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Cover image - Patch reef near the wall off Grotto Beach (photo by Lee Florea).

Monitoring changes in the coastal environment on San Salvador Island using beach profiling, real-time kinematic GPS surveys, and kite imagery

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1. Abstract

Real-time kinematic (RTK) GPS survey data from 2014 and 2015, aerial kite imagery in 2015, and beach profiling at various times over the past decade were conducted at several coastal sites on San Salvador Island in The Bahamas. The areas we studied include the southwest point of the island (Sandy Point), a low dune which acts as beach barrier separating Salt Pond from the Atlantic Ocean on the east side of the island, and the rocky shoreline of the Gulf located on the south coast. The objective of these surveys is to document and investigate the topographic and geomorphological changes along the coast and identify the effects of storms. Previously, coastal changes have been monitored through beach profiling, which has only allowed a two-dimensional view along a select few transects. The RTK GPS surveying method with its centimeter accuracy provides a much more expansive and rapid areal coverage, ultimately allowing a topographic map to be prepared of the study area using ArcGIS contouring software. Kite imagery provides a three-dimensional overview of the area through orthophoto generation using photogrammetry software. These survey data can then be compared to previous studies to examine annual elevation and geomorphic variations. During the observation period which ended in June 2015, our data show that the morphological changes of the coastal environment at Sandy Point, Salt Pond, and the Gulf on San Salvador Island can be attributed to erosion and deposition of sands and rubble caused by hurricanes and other severe storms.

2. Introduction

The coastal environment of carbonate islands is different than those along a continental margin. On islands like The Bahamas, there is no sediment input from the weathering of igneous or metamorphic rocks, or sources of any terrigenous sediment. Sediment delivered to the coastal environment is predominantly dependent on carbonate sources produced in the nearshore environment, or weathering and erosion of carbonate bedrock. Soils are poorly developed on remote islands like The Bahamas and are augmented by long-term input of airborne dust accumulation (Muhs et al. 2007). Thus, the dynamics and morphology of the coastal or beach environment is likely due to the redistribution of available carbonate sediment.

Geologically, The Bahamas are part of an isolated continental platform that formed with the tectonic separation of North America from Africa (e.g. Sealey 2010). The Bahamian archipelago is a series of NW-SE-trending carbonate islands between about 23-20°N latitude in the Atlantic Ocean, located to the east of the Straits of Florida and to the north of the islands of Cuba and Hispaniola. Due to continued subsidence of the Bahamas platform, the exposed bedrock on most of the islands generally represents fossilized Pleistocene dune ridges (e.g. Carew and Mylroie 1995). The dynamics of the coastal environment of Bahamian islands is dependent on the configuration of lithified bedrock along the shoreline and whether the beach is sandy or rocky (Sealey 2010). In the tropical to subtropical environment of The Bahamas, the Atlantic Ocean hurricane season between May

