Geomorphic changes measured on Dauphin Island, AL, during Hurricane Nate

By

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ABSTRACT
Storm surge and waves from Hurricane Nate in 2017 resulted in large overwash and inundation regions on Dauphin Island, Alabama. The overwash event consisted of the transport of water and sediment over the beach, dune, and barrier island system. Seven transects were established to measure pre- and post-storm survey profiles. Nine wave and water level sensors were deployed in an overwash region and captured the overwash conditions including time-varying water levels and waves. All transects experienced a net loss of sediment from the subaerial region surveyed and a range of inundation and sediment overwash. The results highlight the limits of empirical estimates for evaluating the exposure of backdune regions to overwash and inundation.

ADDITIONAL KEYWORDS: Hurricane; overwash; barrier island; sediment transport.

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Coastline exposure to storm surge is a critical vulnerability that can lead to significant damage and loss of life during coastal hazards. When storm surge or wave runup heights exceed a beach crest, an overwash event can occur resulting in the movement of sediment and water across the back side of a beach. Overwash events have been observed at coasts around the world (Leatherman 1981; Kochel and Dolan 1986; Switzer and Jones 2008; and Donnelly *et al.* 2006), and have common attributes including low coastlines, high storm surge, or large wave runup, and are often associated with hurricanes and winter storms. The volume of overwash is dependent on the relative beach dune elevation, water level, wave height, storm duration, back beach topography, vegetation, wind strength, and direction (Donnelly *et al.* 2006).

Sallenger (2000) proposed a four-level scale to represent thresholds of storm impacts: swash regime, collision regime, overwash regime, and inundation regime. The Sallenger (2000) scale provides a basis for theoretical efforts to predict the impact of storms on the coastline. The equation is set as a relative measure between the elevation of runup (R_{HIGH} = mean sea level + wave runup + storm surge) and the dune crest height (D_{HIGH}). If R_{HIGH} exceeds D_{HIGH} overwash occurs, and if R_{LOW} (mean sea level + storm surge) exceeds D_{HIGH} inundation occurs. Although the impact scale introduced by Sallenger (2000) is commonly used to describe barrier island damage, the equation neglects the effects of storm duration, back beach topography, vegetation, and wind on the resulting morphological change.

During overwash events, the storm impact can vary in time and space as coastal interactions create feedbacks (dunes erode and change height) and as storms make landfall. Although numerical and laboratory studies (McCall *et al.* 2010; Smallegan and Irish 2017; Kobayashi and Zhu 2017; Harter and Figlus 2017) have demonstrated these variabilities, time and space varying measurements of overwash events in the field are limited (Fritz *et al.* 2007; Sherwood *et al.* 2014). Large-scale wave flume studies have shown the volume of overwashed water during an overwash episode correlates with the overwash sediment transport rate (Matias *et al.* 2016) as:

$$Q_s = c_s Q \quad (1)$$

where Q_s is the volume transport of sand, Q is the volume transport of water, and c_s is the volumetric concentration having empirically-based values in the range of 0.023-0.056 (Hancock and Kobayashi 1994). The overwash sediment transport rate can be further governed by a sequence of impact regimes, including swash, collision, overwash, and inundation (Harter and Figlus 2017).

This paper highlights observations of storm surge from Hurricane Nate (2017) that produced an overwash event on Dauphin Island, Alabama. The overwash event consisted of the transport of water and sediment over the dune crest, and the result of this work quantifies these two major components through evaluating the island-wide impact, barrier profile response, and time-varying water level and wave measurements. The observations provide time series data that categorizes the major components of the overwash event including the initial wave runup, peak surge, and estimated sediment flux.

STUDY AREA

Dauphin Island is a low-lying (average elevation of 2-3 m), narrow (100-1800 m wide), micro-tidal barrier island in the Gulf of Mexico (Figure 1). The eastern portion of the island contains most of the housing and infrastructure development on the island, with a greater elevation, maritime forest, and established foredunes. The western and central reaches of the island are comprised of a narrow sand spit 400-700 m wide (Froede 2006), where five of the 20 km making up this region are covered with homes and roads. The western portion of the island experiences overwash events regularly during strong winter storms and mild tropical events. Hurricane events are relatively common, and the island has been impacted

