

Influence of Wind-Driven Inundation and Coastal Geomorphology on Sedimentation in Two Microtidal Marshes, Pamlico River Estuary, NC

David Lagomasino · D. Reide Corbett · J. P. Walsh

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Abstract Marsh sediment accumulation is predominately a combination of in situ organic accumulation and mineral sediment input during inundation. Within the Pamlico River Estuary (PRE), marsh inundation is dependent upon event (e.g., storms) and seasonal wind patterns due to minimal astronomical tides (<10 cm). A better understanding of the processes controlling sediment deposition and, ultimately, marsh accretion is needed to forecast marsh sustainability with changing land usage, climate, and sea level rise. This study examines marsh topography, inundation depth, duration of inundation, and wind velocity to identify relationships between short-term deposition (tile-based) and long-term accumulation (^{210}Pb and ^{137}Cs) recorded within and adjacent to the PRE. The results of this study indicate (1) similar sedimentation patterns between the interior marsh and shore-side marsh at different sites regardless of elevation, (2) increased sedimentation (one to two orders of magnitude, $0.04\text{--}4.54\text{ g m}^{-2}\text{ day}^{-1}$) within the interior marsh when the water levels exceeded the adjacent topography (e.g., storm berm), and (3) that short-term sea level changes can have direct effects on sediment delivery to interior marshes in wind-driven estuarine systems.

Keywords Marsh · Sedimentation · Accumulation · Inundation · Microtidal · Berm · Geomorphology

Introduction

Coastal wetlands are one of the most valuable ecosystems providing food and shelter for birds and aquatic organisms, reducing wave impact and flooding associated with storms and trapping contaminants (Costanza et al. 1997; Mitsch and Gosselink 2000). Coastal marsh ecosystems are dynamic transitional environments that are ultimately dependent upon a balance between sediment accretion, subsidence, and short-term and long-term relative sea level rise (Kolker et al. 2009; Friedrichs and Perry 2001). Furthermore, the ability of a marsh to maintain itself is influenced by numerous interrelated factors including organic and mineral sediment accumulation, pore space fluid, inundation dynamics (e.g., duration, depth, and frequency), micro-topography, and storm activity (Bricker-Urso et al. 1989; Mitsch and Gosselink 2000; Friedrichs and Perry 2001).

Sea level is a fundamental control on many of the factors that contribute to the stability of marsh environments, including the frequency, duration, and depth of inundation. Sediment deposition primarily occurs during inundation, and therefore, sedimentation is inversely related to marsh elevation (Cahoon and Turner 1989; Craft et al. 1993; Kastler and Wiberg 1996; Friedrichs and Perry 2001; Neubauer et al. 2002; Darke and Magonigal 2003; Bellucci et al. 2007). Many studies have focused on several aspects of marsh sediment dynamics, including sediment inputs from upland runoff and seabed resuspension (Simmons 1993; Day et al. 1998), short-term sedimentation processes (Leonard and Luther 1995; Möller et al. 1999; Christiansen et al. 2000; Neumeier and Ciavola 2004; Le Hir et al. 2007), organic sedimentation (Frey and Basan

D. Lagomasino
Southeast Environmental Research Center, Miami, FL, USA

D. R. Corbett · J. P. Walsh
Department of Geological Sciences, East Carolina University,
Greenville, NC, USA

D. R. Corbett · J. P. Walsh
Institute for Coastal Science & Policy, Greenville, NC, USA

Present Address:

D. Lagomasino (✉)
Department of Earth and Environment, Florida International
University, Miami, FL, USA
e-mail: david.lagomasino@gmail.com

1978; DeLaune et al. 1994; Nyman et al. 2006), sediment redistribution during rain events (Childers and Day 1990; Mwamba and Torres 2002; Voulgaris and Meyers 2004), storm events (Stumpf 1983; Goodbred and Hine 1995; Turner et al. 2006), and the effects of short-term (Kolker et al. 2009) and long-term sea level rise (Redfield 1972). The combination of these marsh processes contribute to the complexities of marsh sedimentation, and the importance of each mechanism can vary depending on the marsh environment.

Marsh accretion and sedimentation have been monitored on several timescales using a myriad of techniques including marker horizons (DeLaune et al. 1983; Cahoon and Turner 1989), sedimentation–erosion tables (Cahoon and Turner 1989; Cahoon et al. 1998; van Wijnen and Bakker 2001; Perillo et al. 2003), filter paper (Reed 1989), radionuclides (Craft et al. 1993; Nyman et al. 2006; Bellucci et al. 2007), and ceramic tiles (Pasternack and Brush 1998; Neubauer et al. 2002). Some studies have shown that the accumulation rates quantified via radionuclides are comparable with tile-based deposition studies (Neubauer et al. 2002; Darke and Megonigal 2003). However, an exact agreement is not always expected due to changes in current and wave energy over time and because of the differences in timescale integration (Thomas and Ridd 2004). Craft et al. (1993) used ^{137}Cs to evaluate differences in accretion rates between irregularly and regularly flooded marshes in Pamlico Sound and found the former to be significantly higher. Nyman et al. (2006) used radionuclides and noted a strong positive correlation between the rate of vertical accretion and vegetation growth that have also been noted elsewhere (Morris et al. 2002; Hatton et al. 1983; McCaffery and Thomson 1980). Changes in sediment accumulation associated with increased storm frequency, sea level rise, and human disturbances have also been examined using radionuclides (Ciavola et al. 2002; Bellucci et al. 2007).

Studying the interactions between marsh sedimentation, inundation dynamics, geomorphology, and local sea level can provide insight for better model predictions of productivity, sustainability, and assessment of the future state of marsh environments. This work is especially important with concerns of continuing land use change, global climate change, and rising sea levels and can enable better management practices to preserve the critical environmental and economic functions of coastal marshes (Mitsch and Gosselink 2000). This research focused on marsh sediment dynamics from two coastal marshes in the Pamlico River Estuary (PRE) and Pamlico Sound, North Carolina. The primary objective of this work was to evaluate the spatial and temporal variability of sedimentation processes (e.g., resuspension, sediment supply) in relation to geomorphic features (e.g., berm elevation and distance) and inundation.

Study Area

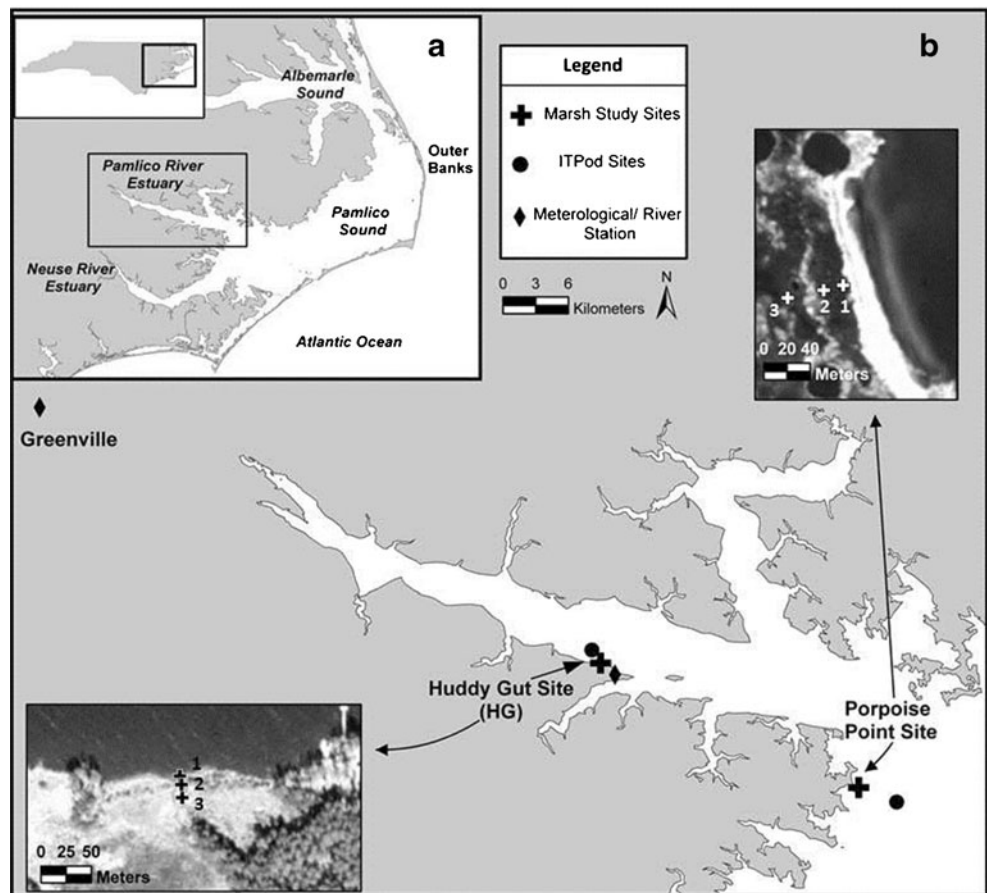
The coastal plain of North Carolina contains the Albemarle–Pamlico Estuarine System (APES), the second largest estuary and the largest lagoonal system in the USA (Fig. 1a). The shorelines of the APES are primarily organic, consisting of either swamp or marsh shorelines (~70 %; Riggs and Ames 2003). The PRE discharges directly into Pamlico Sound, which is separated from the Atlantic Ocean by an extensive barrier island chain known as the Outer Banks. Three inlets in the island chain (i.e., Oregon, Hatteras, and Ocracoke) limit the exchange of sound and ocean waters and dampen the influence of astronomical tides to a range of <10 cm throughout most of the APES (Amein and Airan 1976). Therefore, variations in water levels and marsh inundation are primarily associated with storm and frontal passages along with seasonally variable winds (Pietrafesa et al. 1986; Luettich et al. 2002). Seasonal prevailing winds blow along the long axis of Pamlico Sound (NE—winter, SW—summer), with a significant fetch (Luettich et al. 2002), and can produce relatively large waves (significant wave height of >1 m; Dillard 2008). Organic-rich muds (10–15 % organic) are deposited within the deeper sections of the estuary, and fine-grained siliciclastic sands accumulate along the estuarine margins (Wells and Kim 1989). Sand aprons along the shorelines and shallower segments of the PRE are derived from local shoreline erosion, much of which is supplied from banks and bluffs (Wells and Kim 1989; Riggs and Ames 2003). The banks and bluffs are a small component of the total PRE shoreline when compared to the marsh (Riggs and Ames 2003). Bulkheads and other hardened structures occupy many locations within the upper and middle reaches of the PRE, reducing shoreline erosion in some areas. These shoreline structures were largely constructed in response to storm activity in the latter part of the twentieth century.