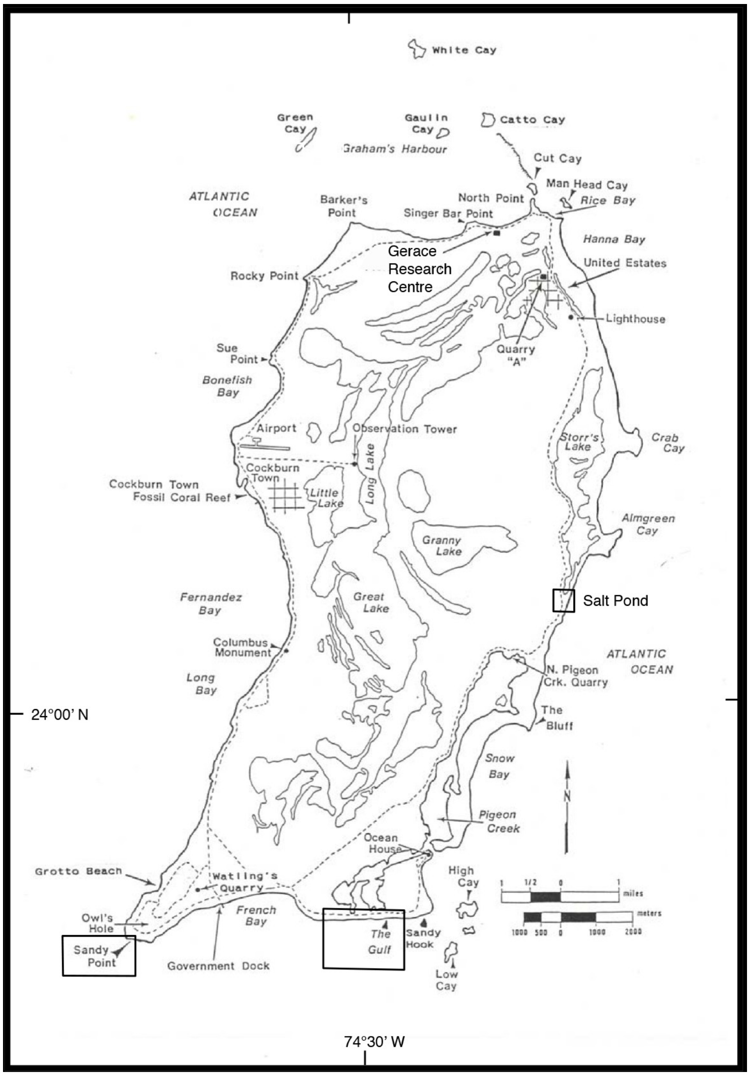

Figure 1. San Salvador, with locations of areas included in this study (within rectangles, from left to right: Sandy Point, the Gulf, and Salt Pond).

and November is the most dominant factor changing the coastal morphology.

The island of San Salvador is located along the eastern portion of the Bahama archipelago, bordered by deep water from the Atlantic Ocean to the east and a channel to the west. Previous studies documented storm damage and coastal change from prior storms including Hurricanes Floyd, Frances, and Irene (e.g. Curran et al. 2001; Niemi et al. 2008; Jackson et al. 2016).

The purpose of this study is to compile previous years' beach profile data from Sandy Point and Salt Pond beach, and to compare these data with newly acquired RTK GPS topographic survey data and kite aerial imagery, in order to determine how the beach environment changes over time. Furthermore, we report on our aerial imaging of Sandy Point and of the Gulf boulder field in 2015, and note observations made in March 2012 after Hurricane Irene. Prior to our survey on San Salvador, the only other aerial imagery collected on the island were several photographs captured from a tethered weather balloon (Lewis and Petruny 2004). Our study represents the first high-resolution orthophoto aerial imagery collected for a coastal section on San Salvador, and serves as a baseline for future studies of the effects of hurricanes.

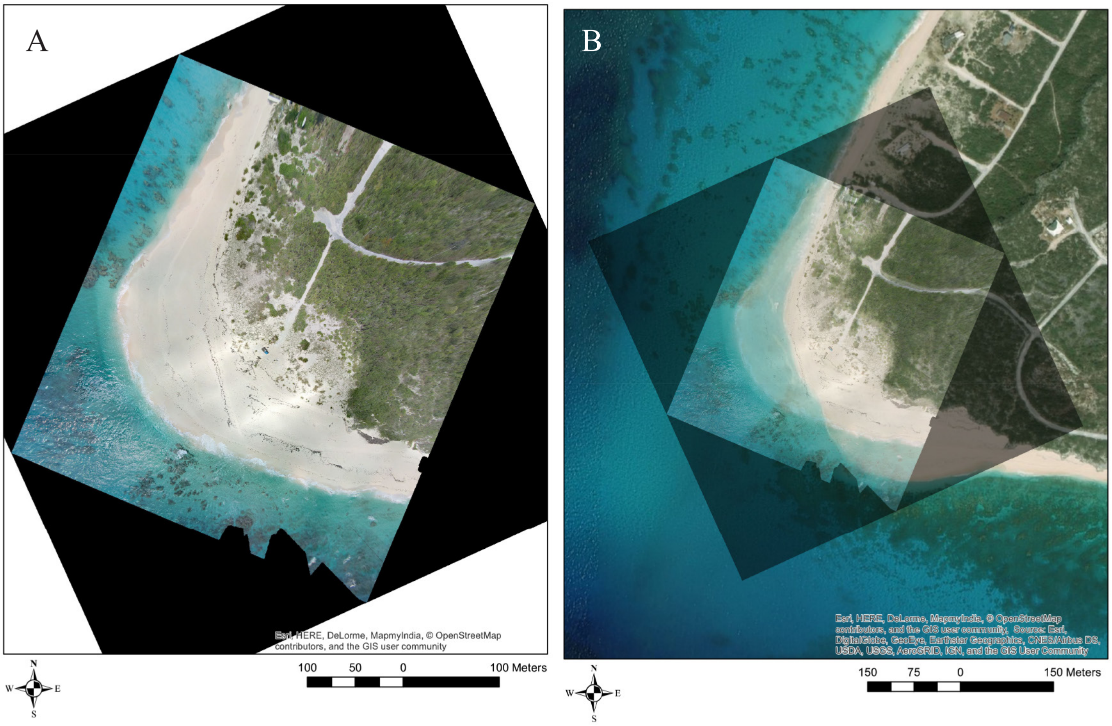

Figure 2. A) Orthophoto mosaic image of Sandy Point from 2015. B) Shows the image overlain onto a Google Earth image from 2014. Note how the sand has shifted from the east-facing position to the west-facing beach.

