Impacts of Hurricane Irma on Florida Bay Islands, Everglades National Park, USA

G. Lynn Wingard 1 · S. E. Bergstresser 1 · B. L. Stackhouse 1 · M. C. Jones 1 · M. E. Marot 2 · K. Hoefke 1 · A. Daniels 3 · K. Keller 4

Received: 29 November 2018 / Revised: 18 July 2019 / Accepted: 11 September 2019 / Published online: 22 November 2019
© The Author(s) 2019

Abstract

Hurricane Irma made landfall in south Florida, USA, on September 10, 2017 as a category 4 storm. In January 2018, fieldwork was conducted on four previously (2014) sampled islands in Florida Bay, Everglades National Park to examine changes between 2014 and 2018. The objectives were to determine if the net impact of the storm was gain or loss of island landmass and/or elevation; observe and quantify impacts to mangroves; and identify distinctive sedimentary, biochemical, and/or geochemical signatures of the storm. Storm overwash deposits were measured in the field and, in general, interior island mudflats appeared to experience deposition ranging from ~0.5 to ~6.5 cm. Elevation changes were measured using real-time kinematic positioning and satellite receivers. Comparison of 2014 to 2018 elevation measurements indicates mangrove berms and transitional areas between mudflats and berms experienced erosion and loss of elevation, whereas interior mudflats gained elevation, possibly due to Hurricane Irma. Geographic information system analysis of pre- and post-storm satellite imagery indicates the western-most island, closest to the eye of the storm, lost 32 to 42% (~11 to 13 m) of the width of the eastern berm, and vegetated coverage was reduced 9.3% or ~9700 m². Vegetated coverage on the eastern-most island was reduced by 1.9% or ~9200 m². These results are compared to previous accounts of hurricane impacts and provide a baseline for examining long-term constructive and destructive aspects of hurricanes on the islands and the role of storms in resiliency of Florida Bay islands.

Keywords Hurricane Irma · Mangroves · Sediment deposition · Elevation · GIS · Resiliency

Introduction

Hurricanes have played a significant role in shaping the existing Greater Everglades ecosystem of south Florida (Perkins and Enos 1968; Risi et al. 1995; Smith et al. 2009; Lodge 2010; Shinn and Lidz 2018), but the long-term significance of these storms is not well understood. Research is needed to address whether storms contribute to build-up and resiliency of the coastal ecosystem through deposition and nutrient supply or whether damage to the coastal mangroves causes persistent change that results in regime shifts over decades. Both destructive and constructive effects of hurricanes have been described (Cahoon 2006; Twilley 2007; Smith et al. 2009; Whelan et al. 2009; Castaeda-Moya et al. 2010; Breithaupt et al. this volume), and recognition of the net long-term (decadal to centennial-scale) impacts of these storms is imperative for future planning in the coastal region (Greening et al. 2006). Jones et al. (2019) have suggested that climate variability played a significant role in rapid (<200 years) transgression of the south Florida coastline between 3400 and 2800 years before present, during a time of relatively low rates of sea-level rise. Their findings highlight the importance of understanding whether the net effect of storms on the coast is constructive or destructive as resource...
managers formulate adaptive management and restoration plans that must account for climate and sea-level changes predicted for this century. The question of resilience of Florida Bay islands is important to resource managers because the islands serve essential ecosystem functions such as providing shoreline habitat and shelter for numerous aquatic species; as rookeries and wintering sites for birds; and along with the complex system of mudbanks, provide a level of protection from storms to the mainland coast (Schomer and Drew 1982; Enos 1989). To improve our understanding of how physical processes have controlled distribution of coastal vegetation (primarily mangroves) and how these processes interact to shape the coastal environment of south Florida, we conducted fieldwork and collected sediment cores from four islands in Florida Bay in 2014 (Fig. 1; Jones et al. 2019).

On September 10, 2017 at 9:10 am (EDT), Hurricane Irma made landfall in Florida as a category 4 (Saffir-Simpson Hurricane Wind Scale) storm on Cudjoe Key, about 34 km (21 miles) east-northeast of Key West and approximately 88 km (55 miles) southwest of the center of Florida Bay (Cangialosi et al. 2018), where our four 2014 field sites were located. At landfall, hurricane force winds extended outward from the eye up to 129 km (80 miles). Irma weakened to a category 3 hurricane as it tracked northward toward Marco Island, on southwest peninsular Florida, where it made landfall around 3:30 pm (EDT), September 10 (Cangialosi et al. 2018).

Detailed studies of the impacts of hurricanes on the islands in Florida Bay have not been conducted since the 1960s when Hurricanes Donna (1960) and Betsy (1965) passed over the bay. Hurricane Irma provided an opportunity for us to directly observe and document the effects of a major storm event on the four islands in Florida Bay that we previously visited and cored in 2014 (Jones et al. 2019) and to utilize methods and equipment not available in the 1960s. The primary goal of this study is to compare the constructive (primarily deposition) and destructive (primarily erosion and loss of vegetation) aspects of the storm to provide context for interpreting long-term impacts of storms on the south Florida coastline and island resiliency. Specifically, our objectives in this study are to (1) determine if Irma caused a net gain or loss of landmass and/or elevation to the islands; (2) examine the sedimentary, biochemical, and/or geochemical signatures of the storm; and (3) observe changes to the mangroves and other vegetation. By identifying distinctive storm signatures that might be preserved in the sediment record, we hope to improve our ability in future studies to interpret the sediment core record of storm history from these islands and to use these tools to test the hypothesis proposed in Jones et al. (2019). Understanding long-term (decadal to centennial) patterns of storm frequency and impacts on the islands and coast of south Florida will provide insights to future coastal ecosystem responses under predicted storm, climate, and sea-level rise scenarios.
Study Area and Storm History

Florida Bay is a shallow subtropical estuary bounded to the north by peninsular Florida and to the east and south by the Florida Keys; to the west, it is open to the Gulf of Mexico (Fig. 1). It consists of a network of mudbanks and islands separated by shallow basins, typically less than 2 m deep. Tides in Florida Bay are mixed semidiurnal, exchanging water with the Gulf of Mexico (diurnal) and the Atlantic Ocean (semidiurnal). The mudbanks and island chains cause the tides to be spatially variable but “strongly damped” in the interior portions of the bay, so the daily tides are almost negligible (Homlquist et al. 1989; Wang et al. 1994; Smith 1997). Changes in water levels within Florida Bay are primarily attributed to meteorological forcing and seasonal patterns, not diurnal tidal cycles (Homlquist et al. 1989; Smith 1997). During the summer, diurnal tidal amplitudes in the eastern portion of the bay are approximately 1 cm and the spring tidal amplitudes are approximately 3 cm (Wang et al. 1994). Winter weather patterns obscure tidal oscillations (Wang et al. 1994).

Florida Bay islands are classified into several distinct types based on topography, elevation, and vegetation, with elevation being the most important factor (Craighead 1964; Enos and Perkins 1979; Swart and Kramer 1997). Islands with higher elevations are typically covered with grasses, palms, and some hardwoods. The four islands included in this study (1) Russell Key, (2) western-most Bob Allen Key, (3) Buttonwood Key #7 near Whipray Basin water monitoring station, and (4) Jim Foot Key are typical of many Florida Bay islands; each has a central open mudflat or flats lying below sea level (Fig. 2) and is surrounded by a mangrove fringe on a higher elevation berm or levee on the island perimeter (Swart and Kramer 1997). Many of the islands also have low ridges running through the open flats that support growth of black mangroves (Avicennia germinans) and other salt tolerant species, and these ridges subdivide the islands into smaller open areas. Red mangroves (Rhizophora mangle) are typically found along the shoreline, with black mangroves, buttonwood (Conocarpus erectus), saltworts (e.g., Batis maritima), and other species on the berms. Open mudflats are typically devoid of vascular plants, but algal communities often form mats on the carbonate mud.

