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RAPID ASSESSMENT OF THE IMPACT OF HURRICANE IRENE ON THE DEPOSITIONAL ENVIRONMENTS OF THE BAHAMAS

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ABSTRACT. The goal of this study was to conduct a large-scale assessment of the effects of Hurricane Irene on the depositional environments of the Bahamas. This rapid assessment revealed that no major changes to the coastal system occurred. Hurricane Irene was a Category 3 storm that passed over Exuma Sound, Bahamas, on August 25, 2011, with maximum sustained winds of 115 mph. In the direct path of the storm, the Exuma Cays sustained storm-force winds and significant storm surge. A helicopter survey conducted on August 31, 2011, six days following the storm, revealed that storm surge from Hurricane Irene browned vegetation by saltwater burning the leaves in low-lying areas and the coastlines of large islands. Hurricane Irene caused significant beach erosion though the subtidal ooid shoal geometries remained unchanged. Open water sediment suspension was only observed in a couple isolated areas.

Away from the storm's center, though still within storm-force winds, the Andros coastline experienced minimal change. Additionally, no large scale or obvious damage was observed on the windward Andros reefs. On the west side of Andros, storm surge flooded the Andros tidal flats, leaving a thin layer of lime mud on the mangroves and in the supratidal zone. The mud has the same composition as sediment collected from the milk-white water west of Andros that was laden with stirred-up mud even 6 days after the storm. No changes to the morphology of the Andros tidal channels were observed. Likewise, the large subtidal ooid shoals of Joulters Cay and Cat Cay remained unchanged. At Joulters Cay, however, storm surge deposited a ~20 cm thick sediment layer on the upper beach 1.2 m higher than the normal high tide line, adding a new layer to the modern back beach storm ridge. Despite these observed effects and the damage to homes, docks, and boats, no major changes to the Bahamas coastal system occurred as a result of Hurricane Irene.

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INTRODUCTION

The effects of hurricanes and storms on coastal systems often raise a debate in the geologic community. Do storms cause major geomorphic changes in coastal systems? What changes can be observed and what is the preservation potential of these changes? Some studies claim that storms cause significant change to a system (Aigner, 1985), while others suggest that the effects are minimal (Rankey et al., 2004).

On August 25, 2011, Category 3 Hurricane Irene passed over Exuma Sound and the Exuma Cays with maximum sustained winds of 115 mph (Figure 1). From August 27-30, 2011, a field team onboard the *R/V Coral Reef II* set out to ground-truth the effects of the storm on the subtidal ooid shoals of Cat Cay and Joulters Cay, the Andros tidal flats, and the reefs east of Andros Island. To assess the near-field effects of the storm, aerial photograph mosaics of the Exuma Cays' windward margin were taken from a helicopter six days following the storm on August 31, 2011 (Figure 2). Although previous studies have documented the effects of hurricanes on the Bahamas (for example, Rankey et al., 2004; Niemi et al., 2008), this was the first time

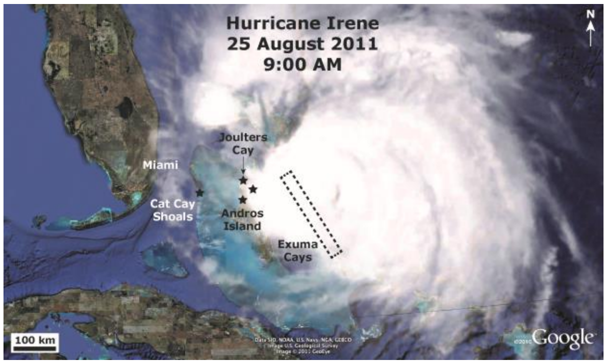

Figure 1. Hurricane Irene passed over Exuma Sound and the Exuma Cays on August 25, 2011, as a Category 3 Hurricane. The dashed black box indicates the approximate location of the Exuma Cays. Black stars indicate field sites of the ground team (Cat Cay subtidal ooid shoals, Andros tidal flats, Andros barrier reef, and Joulters Cay) (Image from Google Earth, 2011).

a survey of such a large region was conducted so rapidly after a storm.

