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Front Cover: *Porites* colony encrusted by red algae in waters of San Salvador, Bahamas; see paper by Fowler and Griffing., p. 41. Photograph by Pascal Kindler, 2011.

Back Cover:. Dr. Jörn Geister, Naturhistorisches Museum Bern, Keynote Speaker for the 15th Symposium and author of "Keynote Address – Time-Traveling in a Caribbean Coral Reef (San Andres Island, Western Caribbean, Colombia)", this volume , p. vii. Photograph by Joan Mylroie.

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RECOVERY OF CARBONATE SAND BEACHES ON SAN SALVADOR ISLAND, BAHAMAS FROM DAMAGE BY HURRICANE FRANCES (2004)

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ABSTRACT

East Beach and Hanna Bay Beach, located on the northeast coast of San Salvador, were two of the island's beaches most heavily impacted by Hurricane Frances (category 3) on September 2, 2004. A maximum storm surge of 3.1 m was reported for East Beach, with erosion occurring up to 70 m inland from the wave-break line and resulting in scarps cut into dunes of up to 1.5 m height. In January 2005, 5 beach profile stations along 1 km of East Beach and 3 stations along Hanna Bay Beach were established to monitor long-term coastal recovery from hurricane damage. East Beach was profiled 6 times and Hanna Bay Beach profiled 5 times using the stake and horizon-sighting method, beginning in January 2005 through January 2010. Dune vegetation also was greatly damaged by Hurricane Frances, and its recovery and stabilizing effects on dunes was noted.

Each profile station revealed a somewhat different history over the 5-year study period. East Beach 1 exhibited a steep dune scarp almost 1.5 m high in January 2005. Subsequent profiles through January 2010 documented slumping of the original scarp and formation of an embryonic primary dune between 2008 and 2010. Other stations recorded different morphologies and varying degrees of recovery from wave-erosion scarping. Overall, East Beach stations showed sediment accumulation between 2005 and the present, with stabilization of the primary dune accompanied by rapid recovery of coastal flora. This is consistent with earlier studies that determined East Beach to be progradational. Hanna Bay Beach profiles documented a similar pattern of primary dune recovery and showed smooth seaward slopes with minor degrees of sediment fluctuation. All stations manifested recovery of flora; *Uniola paniculata* (sea oats) is ubiquitous on the dunes, and the coastal colonizer shrubs *Borrichia arborescens* (silver sea oxeye), *Coccoloba uvifera* (seagrape), and *Scaevola plumieri* (inkberry) are dominant species.

Both beaches have a history of progradation over at least the past ~1,500 years, indicating an offshore sediment supply more than adequate to keep pace with slowly rising, late Holocene sea level. With accelerated sea-level rise predicted for the tectonically stable, subsiding islands of the Bahama Archipelago, future progradation for these beaches and possibly others on San Salvador may be in doubt. This may already be the case at narrow Hanna Bay Beach where progradation was negligible for the period of this study.

INTRODUCTION

Carbonate sand beaches are prominent coastal features of many tropical and subtropical islands around the world, and they also have significant economic importance for tourism in developed areas. Although carbonate sand grains on beaches respond to the effects of waves, currents, and wind in a similar manner to siliciclastic grains, the origin of the two is quite different. Most carbonate beach sand is of biologic origin, generated in the "carbonate factory" of the adjacent shallow-marine offshore zone by breakdown of skeletal materials secreted by calcareous algae, protists, and invertebrates. In contrast, siliciclastic sands result primarily from weathering and erosion of pre-existing inland rock exposures and subsequent transportation of grains by rivers and streams to coastlines.

Relative to their siliciclastic counterparts, carbonate beaches are significantly understudied, probably because of their occurrence in what commonly are remote areas and/or in countries of the tropics with limited scientific expertise and infrastructure. Although many published compilations of siliciclastic beach studies exist, there is only one recent volume with broad geographic coverage of studies of carbonate beaches (Magoon et al., 2002), and few carbonate beaches have been monitored for change over significant periods of time.

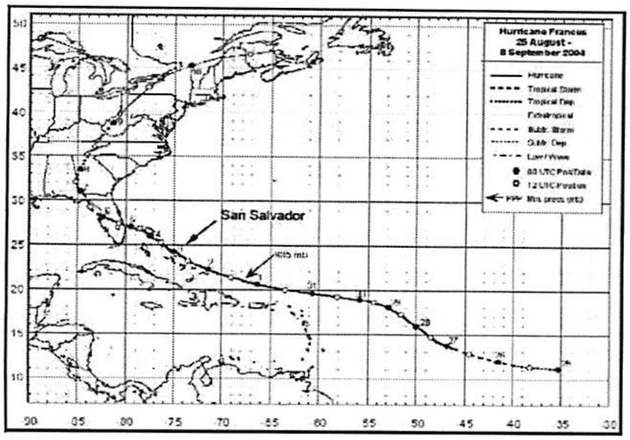
Owing to the presence of the Gerace Research Centre (GRC, formerly the Bahamian Field Station), the carbonate beaches of San Salvador are an exception, with several having been studied in some detail. Clark et al. (1989) characterized the texture and composition of beach sediment from 18 sites around the island's periphery. Brill et al. (1993) and Loizeaux et al. (1993) conducted monitoring studies over an 18-month period beginning in June 1990 at East Beach, on the northeast coast, and Sandy Point, at the island's southwestern corner, to characterize and contrast sediment dynamics of these two beaches. Beavers et al. (1995) extended the monitoring period through January 1993 and further documented the effects of seasonal sediment movement on both beaches. A particularly dynamic season of sediment transport and spit development at Sandy Point in the summer and fall of 2003 was documented by Voegeli et al. (2006).

