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ScienceDirect
Geomorphology xx (2007) xxx–xxx
GEOMORPHOLOGY
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# Factors controlling the survival of coastal dunes during multiple hurricane impacts in 2004 and 2005: Santa Rosa barrier island, Florida

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Received 23 December 2006; received in revised form 8 June 2007; accepted 11 June 2007

**Abstract**

Santa Rosa Island is an 85 km-long, wave-dominated low-lying barrier island situated along the northwestern Florida coast, facing the Gulf of Mexico. The entire island was severely impacted by Ivan, a strong category 3 hurricane that made landfall about 45 km to the west in September of 2004. Ten months later in July of 2005, Dennis, another category 3 hurricane, made landfall about 30 km east of the western tip of the island. Santa Rosa Island is characterized by well-developed but relatively low dunefields, described in this paper as incipient and established dunes, based on the presence of grassy and woody types of vegetation, respectively. The dunes were severely eroded by the two hurricanes. This paper investigates the factors controlling the regional-scale destruction and survival of the dunefields.

Dune survival is controlled by: 1) hurricane characteristics, including intensity, duration, and frequency, and 2) morphological parameters including width of the barrier island, height and width of the dunefields, vegetation type, distance of the dunes to the ocean, and continuity of the dunefields. Three processes of dune destruction are described including, from most to least severe, inundation, overwash, and scarping. The interaction of all the above factors determines the different dune responses to the storm impacts. In general, the extensive and densely woody vegetated dunefields near the bay-side shoreline survived the storms, while the discontinuous dunes with grassy vegetation near the Gulf shoreline were almost completely destroyed.


*Keywords:* Barrier islands; Hurricanes; Coastal dunes; Storms; Gulf of Mexico; Florida

## 1. Introduction

Coastal dunes are formed when sand deposited on the shore dries out and is blown by wind to the back of the beach (e.g. Bird, 1976). Their occurrence is therefore directly related to sand supply and a favorable wind regime (e.g. Hesp, 1999). In such a context, coastal sand dunes tend to develop where there is a large sand supply, a sufficient wind to move it, and a place where it can accumulate (Goldsmith, 1978). The shape of beach profile can also control dune formation. Typically, dune development is favored landward of a flat, dissipative foreshore where large volumes of sand are stored. In contrast, dunes tend to be poorly established behind

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doi:10.1016/j.geomorph.2007.06.004

reflective beaches, where the beach face is steep and sub-aerial storage is low (Short and Hesp, 1982).

Dune heights along the northwestern Florida barrier islands are low, typically less than 4 m, although in some places they can reach more than 10 m (Kurz, 1942). The primary reasons for the relatively small dunes are the lack of sand-sized sediment supply and the lack of persistent onshore winds (Davis, 1994). In addition, the modest widths of most of the islands do not offer adequate space for wind-blown sand accumulation. The overall low dunefield elevations make the Florida barrier islands particularly vulnerable to storm overwash.

The principle types of dunes along the northwestern Florida barriers are foredunes and hummocky terrains. Foredunes are formed adjacent to the surf zone–beach environment (Hesp, 1984). Vegetation is critical in foredune formation and growth, because it traps wind-blown sand. Hesp (1984, 1999) classified the foredunes as *incipient foredunes* and *established foredunes*. Incipient foredunes are actively developing foredunes formed within pioneer plant communities. They may be formed by sand deposition within discrete or relatively discrete clumps of vegetation or individual plants. Incipient foredunes may occur in the form of an incipient foredune ridge or a zone of shadow dunes, coppice mounds and nebkas. Regional variations in the species which act as pioneer colonists and foredune-builders are a function of climate and biogeographical characteristics. In Florida coastal areas, the common species populating incipient foredunes are beach-orange (*Atriplex arenaria*), sea oats (*Uniola paniculata)*, and railroad-vine (*Ipomea pes-caprae*) (Kurz, 1942; Barnett and Crewz, 1997). In the subtropical climate as in part of the Gulf of Mexico, colonization or recolonization of dry sand features rarely takes more than one annual cycle to complete (Ricthie and Penland, 1988).

Established foredunes develop from incipient foredunes and are distinguished by the growth of shrub and woody plant species. Compared to incipient foredunes, established foredunes tend to have greater morphological complexity, i.e., larger variations in height and width (Hesp, 1999). Development of established foredunes occurs gradually over a long period of time, typically 100s to 1000s of years, under conditions of relatively stationary sea level on stable coasts (Hesp and Short, 1999). In Florida coastal areas, the most common plant species associated with established foredunes are saw-palmetto (*Serenoa repens*), live oak (*Quercus geminate*) and slash-pine (*Pinus palustris*) (Kurz, 1942; Barnett and Crewz, 1997). Finally, hummocks are represented as isolated clumps of opportunistic vegetation that act as sand traps and thus lead to the formation of coppice dunes or nebkas (Ricthie and Penland, 1988). The types of vegetation present in hummocky terrains are similar to those in incipient foredunes.

Wave erosion, storm overwash, and deflation are the major forces inducing dune destruction. Normal weather wave erosion is a gradual process causing basal undercutting due to periodic wave attack. The main focus of this erosion is at the foot of the foredune (Carter et al., 1990). Following excessive undercutting, the collapse of the dune face is associated with the cohesiveness of the dune sand, which in turn is related to the density and type of vegetation, soil moisture, and cementation (Carter et al., 1990). Sediment removed from the dune during scarping may return to the slope face under favorable conditions as part of the beach/dune recovery process, being the initial accumulations of what is commonly called echo dunes (Tsoar, 1983; Carter et al., 1990). Topographic acceleration of air flow can rapidly form a deflation surface, providing another destructive regime to the dune field (Carter et al., 1990). The deflation produced by significant wind energy may create blowout dunes in pre-existing dunes and wash-over fans. The blowout dunes may evolve into parabolic dunes (Hesp, 1999).

A major dramatic destructive regime for dune fields is associated with storm-induced overwash (Ricthie and Penland, 1990). Low-lying barrier islands, such as those along the northwestern Florida coast, are particularly vulnerable to storm overwash. Hummocky dunes, dissected foredunes, and foredune remnants are common relict features of dune destruction by storm overwash (Leatherman, 1979). Generally, overwash occurs when elevated water levels, due to storm surge and wave run-up, exceed the height of the barrier island (Donnelly et al., 2006). Direct measurement of the energetic overwash processes is difficult. Fisher et al. (1974), Leatherman (1977) and Leatherman et al. (1977) measured the hydraulic conditions during an overwash event caused by a weak winter storm, obtaining Froude numbers of nearly 1.

Sallenger (2000) developed a storm impact scale for barrier islands, incorporating both storm and morphological parameters. Four parameters, $D_{HIGH}$, $D_{LOW}$, $R_{HIGH}$ and $R_{LOW}$, are developed to evaluate the level of morphological impact of storms. $D_{HIGH}$ is the elevation of the highest part of the first line of defense (e.g., the foredune ridge). $D_{LOW}$ is the elevation of the base of the dune for beaches with a foredune ridge. For beaches without a foredune ridge, $D_{HIGH} = D_{LOW}$. $R_{HIGH}$ and $R_{LOW}$ are representative high and low elevations of the landward margin of swash. The first two impact scales, *swash* and *collision* regimes, are not associated with overwash. A collision regime can cause tremendous and extensive damage to dune fields in the form of dune scarping (Fig. 1). Wang et al. (2006) discussed the extensive and continuous scarping caused by Hurricane Ivan along the northwestern Florida coast, east of the Santa Rosa Island study area. When $R_{\mathrm{HIGH}}$ is higher than $D_{\mathrm{HIGH}}$ but $R_{\mathrm{LOW}}$ is lower than $D_{\mathrm{HIGH}}$, the third impact scale, *overwash regime* occurs (Morton and Sallenger, 2003). The fourth and most severe impact, the *inundation regime*, occurs when $R_{\mathrm{LOW}}$ exceeds $D_{\mathrm{HIGH}}$. Low-lying barrier islands are especially susceptible to inundation regime (Dingler and Reiss, 1995). This paper focuses on the dramatic and regional-scale destruction and survival of dunefields impacted by overwash and inundation regimes.

Insight into barrier island response to extremely energetic storms is crucial to the understanding of the dynamic geomorphology and evolution of barrier islands. Numerous studies have been conducted on previous strong hurricanes. Hayes (1967) investigated the morphological impacts of Hurricanes Carla (1961) and Cindy (1963) on the barrier islands along the Texas coast, USA. He emphasized the significant roles played by intense storms in the geologic record. Schramm et al. (1980) studied Hurricane Frederic in 1979, and its impact along developed and undeveloped segments of the Alabama coast, USA. They discussed the role of a large ebb-tidal delta in dissipating storm energy. Kahn and Roberts (1982) studied the washover deposits caused by Hurricane Frederic along the Louisiana coast. Debussuchere et al. (1991) studied the impacts associated with Hurricanes Danny (1985), Juan (1985), and Gilbert (1988) along the Louisiana barrier islands. They examined the impacts of multiple hurricanes and barrier-island recovery in between the storms. Coch and Wolf (1991) studied the impact of Hurricane Hugo (1989) along South Carolina coast, attesting severe beach and dune erosion. The authors indicated that only high and continuous dune sections provided a solid barrier to storm surge and overwash. Hal and Halsey (1991) examined overwash penetration associated with Hurricane Hugo, suggesting that areas with high long-term pre-storm erosion rates also suffered the greatest overwash penetration during storms. Stone et al. (1993) provided an overview of the dramatic morphological impact of Hurricane Andrew in 1992 along Florida's Gulf and Atlantic coasts. Tedesco et al. (1995) discussed the response along Florida's coastlines to the impact of Hurricane Andrew, attesting that the beaches were reshaped into broad storm ramps. Dingler and Reiss (1995) discussed beach erosion along the Louisiana coast caused by Hurricane Andrew. Stone et al. (2004) studied the impact of Hurricane Opal in 1995 along the northern Gulf of Mexico, suggesting that subaerial portions of barrier islands can conserve mass during storm overwash. Another study of Stone et al. (2005) examined the very high waves and initial impact of Hurricane Ivan in 2004 along the northern Gulf of Mexico barrier islands.

The above studies have focused on various aspects of hurricane impacts and post-storm recovery on barrier

Fig. 1. An extensive dune scarp induced by Hurricane Ivan. The scarp extends nearly continuously for approximately 40 km. The photo was taken about 40 km east of Santa Rosa Island.

islands; however, the regional-scale destruction and survival of barrier-island dunes by multiple strong hurricanes have not been examined systematically. The several intense hurricanes, especially Ivan in 2004 and Dennis in 2005, induced tremendous morphological changes along the northwestern Florida coast. This provided an excellent opportunity to study the factors controlling the destruction and survival of coastal dunes along an extensive low-lying barrier island.