The baseline data for this rapid assessment are maps, aerial photographs, and photos taken by scientists conducting recent research in the visited areas. The lead author has geologically mapped the near-field area of the Exuma Cays during the summers of 2009-2012. In addition, Jackson et al. (2013) and Petrie (2010) conducted extensive sediment sampling and coring throughout the Exuma Cays. In the far-field, recent sedimentologic and stratigraphic studies of the Cat Cay ooid shoal by Cruz (2008) and the muddy tidal flats of Andros Island by Rankey et al. (2004) and Maloof and Grotzinger (2012) provided general baseline data. However, the assessment team visited all the areas in June of 2011, both near- and far-field sites, and their ground-based photographs proved to be the best for assessing the changes to the coastal system caused by Hurricane Irene.

OBSERVATIONS

Near-Field: Exuma Cays

To conduct the aerial survey, a helicopter was flown from Miami, across western Great Bahama Bank, over New Providence, and then

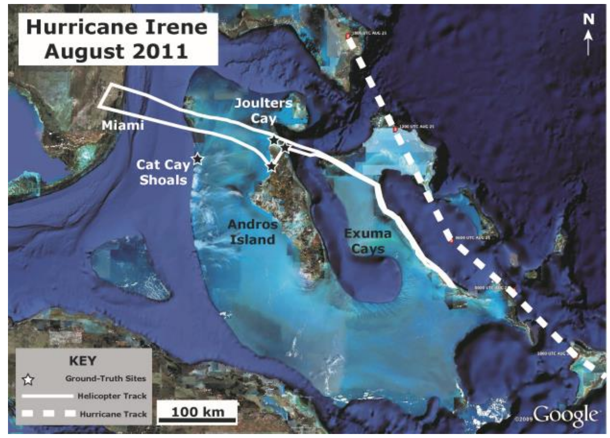

Figure 2. On August 31, 2011, the aerial survey team flew a helicopter approximately 9 hours (solid white line) and took more than 23,000 photographs of the Exuma Cays used to create photo mosaics to document the geologic effects caused by Hurricane Irene (storm track: dashed white line). Stars indicate field sites of the ground truth team (Cat Cay subtidal ooid shoals, Andros tidal flats, Andros barrier reef, and Joulters Cay) (Background image from Google Earth, 2011).

southeastward along the windward margin of the Exuma Cays and then back to the northwest along the leeward side of the Exuma Cays (Figure 2). During the approximately 9 hours of flight time, more than 23,000 high-resolution photographs were shot with two Nikon D7000 16.2 megapixel digital SLR cameras at a frequency of 2 photos per second along two north-south transects to document the near-field changes to the coastal system. Large high-resolution photo mosaics were created using the methodology described in Gracias et al. (2008), Reid et al. (2010), Gintert et al. (2012), and Cantwell (2013). These photo mosaics provide direct documentation of the immediate near-field effects of Hurricane Irene.

The Exuma Cays carbonate windward margin extends 170 km NW to SE, and 5-10 km W to E and is composed of 365 islands. Because of the large region, an aerial photography survey by helicopter is the most efficient method to rapidly assess the impacts of a hurricane. Photo mosaics combined with observation during flight revealed that the islands experienced strong sustained winds