Sampling Sites

Three monitoring stations were placed along a shore-perpendicular transect at two study sites within and adjacent to the PRE, Huddy Gut (HG) and Porpoise Point (PP), respectively (Fig. 1b). The study sites were selected based on accessibility and their proximity to preexisting water quality monitoring sites (Fig. 1b). All topographic elevations referred to at each site are corrected and referenced to NAVD 88. Water levels measured at each station are referenced to the marsh elevation to indicate periods of marsh dry down.

HG and PP have similar geomorphic characteristics; each site consists of a marsh shoreline erosional scarp, a storm berm, and a frequently flooded interior marsh. HG is located in the center of the PRE along the southern shoreline

Fig. 1 Location of marsh study sites, Huddy Gut and Porpoise Point, along the Pamlico River Estuary in eastern North Carolina



approximately 20 km from the Tar-Pamlico River mouth (Fig. 1b). HG has a well-developed, spatially continuous storm berm that is ~2 m from the marsh edge and 0.6 m high (Fig. 2). There was a notable scarp (~0.3 m high) at the shoreline (low water) with small, intermittent pocket beaches along the coast. The vegetation of the shore-side marsh was a sparse mix of *Spartina alterniflora* (short) and *Spartina patens*. Vegetation in the interior marsh was dominated by *Spartina cynosuroides*, with some *Limonium carolinianum*. The HG marsh is located in the vicinity of a rural housing community, a transport ferry docking station, and a large phosphate mining facility.

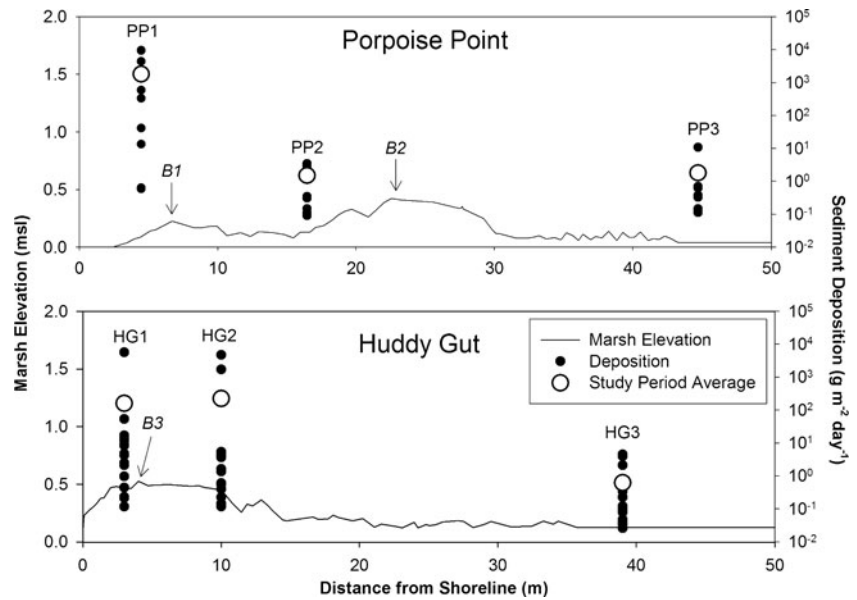
PP was located at the mouth of the PRE (Fig. 1). The studied shoreline was oriented north–south and is exposed to Pamlico Sound. The shore-side marsh has two spatially continuous natural berms (Fig. 2): one (B1) was 0.29 m high and ~5 m from the shoreline (high water); the second much larger berm (B2) was ~0.48 m high and ~20 m from the shore (storm tide). The mean high and low waters in Pamlico Sound were listed by NOAA (<http://tidesandcurrents.noaa.gov/>) and determined from the USGS benchmark 8652648 and correspond approximately with the crest of the seaward berm (B1) and the PP1 station at the PP site, respectively (Fig. 2). The shoreline at PP varied geomorphologically between a marsh shoreline scarp (~0.3 m high) with multiple wave-cut terraces

and small pocket beach areas. The dominant vegetation within the shore-side marsh was *S. alterniflora* (short), but between the two berms, dense patches of *S. patens* were present. Landward of the larger berm was a frequently flooded expanse of *Juncus roemerianus*.

Methods

This study measured marsh surface deposition (biweekly to monthly) and water levels every quarter-hour from September 2007 through October 2008 (Table 1). A fully screened piezometer was installed at each station (six total) along both transects to a depth of ~1 m. An autonomous pressure transducer (Onset HOBO) was placed at the bottom of the six piezometers and set to record marsh water levels at 15-min intervals. The marsh was considered inundated at each station when the water level exceeded the marsh ground surface. Percent flooding frequency during each deployment was determined by the number of days flooded during a deployment and the length of each deployment. Water levels were corrected using temperature, average salinity at each piezometer, and local barometric pressure measured at each site. Marsh topography and well elevation along shore-normal transects at each site were surveyed

Fig. 2 Sediment deposition rates (in grams per square meter per day) at Porpoise Point (*top*) and Huddy Gut (*bottom*) in relation to elevation and location along transect. Stations are denoted by *PP* and *HG*. *B1* and *B2* denote the location of berms at PP; *B3* denotes the location of the berm at HG. *Open circles* indicate the mean study deposition rate; *black circles* represent the average deployment deposition rates. Note that sediment deposition axis is a log scale



using a Trimble real-time kinematic global positioning system (Trimble 5800 GPS receiver) with a vertical accuracy of ± 0.5 cm. Elevation measurements were collected approximately every 25 cm along the study transect starting from the shoreline to the interior marsh.

Supplemental data were used to help constrain environmental factors that could contribute to changes in sediment

deposition. Hourly precipitation and wind velocity data were measured at the Pamlico Aquaculture Field Lab, located within 2 km of HG (Fig. 1), which were acquired from the NC State Climate Office web site (<http://www.nc-climate.ncsu.edu/cronos>). River discharge data were obtained from the Tar River USGS site, 0208400, at Greenville, NC.

