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DETECTION OF BOULDER TRANSPORT VIA STORM SURGE USING DRONE IMAGERY ON GREEN CAY, SAN SALVADOR, THE BAHAMAS

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ABSTRACT

Green Cay is a 6-m-high island located along the northwest reef barrier of San Salvador island in The Bahamas that separates deep Atlantic Ocean from the shallow water of Graham's Harbour. Given its low elevation, Green Cay is often overtopped by waters of hurricanes with sufficient storm surge height. In order to understand the boulder transport processes and change in the coastal environment, we conducted field and underwater snorkel surveys of the southeast shore of Green Cay. We also collected high-resolution, drone aerial imagery in June of 2016 and March of 2017 that was processed into orthophoto mosaics. These data were collected before and after Hurricane Matthew that passed 170 km southwest of San Salvador as a Category 3 storm on October 5, 2016. The Hurricane Matthew storm surge was high enough to overtop Green Cay and move several small boulders which we document in this study.

INTRODUCTION

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. 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, 2006). 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 (Sealey, 2006) 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 controlled by the redistribution of available carbonate sediment.

Due to the location of The Bahamas, the islands experience a frequent number of storms during the Atlantic Ocean hurricane season between June and November. Storm surge is the most dominant factor in rapid change of the coastal morphology. As a storm surge moves on land, large amounts of debris carried from the ocean including human and natural flotsam and jetsam, sand, gravel, and sometimes boulders, are deposited inland. According to calculations by Nott (2003), boulders as large as 2.5 – 3 m^3 and weighing hundreds of tonnes depending on density and porosity are transported in hurricanes. The maximum height of a storm surge is controlled by a number of factors including sustained wind speed, storm forward speed and direction, gradient of the barometric pressure of the storm to atmospheric pressure, beach and coastline topography, and bathymetry (e.g. Weisberg and Zheng, 2006). Riparian vegetation can help reduce damage to coastline. Once damaged, the vegetation needs to recover or the coastline will be vulnerable to additional wave damage in subsequent storms (Bush et al., 1996). When inundated, inland vegetation struggles due predominantly to increased salinity and often dies out until such time that soil conditions can once again become favorable to the native species (Rodgers et al., 2009). Removal of inland vegeta-

