of the dune from the Gulf shoreline is obviously an important factor controlling its survival. This is clearly illustrated by the fact that almost all the frontal dunes are destroyed regardless of their height, continuity, and vegetation. Because a substantial amount of energy should be dissipated as the storm waves propagate landward over the submerged barrier island, the greater the distance from the sea, the weaker the wave energy should be. Therefore, an inverse relationship should exist between the magnitude of impact and distance of the dune to the Gulf shoreline. The only factor that seems to have some detectable counteractive influence to this is dune width.

Dune Morphology and Vegetation

Four aspects of dune morphology influence dune survival significantly: the continuity of the dune ridge, the cross-shore width of the dune field, dune height, and intradune wetlands. Wide, continuous, well-developed, high established dunes are more resistant to storm impact. Examples can be found at the FP, GIP, EG, and NV sites (Figures 5, 8–10, and 12). The LIDAR data indicate that a large portion of established dune systems previously identified by Claudino-Sales, Wang, and Horwitz (2008) was actually intradune wetlands. Ivan's effect on the established dune fields was largely limited to washover deposition within intradune wetlands, rather than erosion of the established dune features.

In contrast to the established dune systems, incipient dunes suffered much greater effects during the passage of Hurricane Ivan. Incipient dunes typically develop in the regions seaward of established dunes. The distribution of intradune wetlands, which provide accommodation spaces for washover deposition, is limited compared with the established dune systems. Consequently, the effects on incipient dunes are dominated by erosion. An estimated 70% of the incipient dunes on Santa Rosa Island were destroyed regardless of their morphological characteristics. The shallow-rooted grass-type vegetation offers little additional resistance to erosion during extreme storms like Ivan. Incipient dunes serve as the barrier islands' first line of defence when the storm hits.

The LIDAR survey data revealed detailed morphological characteristics of the incipient dunes. Longshore continuity of the incipient foredune ridge does not appear to be a dominant factor in promoting dune survival. This can be seen through comparison of antecedent dune morphologies at the GIP-NV and EG sites (Figures 8, 9, and 12). The prestorm semicontinuous foredune ridges at the GIP-NV sites did not result in greater dune preservation. This conflicts somewhat with the assertion by Claudino-Sales, Wang, and Horwitz (2008) that increased longshore continuity improves the chances of dune survival. It is worth noting that GIP-NV sites lie closer to the storm centre than the EG site. As with longshore continuity, the height of the foredune ridge does not appear to improve significantly the chances of dune survival either (Figures 8C, 8D, 9C, 9D, 12C, and 12D). This observation, however, might only hold true for intense storms such as Hurricane Ivan and might not be the case for smaller, weaker, or faster moving storms. A reasonable relationship was identified between the cross-shore width of the dune and an increase in the likelihood of dune survival (Figures 8D and 10). Most of the incipient dunes that survived Ivan are characterized by a large cross-shore width. Dune width should be proportional to the dune's ability to endure an extended period of storm wave attack, therefore representing a primary factor controlling dune survival during extreme storm events.

CONCLUSIONS

The 85-km-long Santa Rosa Island can be characterized generally as a low-lying barrier island. On the basis of a pre-Ivan LIDAR survey, the elevation of berm and back beach is typically 2.0 m above MSL. Incipient dunes range from 2.5 to 10.0 m above MSL, or 0.5 to 8.0 m above the beach. The hummocky dunes that developed over relic washover platforms that likely formed during Hurricane Opal in 1995 are typically less than 4.0 m above MSL. The densely vegetated established dune fields are composed of dunes generally less than 7.0 m high and intradune wetlands lying at or below 1.0 m (above MSL). This landscape was dramatically changed by Hurricane Ivan. The storm resulted in severe beach erosion, destruction of over 70% incipient and hummocky dunes, and extensive infilling of a large portion of the low-lying ephemeral wetlands. The elevation of inundation surface is typically 1 m above MSL, lower than the 1.5–2.5-m washover platform.

Volume calculation based on pre- and post-Ivan cross-island LIDAR profiles provides an assessment of dry beach and foredune erosion and washover deposition. Typically, profile volume losses of 100–200 m^3/m occurred along nearly the entire length of Santa Rosa Island. This volume loss is greater than the 50–100 m^3/m of washover deposition, indicating that more sand was eroded from the subaerial portion of the barrier island (*e.g.,* beach and dune) than was deposited as washover terraces and lobes. This suggests a net loss of sediment to the offshore on the order of 50–100 m^3/m. Evidence of sand moving alongshore related to the oblique orientation of the dunes was also identified. Under an inundation regime, the subaerial sediment deficit might be partially accounted for by subaqueous washover deposition into the back-barrier bay.

Energetic storms such as Hurricane Ivan can dramatically change barrier island morphology on a regional scale—in this case, replacing widespread dune fields with overwash features. The degree of storm-induced morphological change depends not only on the intensity of the storm but also on antecedent morphological characteristics of the barrier island. Storm-induced dune destruction occurred over three impact regimes—inundation, overwash, and collision-scarping—with the survival or destruction of dune fields controlled by a range of interactive factors. This is in contrast to many previous studies emphasizing dune height as the dominating morphological factor.

