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Seasonal Measurements of Sediment Elevation in Three Mid-Atlantic Estuaries

Daniel L. Childers†, Fred H. Sklar‡, Bert Drake§, and Thomas Jordan§

Baruch Marine Lab
University of South Carolina
P.O. Box 1630
Georgetown, SC 29442, U.S.A.

ABSTRACT

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Relative sediment elevations have been measured seasonally since Spring, 1990, in three estuaries representing a range of estuarine geomorphologies, sizes, and watershed inputs: the North Inlet estuary, South Carolina (SC), the Patuxent River estuary, Maryland (MD), and the Rhode River estuary, Maryland (MD). Sediment elevations were quantified using a levelling-arm device that allowed accurate, repeatable measurements at four arm orientations per site (with nine replicates per orientation), a number of habitat sites per location, and a number of locations in each estuary. This hierarchical design allowed variability to be partitioned into nested spatial scales. At North Inlet, we established six locations characterizing a range of freshwater and oceanic influences, and marsh ages. Water level gauges continuously recorded inundation rates at three of the six locations. Six sediment elevation locations along the Patuxent River estuary (one habitat site each) differentiated tributary marshes from main channel marshes, marshes from mudflats, and upper from lower river geomorphologies. Seven sediment elevation sites in the Rhode River estuary were all within the same 0.25 ha area (spatially equivalent to a single habitat site in the other two estuaries), and we used these data to investigate small-scale variability in brackish marsh sediment elevations over time.

Results from North Inlet showed sediment elevations increasing at the greatest rates at locations nearest to freshwater influence. These rates were two to three times apparent sea level rise (ASLR), which is 2–4 mm yr^{-1} in all three estuaries. Sediment elevations in dead end tidal creek marshes—those without direct freshwater inputs—generally increased at rates comparable to ASLR. Geologically older marshes showed little or no net accretion over 2.5 years. A large decline in sediment elevations (-9.4 mm yr^{-1}) at a mudflat located in the headwaters of a geologically young tidal creek appeared to represent the "birth" of a transgressive subtidal creek from an intertidal mudflat. Sediment elevations generally increased at the Patuxent River tributary marsh sites, but at greater rates in lower river than upper river tributaries. In contrast, a lower river main channel marsh and upper river mudflat appeared to be eroding while a middle river marsh and mudflat appeared to be accreting. This pattern suggests that the extensive mid-channel tidal freshwater marshes of the upper river and the isolated tributary headwater marshes of the lower river may be sediment sinks, while others may be sediment sources. The Rhode River study, on the other hand, showed that small-scale variability in brackish marsh sediment elevations may be much greater than seasonal or long-term differences. The consistent use of this accurate and repeatable technique to quantify estuarine sediment elevation dynamics in a number of systems will continue to generate data critical to future comparisons of Atlantic and Gulf Coast estuaries.

ADDITIONAL INDEX WORDS: *Sediment elevations, long-term measurements, estuaries, estuarine geomorphology, spatial variability, intertidal marshes.*

INTRODUCTION

Long-term measurements of changes in sediment elevation in estuarine marshes allow researchers to determine if a given system is maintaining itself relative to local sea level rise (REDFIELD, 1972; LETZSCH and FREY, 1980). Wetland sediment elevation is a parameter that effectively integrates processes occurring (1) locally at the site, such as erosion (REED, 1988) and organic matter production (REJMANEK *et al.*, 1988); (2) at the ecosystem level, such as tidal exchange (CHILDERS and DAY, 1990) and bioturbation (GARDNER *et al.*, 1989), and (3) at the landscape level, such as subsidence (TEMPLET and MEYER-ARENDT, 1988) and watershed sediment inputs (FROOMER, 1980; PHILLIPS, 1991). Most estuarine marshes studies have reported sediment accretion rates, though, rather than actual changes in sediment elevation. In Table, 1 we review a number of recent studies of historical and contemporary sediment accretion from the Atlantic and Gulf coasts of the United States (U.S.) and

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† Corresponding author—current address: National Marine Fisheries Service, SE Fisheries Center, Galveston Lab, 4700 Avenue U, Galveston, TX 77551-5997, U.S.A.

‡ Current address: Everglades Research Division, South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, FL 33416, U.S.A.

§ Current address: Smithsonian Environmental Research Center, P.O. Box 28, Edgewater, MD 21037, U.S.A.

Table 1. *Summary of recently reported marsh accretion rates for the Atlantic and Gulf coasts, plus the macrotidal east coast of England. In each case, the habitat, technique(s) used, local sea level rise, and study citation are also shown.*

Location	Marsh type[1]	Method Used	ASLR[2]	Accretion[3]	Reference
			A. U.S.A.		
Maine	BBar	marker horizon	0.9–2.0	7.5	Wood *et al.* (1989)
Maine	trans.	marker horizon	0.9–2.0	5.3	Wood *et al.* (1989)
Maine	fluvial	marker horizon	0.9–2.0	2.5	Wood *et al.* (1989)
Rhode Is.	SM-lm	Pb-210, Cu	2.6 ± 0.2	4.3, 4.4	Bricker-Urso *et al.* (1989)
Rhode Is.	SM-mm	Pb-210, Cu	2.6 ± 0.2	2.4, 4.7	Bricker-Urso *et al.* (1989)
Connecticut	SM			1.5	Bloom (1964)
Long Is.	SM	Pb-210		6.4	Armentano and Woodwell (1975)
Delaware	SM	core analysis	3.0	5.0	Stumpf (1983)
Delaware	SM			4.0	Stearns and MacCreary (1957)
Maryland	BM	Pb-210, marker hor.	3.9	1.7–3.6	Stevenson *et al.* (1985)
Virginia	SM-fr	Pb-210	2.8–4.2	1.0–2.2	Oertel *et al.* (1989)
S. Carolina	SM	tidal flux	3.0	≈1.5	Wolaver *et al.* (1988)
S. Carolina	SM-lm	Pb-210	3.0	1.4	Sharma *et al.* (1987)
S. Carolina	SM-lm	Cs-137	3.0	4.5, 1.6, 1.3	Sharma *et al.* (1987)
S. Carolina	SM-mm	Pb-210, Cs-137	3.0	2.4, 2.5	Sharma *et al.* (1987)
Georgia	SM	marker horizon		4.0	Letzsch and Frey (1980)
Louisiana	BM	Cs-137, marker hor.	12.0	8.0	DeLaune *et al.* (1983)
Louisiana	SM	marker horizon	10–12	8.4–19	Childers and Day (1990)
Louisiana	SM	marker horizon	10–12	2.4–13	Childers and Day (1990)
			B. U.K.		
Essex	SM	pin measurement	3.0	5.0–11	Reed (1988)
Scolt Head	SM-lm	marker horizon	≈3.0	8.0	Stoddart *et al.* (1989)
Scolt Head	SM-mm	marker horizon	≈3.0	2.0	Stoddart *et al.* (1989)

[1]marsh environment in which measurements were made. Abbreviations: BBar = back barrier salt marsh; trans = transitional salt marsh; fluvial = riverine saline and brackish marsh (terminology from Wood *et al.*, 1989); SM-lm = creekside, or low marsh salt marsh; SM-mm = midmarsh, or interior salt marsh; SM = salt marsh; BM = brackish marsh; SM-fr = barrier lagoon fringing salt marsh

[2]ASLR = apparent sea level rise at each location (referred to as relative SLR in some places), in mm yr^{-1}

[3]accretion = rates of accretion reported in each study, using the designated technique(s), in mm yr^{-1}

from the United Kingdom (U.K.). These data show that most northern U.S. and eastern U.K. marshes are accreting sediments at rates equal to or exceeding local apparent sea level rise (ASLR) while many southeastern U.S. and Gulf of Mexico estuaries are characterized by variable accretion rates that are often lower than ASLR (Table 1). Although European colonization resulted in massive increases in sediment yield to northeastern and mid-Atlantic U.S. estuaries such as the Chesapeake Bay (Gottschalk, 1945; Froomer, 1980), Trimble *et al.* (1987) found that reforestation of 10–28% of the land area in ten southeastern U.S. basins from 1919–1967 reduced stream discharge 4–21%. In this paper, we report on 2.5 years of seasonal sediment elevation measurements made at a number of locations in a southeastern U.S. and two mid-Atlantic U.S. estuaries, and compare our results to published sediment accretion data.