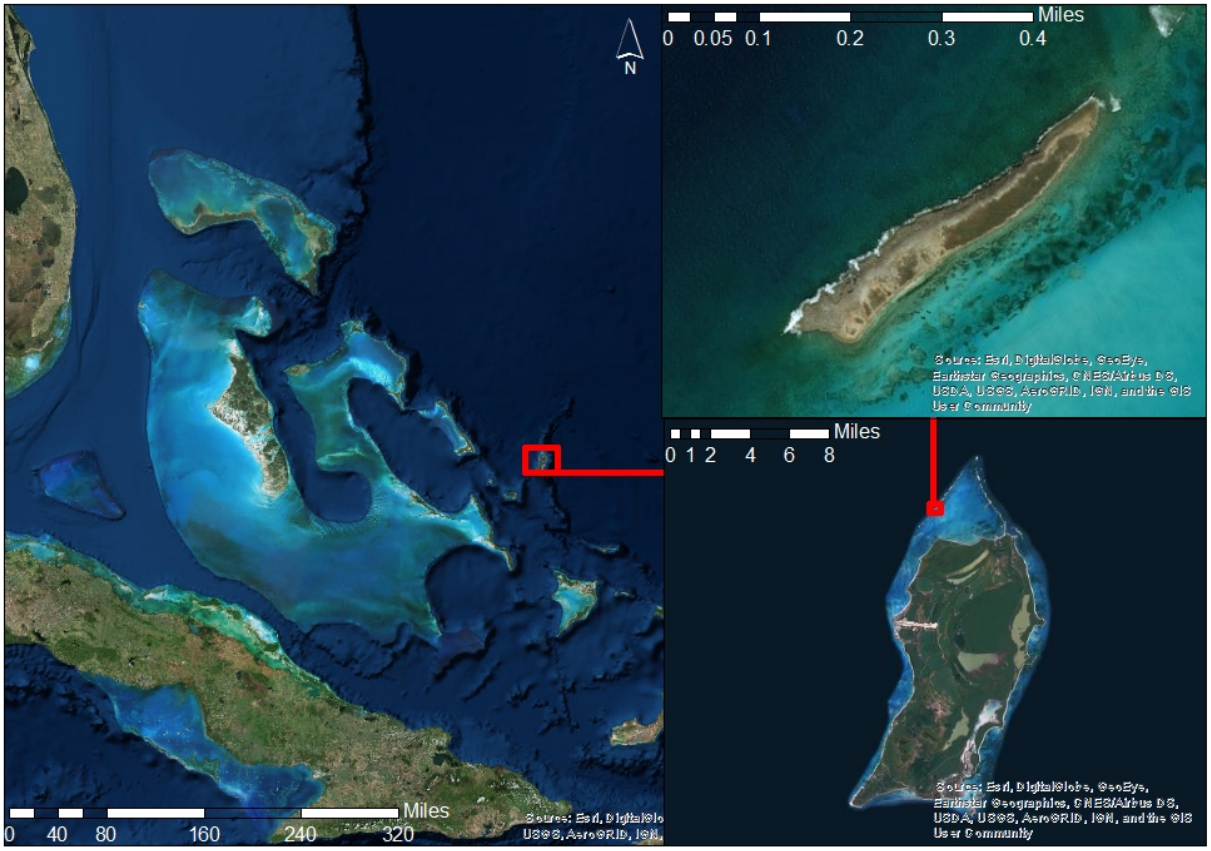

Figure 1: Satellite image of showing the location of San Salvador along the eastern edge of the of the Bahamian platform. Green Cay is a small island along the northwest side of San Salvador helping to enclose the shallow water lagoon of Graham's Harbour.

tion can lead to an increase in maximum inundation distance.

Hurricane Matthew developed as a tropical storm on September 28, 2016 in the Lesser Antilles and rapidly developed into a Category 5 hurricane—the first since 2007 in the Caribbean Sea (Stewart, 2017). The hurricane then moved north between Haiti and Cuba before curving to the northwest in The Bahamas. Hurricane Matthew traveled through The Bahamas as a Category 3 storm with the eyewall passing between Andros and New Providence on October 5, 2016 before moving to the coast of Florida and up the southeast coastal U.S. (Figures 1 and 2). San Salvador island was less impacted by this hurricane compared to direct landfalls of Hurricane Hurricane Floyd in 1999 (Curran et al., 2001; Walker et al., 2001), Frances in 2004 (Parnell et al., 2004; Niemi et al., 2008; Niemi, 2017), and Joaquin in 2015 (Preisberga et al., 2016). With the high frequency of hurricanes on such a small island (Shaklee, 1996), San Salvador Island is an excellent location for studying geomorphological processes caused by storms. In this study, we utilize aerial imagery and field observations from before (June, 2016) and after (March, 2017) Hurricane Matthew to determine the movement of boulders and the change in the morphology on Green Cay—a tiny island at the northwest reef barrier margin of San Salvador.

STUDY AREA

San Salvador Island is located along the northeast edge of the Bahamian archipelago and is an isolated island surrounded by deep Atlantic Ocean water. As a carbonate island, San Salvador

Figure 2: Storm track of Hurricane Matthew from September 28, to October 9, 2016 (NOAA, 2017). https://www.weather.gov/ilm/Matthew

grows through marine sediment being deposited on the margins (Carew and Mylorie, 1985; Hearty and Kindler, 1993). Featuring a relatively low-lying topography, San Salvador is also home to a number of inland lakes, which occur as blue holes, interdunal troughs, or cutoff lagoons, many of which are hypersaline (Teeter, 1995). The sedimentology of the island is comprised of calcarenites, which are grain-supported, fine-to-coarse grained ooids, peliods, and bioclasts sands or calcrudites and boundstones built from Pleistocene coral, and calcretes (Carew and Mylorie, 1985; 1995; Hearty and Kindler, 1993). The calcarenites that form topographic ridges are fossilized sand dunes, often called aeolinites.