The objectives of this paper are to understand: 1) the extent of regional-scale impact of Hurricanes Ivan and Dennis on dune fields on low-lying northwestern Florida barrier islands, and 2) the factors controlling the destruction and survival of coastal dunes during severe storm events. Rectified aerial photos of the entire 85 km-long Santa Rosa Island before the 2004 storm season and those immediately after Hurricanes Ivan and Dennis are examined in order to depict the destruction and survival of coastal dunes. These data were combined with ground observations and pre- and post-storm dune–beach profile surveys.

## 2. Study area

Located along the northwestern Florida Gulf of Mexico coast, Santa Rosa Island extends 85 km from Pensacola Bay at its western end to Choctawhatchee Bay at its eastern end, with Santa Rosa Sound separating the barrier island from the mainland (Fig. 2). Parallel to the northern Gulf of Mexico coast, the barrier island is oriented roughly east–west, with a maximum width of 1.05 km, a minimum of 160 m, and 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 presents well-developed beaches and foredunes, comprising part of the largest dunefields in the state of Florida (Davis, 1997). The foredune elevations average approximately 4 m above Mean Low Water (Stone et al., 2004).

This low profile barrier island is composed of compositionally and texturally homogeneous sediments, with 99% quartz sand and 75% of which lies within the 0.2 to 0.4 mm grain sizes fractions (Stone and Stapor, 1996). The remaining 1% of sediment is mostly heavy minerals such as illmenite and rutile (Stone et al., 2004). Net longshore sediment transport is westward with a maximum rate of approximately 150,000 $m^3$/year near the entrance to Pensacola Bay (Stone and Stapor, 1996). Calculated modal breaking wave heights are 0.7 m. Tides are dominantly diurnal with an average range of 0.43 m, although with distinct variations between equatorial and tropic phases (Stone et al., 2004). The area is subjected to southeasterly winds of moderate speed (Davis, 1997).

The textually and compositionally mature sediment is the result of the absence of significant and active terrestrial sediment sources. The morphodynamics of Santa Rosa Island is largely controlled by the re-distribution of sediment from the inner continental shelf, intertidal zone, back beach, dune field, and back-barrier bay. Extreme storms play essential roles in sediment re-distribution.

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 non-developed portions of the island are examined. Five study areas spanning the entire 85 km barrier island are examined, including from west to east (Fig. 2), Fort Pickens State Park (FP), Gulf Island National Seashore (GIP), the non-developed western

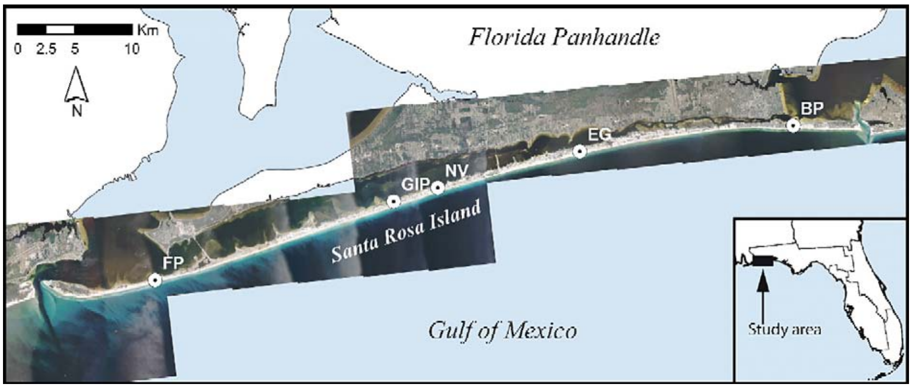


Fig. 2. Pre-Ivan aerial photo mosaic of Santa Rosa Island showing the location of the five study sites: FP—Fort Pickens State Park, GIP—Gulf Island National Sea Shore, NV—Navarre Beach, EG—Eglin Air Force Base, BP—Beasley Park.

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end of Navarre beach (NV), Eglin Air Force base (EG), and Beasley Park (BP). No artificial beach nourishment has occurred at the study sites.

## 3. The hurricane seasons of 2004 and 2005

The 2004 and 2005 Atlantic and Gulf of Mexico hurricane seasons were extremely active and imposed tremendous impacts along the Florida coasts (Stone et al., 2005; Wang et al., 2005, 2006; Wang and Horwitz, 2007). Two of the major hurricanes, Ivan in 2004 and Dennis in 2005, impacted the study areas directly, and are the focus of this study on barrier island dunes (Fig. 2).

Hurricane Katrina, which impacted the Louisiana and Mississippi coasts tremendously in 2005, also influenced Santa Rosa Island. However, the erosion and/or accretion caused by Katrina at the study sites were limited to the backbeach and intertidal zone due to its distal landfall position. In other words, Katrina's impact to the study areas was dominantly in the form of swash regime, and is therefore, not a major focus of this study.

Ivan, a large sustained category 4 hurricane that weakened to a strong category 3 at landfall came onshore near Gulf Shores, Alabama in September 2004 with extreme wind, wave, and surge. Fig. 3 shows the measured wave and surge conditions as the hurricane approached the coastline. The selected tide gauges are close to the open Gulf, and therefore should provide reliable surge measurements. At Ivan 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 impacted by sustained onshore hurricane-strength wind, with the wind–wave–surge forcing decreasing from

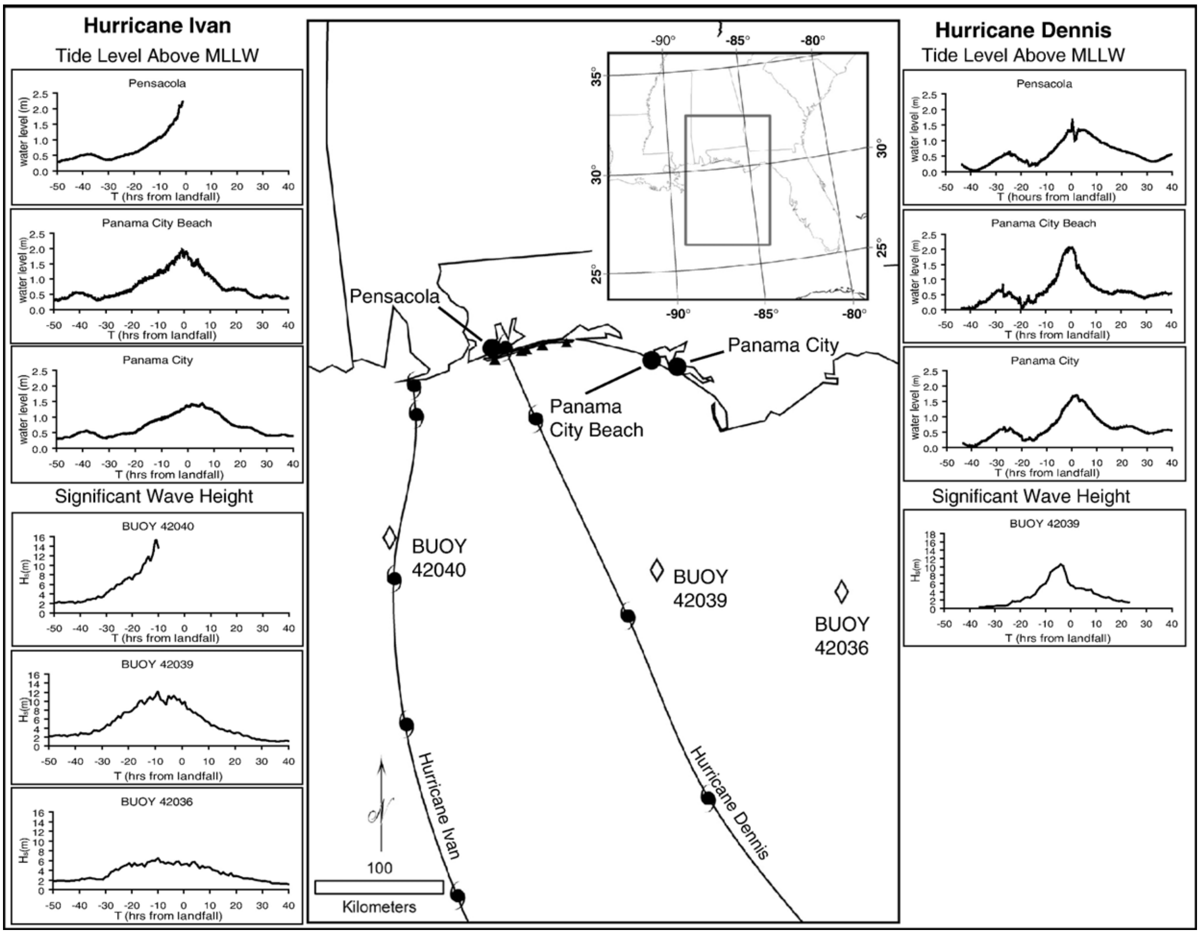


Fig. 3. Map of the northwestern Florida coast (centre panel) showing the locations of tide gauges (circles), offshore wave buoys (diamonds), tracks of Hurricanes Ivan and Dennis, and the study sites (triangles). The left and right panels show water levels and significant wave heights measured during the passages of Hurricane Ivan and Dennis, respectively. Wave buoys 42040 and 42036 were not in operation during the passage of Dennis. Zero hour on the horizontal axis represents the time of landfall.

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west to east as the distance from the hurricane eye increased.

Dennis, a category 3 hurricane, made landfall at roughly the GIP study site in July 2005, with sustained winds of 185 to 195 km/h. Compared to the massive Ivan, Dennis was smaller in size with a faster forward moving speed, e.g., roughly 22 km/hr versus Ivan's 13 km/hr at landfall. The FP study site is located to the west of the Dennis landfall (Fig. 2). The GIP site is located at landfall, and the remaining study sites lie to the east of the landfall.

Extremely high waves were measured at the National Data Buoy Center (NDBC) wave buoys. Shortly before Ivan landfall, 16 m waves were measured at the westernmost buoy 42040 (Fig. 3), which damaged the buoy. At buoy 42039, 220 km to the east, the highest wave was 12 m. Further east at buoy 42036, the highest was 6.4 m. The highest waves at all three buoys were measured shortly before landfall. These extreme offshore wave conditions persisted through the landfall. The high waves generated by Hurricane Ivan offshore 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. The highest waves measured during the passage of Dennis were about 10 m. The greater forward speed of Dennis as compared to Ivan is reflected in the narrower peaks in the wave and surge data (Fig. 3). 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 (Fig. 3), 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).

Significant and sustained surges were measured over a large area during the passages of both Ivan and Dennis (Fig. 3). At the Pensacola tide gauge, the highest surge measured was 2.1 m above Mean Low Low Water (MLLW) for Ivan and 1.5 m for Dennis. The capacity of the gauge was exceeded at Ivan landfall. Many qualitative pieces of evidence indicate that the water level substantially exceeded 2.1 m (Wang et al., 2006). The tide gauge is located to the west of the Dennis landfall. Dominated by offshore winds, the water level measured inside Pensacola Bay may not be representative of conditions on the Gulf-side. 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 both Ivan and Dennis, nearly four times the typical tidal range. Surge levels above 1.5 m (MLLW) persisted for over 10 h (Fig. 3).