Storms are a major factor in the dynamics of Bahamian beaches, and storm energy in the form of high winds, large waves, currents, and higher than normal tides can modify the morphology of affected beaches and dunes in a matter of a few hours. The effects of seasonal storms of "normal" magnitude on East Beach and Sandy Point were reviewed by Beavers et al. (1995). The primary regional storm hazard for the Bahama Archipelago is the hurricane, as the islands are located in the western North Atlantic, an area of high hurricane frequency. In recent years, several hurricanes, Lili (October, 1996), Floyd (September, 1999), and Frances (September, 2004), have passed directly over or very close to San Salvador. The coastal erosion imprint of these storms, and others, can be observed at many locations around San Salvador. The coastal field trip guide of Sealey and Mylroie (2006) is useful for describing such past storm events and their impact on the island's coast.

No post-storm surveys from Hurricane Lili were published, but infrastructure damage was significant, possibly greater than that from Hurricane Floyd (Gamble et al., 2000). On the island's southern coast, the primary dune line bordering French Bay was significantly eroded during Lili, and the erosional scarp remained prominent for at least 10 years following the storm (HAC, personal observation). The extensive impact from Floyd to both San Salvador's infrastructure and coastlines was reported in some detail by Gamble et al. (2000; survey mainly of infrastructure damage) and Curran et al. (2001; survey primarily of coastal modification effects), with storm damage greatest along the western coast of the island.

Frances passed directly over San Salvador as a category 3 hurricane on the afternoon of September 2, 2004 (Beven II, 2004; Fig. 1). As noted by Gamble et al. (2000), a hurricane's path with respect to an island or coastline and the quadrant of the storm making landfall affects the magnitude and extent of damage generated by the storm. Post-storm surveys for Frances by Parnell et al. (2004; survey of both infrastructure and coastal damage) and by Niemi et al. (2008; detailed analysis of storm effects on the island's southeastern coast) both indicated that the effects of Hurricane Frances were profound along the full extent of San Salvador's eastern coast, with lesser effects elsewhere on the island.

East Beach was highlighted by Parnell et al. (2004) as having suffered severe erosion and overwash from the storm surge effects of Hurricane Frances. The purpose of this study was to document post-hurricane shoreline recovery of East Beach, building upon the



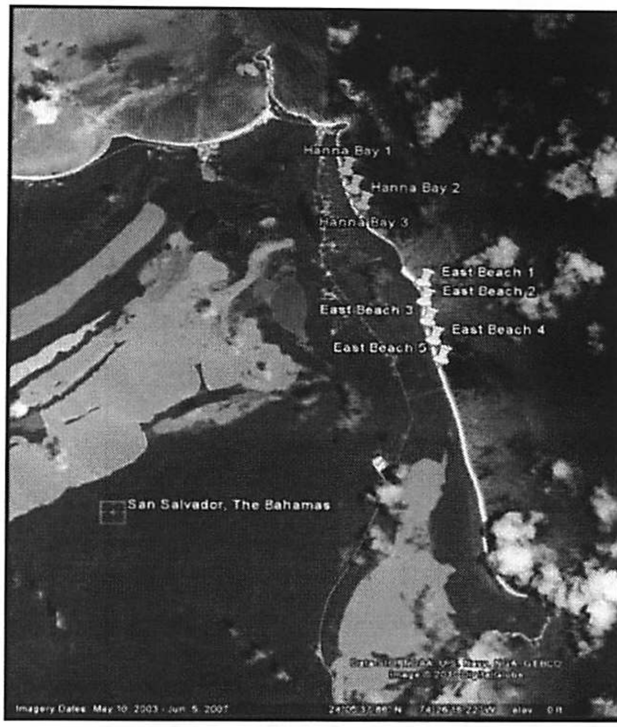


Figure 1. Top) Track of Hurricane Frances, 29 August to 8 September 2004, with location of San Salvador. The storm passed directly over the island during the afternoon of September 2 with category 3 winds (modified from Beven II, 2004). Right) Satellite aerial view of the northeastern corner of San Salvador showing locations of the 5 profile lines on East Beach and 3 profile lines on Hanna Bay Beach, courtesy of Google Earth.

informational database from the coastal profiling studies of Brill et al. (1993) and Beavers et al. (1995). Hanna Bay Beach was investigated by Al and Jane Curran in January 2005 and also was found to have been severely eroded. Given its close proximity to East Beach, Hanna Bay Beach was added to this hurricane recovery study.

SETTING OF EAST AND HANNA BAY BEACHES

East Beach and Hanna Bay Beach are located on the windward northeast coast of San Salvador Island (Fig. 1). Tied to an unnamed, Holocene rocky headland at its north end, East Beach is one of the longest reaches of open beach on San Salvador, running south for about 4.5 km to its anchor-point terminus at Crab Cay (Fig. 2A). Access to the East Beach study area from the Queen's Highway is via a somewhat overgrown trail (~500 m walk) that runs east from its juncture with the road that crosses Fresh Lake to the United Estates Cemetery. The origin point for the Station 2 transect of this study lies immediately to the south of the juncture of the trail with the beach. Hanna Bay Beach lies north of the unnamed rocky headland and runs north for 1.25 km to the Holocene Hanna Bay cliffs (Fig. 2B). The easiest access to Hanna Bay Beach is from a trail, also somewhat overgrown, located behind the fourth house north of the Shortstop Bar on the Queen's Highway. Ask at the house for permission to use the trail; the hike to the beach is about 300 m.