3. Methods

3.1. Emery Method

Beach topographic profiles at Sandy Point and Salt Pond beach were surveyed using the Emery method as part of the UMKC field methods course during March 2007, 2009, and 2011-2015. The Emery pole technique (Emery 1961) provides accurate and repeatable surveys using simple and robust equipment. The equipment consists of two poles joined together by a 2 m string. The poles are 2 m long, graduated in 2 cm increments. The poles are placed vertically on the ground at a 2 m spacing (i.e. the length of the string), or at each noticeable change in slope. The string is placed along a horizontal line using a line level. The horizontal distance and vertical elevation change are recorded along the transect, and then plotted as a topographical profile.

3.2. Real-time kinematic GPS

In March 2014 and March 2015, Trimble R8/5800 Real-Time Kinematic (RTK) GPS surveying equipment was used to conduct topographic surveys of Sandy Point and the dune between Salt Pond and the Atlantic Ocean. The RTK GPS is designed to enhance the precision of position data derived from satellite-based positioning systems. Rather than using the information content of the satellite GPS signal, it measures the phase of the carrier wave of the signal, relying on a single reference station to make real-time corrections. The advantage of this technique is that it provides centimeter-level accuracy. At each location, the Trimble R8 Base GPS Receiver was attached atop a 0.25 m mast to a Seco Tribrach mounted and leveled on a tripod. The Trimble HPB450 radio and antenna, used to communicate between the base and rover GPS receivers, was set up on a tripod 2-3 m north of the base GPS receiver, so as to not block any satellites, in an area with no overhead obstruction for greatest satellite acquisition and optimal reception. In 2014, a Trimble rover backpack was used to mount the Trimble R8 Rover GPS Receiver and worn

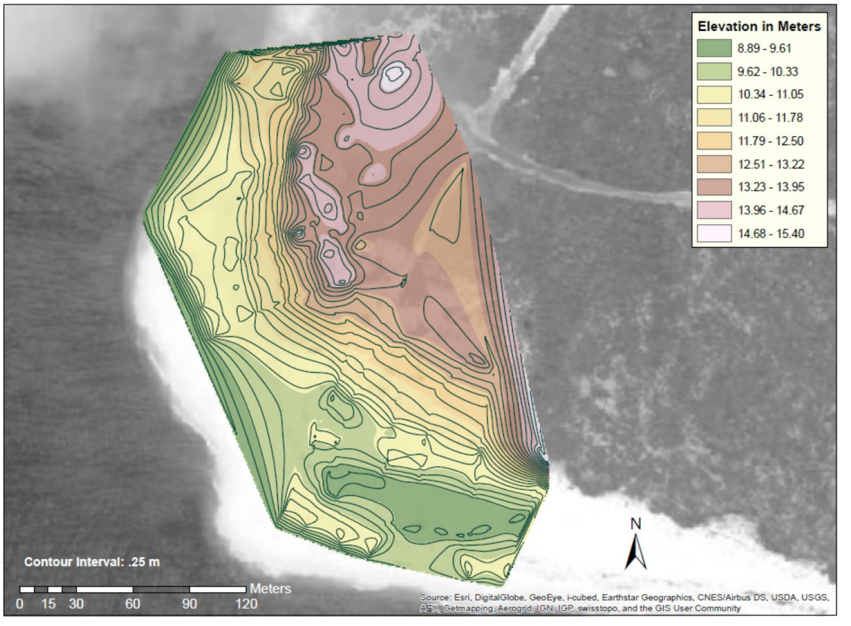

Figure 3. Topographic contour map of Sandy Point collected in March 2014. These data show that the west-facing beach is steep and has a mostly continuous slope. The south-facing portion of the point has a more complex morphology with linear ridges and lows.

while walking across each study area. In 2015, the rover receiver was mounted on an adjustable 2 m Seco Range Pole, which was held vertically and walked continuously, skimming the beach surface with the range pole tip.

The survey controller was configured to use the WGS 84 coordinate system, Zone 18N. Surveys were conducted with the survey controller set to Continuous Topo mode, recording data points at one-second intervals. Our RTK GPS survey of Sandy Point covered an area of 295 m (N-S) and 195 m (E-W) for a total coverage area of approximately 57,525 m^2 (Figure 3). Our RTK GPS survey of Salt Pond covered an area of 235 m (N-S) and 57 m (E-W) for a total coverage area of approximately 13,400 m^2 (Figure 5). In 2014, a total of 9,962 data points and in 2015, 2,329 data points were collected and exported from the TSC2 survey controller into a comma-separated values (.csv) file. The easting, northing, and elevation (x, y, and z) values were loaded from the file into ESRI's ArcGIS 10.2 as a point shapefile, and topographic maps of both Sandy Point and Salt Pond locations were created using raster interpolation and contouring.