Table 1 Summary of deployments throughout the study period, including the duration of each of the deployments (days) and the average accumulation rates based on the tiles placed at each site (in grams per square meter per day) for Porpoise Point and Huddy Gut (short term)

Porpoise Point	9/7/2007	9/28/2007	11/9/2007	12/12/2007	2/8/2008	3/10/2008	5/21/2008	6/24/2008	7/28/2008	8/29/2008	10/9/2008									
	Length of deployment		21	42	33	58	31	72	34	34	32	41								
PP1 ^a		0.64	0.00	0.58	41.10	331	4377	9440	584	1562	13.60									
PP2 ^b		3.04	3.45	0.31	0.35	0.15	2.93	0.09	0.11	0.09	3.40									
PP3 ^b		2.04	0.62	0.33	0.70	0.11	1.64	0.13	0.15	0.38	10.77									
Huddy Gut	9/26/2007	10/18/2007	11/4/2007	12/13/2007	12/20/2007	1/12/2008	1/25/2008	2/15/2008	2/29/2008	3/12/2008	4/11/2008	5/2/2008	6/4/2008	7/12/2008	8/11/2008	8/15/2008	9/3/2008	9/12/2008	9/27/2008	10/10/2008
	Length of deployment		22	17	39		23	13	21	14	12	30	21	33	38	20	14	19	9	15
HG1 ^a		2.47	8.96	^c		53.40	2.23	0.44	0.23	2.12	4.77	15.18	11.71	0.12	0.21	4.29	0.97	5599	8.31	16.82
HG2 ^a		5.40	^c	^c		4.63	0.40	0.61	0.12	0.22	0.55	3.64	0.40	1.64	0.14	0.12	0.6	1693	4739	1.25
HG3 ^b		0.10	^c	^c		0.05	0.04	0.03	0.52	0.23	0.46	3.90	0.34	0.12	0.04	0.03	0.08	2.11	^c	4.54

The gray shade refers to the date tiles that were initially placed at each site—once at PP and twice at HG because of vandalism

^{a,b} Stations that are significantly different ($P < 0.001$)

^c Tiles were not collected at the respective station

An Instrumented TriPod (ITPod) was deployed near each marsh site with a diverse suite of instruments to synchronously record variability in a host of parameters. Waves were measured using a Nortek Vector (point-measuring current meter with pressure sensor, 25 cm above the bottom) and a Nortek Aquadopp (upward-looking acoustic Doppler current profiler, deployed at 98 cm above the bottom). The Vector measured a 4.26-min burst of velocity data at 8 Hz hourly, while the 1-MHz Aquadopp measured current velocities in 0.4-m bins with 8.5-min bursts sampling at 2 Hz. The data from the Vector and Aquadopp were used to calculate non-directional significant wave heights.

Marsh Sedimentation

Modern Deposition

Sediment deposition was measured using 216-cm² ceramic tiles (method modified from Pasternack and Brush 1998). Each sampling station (six in total) consisted of ten ceramic tiles surrounding the station-specific piezometer. Sediment samples were collected from PP every 4–6 weeks and from HG every 2–3 weeks (Table 1) for a period of 12 months. Deposition was normalized to the duration (in days) of each deployment cycle to account for deployment length variability. Samples from HG and PP were usually collected within the same week. Sedimentation tiles were carefully placed flush with the marsh surface, minimizing disturbance in the surrounding sediments. Sediments deposited on the tiles were transferred to sample jars or large sample bags and refrigerated at 4 °C until processed. Sediment samples were filtered through a pre-combusted, pre-weighed, 47-mm diameter, 0.7- μ m glass microfiber filters and then dried at 90 °C. After the filtered sediment samples were dried and weighed, they were placed in a muffle furnace and combusted at 550 °C for 4 h to determine organic content by loss on ignition (LOI). LOI values were recorded as the percent of material lost during combustion and are used as a proxy for the amount of organic matter within the sediment (Heiri et al. 2001).

Mass sediment deposition rates were measured for each deployment by averaging the mass of the sediment collected dividing by the area of the ceramic tiles (three to ten tiles) and the number of days between deployments. The variability in the number of tiles collected and used in the calculation of deposition during deployments depended on the number of tiles (if any) that had been lost or overturned (which occurred predominately at shore-side stations). An annual average deposition was determined by adding the average sediment accumulated during each deployment and dividing it by the duration of the study in days. Linear sediment deposition rates were calculated using the sediment collected from the ceramic tiles and a measured bulk

density. Bulk density was found by averaging water loss-based values from the top 2–4 cm for three short cores collected in the interior and shore-side marsh of HG. Bulk density measurements at HG were applied to both marsh sites because of the similarities in sediment composition: organic-rich sediment in the interior marshes and sandy silts along the shore side

Decadal-Scale Accumulation

Marsh sediment accumulation rates can be determined using the vertical distribution of naturally occurring ²¹⁰Pb ($t_{1/2}$ =22.3 years) and ¹³⁷Cs ($t_{1/2}$ =30 years), a bomb-produced radionuclide that is present in the environment due to atmospheric fallout from nuclear weapons testing. Three cores were collected from each study site along a shore-normal transect for radionuclide analysis. Cores were stored in a refrigerator at 4 °C until processed. The cores were sectioned at 2-cm intervals, and subsamples were placed in pre-weighed beakers and dried at 90 °C. Bulk density was calculated from the water lost during drying, assuming a sediment density of 2.65 g cm⁻³ and correcting for salt content. Once dried, the samples were homogenized using a mortar and pestle and then processed for radionuclide analysis.

Total ²¹⁰Pb was measured by alpha spectroscopy following the methodology of Nittrouer et al. (1979). Approximately 1.5 g of sediment was spiked with ²⁰⁹Po, as a yield determinant, and was partially digested with an 8-N nitric acid (HNO₃) solution by microwave heating. Polonium-209 and ²¹⁰Po in solution was then electroplated onto nickel planchets in a dilute acid solution (modified from Flynn 1968). ²¹⁰Pb_{Excess} was determined by subtracting the ²¹⁰Pb activity supported by ²²⁶Ra from the total ²¹⁰Pb activity, where the supported ²¹⁰Pb activity for a given core was assumed to be equal to the uniform background activity found at depth (Nittrouer et al. 1979).

Samples from the cores were also analyzed for ¹³⁷Cs activity by direct gamma counting on a low-background, high-efficiency Germanium detector coupled with a multichannel analyzer. Samples were packed into standardized vessels and were counted for approximately 24 h. Detectors were calibrated using natural matrix standards (IAEA-300, 312, 314) at the energy of interest (662 keV) in the standard counting geometry for the associated detector.

Sediment accumulation rates were calculated using the constant flux–constant sedimentation model (Appleby and Oldfield 1978) and represent a maximum rate for the length of detectable excess ²¹⁰Pb in the core. Downcore ¹³⁷Cs activities were used to substantiate the ²¹⁰Pb-determined accumulation rates. Wherever possible, the first appearance of ¹³⁷Cs horizon (1952) and the peak of ¹³⁷Cs (1963) activity were used to estimate a sediment accumulation rate.

Data Analysis

Time series data of precipitation, significant wave height, marsh inundation duration, and depths were analyzed for their influence on deployment deposition rates using simple regression analysis. To examine variability in sedimentation between sites, a one-way analysis of variance (ANOVA) was used with a post hoc/Tukey's test to analyze differences in sediment deposition and percent inundation frequency measured at each site. Sediment deposition data collected from the tiles were log-normalized before running statistical analysis to correct for the skewed distribution of deposition rates.

Results and Discussion

Sediment deposition was measured ten times over the study at PP and 17 times at HG and varied greatly, ranging from 0.03 to 9440 g m⁻² day⁻¹ (Table 1). Sediment deposition was not calculated at HG from November 5, 2007 through December 20, 2007 because all the ceramic sedimentation tiles were not found and were presumed to be vandalized. New tiles were placed at that site on December 20, 2007. Three stations (PP2, PP3, and HG3) are described as interior marsh sites due to their location landward of the primary berm (Fig. 2). The other three stations are found shoreward (PP1 and HG1) or on the primary berm (HG2; Fig. 2). Deployment dates are the days in which sediment was collected from the tiles, and the deployment lengths were the length of time between deployments and collections and may not be equal in duration (Table 1).

Variations in Sediment Deposition and Composition

Sediment deposition rates were highly variable at the shore-side marsh sites (PP1, HG1, and HG2), spanning five orders of magnitude and depositing an average of 1807, 159, and 225 g m⁻² day⁻¹, respectively, over the course of the study (Table 2 and Figs. 2 and 3). However, there were a few periods of enhanced deposition that substantially contribute to the high annual sedimentation rate. The sediments deposited at shore-side stations consisted of predominantly siliciclastic materials, ranging from fine to coarse sands with some shell hash, sea grass, and large marsh rip-up clasts. Coarse sands, gravels, and man-made debris (e.g., broken bricks, bottles) were identified in above average sediment deposits at HG1 and HG2 due to their proximity to housing communities (bold values in Table 1; Fig. 3). The high variability and magnitude of shore-side deposition can be attributed to the proximity of the station to the coastline, storm energy in the PRE, and seabed remobilization (Frey and Basan 1978; Hatton et al. 1983; Leonard and Luther

1995; Delaney et al. 2000). The periods of above average deposition rates at PP1 (Table 1 and Fig. 3) consisted of a mix of sand, sea grass, and pieces of eroded marsh. This suggests that the material deposited on the shore-side marsh was derived, at least in part, from the eroded shoreline and the adjacent seabed, as reported elsewhere (Day et al. 1998).

