# Low resistance to overwash promotes sustained accretion of a washover fan on a transgressive barrier island during non-stormy periods

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## Key Points

A 3-year record of changes in washover area and volume along with overwash frequency and magnitude was compiled at a barrier island site.

Overwash and washover deposition occurred mainly in the absence of large storms due to the low elevation and low resistance to inundation.

A large storm is not required for deposition of a voluminous extensive washover, which can also form during frequent small overwash events.

## ABSTRACT

Barrier island overwash occurs when the elevation of wave runup exceeds the dune crest and induces landward transport of sediment across a barrier island and deposition of a washover deposit. Washover deposition is generally attributed to major storms, is important for the maintenance of barrier island resilience to sea-level rise, and is used to extend hurricane records by reconstructing the frequency and extent of washover deposits preserved in the sedimentary record. Here, we present a high-fidelity 3-year record of washover evolution and overwash at a transgressive barrier site.  During the first year after establishment, washover volume and area increased 1,595% and 197%, respectively, from monthly overwash. Most of the washover accretion resulted from the site morphology having a low resistance to overwash, as opposed to being directly impacted by major storms. Washover deposits can accrete over multi-year time scales, therefore, paleowashover deposits are more complex than simply event beds.

## PLAIN LANGUAGE SUMMARY

When the ocean surface exceeds the height of a barrier island, water flows across the island, carries beach sand with it, and forms a sandy washover fan that extends landward onto saltmarsh or into the adjacent lagoon. It is commonly thought that washover fans form rapidly as a major storm strikes an island and ocean water floods over the beach and dunes. The landward movement of sand when the ocean is flowing across the island is hazardous to communities but fortifies barrier islands facing sea-level rise and beach erosion. During 3 years of mapping a washover fan and monitoring water level on a barrier island, we documented frequent ocean flooding that resulted in the continuous growth of a very large fan.  A single major storm did not form the washover fan, rather, most of its growth was due to the low height of the island, which made the site vulnerable to frequent ocean flooding.  The formation of washover fans is necessary for barrier islands to migrate landward with sea-level rise; however, large storms are not a requirement.

**Keywords:** Washover, Overwash, Hurricane, Barrier Island, Paleotempestology, Coastal resilience

# 1. INTRODUCTION

Transport of sediment and water across a barrier island during increased ocean-water levels and wave heights, termed overwash, can be highly detrimental to infrastructure (Kennedy et al., 2011), human health (Presley et al., 2006), and economies (Pielke et al., 2008). Despite those hazards, overwash is essential for sustaining barrier islands faced with rising sea level because it fortifies the island by moving sand landward and depositing it as elevated washover terraces and fans. Washover deposits increase barrier-island width, resilience to sea-level rise, and resistance to erosional events (Lorenzo-Trueba and Ashton, 2014). Episodic overwash drives barrier island landward migration with sea-level rise maintaining sediment budgets in dynamic equilibrium (Leatherman, 1979; Oertel, 1985).

Overwash is commonly linked with storm conditions, mainly investigated by pairing pre- and post-storm observations (Morton and Sallenger, 2003; Stone et al., 2004; Wang and Horwitz, 2007; Shaw et al., 2015), during storm observations (Sherwood et al., 2014), and short-term monitoring (<1 year; e.g. Kochel and Dolan, 1986; Leatherman and Zaremba, 1987). The occurrence of non-storm overwash has been documented (Morton et al., 2000; Matias et al., 2010; VanDusen et al., 2016), demonstrating the capacity of overwash to transport sediment across a shoreline in the absence of a major event. The emplacement of a washover deposit in a back-barrier environment (marshes, lagoons, and ponds), however, is generally interpreted as resulting from a single major storm event, such as a hurricane. Washover deposits preserved in the stratigraphic record are used to reconstruct the spatial and temporal variability of storm activity (e.g., Liu and Fearn, 1993; Wallace et al., 2014; Donnelly et al., 2015). In addition, researchers have interpreted the stratigraphy of a washover deposit to provide information about the timing of deposition during the storm (Shaw et al., 2015) and the sediment source (Hawkes and Horton, 2012). If washover deposits, particularly those that extend into back-barrier intertidal and subtidal areas, accrete significantly in response to tidal flooding or minor storm events, then the research community could be misinterpreting the meaning of some paleotempestites.