3.3. Kite-mounted camera imagery

We utilized a kite-mounted camera to collect aerial photographs of Sandy Point and the Gulf sites. Images were taken using a Canon PowerShot S95 camera mounted on a Brooxes KAP Deluxe gondola, carried on an Into-the-Wind Parafoil 10 kite. The gondola uses a servo to trigger the camera mechanically, controlled by an operator using a four channel Futaba 4YF RC transmitter and receiver, operating in the 2.4 GHz range. The camera can tilt and pan, though there is no stabilization, as it is used for still images. It utilizes a three axis gimbal, and the camera was set to a 3648 x 2736 resolution, ISO 80, shutter speed 1/1000, and a focal ratio of f/6.3.

In March 2015, an aerial survey was made on Sandy Point Beach in conjunction with the RTK GPS topographic survey. Ground control points used in the kite photograph processing were surveyed with the RTK GPS system. Approximately 10 photographs were taken every 60-90 seconds for a total of over 750 images taken during the survey. Of the images captured, 742 were aligned and processed

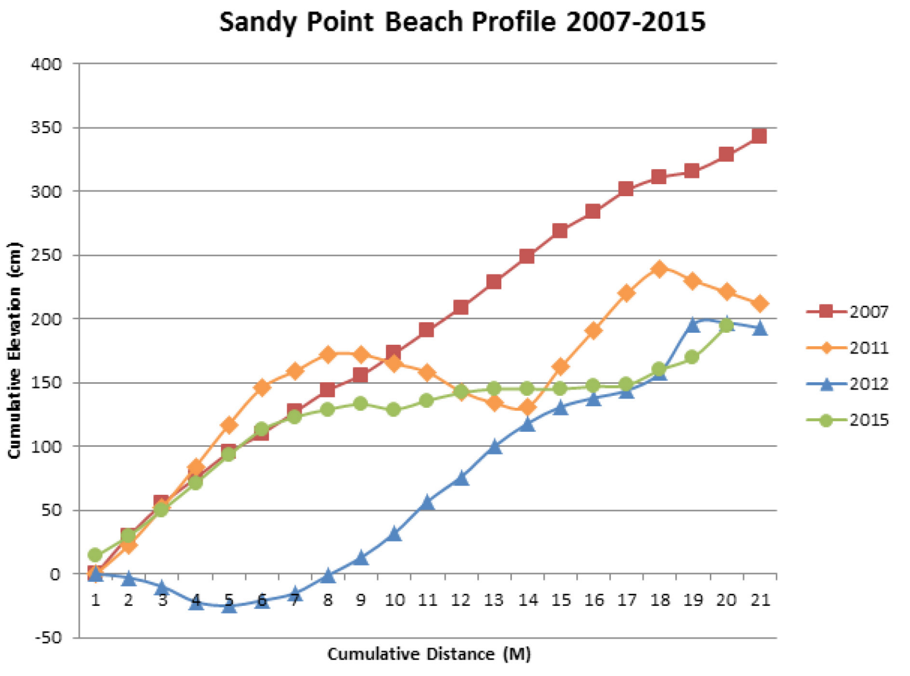

Figure 4. Beach profile data from Sandy Point in March 2007, 2011, 2012, and 2015 showing the seasonal change in the morphology of the sand ridges on the beach. Data points were collected using the Emery method.

using Agisoft Photoscan to create 36,069 tie points that were used to create a dense point cloud of over 622,000 points. These were further processed to create a 3D model of approximately 30,000 individual faces to help reconstruct a 3D digital model of Sandy Point. In June 2015, an additional 582 images were captured on the east-facing beach of Sandy Point, resulting in an additional 574 aligned images, 352,534 tie points, a 3D model over the 78,000 faces, and an orthomosaic with 2735 x 4096 resolution at 2.88cm/pix (Figure 2).

Also in June 2015, 1100 kite images were acquired along a boulder field and cove at the Gulf location on San Salvador (Figure 1) for a ground coverage of approximately 5000 m^2. This extensive dataset resulted in a 3D model of over 1.6 million tie points and over 320,000 faces, which culminated in an orthomosaic with a 4096 x 2747 resolution at 3.91 cm/pix. While greatly improved overlap between images resulted in the alignment of all 1100 images, this massive data set took approximately 36 hours to process.

4. Results and Discussion

4.1 Sandy Point

The beach at Sandy Point, located at the southwesternmost point on the island, is the widest beach on San Salvador. Analyses of the topographic data indicate an elevation difference of 6.51 m across the survey area. The highest elevation is located approximately 80-90 m from the western shore and 250-260 m from the southern shore.