The sediment collected from the sedimentation tiles at the shore-side stations had average LOI values of 12, 0.6, and 0.8 % at PP1, HG1, and HG2, respectively (Table 2). These findings are comparable to other shore-side marsh studies (Hatton et al. 1983; Kastler and Wiberg 1996; Callaway et al. 1997). During the spring and summer months, the percentage of organic matter was more variable than during the winter months, with both the maximum and minimum LOI percentages observed (Fig. 3). This variability is attributed to increased primary production during the spring and summer months, yielding more marsh grass, leaf litter, and other organic debris (e.g., sea grass) in the collected sediment (Pasternack and Brush 2001).

The difference between the shore-side LOI at PP (12 %) and HG (<1 %) is attributed to the nearshore sediment source (Table 2). At PP, the subtidal area adjacent to the marsh edge contains a deteriorating marsh platform, sea grasses, and sands. However, the nearshore material at HG primarily comprised fine to coarse sands. The results indicate that inorganic sedimentation along the shore-side marsh provides the majority of the deposited sediment relative to in situ organic production, and according to Hardaway (1980), the mid-estuary (e.g., near HG) is dominated by low bluffs that are characterized by clayey sands, while shorelines near the mouth of the PRE are dominated by marsh (e.g., PP). The distribution of these two dominant shoreline types likely explains the differences in sedimentology and organic composition between the two shore-side study sites. The HG site consists of a slightly higher inorganic sediment fraction and larger grain sizes than the PP site.

In contrast, the interior marsh stations (i.e., PP2, PP3, and HG3) had less variable and far lower average deposition rates of 1.5, 1.8, and 0.62 g m⁻² day⁻¹, respectively (Table 2 and Fig. 4). Sediments near PP2 generally consisted of dark brown to black sandy silts with some organic detritus (e.g., plant material), while PP3 and HG3 sediments typically consisted of organic-rich silty to sandy mud. The largest sedimentation rates for the interior marsh occurred during the last deployment at PP3 and HG3 (Table 1), coinciding with the passage of a week-long frontal system (Fig. 4, hatched area). Four deployments at PP2, one at PP3, and three at HG3 exceeded the average deposition for the study period (Fig. 4). Each of the above average deposition rates were nearly an order of magnitude greater than the long-term accumulation (radionuclide dating), which has also been reported elsewhere in similar settings (Day et al. 1998). The last two deployments at HG and the last

Table 2 Mean total and organic (loss-on-ignition) deposition rates (in grams per square meter per day) for the study period

Study site	Station	Study period deposition rate	Deposition range	Mean organic matter deposition (%LOI)	Organic matter deposition range
Porpoise Point	PP1	1807±309	0.0–9440	210 (12)	0.0–898
	PP2	1.5±0.3	0.09–3.45	0.29 (19)	0.02–0.73
	PP3	1.8±0.4	0.11–10.8	0.37 (21)	0.03–2.0
Huddy Gut	HG1	159±41	0.12–5,599	1.0 (0.6)	0.01–29.4
	HG2	225±67	0.00–4,739	1.7 (0.8)	0.01–25.1
	HG3	0.62±.2	0.0–4.54	0.16 (25)	0.01–1.0

Values in parenthesis denote the percent LOI of the total deposition rate

deployment at PP coincided with tropical storm Hanna and a frontal system.

There was no significant difference (ANOVA: $P=0.11$) in deployment-based sediment deposition between the study areas (HG versus PP) when all data were combined regardless

of location (interior, shore-side marsh). However, the deposition rates of the shore-side marsh and those of the interior marsh can be grouped together as they have similar depositional magnitudes. Differences in sedimentation rates between the shore-side and interior marshes were significantly different

Fig. 3 Time series data for shore-side marsh stations at Huddy Gut (HG) and Porpoise Point (PP). Deployment deposition rates that exceed the study average deposition rate are represented by *black circles*. Water heights are relative to the ground surface at each station. Inundation values represent the accumulated time in which the marsh was flooded continuously. Sharp declines in cumulative inundation represent water levels dropping below the surface, disrupting continuous inundation. *Hatched area* indicates the passage of tropical storm Hanna and a week-long frontal system

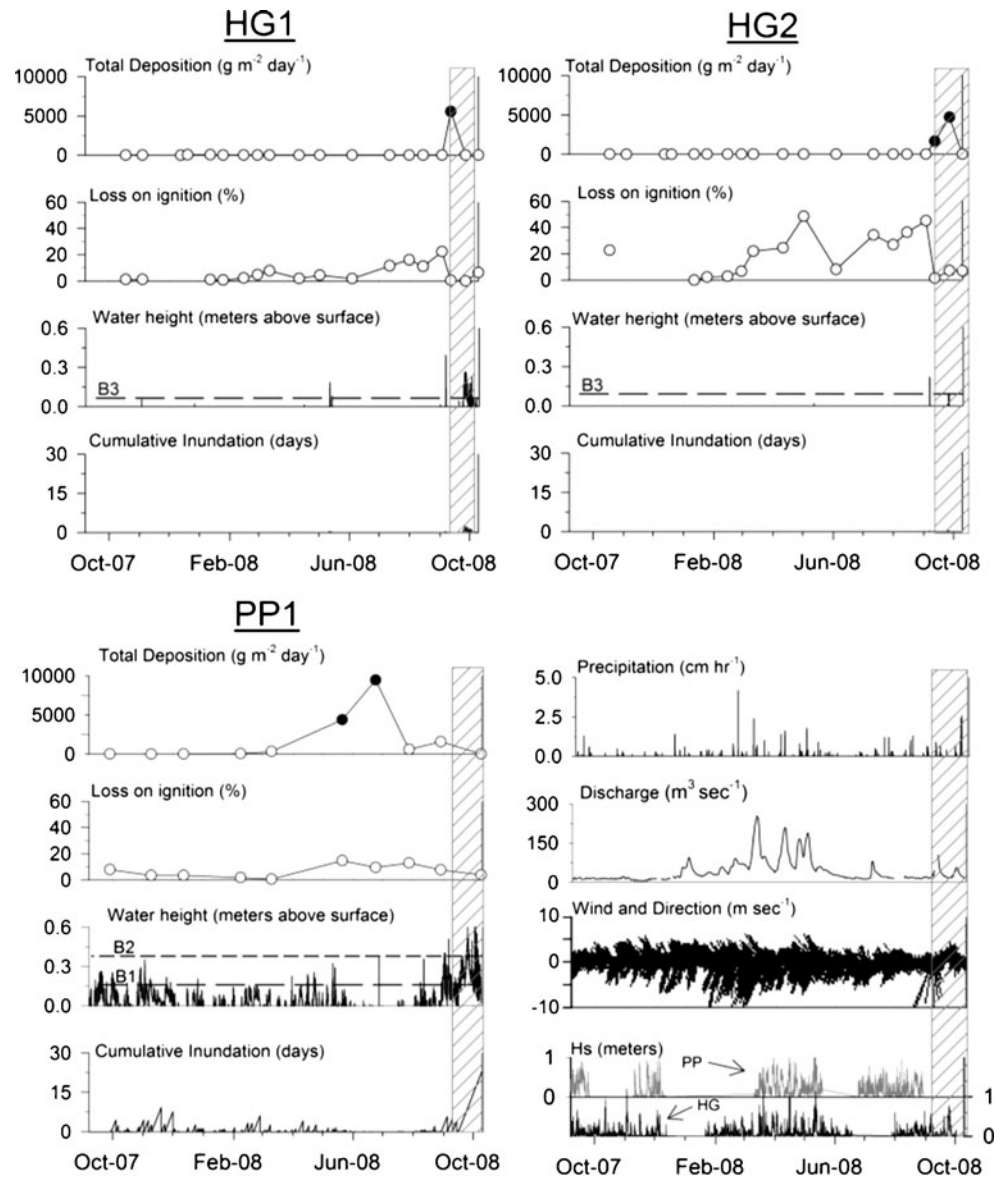
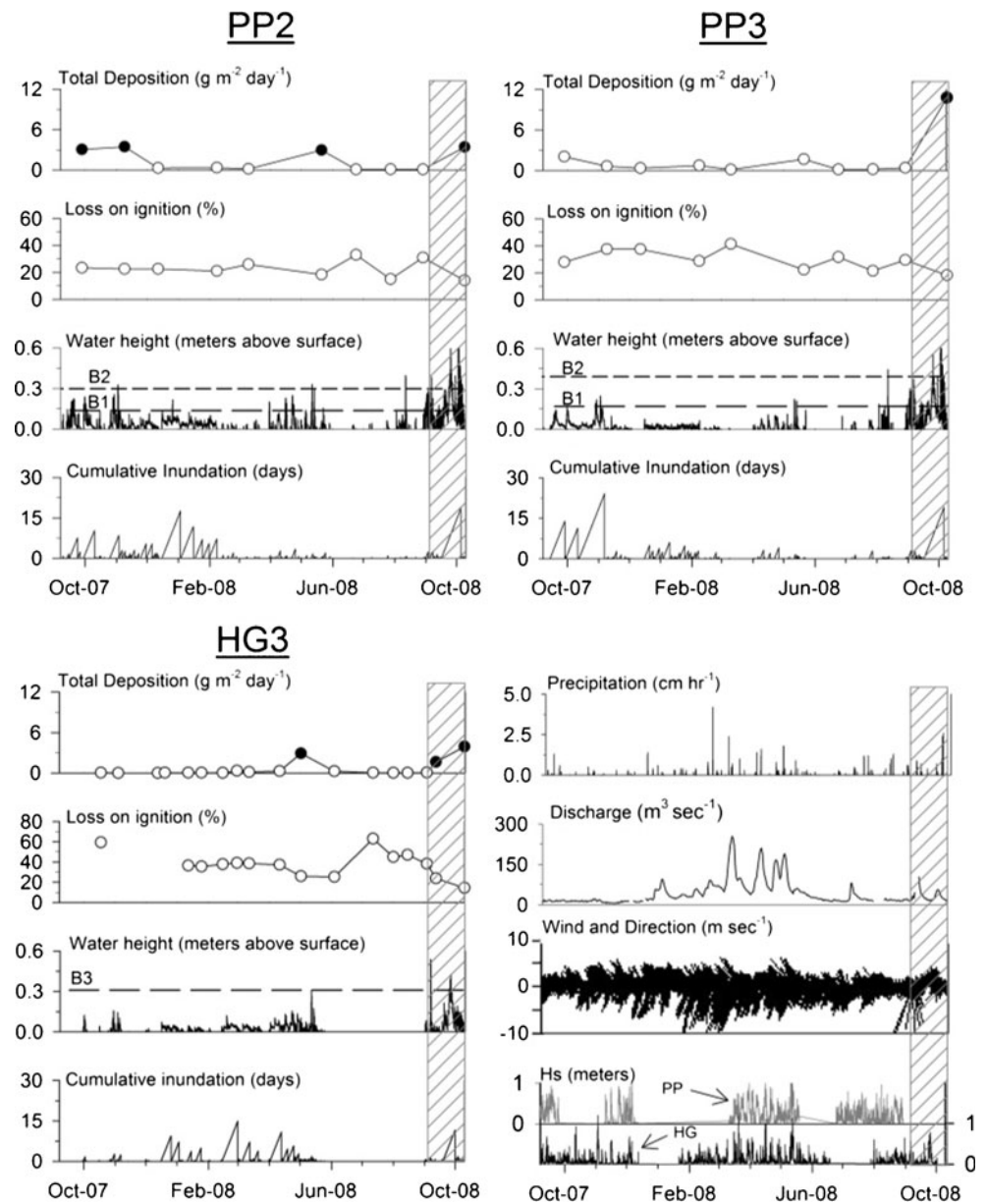