Both beaches are composed of well-sorted, fine- to medium-grained bioclastic sand (Clark et al., 1989). Brill et al. (1993) described East Beach in some detail and characterized it as a medium-energy shoreline with normal wave energy somewhat dampened by the kilometer-wide shelf and presence of numerous closely spaced coral patch reefs. Under fair-weather conditions, the prevailing trade winds generate

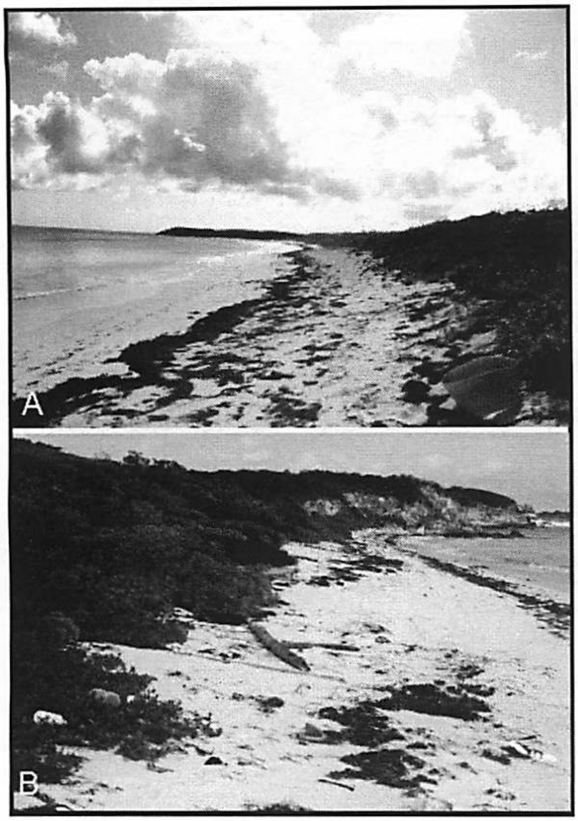


Figure 2. A) East Beach looking south toward Crab Cay from near Profile line 2. B) Hanna Bay Beach looking north toward the Hanna Bay cliffs from near Profile line 2.

waves that break almost parallel to shore, and sediment transport tends to be northward with the longshore current. The beach itself is broad, relative to most on San Salvador, and typically has a well-defined berm crest with a gently seaward-dipping foreshore and wide backshore. Hanna Bay Beach is narrower and steeper than East Beach and typically does not have the clear definition of foreshore, berm crest, and backshore found on East Beach. Beach cusps are commonly developed on both beaches, but beachrock is absent. A thick wrackline consisting of mixed fragments of the brown alga *Sargassum*, seagrasses, and anthropogenic debris transported from offshore is normally prominent on both beaches.

White and Curran (2006) conducted debris surveys on these beaches between January 1998 and June 2004 and characterized the incredible range of types of anthropogenic materials and objects present (hard plastic objects are dominant). These surveys showed that much of the marine debris ends up on and behind the primary dune line following strong storms, such as Hurricane Frances (Fig. 3). The dunes along both beaches are heavily vegetated by low-growing succulents, beach grass, and several species of shrubs (Fig. 4). The trail to East Beach crosses a zone of older, coast-parallel dune ridges and troughs of 400 to 500 m width, ending with the primary dune line and the beach itself. This pattern of coastal topography and the modern beach data collected and interpreted by Brill et al. (1993) and Beavers et al. (1995) led both research groups to conclude that East Beach is prograding today and most likely has been for at least the past 1,500 years. Such progradation is similar to that of the beach ridges at Sandy Hook on the southeastern corner of San Salvador (Andersen and Boardman, 1989).

METHODS

In January 2005, East Beach and Hanna Bay Beach were inspected visually by Al and Jane Curran for erosion and other damage resulting from Hurricane Frances. The Parnell et al. (2004) survey reported a maximum storm

Figure 3. Anthropogenic debris washed into the dunes of East Beach by storms. Photo taken in January 2010.

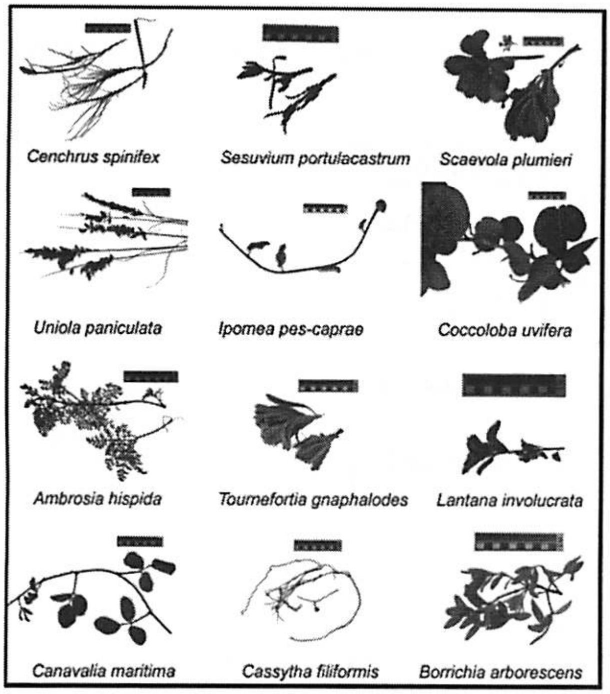


Figure 4. Common plant species living on the dunes and, in some cases, upper beach backshore of the study areas. Identifications from Bacon (1978), Kass (2005), and Smith (1993).

surge of 3.1 m at East Beach, with erosion occurring as much as 70 m inland from the wave-break line and resulting in scarps cut into the dunes of at least 1.3 m in height. It was not hard to "find the storm" in early 2005, as significant scarping was present everywhere along both East Beach (Fig. 5A) and Hanna Bay Beach, with much damage to coastal vegetation and major debris overwash.