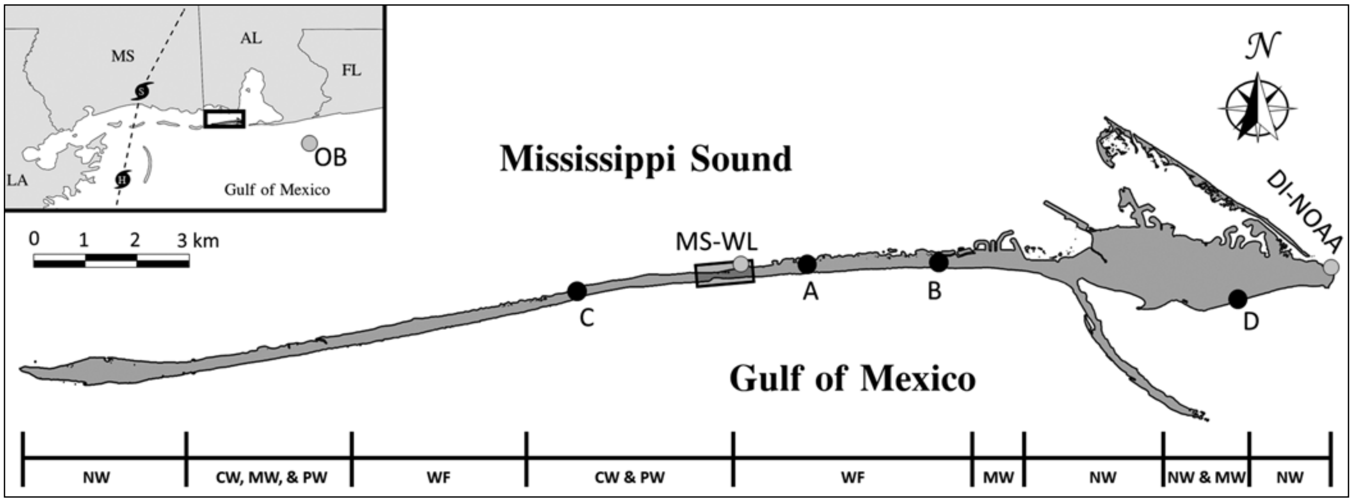

Figure 1. Map of Dauphin Island highlighting the study site in red; wind, water level and wave observation sites (yellow dots); and regions impacted by no overwash (NW), minimal overwash (MW), overwash fan (WF), partial overwash (PW), and complete overwash (CW). Insert panel shows the hurricane track as a dashed line. Black points A-D correspond to the locations of photos in Figure 3.

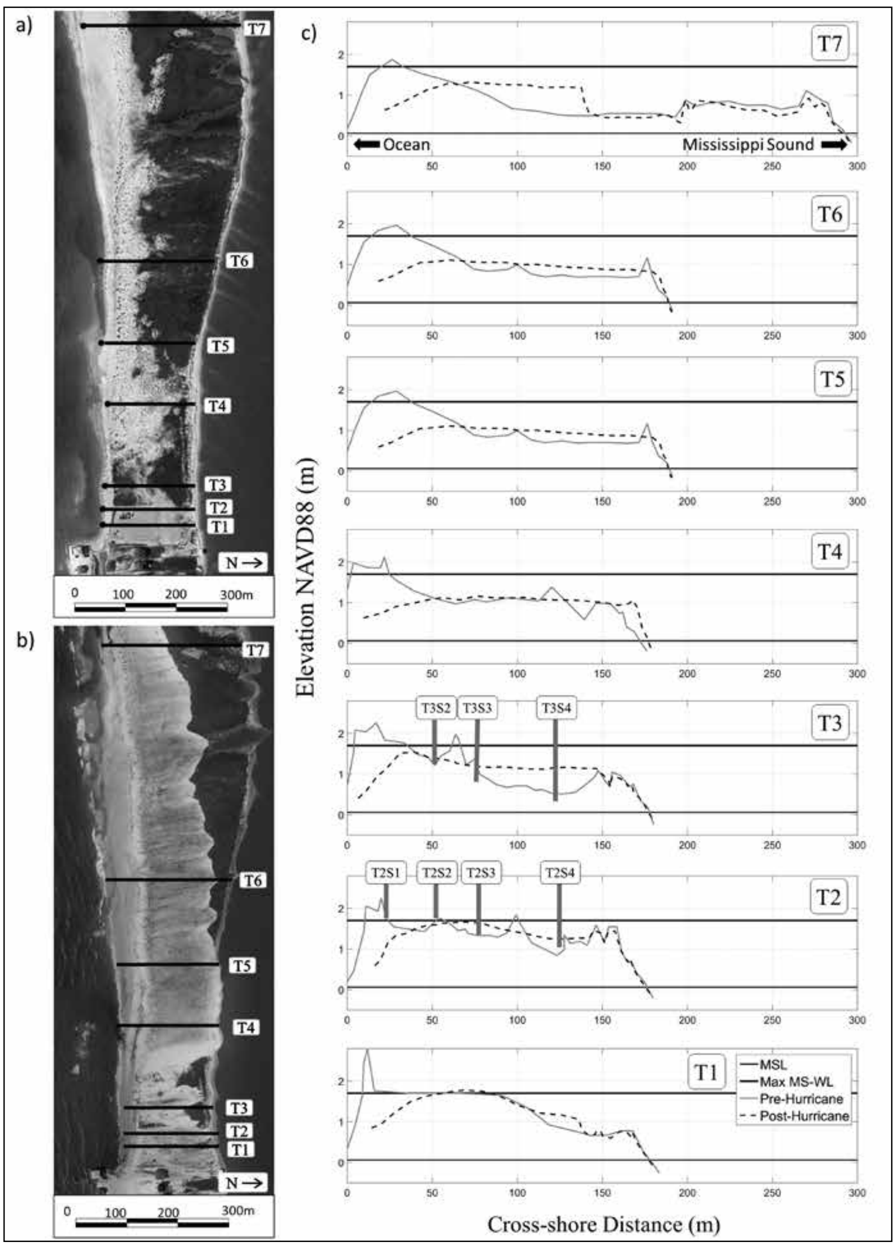

Figure 2. Overwash variability near the study site (a) before and (b) after and (c) beach profiles show pre-hurricane, post-hurricane, maximum surge recorded by the MS-WL sensor, and MSL. Vertical lines on T2 and T3 denote sensor locations deployed during the hurricane.

by 10 named storms in the past 25 years. Previous research has noted overwash fans, inundation, and breaches created by Hurricanes Frederic, Katrina, and Ivan (Penland and Suter 1984; Froede 2006; Froede 2008).