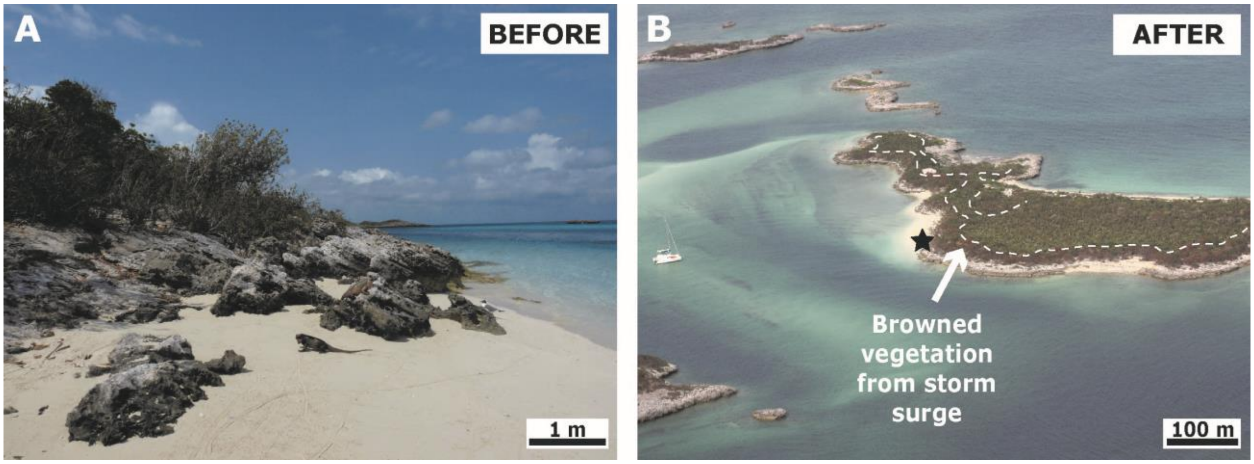

Figure 3. Leaf Cay, Northern Exuma Cays. (A) Leaf Cay leeward beach on June 8, 2011. Vegetation on the coastline is healthy. Black star in (B) indicates location of the baseline photograph in (A). (B) Aerial photograph of Leaf Cay on August 31, 2011, showing the extent (dashed line) of browned vegetation caused by salty storm surge inundation from Hurricane Irene.

and significant storm surge on the order of several meters as evidenced by browning of the vegetation around the edges of the islands caused by saltwater inundation. This ring of brown vegetation was easy to identify from the air and is documented in the photos (Figure 3). The browning of vegetation was apparent along the majority of the windward margin, particularly in the low-lying areas and along the coastlines of the larger islands. Despite the widespread extent, this did not have sustained effects on the depositional environments of the Exumas, and most of the vegetation has recovered in the 3.5 years since the storm.

The most significant impact Hurricane Irene had on the Exuma Cays was severe beach erosion, particularly on the windward sides of the islands. Figure 4 shows a before and after example from Compass Cay where the dramatic reduction in width of the beach is clear. From the air it appeared that some sediment was deposited on existing back beach storm ridges though exact elevations of sediment deposition were not documented since there was no ground survey conducted here.

The geometries of the subtidal ooid shoals

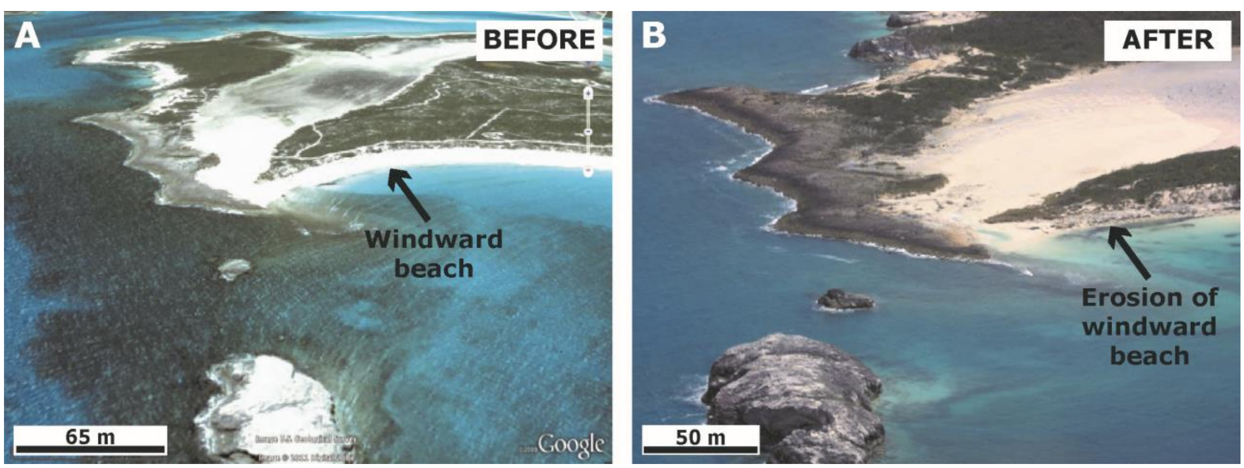

Figure 4. Compass Cay, middle Exuma Cays. (A) Google Earth image of the Compass Cay windward beach before Hurricane Irene. Note the width of the beach (Background image from Google Earth, 2011). (B) Photo of Compass Cay windward beach from helicopter survey after Hurricane Irene. Note the reduction in the width of the beach indicating extensive beach erosion.