South Florida is struck by a hurricane every 7 to 8 years on average and a major hurricane every 14 to 19 years (based on data gathered since 1886; NOAA https://www.nhc.noaa.gov/climo/). Twenty-one major hurricanes (category 3 and above, Saffir-Simpson scale) have made landfall within an 80-nautical mile radius (148 km) of Florida Bay between 1888 and the present based on National Oceanic and Atmospheric Administration (NOAA) records (Fig. 3) and the twelve strongest are compared in Table 1. Previous authors have described the impacts on south Florida from five of the hurricanes—Labor Day Storm (1935, category 5), Donna (1960, category 4), Betsy (1965, category 3), Andrew (1992, category 5), and Wilma (2005, category 3) (Ball et al. 1967; Perkins and Enos 1968; Wanless et al. 1994; Risi et al. 1995; Houston and Powell 2003; Smith et al. 2009; Castaeda-Moya et al. 2010; Breithaupt et al. 2014). This previous research has primarily focused on storm surge and its immediate erosional and depositional effects, as well as the longer-term effects of the storms on the ecosystem, such as loss of mangroves in the coastal zone. However, no field research has been conducted on Florida Bay islands since Hurricanes Donna and Betsy. These studies provide a basis to compare changes to the islands following Irma to previous findings.

Hurricane Irma ranks as the sixth strongest recorded storm since 1888 to pass near Florida Bay in terms of pressure (931 mb) and is tied for sixth with unnamed 1945 and 1947 storms in terms of windspeed (132 mph) (Table 1). In the Lower Florida Keys, from Cudjoe Key east to Bahia Honda Key, storm surge was reported at 5 to 8 ft (1.5 to 2.4 m) above ground level (Cangialosi et al. 2018). In the Middle and Upper Keys, water levels reached 4 to 6 ft (1.2 to 1.8 m) above ground level (Cangialosi et al. 2018). Along the southwest coast of Florida, between Cape Sable and Cape Romano, the effects of tide and storm surge raised water levels 6 to 10 ft (1.8 to 3 m) and along the shores of Biscayne Bay on the southeast coast water levels reached 4 to 6 ft (1.2 to 1.8 m) above ground level (Cangialosi et al. 2018). Storm tide data from gauges in south Florida (Fig. 4) illustrate the differential effects of wind direction, diurnal tidal range, and basin geography on the elevation of the water and ultimately the storm surge. As Irma approached shallow coastal regions, strong offshore east winds caused an abnormal lowering of water levels, followed by rapid increases within a few hours following the passage of the eye and the reversal of the winds. Everglades National Park (ENP) water monitoring station at Duck Key in northeast Florida Bay recorded a 7.15-ft (2.2 m) change in water level over a 19-h period (as stated above, diurnal tidal range in this part of the bay is negligible). Residents reported the phenomenon of “water draining” ahead of the storm at Buttonwood Sound, Sunset Cove and other locations on the Florida Bay side of the Upper Keys in advance of the storm, which exposed the bay bottom in the shallow areas (Christopher Kavanagh, Everglades National Park, pers. comm. 2018). However, no direct observations of the impact to the islands or mudbanks of Florida Bay were recorded during the passage of the storm.

Materials and Methods

Fieldwork and Laboratory Analyses

Field investigation of the four islands was conducted January 29, 2018 through February 1, 2018, less than 5 months after Hurricane Irma. No subsequent 2017 hurricanes or other major storms affected Florida Bay during those 5 months;
therefore, the storm impacts noted on the islands could confidently be attributed to Irma. In addition, between 2014 and 2018, no tropical depressions or tropical storms passed within 150 km of the study area and no hurricanes passed within 270 km of the study area; therefore, we assume that changes noted on the island were primarily due to Irma (an assumption supported by satellite data as discussed below). On each island, we completed the following:

1) Relocated core sites that were previously sampled in 2014 (within 0 to 13 m) and obtained elevation data.
2) Collected four replicate “Russian” cores from the upper 50 cm of sediment in close proximity (typically within 2–5 m) to 2014 core sites as determined in step 1.
3) Measured the depth of deposition, photographed, and collected samples from overwash deposits.
4) Examined sedimentation patterns on berms, and where possible, measured elevation; collected 50-cm Russian cores at selected berm sites.
5) Searched for, documented, and photographed other changes to islands and features that may be preserved in sediments.

Site elevations were measured at twelve sites (Table 2) in 2018 by real-time kinematic (RTK) positioning technique using a Spectra Precision SP80 Global Navigation Satellite System (GNSS) receiver (Supplemental Table S-1). One static measurement was made at each of the twelve sites, and the cumulative error was calculated from the measured horizontal and vertical position, recorded at 1-s intervals for the occupation time (generally 30 min or longer). Position corrections were transmitted from a fixed reference station (FLPK of the Florida Permanent Reference Network (FPRN)) with a maximum distance of 20 km from the field sites. For the 2018 measurements, excluding the two measurements with high standard deviations (BAP3, WRP1), the cumulative vertical error ranged from 19.9 to
39.8 mm. Jim Foot Key was beyond the range for the RTK to connect to the base station, so for this site, raw SP80 GNSS data were collected at a single site and post-processed to a base station set up at the Key Largo Ranger Station, ENP. Where applicable, the 2018 data were compared to 2014 site elevations (Supplemental Table S-2), which were measured using an Ashtech differential GPS (dGPS) receiver and geodetic antenna recording at 1-s intervals with a minimum occupation time of 30 min per site. The 2014 dGPS data were post-processed to a temporary base station established at the Keys Marine Laboratory on Long Key with a maximum base line of 33 km. A cumulative vertical error was calculated from the standard deviation of the processed data and a 1 part per million base line error; this value ranged from 27.1 to 36.0 mm for the 2014 measurements.

Thirty-one 50-cm long Russian 1 cores (direct push, non-compressional side-filling chambered-type, repeat-drive coring device) were obtained from nine sites including most of the 2014 sites on each island, plus additional berm sites (Table 2; at one location the full 50 cm was not captured). Cores were transported back to the USGS laboratory and placed in cold storage. Core analyses were conducted to determine...
sedimentation rates and patterns at the sites. All cores were photographed and analyzed for magnetic susceptibility and color on a Geotek MSCL 7.9 non-destructive multi-sensor core logger using point sensors within 5 weeks of collection (Supplemental Figs. S-131). RUSP4A and BAP3A were sliced wet into 1-cm sections and processed for bulk density and loss-on-ignition (LOI) (Supplementary Table S-3). Organic matter content was determined by LOI, which was performed on 1 cm³ of sample at 550 °C using standard procedures (Dean 1974). Bulk density was calculated by dividing the dry mass of the sample by the measured volume of the sample (Supplemental Table S-3). To determine recent (decades to century) sedimentation rates and look for evidence of sediment disturbance at two berm sites, we measured 210Pb in the fine (< 63 μm) fraction of sediment from RUSP (replicates B and C combined) and BAP (replicates A and B combined) using alpha spectroscopy following the methods described in Marot et al. (2016) (Supplemental Table S-4). We used the constant flux/constant sedimentation (CFCS) model, which assumes constant sedimentation (Appleby 2002), to estimate sediment chronologies.

Overwash deposits were located around the island perimeters, interior of the berms. Overview, close-up, and cross-sectional photographs were taken in situ to document the nature of the deposits and field descriptions were made. Material was very cohesive at most sites, so intact blocks at specific locations were removed and packaged for transport back to the USGS laboratory for future examination.

**Geographic Information Systems (GIS) Analysis**

Satellite imagery of the four islands was obtained from a few weeks before and a few days after the storm to highlight areas of potential change to guide field investigations conducted in January 2018. For the digital analysis of pre- and post- Irma changes to the islands, high-resolution WorldView-2 multispectral satellite imagery was acquired for August 13, 2017, about a month prior to Irma, and July 13, 2018, approximately 10 months after the hurricane. These images were manually interpreted within GIS to create digitized land mass polygons for each of the four islands that distinguished vegetated areas, non-vegetated areas, and island perimeters. The areas of the polygons generated from the 2017 imagery were compared to the areas of the 2018 imagery polygons to assess changes to the islands between August 2017 and July 2018. Since the analysis involved visual interpretation, it was important to compare images from similar times in the seasonal rain cycles for each year so that vegetation and sediment/water cover were analogous between the two images. Diurnal tidal amplitudes in Florida Bay are very minor, 1 to 3 cm through much of the interior portions of the bay, and water levels are controlled primarily by meteorological forcing or seasonal patterns (Homlquist et al. 1989; Wang et al. 1994; Smith 1997). Therefore, the time within a daily tidal cycle that the image was acquired was not significant for the analysis. The 10-month interval between the storm and the post-Irma image analysis minimized the possibility of mistaking floating debris present following the storm for island land mass and allowed us to detect more permanent changes to the islands.