The study site focused on the central portion of the island (Figure 1), which is a largely undeveloped natural environment. The eastern side of the transect area is marked by a parking lot used for beach access, and the western side is marked by a rubble mound structure put in place in 2010 to fill Katrina Cut, a breach that originally formed in the island during 2004 from Hurricane Ivan, but widened substantially in 2005 following the passage of Hurricane Katrina (Webb *et al.* 2011). The habitat in this area is covered with four zones: beach, dune, meadow, and intertidal marsh, as described by Enwright *et al.* (2017). The beach region is a sparsely vegetated area from the water line to the dune crest. The dune regions include areas of both bare dunes and vegetated dunes. Meadow areas are comprised of dense herbaceous vegetation (>30%) covering the backslope of dunes. Intertidal marshes are also present in the study area and are made up of tidal wetlands with >30% cover of herbaceous hydrophytes.

METHODOLOGY

Seven transects were established to measure pre- and post-storm survey profiles. Initial beach profile elevation data were collected on 6 October 2017 within the central portion of Dauphin Island (Figure 1 boxed region) using a *real-time kinematic* (RTK) Trimble R8 *global positioning system* (GPS). Data were collected in Universal Transverse Mercator (*UTM*) zone 16 with respect to the North American Vertical Datum of 1988 (NAVD 88). Profiles extended from the subaerial portion of the beach to ~1 m water depth. Two different sensor types, a wave sensor described in Kennedy *et al.* (2010) and Webb *et al.* (2012) and a HOBO water level sensor, were deployed across the island on two of the beach profile transects. The wave sensors recorded at 2 Hz and the water level sensors sampled once every 30 s. The sensor locations are marked in Figure 2 (T2 and T3) with vertical gray lines and are also described in Table 1. An additional sensor in Mississippi Sound measured the bay side water level (MS-WL Figure 1). Other available time series data included water level measured every six minutes at the National Oceanic and Atmospheric Administration (NOAA) station 8735180 (DI-NOAA Figure 1), two-minute average wind speed and direction measured every six minutes also at NOAA station 8735180, and offshore wave observations at NOAA buoy 42012 (OB Figure 1) in 25.9 m mean water depth.

Sediment fluxes and net profile change were calculated using the beach profile data. Each profile was segregated into a foredune and backdune region defined by the first intersection between the pre- and post-hurricane profile delineating a point that did not change elevation during the storm (i.e. the nodal point between erosion and deposition). From this point, subaerial sediment volume changes were calculated for the foredune, backdune (Figure 3), and the entire transect line. The subaerial portion of the beach was identified by a vertical datum at 0.3 m NAVD88. This datum was chosen based on the minimum backdune elevation and is 0.24 m greater than MSL at Dauphin Island. Data were interpolated from the profile slope when elevations were not available.

Of the nine sensors deployed, one was lost, one moved, and four were buried by overwash but continued to collect data.

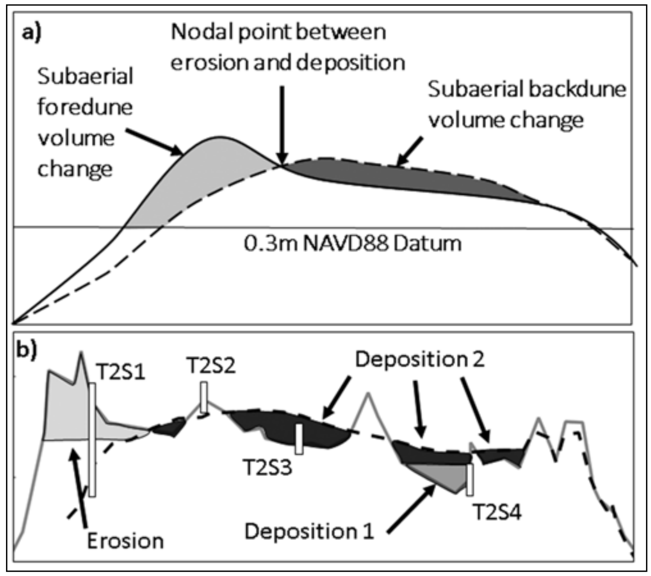

Figure 3 (left). Diagram showing (a) beach volume change regions calculated for Transects T1-T7 and shown in Table 2, and (b) estimates of area eroded when T2S1 fell, deposition in area 1 when T2S4 was buried, and deposition in area 2 when T2S3 was buried.