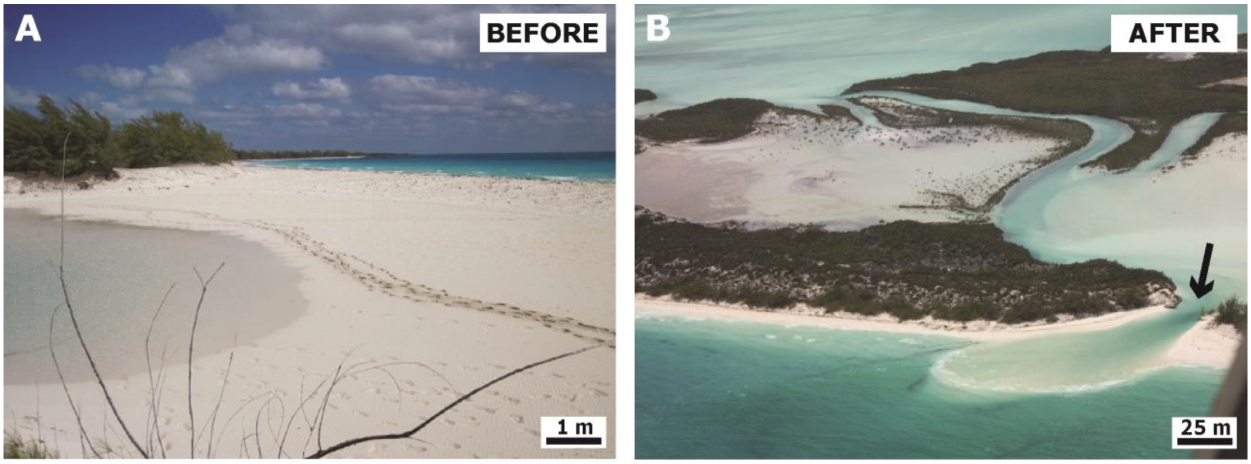

Figure 5. (A) Photo from March 2011 showing a sand barrier between the interior of Shroud Cay (left) and the windward margin (right) with Exuma Sound in the distance (darkest water). (B) Storm surge from Hurricane Irene broke through this previously clogged channel. The black arrow points to where the sand barrier in (A) was located before Hurricane Irene.

and flood tidal deltas remained unchanged, documented by comparing satellite imagery acquired before the storm with photo mosaics created during this assessment. The only minor geomorphic change observed was on the windward (eastern) side of Shroud Cay where Hurricane Irene re-opened a previously clogged tidal channel into Exuma Sound (Figure 5).

The Exuma Cays depositional environments contain very little to no mud, as it is a high-energy windward grain-dominated margin. When the storm passed and suspended sediment in the nearshore, the dominantly sand-sized grains settled very quickly which is why water appeared clear when the survey was conducted 6 days following the passing of the storm. Only in a couple isolated places, such as Rat and Boysie Cays in the southern Exumas (Figure 6), were mud-sized particles still suspended at the time of the aerial survey. Due to the strong tidal control in this region, the suspended mud was funneled through the tidal channels and may have settled in the channels. In other areas, the