Generally, researchers have used accretion data from vertical distributions of radionuclides (such as ^{210}Pb, ^{137}Cs, ^{7}Be) or core analysis to infer historical rates of change in marsh sediment elevations, while contemporary rates are based on marker horizons, sediment stakes, or precision surveying, or are calculated from actual flux measurements (Table 1). We have made actual measurements of sediment elevation using a levelling-arm device. This device was developed by Boumans and Day (1992) as a modification of a similar instrument used by Schoot and De Jong (1982) in Europe. Boumans and Day are currently using this levelling-arm device (which they refer to as a sedimentation-erosion table, or SET) to monitor sediment elevations at a number of locations in several Louisiana estuaries and in the marshes of Cumberland Island, Georgia (GA). Since our SET was constructed using their specifications, our data sets are compatible (future collaborations will involve comparisons of sediment elevation dynamics in a diverse range of Atlantic and Gulf Coast U.S. estuaries). Here, we use our data to investigate variability in sediment elevations within estuarine ecosystems and to relate that variability to landscape-level inputs.

MATERIALS AND METHODS

The Sites

The three estuaries we studied represent a range of geomorphologies, sizes, and watershed inputs characterizing the Atlantic coast. The North Inlet salt marsh estuary, located in Georgetown County, SC, U.S.A. (Figure 1), has little direct freshwater input and no salinity stratification; the inlet, tidal creeks, and *Spartina alterniflora* marshes comprise about 3,400 hectares (8,400 acres). North Inlet is a transgressive system, and marsh basins closest to the land margin are geologically youngest while those closest to the barrier islands are oldest (GARDNER and BOHN, 1980; DAME *et al.*, 1992; DAME and GARDNER, in press). The estuary is bordered to the west by maritime coastal forest and receives intermittent freshwater streamflow from approximately 1,000 ha of this forest. To the south, North Inlet adjoins Winyah Bay, which receives riverflow from the 47,900 km^2 Pee Dee/Yadkin drainage basin. Although only about 4% of this basin's gross eroded sediment reaches Winyah Bay on an average-annual basis, this amounts to nearly 1×10^6 tons yr^{-1} (PHILLIPS, 1991). Analyses of long-term water chemistry data (SKLAR, in review), estuarine water column transects (CHILDERS, *unpublished data*), and short-term sediment flux data (SKLAR, *unpublished data*) have repeatedly affirmed the importance of sediment inputs from Winyah Bay and the Pee Dee River. We measured sediment elevation seasonally from spring 1990 through autumn 1992 at six locations that represent the various watershed inputs and marsh ages found in the North Inlet system (Figure 1). Two marsh locations were near freshwater sources—one near forest drainage (Oyster Landing, to the north) and one near Winyah Bay (South Town Creek, to the south). Notably, Oyster Landing is a Long Term Ecological Research site, where a large number of floral, faunal, chemical, and physical parameters have been monitored for over ten years. Two locations were near the ends of tidal creeks receiving little or no uplands drainage (Debidue Creek, to the north and Bly Creek, to the south), and two locations were in geologically older, mature marshes (Old Man Creek, to the north, and Sixty-Bass Creek, to the south). Notably, the Oyster Landing and Bly Creek locations were in geologically young marshes.

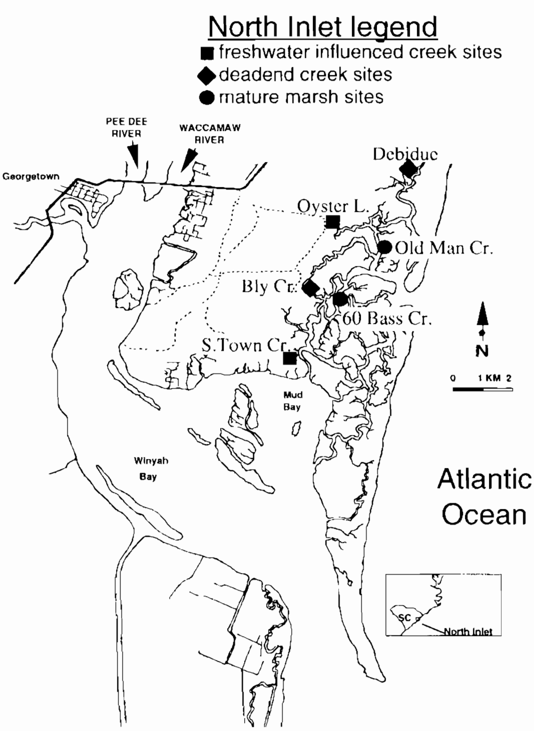

Figure 1. Map of the North Inlet estuary showing the six sediment elevation sampling locations. South Town Creek and Oyster Landing are near freshwater influence (squares), with 2 and 1 habitat sites, respectively; Debidue and Bly Creek are in dead-end tidal creeks (diamonds) with 1 and 4 habitat sites, respectively, and Old Man Creek and Sixty Bass Creek are in mature marsh (circles), with 2 and 3 habitat sites, respectively.

The second estuary is the Patuxent River drainage, MD, U.S.A., a sub-estuary of the Chesapeake Bay (Figure 2). While North Inlet is a back-barrier estuary, the Patuxent sub-estuary is a riverine system. The drainage basin encompasses 2,400 km^2, making it about 35 times larger than the North Inlet estuary. We measured sediment elevations seasonally from spring 1990 through winter 1992 along the estuarine portion of the river between Solomons, MD (at the river mouth) and Jug Bay (Figure 2). This ≈60 km segment is geomorphologically diverse. The upper river, from Jug Bay to about Benedict, MD, has a narrow channel that meanders through extensive tidal freshwater marshes. Landscape influences on this upper river are dominated by drainage through a large number of small, often ephemeral creeks as well as by

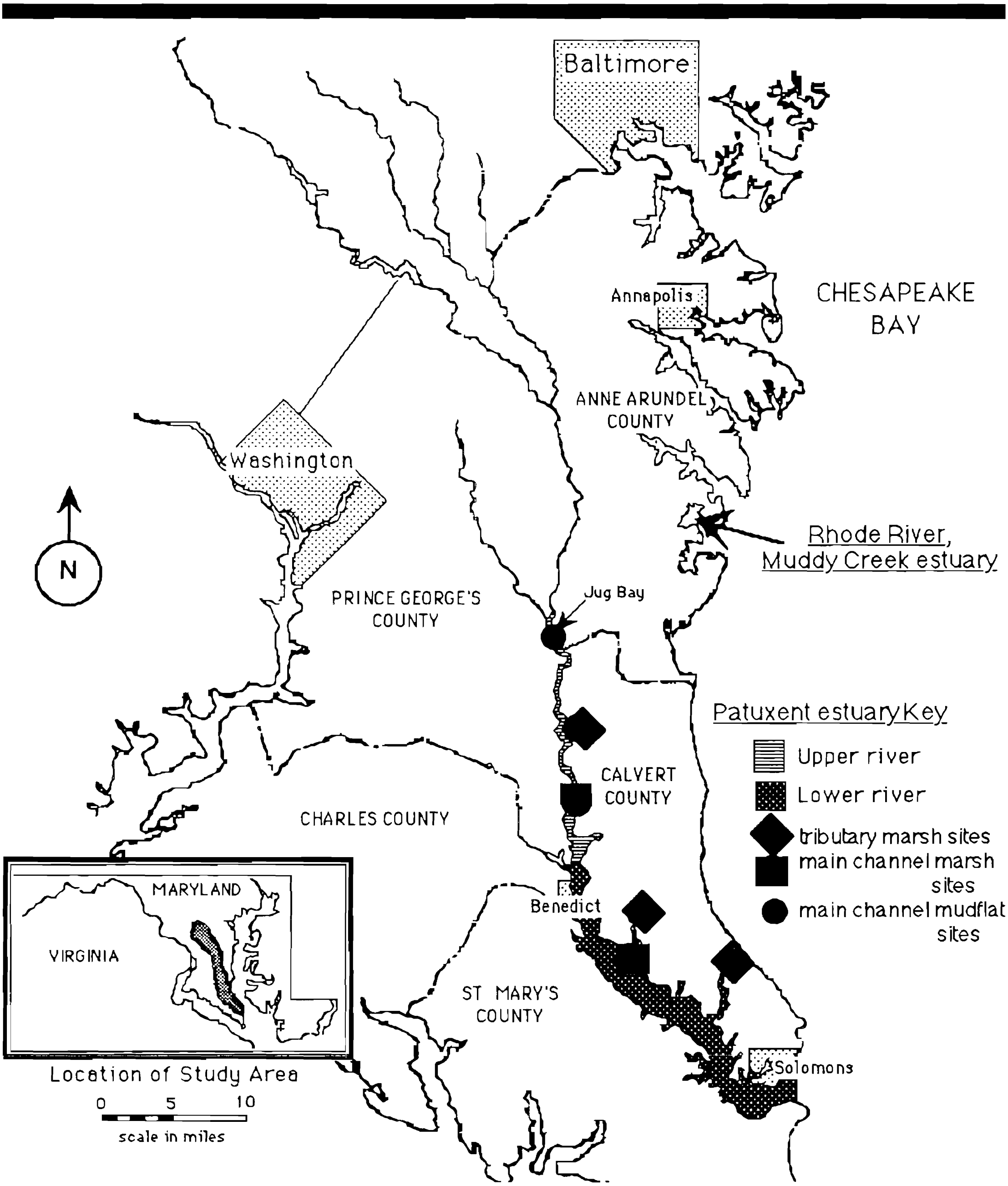

Figure 2. Map of the Chesapeake Bay subestuaries. The Patuxent River estuary is divided into upper and lower rivers based on geomorphology (see text), and the six sediment elevation sampling locations are distinguished as tributary marsh sites (diamonds, total of three), main channel marsh sites (squares, total of 1.5), and main channel mudflat sites (circles, total of 1.5). Note that both marsh and mudflat are sampled at the main channel site in the upper river (referred to as the middle river in text). The Rhode River, Muddy Creek estuary is also shown.