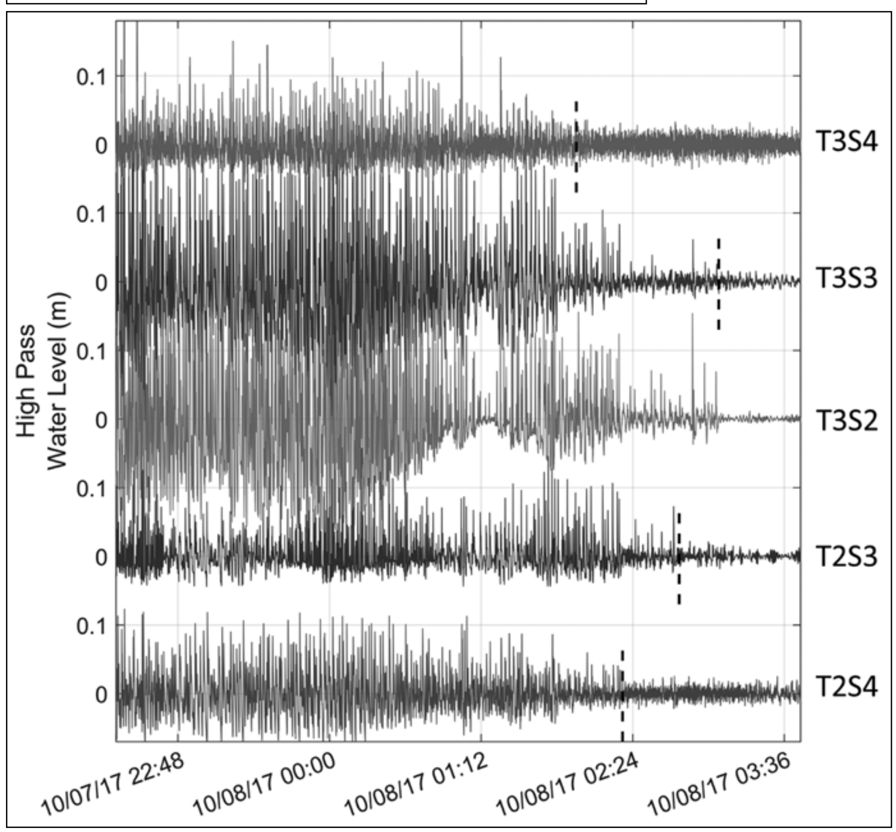

Figure 4. High pass wave data at T2S3, T2S4, T3S2, T3S3, and T2S4 used to estimate burial times for the sensors, denoted by vertical black dash lines.

Estimates of sensor burial times and timing of movements were made using sensor measurements and assumptions. A qualitative assessment of when the low-pass (4 min) water level data showed a distinct increase in depth, as a result of the gage mount falling over, was used to infer the movement of sensor T2S1. A 1.5-m-long galvanized pipe was used to deploy the sensor and it was assumed that the attached sensor fell over when one-half of the pipe (0.75 m) was exposed as a result of erosion. It was further assumed that the sand from the dune in front of the sensor eroded before the sensor moved, and this allowed for an estimate of sediment flux during the hurricane. Figure 3b shows this estimated area of erosion and location of the pipe and sensor for T2S1. The time at which a wave sensor became buried was estimated based on when the high-pass (30 s) wave data showed a reduction in wave height with respect to the unburied sensors. This method used

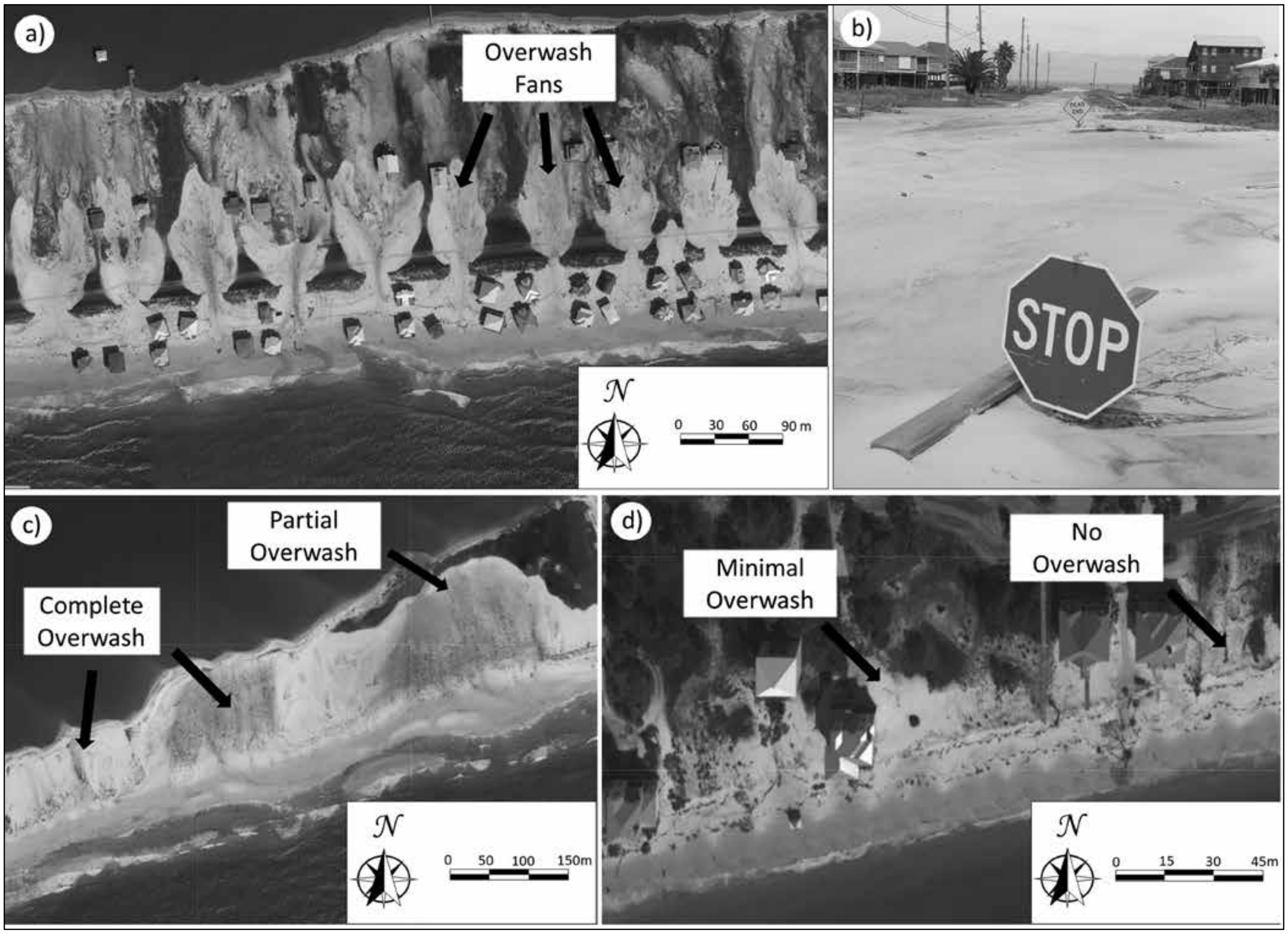

Figure 5. Images capturing the varying types and extent of overwash fans impacting infrastructure on Dauphin Island (a,c,d) captured by NOAA emergency response aerial imagery and (b) 1.4 m deep sand deposited at a stop sign. The locations of figures correspond to points A-D in Figure 1.