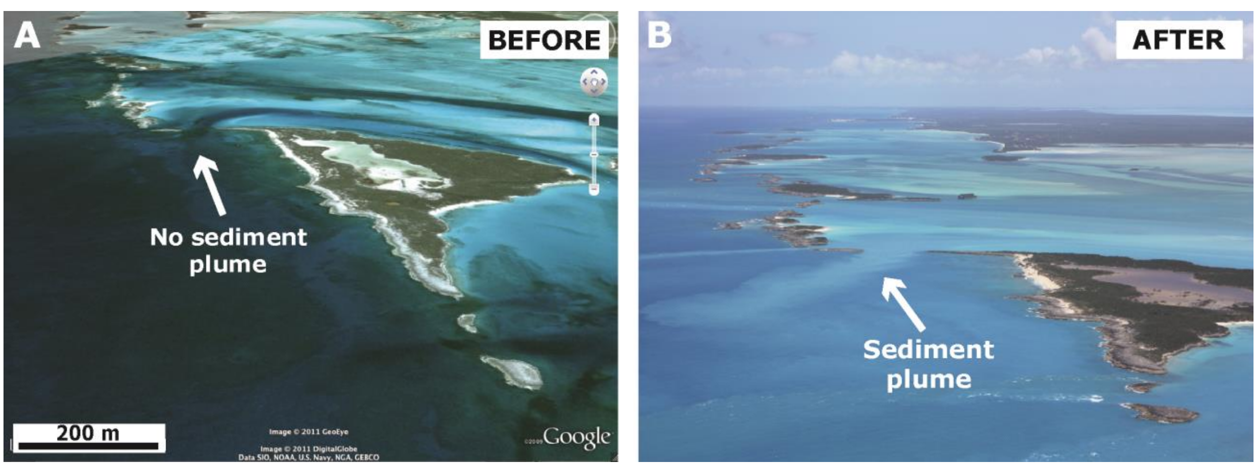

Figure 6. Rat and Boysie Cays, Southern Exuma Cays. (A) Google Earth Image looking southeast along the Exumas' windward margin. Dark color represents the deeper waters of Exuma Sound. Note that there is no sediment plume coming out of the channel into Exuma Sound between Rat and Boysie Cays (Image from Google Earth, 2011). (B) Aerial photograph of Rat and Boysie Cays taken on August 31, 2011, showing a plume of suspended sediment extending into Exuma Sound 6 days after Hurricane Irene passed.