Following the visual survey, 5 beach-profile stations, separated by intervals of 250 m, along a 1-km reach of East Beach and 3 evenly spaced stations spanning the length of Hanna Bay Beach were established to monitor long-term coastal recovery from the effects of Hurricane Frances. Meter-length PVC stakes were driven into the sand well behind the front of the eroded primary dune line at each location and geographic coordinates were recorded with a GPS unit (Table 1). The top 25 cm of each stake was left exposed so that the stakes could be relocated yet not be highly visible between survey team visits. All stakes have remained in their original positions since the time of installation, but owing to the rapid development of vegetation at both beaches, one of the main time requirements for profiling is relocating the stakes, even with the aid of a GPS unit and stake location coordinates.

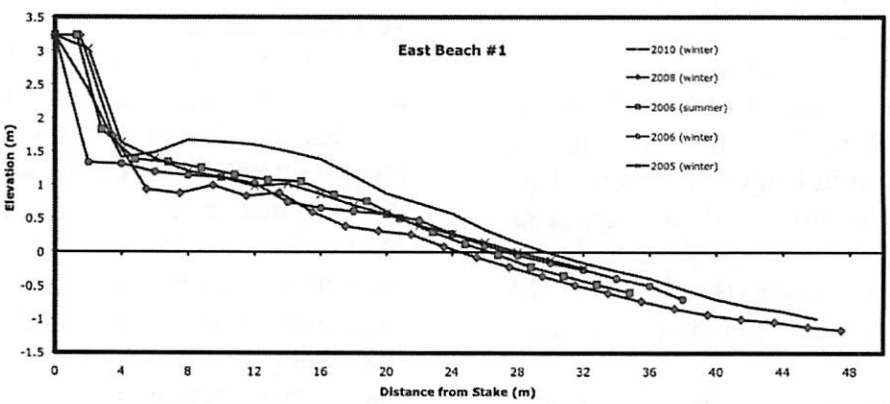
These stakes serve as the origin points for the survey profile lines. All profiles run normal to the beach into the sea, typically to a depth of 1-1.5 m. Using the stake and horizon-sighting method (Fox, 1983, p. 134-136), East Beach was profiled 6 times: January 2005, 2006, June 2006, January 2008, 2009, and 2010 (Figs. 5-9). Hanna Bay Beach was profiled 5 times: January 2005, 2006, 2008, 2009, and 2010. Hanna Bay Station 3 was only profiled 4 times, beginning in January 2006, owing to a need to reposition this station in 2006 for better spatial distribution of the 3 stations. The January 2009 profiles from all stations of both beaches were very similar to those of January 2010, so the 2009 profiles were omitted from the beach profiling summary figures to reduce "data clutter" and enable better interpretation of beach profile changes over the 6-year study period.

Dune vegetation also was greatly damaged by Hurricane Frances, so voucher samples were taken of the most common plants present on both beaches and were identified using the botanical references available in the GRC library (Fig. 4). Once the plants were identified, vegetation recovery was monitored in an informal way over time of the study to record floral colonization, development, changes, and stabilizing effects on the dunes (photos of Figs. 5-9).

This is not a perfect study in many respects, and it illustrates well the logistical difficulties of first-hand monitoring of environmental change in remote locations, even on islands such as San Salvador with a research-oriented field station. Although only basic equipment is needed, beach monitoring and interpretation of the data would be much better with greater frequency of surveys. With 8 stations, each field survey is time-consuming and ideally requires a team of three: a rod person, a data recorder, and the sighting reader. The personnel are simply not available on the island

Table 1. GPS coordinates of the origin-point profile stakes for the 5 profile lines of East Beach and the 3 profile lines of Hanna Bay Beach.

Station	Latitude	Longitude
East Beach 1	N 24°06.106'	W 74°26.514'
East Beach 2	N 24°05.973'	W 74°26.513'
East Beach 3	N 24°05.836'	W 74°26.495'
East Beach 4	N 24°05.705'	W 74°26.461'
East Beach 5	N 24°05.574'	W 74°26.415'
Hanna Bay 1	N 24°06.889'	W 74°27.002'
Hanna Bay 2	N 24°06.764'	W 74°26.958'
Hanna Bay 3	N 24°06.648'	W 74°26.900'



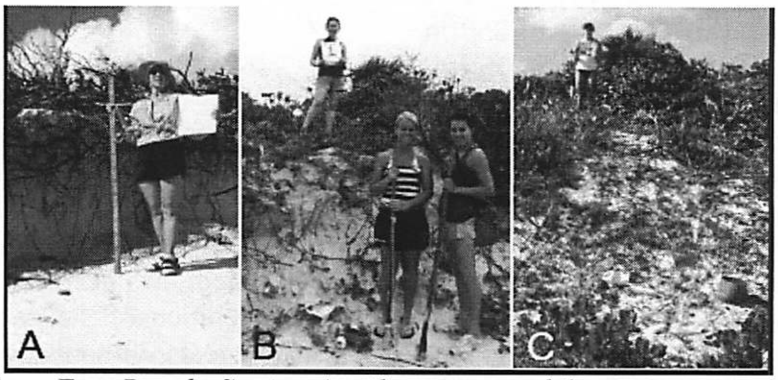


Figure 5. Top) Profiles from East Beach, Station 1. Photo views of the prominent scarp cut by Hurricane Frances; profile-origin stake is 1 m inland from scarp: A) January 2005; B) June 2006; C) January 2010.