Results from Santa Rosa Island indicate that the chances of dune survival increase with increasing distance from hurricane landfall, width of the barrier island, distance to the ocean, overall elevation, vegetation density, presence of woody vegetation, continuity of the dune field, and width of the dune field. Conversely, the chances of dune survival decrease with increasing site-specific storm intensity, duration and frequency, and proximity to relic washover terraces. The incipient dune fields, which tend to lie proximal to the ocean (Gulf of Mexico) and over relic washover platforms, are more vulnerable to the effects of the storm. Established dune fields, especially those lying close to the bayside shoreline, are capable of surviving very strong hurricanes.

LITERATURE CITED

Claudino-Sales, V.; Wang, P., and Horwitz, M.H., 2008. Factors controlling the survival of coastal dunes during multiple hurricane impacts in 2004 and 2005: Santa Rosa barrier island, Florida. *Geomorphology,* 95, 295–315.

Davis, R.A., Jr., 1994. Barriers of the Florida Gulf Peninsula. *In:* Davis, R.A., Jr. (ed.), *Geology of Holocene Barrier Island Systems.* Berlin: Springer-Verlag, pp. 167–205. C1

Davis, R.A., Jr., 1997. Geology of the Florida coast. *In:* Randazzo, A.F. and Jones, D.S. (eds.) *The Geology of Florida.* Tampa, Florida: University Press of Florida, pp.155–168. C2

Dean, R.G., 1999. Hurricane Erin and Opal Hydrodynamics and Erosion Potential. Florida Department of Environmental Protection Technical Report, 21p.

Dean, R.G. and Suter, C.L.,1999. Hurricane Opal: Results from Washover Analysis Task E: Characterization of Beach and Dune Response. Florida Department of Environmental Protection Technical Report, 4p.

Donnelly, C.; Kraus, N.C., and Larson, M., 2006. State of knowledge on measurements and modeling of coastal overwash. *Journal of Coastal Research,* 22, 965–992.

Finkl, C.W. and Andrews, J.L., 2008. Shelf geomorphology along the southeast Florida Atlantic continental platform: barrier coral reefs, nearshore bedrocks, and morphosedimentary features. *Journal of Coastal Research,* 24, 823–849.

Kurz, H., 1942. Florida Dunes and Scrub, Vegetation and Geology. Tallahassee, Florida: The State Geological Survey.

NOAA (National Oceanic and Atmospheric Administration), 2009. Topographic Change Mapping—Coastal Elevation Mapping. Coastal Services Center http://maps.csc.noaa.gov/TCM/ (accessed March 10, 2008).

O'Neal-Caldwell, M.; Wang, P.; Horwitz, M.H.; Kirby, J.H., and Guha, S., 2005. Regional Overwash from Hurricanes Frances-Jeanne and Ivan. New Orleans, Louisiana: Transactions Gulf Coast Association of Geologic Societies, Vol. 55.

Otvos, E.G., 1981. Barrier platforms: northern Gulf of Mexico. *Marine Geology,* 63, 285–306.

Roberts, T.M.; Wang, P., and Kraus, N.C., 2009. Limits of wave runup and corresponding beach-profile change from large-scale laboratory data. *Journal of Coastal Research,* in press.

Sallenger, A.H., 2000. Storm impact scale for barriers islands. *Journal of Coastal Research,* 16, 890–895.

Sallenger, A.H.; Krabill, W.B.; Swift, R.N.; Brock, J.; List, J.; Hansen, M.; Holman, R.A.; Manizade, S.; Sontag, J.; Meredith, A.; Morgan, K.; Yunkel, J.K.; Frederick, E.B., and Stockdon, H.F., 2003. Evaluation of airborne topographic LIDAR for quantifying beach changes. *Journal of Coastal Research,* 19, 125–134.

Stockdon, H.F.; Sallenger, A.H.; List, J.H., and Holman, R.A., 2002. Estimation of shoreline position and change from airborne scanning LIDAR data. *Journal of Coastal Research,* 18, 205–513.

Stone, G.W. and Stapor, F.W., 1996. A nearshore sediment transport model for the northeast Gulf of Mexico Coast. *Journal of Coastal Research,* 12 (3), 786–792.

Stone, G.W.; Liu, B.; Pepper, D.A., and 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. *Marine Geology,* 210, 63–78.

Stone, G.W.; Walker, N.D.; Hsu, S.A.; Babin, A.; Liu, B.; Keim, D.; Teague, W.; Mitchell, D., and Leben, R., 2005. Hurricane Ivan's impact along the Northern Gulf of Mexico. *EOS Transactions,* American Geophysical Union, 86, 497–508.

Wang, D.W.; Mitchell, D.A.; Teague, W.J.; Jarosz, E., and Hulbert, M.S., 2005. Extreme waves under Hurricane Ivan. *Science,* 309(5736), 896.

Wang, P. and Davis, R.A., Jr., 1998. A beach profile model for a barred coast—case study from Sand Key, west-central Florida. *Journal of Coastal Research,* 14(3), 981–991.

Wang, P. and Horwitz, M.H., 2007. Erosional and depositional characteristics of regional overwash deposits caused by multiple hurricanes. *Sedimentology,* 54, 545–564.

Wang, P.; Kirby, J.H.; Haber, D.J.; Horwitz, M.H.; Knorr, P.O., and Krock, J.R., 2006. Morphological and sedimentological impacts of Hurricane Ivan and immediate post-storm recovery along the northwestern Florida barrier-island coasts. *Journal of Coastal Research,* 22 (6), 1382–1402.

Wozencraft, J.M., 2000. Vertical Datum Conversions for Regional Coastal Management. http://shoals.sam.usace.army.mil/downloads/Publications/Wozencraft_2000PIANCGWA.pdf (accessed Month XX, 200X).