Table 1.

Sensor locations on transect lines T2 and T3. Sensor locations are shown in Figure 5 as gray lines.

	Sensors	Cross-shore position (M)	Pre-storm sand (M)	Post-storm sand (M)	Sensor height (M)	Comments
T2S1	Wave/WL	23	1.74	0.92	1.93	Moved
T2S2	Wave	53	1.73	1.41	2.02	Operational
T2S3	Wave/WL	81	1.33	1.61	1.47	Buried
T2S4	Wave	128	0.98	1.25	1.16	Buried
T3S1	Wave/WL	17	2.26	1.08	2.42	Missing
T3S2	Wave	53	1.32	1.39	1.68	Operational
T3S3	Wave/WL	80	0.95	1.17	1.1	Buried
T3S4	Wave	126	0.52	1.25	1.25	Buried

a qualitative assessment to determine at what time sensors T2S4, T3S4, T2S3, and T3S3 became buried. Since the time of burial was estimated based on the changing differences in wave height between an unburied sensor (T3S2) and the buried sensors, periods when the unburied sensor wave energy decreased made estimates of burial time difficult and increased the range of uncertainty (Figure 4).

NOAA emergency response aerial imagery were used to qualitatively assess the level of overwash impacts on the island. Five categories describe the range of impacts: no overwash, minimal overwash, overwash fan, partial overwash, and complete overwash. Minimal overwash regions showed evidence of sand overwashing the dune but only for a couple of meters. Overwash fans were areas with a small breach in the dune and overwashed sediment and water that spread laterally in the backdune region. Areas where sand and water inundated entire regions of the alongshore, with no obvious constriction at the dune, were defined as either partial overwash or complete overwash. The partial or complete overwash distinction was made when overwash covered the entire cross-shore region of the island (complete overwash) or did not cover the entire cross-shore region (partial overwash). Examples of these five categories are highlighted in Figure 5.

HURRICANE NATE

On 4 October 2017, Hurricane Nate formed as a tropical depression near Central America and strengthened to a Category 1 storm on the Saffir-Simpson wind scale as it entered the Gulf of Mexico (Beven and Berg 2018). On 7 October 2017 the storm peaked in intensity with winds around 41 m/s and traveled across the Gulf of Mexico at a speed of 13 m/s. At 19:00 local time on 7 October 2017, Nate made landfall as a Category 1