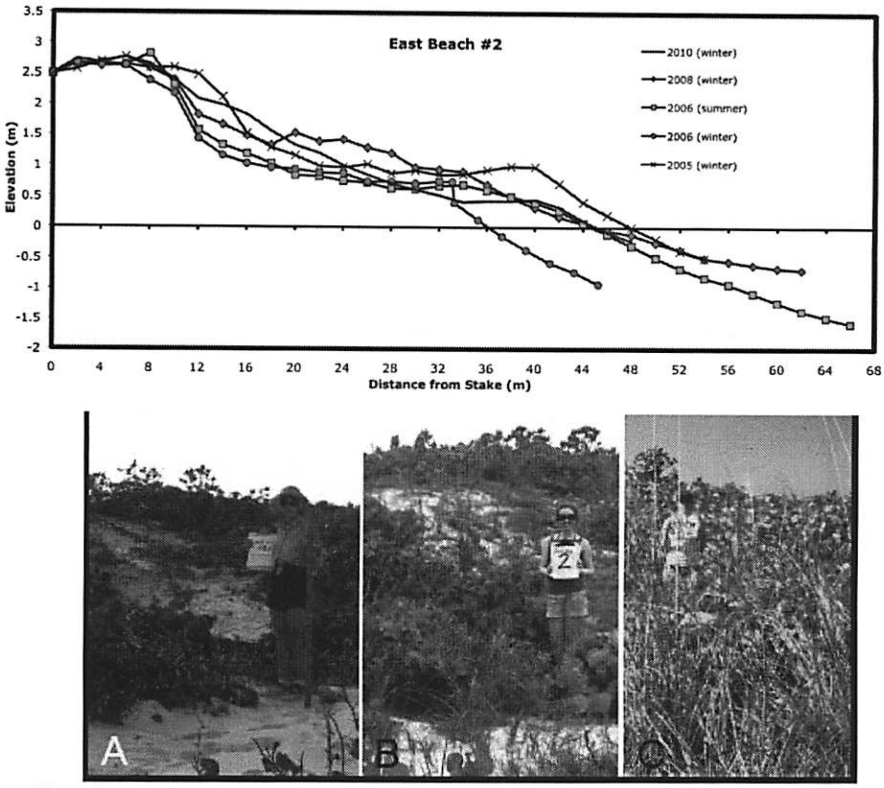


Figure 6. Top) Profiles from East Beach, Station 2, located immediately south of the access trail leading to the beach. Photo views looking inland and normal to the beach with profile team member standing adjacent or very close to the profile-origin stake: A) January 2005; B) June 2006; C) January 2010.

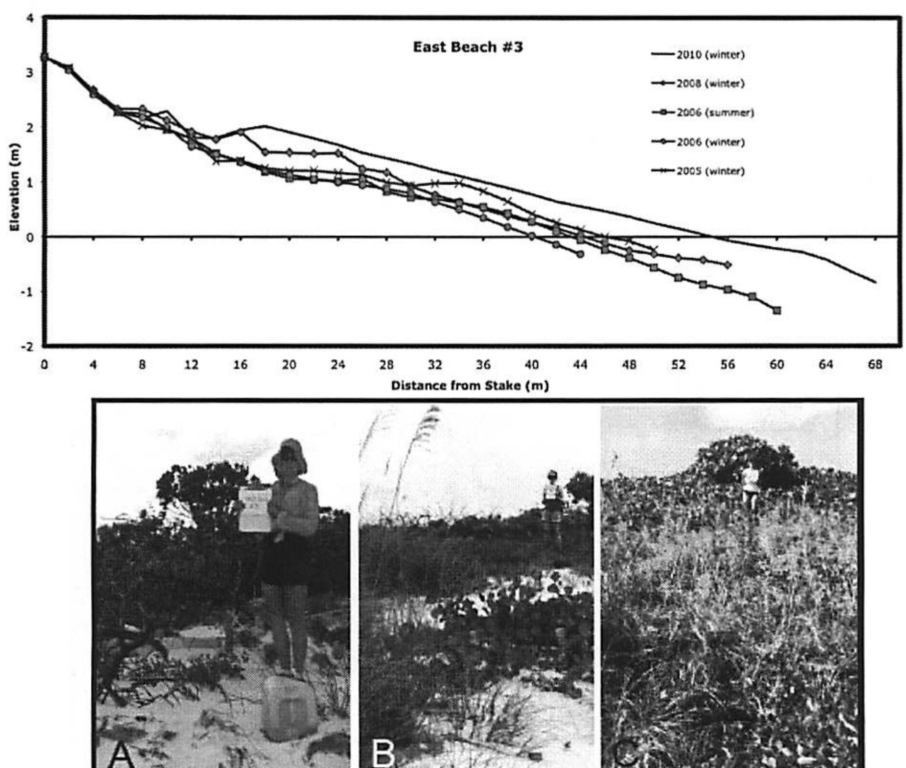


Figure 7. Top) Profiles from East Beach, Station 3. Photos oriented as previously: A) January 2005; B) June 2006; C) January 2010.