upstream inputs. South of Benedict, the river channel becomes markedly wider, deeper, and straighter. In the lower river, the Chesapeake Bay proper exerts a stronger influence (salinities range from 8–12 ppt) and drainage from the surrounding landscape is primarily directed into several large feeder creeks similar in morphology to the lower river itself. The Patuxent River is often conceptualized as a microcosm of the entire Chesapeake Bay, mainly because its basin has been subjected to many of the developmental pressures affecting the bay. Development along the upper river is primarily agricultural while development along the lower river is largely suburban residential. Topographic relief is markedly greater to the south. Our six locations reflect the variables (a) marsh types, (b) geomorphology, (c) topography, and (d) developmental pressures characterizing the Patuxent River estuary. Three sites were located in headwater marshes of major tributaries (an upper river site in a vegetatively-diverse freshwater marsh, and two lower river sites in *Spartina patens* marshes); two sites were located in main channel marshes (a mid-river site in a *Phragmites* marsh and a lower river site in a *Spartina patens* marsh); and two sites were located in main channel mudflats (one upper river, one mid-river)—we measured both marsh and mudflat sediment elevations at the main channel mid-river location (Figure 2).

We also measured seasonal change in sediment elevations at seven brackish marsh sites along Muddy Creek from autumn 1990 through winter 1992 (Figure 2). These sites were all within close proximity of each other ($\approx$0.25 ha) in a relatively high and irregularly flooded brackish marsh. Muddy Creek is a part of the Rhode River estuary, and *Scirpus olneyi* and *Spartina patens* are the dominant marsh vegetation (JORDAN *et al.*, 1986; our sites were exclusively vegetated by *Scirpus olneyi*). Landuse in the 2,300 ha Rhode River watershed is mixed agricultural (35%) and forested (65%; CORRELL, 1977). The basin has been intensively studied by researchers at the Smithsonian Environmental Research Center (SERC) for many years (JORDAN *et al.*, 1991). This study was in conjunction with a large project investigating the effects of elevated CO_2 concentrations on brackish marshes (DOE-funded, B. Drake, P.I.), testing the hypothesis that CO_2 enrichment stimulates below-ground C allocation which, in turn, leads to the [synergistic] upward "swelling" of marsh sediment elevations. We will report sediment elevation data from marshes adjacent to four control and three experimental chambers in this paper.

Measuring Sediment Elevation

Sediment elevation measurements were made in all three estuaries using a levelling-arm device identical to that of BOUMANS and DAY (1992). In brief, the sedimentation-erosion table (SET) is a portable arm that is placed into permanent seat pipes, levelled in the horizontal and vertical planes, and from which nine pins are slowly dropped to the sediment surface and measured. The seat pipes were vibracored into the substrate to refusal and surveyed to known benchmarks periodically. Each seat pipe was notched to lock the arm into four orientations. BOUMANS and DAY (1992) consider the nine pin measurements at each orientation to be replicates of the sediment elevation in an area approximately 0.25 m on a side. They determined the precision of the SET technique by repeatedly measuring elevations at a number of sites after dismantling, reassembling, and relevelling the SET between each measurement. From these precision measurements, they reported a 95% confidence interval for SET elevations that ranged from $\pm$ 0.4 mm to $\pm$ 1.5 mm, depending on substrate characteristics.

The Sampling Design

In the North Inlet estuary, sediment elevation measurements were nested into several [spatial] hierarchical levels (Figure 3). At the lowest level, we took nine replicate samples (*i.e.*, nine pins) at each orientation. The four orientations together comprised a population of sample means for a given site, or habitat type (*i.e.*, high marsh, mid-marsh, low marsh, mudflats). At a given location within the estuary, we had one to four habitat sites, and we had six locations around the estuary. We were thus able to partition variability into (1) within habitats, based on the four orientations; (2) between habitats within a given location; (3) between habitats across locations; (4) between locations within the estuary; and (5) between estuaries.

For each levelling arm orientation, we made nine pin measurements every season (sometimes fewer, when obstructions were encountered). A mean elevation change ($\Delta h/\Delta t$, $\pm$ SD) was calculated for each orientation using the difference between each pin and its respective measurement

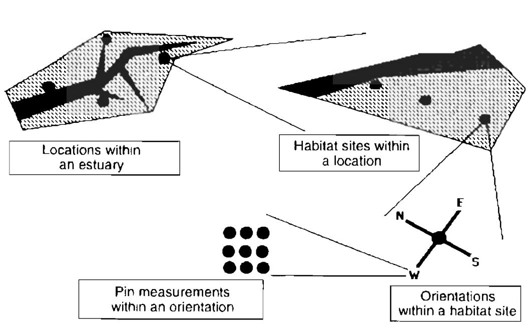

Figure 3. The spatial hierarchical design used to sample sediment elevations. From the finest scale (measurements within an orientation, ≈0.25 m × 0.25 m) to the coarsest scale (locations within an estuary, ≈100's ha), each level is nested within the next higher level. Note that our spatial design for the North Inlet estuary encompasses all levels shown while the Patuxent River design does not distinguish habitat sites (habitat types) within a location and the Muddy Creek design does not distinguish locations within the estuary.

the previous season (in mm mo^{-1}). From the population of these four means (four arm orientations per site; Figure 3), we calculated a habitat mean $\Delta h/\Delta t$ (± SE). We also calculated a net annual elevation change for each arm orientation and for each habitat (in mm y^{-1}) based on the first elevation measurement subtracted from the last. The spatial sampling design described above was clearly compatible with several different analysis of variance (ANOVA) models, but elevation change data from sequential seasons were not independent; thus, the seasonal $\Delta h/\Delta t$ data violated this basic assumption of ANOVA testing. To preclude this limitation, we used a repeated measures 2-way ANOVA to separate temporal effects from the within-level variance in all three data sets (SOKAL and ROHLF, 1981; HICKS, 1982). A more powerful nested repeated measures design was used on the North Inlet data to account for variability within several [spatial] hierarchical levels (ZAR, 1984). Multiple comparison post-hoc tests were run on the means, using Sheffe's S and Bonferroni-Dunn as the primary tests. Finally, we pooled the net annual elevation change data from all three estuaries and used multifactorial randomized block deisgn (RBD) ANOVA models to investigate interestuary differences (STEELE and TORRIE, 1980). For these comparisons, data were classified (1) by marsh type (*e.g.*, salt marsh, brackish marsh, fresh marsh); (2) by habitat (*e.g.*, high marsh, midmarsh, low marsh, mudflat); and (3) by proximity to freshwater influence.

Hydrologic Data

Hydrologic variables important to long-term measurements of sediment elevation include river discharge and marsh inundation. Discharge data from 1990–1992 for the Pee Dee River at Pee Dee, South Carolina, U.S.A. and for the Patuxent River at Bowie, Maryland, U.S.A. were averaged for the seasonal intervals appropriate to the North Inlet and Patuxent River sediment data, respectively. In both cases, these U.S.G.S. gauge data were from locations above tidal influence. At North Inlet, we also measured water levels at one freshwater-influenced location (South Town Creek), at one deadend creek location (Bly Creek), and at one mature marsh location (Old Man Creek) using Richard's type water level recorders. We surveyed the elevation sites at each location to the gauge datum and thus calculated daily tidal inundations from the continuous water level records. Seasonally-averaged marsh inundation was determined for the Muddy Creek brackish marsh by combining site elevation data with tide gauge data located at the SERC dock just downstream from our study site. Seasonally averaged river discharge and seasonally averaged daily inundation (± SD) were regressed as independent variables against the corresponding seasonal change in sediment elevation ($\Delta h/\Delta t$, ± SE; dependent variables) for all three estuaries.