Fig. 4 Time series data for interior marsh stations at Huddy Gut and Porpoise Point. Deployment deposition rates that exceed the study average deposition rate are represented by *black circles*. Water heights are relative to the ground surface at each station. Inundation values represent the accumulated time in which the marsh was flooded continuously. Sharp declines in cumulative inundation represent water levels dropping below the surface, disrupting continuous inundation. *Hatched area* indicates the passage of tropical storm Hanna and a week-long frontal system



for both sites (ANOVA: $P < 0.001$). Deposition in the interior marsh was two to three orders of magnitude less than those measured closer to the shore (Tables 1 and 2).

Interior marsh stations had the greatest organic matter (OM) deposition rates and similar average rates of OM deposition based on LOI percentages (Table 2). The average LOI percentage of the surficial sediments in the interior marsh ranged between 19 and 25 %. Similar to the shore-side marsh, the OM deposition for the interior marshes was more variable from spring to fall. Minimum and maximum OM deposition values also occurred during this period, with the study minimums from each interior station occurring during the last deployment. The minimum OM deposition during the last deployment was likely a result of a greater flux of mineral sediments entering the interior marsh

because of flooding from storm surge and the associated wave-generated sediment resuspension and transport (Goodbred and Hine 1995; Friedrichs and Perry 2001).

Short-Term Deposition Versus Long-Term Accumulation

Decadal-scale accumulation rates were measured using ^{137}Cs and ^{210}Pb at four of the six sites—PP1, PP2, PP3, and HG3 (Table 3 and Fig. 5). The accumulation rates measured for the interior marshes are similar to those reported by other researchers in this system (0.24–0.90 cm year^{-1} ; Craft et al. 1993) and near, but below, the current rate of relative sea level rise (Horton et al. 2006; Kemp et al. 2009). Accumulation rates could not be calculated for most of the shore-side sites because of the high variability in ^{210}Pb and ^{137}Cs activity

Table 3 Measured and calculated sediment accumulation rates (in centimeters per year) for all stations using ceramic tiles (monthly integration) and radionuclides (decadal integration)

Station	Ceramic tiles	^{210}Pb	^{137}Cs
PP1	21.9±8.1	0.36±0.03	>0.20
PP2	0.28±0.11	0.30±0.04	>0.11
PP3	0.35±0.06	0.28±0.01	0.20±0.02
HG1	4.4±1.1	–	–
HG2	7.3±1.7	–	–
HG3	0.1±0.03	0.35±0.03	0.33±0.02

attributed to the coarse grain size as well as a reflection of the non-steady-state depositional environment (Fig. 5). However, the core collected at PP1 had coarse sand on top of peat material and was analyzed for ^{137}Cs and ^{210}Pb . The organic-rich sediments below 17 cm were used to evaluate a rate of accumulation (Fig. 5) that is similar to that of the interior marsh, suggesting that this behaved sedimentologically as an interior marsh not too far in the recent past. Rates of shoreline erosion of the APES marshes can be as high as 0.25 m year⁻¹

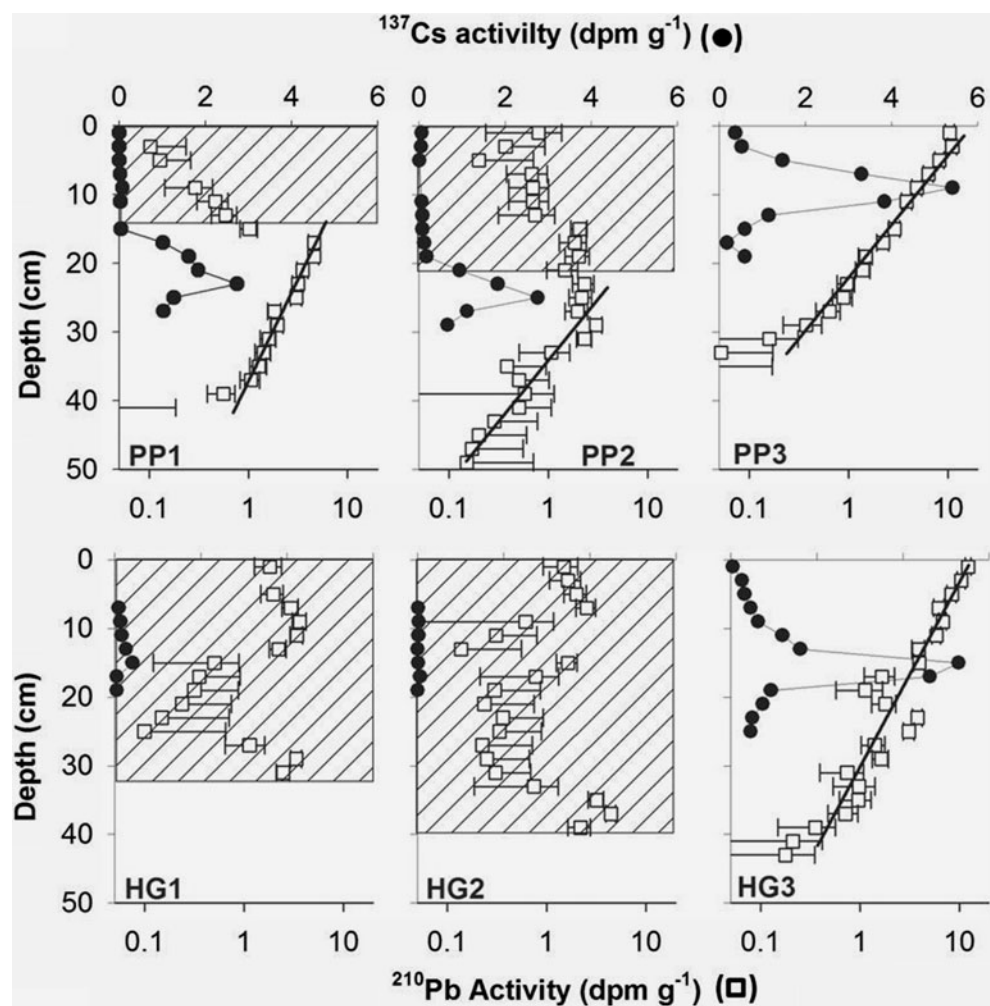
(Coward et al. 2010). PP1 was found at the water's edge, accumulating sandy sediments primarily during wave-intense periods. This highlights how the marsh shore is in a state of transgression.