Acquiring satellite imagery with a high spatial resolution of approximately 50 cm allowed for detail to be captured within the digitization process. Visual interpretation of the vegetated land mass, characterized by trees and shrubs, was based on several spectral elements. Most notably, variations in texture and tone between the vegetated and the water-covered/bare

### Table 1

Comparison of storm data from the twelve strongest hurricanes (ranked by pressure in mb) that passed within an 80-nautical mile radius of Florida Bay since 1888. Data represent recorded information closest to time and position of landfall for all storms except Betsy and the unnamed 1926 storm; data for Betsy are from center of Florida Bay and for the 1926 storm from offshore of Bahia Honda. Location of storm tracks is shown in Fig. 3. Category listed is the Saffir-Simpson Hurricane Wind Scale.

| Hurricane | Date       | Location of reading | Coordinates of reading | Pressure (mb) | Windspeed (mph) | Category |
|-----------|------------|---------------------|------------------------|---------------|-----------------|----------|
| Labor Day Storm | 9/3/1935 | Long Key | N 24.80; W 80.80 | 892 | 184 | 5 |
| Andrew    | 8/24/1992 | Miami    | N 25.50; W 80.30 | 922 | 167 | 5 |
| Unnamed 1919 | 9/10/1919 | Dry Tortugas | N 24.60; W 82.80 | 927 | 150 | 4 |
| Unnamed 1926 | 9/18/1926 | Cutler, south Miami | N 25.60; W 80.30 | 939 | 144 | 4 |
| Donna     | 9/10/1960 | Islamorada | N 24.80; W 80.90 | 930 | 144 | 4 |
| Irma      | 9/10/2017 | Cudjoe Key | N 24.70; W 81.50 | 931 | 132 | 4 |
| Unnamed 1947 | 9/17/1947 | Fort Lauderdale | N 26.10; W 80.10 | 943 | 132 | 4 |
| Unnamed 1929 | 9/28/1929 | Tavernier | N 25.00; W 80.50 | 948 | 115 | 3 |
| Unnamed 1926 | 10/21/1926 | Offshore, Bahia Honda | N 24.50; W 81.00 | 949 | 127 | 3 |
| Unnamed 1945 | 9/15/1945 | Key Largo | N 25.30; W 80.30 | 949 | 132 | 4 |
| Wilma     | 9/24/2005 | Marco Island | N 25.90; W 81.70 | 950 | 121 | 3 |
| Betsy     | 9/8/1965  | Florida Bay | N 25.10; W 80.70 | 952 | 127 | 3 |

Data acquired from http://coast.noaa.gov/hurricanes
ground areas helped to distinguish them. The appearance of water or bare ground is smooth compared to the rough texture of areas of vegetation (Fig. 5a; compare areas labeled 1 and 2). Much of the islands’ interiors are characterized by barren or sparsely vegetated mudflats that are either ephemerally covered by water or constantly covered by shallow water. Because of this, the variations in tone, namely brightness and color, of these areas are determined by the color of the sediment below the surface. Therefore, areas without vegetation and shallow water appeared white, light green, or brown in the satellite imagery (Fig. 5; labels 1 and 3). They were often lighter than vegetated areas, although deeper water sometimes appeared darker. Conversely, the tone of vegetation had a narrower range of variation, typically consisting of shades of green and brown (Fig. 5; labels 2, 4, 5). Areas were classified as either vegetated landmass or non-vegetated; non-vegetated denotes bare ground or areas covered by water. Figures 5 and 6 show examples of vegetated land mass...
distinguished from non-vegetation on Buttonwood #7 and Jim Foot Keys. The areas classified as vegetated may include mangroves that were defoliated by the storm. For example, comparing areas labeled 4 and 5 in Fig. 5, the mangroves in area 4 (pre-storm) appear dense and healthy whereas the mangroves in area 5 (post-storm) appear defoliated; however, area 5 is still classified as vegetated for the purposes of this analysis. This approach means that our estimates of reductions in vegetated land-mass due to Irma were conservative and may have underestimated the actual damage.

Integrating Fieldwork and Imagery Analysis

The combination of field observations and laboratory analyses with satellite imagery and GIS analysis has provided corroboration of information that otherwise would have required assumptions be made. The 4-year gap between our 2014 and our 2018 fieldwork meant that we could not definitively state that all the changes we saw were due to Irma; however, in many cases, examination of the satellite imagery over this four-year time span allowed us to attribute visible changes, particularly reductions in vegetated land mass to Irma. Conversely, general knowledge of the field area and specific field observations assisted in analysis and interpretation of the satellite imagery. For example, from our fieldwork, we know the types of vegetation found on the islands, the transitions from berms to mudflats, and the seasonal variations in water cover on the mudflats. The flat nature of the islands, shallow water depths, and light-colored carbonate muds mean the possibility of misclassifying land for water, and vice versa, is high. Areas of short vegetation and areas covered by shallow water often appear similar within imagery. Therefore, satellite image interpretation should not be used alone to study changes on these islands. Our approach allowed the satellite imagery to inform field observations in terms of timing and severity of change and locating areas for sampling, and general knowledge of the field area, specific field observations, and field photographs informed interpretation of the satellite imagery.

Results

Field Observations

Many field observations in 2018 could be attributed to recent storm effects. The apparent fresh deposition of carbonate mud on the island interiors was immediately obvious. In 2014, several of the islands had distinct algal mats on the interior mudflats. The mat on Bob Allen was particularly thick, rubbery and firm in 2014, so it made a clear stratigraphic marker to identify post-2014 deposition (Fig. 7a, b; Fig. S-32). The texture and consistency of the carbonate mud overlying the algal mat indicated deposition in a single event and relatively fresh \textit{Thalassia} blades and tufts of \textit{Batophora} in the mud, indicated estuarine/marine origin. Thickness of the mud deposits on Bob Allen varied from 0.5 cm in the wet central portions of the island to 1.5 to 4.5 cm in the overwash deposits near the southern edge of the island (Fig. 7b; Fig. S-32 b, d, f). On Jim Foot, most of the open mudflats were covered with a reddish algal film in 2014 (Fig. 8a). In 2018, a red algal layer is visible under what appeared to be recent overwash deposits in the southeast and southwest corners of Jim Foot. Distinct layering was visible, and in the southwest corner, large amounts of relatively fresh \textit{Thalassia} were intermixed in the mud, which ranged from 5.0 to 6.5 cm in thickness (Fig. 7c, f; Fig. S-33). Unlike Bob Allen and Jim Foot, Russell Key did not have a distinct algal layer at the surface in 2014; however, post-2014 deposition was indicated by a sharp boundary.

Table 2

| Island       | Station/Core ID | Setting    | Date       | Latitude (decimal) | Longitude (decimal) | 2018 Data collection |
|--------------|-----------------|------------|------------|--------------------|---------------------|----------------------|
| Bob Allen    | BAP1*           | Mudflat    | 1/29/2018  | 25.0278032         | −80.68565034        | 4 Cores, elevation   |
| Bob Allen    | BAP2*           | Mudflat    | 1/29/2018  | 25.0287028         | −80.68498868        | 4 Cores, elevation   |
| Bob Allen    | BAP3            | Berm       | 1/29/2018  | 25.0267422         | −80.68620833        | 2 Cores, elevation   |
| Bob Allen    | BAP4            | Berm       | 1/29/2018  | 25.0273668         | −80.68714513        | Elevation only       |
| Bob Allen    | BAP5            | Berm       | 1/29/2018  | 25.0262584         | −80.68480293        | Elevation only       |
| Buttonwood #7| WRP1*           | Mudflat    | 2/1/2018   | 25.0688895         | −80.73474843        | 4 Cores, elevation   |
| Buttonwood #7| WRP3*           | Transition | 2/1/2018   | 25.0717815         | −80.73465421        | 4 Cores, elevation   |
| Buttonwood #7| WRP5            | Berm       | 2/1/2018   | 25.068978          | −80.73542248        | Elevation only       |
| Jim Foot     | JFP1*           | Transition | 1/30/2018  | 25.069653          | −80.788386          | 4 Cores, elevation   |
| Jim Foot     | JFP4            | Berm       | 1/30/2018  | ~25.0686           | ~−80.7876           | 1 Partial core only  |
| Russell      | RUSP2*          | Berm       | 1/30/2018  | 25.0826377         | −80.64035242        | Elevation only       |
| Russell      | RUSP3*          | Mudflat    | 1/30/2018  | 25.0753526         | −80.64625249        | 4 Cores, elevation   |
| Russell      | RUSP4           | Berm       | 1/30/2018  | 25.0748803         | −80.64668011        | 4 Cores, elevation   |