The measured surge levels (Fig. 3) do not include the wave set-up and swash run-up that occurs along open beaches. Based on measured pre- and post-storm beach-profile changes, Wang et al. (2006) found that the highest elevation of beach erosion extended considerably above the measured storm-surge level, indicating that storm-wave set-up and swash run-up played essential 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 during Ivan impact. Therefore, wave set-up and swash run-up should contribute significantly to overwash processes and dune destruction.

## 4. Materials and methods

A major part of the study was conducted through the analyses of four time-series rectified aerial photos. The first series is a set of pre-Ivan Digital Orthophoto Quarter Quad (DOQQ), obtained from the Land Boundary Information Service (LABINS) of the Bureau of Survey and Mapping, Florida. The second series, acquired from the National Oceanic and Atmospheric Administration (NOAA) Remote Sensing Division, are orthophotos taken in September 2004, immediately after the landfall of Ivan. The third series, also acquired from the NOAA Remote Sensing Division, are orthophotos taken in July 2005, directly following Dennis's landfall. The fourth series are low altitude oblique photos, taken by this study three months after Ivan's landfall. All the aerial photos were geo-referenced and rectified using ESRI Arcmap GIS software.

Field investigations, including dune–beach profile surveys and ground photographing, were conducted at all five study sites before and after each storm event. Trenching and Ground Penetration Radar (GPR) imaging were also conducted (Wang and Horwitz, 2007), but are not the focus of this paper. Beach–dune profiles were surveyed following the standard level-and-transit procedures using an electronic total station (Wang and Davis, 1998). Temporary survey benchmarks were established two days before Ivan landfall at places that were believed to be more likely to survive the storm, such as a solid post on top of a high dune, the corner of a large building, the middle of a road, or the base of a large power line pole, etc. Not all the pre-storm beach–dune profiles were recovered after the storm because the survey benchmarks were destroyed, especially after Ivan. Three profiles each at the FP site (pre- and post-Dennis), GIP site (pre- and post-Dennis), and BP site (Ivan and Dennis) were re-occupied. The BP profiles are referenced to the National Geodetic

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Vertical Datum (NGVD), which lies approximately 0.2 m below sea level. The rest of the profiles are referenced to an estimated sea level established during the pre-storm surveys. Given that the tidal range is rather small (0.4 m), the field estimation should be accurate. In addition, the reference level does not influence the comparison between pre- and post-storm profiles from a common benchmark. Numerous pre- and post-storm ground photos were taken, and used to supplement and ground truth the systematic aerial imagery.

Due to the narrow width of the Santa Rosa Island, the beach/backbeach interaction resulted in the development of foredunes along both Gulf-side and Bay-side shorelines, and across most of the barrier island. However, in some of the wider parts of the island, there are inland (woody) vegetated dunes that cannot be clearly defined as foredunes. Therefore, for the convenience of discussion, the dunes on Santa Rosa Island are generally distinguished here as incipient dunes with grassy vegetation and established dunes with woody/shrub vegetation. Incipient and established dunes are easily identifiable on the aerial photos due to the different vegetation type and density, and their location relative to the Gulf- and Bay-side shorelines. Typically, established dunes are covered by dense tree and scrub-type vegetation (shown in the aerial photos in dark color) and tend to distribute close to Bay-side shoreline and in the interior of the barrier (Fig. 4A and B). Incipient dunes are lighter in color on the aerial photos due to grassy-type vegetation and tend to distribute near the Gulf shoreline (Fig. 4C and D).

## 5. Results: impact of multiple hurricanes on Santa Rosa Island dunes

Hurricanes Ivan and Dennis induced tremendous regional-scale morphological changes to the dunes on Santa Rosa Island. Three principal erosive processes were distinguished through the analysis of the time-series photos and ground surveys. The three processes, partly based on the impact scales of Sallenger (2000), are: *inundation*, *overwash*, and *scarping*.

Inundation, the most destructive regime, occurs when the storm-elevated water level submerges nearly the

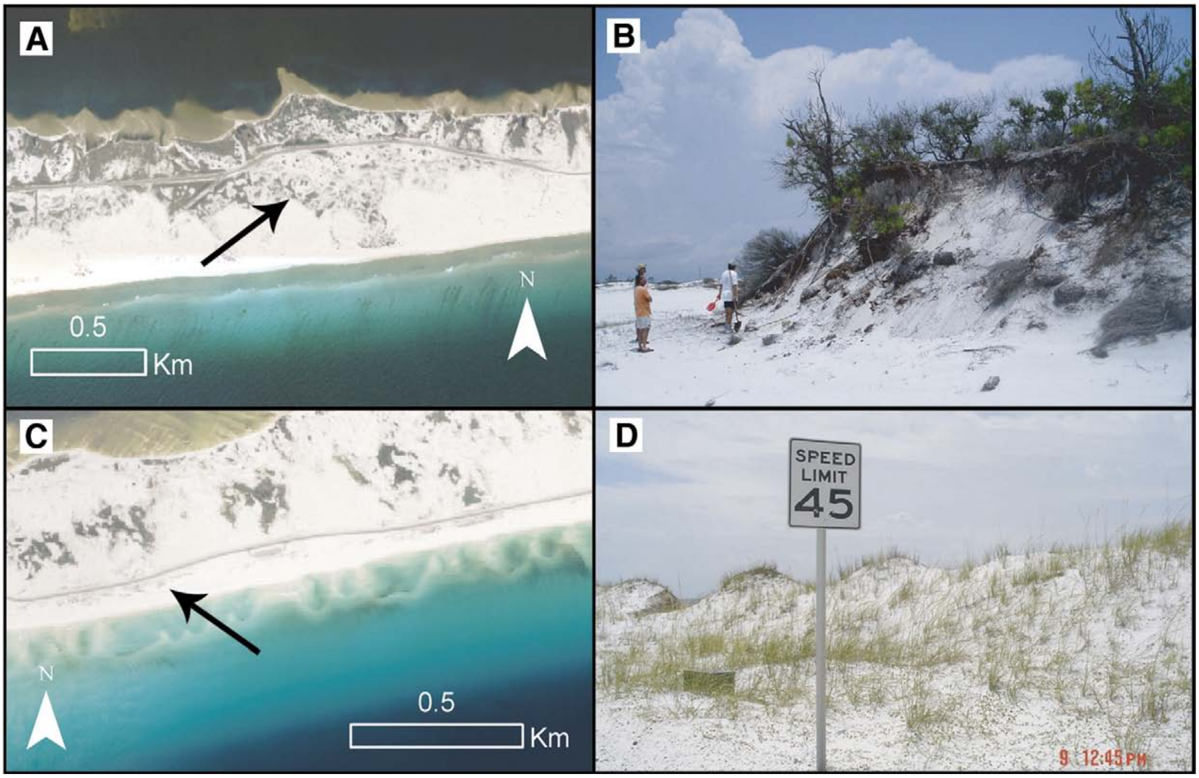


Fig. 4. Aerial and ground views of established and incipient dunes. A: pre-Ivan aerial view of a typical established dune (arrow). B: post-Dennis ground view of the established dune shown in A. C: pre-Ivan aerial view of a typical incipient dune (arrow). D: post-Ivan, pre-Dennis ground view of the incipient dune shown in C.

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entire barrier island, and the once sub-aerial segments become impacted directly by energetic surf-zone processes (Sallenger, 2000). Inundation results in complete destruction of dune fields, both incipient and established. Wang and Horwitz (2007) documented a large amount of landward sediment transport during inundation. Overwash occurs when a portion of the barrier island is submerged. Typically, overwash results in the removal of low-lying dunes and partial destruction and scarping of large dunes. Sediment eroded from the dunes is in turn transported landward and deposited as washover in the barrier interior and back-barrier bay (Wang and Horwitz, 2007). The scarping process erodes the dunes without overtopping, therefore leaving no washover deposits.

### 5.1. Fort Pickens State Park (FP)

The FP study site is located at the western end of Santa Rosa Island (Fig. 5), approximately 45 km east of Ivan landfall, and 30 km west of Dennis landfall. This segment illustrates the greatest variation in barrier-island width over the entire island (Fig. 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 substantially to about 220 m at the eastern portion of the FP site. Three representative segments are examined along this section of the barrier island (Fig. 5).

#### 5.1.1. Pre-Ivan condition

The western segment contains the most extensive sequence of established dunes observed on Santa Rosa Island (Fig. 6A1). A considerable amount of incipient-dune development has also occurred along the western end. These younger dunes appear to preferentially form over spit platforms and washover terraces. Some incipient dunes also occur landward of the Gulf beach. These incipient dunes translate northward (landward) and westward into continuous shrubby and woody established dunes, orientated roughly SE–NW. Along the Gulf-side, a pond, roughly 39,000 $m^2$ in area extends approximately parallel to the shoreline.

The central segment, ranging roughly from 340 to 450 m in width (Fig. 6B1), is a rather unique section. Three ponds, with the largest covering an area of 20,500 $m^2$, occur near the Bay-side shoreline. The ponds are surrounded by established dunes. Extensive incipient-dune development has occurred between the established dunes and the road.

The third and easternmost segment (Fig. 6C1) represents a relatively narrow section of the island. This segment is dominated by incipient dunes extending from just Gulfward of the road across nearly the entire barrier island. A thin line of established dunes populate the Bay-side beach only a few meters from water.

#### 5.1.2. Impacts of Hurricane Ivan

Along the relatively wide, western portion of the island (Fig. 6A2), the woody established dunes populating the center of the island remained mostly intact. Landward of the Gulf beach (Fig. 6A2 lower center), overwash penetrated 290 m landward eroding most of the incipient dunes which had served as the barrier's first line of defense. The washover deposits terminate roughly along the edge of the established dunes. Modest sedimentation occurred at the two ends of the pond. Some of the incipient dunes in the middle of the western tip survived Ivan. The western tip of the island is considerably narrower after Ivan. Little change can be observed along the Bay-side. This segment represents an example of overwash penetration constrained by a very well-developed and wide established dune system.