A large storm is typically thought of as the primary mechanism driving overwash; however, cross-island transport of water and sand is fundamentally a function of island geomorphology (height and width) and oceanographic conditions including tide, storm surge, wave setup, and wave runup (Sallenger, 2000). Large storms are not a requirement for washover deposition in the backbarrier because with decreasing island width and elevation the resistance of a barrier to overwash decreases. Beach erosion, which impacts about 70% of Earth's sandy beaches (Bird, 1985), is the main driver of decreasing island width and elevation. Accelerating sea-level rise (Pethick, 2001; Zhang et al., 2004; Wallace and Anderson, 2013), decreasing sediment supply (Morton and McKenna, 1999; Penland et al., 2005), anthropogenic influences (Hsu et al., 2007) and changing storm climate (Johnson et al., 2015) exacerbate beach erosion. This suggests that resistance to overwash should be decreasing globally. To better understand the transition of a barrier island from a coastal morphology that was resistant to overwash to one experiencing persistent overwash and washover deposition, we present a three-year time series of oceanographic conditions, overwash, and morphologic changes.

## 2. METHODS

### 2.1 Site Selection

The study site is located on Onslow Beach, NC (Figure 1), which was part of a 5-year monitoring project of beach morphology that began in 2007. During that study, investigators mapped a narrow (supratidal cross-shore distance 45 m), low-elevation (max. 2.5 m NAVD88) sector of the barrier that appeared to have a low resistance to overwash (same area as Site F2 from Theuerkauf and Rodriguez, 2014). At the end of that project, Hurricane Irene, a Category 1 storm, caused overwash of Site F2 on August 27, 2011 and washover deposits buried back-barrier fringing saltmarsh (Figure 1). The present monitoring study began after Hurricane Irene.

### 2.2 Mapping

The site was mapped 16 times from May 21, 2012 to October 12, 2015 using a Riegl three-dimensional LMSZ210ii terrestrial laser scanner mounted on a truck. The average time between mapping excursions was 83 days with a maximum and minimum of 175 days and 8 days, respectively (supplementary table 1). The scanner was set to emit around 2 million laser