*Locations also measured in 2014; measurements compared in Table 3
between a dark gray to greenish black mud overlying a light tan layer (Fig. 7e; Fig. S-34), which ranged from 1.8 to 4.5 cm in thickness where measurements were made. Buttonwood #7 also did not have a distinctive surface layer in 2014; therefore, it was harder to distinguish deposition caused by Irma (Fig. 7d; Fig. S-35). It appeared that at least a few centimeters of mud were deposited around the perimeter on the western and northern edges of the island that we investigated; additional analyses may clarify the composition and origin of the underlying dark layers (Fig. S-35a–e). Also, no sign of fresh deposition in the open interior of Buttonwood #7 existed, indicating the surge either did not cover the island or it only deposited mud on the periphery. However, a wedge of mud was visible along the western and northwestern shorelines, tapering off toward the interior, and possibly marking the extent of the overwash (Fig. S-35f).

In addition to the overwash deposits, many other features most likely can be attributed to Hurricane Irma. Large piles (some > 1 m) of bleached Thalassia were found on all four islands along the berms, entangled in the branches and prop roots of the mangroves, and in many cases in the island interior. Russell Key is subdivided into smaller subbasins rimmed with mangroves and here we measured thick mats of Thalassia over 150 m inland from the shoreline and up to 80 cm above the ground surface, suspended in the mangroves (Fig. S-36a) that were not present in 2014. In addition, very thick layers of

Fig. 5 Satellite imagery of southern tip of Buttonwood #7 before Hurricane Irma (a) and after (b). The digitized vegetated land mass of the island is delimited by the thin outline. The circled areas indicate areas of reduced vegetated cover. (1) Area classified as water/bare ground. (2) Area classified as vegetated. (3) Area classified as water/bare ground. (4) Healthy mangroves pre-storm, classified as vegetated. (5) Damaged/defoliated mangroves post-storm, classified as vegetated. The satellite imagery was obtained from DigitalGlobe’s WorldView-2 satellite, August 13, 2017 (a) and July 13, 2018 (b)

Fig. 6 Satellite imagery of eastern berm of Jim Foot before Hurricane Irma (a) and after (b). The digitized vegetated land mass of the island is delimited by the thin outline. The locations of the thick lines (indicated by arrows, thickness in meters) show where the vegetated berm was measured on the image, and a comparison of a and b indicates a decrease in berm width. The satellite imagery was obtained from DigitalGlobe’s WorldView-2 satellite, August 13, 2017 (a) and July 13, 2018 (b)
Thalassia covered the surfaces of some of the mudflats on Bob Allen, Russell, and Jim Foot Keys that were not noted in 2014 (Fig. S-36b). Imbricated mangrove leaves were abundant in the open mudflats on all four islands (Fig. S-36c), probably due to the combined effects of wind denuding the mangroves and the leaves settling out of the water as the surge receded. We interpreted a large concentration of small dead fish (primarily Lucania parva and Floridichthys carpio) on Russell Key (Fig. S-36d, f) as indicative of transport by storm surge; the fish were in a low area and most likely concentrated in a pool as the water receded and/or evaporated. Similarly, large concentrations of live Batillaria minima (gastropod) were found on the flats just inside the berm on Bob Allen (Fig. S-36e). This species normally lives on the estuarine flats offshore from Bob Allen and is frequently found there in large numbers; we believe the storm surge deposited them on the island. Denuded mangroves were noted on every island, and the black mangroves (Avicennia germinans) appeared considerably more affected by leaf loss than the red mangroves (Rhizophora mangle). On Bob Allen, black mangroves on the interior side of the berm with 10 to 20 cm of apparent overwash were still defoliated in January 2018, while those on the berm without recent deposition were sprouting new leaves. The impact to the mangroves and other vegetation on the eastern shoreline of Jim Foot Key was particularly notable (Figs. 6 and 8); images from June 2018 indicate that some recovery is beginning to occur, but it is questionable whether the shoreline will revert to the 2014 condition.

**Elevation Measurements**

Although we only had a few points for comparison, dGPS measurements made indicate that mudflat sites on the interior
of the islands (BAP2, RUSP3) gained between 41 mm (± 23–36 mm) and 56 mm (± 23–27 mm) of elevation between 2014 and 2018 (Table 3). The exceptions are the WRP1 mudflat site where we were unable to obtain a fixed position and the BAP1 site where the apparent elevation gain of 23 mm falls within the cumulative vertical error of 20 to 27 mm. Only one berm was measured in 2014 (RUSP2), on the east side of Russell Key, and this site lost 389 mm (± 23–36 mm) in elevation between 2014 and 2018. Two sites are considered transitional because they are located on open mudflats, but within a few meters of the fringing mangroves and the island shoreline (JFP1, WRP3). JFP1 site lost 56 mm of elevation (± 28–40 mm) and WRP3 site lost 167 mm (± 28–30 mm) between 2014 and 2018. Based on the limited number of elevation measurements repeated in 2018 from the 2014 locations, the berm (n = 1) and transition (n = 2) sites lost elevation, and two out of four mudflats gained elevation, while the other two fell within the measurement error between 2014 and 2018 (Table 3).

**Laboratory Analyses**

Images of the cores obtained on the Geotek MSCL 7.9 indicate general patterns of sedimentation (Fig. 9; images of all cores and associated data are available in Figs. S-1–31). The berm cores from Bob Allen (BAP3) and Russell (RUSP4), and the transition core from Jim Foot (JFP1), contain coarser material throughout compared to the mudflat cores from Buttonwood #7 (WRP1), Bob Allen (BAP1, BAP2), and Russell (RUSP3). The uppermost portion of the transition core at Buttonwood #7 (WRP3) also contains coarse material. The berm cores show a shift in composition between 15 and 20 cm below the surface and the mudflat cores between 2 and 7 cm below the surface. In general, the measures of core color (lightness expressed as CIELAB L and color as CIELAB a*b*) are consistent with the visual inspection of the core images and provide a more quantitative means of describing the variations seen. Light colors generally indicate carbonate deposition and darker colors indicate organics. Magnetic susceptibility ranged from −3 to 4 × 10⁻⁵ SI, indicating the minerals in the sediments primarily were diamagnetic (lack magnetic properties) and, therefore, not useful in detecting storm deposition in this setting.

Analytical results for two sets of berm cores—Bob Allen (BAP3) and Russell (RUSP4)—were compared (Fig. 10). ²¹⁰Pb results provided insights into the patterns of sedimentation on the berms. The BAP3 berm core shows ²¹⁰Pb decreasing logarithmically with depth, suggesting uninterrupted sedimentation, while the ²¹⁰Pb activity at Russell is relatively constant to a depth of 11 cm and then slowly decreases. Using the constant flux/constant sedimentation (CFCS) model (Appleby 2002), an accretion rate of 1.4 ± 0.3 mm/year for BAP3 is obtained (SI Table 4). In RUSP4, the nearly constant activity in the upper 11 cm may indicate a zone of physical or biological mixing or of episodic deposition, such as a storm deposit, and the CFCS model cannot be applied. For the lower portion of the ²¹⁰Pb profile at RUSP4, the CFCS model yields an accretion rate of 2.4 ± 0.08 mm/year. In general, bulk density increases with depth in BAP3 and RUSP4 (Fig. 10) as...
expected due to compaction, but coarse shell debris in the berm cores corresponds to lower bulk densities, indicating these changes in bulk density also reflect changes in the coarseness and sorting of the sediment. Fluctuations in the bulk density in RUSP4 correspond to changes in sedimentation visible in the 210Pb profile and the Geotek image and indicate an increase (low bulk density) or decrease (high bulk density) of shell debris, which may be the result of storm-related deposition. In addition to lithology, these changes in bulk density could be a useful proxy for identifying storm deposits on island berms. Additional analyses of the sediments, grain size, and composition will be necessary to confirm this. LOI is highest in the upper 5 cm of RUSP4 and the upper 10 cm of BAP3, consistent with field observations that organic material from mangroves was concentrated in the upper layers of the berms.