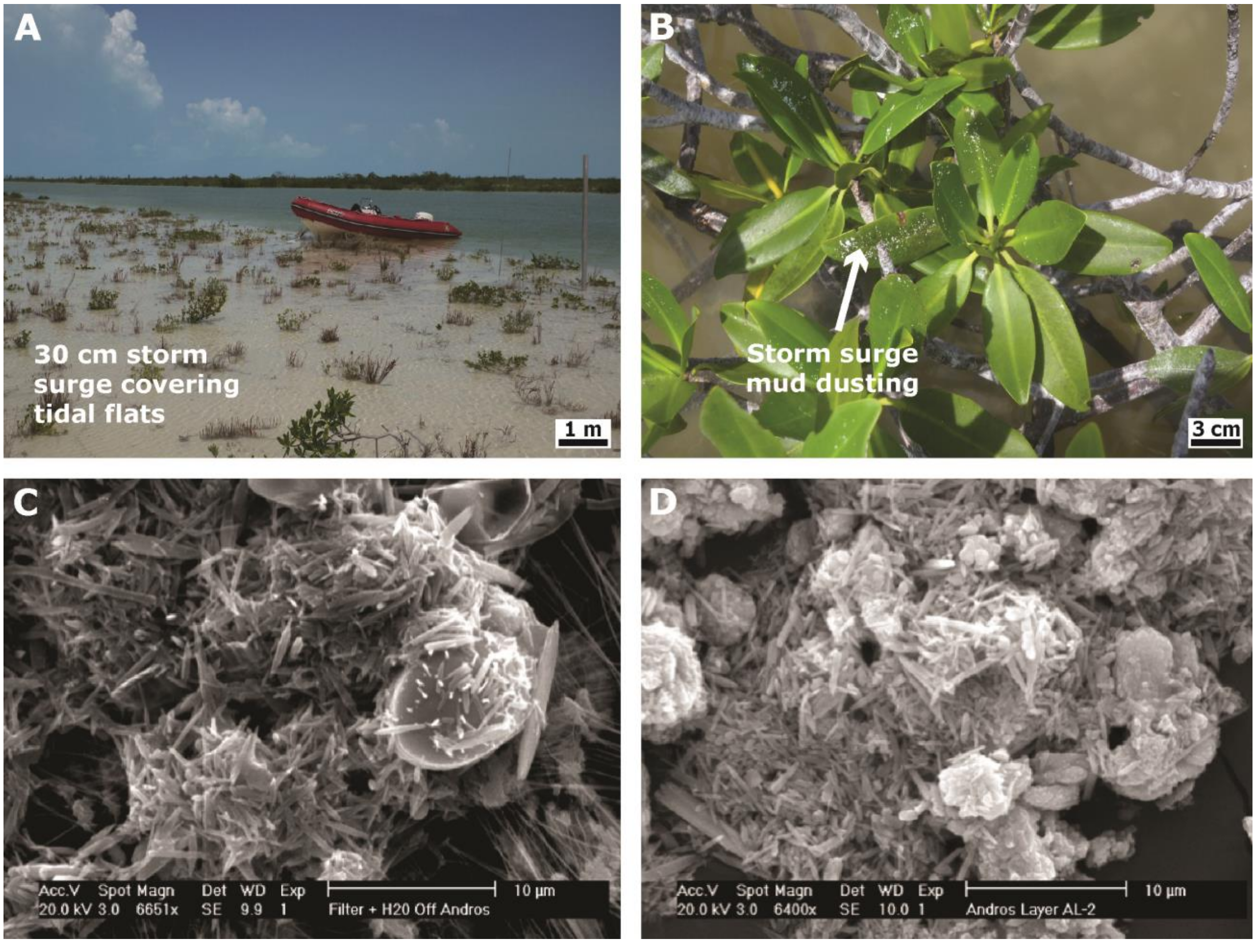

Figure 7. Andros Island. (A) Three days following Hurricane Irene, the storm surge had not completely retreated and the supratidal areas of the Andros tidal flats were still covered with approximately 30 cm of water. (B) A light dusting of aragonitic mud was observed on mangrove leaves located on the Andros tidal flats. The presence of the mud indicates the storm surge must have been at least an additional 50 cm higher than the observed high water in (A). (C) SEM photomicrograph of suspended sediment in a seawater sample collected off the leeward side of Andros two days after Hurricane Irene passed. The water sample contains aragonite needles and organic matter from carbonate mud suspended in the water column. (D) SEM photomicrograph of the millimeter-thick mud layer deposited on the Andros tidal flats during Hurricane Irene. Note the similarity of the composition and the abundance of aragonite needles between (C) and (D).

suspended material was drawn into Exuma Sound creating sediment plumes visible from the helicopter (Figure 6B). Several tidal channels in the Exumas feature muddy layers and mud clasts that have been interpreted as storm deposits from previous hurricanes (Shinn et al., 1993). Overall, the water along the Exumas windward margin remained clear of suspended mud.

Hurricane Irene’s sustained winds and significant storm surge damaged homes, docks, and boats, but no major changes to the Exuma Cays coastal system occurred. Storm surge inundation caused vegetation to brown, windward beaches experienced significant erosion, and mud was suspended only in a couple isolated locations, but overall no major geomorphic changes occurred.

Far-Field: Andros Tidal Flats

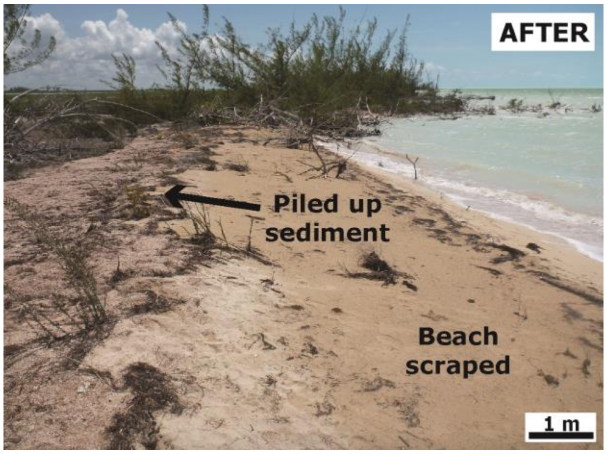

Figure 8. The western edge of the Andros tidal flats features a beach ridge composed of coarse-grained skeletal rudstone, or poorly sorted Cerithid sp. *gastropods, sands, and gravels. Hurricane Irene's winds and storm surge directly hit this beach and as a result the frontal portion of the beach was scraped and sediment was piled on top of the existing beach ridge.*

Away from the storm's center, though still within storm-force winds, the Andros coastline and offshore reefs experienced minimal damage. On the west side of Andros, the storm surge flooded the Andros tidal flats (Figure 7A). No changes to the morphology of the tidal channels were observed. The waters on the leeward side of Andros were milk-white even 6 days after the storm due to the suspension of mud. Interestingly, the storm surge had not completely retreated three days following the storm, and the supratidal areas were still covered with about 30 cm of water (Figure 7A). Peak storm surge was at least 50 cm higher because the mangrove leaves were dusted with lime mud from the storm waters at this height (Figure 7B). Scanning electron microscopy (SEM) conducted on a mud sample isolated from the storm waters collected from the western side of the Andros reveals that the suspended sediment consists mostly of fine aragonite needles (Figure 7C). The millimeter-thick layer of fine white mud deposited on the mangroves and tidal flats has the same composition when analyzed with SEM (Figure 7D).