In contrast to the western segment, the central FP segment is much narrower (Fig. 6B). Inundation occurred along the narrow eastern and western ends, while overwash dominated the wider central portion of the segment (Fig. 6B2). Overwash and inundation destroyed

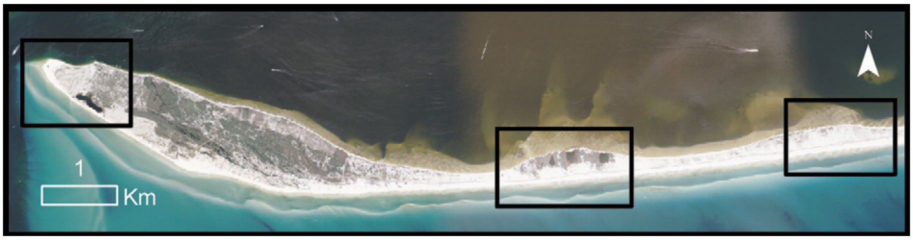


Fig. 5. Pre-Ivan aerial photo of the FP study site. Three segments, as outlined, were examined in detail. The western segment (Fig. 6: A1–A3) represents the widest section of Santa Rosa Island. The middle segment (Fig. 6: B1–B3) is characterized by three ponds near the Bay–side shoreline, and the eastern segment (Fig. 6: C1–C3) is relatively narrow.

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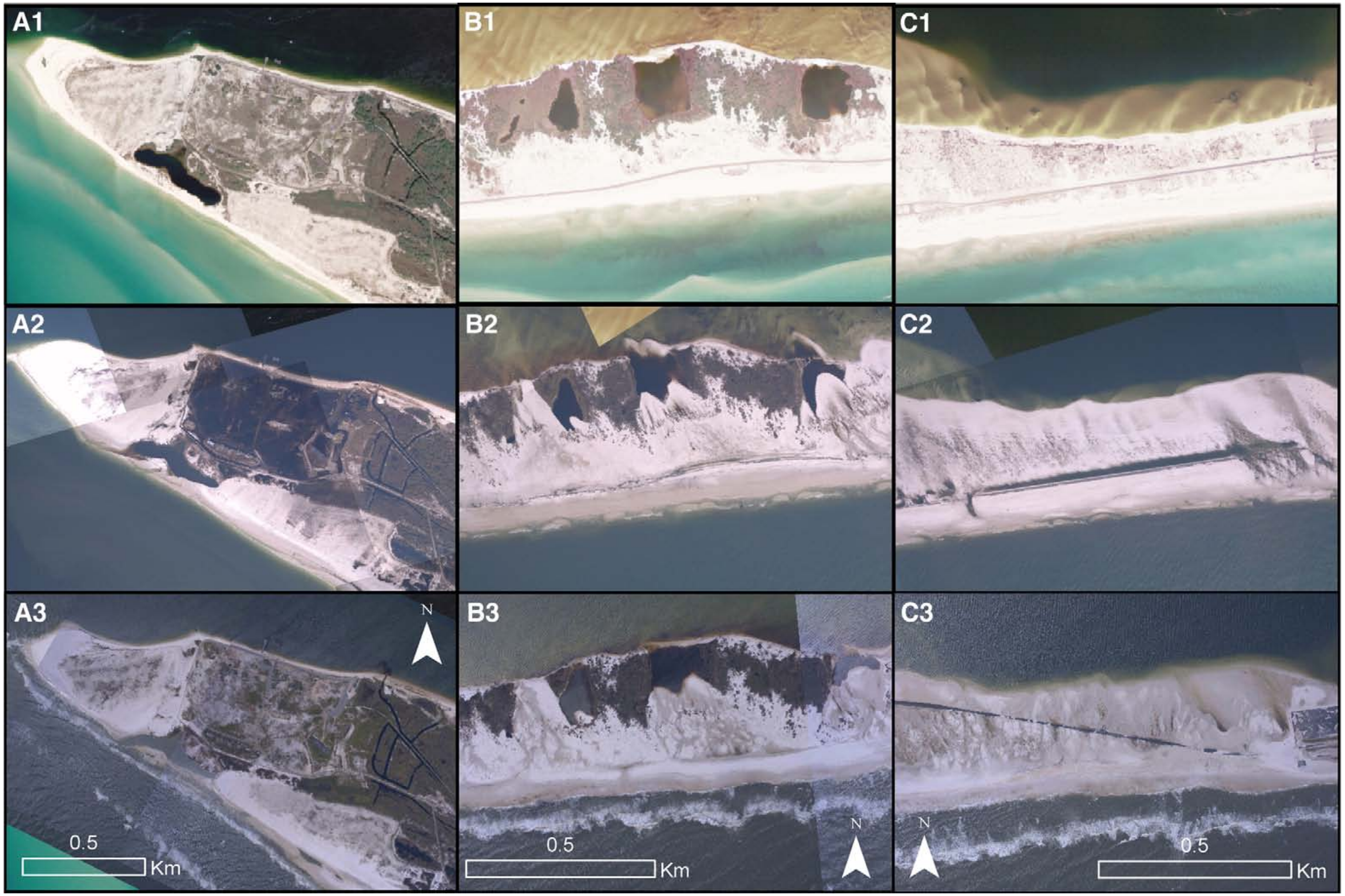


Fig. 6. Hurricane impacts at the FP study site. A1, B1 and C1 illustrate pre-Ivan conditions. A2, B2 and B3 show post-Ivan, pre-Dennis change, and A3, B3 and C3 show post-Dennis change.

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nearly all the incipient dunes populating the southern half of the segment along the Gulf-side. The washover lobes extended into the ponds. The woody vegetated established dunes populating the northern (Bay-side) portion of the segment remained largely intact, with washover deposition occurring in the inter-dune regions. This segment of the barrier island demonstrates an example of severe incipient dune destruction by overwash process with localized inundation.

Inundation dominated the 4.2 km stretch of the barrier island extending east from the central segment (Fig. 5). The inundation resulted in complete destruction of both the extensive pre-storm incipient dunes and the thin line of established dunes lying near the Bay-side shoreline (Fig. 6C1, Fig. 6C2). Also illustrated in Fig. 6C2, is washover deposition which yielded more than 30 m of accretion along the Bay-side shoreline. The maximum landward migration of the Bay-side shoreline was nearly 100 m, measured to the west of the photo. This segment represents an example of complete dune destruction by regional-scale inundation. A 2.4 km-long channel developed parallel to, and along the landward side of the severely damaged road. Scour along the landward side of the road is a common feature observed at numerous places along the entire length of the island.

### 5.1.3. Impact of Hurricane Dennis

Hurricane Dennis made landfall along the central portion of Santa Rosa Island east of the FP site 10 months after Ivan. Dennis' impact was largely influenced by the Ivan "foot print". Little post-Ivan recovery, including the growth of some young vegetation and development of low hummocky dunes occurred during the 10 month period. Although short-term dune recovery was observed on the ground, it cannot be distinguished on the aerial photos. Overall, Hurricane Dennis' impact to the dune fields was limited and largely local. The well-developed established dunes that survived Ivan also survived Dennis. It is worth noting that Dennis passed to the east of the FP area. As discussed in the following paragraph, high waves preceding landfall had significant impact on the post-Ivan morphology; however, at landfall, wind forcing was largely directed offshore. An obvious impact attributed to Dennis is the breaching of two ponds, one along the Gulf shoreline (Fig. 6A3), and the other along the Bay-side shoreline (Fig. 6B3).

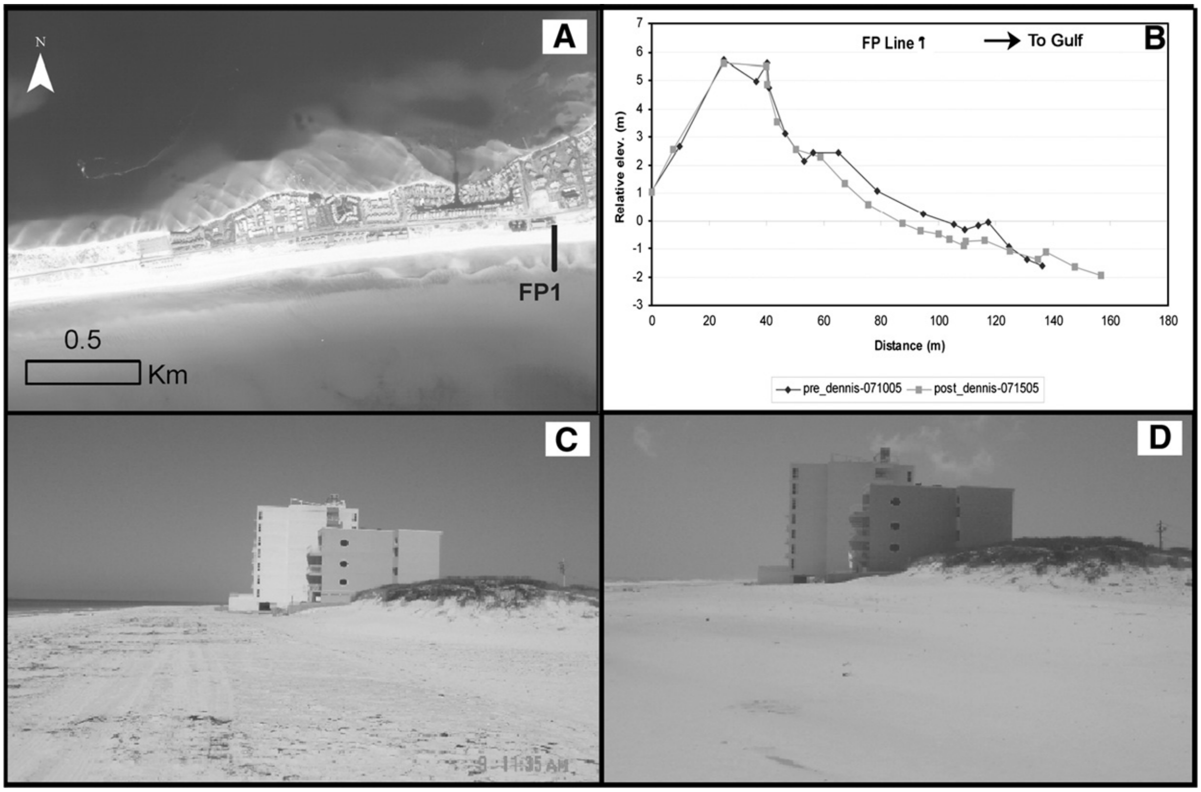


Fig. 7. A beach–dune profile immediately east of the FP study site. A: aerial view of the established dune. B: pre-Dennis and post-Dennis profiles. C: pre-Dennis ground view. D: post-Dennis ground view.

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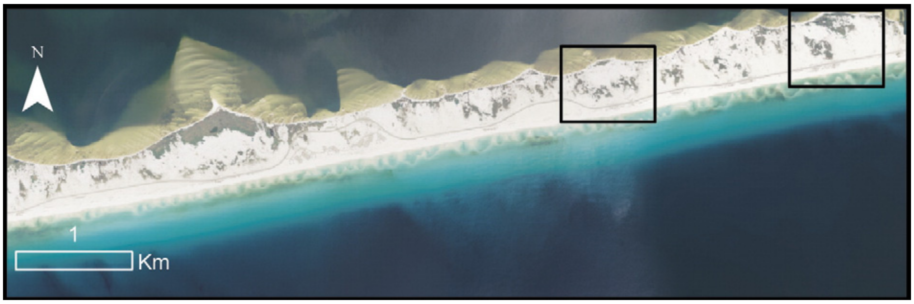


Fig. 8. Pre-Ivan aerial photo of the central portion of Santa Rosa Island showing the GIP (west) and NV (east) study sites.