GIS and Satellite Imagery

The GIS analysis indicates that vegetated cover has decreased on all four of the islands following Hurricane Irma, even though we were conservative in our classification of what constituted a reduction in vegetation. The vegetated area of Jim Foot decreased by approximately 9.3% (9708 m²), Buttonwood #7 by 7.1% (17,778 m²), Bob Allen by 4.9% (6641 m²), and Russell by 1.9% (9176 m²) between August 2017 and July 2018. Figure 11 details the areas of most notable change on the islands indicated by the circles and arrows. Most of the changes occurred to the interiors of the islands; however, there was a loss of vegetated berm on the eastern side of Jim Foot, with a reduction of ~ 11.5 to 13 m or 32–42% of the berm width (Fig. 6). On Russell Key, an existing breach of the southeast berm widened following the storm (Fig. 11a, arrow on Russell Key post-Irma image). The islands closest to the track of the eye of the hurricane, Jim Foot and Buttonwood #7, were the two islands that had the greatest percent reduction in vegetated coverage (Figs. 5 and 6) and, in terms of areal extent, Buttonwood #7 lost the largest amount of vegetative cover (Fig. 11).

Discussion

Constructive and Destructive Impacts of Irma

In the near-term aftermath of Hurricane Irma, our field observations, GIS analysis, elevation measurements, and laboratory analyses indicate that both constructive and destructive impacts to Russell, Bob Allen, Buttonwood #7, and Jim Foot Keys occurred. Our interpretations were aided by, and are consistent with, 1960s studies of hurricane effects on islands in Florida Bay (Craighead and Gilbert 1962; Craighead 1964; Ball et al. 1967; Perkins and Enos 1968). However, our observations are enhanced by the addition of elevation measurements, GIS-analysis, and laboratory investigations not available in the 1960s.

The constructive aspects of Hurricane Irma in the open central areas of the islands are evident from the overwash deposits, the mudflat core tops, and the elevation gains measured on the mudflats at Bob Allen and Russell Keys. Our observations of storm overwash deposits on the islands are remarkably similar to observations made following Hurricane Donna (Ball et al. 1967, p. 590); their description of Crane Key (~ 7 km southeast of Bob Allen) was “an almost continuous layer of mud and extensive mats of marine grass were left after the storm on the surface of this island.” Their images of overwash deposits resting on previous algal surfaces are nearly identical to ours (compare Ball et al. 1967, Plate 9 to Fig. 7b). At Bob Allen Key, where the 2014 algal mat provided a good marker for new deposition, increases of
2.3 cm (within error of instrument) and 5.6 cm in elevation at the mudflat core sites between 2014 and 2018 (Table 3) were consistent with overwash deposits and core top layers ranging from ~2 to 4.5 cm in thickness. An elevation increase of 4.1 cm on a western Russell Key mudflat was consistent with overwash deposits and core top layers ranging from 1.8 to ~7 cm thick. Although no elevation measurements or interior mudflat cores were collected at Jim Foot, the overwash deposits there showed the most obvious signs of deposition as a single thick (5 to 6.5 cm) package of sediment. No elevation gain was detected on the interior of Buttonwood #7 and deposition of sediment on the interior mudflats seemed restricted to the western margin of the island. Comparing across the islands, we measured deposits ranging from 0.5 to 6.5 cm, which is within the range of deposition described for Hurricane Donna from “a trace” (Craighead and Gilbert 1962) to 5 to 10 cm (Ball et al. 1967; Perkins and Enos 1968).

The relationship of overwash sediment deposition to long-term accretion remains a topic of active research (Cahoon 2006; Castaeda-Moya et al. 2010; Barr et al. 2012; Breithaupt et al. 2014). Initial sediment deposition is subjected to dewatering, shallow subsidence, and other subsurface processes than can reduce the long-term impact on accretion (Cahoon 2006; Whelan et al. 2009). On the islands in Florida Bay, the goal is to evaluate if different sedimentary processes are acting on the berms compared to the mudflats and to determine the net effects of these processes. As stated above, the mudflats were sites of storm deposition near our study sites and showed increases in dGPS elevation between 2014 and 2018. The processes acting on the berms, however, are less clear. Of the two berm cores with a 210Pb profile, only the berm at Bob Allen (BAP3) suggests constant accretion, while the profile of the upper portion of Russell (RUSP4) suggests episodic storm deposition and/or bioturbation of the berm sediments. The one berm with a repeat dGPS measurement in 2014 and 2018 (RUSP2) indicates a net loss of elevation of 389 ± 59.2 mm over the 4-year interval and suggests the berms may lose elevation through erosion, potentially

![Geotek MSCL 7.9 images of A cores from each location (see Table 2 for location information). Transition cores are taken just inland of the berms on the mudflats. (Geotek images of all cores are in Figs. S-1–31.)](image-url)
Analyses conducted on berm cores from a Bob Allen Key (BAP3) and b Russell Key (RUSP4). Core image and CIELAB L (measure of light (higher values) and dark (lower values) colors) are output from Geotek MSCL 7.9. Loss on ignition (LOI) and bulk density methods are described in text. $^{210}$Pb analyses performed on combined samples from 2 replicate cores to obtain enough sample volume for analysis. (Data are in Supplemental Tables S-3 and S-4.)

during storms. The berms are the only part of the islands currently above sea level; therefore, their ability to maintain accretion rates above the rate of sea-level rise is necessary for island resiliency. However, the constant accretion rate of 1.4 ± 0.3 mm/year on the Bob Allen berm is too low to outpace the current rate of sea-level rise in south Florida (2.4 to 3.6 mm/year). While information on the berms is limited at this time, the differences in accretion rates and elevation suggest that the position of the berm relative to storm trajectory and surges can result in differences in sedimentation, erosion, and elevation on the berms. Our measurements also support what other researchers ( Cahoon 2006; Whelan et al. 2009 ) have shown—that sediment accretion rates and net changes in elevation differ and that more analyses are needed to evaluate the spatial and temporal patterns of berm formation, sedimentation, and erosion.

The destructive aspects of Hurricane Irma to the berms and vegetated portions of the islands are apparent in the satellite imagery and GIS analyses and in the elevation losses detected on the berm at Russell Key and the transition areas of Jim Foot and Buttonwood #7. The GIS analysis indicates a loss of over 9% (-9700 m$^2$) of the vegetated cover on Jim Foot (westem-most and closest to the eye of the storm). Comparing areal extent, the largest losses were on Buttonwood #7 (17,778 m$^2$) and areal losses at Russell Key were similar to Jim Foot (9176 m$^2$); however, in terms of island resiliency, larger percent losses will most likely make an island more vulnerable to further loss of land and rising sea level, particularly if the berm is damaged, as on Jim Foot.

Hurricane Donna also affected Jim Foot; damaged mangroves in the interior of the island appear in a 1963 aerial photo (Craighead 1964, fig. 5) and today, this open area has remnant stumps (some visible in Fig. 8), indicating the trees never recovered. Comparing our assessment of vegetation changes on the islands to other reports from south Florida is difficult because different methods and criteria are used to assess changes; however, our estimates are lower than other mangrove damage assessments following Irma, perhaps due to our conservative estimates of reductions in vegetative cover. Radabaugh et al. (this volume) report an average of 19% mortality 2 to 3 months after Irma, and 36% mortality 9 months post-storm at eleven surveyed plots in the Lower Florida Keys located near the passage of the eye. Proximity to the strong eyewall winds also may explain why their rates are higher than what we estimate for the islands in Florida Bay. Damage to the tall canopy mangrove forests of Florida’s southwest coast were estimated at 60% following Irma, but along the intertidal waterways, damage was described as “significantly less” (Lagomasino et al. 2018) and may be comparable to our findings.