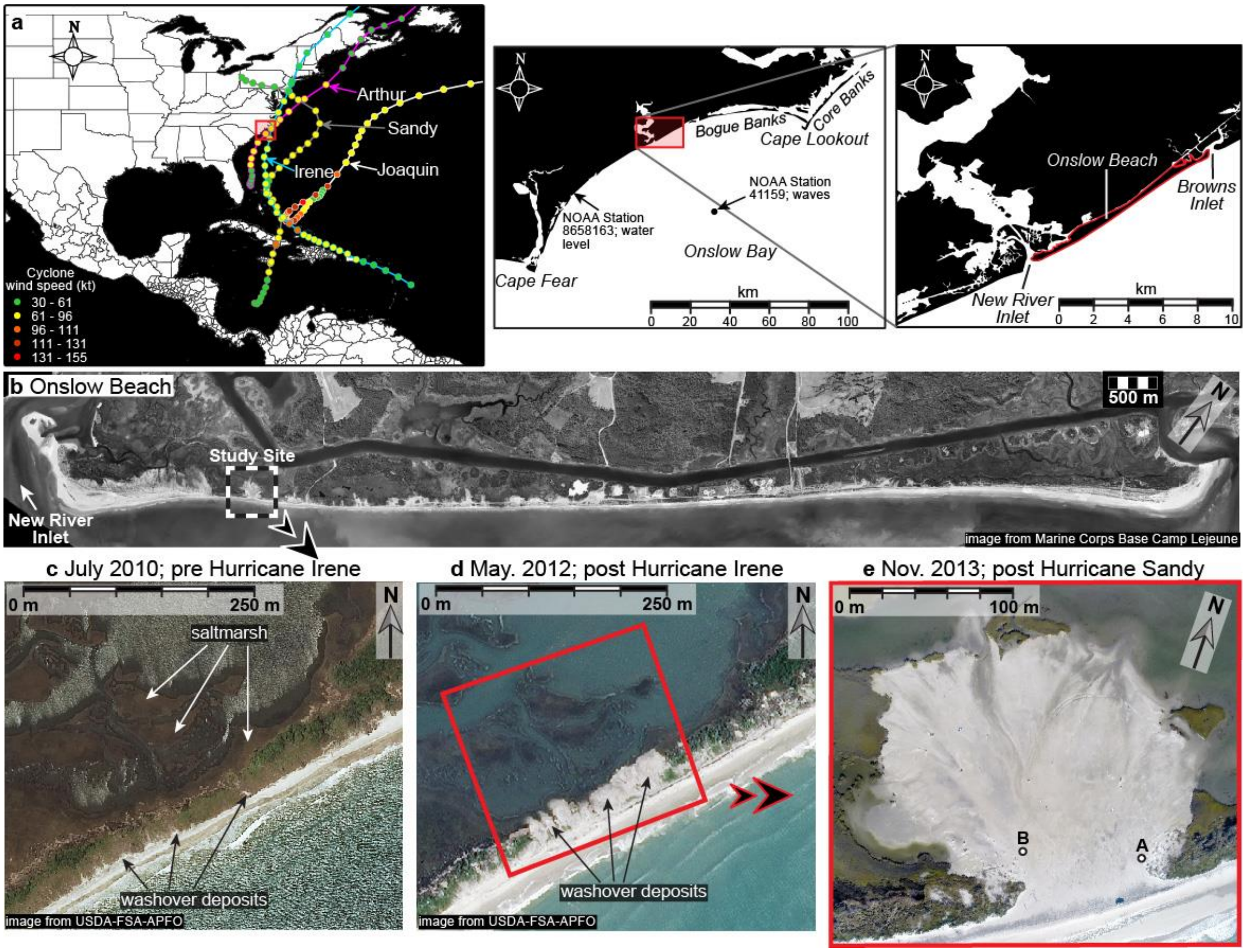


Figure 1: Locations of Onslow Beach and the study site. a, The relevant hurricanes that impacted the site between August 2011 and November 2014. b, Image of Onslow Beach from April 2013 outlining the location of the site. c, Numerous washover deposits were isolated to the coastal-dune area. d, Hurricane Irene (August 27, 2011) caused washover deposits to extend landward and bury fringing saltmarsh. Photographs in c and d are from United States Department of Agriculture Farm Service Agency Aerial Photography Field Office (USDA-FSA-APFO). e, Hurricane Sandy (October 29, 2012) caused overwash and formation of a large washover fan. Overwash-sensors located at A and B (photograph obtained using a drone).

beams with about 1 million being reflected by objects and returned as x, y, and z data points per scan. Scan locations were positioned ~200 m apart. Data points were referenced using seven or nine surveyed and leveled reflectors (using a Trimble R8s GPS receiver) distributed around the area of each scan position. Field excursions were limited to the two hours before and after low tide to maximize data coverage along the perimeter of the fan (the scanner cannot image through water).

Using Merrick Advanced Remote Sensing Software, we isolated ground points from the point clouds and created digital elevation models (DEMs) using Delaunay Triangulation (VanDusen, 2013). Those DEMs were imported into Golden Software's Surfer with a 0.50-m grid spacing for analysis. We consistently used the break in slope along the perimeter of the washover fan on each DEM to delineate it from adjacent lower-elevation saltmarsh and beach and higher-elevation dunes with an average digitizing error of 0.75 m. Washover area ($W_a$) and volume ($W_v$) were calculated from the DEMs. Error associated with measuring $W_a$ ($EW_a$) was defined as $\pm$ 1.25 $\times$ perimeter with 1.25 being the sum of the DEM grid spacing and the digitizing error. We measured $W_v$ using a DEM created from airborne lidar data collected in 2010 (https://coast.noaa.gov) as a constant basal surface. The 2010 DEM was subtracted from each successive DEM of the washover fan to calculate $W_v$. The potential sources of error that could have impacted measuring $W_v$ include GPS error, laser-scanner instrument error, error with manually levelling the reflectors and associating them with the surveyed points, error associated with editing the point cloud, and error associated with the interpolation algorithms used to create DEMs. We quantified these errors experimentally by scanning the same beach area three times during a 2-hour period and creating DEMs (resulting vertical error = 0.043 m; see supplemental Figure 1 for details). Measurement and procedural error associated with calculating $W_v$ was defined as $\pm$ 0.043($W_a$ + $EW_a$). Negative elevation change from compaction of the sediments must have occurred during the period, could not be quantified with our remote-sensing method, and is spatially heterogeneous, likely largest in landward areas where sand was deposited on top of saltmarsh peat. Volumes reported here should be considered minimum values because compaction was not addressed.