The western edge of the northern Andros tidal flats is marked by a beach ridge of coarse-grained skeletal rudstone, or poorly sorted skeletal *Cerithid sp.* gastropods, sands, and gravels. The storm surge and winds from Hurricane Irene hit this beach directly (Figure 8). As a result, the frontal portion of the beach was scraped and piled up on top of the existing beach ridge; the storm surge was not strong enough to wash material back into the tidal flat area. Washover deposits of older storms with either higher storm surge or wind however, exist behind the ridge, extending irregularly some tens of meters into the tidal flats.

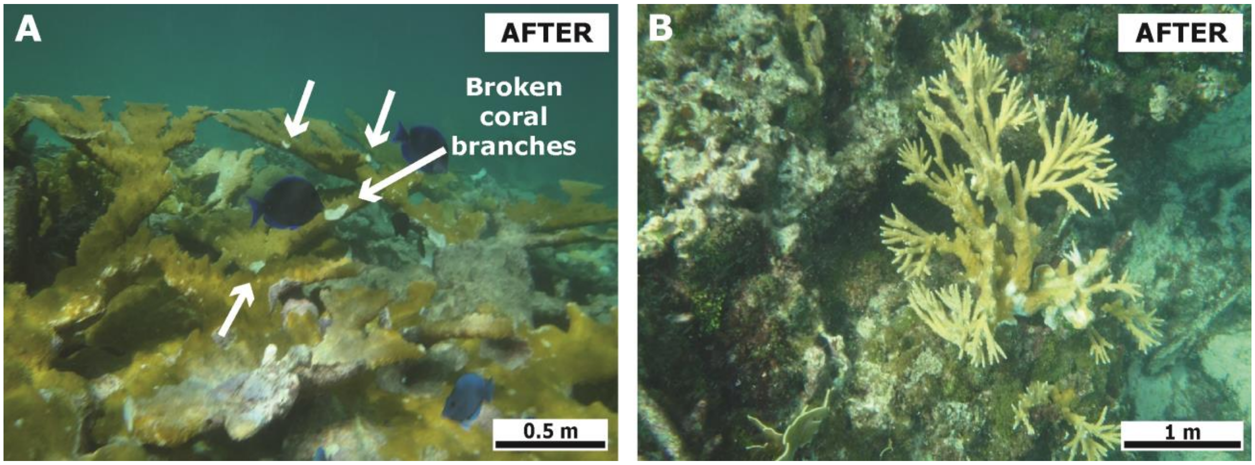

Figure 9. Reefs East of Andros Island. (A) Acropora palmata *observed while snorkeling a few days after Hurricane Irene. Note the broken branches. Water depth is approximately 2.5 m. (B)* Acropora cervicornis *(approximately 2 m water depth) unaffected by the storm. Most corals and soft corals were unaffected by Hurricane Irene.*