The satellite images (Figs. 6 and 8) highlight the destructive impact and illustrate the value of our multi-disciplinary approach by allowing us to definitively state that the changes seen in Fig. 8 were due to Hurricane Irma; without the satellite images, the argument could be made that those changes happened gradually between 2014 and 2018. The berm on the eastern side of Jim Foot decreased in width ~11.5 to 13 m or 32–42% following the storm. Elevation data in the transitional area between the interior flats and the berm on Jim Foot indicate a loss of 5.6 cm (±28–40 mm) between 2014 and 2018 (Table 3). While we cannot confirm that the loss in elevation was due to Irma alone, the proximity to the highly altered berm area indicates the storm is a likely cause. The transition area on the north side of Buttonwood #7 and the berm on the east side of Russell also show a loss of elevation between 2014 and 2018 (16.7 cm ± 28–30 mm and 38.9 cm ± 23–36 mm, respectively). Changes on the southern tip of Buttonwood #7 (Fig. 5) highlight the reduction in vegetated coverage at this site.

Comparison of Hurricane Pathways and Impacts

The 1935 Labor Day Storm (category 5) and Hurricane Donna (1960, category 4) followed nearly identical paths through the Florida Keys, Florida Bay, and the southwest coastal Everglades (Fig. 3). Irma (category 4) followed a similar path, although it approached the Keys on a more northerly route approximately 80 km west of the Labor Day Storm and Donna. Florida Bay was in the right quadrant of all three storms—considered the most destructive region of hurricanes ( Doyle et al. 1992 ) with higher winds and storm surge; however, the eyewall of the Labor Day storm and Donna passed directly over Florida Bay (Craighead and Gilbert 1962; Ball et al. 1967), whereas Irma’s was west of the bay (Cangialosi et al. 2018). Reports of the effects of the Labor Day Storm are primarily anecdotal but indicate nearly complete destruction of structures in sections of the Keys and extensive damage to islands in the Keys and Florida Bay (Craighead and Gilbert 1962; Houston and Powell 2003) and to Cape Sable ( Smith et al. 2009 ); however, the lack of scientific observations makes direct comparison between the Labor Day Storm and subsequent hurricanes impossible. Similar to Irma, Donna caused water levels to drop preceding the storm with winds coming out of the northeast and as the storm passed, winds shifted to the south/southwest and water moved back in rapidly, with a 13.5-ft (4.1 m) change in water level over approximately a 7-h period (Ball et al. 1967; Perkins and Enos 1968; Houston and Powell 2003). Many of the islands in Florida Bay were damaged, as on Buttonwood #7 and the berm on the east side of Russell also show a loss of elevation between 2014 and 2018 (16.7 cm ± 28–30 mm and 38.9 cm ± 23–36 mm, respectively). Changes on the southern tip of Buttonwood #7 (Fig. 5) highlight the reduction in vegetated coverage at this site.

---

2 Rate of sea-level rise for south Florida based on data from NOAA tide gauge stations at Key West (2.42 mm/year; 1913–2018) and Vaca Key (3.66 mm/year; 1971–2018). Data available at https://tidesandcurrents.noaa.gov/sltrends/sltrends.html
Bay were described as “profoundly altered” (Craighead 1964, p. 10) and the mangrove berms “badly broken, especially on the east and south sides” (Craighead and Gilbert 1962, p. 6) by Donna and, as described above, extensive deposition of marine muds occurred on the islands. Although not quantitatively documented, Craighead (1964, figs. 6–7, 10–12) shows images of mangrove destruction on islands in Florida Bay primarily from Donna, but also older damage he attributes to

Fig. 11 Comparison of the four islands before Hurricane Irma (August 13, 2017) and approximately 10 months after (July 13, 2018): (A) Russell Key, (B) Bob Allen Key, (C) Buttonwood #7 Key, and (D) Jim Foot Key. The digitized vegetated land coverage of each island is filled with solid color. Circled areas and arrows signify the areas of most notable change. Graphs illustrate the reduction in vegetated land area.
the Labor Day Storm. He states that all trees on several islands investigated on foot were completely defoliated (Craighead and Gilbert 1962), and in general, the images (Craighead 1964) indicate Donna was more destructive to island mangroves than Irma, most likely because Donna’s eyewall passed over Florida Bay subjecting the islands to stronger winds.

Hurricane Betsy (1965, category 3) followed a very different path across south Florida moving east to west just over the northern portion of Florida Bay (Fig. 3). In contrast to Donna and Irma, supratidal deposition from Betsy was low (<1 to 2.5 cm) on islands examined in Florida Bay (Perkins and Enos 1968). Perkins and Enos (1968) speculated that the differences between Donna and Betsy were related to the storm paths and subsequent storm surge effects. The right quadrant of Betsy passed primarily over the southern Everglades, and Florida Bay was primarily in the left quadrant of the storm. Although high tides were associated with Betsy (7.4 ft (2.25 m) at Flamingo), water was not substantially lowered in advance of the storm and therefore no subsequent rapid return of water to Florida Bay basins occurred (Perkins and Enos 1968). Hurricane Betsy, however, did cause notable changes on Cape Sable, which lay directly in the path of the eye.

The path of Hurricane Andrew (1992, category 5) paralleled Betsy moving east to west (Fig. 3) but was shifted to the north crossing directly over the Everglades, placing Florida Bay in the left quadrant of the storm. No references to Andrew’s impacts on Florida Bay islands could be found, but Andrew did have both constructive and destructive effects on the southwest coastal mangroves, especially those within the path of the eye and the right quadrant of the storm (Doyle et al. 1992; Houston and Powell 2003). The strong winds knocked down 28,000 ha of mangroves (Davis et al. 1993), caused extensive damage to the canopy trees (Smith et al. 1994; Arementano et al. 1995; Doyle et al. 1995) and the storm surge deposited an average of 7 cm of sediment across 110 km² of the mangrove forest (Risi et al. 1995).

Hurricane Wilma (2005, category 3) approached from the southwest and made landfall in the Ten Thousand Islands area, ~100 km north-northwest of Florida Bay, destroying 1250 ha of mangroves, defoliating nearly 100% of the upper canopy, and damaging forests that had begun to recover from Andrew (Smith et al. 2009; Barr et al. 2012). Wilma deposited sediments in the southwest mangrove forest ranging from 3.7 to 5.6 cm (Whelan et al. 2009) and < 10 cm (Smith et al. 2009). The Florida Keys and Florida Bay fell in the right quadrant of Wilma and the Keys experienced substantial storm surges from 5 to 8 ft (1.5 to 2.4 m) above mean sea level (Kasper 2007). Florida Bay also experienced storm surges of up to 3 ft (0.91 m) above NAVD88 recorded at some ENP water monitoring stations, and there is evidence that water levels lowered in advance of the storm at some sites (data provided by C. Kavanagh, ENP, from Data4EVER database, but there are no published reports of dramatic lowering of water levels prior to the storm, as documented for Donna and Irma. No descriptions of Wilma’s effects on islands in Florida Bay could be found; however, storm deposition on Butternut #7 was visible from the water in December 2005 (Wingard, field observation 12/11/2005).

Perkins and Enos (1968) stated that the direction of approach of a storm is a key factor, along with storm intensity, duration, width of the eye wall, and a number of other factors, in determining the constructive and destructive effects of the storms. Based on the limited information we have for comparison, Florida Bay seems to be more vulnerable when storms approach from a southerly direction (as the Labor Day Storm, Donna, and Irma did) and possibly from the west or southwest (as Wilma did) placing the bay in the right, most destructive, quadrant of the storm. In addition, storms approaching from the south set up a scenario for maximum tidal range by pushing water out of Florida Bay (open to the southwest) with winds from the northeast as the storm approaches and driving water back into the bay with winds from the southwest as the storm passes (Perkins and Enos 1968; Houston and Powell 2003). This combination of placement in the right quadrant and the effect of bay geometry on storm surges plays an important role in determining the amount of supratidal deposition on Florida Bay’s islands, the degree of erosion of island margins, and the damage to the mangroves. Analyzing the influence of direction of approach on the impacts of future storms on Florida Bay is an important area for future research.