RESULTS

North Inlet Sediment Elevations

The most consistent increases in sediment elevations at North Inlet were observed at the two locations in closest proximity to freshwater inputs. At the Oyster Landing midmarsh site near a forest stream outflow, the average annual elevation change (11.9 ± 5.5 mm yr^{-1}) was markedly greater than at South Town Creek, near Winyah Bay (3.0 ± 2.3 and 6.4 ± 1.1 mm yr^{-1} for midmarsh and low marsh sites respectively (Figure 4). Much of that difference was attributable to the rapid elevation increases in 1992 after deposition of large wrack rafts and subsequent *Spartina* dieoff at the Oyster Landing site (loose wrack not incorporated into the sediment matrix was removed prior to the summer and autumn 1992 measurements). Oyster Landing sediment elevations generally increased in all seasons except winter (Figure 5a). Seasonal patterns at the midmarsh and low marsh sites at South Town Creek were mirror images of each other in 1990, with nearly identical sediment elevations by winter

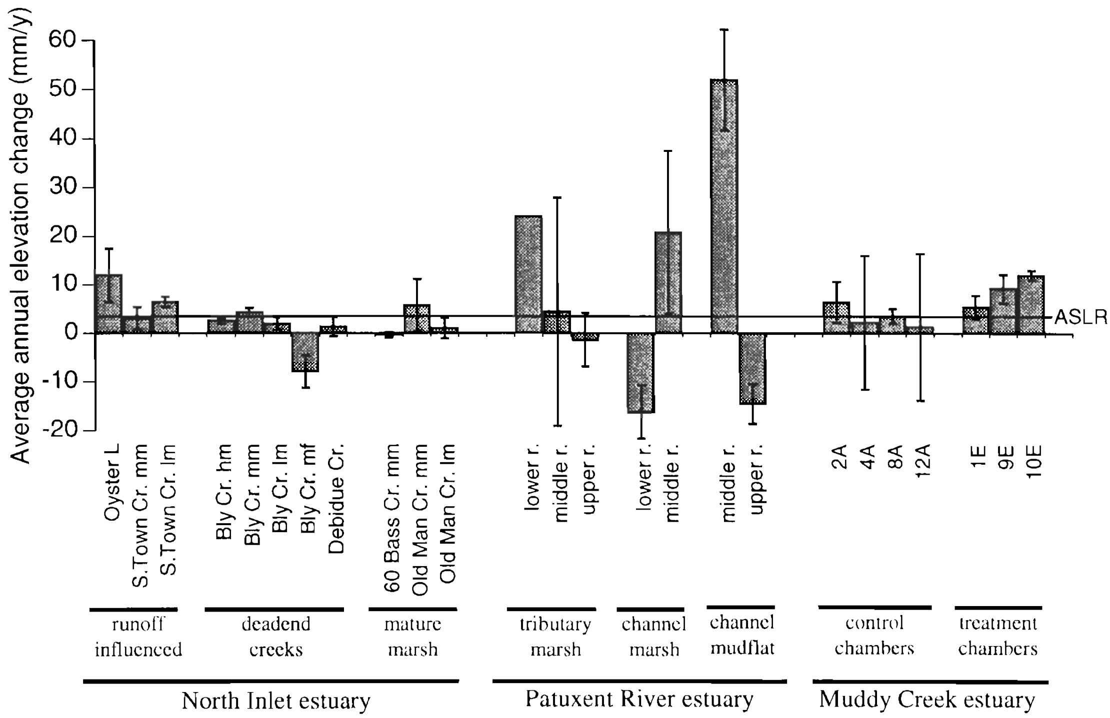

Figure 4. Average annual changes in sediment elevations at all SET sites with sites in each estuary grouped as discussed in the text. Average elevation change (mm yr^{-1}) was determined by subtracting initial SET arm orientation means (calculated from a population of nine pin measurements) from final means, then dividing by total time elapsed. Error bars represent the standard error of each site mean, calculated from the 4 arm orientation means. ASLR = apparent sea level rise of 2–4 mm yr^{-1}. "lm" = low marsh; "mm" = midmarsh; "hm" = high marsh; "mf" = mudflat.

1991. Throughout 1991 and 1992, though, we observed parallel trends at the two sites with greater elevation increases at the low marsh site (Figure 5b). The South Town Creek data generated the only inundation $\Delta h/\Delta t$ relationship. A multiple regression model with seasonally averaged Pee Dee River discharge and average [site-specific] tidal inundation as independent variables predicted about 50% of the variability in elevation change (SE of $\Delta h/\Delta t$) at these marsh sites ($r^2 = 0.49$, $p = 0.02$, $n = 14$).

North Inlet sites located near the headwaters of Bly Creek and Debidue Creek receive relatively little freshwater input. Seasonally, sediment elevations did not vary greatly across the Bly Creek marsh (Figure 6a). High marsh elevations fluctuated least while midmarsh elevations were most dynamic. Average annual elevation change was lowest at the low marsh site (1.9 ± 1.3 mm yr^{-1}), highest at the midmarsh site (4.3 ± 0.9 mm yr^{-1}), and intermediate at the high marsh site (2.5 ± 0.6 mm yr^{-1}; Figure 4). We also measured sediment elevations on a mudflat near the Bly Creek marsh transect and recorded a clear decline in elevation over the 2.5 years (Figure 6b). The steady decline was punctuated by small elevation increases in both winters. There were no significant relationships between seasonally averaged Pee Dee River discharge and site-specific inundation, and Bly Creek $\Delta h/\Delta t$ data. We observed the greatest intrasite variability at the Debidue Creek low marsh (the other deadend creek location at North Inlet). In fact, there were no discernible patterns in either mean sediment elevation or variation about the mean (Figure 6c). The elevation increase in 1992 was not significant on a season-to-season basis, and the average annual accretion rate at this location was only 1.3 ± 2.0 mm yr^{-1} (Figure 4).

In a rising sea level scenario, transgressive marsh-barrier complexes such as North Inlet migrate landward at rates determined by topograph-

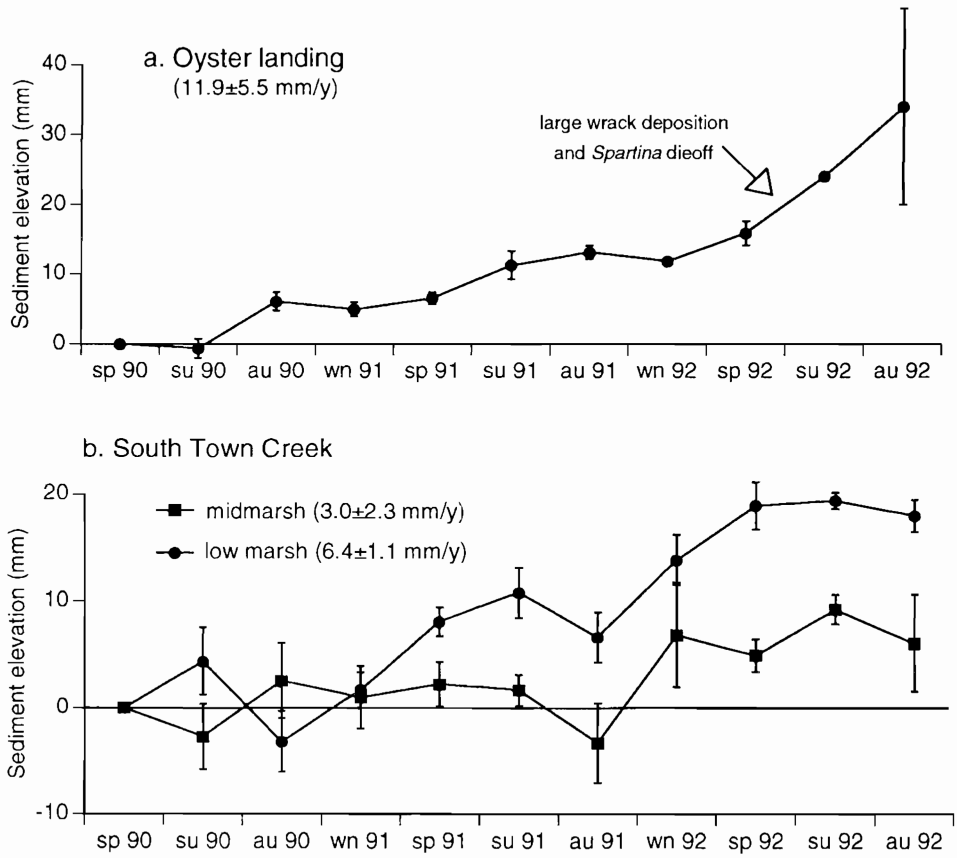

Figure 5. Sediment elevations over time (as the mean ± SE of the 4 orientation means) at the freshwater-influenced locations in North Inlet, relative to the initial zero value. (a) Oyster Landing (1 habitat site), near local forested uplands drainage; (b) South Town Creek (2 habitat sites), near Winyah Bay and remote watershed inputs.