Comparisons of beach profiles from 2007, 2011, 2012, and 2015 (Figure 4) conducted on the west-facing beach close to the tip of the point, starting from the shoreline and traveling inland, reveal notable changes in beach shape. While 2007, 2011, and 2015 exhibit similar foreshores, 2007 had the highest sand build-up at approximately 150 cm above 2011 levels, and 200 cm above 2015, with 2011 and 2015 profiles displaying very similar shapes. The 2012 profile shows a more eroded foreshore at nearly 200 cm lower than 2007 and 2011, and nearly 150 cm lower than 2015, not sloping

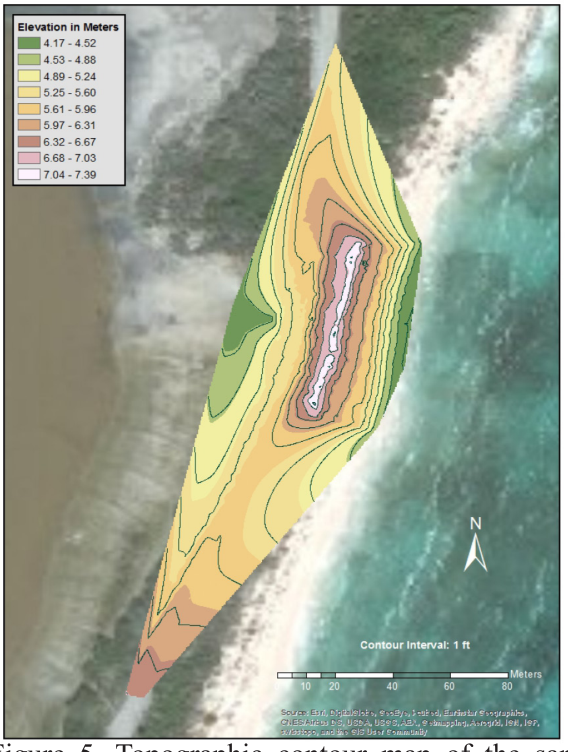

Figure 5. Topographic contour map of the sand dune which acts as a barrier between the Atlantic Ocean on the east and Salt Pond on the west.

upward until about 15 m from the shoreline. The change in the 2012 profile may be the result of erosion from the 2011 Hurricane Irene. The beach profiles show ridges and lows as also seen in the RTK contour maps that were created from March 2014 surveys (Figure 3). Aerial imagery captured in March 2015 appear to reveal more sand build-up on the west-facing beach just around the tip of the point, with a narrower beach on the south side (Figure 2). These observations were made during the seasonal transition from late winter to early spring; we also see no spit development.

Previous studies at Sandy Point show the sand transport dynamics around the southwest edge of the island are dominated by seasonal patterns of sand movement around the point by longshore currents (Loizeaux et al. 1993; Beavers et al. 1995). The prevailing easterly trade winds during fair weather conditions transport sand from east to west along the south-facing beach, around the point to the north. The late spring and summer experience long periods of fair weather, producing sand build-up on the west side of the point in the form of a spit. Reversing this pattern during the late fall and winter, northwesterly storms erode sand from the west-facing beach of the point, transporting it to the south and east along the south-facing beach of the point, exhibiting ridge and runnel morphology.

In both summer 2003 and 2004, Voegeli et al. (2006) reported extended periods of fair weather leading to unusually large spit development at Sandy Point, exposing a previously unreported extensive beachrock ridge along the south-facing beach. The unpredictable nature of tropical storms and hurricanes also play a role in upsetting the seasonal sand-transport pattern. Curran et al. (2001) indicated that Hurricane Floyd carved a large erosional scarp on the west-facing beach of Sandy Point. Reconnaissance of Sandy Point after Hurricane Frances in March 2005 and interpretation of satellite imagery revealed evidence of narrowing of the beach and a 2 m high erosional beach scarp caused by the storm surge (Niemi et al. 2008), although, the erosional effects were much less than from Hurricane Floyd (Voegeli et al. 2006) possibly due to buffering from the wide beach of summer 2004 and the larger than normal spit.

4.2. Salt Pond Beach

Salt Pond is located south of Storr's Lake on the east side of San Salvador. Salt Pond is separated from the Atlantic Ocean by a sand dune. The beach at the Salt Pond location is very narrow (<10 m). Analyses of the topographic data indicate an elevation difference of 3.2 m across the dune ridge that separates the Atlantic Ocean on the east from the small hypersaline Salt Pond to the west. The highest elevation of the dune ridge in the survey area is 20-25 m from the foreshore of the beach.