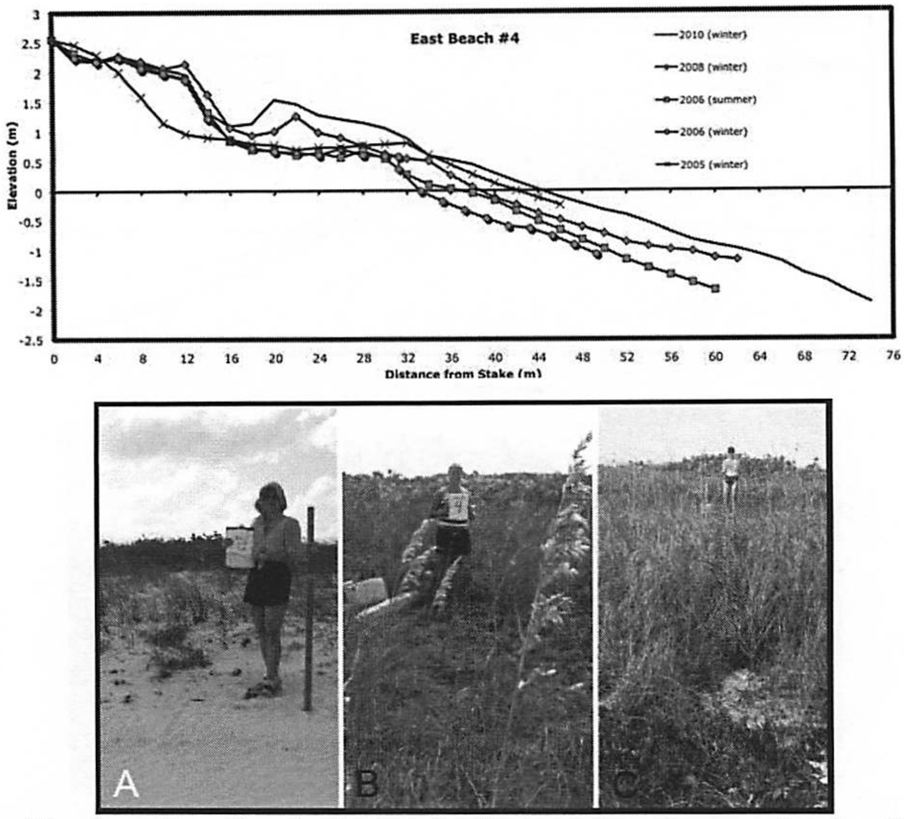


Figure 8. Top) Profiles from East Beach, Station 4. Photos oriented as previously: A) January 2005; B) June 2006; C) January 2010.

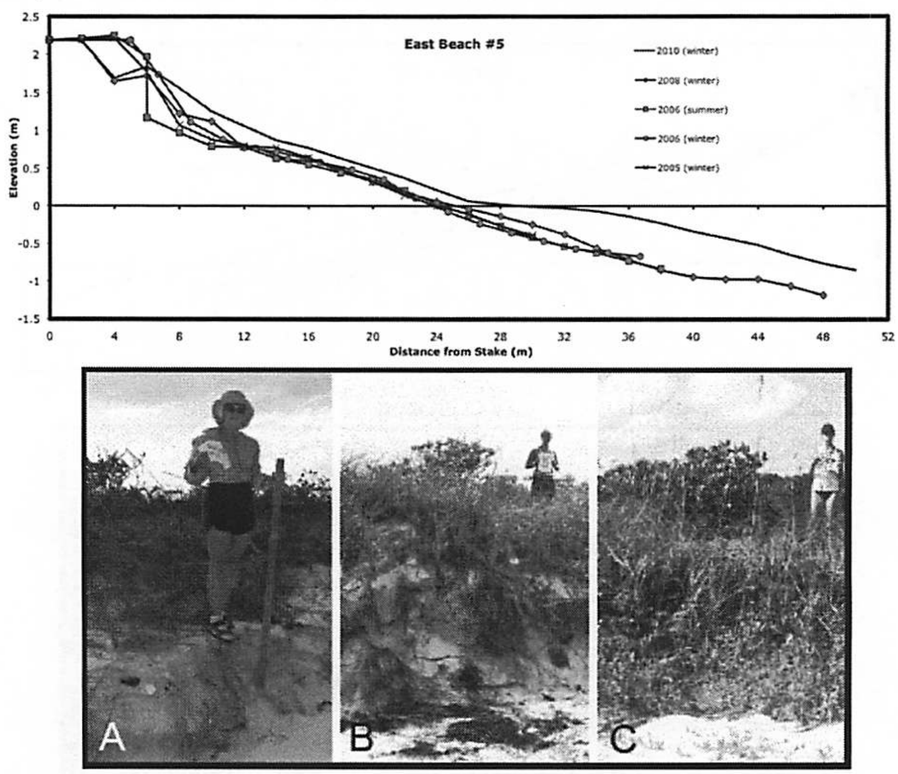


Figure 9. Top) Profiles from East Beach, Station 5, the southern-most study location. Photos oriented as previously: A) January 2005; B) June 2006; C) January 2010.

for monthly or even quarterly monitoring for a project of this type. After collection, the data must be processed and interpreted. For this study, the time and expertise were not available to make calculations of sediment volume change between survey intervals, but accurate long-term sediment volume deposition and erosion figures are available for East Beach in the monitoring studies of Brill et al. (1993) and Beavers et al. (1995).