Green Cay is a small island located 2.5 km northwest of Barker's Point on San Salvador island. Measuring only 600 m from end to end and 85 m at maximum width, Green Cay is located among a line of islands and shoals forming a separation from deep Atlantic waters from Graham's Harbour, a large, shallow lagoon. The island has a gentle slope toward the southeast and a northeast-trending ridge that marks the crest of the Pleistocene aeoliniate (Carew and Mylroie, 1985). The northwestern margin of Green Cay is steeper and marked by active cliff retreat erosion. Areas of extensive mass wasting are evident where arcuate-shaped, headwall scarps punctuate the ocean-facing island margin. The highly weathered, pitted, and jagged surface of the bedrock is a product of karst weathering.

The bedrock stratigraphy of Green Cay is exposed along the cliffs that face toward the northwest and can be divided into two units. The lower rock section is comprised of a cross-bedded, carbonate sandstone (calcarenite). The upper section is a heavily bioturbated calcarenite with plant trace fossils, including root casts and tree trunk molds (e.g. Mylroie and Carew, 2008). Capping the bioturbated unit is either a calcrete crust or remnants of a terra rossa paleosol. Geologically, the rocks are interpreted as fossilized Pleistocene sand dunes (aeolianites) that were heavily vegetated and rapidly lithified. The morphology of Green Cay preserves some of the original Pleistocene sand dune topography.

DATA COLLECTION

During three separate visits to San Salvador Island in June of 2016 and March and June of 2017, we made field observations of the boulders on the Green Cay island and in the shallow water southeast of the island. We photographed the boulders within the erosional cove and within the washover zone along the southwestern portion of the island. We also conducted a snorkel survey south of Green Cay and within the Graham's Harbour near the island to determine if there is a large subtidal boulder field adjacent to the island.

These field observations were compared to aerial photos obtained using a DJI Phantom 3 Quadcopter mounted with 12 Megapixel, 4K video camera with geo-referencing. Flight plans were laid out utilizing Pix4D Capture, version 3.0.1 in June 2016 and version 3.7.1 in March 2017. Pix4D Capture is a GPS-enabled Android application for quadcopters that allows the user to create projects with multiple missions allowing the same path to be flown multiple times. Flight height, coverage pattern, photograph overlap percentage, and camera angle can all be controlled, as well as offline maps allowing usage in remote areas and still providing a base map for accuracy. For this project, a programmed flight path obtained photos at 50 m of elevation with 70% overlap with 100% vertical camera angle, collecting 420 and 474 images, respectively, of the Green Cay study area. Extra photos were taken in March of 2017 due to extremely high winds stalling the quadcopter resulting in gaps in coverage, these areas had to be flown again.

Orthophoto mosaic photos and Digital Elevation Models (DEM) were created with Agisoft Photoscan Professional; software versions 1.2.4 build 2399 and 1.3.0 build 3772, respectively. To produce these images, photo alignment was performed at high accuracy with a key point limit of 40,000, and a 10,000 tie point limit utilizing the adaptive camera model fitting feature. A dense cloud was then constructed under the highest quality setting with aggressive depth filtering. Next, a height field-type mesh was produced from the dense cloud with high face count and interpolation enabled. Finally, the texture was assembled from the orthophoto, with mosaic blending, and texture size/count set to 8192 x 1 with both color correction and hole filling enabled.