Beach profiling of the sand dune in 2005 as reported in McCabe and Niemi (2008) indicate that the dune height was as low as 2.15 m at the main location where erosion and washover

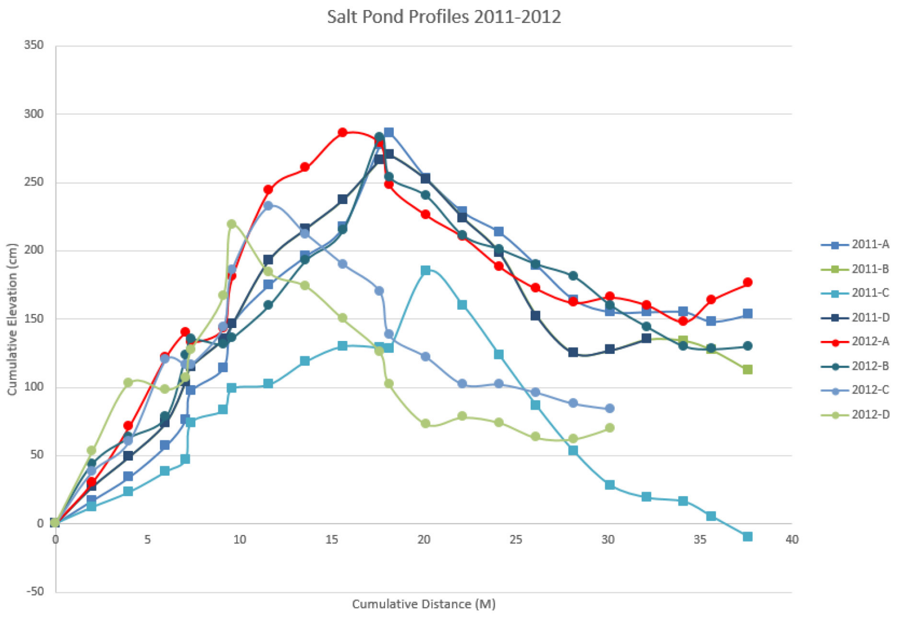

Figure 6: Topographic profiles of the sand dune at Salt Pond beach from March 2011 and March 2012. Data points were collected using the Emery method.

into Salt Pond during Hurricane Frances was extensive. Vegetation was stripped from the sand dune and deposited in Salt Pond as part of the overwash fan. The height of the sand dune at the south end of the dune barrier in 2004 was 2.77 m. Profiling of the sand dune in March 2011 and March 2012 indicate that the barrier remains low with an east-facing scarp that formed due to Hurricane Irene in 2011 (Figure 6). New flotsam and jetsam were deposited in the Hurricane Irene (2011) storm surge which was likely as high as 3 m. The sand dune is partially revegetated with sea oats, bay marigold, spur grass, railroad vine, and other plants.

4.3. The Gulf

The Gulf is located along the south shore of San Salvador Island where the deep water of the Atlantic Ocean is closest to the island. The wall of the fringe reef is only 25 m offshore. The rocky coastline at the Gulf is oriented approximately east-west. To the west are French Bay and Sandy Point, and to the east is the accretionary sand ridge area known as Sandy Hook, which forms the southeastern tip of the island.

The shoreline at the Gulf is marked by a cliff that is approximately 3 m in height (Figure 7B). At low tide, the rocks of the fossilized Pleistocene reef are exposed along the platform. Overlying the fossil reef are cross-bedded calcarenites interpreted as eolianites or lithified Pleistocene sand dunes that comprise most of the cliff face (Carew and Mylroie 1995). Both rock units belong to the Cockburn Town Member of the Grotto Beach Formation, showing the relationship between Pleistocene subtidal coral reef rocks and subaerial sand dune deposits from the Pleistocene (Mylroie and Carew 2010).

Waves during fair weather conditions have created a wave-cut platform at the base of the cliff. Wave action at the base of the cliff has caused undercutting, collapse, and coastal retreat. The erosional retreat of the cliff face is uneven, forming coves and jagged points along the shore. Boulders and large slabs of bedrock eroded from the cliff have accumulated on the wave-cut platform near the base of the cliff (Figure 7B). The bedrock slabs are longer and wider than they are in height because they have broken off along bedding planes of