RESULTS AND INTERPRETATION

East Beach

As one might expect from lines drawn perpendicular to the sea at different geographic points along a beach, the data from each profile station revealed somewhat variable histories over the 5-year study period of January 2005 to January 2010. Results from each station are summarized below and in Figures 5-9. No major storms were recorded by the profiles over the study period. This supports the hypothesis of Brill et al. (1993) that sediment deposition and erosion on East Beach is storm-event driven. The erosional scarps cut into the primary dune line by Hurricane Frances in September 2004 at many places along East Beach remain today, but they have softened progressively over the study period (see the photo sets of Figs. 5-9). Likewise, the photos at all stations reveal strong recovery and expansion of coastal vegetation cover. The stands of *Uniola paniculata* (sea oats) are particularly dense along the southern part of the East Beach study area, between stations 3 and 5.

Events of wave erosion and sediment deposition were within a fairly narrow range of magnitude over the study period and certainly could be considered normal for an open, windward beach coast. Overall, the 2006 winter profiles showed the least amount of sand on East Beach, and the 2010 winter profiles revealed the greatest amount of sand, indicating general progradation of East Beach over the study period. The summer 2006 profiles documented a modest amount of sand accumulation over those of winter 2006, adding support to the findings of the Brill et al. (1993) and Beavers et al. (1995) studies that East Beach displays a seasonal pattern of fall-winter erosion and spring-summer sediment accumulation.

East Beach 1 (Fig. 5): The prominent scarp cut by Hurricane Frances has remained the dominant feature at this location, even as it has softened with time (see Fig. 5 photo set). The 2010 profile documented development of an embryonic primary dune and significant sand deposition since 2008. The 2006 summer profile was almost identical to the winter profile of 2005. Opportunistic plants have advanced seaward, with the dominant species being *Uniola paniculata* and *Borrichia arborescens*.

East Beach 2 (Fig. 6): This station is located immediately south of the juncture of the access trail to the beach. The 2010 profile displayed little morphologic variation compared with 2008 when a distinct trough and dunelet were present. Surprisingly, the summer 2006 profile showed more erosion than any of the winter profiles, documenting erosion from storm activity in the first half of 2006. Vegetation density increased substantially between January 2008 and January 2010 in the small overwash area where the profile stake is located (Fig. 6 photo set).

East Beach 3 (Fig. 7): Similar to East Beach 2, the 2006 summer profile also indicated erosion in the first half of 2006. The 2010 profile showed continued development of an embryonic primary dune that first appeared in 2008. This station and East Beach 4 have had significant sand accumulation since winter 2005. Vegetation has advanced, with the upper part of the backshore now densely covered by *Uniola paniculata* (sea oats; Fig. 7 photo set).

East Beach 4 (Fig. 8): In addition to overall sand accumulation, the most prominent feature is the continued development of an embryonic primary dune, between 16 and 32 m, since summer 2006. Starting at 18 m, the 2010 profile documented significant buildup of this new primary dune. Vegetation, again dominated by *Uniola paniculata* (Fig. 8 photo set), has greatly thickened and advanced seaward.

East Beach 5 (Fig. 9): The 2010 profile highlighted the continuous and fairly uniform increase in sediment since winter 2005 with softening of the scarp cut by Hurricane Frances in the front of the primary dune line. The subsea part of the 2010 profile indicates recent sediment progradation. A wide variety of plants were observed in this area, with the dense ground cover consisting mainly of *Ipomea pes-caprae* and *Lantana involucrata* (see Fig. 9 photo set).

Hanna Bay Beach

This narrow and relatively short expanse of beach suffered severe erosion from Hurricane Frances. A prominent scarp was cut into the primary dune line on the full southern half of the beach. Along the northern half leading toward merger of the beach with the Hanna Bay cliffs, much sand was removed from the face of the primary dune, revealing the poorly lithified eolianite rock that lies below and behind the primary dune (Fig. 10). The extent and degree of solid lithification in the exposed beds at the back of the beach was somewhat of a surprise.

Profiles for the 3 stations at Hanna Bay are fewer in number and generally steeper, less variable, and shorter in length than those taken at East Beach. There is almost no backshore development at Hanna Bay. The vegetation cover has shown generally less recovery since Frances than on East Beach (Fig. 11, photo set), and the erosional scarp has softened during the study period. However, relative to East Beach, overall sand accumulation since Frances has been minimal and there is no true evidence of beach progradation.

Figure 10. The severely eroded face of the primary dune at Hanna Bay Beach with exposure of underlying poorly lithified eolianite rock. Photo taken in January 2005.

Hanna Bay 1 (Fig. 11): Hurricane Frances cut a distinct scarp in the beach at this station, as shown in the 2005 profile. Subsequently, the scarp has softened, as seen in the 2008 and 2010 profiles. The 2010 profile showed sediment increase and formation of an embryonic dune between 5-12 m and development of a berm crest at 20-22 m. This profile represented the most accumulation of sand anywhere on Hanna Bay Beach since 2005. The shrub *Scaevola plumieri* showed a spurt of new growth since 2008, but noticeable development was minimal for other plant species.

Hanna Bay 2 (Fig. 11): Profiles here have exhibited only minor change since winter 2005. The 2010 profile documented a steeper seaward slope after development of the sharp berm crest present at 6 m. The steep slope correlated with a loss of sediment since 2008. *Ambrosia hispida* has become a larger component of the ground cover as compared to other plant species in the profile origin area (Fig. 11 photo set).

Hanna Bay 3 (Fig. 11): Due to adjustment in station location, data collection did not begin here until winter 2006. The 2006 profile revealed erosional characteristics with a distinct scarp at about 6 m. Overall sediment accumulation occurred until 2008. Since then, the beach slope has remained relatively constant. *Uniola paniculata*, *Coccoloba uvifera*, and *Scaevola plumieri* are abundant at this site and showed little change from 2008 to 2010.