### 2.3 Overwash Processes

Overwash was recorded at two locations on the washover using HOBO water-level data loggers suspended in shallow wells (Figure 1). Results were validated visually with trail cameras programmed to take photographs every 5 minutes during daylight hours. Overwash occurs when total water elevation exceeds the foredune ridge or beach berm elevation and is commonly parsed into a lower magnitude runup overwash regime, where wave runup overtops the dune or berm crest and an inundation overwash regime where the island is submerged (Sallenger, 2000; Donnelly et al., 2006). Following the same methodology outlined in VanDusen et al. (2016), we recorded runup overwash, low-inundation overwash (water level <10 cm above ground), and high inundation overwash (water level ≥10 cm above ground) from June 4, 2012 to July 16, 2015. The wells are located on the washover fan ~80 m apart and were initially installed at similar elevations. As the monitoring progressed, the elevation of the ground around the wells fluctuated. The ground level 1.0 m away from Well A (period average = 0.91 ± 0.15 m; ± SD) generally increased through time resulting in that area becoming more resistant to overwash. The elevation of the ground around Well B (period average = 0.72 ± 0.07 m; ± SD) was generally lower than Well A. For this study we were interested in overwash that was most likely capable of transporting sediment across the island; therefore, we only included overwash events with a duration ≥30 minutes. We created a composite overwash record such that if both wells experienced overwash, then we only included the highest water level and if one well recorded overwash, then we used that one well to characterize water level during the event. No data were recorded at Well B from October 24 to December 28, 2012 due to storm damage. Overwash at the site was placed in context with significant wave height ($H_s$) and water-level data obtained from NOAA Station 41159, located 50 km southeast of the study area, and Wrightsville Pier NOAA Station 8658163, located about 55 km southwest of the study area, respectively (Figure 1). Station 41159 was removed from service in 2015.

## 3. RESULTS

The site experienced multiple episodes of overwash, landward transport of sand, and washover fan lateral accretion during the 1240-day study period. Those episodes did not always occur simultaneously with a large storm. Initially, the study site experienced runup and low-inundation overwash during the months of June, August, September and October of 2012 (Figure

2). Overwash occurred through two throat channels that had cut through the foredune during previous storm events. From June through October 2012, overwash occurrence was neither related to stormy conditions nor increased the size of the washover fan (Figures 2 and 3). On October 24, 2012, the size of the washover fan was 3,290 ± 165 $m^2$ and 1,116 ± 131 $m^3$, using the 2010 DEM as a base, and the foredune was discontinuous with a maximum width of 11.5 m and an average height of 2.5 m (Figures 2 and 4). As Hurricane Sandy passed offshore of the area on October 29, 2012, the maximum ocean water level and $H_s$ was 1.16 m and 4.65 m, respectively, resulting in 20 hours of high-inundation overwash that began in the afternoon of October 27, with ~20 cm of water measured above the ground surface at Well A. On November 1, two days after the storm passed, the washover fan had increased in size to 8,204 ± 410 $m^2$ and 4,531 ± 327 $m^3$ (Figure 2). In comparison to the pre-storm survey, the foredune eroded, decreasing ~1.5 m in elevation, and the 0.04 m elevation contour of the beach moved landward a maximum and minimum of 25 m and 12 m, respectively (Figure 3). Conditions associated with Hurricane Sandy deepened the southwestern throat channel near the location of Well B to an elevation below MHHW, inundated the area where the foredune previously existed, and transported sediment landward to produce the 149% and 306% increase in washover fan area and volume, respectively (Figures 2 and 3). Well B was damaged and not recording water levels from October 24 to December 28.

Over the next two months the site was impacted by two nor'easter events in the middle of November and the middle of December with a maximum ocean water level and $H_s$ of 1.40 m and 3.35 m, respectively. During those two months, Well A recorded low-inundation overwash for 1 hour on December 13 and runup overwash during peak high tides on December 14 and 15 (Figure 2). Well B was inoperable at that time, but overwash was likely more frequent at that lower-elevation western end of the washover in the vicinity of the throat channel, than what was recorded by Well A. The washover fan grew during that two-month period as it had during Hurricane Sandy. By December 28, the washover fan had increased in size to 19,396 ± 924 $m^2$ and 8,484 ± 873 $m^3$. Accretion of the washover fan was likely due to overwash transporting sediment across the entire site because the strike-aligned profile sampled through the maximum elevations of the site decreased to a level close to MHHW at the transition between the foreshore and the landward-sloping washover (Figures 2, and 3). The 0.04 m elevation contour on the