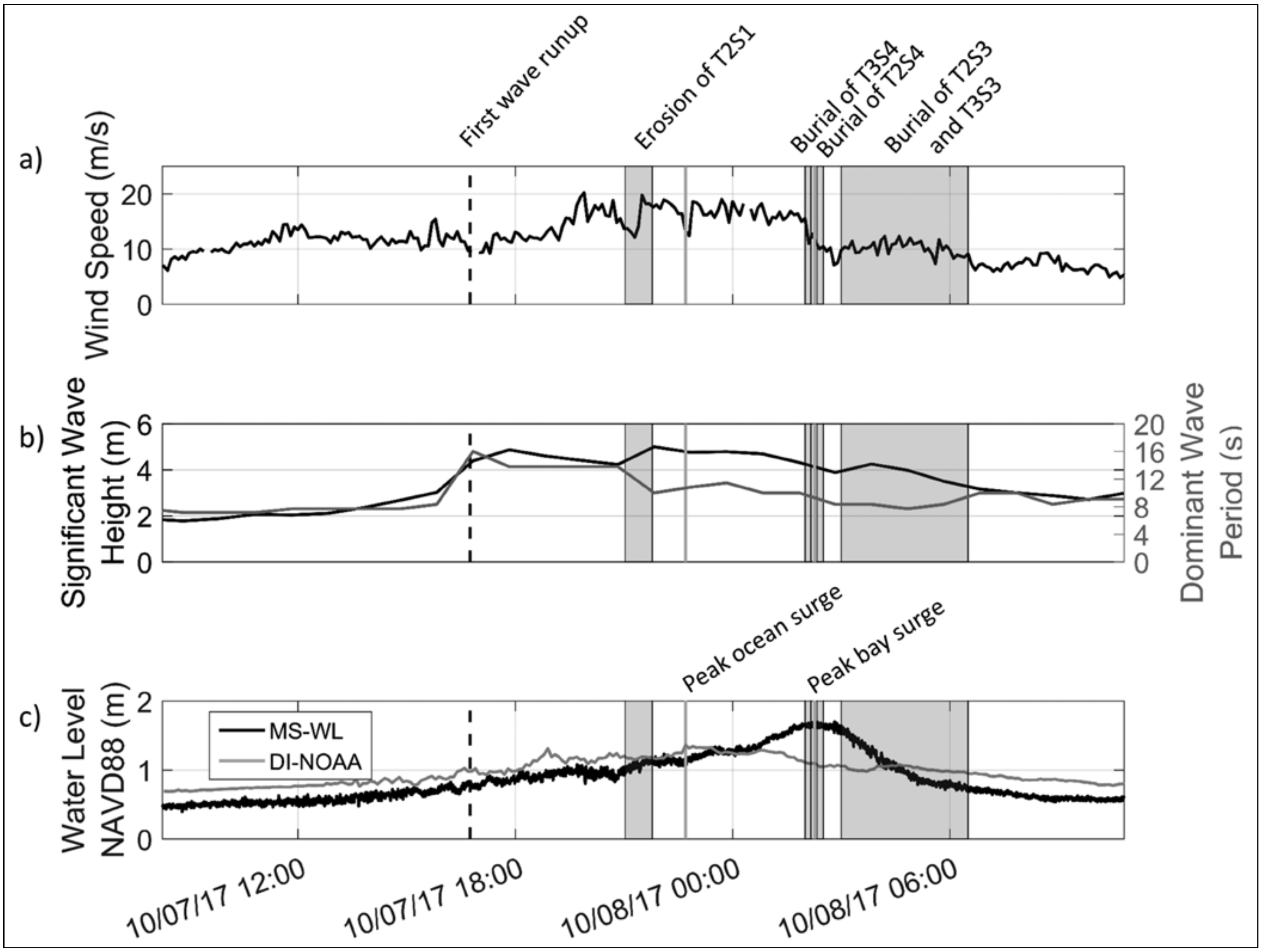

Figure 6. Time series of (a) wind speed at DI-NOAA, (b) offshore wave height and period at NOAA buoy 42012 (OB) 65 km SE of the study site, (c) water level at the study site (MS-WL) and DI-NOAA. Vertical lines and shading denote major events: first wave run up (black dash), erosion (red) and burial of sensors (green).

hurricane near Gulfport, MS (dashed line in Figure 1 insert panel), approximately 90 km west of the study site. Storm surge in Gulfport peaked at 1.9 m and an estimated 500 km of coastline had a storm surge of > 0.6 m above Mean Higher High Water (Beven and Berg 2018).

RESULTS

Hurricane Nate produced little structural damage to the infrastructure on Dauphin Island but did cause overwash and sediment deposition on 4.5 km of the island's roads. Overall the impact of sediment transport on the island was (shown in Figure 1): 34% of the island had no overwash, 9% experienced minimal overwash, 32% had overwash fans, 14% was covered by some partial overwash, and the remaining 11% was covered by complete overwash. The 32% of the island that experienced overwash fans was largely a result of low elevations in dune gaps used for driveways and roads (Fig 5a). The overwash fans were approximately 0.5-1 m thick. The partial and complete overwash that occurred in the surveyed study site deposited 0.2-0.7 m of sand across the island. The surveyed study sites were located where considerable variability in overwash and inundation exposure occurred, such as varying extents and sizes of overwash fans, and partial and complete overwash of the island.

The beach profile surveys covered an area with variable vegetation coverage and density and some low-lying areas that had standing water before the hurricane (Figure 2). All transects experienced a net loss of sediment from the subaerial region surveyed (Table 2). Sediment loss occurred in the foredune region where erosion occurred on each of the survey lines. Most of the sediment lost was likely advected offshore early in the storm during the swash and collision regimes (Sallenger 2000). During sensor deployment, erosion of the beach was already evident. Additional observations, based on the movement of sensor T2S1, suggest 13.8 m^3m^{-1} of sand was eroded by 21:45 *Central Daylight Time* (CDT) when sensor T2S1 moved. An estimated erosion rate was calculated from the time of the first wave runup at 16:45 CDT to obtain a loss of 2.8 $m^3m^{-1}hr^{-1}$. The sedi-

Table 2.

Subaerial volume change (m^3m^{-1}) measured to 0.31 m NAVD88 vertical datum. Foredune and backdune were marked by the intersection of pre- and post-hurricane profiles marking the nodal point between erosion and deposition.

Station	Foredune	Backdune	Net change
T1	-23.3	7.3	-16.0
T2	-25.9	10.7	-15.2
T3	-35.5	27.1	-8.3
T4	-45.7	12.8	-32.9
T5	-48.2	20.2	-28.0
T6	-48.7	18.0	-30.7
T7	-38.5	23.0	-15.5

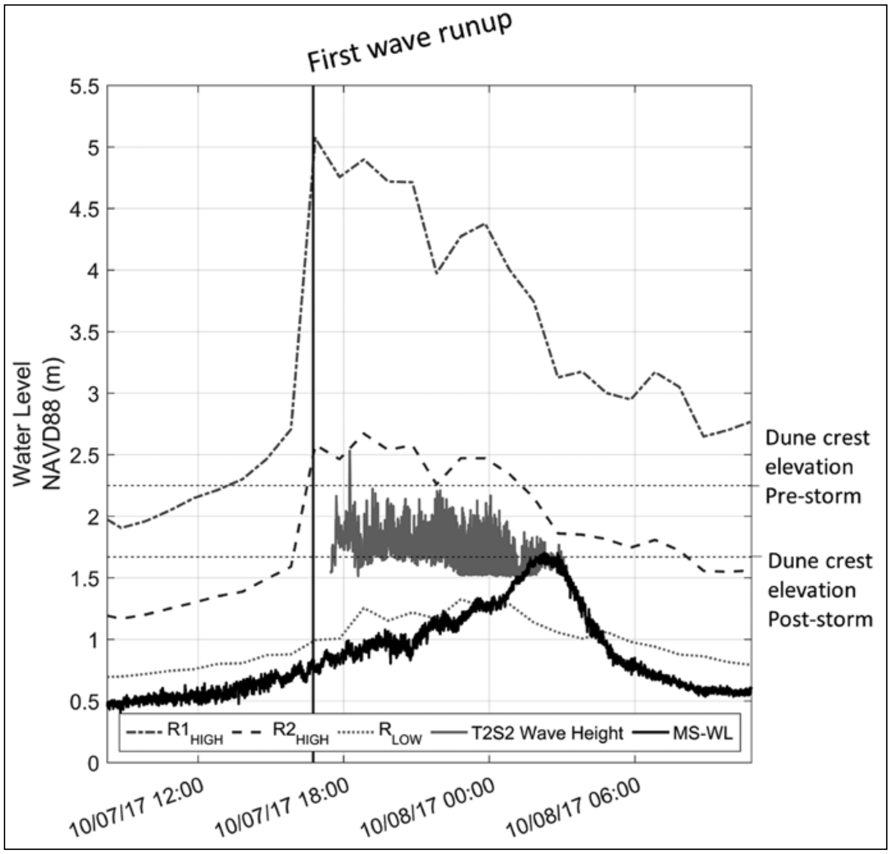

Figure 7. Low and high wave runup heights compared with wave heights measured at T3S2 and water level measurements from Mississippi Sound.