The short-term rates of deposition agree within error of decadal-scale accumulation rates for the interior sites at PP2 and PP3. There was no significant difference between the tile-based deployment accumulation rates at all three interior marsh sites; however, the total amount of sediment deposited at HG3 over the study was three times less than the decadal-scale accumulation rate (Table 3). Perhaps sediment deposition during this study was a period of minor sediment supply to the interior marsh as a result of fewer high-water, high-energy storm events impacting the mid-estuary, and/or sedimentation at the HG site may have been altered due to nearby hardening shorelines (Currin et al. 2008; Mattheus et al. 2010).

Inundation Dynamics and Environmental Factors

Water-level fluctuations at the two study areas were generally <0.2 m during the winter and early spring and higher

Fig. 5 ^{137}Cs (black circles) and ^{210}Pb (open squares) activity profiles for sediment cores at Porpoise Point (top) and Huddy Gut (bottom). Hatched area indicates the layer of mixing and not used in ^{210}Pb accumulation rate calculations. Lines represent regressions used in calculating accumulation rates



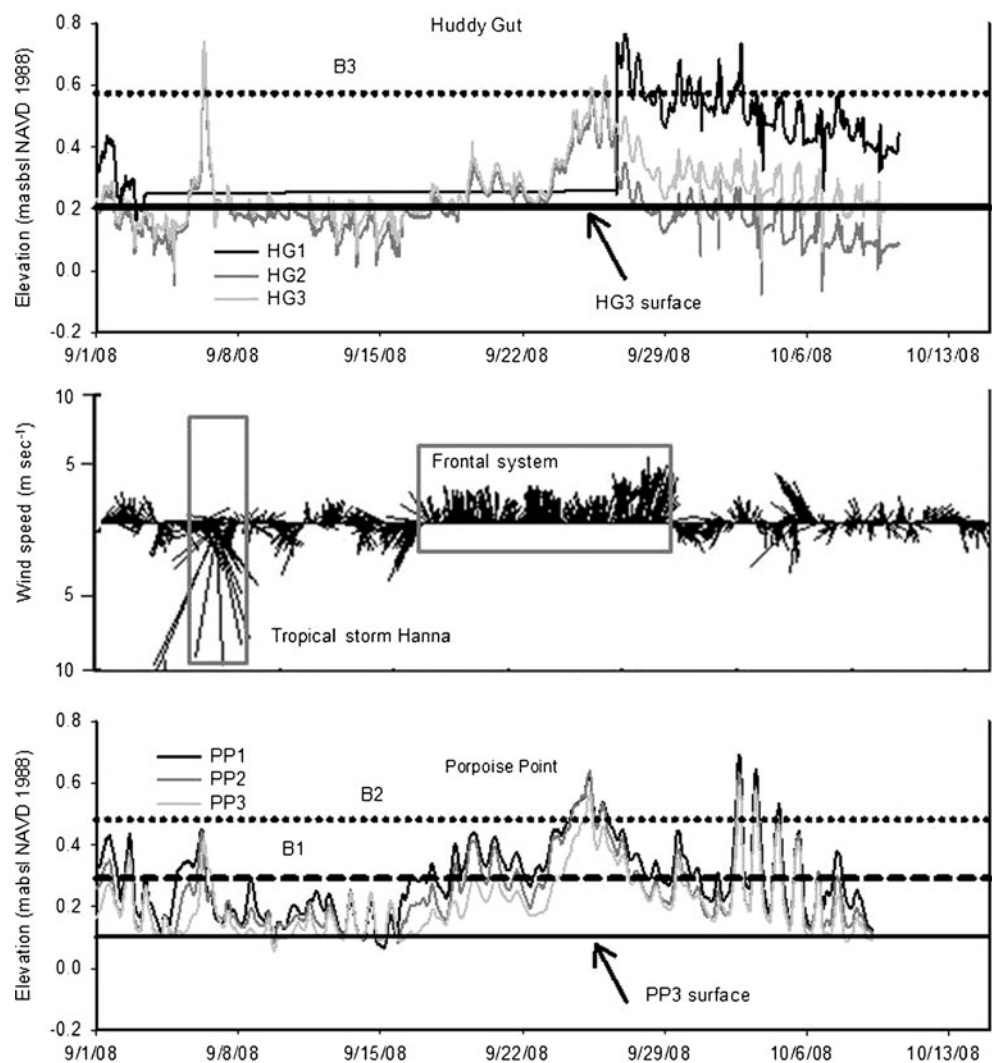
and more variable during the early summer and late fall as a result of the dominant seasonal winds (Figs. 3 and 4). Fetch relative to shoreline orientation seemed to determine marsh inundation as the water levels at PP were generally higher with winds from the southwest and the water levels at HG were highest with winds from the north–northeast. Not surprisingly, the greatest inundations at both sites were experienced when winds exceeded $\sim 4 \text{ m s}^{-1}$. During the passage of tropical storm Hanna (Figs. 3 and 4, hatched area), average hourly winds exceeded 10 m s^{-1} from the southeast and rotated to the southwest on September 6. This wind stress forced water levels higher at HG and PP and then was followed by a rapid decline in water levels after the passage of the storm (Fig. 6). The maximum flooding levels at PP and HG were both around 0.5 m above the interior marsh surface and occurred during tropical storm Hanna at PP and the frontal system at HG (Figs. 4 and 6).

Inundation depth and frequency do not appear to be related to precipitation as only one site (HG3) portrayed a

significant positive relationship ($R^2=0.55$, $P<0.001$; data not shown). The lack of a strong correlation suggests that inundation is largely controlled by wind-driven water levels in the adjacent PRE and Pamlico Sound; nevertheless, precipitation may affect flooding and sediment redistribution (Mwamba and Torres 2002; Voulgaris and Meyers 2004). For example, moderate rain event during the May 2 deployment at HG3 could explain why sedimentation during this period exceeded the annual mean deposition rate (Table 1 and Fig. 4). However, the source of this sediment would likely be derived from sediment resuspension of the marsh surface and not include much new allochthonous material.

Interestingly, there was not a clear relationship between the sediment deposition rates and inundation times as seen elsewhere in similar environments (Stevenson et al. 1988; Christiansen et al. 2000; Temmerman et al. 2003; Fig. 7). Interior marsh sites PP2 and PP3 had a weak positive relationship between flooding frequency and deposition rate.

Fig. 6 Water levels at each station for Huddy Gut (*top*) and Porpoise Point (*bottom*) and wind velocities (*middle*) during the last 2 months of the study. Tropical storm Hanna and the week-long frontal system are shown. Note the water level differences between the two marshes during each storm



Shore-side marsh deposition was generally very low throughout the study period, except during a couple of events when large quantities of sediment ($>4,000 \text{ g m}^{-2} \text{ day}^{-1}$) were deposited. Shore-side marsh sites HG1 and HG2 only had a total of three periods that experienced flooding (Fig. 3), and all three were during the two storm periods nearing the end of the study. The lack of flooding at these two stations was because of their elevation and location on the shoreward and leeward faces of the berm, respectively (Fig. 2).

Marsh surface elevation changes (e.g., deposition and erosion) along estuarine shorelines can be significantly affected near mean high water and mean low water because of wave-driven transport (Jackson 1995). But the low deposition at PP1 during prolonged inundations (Fig. 7) may be attributed to the remobilization and removal of sediments due to increased wave action during high water. However, there was high deposition at the HG1 and HG2 during the same time period. The difference in deposition may be a function of marsh and berm elevation, high water levels, and wave energy.