ic slope and the rate of SLR itself (GARDNER and BOHN, 1980; HAYDEN *et al.*, 1991). The back-barrier estuary thus includes marshes of different geologic ages, with the youngest marshes closest to the terrestrial ecotone where state change actually occurs (DAME *et al.*, 1992; DAME and GARDNER, in press). Using this model, our Oyster Landing and Bly Creek sampling locations were in relatively young marsh—with Bly somewhat older than Oyster—and our Sixty Bass and Old Man Creek sites were in older and presumably ecologically more mature marsh (see Figure 1). Our sediment elevation data from Sixty Bass Creek showed no discernible seasonal trends across the marsh (Figure 7a), and no real change over the 2.5 years (missing data from the creekside midmarsh and low marsh sites precluded reliable calculations of average annual elevation change; Figure 4). Total elevation change at the Old Man Creek low marsh site was essentially zero after 2.5 years while elevation at the midmarsh site steadily increased (Figure 7b) at a net rate of 5.7 ± 5.3 mm yr^{-1} (Figure 4). The large difference in low and midmarsh sites at this location is primarily a result of the 1990 and 1991 autumnal declines in sediment elevation measured at the low marsh but not at the midmarsh. Excepting this inequity, trends in sediment elevation were similar at the two sites. We found no significant relationships between seasonally averaged Pee Dee River discharge and site-specific inundation, and $\Delta h/\Delta t$ data from the Old Man Creek location.

Two-way repeated measures ANOVA testing generated significant differences ($p < 0.01$) between (a) locations in the North Inlet estuary, (b) habitat [marsh] types, and (c) small-scale (≈2 m

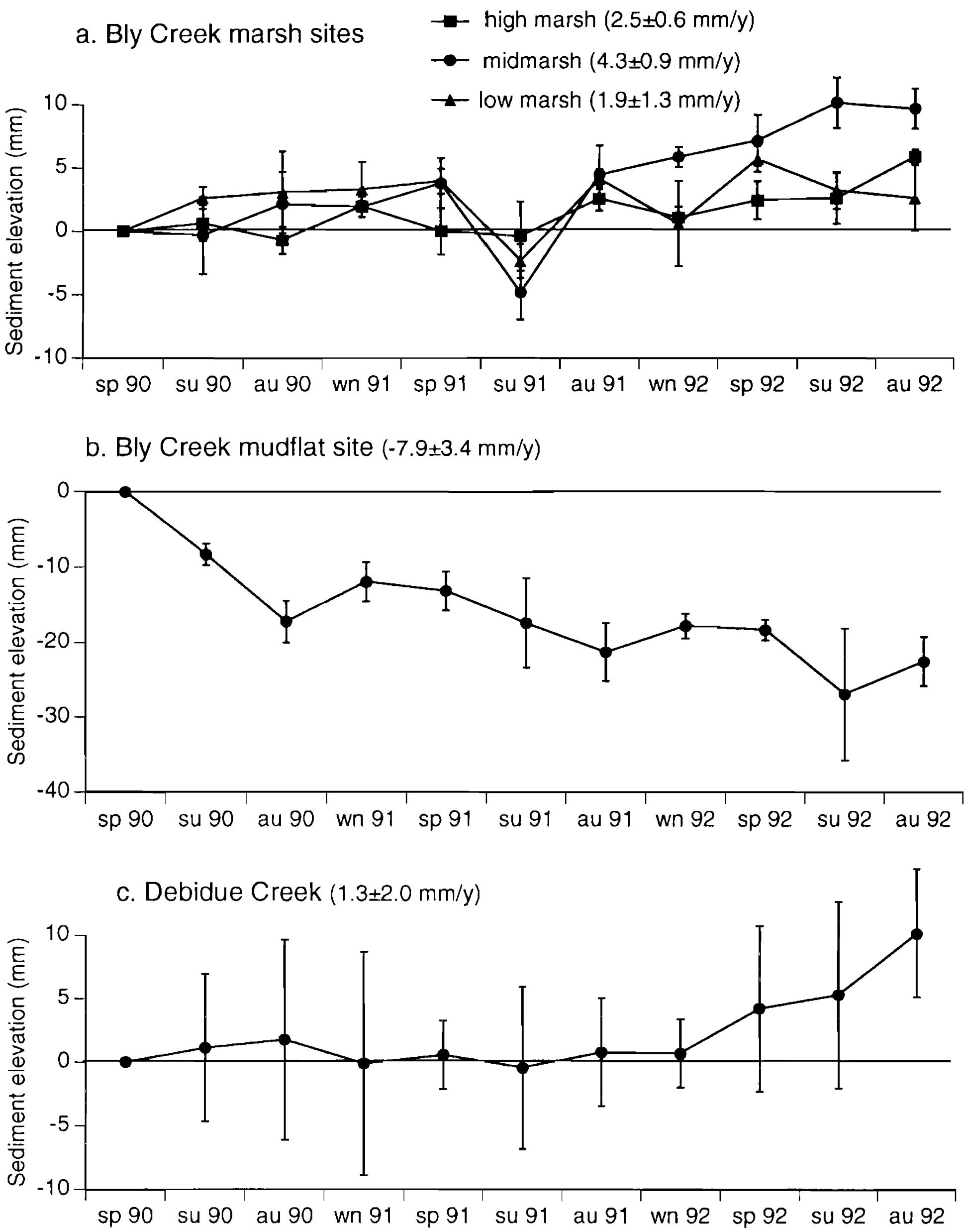

Figure 6. Sediment elevations over time (as the mean ± SE of the 4 orientation means) at the deadend tidal creek locations in North Inlet, relative to the initial zero value. (a) Bly Creek marsh sites (3 habitat sites); (b) Bly Creek mudflat site; (c) Debidue Creek (1 habitat site).

× 2 m) variability within locations and habitats. Although time was not a significant main effect within subjects (location, habitat, orientation), the time interaction was significant for all subjects, indicating significantly different temporal behaviors depending on location in the estuary and habitat type. We used post-hoc multiple comparisons tests (Bonferroni-Dunn and Sheffe's S) to eluci-

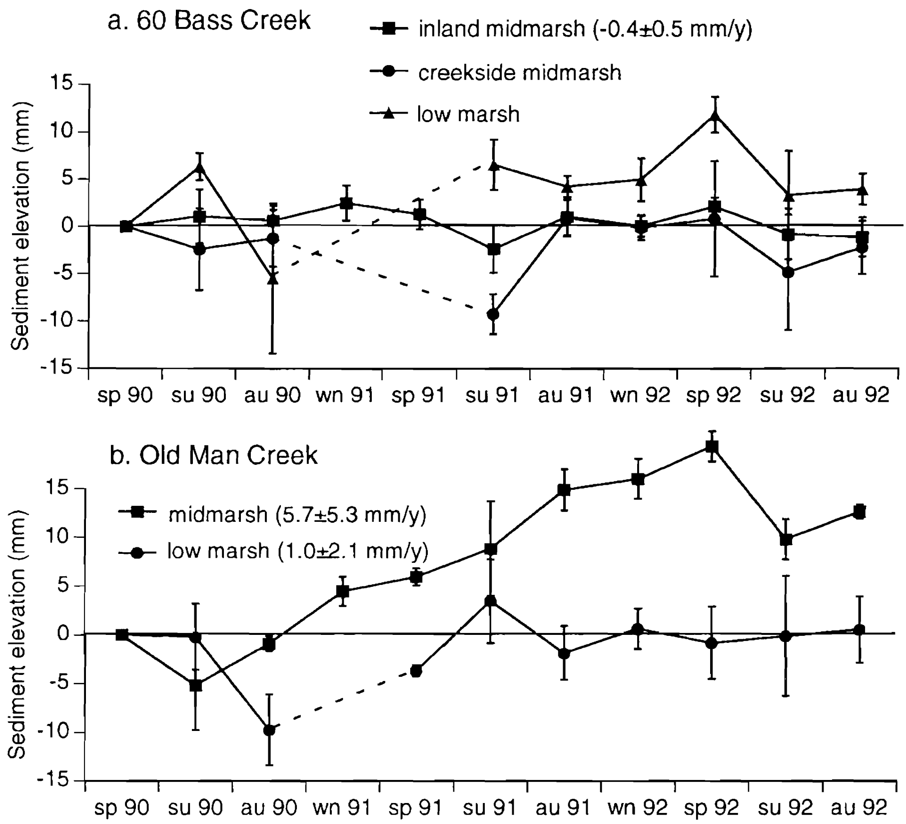

Figure 7. Sediment elevations over time (as the mean ± SE of the 4 orientation means) at the mature marsh locations in North Inlet, relative to the initial zero value. (a) Sixty Bass Creek (3 habitat sites); (b) Old Man Creek (2 habitat sites).