Additional washover deposition occurred along the eastern end of the middle segment (Fig. 6B3). Along the eastern segment (Fig. 6C3), the most obvious impact attributed to Dennis is the substantial Gulf-side beach erosion. Up to 50 m of shoreline loss was measured from the rectified aerial photos, and further confirmed by the pre- and post-Dennis beach/dune profile surveys.

One pre- and post-Dennis dune profile was surveyed along the far eastern portion of the study area (Fig. 7). The profile extends across an isolated established dune that survived Ivan (Fig. 7B). While Dennis' impact included a significant amount of beach erosion (Fig. 7C, D), impact to the dune was minimal and limited to scarping along the Gulf-side dune face.

### 5.2. Gulf Island National Seashore (GIP) and Navarre Beach (NV)

These two study sites represent a roughly 9 km stretch of Santa Rosa Island, and illustrate rather uniform widths (Fig. 8). Most of this stretch is 400 m to 500 m-wide, with the maximum width of about 750 m. The Bay-side shoreline shows a somewhat rhythmic feature with several sandy headlands separated by a gentle embayment. This Bay-side shoreline configuration may be originated and reworked from previous washover lobes. The headlands tend to be covered by established dunes. The Gulf-side shoreline is generally straight.

#### 5.2.1. Pre-Ivan Condition

Discontinuous but well-developed established dunes are distributed along this stretch of the barrier island (Fig. 8). Small ponds occur in the inter-dune regions. At both study sites, a discontinuous series of incipient foredunes lie adjacent to the Gulf-side beach (Figs. 9A, 10A). Extensive incipient-dune development has occurred in the interior sections over prior washover platforms. Overall, the GIP site at the western end of this stretch demonstrates very similar characteristics as compared to the NV site at the eastern end.

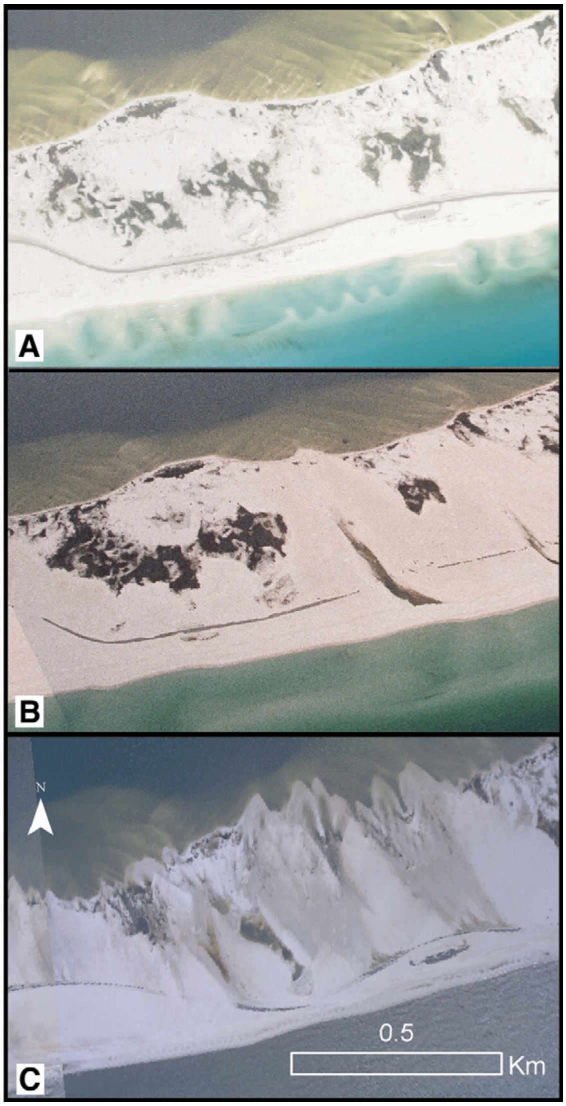


Fig. 9. Time-series aerial images of GIP study site. A: pre-Ivan. B: post-Ivan, pre-Dennis. C: post-Dennis.

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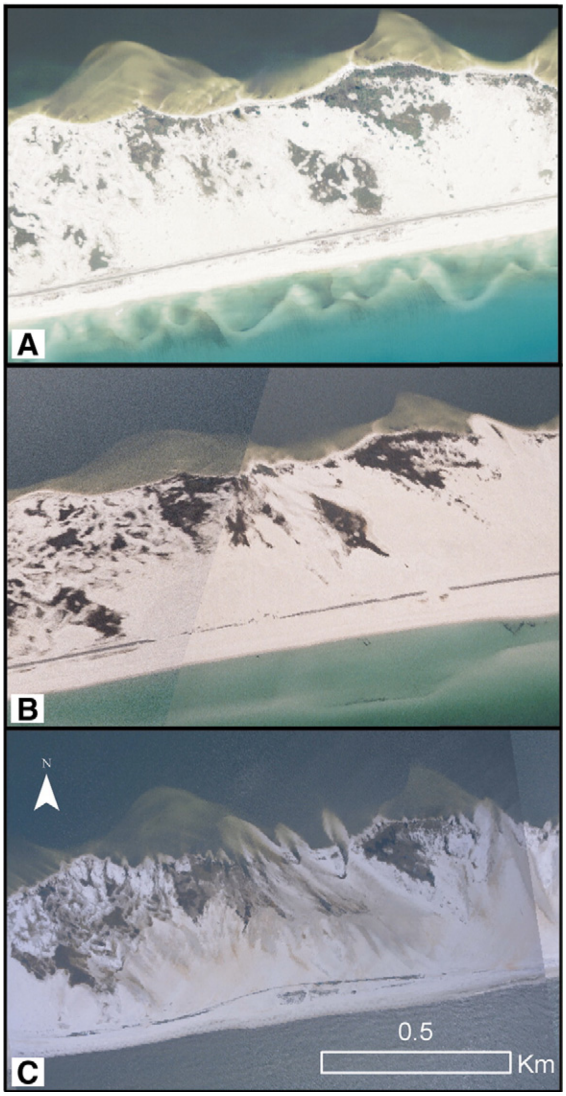


Fig. 10. Time-series aerial images of the NV study site. A: pre-Ivan. B: post-Ivan, pre-Dennis. C: post-Dennis, the dark spots south of the road (middle bottom) are piles of asphalt from post-Ivan road repair.

### 5.2.2. Impact of Hurricane Ivan

The GIP and NV sites are located approximately 70 km and 77 km east of Ivan landfall, respectively. Overall, the impact of Hurricane Ivan is quite similar at the two sites (Figs. 9B, 10B). Almost all the discontinuous well-developed established dunes survived the storm. Extensive overwash occurred across the roughly 400 m-wide GIP site, and the 500 m-wide NV site, destroying most of the incipient dunes. However, some of the incipient dunes survived Ivan (Fig. 11A). Washover deposits terminate roughly along the edge of the established dunes. Two shore-perpendicular channels were identified in the photos taken 3 months post-Ivan (Fig. 9B). The extent of these channels may have been greater immediately after Ivan. Localized inundation is evident landward of the channels. The GIP and NV sites represent examples of substantial incipient-dune destruction by overwash limited landward by well-developed established dunes, with survival of some isolated incipient dunes.

### 5.2.3. Impact of Hurricane Dennis

The GIP site lies essentially at the landfall position of the fast-moving Hurricane Dennis. This site was largely inundated by Dennis (Fig. 9C). The well-developed established dunes that survived Ivan were mostly destroyed by Dennis, with washover deposits in the form of narrow lobes extending into the back-barrier bay. A shore-perpendicular scarp developed along one of the established dunes (Fig. 9C, center), likely due to overwash flow across the barrier island. Seaward of the established dune, a portion of an incipient dune also survived.

Three dune profiles were surveyed immediately pre- and post-Dennis impact (Fig. 11). A survey benchmark established at the crest of a 9 m-high dune during the post-Ivan road re-construction fortunately survived Dennis, and was used for vertical control for all three profiles. The first dune profile, GIP1, extended Gulf-ward from the benchmark. The dune along GIP1 largely survived Dennis although a scarp nearly 2 m-high developed along its seaward face (Fig. 11C). Substantial beach erosion occurred seaward of the dune. The second dune profile, GIP2, is located about 100 m west of GIP1. The profile extended across a 6.5 m-high isolated incipient dune (Fig. 11A, D), situated about 20 m landward of the Gulf shoreline. This relatively large dune (pick-up truck in photo for scale) isolated by Ivan, was completely eroded by Dennis, leaving a flat washover platform in its place (Fig. 11B, D). The third dune profile, GIP3, is located roughly 100 m west of GIP2. This nearly 6 m-high dune was very narrow, about 20 m-wide at the base, and lies approximately 80 m from the Gulf shoreline, similar to the dune at GIP1. Although located much further landward, this narrow dune was completely eroded by Dennis, yielding a largely flat washover platform, similar to that along GIP2 (Fig. 11B, E). In summary, the survival of the post-Ivan dunes seems to be controlled by the distance to the Gulf shoreline, the size of the dune, and its connection to extensive established dunes.