ment volume loss at 21:45 *CDT* equates to 53% of the total sand that was eroded from the foredune region. With the burial of the first sensor not occurring for another 3.75 hours, it is likely that most of this sand was transported offshore. The net change for this transect was a loss of 15.2 m^3m^{-1} and suggests that the initial erosion of the dune (13.8 m^3m^{-1} based on the movement of T2S1) was advected offshore and the remaining 12.1 m^3m^{-1} lost from the foredune was washed over the island (10.7 m^3m^{-1}) and advected offshore (1.4 m^3m^{-1}) later in the storm. It should be noted these transport pathways do not account for any gradients in the longshore sediment transport and this is likely another source of sediment loss and accretion.

The timing of burial for the two bayside sensors occurred prior to other sensors and indicated that overwashed sand in this region filled the low-elevation parts of the profile first. This assumption was used to calculate deposition rates for these profiles starting with the burial of T2S4 and T3S4 (Figure 3b deposition 1) and ending with the final profile shape with the burial of T2S3 and T3S3 (Figure 3b deposition 2). T2 had a potential deposition rate ranging from 2.9 to 18.6 $m^3m^{-1}hr^{-1}$ whereas values for T3 ranged from 7.7 to 36.9 $m^3m^{-1}hr^{-1}$. These ranges reflect the uncertainty in identifying likely sensor burial times based on the high-pass filtering technique applied to the data.

DISCUSSION

Dauphin Island experienced a range of runup and overwash conditions as a result of Hurricane Nate. The area most susceptible to partial and complete overwash was near the study region where the island had previously breached from Hurricane Katrina (2005). As a result, this narrow low-lying region was most heavily impacted by partial and complete overwash compared to the rest of the island. The area was also flanked on either side by overwash fan regions.

All beach profiles showed large changes and varying degrees of overwash. From T3 to T4, an overwash fan transformed to a complete overwash region covering the entire width of the island that then became less severe farther west towards T7. Since the spatial variability of nearshore waves was unknown for this study, discussion is limited to conclusions made using the measured profile data. Between T3 and T4 observed changes included vegetation coverage and dune heights (Figure 2) where T3 and T4 had maximum dune crests of 2.3 m and 2.1 m respectively. The level of inundation near T3 may have been limited by the second smaller dune on T3 (cross-shore location 60 m). Additionally, the change in dune height on T4 was greater at a 1 m loss, than the 0.7 m loss on T3 potentially due to vegetation differences. Following the Sallenger (2000) methodology, this 1.2 m D_{HIGH} berm post-hurricane on T4 was low enough to result in inundation when R_{LOW} peaked at 1.3 m.

Farther west towards T7, the length of overwash in the cross-shore direction decreases as the island width changes. Stations T4-T6 all show relatively low deposition across the island when compared with T7 where a thick layer of overwash existed. Station T7 had the lowest inland elevation of 0.3 m, as compared to 0.5 m on T6, and T7 also had more standing water and marsh vegetation pre-hurricane that influenced the difference in sediment accretion between T6 and T7.

The time series data from T2 and T3 allowed a closer examination of the overwash event when divided into five time periods: initial wave runup, dune erosion (movement of sensor T2S1), peak ocean surge, peak bay surge, and sediment accretion (Figure 6). The observation periods can be evaluated with respect to the Sallenger (2000) storm impact scale. R_{HIGH} was estimated using observed storm surge data from DI-NOAA, and Stockdon *et al.* (2006) was used for wave runup, R_2 (defined by the 2% exceedance value):

$$R_2 = 1.1\ (0.35\beta(H_0L_0)^{0.5} + 0.5\ [H_0L_0(0.563\beta^2 + 0/004)]^{0.5}) \qquad (2)$$

where H_0 is the deepwater wave height, L_0 is the deepwater wave length, and β is the beach steepness. Equation 2 is based on a best fit linear model from 10 field experiments on Atlantic, Pacific, and North Sea coastlines. This empirical parameterization does omit a number of important processes (wave direction, frequency spectral variations, nearshore bathymetry complexity) but for the interest of this work it provides a simple estimate of runup to compare predicted overtopping with observations. The deepwater wave height was determined by reverse shoaling observations from station OB. Two sets of R_{HIGH} were solved: $R1_{HIGH}$

Table 3.
Elevation of D_{HIGH}, R_{HIGH}, and R_{LOW} for each transect and the corresponding Sallenger (2000) scale.

	$R1_{HIGH}$	$R2_{HIGH}$	R_{LOW}	Pre D_{HIGH}	Post D_{HIGH}	Sallenger (2000) scale
T1	5.07	2.67	1.36	2.78	1.78	Overwash
T2	5.07	2.67	1.36	2.25	1.67	Overwash
T3	5.07	2.67	1.36	2.26	1.54	Overwash
T4	5.07	2.67	1.36	2.12	1.62	Overwash
T5	5.07	2.67	1.36	1.97	1.11	Inundation
T6	5.07	2.67	1.36	1.81	1.05	Inundation
T7	5.07	2.67	1.36	1.87	1.32	Inundation

Table 4.
Sensor distance from sand, estimated water volume over washed, sediment volume change and calculated volumetric concentration at each sensor.