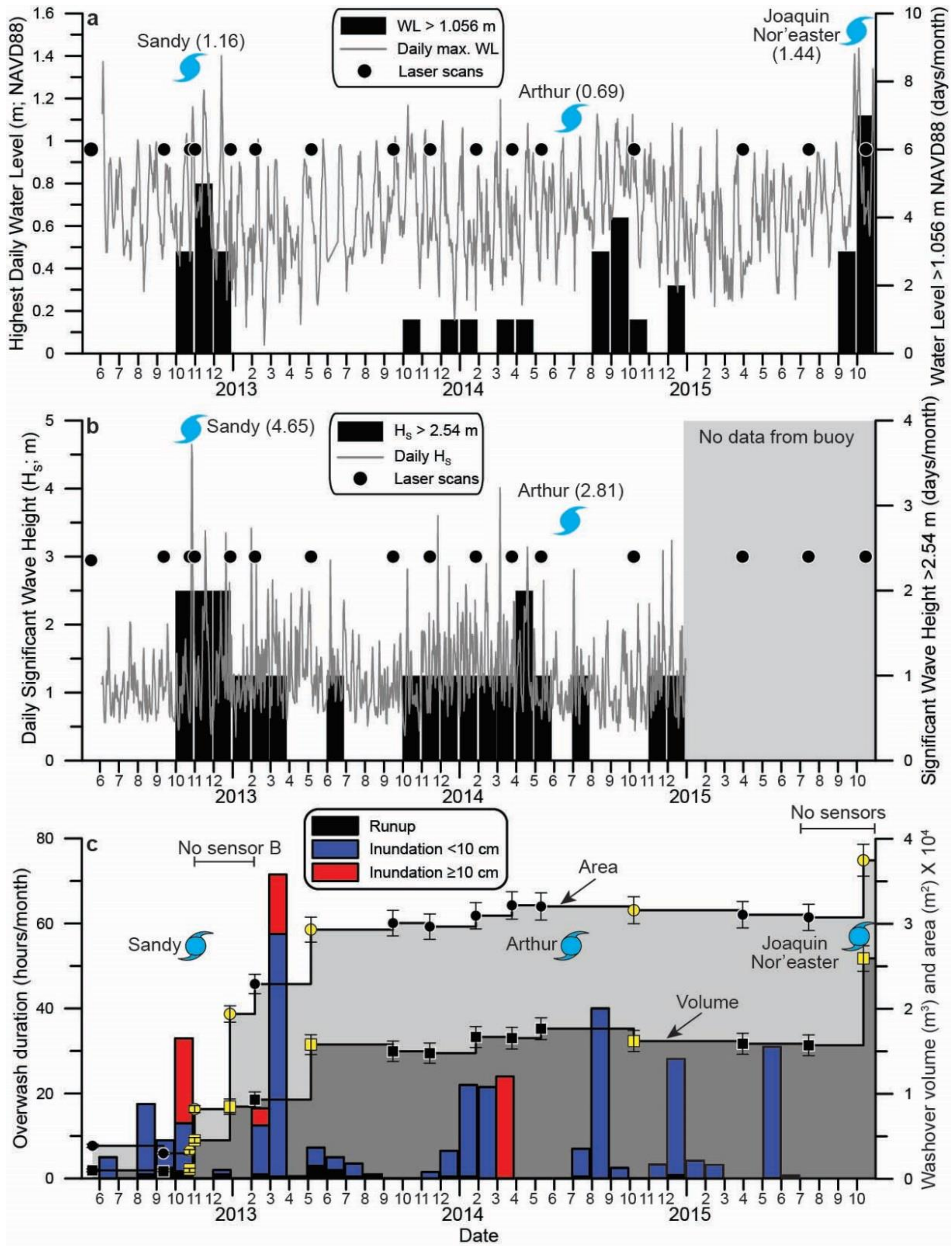


Figure 2: Time series of physical processes and data collection at the site from May 2012 to November 2014. a, Highest daily water levels at NOAA station 8658163. b, Daily significant wave heights at NOAA station 41159. c, Overwash duration and water level at the site- a composite record from two sensors located on Figure 1e. Measurements of area (circles) and volume (squares) were made using the DEMs and yellow points are measurements based on those DEMs shown in Figure 3.