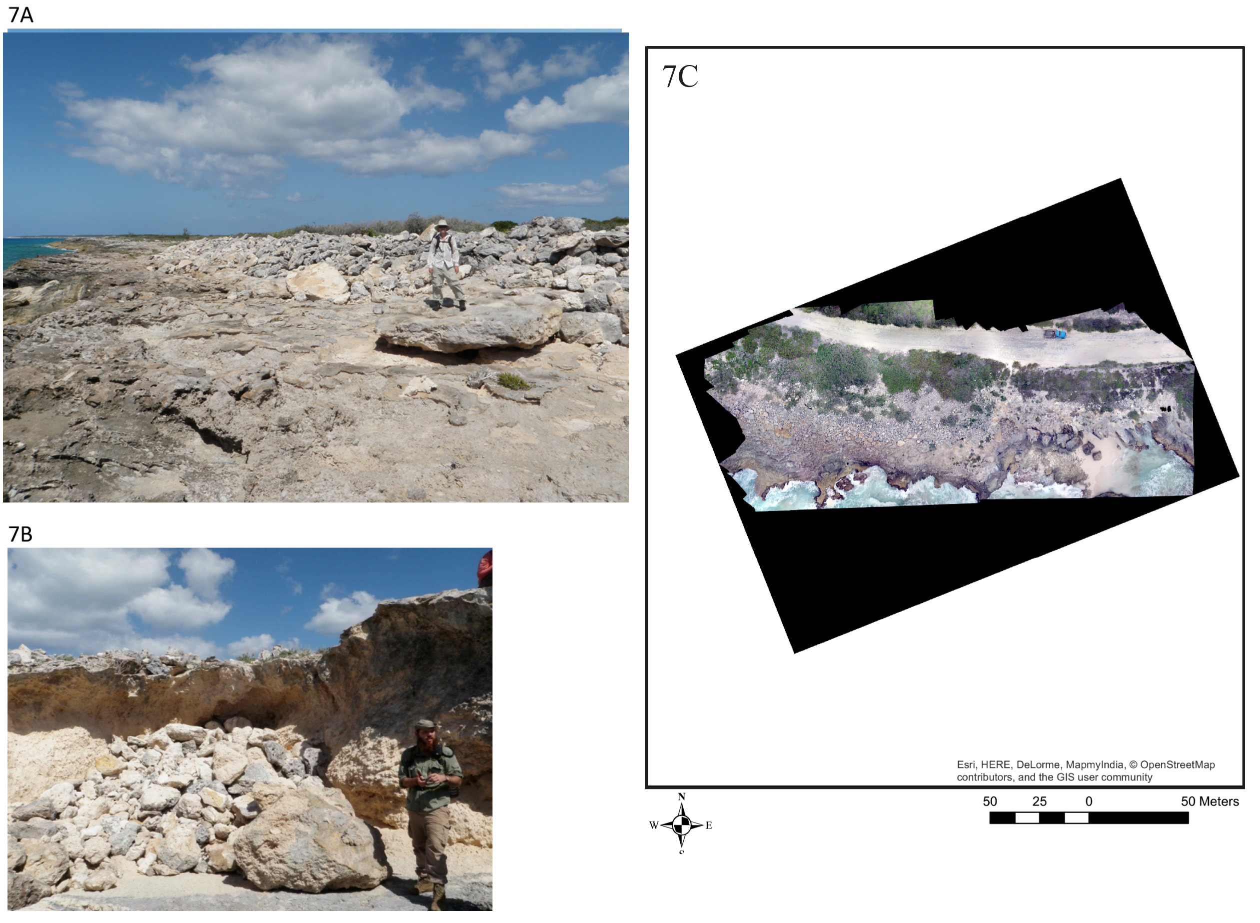

Figure 7. A) Boulder ridge in 2012 above cliff that forms the Gulf coast. White fresh calcarenite have recently moved by the storm surge. Photograph shows a large bedrock slab that slid landward as can be seen in the fresh scar adjacent to the boulder. View toward the west. B) The cliff at the Gulf. Boulders at the base of the cliff in cove are staged to move up to the top of the cliff to the boulder ridge seen in Figure 7A. C) Orthophoto mosaic of a portion of the rocky coast at the Gulf imaged in 2015. The cove seen in Figure 7B is marked with an arrow. South of the road and about 9 m north of the cliff edge is the boulder ridge as seen in Figure 7A.

the Pleistocene eolianite bedrock. Very large boulders and bedrock slabs are imbricated with slopes toward the south at the base of the cliff, as previously documented by Niemi et al. (2008). They also reported that some large boulders (> 1 m long) were deposited on the road, as much as 50 m inland in the storm surge of Hurricane Frances in 2004 (Niemi et al. 2008).

In June 2015, we focused our data acquisition on a small cove where geology groups visit an interesting bedrock exposure of the Cockburn Town Member of the Grotto Beach Formation, using kite-mounted camera photography (Figure 7C). Boulders in coves at the base of the cliff (Figure 7B) are in a staging ground to be elevated during intense storm events, as these are locations where wave action is likely focused, possibly increasing the potential for lift. Boulders have accumulated on a second flat platform or terrace level at the cliff top that is at an elevation of about 3 m above present sea level. Along this upper platform is a boulder ridge – the accumulation of millions of boulders (Figure 7A). The boulders appear to be graded by size. Larger boulders are closer to the edge of the cliff, and smaller ones are farther inland.