date similarities and differences at each level. At the coarsest scale, the two locations in closest proximity to freshwater influences (Oyster Landing and South Town Creek) were similar and had higher mean rates of sediment elevation change ($\Delta ht/\Delta t$), but were significantly different from the other four locations. Marsh habitats were similar, but were significantly different from the mudflat site. The trend in mean $\Delta ht/\Delta t$ was midmarsh > high marsh > low marsh > mudflats (0.26 ± 0.07, 0.04 ± 0.13, 0.01 ± 0.14, −0.64 ± 0.19 mm mo^{-1}, respectively). The finest spatial scale was between orientations within each site (variability over an area ≈2 m × 2 m). Mean $\Delta h/\Delta t$ measured at orientations closest to a creek (furthest downslope, −0.32 ± 0.17 mm mo^{-1}) were significantly different from those measured upslope (0.13 ± 0.11 to 0.31 ± 0.11 mm mo^{-1}). Summer and autumn 1991 mean $\Delta h/\Delta t$ values were lower (at −0.22 ± 0.18 and −0.29 ± 0.18 mm mo^{-1}, respectively), and significantly different from winter and spring (with $\Delta h/\Delta t$ means ranging from −0.02 ± 0.16 to 0.37 ± 0.12 mm mo^{-1}).

Patuxent River Sediment Elevations

Three of the six Patuxent River study locations were placed in tributary marshes. We observed the greatest increase in sediment elevations over the two years of sampling at the lower river tributary location (Figure 4). Sediment elevations declined through 1990 at all three sites (Figure 8a), then increased at similar rates at the lower and middle river sites while the upper river tributary marsh changed little in 1991. Average annual rates of sediment elevation change in tributary marshes showed an upriver decline (from 24.0 → 4.4 ± 23.4 → −1.4 ± 5.5 mm yr^{-1}; Figure 4).

We had two marsh sites located in the main

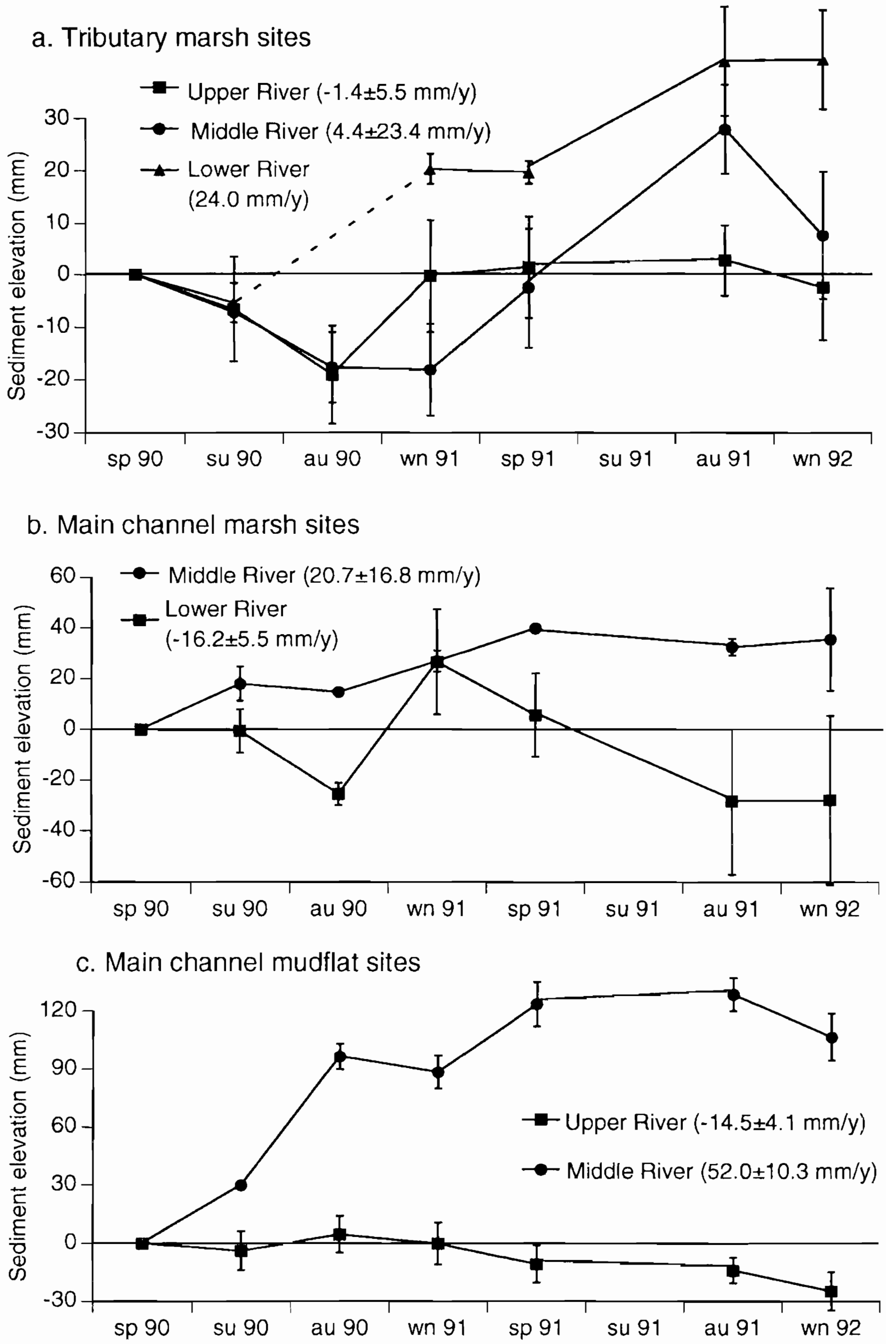

Figure 8. Sediment elevations over time (as the mean ± SE of the orientation means) from the Patuxent River estuary, relative to the initial zero value. (a) Tributary marsh locations (3 sites); (b) main channel marsh locations (1.5 sites); (c) main channel mudflat locations (1.5 habitat sites).

river channel—notably, the "lower river" location in Figure 8b was actually near the mouth of the creek where we placed the middle river tributary location (see Figure 2). The seasonal trends and average elevation changes in these two main channel marshes were opposite those of the tributary marshes. Sediment elevation increased upriver at the middle river site (20.7 ± 16.8 mm yr^{-1}) while it decreased at the lower river site (−16.2 ± 5.5 mm yr^{-1}; Figure 4). The small-scale spatial variability (≈2 m × 2 m), as standard errors of the orientation means (the error bars in Figure 8), was markedly greater at the lower river main channel site, which had only two measurable orientations. The middle river main channel marsh site was also based on only two marsh orientations; the other two orientations measured at this site were on a mudflat. Sediment elevations at this middle river mudflat showed similar variability to those measured on a mudflat in Jug Bay, at the extreme upper river (see Figure 2), but the middle river mudflat accreted at 52 ± 10.3 mm yr^{-1} while the upper river mudflat declined at 14.5 ± 4.1 mm yr^{-1} (Figure 4). The two mudflats had parallel seasonal trends in all but two seasons—summer 1990 and spring 1991—when elevations at the middle river mudflat increased dramatically (Figure 8c). In four of six seasons, $\Delta h/\Delta t$ measurements at the middle river marsh and mudflat sites (located within 2 m of each other) were in opposite directions. Sediment elevations at the middle river mudflat declined only in the winter, in a pattern opposite that observed at the North Inlet Bly Creek mudflat site (compare Figures 6b and 8c).