Using ARCGIS, the two orthophoto mosaic images (Figure 3 and 4) were made into base maps. Visual comparisons were made between 2016 and 2017 of potential boulder movement. Orthophotos and DEMs created and exported from Agisoft should be in a projected coordinate system for measurement of area. Shapefiles were obtained from GADM and used for georeferencing. Boulders were measured in ArcMap using changes in elevation. Using a point vector feature class, 6-8 locations around the boulders and three on the top of each boulder were selected using DEM and Z-values were gathered using Extract Values to Points tool. The Z-values around the boulders were used to generate an average ground elevation and the three points on the boulders were averaged to determine a change in height with respect to the ground, generating the height of each boulder. Using the ArcMap measuring tool, the 2-dimensional area of the top face of each boulder was measured, allowing for the approximate volume of each boulder.

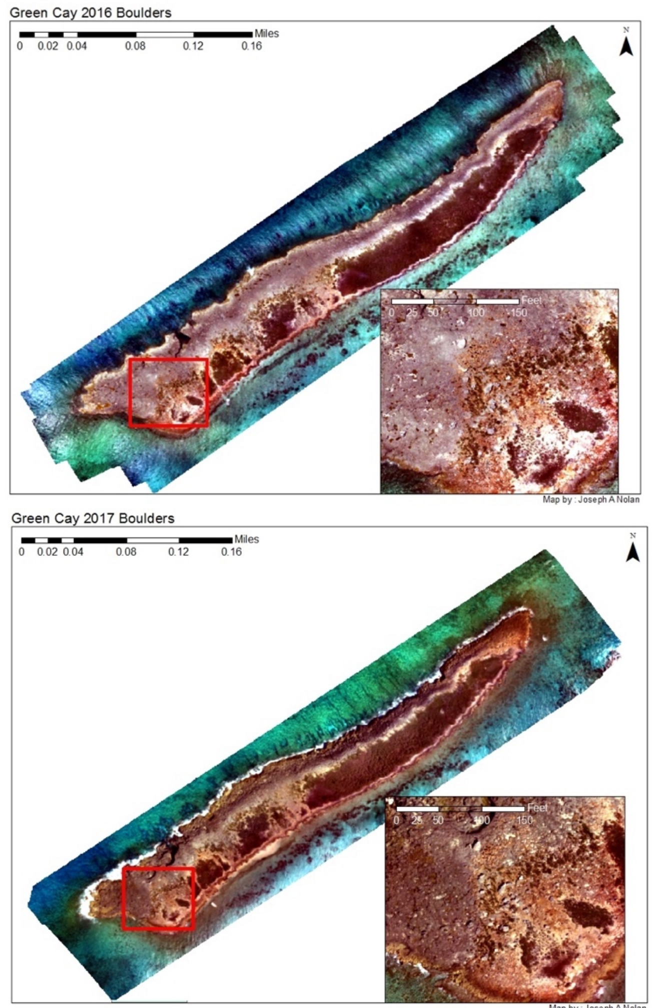

Figure 3: Orthophoto mosaics of Green Cay that were created by processing drone imagery acquired in June 2016 (upper image) and in March 2017 (bottom image). Details of the southwest area is shown in Figure 4.

RESULTS

Two orthophoto mosaic images were made into base maps (Figure 3 and 4) and a visual comparison was made between the 2016 and 2017 images to identify potential boulder movement. The southern end of Green Cay has a large overwash zone that is largely devoid of brush vegetation as storm surge has repeatedly overtopped the island at this

Figure 4: Detailed images of the scattered boulder field on the south side of Green Cay. Circles note the areas where boulder movement was documented.

location. In the overwash zone, there is a boulder field that is characterized by large isolated boulders and small clusters of boulders (Figure 5). Boulders in the field are widely spaced. We identified four boulders on Green Cay that moved between 2016 and 2017 (Figure 4). These boulders measure approximately <0.5 m in width and length. Very large boulders clearly were neither translated or rotated and can be directly matched in the two aerial images. It is likely that many smaller boulders and cobbles were transported, but this movement is beyond the resolution of this method. The biggest storm to have passed through The Bahamas in this time period was Hurricane Matthew.