In March 2012, we observed boulders within the boulder ridge and along the upper terrace that had different weathering veneers. The fresh white carbonate surfaces suggest that these boulders were recently moved. Some spots on the upper bedrock terrace surface showed fresh exposures of a bright white surface adjacent to very large boulders indicating that the larger boulder slid landward in the last storm event (Figure 7A). We also noted numerous boulders that moved to a different position in the boulder ridge based on the fresh white surfaces of the boulders. Our team documented one very fresh boulder sitting on top of vegetation that was moved 18 m inland above a cove along a N60°W azimuth. This boulder measured 30 cm by 25 cm by 20 cm.

We attributed the observed boulder movement and the displacements of other boulders to the storm surge of Hurricane Irene. Data from the gulf and from elevation of flotsam and jetsam on the east side of San Salvador suggests that the storm surge height for Hurricane Irene was >3 m. As we do not have precise pre-2012 photographic data at this location, it is also possible that the boulder movement occurred in 2004 during Hurricane Frances, but our observations in the intervening time suggest this is not likely (pers. obs.). The bedrock of the eolianite ridge at the Gulf location was clearly excavated and removed in part to build the road. It is possible that some of the boulders in the boulder ridge may be from road construction. But overwhelmingly, the grading of the boulders, the imbrication, and weathering pattern indicate a storm surge emplacement mechanism for the boulder ridge.

4.4. Hurricane Impacts

The most recent hurricanes to impact San Salvador (not including the 2015-2016 seasons) were Hurricane Floyd in 1999, Hurricane Frances in 2004, and Hurricane Irene in 2011. Hurricane Floyd, a Category 4 storm with winds up to 249 km/h was a near hit with San Salvador Island on September 13-14, 1999. Curran et al. (2001) report that most of the coastal modification on San Salvador was on the west coast of the island, with extensive beach erosion, backbeach dune scarping, damage to vegetation, and over wash. The southwest portion of the island from Grotto Bay to Sandy Point exhibited severe erosion.

Hurricane Frances struck San Salvador, Bahamas as a Category 4 hurricane on September 2, 2004. The storm tracked from the southeast to the northwest, with the eye passing directly over the island, and wind speeds of up to 233 km/h. As such, the heaviest damage to buildings occurred in the United Estates on the northeast side of the island, though there was also damage to structures in Cockburn Town and near the airport on the west side of the island (Parnell et al. 2004). Niemi et al. (2008) measured a storm surge height of 4.8-5.5 m based on the upper limit of flotsam and jetsam at beaches along the southeast side of the island. They also reported boulder movement and imbrication, salt spray vegetation damage, overturned trees, and dune erosion. Using satellite imagery before and after the hurricane, Daehne and Niemi (2010) report that vegetation damaged in the hurricane rapidly recovered with the increase in rainfall.

Hurricane Irene was a Category 3 hurricane that hit The Bahamas in August 2011. The storm tracked from the southeast edge of the Bahamian Islands, turning north to parallel the Atlantic seaboard. With sustained winds of 185 km/h, the storm passed directly over Exuma Sound and the Exuma Cays. Jackson et al. (2016) performed a study only six days after the storm using aerial photographs, maps, and photographs taken by others in the area. While previous hurricanes indicated visible changes in Bahamian coastal morphology, only minimal change was observed on the Andros coastline where a layer of lime mud was deposited by the storm surge. The largest effect of Hurricane Irene was a 20 cm thick deposit to its upper beach at an area 1.2 m higher than the normal tide line on Exuma Cay. The data received on the immediate storm effects of Hurricane Irene are somewhat unique in this study because of the immediacy in which it they were obtained, less than a week after the hurricane occurred.

4.5. Conclusions

The location of San Salvador on the far eastern flank of The Bahamas archipelago leaves it exposed to Atlantic hurricanes and superstorms. Sea surface temperature, along with latitudinal and prevailing winds, contribute to the creation of hurricanes. Between 1899 and 2015, San Salvador Island experienced near or direct hits from 59 tropical storms and hurricanes with wind speeds ranging from 128 to 250 km/h (Hurricane City 2016). This means San Salvador has been brushed or hit by a tropical storm or hurricane, on average, once every 2.44 years over this period. However, storms are not evenly spaced over time; the longest gap between storms was 25 years (1956-1981), and the island sustains a direct hit, on average, every 5 years.

A summary of the coastal damage from these storms on San Salvador or in The Bahamas is described below. Our data show that Hurricane Irene in 2011 did have a subtle but measurable effect on the coastal environments of San Salvador that were measured in March of 2012. Sandy Point developed a steeper eroded foreshore and ridge and runnel topography. The sand dune adjacent to Salt Pond had a new scarp. Rope and other flotsam and jetsam were deposited above the scarp. The dune appears to have recovered some sand on the scarp that was covered by the 2014 RTK GPS survey. Boulders at the cliffs along the Gulf site clearly moved. The storm surge height for Hurricane Irene on San Salvador was at least 3 m.

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