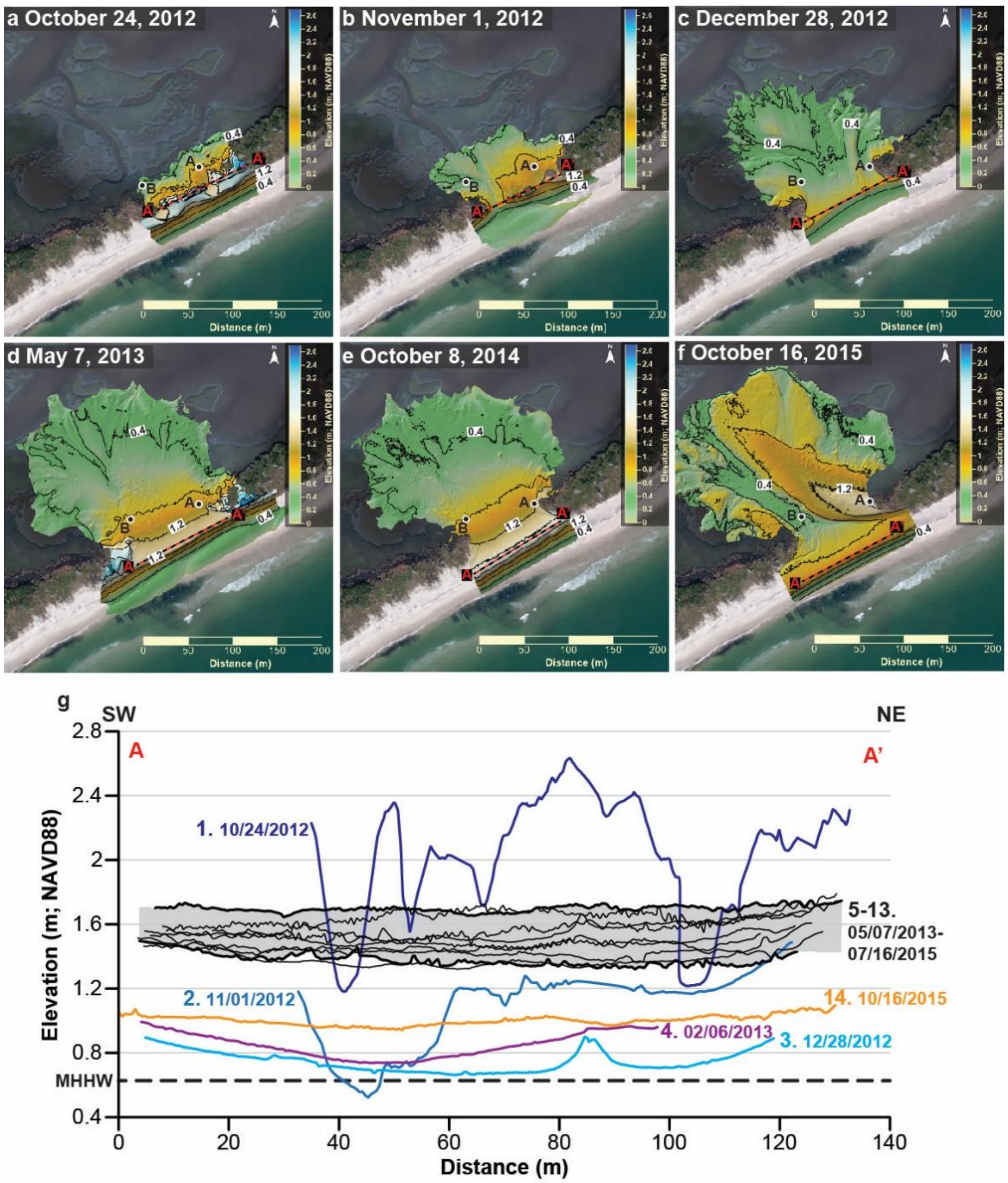


Figure 3: DEMs showing morphologic changes at the site. Background image taken August 2011 and obtained by Marine Corps Base Camp Lejeune. Circles show well locations. a, Morphology of the site five days before Hurricane Sandy. b, The washover deposit had more than doubled in size two days after Hurricane Sandy. c-d, The washover deposit continued to grow during the subsequent six months. e-f, The size of the washover deposit changed little until Hurricane Joaquin on October 12, 2015. g, Along-shore elevation profiles extracted from all DEMs obtained. Profiles are from where the elevation is at a maximum (commonly the foredune crest) and numbered consecutively from October 2012. The gray shading highlights profiles from DEMs showing little change in washover area and volume (5-13; supplemental Figure 2). Dashed line=Mean Higher High Water (MHHW).

beach remained relatively stationary in comparison to the previous November 1 survey (Figure 3).

The site experienced no overwash during the following month (January, 2013; Figure 2) and the DEM of February 6, 2013 shows that the washover fan gained no volume (within error), but the beach had accreted (Figure 3) and the 0.4 m contour moved seaward ~20 m to the pre-Hurricane Sandy position. After topography data were collected on February 6, 2013, the site experienced the highest frequency of overwash on record, with 4 days in February and 7 days in March for a total of 1.5 hours of runup overwash, 68.5 hours of low-inundation overwash, and 18 hours of high-inundation overwash with a maximum water depth of 24 cm above ground level measured at Well B. During that two-month period, no large storm waves or high-water events were recorded in the ocean (Figure 2). The May 7, 2013 DEM shows that the washover fan increased in size to 29,321 ±921 $m^2$ and 15,790 ±1,300 $m^3$ (Figures 2 and 3). Topography data for that May DEM was obtained one month after the overwash events occurred, and by that time a continuous narrow incipient foredune had established with an average elevation of 1.45 m (Figure 3). During the 187 days after the post-Hurricane Sandy topography data were collected, the washover increased in area and volume 257% and 249%, respectively.