	Sensor distance above sand (M)		Water transport (m^3m^{-1})	Sediment volume (m^3m^{-1})	Cs
	PRE	POST			
T2S2	0.6	0.7	106-122	9.1	0.075-0.085
T2S3	0.3	0.0	281-908	9.4	0.010-0.033
T2S4	0.3	0.0	597-901	-0.8	0
T3S2	0.4	0.3	2,029-2,064	25.9	0.012-0.013
T3S3	0.4	0.0	1,685-2,124	34	0.016-0.020
T3S4	0.5	-0.1	648-1,235	15.5	0.012-0.024

using the initial beach slope (β_1=0.11) measured on 6 October 2017, and $R2_{HIGH}$ using a nearshore beach slope (β_2=0.11) measured from a water depth of 0.9 m to 2 m based on a 2015 bathymetric survey (DeWitt *et al.* 2017). R_{LOW} was set equal to the water level recorded at NOAA-DI (Figure 7). It should be noted Sallenger (2000) defines this continuously subaqueous level as R_{HIGH} minus the swash amplitude but this was simplified and set equal to water level at NOAA-DI for analysis in this study.

Figure 7 shows a black vertical line marking the first wave runup from observations on the bay side of the dune crest (T2S1). The first wave runup observation point coincides with the increase of $R2_{HIGH}$ exceeding the dune crest elevation of 2.2 m and marking the transition from collision regime to overwash regime. $R1_{HIGH}$ largely overpredicted the observed runup as a result of the wave breaking occurring farther offshore and not on the steep upper beach face used to calculate . R_{LOW} never exceeded the dune height and, as a result, the study site did not enter an inundation regime. The water level sensor in Mississippi Sound (MS-WL) did exceed the final dune height peaking at 1.7 m and resulted in inundation of the island from the bay side as water returned to the gulf late in the storm event. This bay side flooding produced a distinct modulation in the wave heights observed at T2S2. As the predicted runup height decreased, wave heights at T2S2 also decreased and reached a low at 01:15. However, when the bay side flooding exceeded 1.5 m, an increase in observed runup occurred and peaked at 02:15 due to the compounding impacts of the offshore waves interacting with the bay side flooding (Figure 7). Table 3 shows a comparison of D_{HIGH}, $R1_{HIGH}$, $R2_{HIGH}$, and R_{LOW} for each transect, where T1-T4 met the criteria for overwash, and T5-T7 met the criteria for inundation using Eq. 2 and water level at NOAA-DI.

Estimates of sediment and water transport over the island were also evaluated using both theory and observations. The wave height at each sensor was calculated from high-pass time series data. These time series observations were converted to a spatial reference frame based on where c is the wave celerity, is the change in space and is the change in time. The wave celerity based on solitary theory is:

$$c=\sqrt{g(h+H)} \quad (4)$$

where g is gravity, h is the water depth, and H is the wave height (Komar 1976). From this conversion, unit width volume of water transported past the sensor can be determined. This simple estimate assumed the standing water (h) is stationary, all the water under the wave (H) was transported from offshore to onshore, and the waves were shore normal. The values presented in Table 4 provided a first order estimate of how the volume of water that overwashed the island changed between Transects 2 and 3 and between sensors. Transect 3 had almost twice as much water overwash the dune compared to T2. Transect 3 also had a general pattern of decreased water transport with distance from the ocean. However, the sediment transport was greatest at the middle sensor (T3S3) due to a second dune between T3S2 and T3S3 (Figure 2). This complex back dune morphology presents challenges in understanding and simplifying the transport of sand during these overwash events.

Using Eq. 1, c_s values were calculated for each sensor (Table 4) where the change in sediment volume was calculated from the sensor to the last profile point on the bay side. Despite the back dune complexities, there is still relative consistency among the c_s values (0.012-0.024) for Transect 3. The calculated values fall on the low side when compared to those made by Hancock and Kobayashi (1994). This difference is likely due to errors resulting from the rudimentary water volume calculation methods used in this study, but also the Hancock and Kobayashi (1994) study was carried out in a 33 m long wave flume for unvegetated dunes. The lower c_s values observed in this study present a level of comparison for real-world observations and suggest there is less sediment transport for a given volume of water.

The volume of water estimates also highlight some limits of the methods used where T2S2 was 0.6 m above the sand and missed a large portion of the smaller waves passing under the sensor. Additionally, as the sand level was eroded and accreted below the sensor, this change impacted estimates of h and led to the variability in water transport. Estimates of c_s also had some outliers where T2S2 had a poor water transport estimate, and T2S4 was in front of a rising slope where the assumption that all the water under the wave was transported from offshore to onshore may not have held true. These outliers highlight the sensitivity of the methods used.

CONCLUSION

Observations during Hurricane Nate provide new insight into the spatial and temporal geomorphic changes occurring during overwash events. The results highlight the use of empirical estimates for evaluating the exposure of backdune regions to overwash and inundation. The varying level of overwash and inundation changes between survey locations suggest initial condition (D_{HIGH}) and feedbacks during the storm (changes that occur to D_{HIGH}) have a large impact on the level of inundation or overwash that can occur. From this understanding, knowing dune height, erosion potential, and fate of sediment transport with respect to dune width and vegetation can greatly improve coastal planning and limit exposure to overwash events. Anticipated future research based on this unique dataset include: comparisons of geomorphologic model predictions to intra-storm measurements of water levels and waves and post-storm profile data; and descriptions of wave dissipation over the barrier beach during overwash and inundation.

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