The dominant seasonal wind velocities were a considerable factor directly affecting marsh inundation. However, it was a combination of high water levels and storm-related winds that forced the water levels up and over the berm at each site (Fig. 6). Elevated wind speeds and wave heights exceeding 0.5 m have been shown to increase sediment resuspension near the study area (Giffin and Corbett 2003; Walsh et al., in revision). These insights may explain the larger sediment accumulation rates in the interior marsh during periods of higher water levels at both study sites. The higher water levels on the marshes were generated from winds near or greater than 4 m s^{-1} , when local significant wave heights would have been increased and suspended sediment concentrations elevated through resuspension (Figs. 4 and 6).

Role of the Storm Berm and Storm Events

Berms parallel to the shorelines at PP and HG likely play an important role in controlling inundation and sediment deposition within the interior marsh (Fig. 2). The berm closest to the shore at PP (B1) stands ~ 0.22 and ~ 0.16 m higher in elevation than the marsh surface at PP1 and PP2, respectively (Fig. 2). A substantially larger second berm (B2) separated PP2 from PP3, and it reaches ~ 0.35 and ~ 0.44 m higher in elevation than the marsh surface at stations PP2 and PP3. At HG, there was a single berm (B3) ~ 0.45 m higher than the interior marsh surface (Fig. 2). It is important to note that the difference in elevation between the interior marsh sites (i.e., PP3 and HG3) and the large levee (i.e., B2 and B3) is similar, though the elevation throughout HG was generally 10 cm higher than at PP (Fig. 2).

All tile deployments in the interior marsh at PP that exhibited above average deposition rates occurred during

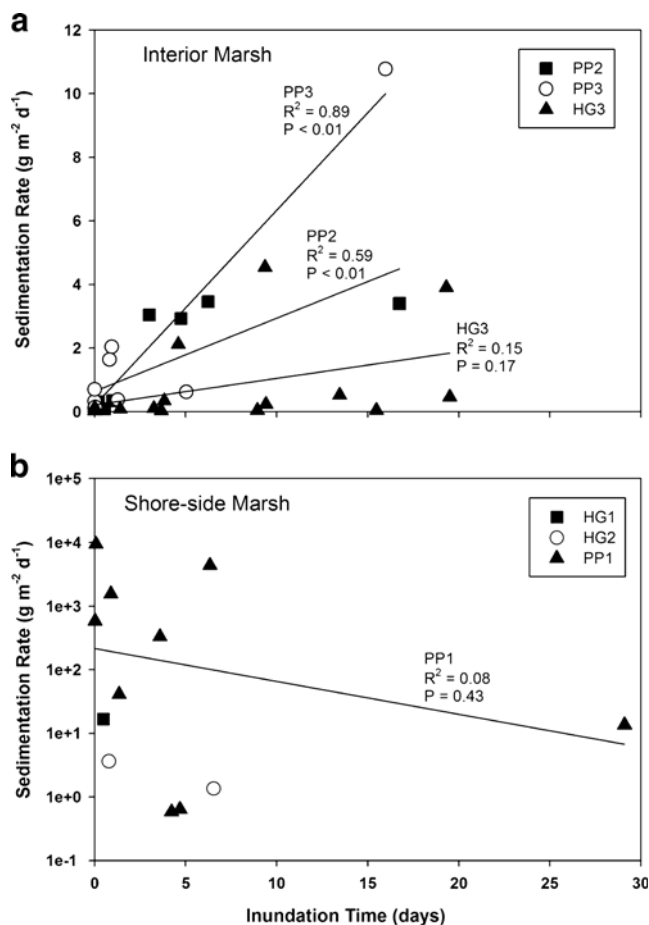


Fig. 7 Sedimentation rates versus inundation times for interior marsh sites (*top*) and shore-side marsh sites (*bottom*). Note scale change between interior and shore-side stations. Inundation times were calculated by summing the total time, in 15-min increments, that water levels were above the marsh surface at each station for each deployment

events when the water levels in the estuary exceeded the elevation of the adjacent seaward berm (B1 for station PP2 and B2 for station PP3; Fig. 4). The water levels at PP significantly exceeded the elevation of B2 for an extended period during the last deployment, October 9, 2008 for 0.69 days. At HG3, the level of inundation only exceeded B3 twice during the study: 0.21 days during the September 12 deployment and 0.33 days during the September 27, 2008 deployment. These water level events that exceeded the larger berms were associated with tropical storm Hanna and a frontal system (Fig. 6).

The deposition rates during deployments in which inundation exceeded the berms were an order of magnitude greater than those deployments that did not overtop the berm (Fig. 4). Additionally, the larger deposits were generally less organic as a result of more allocthonous sediments likely resuspended from the estuary floor (Fig. 4). As the water levels rose during the storm events, the large berm was overtopped or breached, allowing sediment-laden water

to enter the interior marsh. The suspended sediment was then deposited on the marsh surface when the water retreated and wave energy reduced.

The passage of tropical storm Hanna and the following frontal system deposited over 40 % of the annual deposition for the study at the interior sites HG3 and PP3 (Table 1). Winds during these two events raised the water levels at all the interior sites to some of the highest levels throughout the study (Figs. 4 and 6). The long duration of the frontal system in addition to the elevated water levels (above B3) caused prolonged inundation over the elevation of the berm and increased inorganic sediment supply to the interior marsh (Figs. 4 and 6). As an example, sediment was deposited at a rate of $2.11 \text{ g m}^{-2} \text{ day}^{-1}$ during the September 12, 2008 deployment at HG3, which was affected by tropical storm Hanna, and over twice that ($4.54 \text{ g m}^{-2} \text{ day}^{-1}$) during the October 10, 2008 deployment, which coincided with the frontal system (Table 1 and Fig. 4). Although there was no clear relationship between the inundation frequency or duration and sediment deposition (Fig. 7), the sediment supply to the interior marsh sites was controlled by inundation, but more largely a function of water levels relative to the height of the berm, which was approximately 50 cm above the interior marsh surface at both sites (Fig. 6).

This geomorphic control on deposition is not surprising as the elevation of the berm dictates the elevation at which the sea level needs to rise in order to deposit a significant amount of sediment in the interior marsh. Moreover, the elevation of the berm is determined in the short term by water level and wave processes, such as tidal and lunar cycles and meteorological events (Hine 1979). Marsh inundation behind the berm during periods of calmer conditions may be influenced by groundwater levels, upland surface runoff, or from tidal creek flooding; however, this type of flooding, where the water levels stay below the berm, will not allow large quantities of allochthonous sediment to be supplied to maintain marsh elevation at these or similar marsh sites.

The storm berm geomorphology of HG and PP were similar in width and relative height, but differ in absolute elevation and distance from the shoreline (Fig. 2). These relationships suggest that the water level and wave processes that control berm formation are similar between the two sites, but may develop at different storm tide levels because of location, fetch, and shoreline orientation. The development of a spring tide berm did not occur at HG and could be a factor of shore-side marsh degradation from higher water levels at the mid-estuary and removal of sediment in the swash zone.

The interior marsh sites at HG and PP both receive substantial sediment during wind events when the water levels exceeded the elevation drawn up and over the berm. In a similar but smaller lagoon in Venice, increased frequencies

of “Acqua Alta,” or high water, have been correlated with greater marsh accretion rates (Bellucci et al. 2007). These above average rates are attributed to wave resuspension associated with high water levels and is consistent with the idea that low-frequency, high-magnitude storms are extremely important in delivering sediment to the interior marsh in wind-dominated systems (Reed 1989; Goodbred and Hine 1995; Cahoon and Reed 1995). The results of this study identify some of the geomorphic (i.e., berm) and process-oriented (i.e., water levels, wind patterns) mechanisms that control the deposition in interior marshes of irregularly flooded environments. This relationship between geomorphology and local wind patterns are likely to be true for other microtidal marsh environments.

Unlike other studies, the duration of marsh inundation alone did not appear to be a major factor impacting marsh deposition, although flooding depths that exceeded the elevation of the berm directly contribute significant sediment to the interior marsh. The uncertainty in the forecasted tropical disturbance frequency with a predicted rise in tropical storm intensity (Goldenberg et al. 2001; Giorgi et al. 2001; Knutson et al. 2010), in addition to the increase in relative sea level rise (Horton et al. 2006; Kemp et al. 2009), complicates how the berm and interior marsh respond to changing water levels. A decrease in low-pressure, high-wind events could starve the interior marsh of inorganic sediments and prevent the marshes in keeping pace with long-term sea level rise. On the other hand, interior marsh deposition may be enhanced because of more frequent and stronger storms that would deliver more sediment behind the berm.