Patuxent River discharge averaged for each season was compared with intertidal sediment elevation changes at different locations in the estuary. We found no significant relationship between $\Delta h/\Delta t$ (or the SE of $\Delta h/\Delta t$) and river discharge when all sites were pooled together, nor when sites were pooled by habitat (*e.g.*, tributary marsh, main channel marsh, main channel mudflat). Seasonally averaged Patuxent River discharge did, however, explain a significant 69% of the seasonal variability in $\Delta h/\Delta t$ measured at the middle river main channel marsh location (see Figure 8b; $r^2 = 0.69$, $p = 0.04$, $n = 6$) and a significant 89% of the small-scale (≈2 m × 2 m) variability in sediment elevation changes (as SE of $\Delta h/\Delta t$) measured at the upper river tributary marsh location (see Figure 8a; $r^2 = 0.89$, $p = 0.005$, $n = 6$). While the discharge-$\Delta h/\Delta t$ relationship at the middle river main channel mudflat—adjacent to the corresponding marsh location—was not significant ($p = 0.23$), the regression coefficient was 0.33.

Repeated measures ANOVA was used to look at habitat effects over time (comparing both marsh *vs.* mudflat and tributary marsh *vs.* main channel marsh *vs.* main channel mudflat). The between-habitat effect was significant using the three habitat designations ($p = 0.034$) but not with the marsh vs. mudflat designations ($p = 0.133$). Within habitats, season was a significant factor in both models. This seasonal effect is visually apparent as different temporal patterns at the tributary marsh and main channel marsh sites (Figure 8a and b), and the marsh patterns were clearly different from the mudflat trends (Figures 8a, b and c). Multiple comparisons tests indicated that the mean elevation changes at the three tributary marshes were similar while the middle river main channel location (with both marsh and mudflat measurements) was different from all other locations. Using the same Sheffe's S and Bonferroni-Dunn tests, we also found tributary marsh, main channel marsh, and main channel mudflat habitat means ($\Delta h/\Delta t$ means of 0.42, 1.00, and 1.28 mm mo^{-1}, respectively) to be similar, and marsh and mudflat means ($\Delta h/\Delta t$ means of 0.60 and 1.28 mm mo^{-1}) to be similar. The Bonferroni-Dunn post-hoc test indicated that mean winter elevation changes at all sites were different from all other seasons while the Sheffe's S test only separated winter 1992 from the rest. Interestingly, the winter 1991 mean $\Delta h/\Delta t$ value for all six locations was highest of all seasons (2.58 ± 0.54 mm mo^{-1}) while the winter 1992 mean $\Delta h/\Delta t$ was lowest (−1.92 ± 0.57 mm mo^{-1}).

Muddy Creek Sediment Elevations

We separated the Muddy Creek elevation data into sites adjacent to control chambers (receiving ambient CO_2 concentrations; Figure 9a) and those adjacent to experimental chambers (receiving elevated CO_2 concentrations; Figure 9b). The variability within a given site was greater near control chambers (compare error bars in Figure 9a to 9b), but one site (12A) was responsible for most of this variation (12A had only one non-chamber orientation compared to two at all others). Average rates of elevation change were also somewhat lower adjacent to control chambers compared to those near experimental chambers (Figure 4). Seasonal patterns were difficult to discern, though there

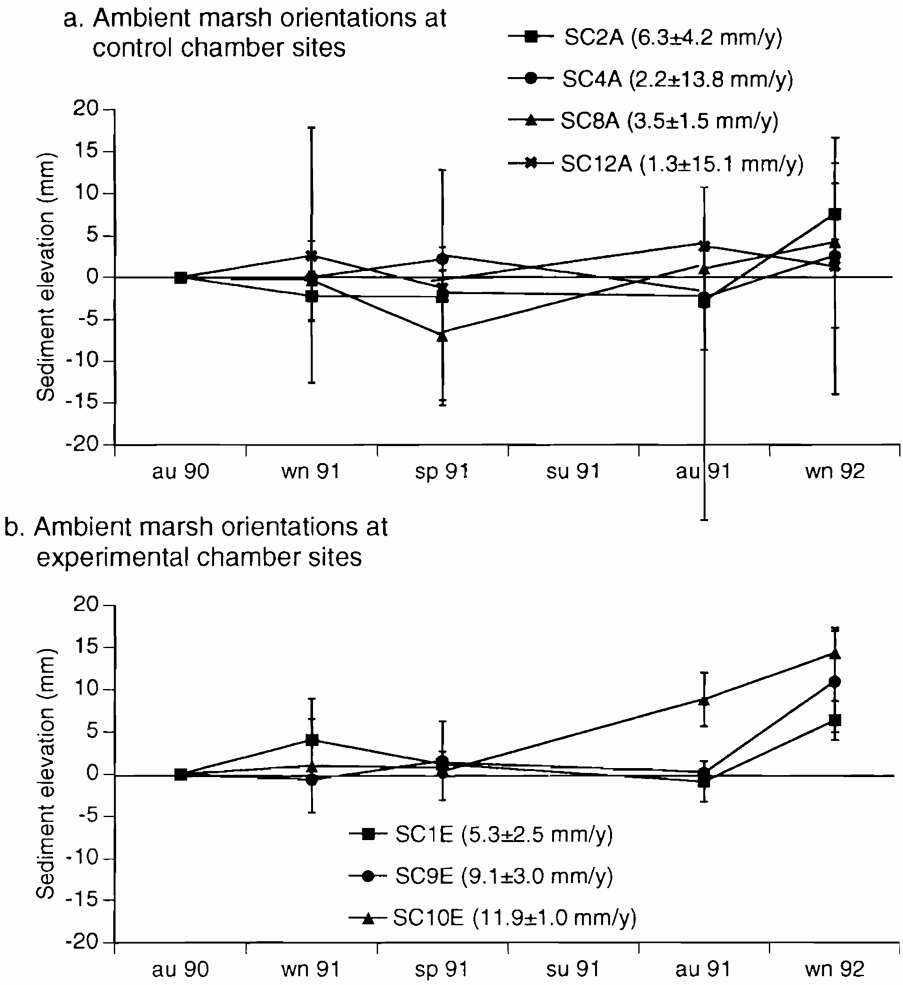

Figure 9. Sediment elevations over time (as the mean + SE of the orientation means) from the Muddy Creek estuary, relative to the initial zero value. (a) Sites adjacent to control chambers (4 sites); (b) sites adjacent to experimental chambers (3 sites).

was some indication of parallel trends at sites 2A and 4A, at sites 8A and 12A, and at sites 1E and 9E. The 2A–4A pattern mirrored the 8A–12A pattern while 1E–9E varied little (Figure 9b). We found no significant relationships between $\Delta h/\Delta t$ (or the SE of $\Delta h/\Delta t$) and seasonally averaged marsh inundation for individual sites, when all sites were pooled together, or when sites were pooled by chamber type (*e.g.*, ambient [control] or elevated CO_2) or relative proximity to Muddy Creek (sites 1E, 2A, and 4A were grouped together and were located about 50 m further from Muddy Creek than sites SC8A, SC9E, SC10E, and SC12A).

Because elevation sites were all within a 0.25 ha area, data from Muddy Creek were analogous to seven replications within a given habitat site where we had only single sampling posts in the North Inlet and Patuxent River estuaries. A repeated measures ANOVA test indicated a significant site effect and a significant seasonal effect ($\alpha < 0.05$), but no effect of within-site measurements over time. Likewise, there was no orientation effect nor was there a temporal effect at the orientation scale. Although multiple comparisons tests indicated that all sites and all seasons were similar, the average annual accretion rates (Figure 4) and mean $\Delta h/\Delta t$ values for sites adjacent to experimental chambers were greater than those near control chambers. Seasonal mean $\Delta h/\Delta t$ values for all seven sites generally increased from winter 1991 to winter 1992 (0.15 ± 0.42 → 0.09 ± 0.73 → 0.55 ± 0.44 → 1.66 ± 0.38).

Inter-estuary Comparisons

As a final exercise, we compared net annual sediment elevation changes across the three estuaries using RBD ANOVA models. Each sampling site was represented with a net annual sediment elevation change for each SET arm orientation. These data were classified by estuary, habitat type (*e.g.*, high marsh, midmarsh, low marsh, or mudflat), marsh type (*e.g.*, fresh, brackish, or salt marsh), and relative freshwater influence (yes or no). A simple, 1-factor RBD analysis indicated that the three estuaries were significantly different ($p = 0.023$), but when we expanded the model to include habitat type, marsh type, or freshwater influence factors the inter-estuary difference lost significance ($p = 0.40$). In fact, there was no significant difference between habitats, between marsh types, or in proximity to freshwater inputs across the three estuaries. Multiple comparisons tests confirmed this similarity across estuaries at all factorial levels (inter-estuary, marsh type, habitat type, and proximity to freshwater influence).