The NV site is located about 7 km east of Dennis's landfall position. The impact here was not as severe as at the GIP site. Localized inundation occurred between well-developed established dunes, producing washover

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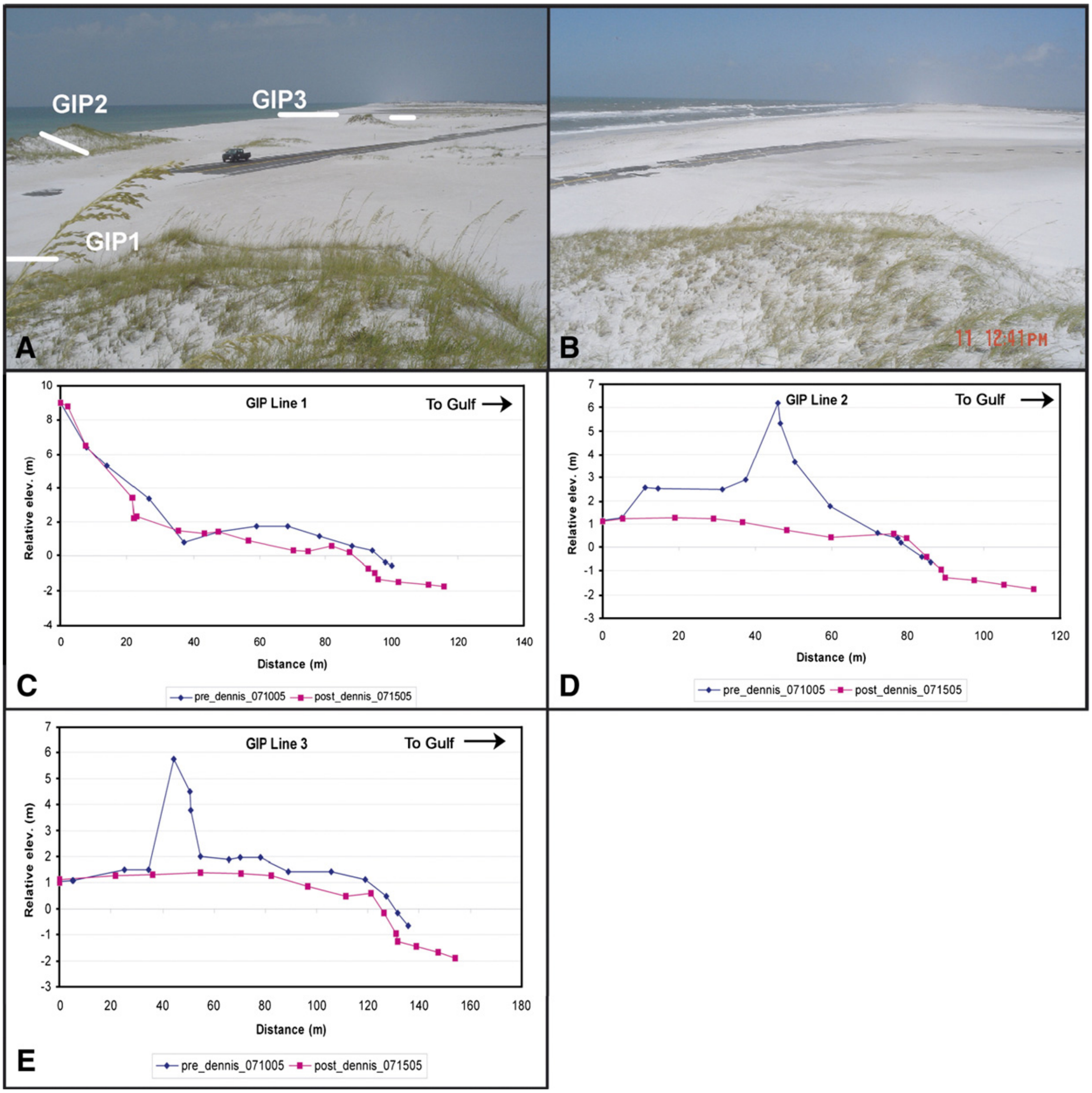


Fig. 11. Pre-Dennis and post-Dennis beach–dune profiles across post-Ivan isolated dunes. A: pre-Dennis ground view of the three dunes (pick-up truck shown for scale). B: post-Dennis ground view of the same area with one surviving dune. C: pre- and post-Dennis profiles at GIP1. D: pre- and post-Dennis profiles at GIP2. E: pre- and post-Dennis profiles at GIP3. Note the variations in dune size and distance to the Gulf shoreline.

lobes extending into the back-bay (Fig. 10C). The washover deposits created an irregular Bay-side shoreline configuration with several short overwash channels developing near the pre-storm shoreline. Most of the well-developed established dunes at the NV site survived Dennis with washover deposits developed in between them. The isolated post-Ivan incipient dunes were largely destroyed, similar to that at the GIP site. The NV site represents an example of inundation process partially limited by well-developed established dunes. It is worth noting that Dennis' impacts were developed over the massive Ivan destruction, without which the Dennis inundation might not have occurred.

### 5.3. Eglin Air Force Base site (EG)

In contrast to the GIP and NV sites, the EG site is located along a stretch of the barrier island that is

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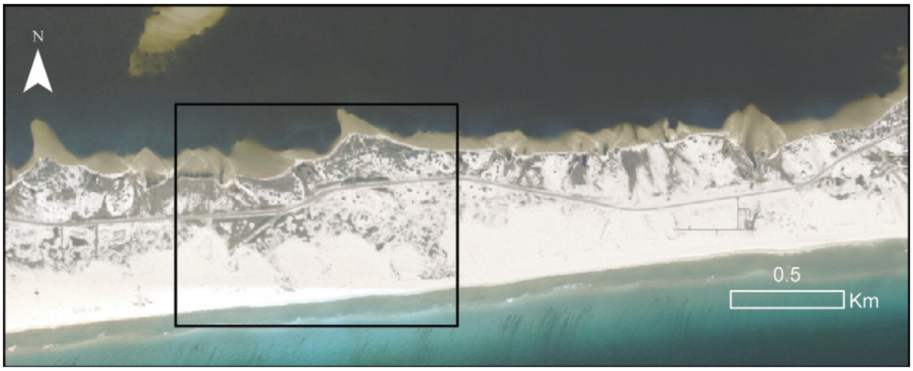


Fig. 12. Pre-Ivan aerial photo of the larger EG study site. Note the headlands protruding into the back-barrier bay.

considerably wider, ranging from 550 m to 750 m in width (Fig. 12). The Bay-side shoreline also displays rhythmic features, with sandy headlands separated by a broad embayment. The Gulf-side shoreline is generally straight.

### 5.3.1. Pre-Ivan condition

A nearly continuous belt of established dunes extends along the Bay-side shoreline at the larger EG study site (Fig. 13). A few blowouts were observed in between the established dunes. Along the western end of the EG site, established dunes populated nearly the entire barrier island. Numerous incipient dunes are scattered over a previous washover platform. A considerable number of inter-dune ponds are distributed along the Bay-side shoreline.

### 5.3.2. Impact of Hurricane Ivan

The EG site lies about 85 km east of the Ivan landfall. Along the Bay-side shoreline, most of the established dunes survived the storm with little change. Two small washover lobes extend into the back-barrier bay from the ponds along the Bay-side shoreline. Along the Gulf-side, extensive overwash penetrated up to 300 m landward, destroying almost all the incipient dunes and some established dunes (Fig. 13). Some of the large incipient dunes survived Ivan but were left isolated, similar to those at the GIP site (Fig. 11). The EG site represents another example of severe regional-scale overwash causing destruction of the majority of the incipient dunes, and survival of most of the established dunes.

### 5.3.3. Impact of Hurricane Dennis

Hurricane Dennis made landfall approximately 20 km west of the EG site. The established dunes along the Bay-side shoreline that survived Ivan remained largely unchanged by Dennis. Extensive additional washover deposition occurred over the broad Ivan washover

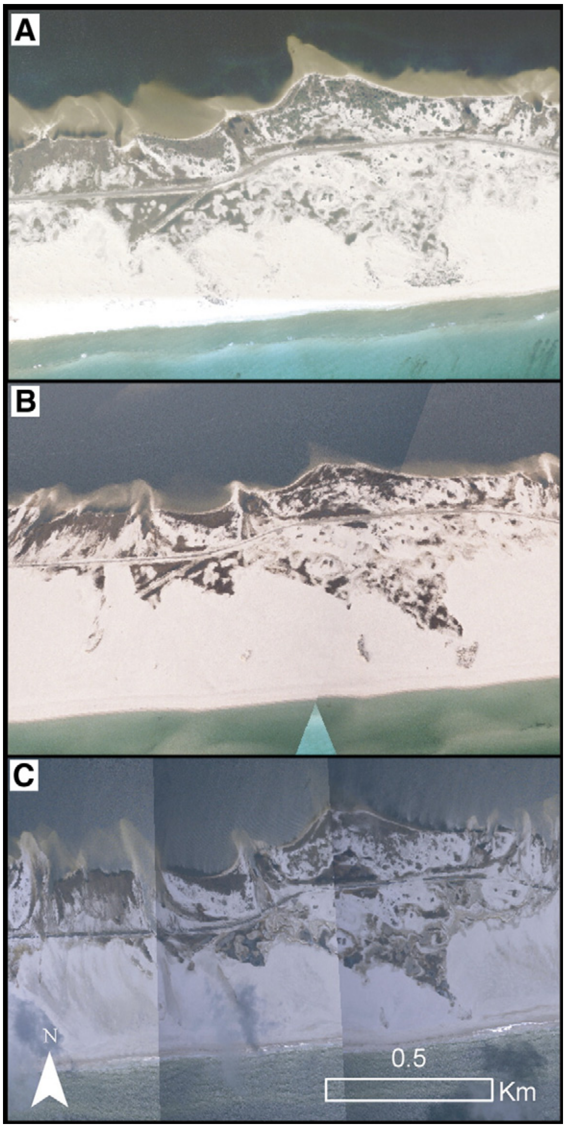


Fig. 13. Time-series aerial images of the EG study site. A: pre-Ivan. B: post-Ivan, pre-Dennis. C: post-Dennis.

Fig. 14. Ground photo at the EG site, showing partially buried and tilted post-Ivan sea oats. The photo was taken 20 days post-Dennis.

platform (Wang and Horwitz, 2007). Some of the small post-Ivan isolated incipient dunes near the Gulf shoreline were destroyed. What little dune recovery that had occurred post-Ivan, in addition to small hummocky dunes and recently established vegetation, was largely destroyed by overwash induced by Dennis (Fig. 14). In summary, at the EG site, the distribution of Dennis washover largely mimicked that deposited by Ivan, while most of the Bay-side established dunes survived.

### 5.4. Beasley Park (BP)

The BP study site is located at the eastern end of Santa Rosa Island (Fig. 15), roughly 110 km and 40 km east from Ivan's and Dennis's landfall, respectively. Due to the longer distance from the hurricanes' landfall positions, the overall impact at this site is not as severe as compared to the four western sites. In addition, east of the BP site, the impacts associated with both Ivan and

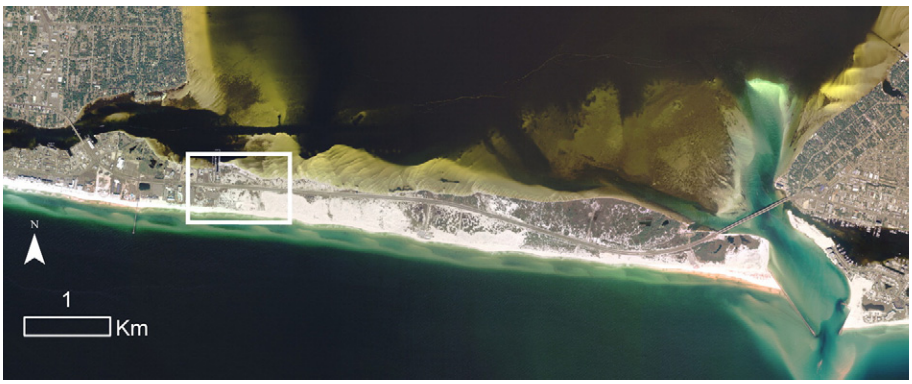


Fig. 15. Pre-Ivan aerial photo of the greater BP study site. Note the broad washover terrace deposited by Hurricane Opal in 1995.