Our field observations indicate that boulders are currently forming a boulder ridge along the crest of Green Cay. The boulder ridge is only seen at several locations and is not continuous (Figure 6). The imbricated boulders have a fresh, unweathered appearance on at least one of their faces. This indicates transportation in recent storms.

Our underwater snorkel survey identified a subtidal boulder field located south and southeast of Green Cay in ca. 3m of water. The clast size in this location is cobbles to small boulders. In very shallow water, a boulder field with boulders >1m in the long dimension was found (Figure 7). These boulders are likely to have been transported off of Green Cay in previous hurricanes and accumulated in the underwater boulder field close to the island. They are unlikely to move farther.

Together these data support an earlier study by Niemi (2017) that showed that the boulder field was produced by storm surge transport of cliff-derived boulders. Cliff retreat that is accelerated within coves found along the northwest cliff provide the boulders that are transported. Very large boulders >1m in long dimension can be transported in a Category 4 hurricanes such as Hurricane Frances in 2004 (Niemi, 2017). Because Hurricane Matthew was only a Category 3 storm and the eye of the storm tracked over 170 km southwest of San Salvador, our study documented that only a few small boulders were transported by the Matthew storm surge.

Figure 5: Photograph of the crest of Green Cay looking toward the southwest across the along washover zone. The black arrow points to very large boulders in the distance along the downslope (SE) side of the island. The deep water of the Atlantic Ocean is on the right (west) and the shallow protected water of Graham's Harbour is on left (east). Transported boulder in the foreground next to 2 m stick. Measuring stick for scale with 2 cm increments. View toward the southwest.

DISCUSSION AND CONCLUSIONS

A correlation between storm intensity and wind speed predicts storm surge height based on the Saffir-Simpson scale (Irish et al., 2008). Although wind speed is a factor in the magnitude of the storm surge, it is not the only factor. Lowering the normal atmospheric pressure causes the water itself to swell upward in the eyewall. Weisberg and Zheng (2006) state that "wind stress acting on the sea surface, when confronted by a rigid boundary, causes water to accumulate along that boundary such that the pressure gradient force associated with the surface slope, times the water depth, tends to balance the difference between the wind and bottom stresses." The forward speed and direction of the storm, atmospheric pressure fields, angle of approach, and geographic locations are just as important in maintaining the storm surge accumulation (Weisberg and Zheng, 2006). Higher forward speed add to the maximum surge accumulation. The difference in forward speed of the hurricane can make a difference of up to 37% more surge peak (Rego and Li, 2009). Conversely, a slower speed hurricane can be more damaging; while the peak surge amplitude may be smaller, the storm has more time to bring a larger volume of water onshore (Rego and Li, 2009). Topography, bathymetry, sand grain size, vegetation, and beach profile all play roles in the storm surge peak amplitude (Morton, 2002).

Figure 6: Boulder ridge at the crest of Green Cay along the northern portion of the washover zone. Note the imbrication of the boulders and the fresh unweathered appearance of some of the boulders. Measuring stick for scale with 2 cm increments. View toward the northeast.

During tropical storm surge inundation, the surge has the potential to carry a large amount of sediment, oceanic salts, and large debris inland. Material entrained in the floating mass is stranded