From May 7, 2013 to July 16, 2015 we mapped the topography of the site 8 times with a maximum and minimum period between scans of 175 and 47 days, respectively, and neither the area nor volume of the washover fan changed above the measurement error (Figure 2). The strike-aligned profiles sampled through the maximum elevations of the site also showed little variation during that period, with average profile elevations ranging between 1.38 ±0.04 and 1.70 ±0.02 m NAVD88 (Figure 3g). Hurricane Arthur, a Category 2 storm, passed directly over the site in the middle of that period (July 4, 2014) but had little effect on the ocean waves, water level, or morphology of the site (Figures 1 and 2). The wells and water-level loggers were removed after the July 2015 topography survey because we thought ecological succession and aeolian processes would continue to accrete sediment and increase resistance of the site to overwash; however, that was not the case. Hurricane Joaquin passed offshore of the site on October 4, 2015 as a Category 1 storm, coincided with a strong nor'easter, and produced an extended period of surge (Figures 1 and 2). Hurricane Joaquin reinitiated overwash of the site and expanded the size of the washover fan to 37,471 ±1,243 $m^2$ and 25,927 ±1,664 $m^3$ on

October 12, 2015 (Figures 2, and 3). That was the last time we could access the island for field work, but aerial photography from other sources (e.g. the USGS and NOAA) showed that the island continued to overwash and the washover fan continued to expand landward and alongshore at least until August 2020.

## 4. DISCUSSION

The deposition of washover sediment during the study period at our site was not unprecedented. Although historical maps and aerial photography recorded no previous washover at the site since 1889, the geologic record shows that a single earlier washover deposit was preserved in the stratigraphy (Rodriguez et al., 2018). The landward portion of that earlier washover was sampled as a 40-cm thick sand bed in saltmarsh strata at a depth of 1.60 m, emplaced sometime between 1775 and 1807 (Rodriguez et al., 2018). The presence of only one earlier washover suggests the site had been resistant to overwash capable of transporting sand across the dunes and into the back-barrier saltmarsh for ~200 years. The resistance of the site to overwash progressively decreased leading up to Hurricane Irene in 2011, a result of continuous beach erosion. The average rate of landward shoreline movement, based on linear regression, from 1875 to 2004 was 2.62 m $yr^{-1}$ ($R^2 = 0.93$) and from November 2007 to May 2011 ~3,880 $m^3$ of sand was eroded from the foredune crest (Theuerkauf and Rodriguez, 2014). Sea-level anomalies in 2009-2010 also facilitated erosion of the backshore and foreshore further decreasing the resistance of the site to overwash (Theuerkauf et al., 2014). Eventually, with the beach and dunes narrowed, the maximum elevation of the site decreased to levels where overwash was imminent.

Washover deposition initiated at the study site during Hurricane Irene in 2011, but that was mainly the result of the morphology of the site being conducive to overwash as opposed to the Category 1 hurricane being an extraordinary event. A washover fan was deposited 500 m southwest of the study site in 1996 during Category 3 Hurricane Fran, which made landfall at Cape Fear 95 km southwest of Onslow Beach (Rodriguez et al., 2018). The beach and dunes of that southwestern Hurricane Fran washover area had accreted and built elevation by 2011 making that area resistant to overwash from Hurricane Irene. Similarly, the site examined in this study had recovered elevation since the storm event around 1790 and was resistant to overwash from Hurricane Fran. The impact of a storm on a barrier island commonly varies spatially and temporally due to along-shore variations in island morphology, the time scales over which an area accretes, the rate of shoreline movement, and the frequency and magnitude of erosive events (Stockdon et al., 2007; Bilskie et al., 2014; Houser et al., 2015).

The washover fan examined here is not an event deposit, rather, it accreted throughout the three-year study period and continues to accrete. Overwash transport of sediment was not only active during the largest storms, such as hurricanes, because of the site's persistently low resistance to overwash. Hurricane Irene made landfall 60 km northeast of our site near Cape Lookout, and caused initial overwash and deposition of a small washover terrace at the site; however, most of the overwash and washover deposition happened after Hurricane Sandy, a large storm (Category 1), but one that passed 490 km offshore of the site and did not produce hurricane conditions locally. The washover deposit increased in area 257% and accreted landward 110 m during the 187 days after Hurricane Sandy, the result of frequent overwash during extra-tropical storms and spring tides. The occurrence of overwash in response to events other than major storms has been documented elsewhere, including along the Pacific Coast of South America (Morton et al., 2000), the eastern north Atlantic Coast (Matias et al., 2010) and the Gulf of Mexico Coast (Eisenmann et al., 2018), underscoring the capacity of overwash to transport sediment across a shoreline in the absence of local hurricane or tropical storm conditions. The adjacent Hurricane Fran washover area had a similar depositional history to the site examined here and after initial formation, the Hurricane Fran washover fan also increased in area and accreted laterally 120 m landward between 1998 and 2002, a period that included Hurricane Bonnie (1998) and multiple other tropical and extratropical storms (Rodriguez et al., 2018). Both washover deposits on Onslow Beach amalgamate numerous depositional events with overwash as the primary mechanism for transporting sediment as recorded in the Hurricane Fran deposit as stacked fining-upward sand beds (Rodriguez et al., 2018). Composite washover deposits are not uncommon and have been recognized along other coastlines, including the coast of Denmark (Aagaard and Kroon, 2019), Australia (Switzer and Jones, 2008; May et al., 2017), and Louisiana, USA (Williams, 2011); however, deposition of individual beds in those studies were attributed to large storm events as opposed to a low resistance to overwash of a shoreline.