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Dennis were dominated by collision regime, yielding extensive dune scarping (Fig. 1; Wang et al., 2006). Limited overwash occurred east of the BP site.

### 5.4.1. Pre-Ivan condition

The BP site is located at the eastern end of a heavily developed stretch of the barrier island. Based on conversations with local residents, the study site was overwashed by Hurricane Opal in 1995. The western half of the BP site is populated with a discontinuous series of established dunes, which extend across nearly the entire width of the barrier island (Fig. 16A). Along the eastern half, scattered established dunes dominated the region north of Highway 98, while south of the road, post-Opal incipient dunes developed over the Opal washover platform. Three profiles were surveyed at the BP site pre- and post-Ivan, and pre- and post-Dennis (Fig. 17A). Profile BP1, located at the west end of the study area, is a dune profile extending from the top of an established dune seaward to the Gulf shoreline (Fig. 17B). Profile BP2, located in the central portion of the study area, is also a dune profile, which extends seaward from the top of a high isolated incipient dune (Fig. 17C). The third and easternmost profile BP3 is a cross-island profile which extends across the Opal washover platform (Fig. 17D, E and F).

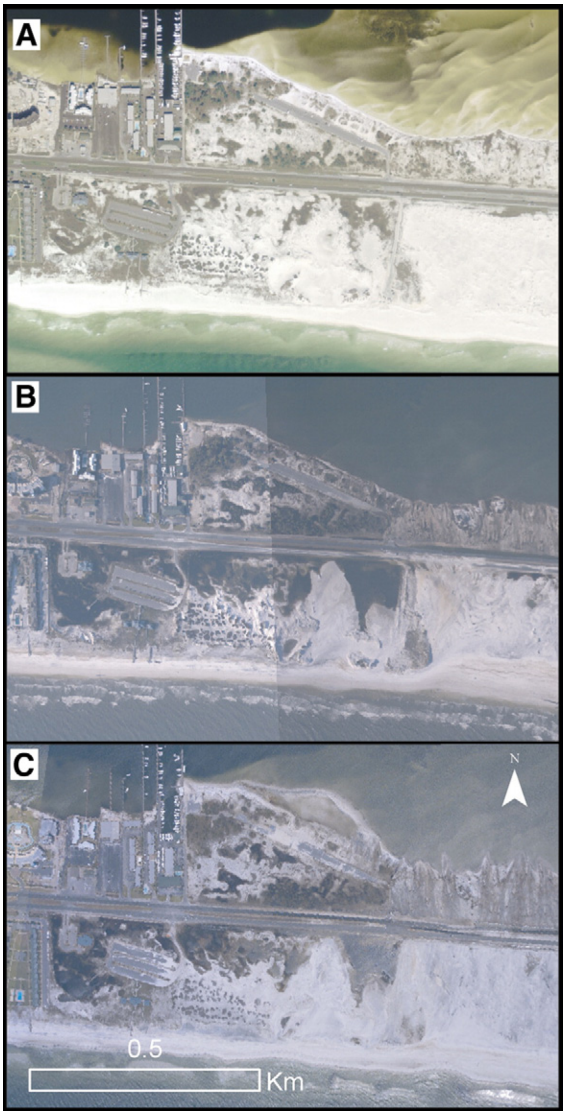


Fig. 16. Time-series aerial images of the BP study site. A: pre-Ivan. B: post-Ivan, pre-Dennis. C: post-Dennis.

### 5.4.2. Impacts of Hurricanes Ivan and Dennis

The established dunes at the western half of the BP site largely survived the Ivan impact (Fig. 16B). The small incipient dunes in front of the established dunes were eroded, leaving a 0.6 m-high scarp (Fig. 17B). Substantial beach erosion was also measured. Further to the east, along profile BP2, the 12 m-high isolated incipient dune survived, although substantial dune face and beach erosion occurred (Fig. 17C). Immediately west of BP2, overwash associated with Ivan penetrated landward through a gap between incipient foredunes, forming a small washover lobe, over a previous washover lobe. The washover destroyed most of the small hummocky and incipient post-Opal dunes (Fig. 16). Ground penetrating radar (GPR) imaging over the washover lobe revealed a truncated dune just northwest of the BP2 dune (Fig. 18). This dune was not truncated by Ivan or Dennis based on pre- and post-storm field observation. It is not clear which previous storm is responsible. This dune truncation indicates the significance of severe storms in the development of barrier-island stratigraphy.

The BP3 site, located in between sections with well-developed established dunes (Fig. 15), presented a weak link and was overwashed by Hurricane Ivan (Fig. 17D, E, and F). Nearly all the incipient dunes that had recovered from Hurricane Opal in 1995 were destroyed and replaced by a flat washover platform. The impacts of Dennis were largely developed over the “footprint” of Ivan, without further extending the area of dune damage, although significant beach erosion was measured (Fig. 17). Overall, little damage to established dunes occurred during both Ivan and Dennis. The BP site illustrates an example of dune destruction by localized overwash processes and a transition from overwash to collision regime.

In summary, at the western FP and GIP sites, inundation was the dominant process during Ivan except along the wide, western end of Santa Rosa Island.

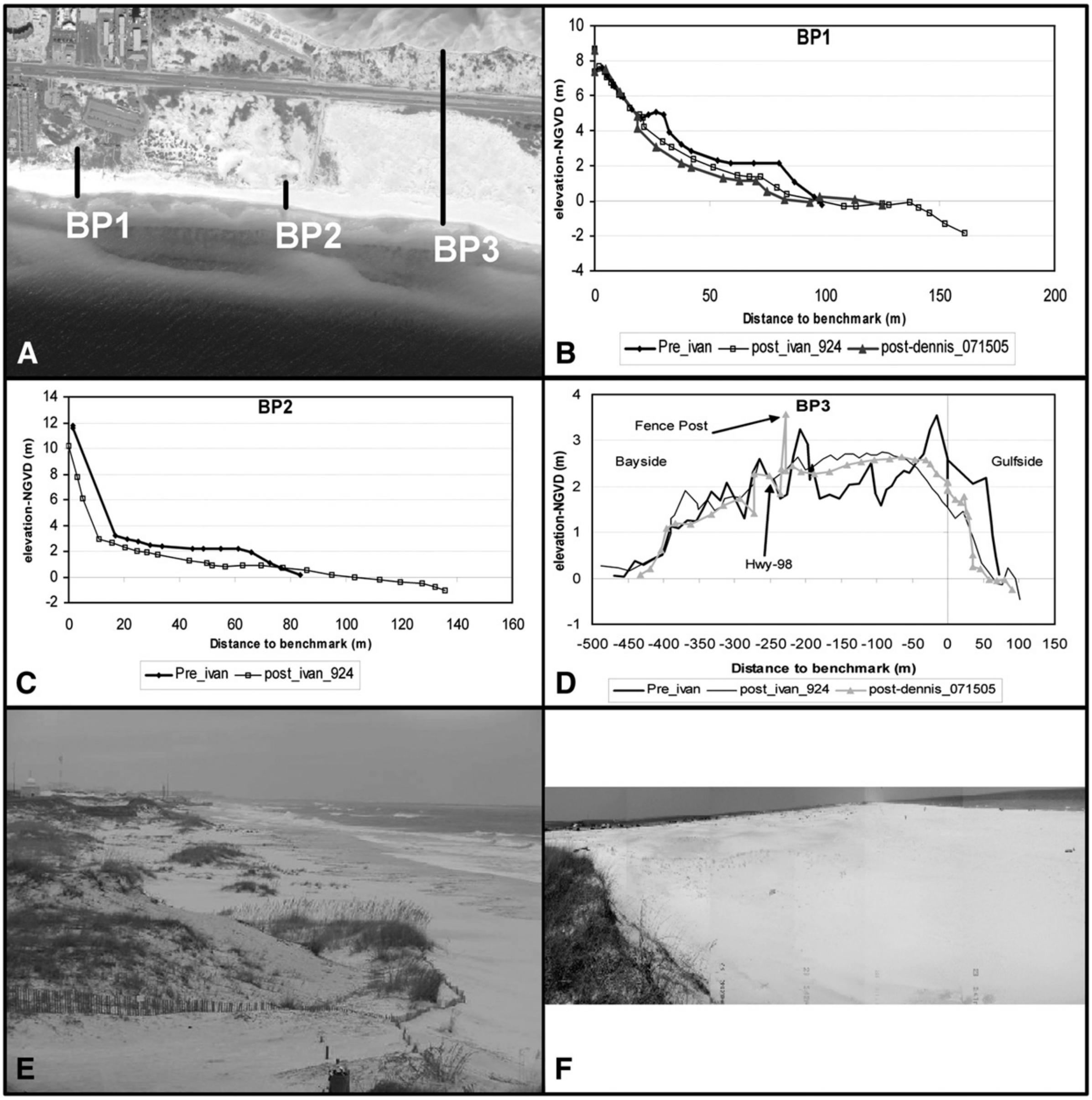


Fig. 17. Pre-Ivan, post-Ivan, and post-Dennis beach–dune profiles at the BP site. A: pre-Ivan aerial view showing the locations of the three profiles. B: pre-Ivan, post-Ivan, and post-Dennis profiles at BP1. C: pre- and post-Ivan profiles at BP2. D: pre-Ivan, post-Ivan, and post-Dennis profiles at BP3. E: pre-Ivan foredunes developed post-Opal (1995). F: ground view of the area in E after Ivan. Note the complete destruction of the post-Opal incipient dunes.

During Dennis, the GIP site was largely inundated due to its close proximity to the storm's landfall. This inundation resulted in nearly complete destruction of both established and incipient dunes and sedimentation in the back-barrier bay resulting in landward migration of the Bay-side shoreline. At the NV and EG sites, the principal morphological impact during both hurricanes was regional-scale overwash. The severe overwash destroyed most of the incipient dunes, while most of the established dunes along the Bay-side shoreline survived. The easternmost BP site illustrates the transition from overwash to collision regime.

## 6. Discussion: factors controlling the survival of the coastal dunes

The survival of incipient as well as established dunes on Santa Rosa Island during the passages of Hurricanes

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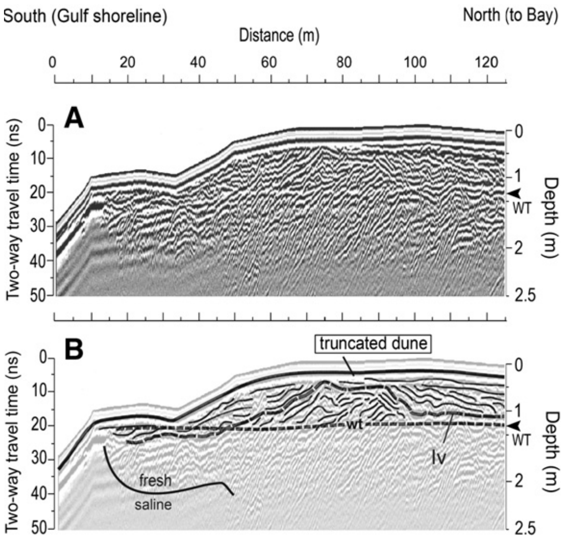


Fig. 18. A GPR profile just west of the BP2 profile, illustrating a truncated dune by a previous storm. WT: water table; Iv: base of Ivan deposit. The depth conversion is based on a velocity of 0.12 m $ns^{-1}$ above the water table, and 0.06 m $ns^{-1}$ below.