**Long-Term Decadal Scale Effects**

The physical, biological, and biogeochemical effects of hurricanes on mangrove coastal ecosystems are complex and a number of factors interact over decadal time periods to determine resiliency of the system. The majority of research done on these ecosystems has been conducted on coastal mangrove forests—ecosystems that have space to retreat, unlike the Florida Bay island mangroves. Castaeda-Moya et al. (2010), working in coastal mangrove forests of Everglades National Park, estimate that vertical accretion from hurricane deposition can be eight to seventeen times greater than the 50-year averaged annual accretion rate. Breithaup et al. (this volume) estimate that deposition from Irma was approximately equal to the annual average accretion rate for the previous decade and affected the biogeochemistry of the coastal mangrove soils by significantly increasing the deposition of organic carbon, total nitrogen, and total phosphorus compared to the average annual rate for the last century. These values highlight the importance of coastal storms as land-building processes but, conversely, storm deposition, may have a negative impact on black mangroves by covering pneumatophores and when combined with the wind damage to all types of mangroves can cause additional stress that leads to die-off (Smith et al. 2009).

Overstepping of the coastal berm along south Florida’s mainland following hurricanes has been well documented.
(Wanless et al. 1994; Smith et al. 2009). Toppling of mangroves—not erosion of the shoreline—starts a complex set of feedback loops. Canopy loss affects soil temperatures, and downed trees create depressions where the roots existed. Combined, these factors affect the ability of mangrove saplings to take root, which then leads to decreased peat elevation, and additional saltwater intrusion, ultimately converting the forest to a mudflat over time (Smith et al. 1994; Barr et al. 2012). These processes have been documented at monitoring sites established on Cape Sable following Hurricane Andrew and these sites illustrate the net effects of hurricanes over decadial time-scales. The Big Sable Creek area of Cape Sable has been affected by the Labor Day Storm, Donna, Andrew, Wilma (Smith et al. 2009), and now Irma. The area was a dense mangrove forest prior to the Labor Day storm based on historical accounts, but each subsequent storm has contributed cumulative impacts, setting back mangrove recovery from prior storms, leading to the conversion of this site to extensive mudflats (Wanless et al. 1994; Smith et al. 2009). Coupled with elevated rates of sea-level rise, repeated storm overstepping could facilitate rapid shoreline transgression, as is believed to have occurred in south Florida in the late Holocene (Jones et al. 2019).

To date, no long-term monitoring studies have been conducted on islands in Florida Bay. Our observations, measurements, and analyses of Hurricane Irma’s impact on four islands in Florida Bay have captured a snapshot of the short-term effects of the storm. Continued investigation is needed to understand the long-term impacts caused by the complex interaction of processes related to the constructive and destructive storm effects. The role of storm deposition in building up and/or maintaining the islands is critical. Ginsburg and Lowenstam (1958) believed that almost all sediment accumulating on the interior mudflats on Florida Bay islands is deposited by storms. Because the open mudflats in the center of the islands lie at or below sea level (Table 3), an intact mangrove fringe and berm is necessary to trap sediments deposited by storms in the interior and potentially allow island build-up to keep pace with sea-level rise. Yet, in the case of Jim Foot Key, it appears that the damage caused to the mangrove berm may outweigh the land-building components of storm deposition; the berm required to trap those sediments has been nearly leveled on the eastern side of the island. In addition, loss or reduction of island berms increases the frequency of flooding, which alters the salinity/freshwater balance and can lead to additional die-off and conversion of the vegetation (Swart and Kramer 1997).

Monitoring over the coming decades will indicate whether the constructive forces of Irma, and subsequent hurricanes, are enough to overcome the destructive forces and to allow the islands to be resilient and keep pace with sea-level rise. Mangrove forests are considered highly resilient to tropical storms and hurricanes (Castaeda-Moya et al. 2010), but it is unclear whether mangrove islands have the same resilience. With interiors of the islands at lower elevations than the berms, these mangroves have no place to retreat. Elevation measurements were made in 2018 with the intention of repeating these measurements in future years to monitor change and studies of sediment accumulation rates on the mudflats and berms are ongoing. Close monitoring of Jim Foot Key is particularly warranted because in 2014 we noted it had the lowest elevation of all the islands and had already developed a breach in the southeastern corner where tidal exchange occurred between the mudflat and the estuary. Considering the reduction in vegetated landmass and particularly the degradation of the eastern berm following Irma, Jim Foot may be an excellent place to examine changes over the next decade.

### Summary

When it made landfall on September 10, 2017 as a category 4 storm, Hurricane Irma had a substantial impact on four islands investigated in Florida Bay, Everglades National Park, Florida. Hurricane Irma had both constructive and destructive impacts based on our field observations, elevation measurements, and GIS analysis of satellite imagery. Overwash deposits from Hurricane Irma consisted of carbonate mud, ranged from ~0.5 to ~6.5 cm in thickness, and were limited primarily to the interior of the islands. Other indications of storm surge included mats of dead seagrass washed into the island centers, concentrations of estuarine organisms stranded on the islands, and imbricated mangrove leaves. Defoliated mangroves were noted on every island, particularly black mangroves. A comparison of elevation measurements between 2014 and 2018, although limited in number, indicate that, in general, berms and transition areas between the mudflats and berms lost elevation and mudflats gained elevation. Satellite imagery showed the western-most island (Jim Foot Key), closest to the passage of the eye of the storm, lost approximately 9.3% of its vegetated land coverage, while the eastern-most island (Russell Key) lost the least (~1.9%). Particularly significant was the reduced width (loss of ~11.5 to 13 m, or 32–42%) of the berm on the east side of Jim Foot Key. Future monitoring of Jim Foot may provide valuable information on island responses to the combined effects of constructive and destructive hurricane impacts.

Our field observations compare closely to those documented for Hurricane Donna (1960), a storm of similar strength and path. Limited comparative data and knowledge of wind dynamics in hurricane quadrants suggests that Florida Bay islands may be more impacted by hurricanes approaching from the south, as the Labor Day Storm, Donna, and Irma did, than from other directions. A southerly approach sets up a scenario for maximum tidal range and storm surge in Florida Bay. Understanding the influence of direction of approach
may be an important predictive tool for resource management and protection but additional storm modeling is needed.

The fate of Florida Bay Islands in the coming decades may be a forerunner of changes to the Florida coastline over the next century. Research on the history of these islands 3400 to 2800 years ago indicates that climate variability may play a key role in rapid coastal inundation, even during times of low sea-level rise rates (Jones et al. 2019). The data and insights gained from studying island responses to this single event—Hurricane Irma—provide a baseline for examining cumulative impacts of future storms and for retrospective examinations of the sediment record. Understanding the complex interactions and net long-term effects of the constructive and destructive aspects of storms is critical for resource managers tasked with assessing how Florida Bay may respond to future climate and sea-level changes and ultimately determining the resiliency of the islands.

Acknowledgments We would like to thank Everglades National Park (ENP) for providing access to the research sites and Christopher Kavanagh, Marine Ecologist, Florida Bay Interagency Science Center, Everglades National Park, for providing data on water levels in Florida Bay and observations of storm effects. We appreciate the thorough comments and suggestions provided by two anonymous reviewers, which considerably improved this paper. Francis Ashland, USGS, and Michael Toomey, USGS, provided helpful suggestions during an early review of the manuscript. We thank Jessica Rodysill, USGS, for training and assistance with the Geotek. Diana Carrick, USGS, and Cheyenne Everhart, USGS contractor with Cherokee Nations Technologies, assisted with laboratory analyses. Fieldwork in 2014 was conducted with assistance from Christopher Bernhardt and Terrence McCluskey, USGS, James Murray, former USGS, and Anna Wachnicka, SFWMD. Rachel Stevenson and Allison Bauser, Nova Southeastern University graduate students, assisted with fieldwork and photography in 2018.

Funding Information Research was funded by the U.S. Geological Survey (USGS) Greater Everglades Priority Ecosystems Science (GEPES) program. The samples and cores were collected as part of National Park Service (NPS) Study number EVER-00141.

Compliance with Ethical Standards

Disclaimer Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US government.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

Appleby, P.G. 2002. Chronostratigraphic techniques in recent sediments. In Tracking environmental change using lake sediments. Developments in paleoenvironmental research 1, ed. W.M. Last and J.P. Smol, 171–203. Dordrecht: Springer.

Arenentano, T.V., R.F. Doren, W.J. Platt, and T. Mullins. 1995. Effects of Hurricane Andrew on coastal and interior forests of southern Florida: overview and synthesis. Journal of Coastal Research 21: 111–144.

Ball, M.M., E.A. Shinn, and K.W. Stockman. 1967. The geologic effects of hurricane Donna in south Florida. The Journal of Geology 75 (5): 583–597.