CONCLUSIONS

1. Hurricane Frances caused significant erosion of East Beach; large scarps cut into the dunes were obvious in January 2005 when the initial profiles were made. Since 2005, beach

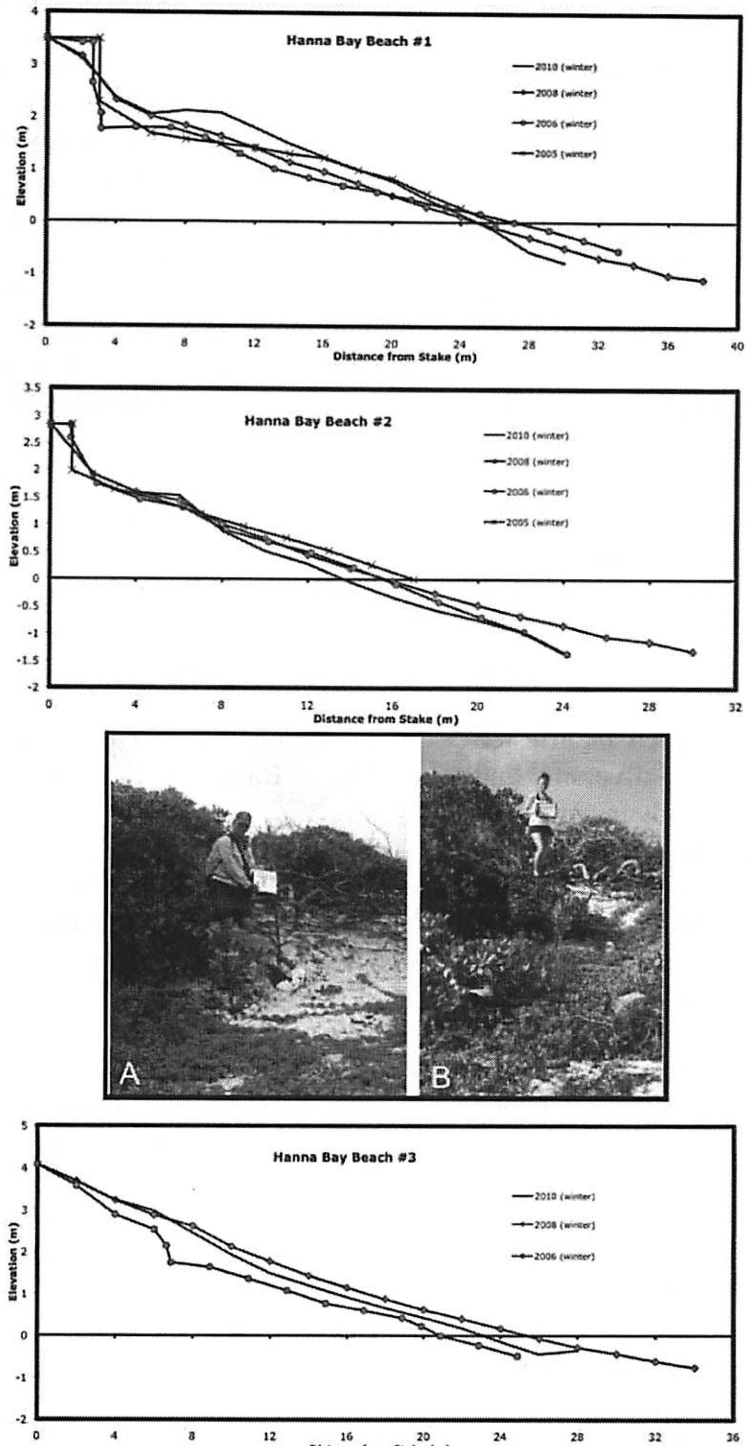


Figure 11. Profiles from Hanna Bay Beach, Stations 1, 2, and 3. Photos document growth of vegetation near the scarp of Station 2 between A) January 2008, and B) January 2010.

recovery has occurred and is manifested by continued progradation as reflected with the steady addition of sediment to the backshore and foreshore exhibited at all stations. All East Beach profiles of 2010 revealed a more stable primary dune compared to earlier profiles. The steep scarp present at East Beach 1 in 2005 has softened over the 5-year study period due to sand slumping and reworking by wind. Development of a more gradual slope appears to have facilitated the seaward formation of an embryonic primary dune.

2. Hanna Bay Beach profiles showed a similar softening of the primary dune scarp with time, as observed at East Beach. However, on this narrow beach, the profiles appear to indicate an overall slower rate of recovery from Hurricane Frances. Hanna Bay profiles 2 and 3 exhibited an overall decrease in the amount of sediment present, indicating that this section of beach may be receding.

3. All stations at East Beach manifested noticeable increase in vegetation diversity and density with recovery. Seaward advancement of vegetation onto the landward part of the backshore has provided further stabilization for the primary dune and small, seaward dunelets at several places and likely accounts for the relatively unchanged profiles between 2008 and 2010.

4. East Beach and Hanna Bay Beach have a history of progradation over at least the past ~1,500 years, indicating an offshore sediment supply sufficient to keep pace with slowly rising, late Holocene sea level. With accelerated sea-level rise predicted for the essentially tectonically stable and isostatically slowly subsiding islands of the Bahama Archipelago and probably already a reality, future progradation for beaches on San Salvador may be in doubt. This may already be the case at Hanna Bay, where the present beach is narrow and progradation appears to be negligible.

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