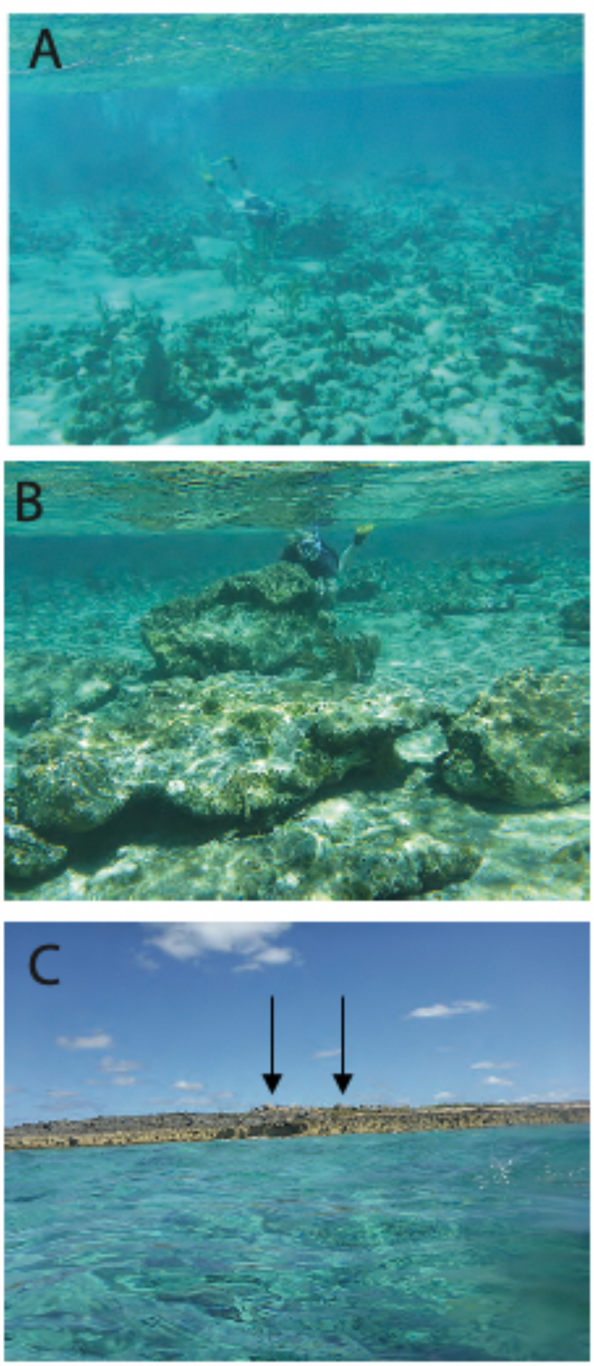

Figure 7: A) Underwater boulder field located south and southeast of Green Cay in ca. 3m of water. The clast size in this location is cobbles to small boulders. B) In very shallow water, a boulder field with boulders >1m in the long dimension was found. C) View from the offshore boulder field toward the northwest to Green Cay. Black arrows point to very large boulders on Green Cay.

as a wrack line. The wrack line, or wet line, is used as a marker to the line of inundation as the deposition tends to be at or very near the maximum water level before the time of retreat (Morton, 2002). The wrack line debris includes a substantial amount of human plastics and other materials as well as natural floating vegetation and debris. Only when the debris encounters a riparian vegetation zone does the wrack line lose accuracy (Bush et al., 1996).

Boulders as large as 2.7 m^3 have been determined to have been transported by means of storm surge inundation (Nott, 2003). These hydrodynamic formulas have been derived and used to provide a theoretical wave height needed for boulder transport. Based on the mass of the boulder in question, these formulas offer a numerical estimate for required wave amplitude of a storm surge. Researchers continue to debate over the true power of storm surge (Nott, 2003; Imamura et al., 2008; Spiske et al., 2008). However, one thing is certain, storm surge is very dangerous.

Previous study of boulder movement on Green Cay showed that a large boulder (8.5 m^3) that weighs approximately 16 metric tons was transported from a lower cove position up to the ridge by the storm surge in the Category 4 Hurricane Frances in 2004 (Niemi, 2017). These data suggest that the wave equations of Nott (2003) somehow underestimate the energy of storm surge transport. The eyewall of Hurricane Frances made direct landfall on San Salvador which led to very large storm surge heights (Parnell et al., 2004; Niemi et al., 2008). However, since Hurricane Matthew was only a Category 3 storm and passed southwest of the San Salvador, the storm surge height and duration were smaller that in Hurricane Frances. Thus, only small boulders moved with the Matthew storm surge on Green Cay.

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