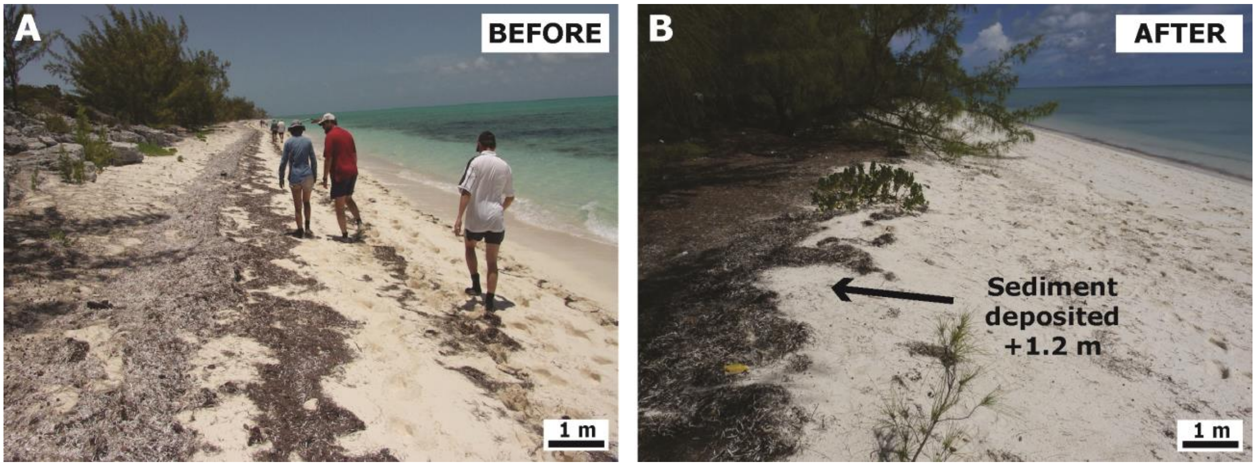

Figure 10. Joulters Cay. (A) The Joulters Cay beach before the storm has low and high tide berms that are marked by washed up sea grass. (B) Hurricane Irene smoothed out the beach profile and pushed sediment up to create a new ridge 1.2 m above high tide, partially burying vegetation.

Far-Field: Reefs East of Andros Island

Although the east side of Andros Island, including Joulters Cay, probably experienced hurricane-force winds, the coral reefs incurred little damage. Besides some small pieces of broken corals, no damage to the ecosystem was discernible while snorkeling four days after the storm (Figure 9). Soft corals and gorgonians were still intact and the only noticeable damage was broken tips of *Acropora palmata*.

Far-Field: Joulters & Cat Cay Ooid Shoals

Also located away from Hurricane Irene's center, though still within the hurricane-force wind field, the morphology of the large subtidal ooid shoals of Joulters Cay and Cat Cay remained unchanged. At Cat Cay, three days after the hurricane, the subtidal ooid bars were as usual ornamented with migrating sand waves. The transition to the surrounding sea grass to covered platform interior remained sharp and no transport of ooids from the shoals to the adjacent area was observed.

Likewise at Joulters Cay, the subtidal and intertidal areas exhibited the same morphology as two months earlier. This observation was surprising, as the passage of Hurricane Andrew in 1992 caused a major disruption to the shoal morphology and a concomitant deposit of a mud layer (Major et al., 1996). It took the daily tides several months to re-establish the original morphology. Hurricane Irene was obviously not strong enough to move the sediments in this location, and the storm surge was not high enough to bring suspended bank waters on top of the shoal.

Along the ocean facing, eastern side of the islands, however, the storm surge altered beach profiles. These islands are laterally accreting back beach storm ridges (Harris, 1979) that form when storm surges push sediment above the spring high tides. Each beach ridge is formed by several storms. Hurricane Andrew, a Category 5 hurricane, did not add to the storm beach ridges because the main wind direction was from the west. Hurricane Irene, despite its smaller magnitude, added sediment to the seaward edge of the youngest beach ridge. It piled a 20-40 cm thick sediment layer above the modern beach to form a new beach ridge 1.2 m higher than the normal high tide (Figure 10).

CONCLUSIONS

The combination of aerial photography and ground-truthing allowed the rapid assessment of the effects of Hurricane Irene on a large region of carbonate islands and sediments. This rapid assessment of grain-dominated (Exuma Cays) and mud-dominated (northwestern Great Bahama Bank) carbonate environments offered a unique opportunity to understand the effects of large storms on coastal and shallow-water systems. Large storms, like Hurricane Irene, cause significant damage to man-made structures and boats but geologically, these storms do not greatly affect depositional environments. The most significant geologic effect caused by Hurricane Irene was significant beach erosion on the windward Exuma Cays. No changes to the subtidal ooid shoals in the near- or far-field localities were observed. The Exuma Cays have little to no mud in their high-energy windward setting and therefore the grains settle almost immediately after the storm and leave the waters as clear as they were prior to the event. In muddy environments, such as Andros, the bank water becomes cloudy due to the suspension of the abundant aragonitic mud. None of the observed changes will permanently change the coastal or subtidal systems. In the 3.5 years since Hurricane Irene, daily tidal fluctuations already minimized and in most cases erased the observed effects.

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