Ivan and Dennis is controlled by a number of interactive factors including: (1) the intensity and duration of storms, (2) the width of the barrier island, (3) characteristics of the dunefield and the presence and type of vegetation, (4) distance to the ocean, and (5) the interval between subsequent storms and the existence and extent of prior washover terraces. In the following, each of these factors and their interactions are discussed.

### 6.1. Storm intensity at the specific site

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

Hurricanes Ivan and Dennis had similar maximum sustained wind speeds of about 200 km/hr at landfall. However, Ivan was a much larger storm in terms of size, and moved much slower than Dennis. This is clearly reflected in the contrasting levels of impact generated by each storm. Ivan caused extensive inundation extending from the FP to NV site, a distance of nearly 25 km. Except along several wide sections of the barrier island populated with high, densely vegetated established dunes, such as the western end of the FP site (Fig. 6A), most of the incipient dunes as well as the established dunes were destroyed (Figs. 6, 9, and 10). The degree of dune destruction decreased while the chance of dune survival increased from west to east. Extensive overwash occurred from the NV site eastward to just west of the BP site, a distance of roughly 40 km. Most incipient dunes were destroyed but most of the established dunes, particularly those located near the Bay-side, survived (Figs. 10 and 13). The BP site is located in the transition zone from overwash to collision regime. Extensive scarping along the Gulf-facing dunes occurred. However, most of the large incipient dunes and nearly all the established dunes survived (Fig. 16). The small recovering incipient dunes developed over recent overwash terrace, e.g., that of Opal in 1995, were destroyed. This suggests that substantial dune recovery may take longer than a decade in this case.

The impact of the smaller and faster-moving Dennis to the dune field was much less extensive as compared to that of Ivan. It is worth noting that the areal extent of Dennis overwash may be exaggerated by the fact that it hit only 10 months after Ivan. Inundation regime with nearly complete destruction of post-Ivan incipient and established dunes, in addition to washover into the back-bay, occurred at the GIP site and extended about 6 km. Extensive overwash over the Ivan washover platform and destruction of most isolated dunes occurred from NV to EG sites. Nearly all the Bay-side post-Ivan established dunes remained intact. At the BP site and the surrounding areas, Dennis caused substantial beach erosion and additional scarping along the Gulf-side foredunes. However, further destruction to interior dunes was limited. In addition, what little post-Ivan dune recovery that had occurred was subsequently destroyed by Dennis (Fig. 14).

### 6.2. Barrier island width

The width of the barrier island is directly related to the characteristics of the dune field and the vegetation. Wider sections of the island provide more space for dune development, especially the more storm resistant established dunes. The western end of the FP site provides a direct example of a wide barrier island with an extensive established dune field. Despite the fact that this site is the closest to Ivan's landfall, the survival of most of the established dunes can be directly attributed to the increased relative width of the barrier island. In contrast, inundation regime with the complete destruction of incipient dunes, established dunes, and hummocky terrain is clearly favored by the narrower sections of the barrier island. The control of the barrier-island width is also reflected along the Bay-side headlands. Typically, these headlands are populated with well-developed established dunes. Along the entire length of the 85 km-long Santa

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Rosa Island, almost all the established dunes on the Bay-side headlands escaped inundation. In addition, greater island widths generally correspond with increased distances between the dunes and the ocean (the Gulf). Accordingly, more energy dissipation would be expected, therefore favoring reduced impact to the more distant dunefields.

### 6.3. Dune morphology and vegetation

Three aspects of the established dune morphology have a significant influence on dune survival: the continuity of the dune ridge, the cross-shore width of the dune field, and dune height. Wide, continuous, and well-developed high established dunes are more resistant to storm impact. Examples can be found at the FP and EG sites (Figs. 6A and B, 13). In addition, the established dunes are typically covered by dense woody and shrubby vegetation. This densely rooted vegetation and the associated somewhat cohesive soil layer may increase the dune's ability to resist erosion (Fig. 4). A favorable combination of the above factors coincides with the fact that many times the overwash deposits terminate along the edge of the established dune ridge.

Incipient dunes are typically distributed seaward of the established dunes. The morphology of incipient dunes can also be characterized by the continuity of the dune ridge, the cross-shore width of the dune field, and dune height. However, due to the overwhelming impact of Hurricane Ivan, an estimated 70% of the incipient dunes on Santa Rosa Island were destroyed regardless of their morphological characteristics. In addition, Hurricane Dennis destroyed many of the incipient dunes that survived Ivan (Fig. 11). The weakly rooted incipient-dune vegetation offers little additional resistance to the impacts of extreme storms like Ivan. In addition, incipient dunes tend to be distributed seaward of the established dunes, and serve as the barrier islands' first line of defense during storm impact.

### 6.4. Distance from the ocean

The distance of the dune from the Gulf shoreline is obviously an important factor controlling its survival. Since a substantial amount of energy is dissipated as the storm waves propagate landward over the submerged barrier island, the greater the distance from the ocean, the weaker the wave energy should be. Therefore, an inverse

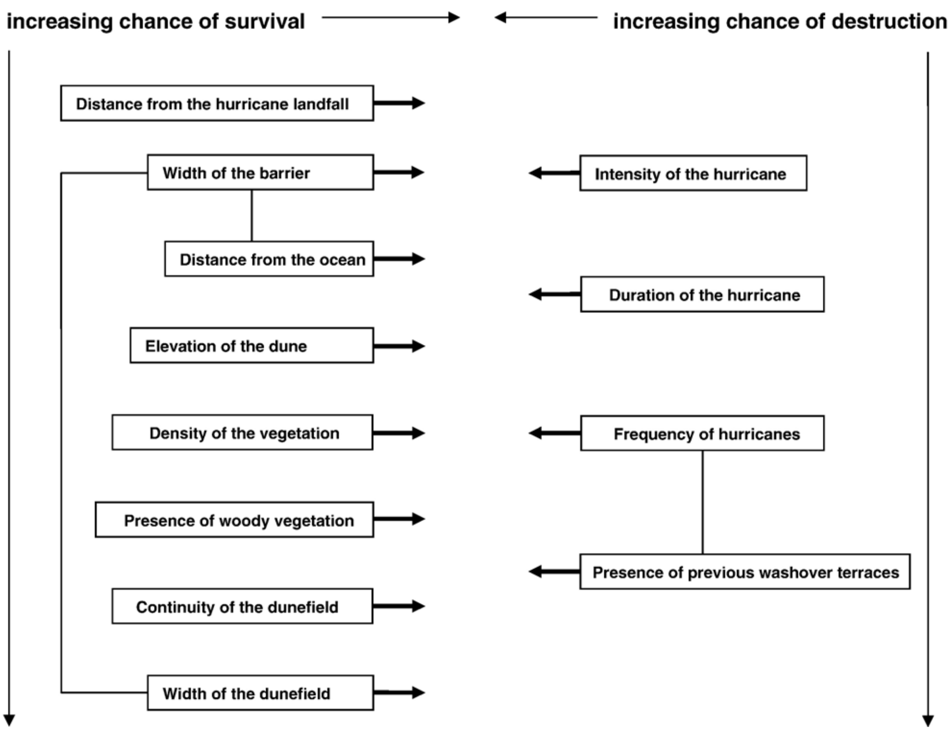


Fig. 19. A conceptual model for the destruction and survival of low-lying barrier-island dunes. The short arrows next to each factor indicate the direction of an increasing trend. Lines indicate the factors that tend to be closely linked. The relative importance of the factors, as determined based on the Santa Rosa Island study, decreases from the top to bottom.

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relationship exists between the magnitude of impact and distance between the dune and the Gulf shoreline. Greater island width tends to yield increased distances between dune and shoreface. On Santa Rosa Island, dune survival increased directly with island width. This was especially evident along the Bay-side headland.

### *6.5. Interval between subsequent storms and presence of previous overwash morphology*

The morphology of numerous previous overwash lobes can be identified from the pre-Ivan aerial photos. Since the last significant storm impact of comparable scale was from Opal nine years ago (the impact of Hurricane Georges in 1998 was not as severe), the previous washover platform was largely covered by relatively well-developed incipient dunes (Fig. 17). The overwash induced by Ivan and the associated dune destruction are clearly influenced by antecedent morphology. The extreme impact from Ivan has expanded numerous previous overwash fans, as apparent from nearly all the pre- and post-Ivan aerial photos. Dennis' impact was strongly influenced by the overall post-Ivan morphology. Dunes, particularly the established dunes that survived Ivan tended to survive Dennis, except very near Dennis' landfall position at the GIP site (Fig. 10). However, many of the dunes that were isolated by Ivan were subsequently destroyed by Dennis.

The relative importance and interaction of each of the above controlling factors, to the destruction and survival of the Santa Rosa Island dunefields are summarized in a conceptual model illustrated in Fig. 19. 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, continuity of the dune field, and width of the dune field. These factors are listed on the left side of Fig. 19. Conversely, the chances of dune survival decrease with increasing site-specific storm intensity and duration, storm frequency, and the presence of previous washover terraces. These factors are listed on the right side of the model.

## 7. Conclusions

Hurricanes play crucial roles in the regional morphological evolution of low-lying barrier islands. The degree of storm-induced morphological change depends not only on the intensity of the storm but also on the antecedent morphological characteristics of the barrier island. Energetic storms can dramatically change barrier-island morphology, in this case, replacing widespread dune fields with overwash features. Storm-induced dune destruction on barrier islands occurs through three processes: inundation, overwash, and collision.

The survival or destruction of dune fields on low-lying barrier island is 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 the 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 the presence of previous washover terraces.

The incipient dunefields are more vulnerable to storm impact. On Santa Rosa Island, they tend to be distributed close to the ocean (Gulf of Mexico) and over previous washover deposits. Washover platforms and lobes have a significant control over the cycle of growth of incipient dunes. Established dunefields, especially those distributed close to the Bay-side shoreline, are capable of surviving very strong hurricanes.

## Acknowledgements

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

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Please cite this article as: Claudino-Sales, V. et al. Factors controlling the survival of coastal dunes during multiple hurricane impacts in 2004 and 2005: Santa Rosa barrier island, Florida. Geomorphology (2007), doi:10.1016/j.geomorph.2007.06.004