Barr, J.G., V. Engel, T.J. Smith, and J.D. Fuentes. 2012. Hurricane disturbance and recovery of balance, CO2 fluxes and canopy structure in a mangrove forest of the Florida Everglades. Agricultural and Forest Meteorology 153: 54–66. https://doi.org/10.1016/j.agrformet.2011.07.022.

Breithaupt, J.L., J.M. Smoak, T.J. Smith III, and C.J. Sanders. 2014. Temporal variability of carbon and nutrient burial, sediment accretion, and mass accumulation over the past century in a carbonate platform mangrove forest of the Florida Everglades. Journal of Geophysical Research: Biogeosciences 119 (10): 2032–2048. https://doi.org/10.1002/2014JG002715.

Breithaupt, J.L., N. Hurst, H.E. Steinnuller, E. Duga, J.M. Smoak, J.S. Kominoski, and L.G. Chambers. This volume. Biogeochemical impacts of storm surge sediments in coastal wetlands: Hurricane Irma and the Florida Everglades. Estuaries and Coasts this volume.

Cahoon, D.R. 2006. A review of major storm impacts on coastal wetland elevations. Estuaries and Coasts 29 (6): 889–898. https://doi.org/10.1007/BF02798648.

Cangialosi, J.P., A.S. Latto, and R. Berg. 2018. Hurricane Irma (AL112017): 30 August–12 September 2017. National Hurricane Center Tropical Cyclone Report 111. https://www.nhc.noaa.gov/data/tcr/AL112017 Irma.pdf. Accessed 28 November 2018.

Castañeda-Moya, E., R.R. Twilley, V.H. Rivera-Monroy, K. Zhang, S.E. Davis III, and M. Ross. 2010. Sediment and nutrient deposition associated with hurricane Wilma in mangroves of the Florida Coastal Everglades. Estuaries and Coasts 33 (1): 45–58. https://doi.org/10.1007/s12237-009-9242-0.

Craighead, F.C. 1964. Land, mangroves and hurricanes. The Fairchild Tropical Garden Bulletin 19: 5–28.

Craighead, F.C., and V.C. Gilbert. 1962. The effects of Hurricane Donna on the vegetation of southern Florida. Quarterly Journal of the Florida Academy of Sciences 25: 1–28.

Davis, G.E., M. Flora, L.L. Loope, B. Mitchell, C.T. Roman, G. Smith, M. Soukup, and J.T. Tilmant. 1993. Assessment of Hurricane Andrew’s immediate impacts on natural and archeological resources of Big Cypress National Preserve, Biscayne National Park, and Everglades National Park. George Wright Society Forum 10: 30–40.

Dean, W.E. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. Journal of Sedimentary Research 44 (1): 242–248.

Doyle, T.W., T.J. Smith, and M.B. Robblee. 1992. Wind damage effects of Hurricane Andrew on mangrove communities along the southwest coast of Florida, USA. Journal of Coastal Research, spec. issue 21: 159–168.

Enos, P. 1989. Islands in the bay – a key habitat of Florida Bay. Bulletin of Marine Science 44: 365–386.

Enos, P., and R.D. Perkins. 1979. Evolution of Florida Bay from island stratigraphy. Geological Society of America Bulletin 90 (1): 59–83.

Ginsburg, R.N., and H.A. Lowenstam. 1958. The influence of marine bottom communities on the depositional environment of sediments. Journal of Geology 66 (3): 310–318.

Greening, H., P. Doering, and C. Corbett. 2006. Hurricane impacts on coastal ecosystems. Estuaries and Coasts 29 (6): 877–879. https://doi.org/10.1007/BF02798646.

Homlquist, J.G., G.V.N. Powell, and S.M. Sogard. 1989. Sediment, water level, and water temperature characteristics of Florida Bay’s grass-covered mud banks. Bulletin of Marine Science 44: 348–364.
Houston, S.H., and M.D. Powell. 2003. Surface wind fields for Florida Bay hurricanes. *Journal of Coastal Research* 19: 503–513.

Jones, M.C., G.L. Wingard, B. Stackhouse, K. Keller, D. Willard, M. Marot, B. Landacre, and C. Bernhardt. 2019. Rapid inundation of southern Florida coastline despite low relative sea-level rise rates during the late-Holocene. *Nature Communications* 10 (1): 3231. https://doi.org/10.1038/s41467-019-11138-4.

Kasper, K. 2007. Hurricane Wilma in the Florida Keys. NOAA National Weather Service Forecast Office Report. https://www.weather.gov/key/wilma. Accessed 15 May 2019.

Lagomasino, D., T. Fatoyinbo, D.C. Morton, B. Cook, P. Montesano, E. Castañeda-Moya, C.S.R. Neigh, R.P. Moyer, K. Radabaugh, J.M. Smoak, and T. Troxler. 2018. Heterogeneous patterns of mangrove disturbance and recovery from hurricane Irma. *American Geophysical Union Fall Meeting Abstract*: B41F–B2775F.

Lodge, T.E. 2010. *The Everglades handbook: understanding the ecosystem*. 2nd ed. Boca Raton, Florida: CRC Press.

Marot, M.E., C.G. Smith, A.M. Ellis, and C.J. Wheaton. 2016. Evaluating the potential effects of hurricanes on long-term sediment accumulation in two micro-tidal sub-estuaries: Barnegat Bay and Little Egg Harbor, New Jersey. *U.S. Geological Survey Data Series* 993. https://doi.org/10.3133/ds993.

Perkins, R.D., and P. Enos. 1968. Hurricane Betsy in the Florida-Bahama area – geologic effects and comparison with hurricane Donna. *The Journal of Geology* 76 (6): 710–717.

Radabaugh, K.R., R.P. Moyer, A.R. Chappel, E.E. Dontis, C.E. Russo, K.M. Joyse, M.W. Bownik, A.H. Goeckner, and N.S. Khan. This volume. Mangrove damage, delayed mortality, and early recovery following Hurricane Irma at two landfill sites in southwestern Florida, USA. *Estuaries and Coasts* this volume.

Risi, J.A., H.R. Wanless, L.P. Tedesco, and S. Gelsanilter. 1995. Catastrophic sedimentation from hurricane Andrew along the southwest Florida coast. *Journal of Coastal Research* 21: 83–102.

Schomer, N.S., and R.D. Drew. 1982. An ecological characterization of the lower Everglades, Florida Bay, and the Florida Keys. Washington, D.C.: U.S. Fish and Wildlife Service, Office of Biological Services FWS/OBS-82/58.1.

Shinn, E.A., and B.H. Lidz. 2018. *Geology of the Florida Keys*. Gainesville: University Press of Florida.

Smith, N.P. 1997. An introduction to the tides of Florida Bay. *Florida Scientist* 60: 53–67.

Smith, T.J., III, G.H. Anderson, K. Balentine, G. Tiling, G.A. Ward, and K.R.T. Whelan. 2009. Cumulative impacts of hurricanes on Florida mangrove ecosystems: sediment deposition, storm surges and vegetation. *Wetlands* 29 (1): 24–34.

Swart, P.K., and P.A. Kramer. 1997. Geology of mud islands in Florida Bay. In *Geology and hydrogeology of carbonate islands: developments in sedimentology*, ed. L. Vacher and T. Quinn, 54th ed., 249–274. Amsterdam: Elsevier Science.

Twilley, R.R. 2007. Coastal wetlands and global climate change: Gulf Coast wetland sustainability in a changing climate. Arlington: Pew Center on Global Climate Change http://dev.cakex.org/sites/default/files/Regional-Impacts-Gulf.pdf. Accessed 28 November 2018.

Wang, J.D., J. van de Kreeke, N. Krishnan, and D. Smith. 1994. Wind and tide response in Florida Bay. *Bulletin of Marine Science* 54: 579–601.

Wanless, H.R., R.W. Parkinson, and L.P. Tedesco. 1994. Sea level control on stability of Everglades wetlands. In *Everglades: the ecosystem and its restoration*, ed. S.M. Davis and J.C. Ogden, 199–223. Delray Beach: St. Lucie Press.

Whelan, R.T., T.J. Smith, G.H. Anderson, and M.L. Ouellette. 2009. Hurricane Wilma’s impact on overall soil elevation and zones within the soil profile in a mangrove forest. *Wetlands* 29 (1): 16–23.