The enclosure of the two marsh sites within the larger Pamlico Sound lagoon makes these marshes more susceptible to short-term dynamically driven sea levels relative to long-term sea level rise in more tidally dominated systems (Temmerman et al. 2003; Kolker and Hameed 2007; Kolker et al. 2009). Water levels at HG and PP show similar responses to meteorological forces and may indicate similar water level fluctuations in other embayments along the east coast, as suggested by Kolker et al. (2009). Regional-scale atmospheric and meteorological conditions may contribute to the unique water level signatures seen in different locations throughout the southeastern US coast.

Conclusion

This research examined marsh sediment samples, radionuclide data from six cores, and in situ water levels along an estuarine gradient of the wind-dominated PRE. The findings in this research are consistent with previous studies noting that extreme events are majorly responsible for marsh accretion in microtidal and wind-driven environments. However, new

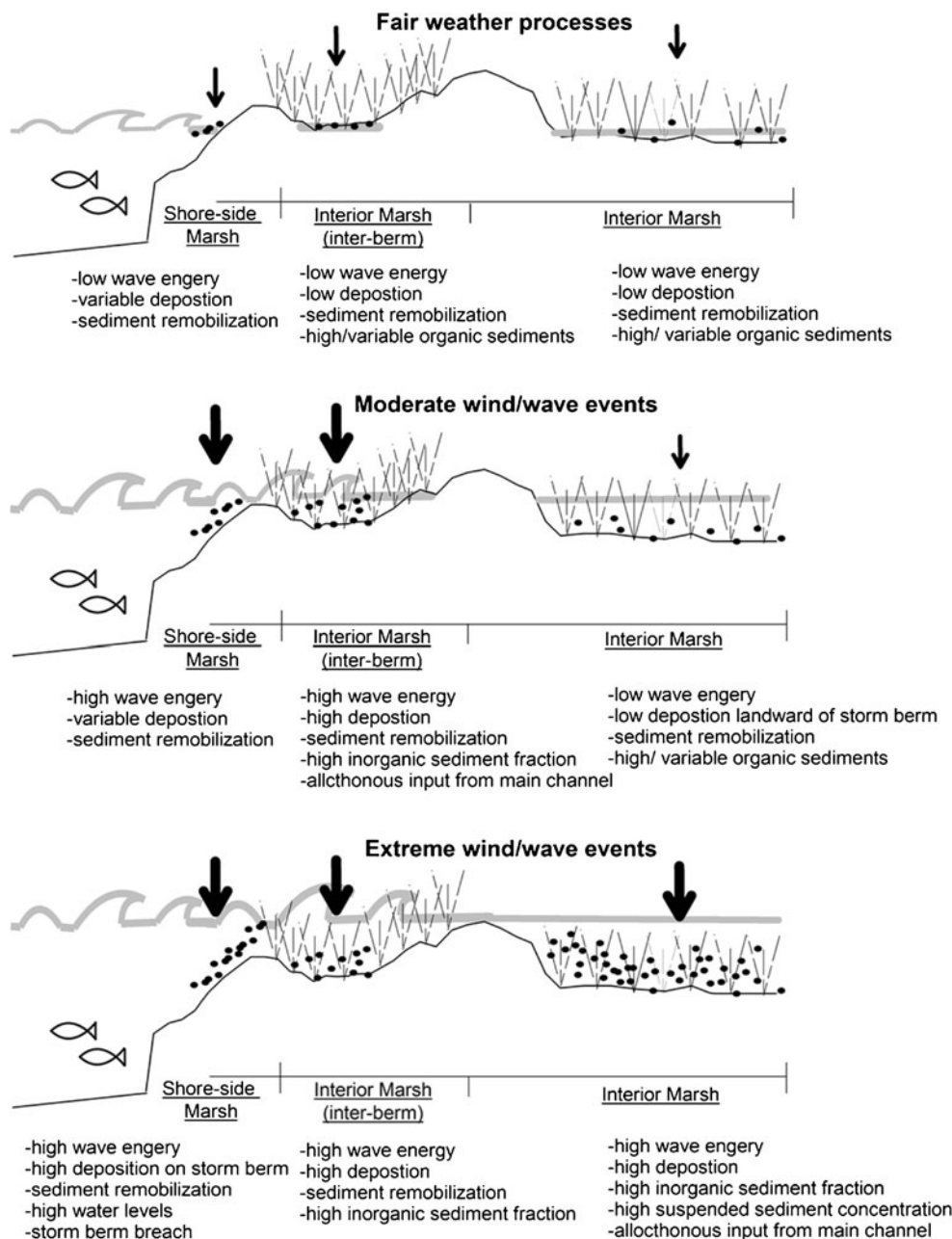
insights regarding marsh geomorphology and wind–water level interactions have been presented here and clearly indicate a strong relationship between the storm berm and interior marsh.

Based on this research, a conceptual model was developed to explain the differences in sediment deposition between the two marsh sites in a wind-driven microtidal estuary (Fig. 8). The two marsh sites in this study are remarkably similar with regard to the storm berm structure and interior marsh deposition, but differ in the shore-side marsh geomorphology and response to wind-driven events. The observations detailed in this paper reinforce previous findings from similar environments as well as introduce new

information regarding wind–water interactions and sediment dynamics associated with marsh geomorphology.

Sediment deposition was significantly different between the shore-side and interior marsh stations. Shore-side sedimentation was highly variable, predominantly inorganic, and was dependent on water levels. Sediments along the shore are most likely deposited, remobilized, and eroded throughout the year. Interior marsh deposition was less variable and more organic-rich. Sediment deposition was an order of magnitude greater during inundation periods higher than the elevation of the marsh berm. In fair weather conditions, each site generally had low deposition but a greater range in deposition along the shore-side marsh.

Fig. 8 Conceptual model of fair weather (*top*), moderate (*middle*), and storm (*bottom*) processes, summarizing the major depositional mechanisms. *Arrows* indicate the relative sediment flux



Contemporaneously, sediment deposition was lower with relatively higher LOI content within the interior marsh basin. Moderate weather conditions resulted in slightly higher and more variable water levels that would result in above average deposition in the interior marsh between the high water berm and the storm water berm. However, this process does not occur at the HG marsh as erosion, marsh degradation, and human modifications (e.g., bulkhead) contribute to shore geomorphology.

Storm weather conditions caused increased deposition to the berm and interior marsh. This was due to a combination of increased seabed resuspension and high wind-driven water levels, introducing new material as water overtopped the berm. Storm deposition for the interior marsh sites account for ~40 % of the total sediment deposited during the year.

Marsh inundation was influenced by wind direction and magnitude. Short-lived storms, like tropical storm Hanna, with stronger winds may have similar impacts on the depth of flooding as sustained frontal systems; however, longer-lived fronts with weaker winds may increase the sediment supply by increasing the duration of inundation above the storm berm. PP stations were flooded more often and to greater depths relative to HG stations due to lower elevations of the marshes at the mouth of the estuary, and these processes were manifested in sedimentation rates two times greater at PP. During fair weather conditions, marsh surface water levels are lower and do not exceed the elevation of the berms. In contrast, during storm conditions, the estuary surface water levels can rise or fall. Low water and strong waves can deposit or remove sediment from the shore-side marsh, while high water and strong waves can breach the berm and flood the interior marsh with allochthonous, sediment-rich water (Fig. 8).

Decadal-scale sediment accretion rates range between 0.20 and 0.35 cm year⁻¹ for the interior marsh sites. These rates are similar to other microtidal environments (Kastler and Wiberg 1996; Ward et al. 1998; Bellucci et al. 2007); however, these rates are lower than the long-term relative sea level rise measured along the Outer Banks (0.35–0.46 cm year⁻¹; Kemp et al. 2009). Variations in marsh sediment accumulation are a result of tropical storm and frontal system frequency that lead to increased resuspension and inundation. Short-term water level fluctuations from regional atmospheric and meteorological forcings may result in signature events that can be traced throughout different protected coastal and estuarine marshes along the east coast (Kolker et al. 2009).

The dynamics of marsh deposition in wind-dominated environments are complex, involving relationships between wind patterns, water levels, and marsh geomorphology. Our findings are limited to the PRE system, but have implications for a better understanding of other coastal and estuarine marshes. It is important to consider geomorphology and

berm processes when modeling natural and constructed marsh response to both short-term and long-term sea level rise as these structures restrict the supply of sediment to the interior marsh to only periods when the water levels are higher than the berms. Additionally, alterations to the dominant atmospheric and meteorological patterns that are expected as a result of climate change will have inevitable consequences to both storm berm development and marsh accumulation.

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