The location, timing, and extent of washover deposition is controlled by site morphology, in addition to storm characteristics such as wind speed and storm track. The geological record can preserve washover deposits; however, interpreting what the wind, water-level, and wave conditions were like during deposition from mapping the extent of a paleo-washover sand bed or laminae could yield spurious results if the morphology of the island (width, height, beach slope) immediately preceding the storm is assumed to be uniform through time. Many studies aimed at extending storm records into prehistorical time use a recent washover deposit and direct measurements of storm conditions during its deposition as a proxy for interpreting the geologic record, with the caveat that the geomorphology of the beach, dunes, and backbarrier are constant and recover rapidly between overwash events (Liu and Fearn, 1993; Donnelly et al., 2001; Elsner et al., 2008; Wallace and Anderson, 2010; Donnelly et al, 2015). That assumption has received some criticism (Otvos, 2009). Accurate storm-impact assessments require beach slope and dune height to be constrained immediately preceding or during a storm, even when water level and wave characteristics are well constrained (Long et al., 2014; Guisado-Pintado and Jackson, 2019; Straub et al., 2020). The difficulty in accurately predicting the modern occurrence of overwash without updated information on beach morphology suggests interpreting hurricane magnitude from a paleo-washover deposit using a modern washover as an analog could be misleading and increasingly so the further back in time a storm record extends. The assumption of uniform island morphology in paleo-storm records is difficult to circumvent because paleo-beach morphology can be impossible to reconstruct. Confidence in paleotempestologic records is provided by independently derived records from distinct locations along the Northwest Atlantic and Gulf of Mexico coasts that correspond well (Liu et al., 2008; Donnelly et al., 2015). While assumptions are necessary in extending hurricane records beyond historical accounts and correspondence between the numerous records lends credence to the approach, paleo-storm records alternatively could be indicating changes in storminess and a related decrease in the resistance of a shoreline to overwash, as opposed to changes in the frequency of a specific type of storm (cyclones, hurricanes, nor'easters, etc.). The assumption that beach morphology is resilient and washover extent can be related to an individual storm is not applicable to Onslow Beach and likely other transgressive barrier islands.

# 5. CONCLUSIONS

The Onslow Beach study area was resistant to overwash and washover deposition for 220 years prior to Hurricane Irene in 2011. During that period, beach and dune erosion continuously narrowed the site and decreased resistance to overwash until, around 2011 having crossed a morphologic threshold, overwash became a frequent occurrence. The volume and area of the washover fan increased rapidly, an average of 427 ±28 $m^3$ $day^{-1}$ and 614 ±28 $m^2$ $day^{-1}$ during the eight-day time step around Category 1 Hurricane Sandy, which passed far offshore of the site. Although the rate of washover fan accretion was highest during that short period around Hurricane Sandy, most of the volume and area gain occurred during the subsequent 187 days at lower average rates of 60 ±2 $m^3$ $day^{-1}$ and 112 ±5 $m^2$ $day^{-1}$. Most of the deposition of washover sediment occurred in the absence of large storms, mainly due to the low resistance of the site to overwash. Overwash and associated deposition of washover sediment is necessary for barrier island transgression but large storms are not a requirement. The impact of large storms on barrier islands is difficult to predict due to uncertainties in storm characteristics, and beach morphology at the time of influence, such as when Category 2 Hurricane Arthur passed directly over the site and caused no deposition of washover sediment. The areal extent and thickness of paleo washover fans preserved in the stratigraphic record is the product of both the resistance of a site to overwash (island morphology during storm impact) and the storm character (type and magnitude) that affected the site, thus caution should be exercised when interpreting these records in the context of individual major storm events. Furthermore, the time-series of overwash and washover extent presented here shows that large washover deposits can develop over a >10-year period and are not necessarily event deposits.


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