DISCUSSION

Regardless of the mechanisms by which marshes accrete vertically, most researchers agree that, in the long term, the rate of vertical accretion must match sea level rise for a marsh to remain subaerial (REDFIELD, 1972; LETZSCH and FREY, 1980; STEVENSON *et al.*, 1988). Although our two to three year data sets may not qualify as long-term measurements, the long-term rate of sea level rise provides an important baseline for comparison. Apparent sea level rise (ASLR) is 2–4 mm yr^{-1} at the three estuaries we studied (Table 1; SHARMA *et al.*, 1987; LYLES *et al.*, 1988; KEARNEY and STEVENSON, 1991). At North Inlet, average annual rates of elevation change were lower than ASLR at: (1) the low marsh and mudflat sites at Bly Creek and the low marsh site at Debidue Creek (deadend tidal creek locations) and (2) Sixty Bass Creek and the low marsh site at Old Man Creek (mature marsh locations). All locations near freshwater influence had elevation change rates exceeding ASLR (Figures 4 and 5). Differences in average annual rates of elevation change along the Patuxent River estuary appeared to be a function of both habitat type and location in the landscape. The upper river tributary marsh site, the lower river main channel marsh site, and the upper river main channel mudflat site all had declining elevations (clearly lower than ASLR; Figure 8). In general, the brackish marshes of the Muddy Creek estuary showed average elevation change rates equivalent to or exceeding ASLR, though without greater spatial articulation this interpretation is probably location-specific for this estuary.

There is some debate whether contemporary sediment inputs to estuarine systems are from marine (BARTBERGER, 1976; GARDNER *et al.*, 1989) or freshwater sources (BIGGS, 1970; SCHUBEL and CARTER, 1976; MILLER, 1983; RENWICK and ASHLEY, 1984; WELLS and KIM, 1989), though most researchers agree that connectivity to major riverine systems and/or the coastal ocean strongly determines extant sources. Clearly, the ultimate source of mineral sediments to estuarine systems must be terrestrial weathering, though offshore deposits of these sediments may significantly contribute to inputs (GARDNER and BOHN, 1980). In some marshes, *in situ* production is largely responsible for observed vertical accretion (STEVENSON *et al.*, 1985; REJMANEK *et al.*, 1988), particularly in marshes where autochthonous sediment deficits trigger or exacerbate secondary mechanisms of marsh loss (BAUMANN *et al.*, 1984; PHILLIPS, 1986; TEMPLET and MEYER-ARENDT, 1988; CHILDERS and DAY, 1990).

Of the three estuaries we studied, only North Inlet is directly connected to both the coastal ocean and to a river system. The most consistent increases in sediment elevations were observed in the two locations nearest freshwater inputs (Figures 4 and 5). These locations were statistically similar to each other but different from the other four locations (based on mean $\Delta h/\Delta t$ values, $p < 0.05$). Maximal river discharge into Winyah Bay occurs in the winter and spring, and the South Town Creek sediment elevations reflected this influence with greatest measured increases in these seasons (Figure 5b). Forest drainage into North Inlet is also maximal in the winter and spring, and streams draining these forests are often dry through the summer and fall. However, we did not observe large increases in sediment elevation at the Oyster Landing location [influenced by forest drainage] during winter and spring, suggesting little seasonal coherence between potential sediment input and actual sediment elevations. We did observe a large increase in sediment elevations following a major *Spartina* wrack deposition event in the spring of 1992 (Figure 5a), suggesting the importance of organic deposition even when the *Spartina* at a given location has been killed off.

South Town Creek was topographically the highest of our six North Inlet study locations, and seasonally averaged daily inundations were only 33–50% of the other locations (ranging from 4.5 ± 1.3 to 6.6 ± 3.4 h day ^{1} at the midmarsh compared to 6.9 ± 3.6 to 13.9 ± 4.1 h day^{-1} and 13.6 ± 3.8 to 16.2 ± 2.5 h day^{-13} at the Old Man and Bly Creek midmarsh sites, respectively). This difference suggested a reduced importance of tidally-driven processes and an increased influence of low tide storms at South Town Creek. In fact, the significant and negative multivariate relationship between variation in sediment elevations (as the SE of $\Delta h/\Delta t$) and seasonally averaged inundation rates and Pee Dee River discharge at this location showed this correspondence between increases in tidal exposure, decreases in riverine sediment supply, and small-scale spatial variability in sediment elevation dynamics. Much of that increased variability may be due to rain-induced erosion during the longer low-tide exposure (GARDNER and SETTLEMYRE, 1975; CHALMERS *et al.*, 1985).

The marsh gradient sampled at Bly Creek (a deadend creek location) generated some interesting spatial differences in sediment elevation dynamics. The low marsh, midmarsh, and high marsh sites often alternated seasonal trends, with a decline in elevation at one site and an increase at another (Figure 6a), perhaps suggesting a pulsed or lagged movement, or exchange, of sediments across the marsh. A similar process of sediment reworking across the marsh surface after creekside deposition was reported by REED (1988). In fact, we found that, overall, downslope orientations had declining mean elevations and were significantly different from increasing upslope elevations, suggesting that the salt marshes throughout North Inlet may actually be steepening. [A noteworthy exception was the autumn 1992 Oyster Landing measurements, when the marsh appeared to be leveling rather than steepening, after more than a season of wrack cover and devegetation, as downslope orientations increased in elevations while upslope orientations decreased—causing the relatively high intrasite variability; Figure 5a]. At Bly Creek, however, the average annual rate of elevation change was significantly greater at the midmarsh than the low or high marsh, suggesting that [if across-marsh movement of sediments is occurring] this reworking either (1) is not a strictly upslope phenomenon or (2) is a long-term process not completely represented with our data set.

When placed into the transgressive context of North Inlet's geomorphology, our data were consistent with the marsh maturity sedimentation model of FREY and BASAN (1978), in which immature marshes accrete at greater rates than mature marshes. With only one exception, none of our five mature marsh sites showed significant increases in sediment elevations over the 2.5 years we sampled, and two 60 Bass Creek mature marsh sites actually showed declines (Figures 4 and 7). In a transgressive back-barrier marsh system, the oldest marshes are those closest to oceanic influences. The lack of elevation increases at our mature marsh locations may have been associated, to some degree, with inundation by sediment-depauperate oceanic waters. We also observed steadily declining sediment elevations at the Bly Creek mudflat site (Figure 6b). This mudflat is part of the dendritic headwaters of Bly Creek (Figure 1), a geologically young tidal creek (GARDNER and BOHN, 1980). We believe that the steady decrease in mudflat sediment elevations shown in Figure 6b, punctuated only by occasional increases, was a real-time measurement of the "birth" of a tidal creek. This phenomenon fits well into the DAME and GARDNER (1992) model of the geologic development of transgressive marsh-estuarine systems in which sea level rise drives the landward migration, and subsequent deepening and widening, of tidal creeks. DAME *et al.* (1992) referred to these intertidal headwater creeks as "ephemeral". Thus, the deepening phenomenon we observed appears to be a deepening of this mudflat—actually an ephemeral tidal creek—into a subtidal system.

Over the last 100 years, while the Eastern Shore of the Chesapeake Bay has been experiencing accelerated marsh and island loss (KEARNEY and STEVENSON, 1991), marshes toward the heads of Eastern Shore subestuaries were characterized by accretion rates well in excess of relative sea level rise (KEARNEY and WARD, 1986). KEARNEY and STEVENSON (1991) attributed this disparity to upstream fluvial trapping of sediment, enhanced by increased upland erosion and runoff from land clearing. We have observed a similar pattern at our tributary marsh locations along the Patuxent River. In the lower river where local topography is hilly and recent suburban development is fairly intense, sediment elevations at our tributary marsh site increased dramatically, while further upriver where the land is flatter and landuse is dominated by extant, low intensity agriculture, the tributary marsh elevations increased considerably less or actually decreased (Figures 4 and 8a). In fact, seasonally-averaged Patuxent River discharge explained 89% of the small-scale ($\approx$2 m $\times$ 2 m) variability in sediment elevations at our upriver tributary marsh location, suggesting that the hydrology of the main river channel, not of the tributaries, may control sediment dynamics in tributary marshes of the upper river. This spatial trend reversed in marsh locations along the main river channel, where our lower river marsh site actually appeared to be eroding while our middle river marsh site increased in elevation (Figures 4 and 8b). This difference may have been a function of river morphology, as marshes along the wide, deep lower river channel were much more susceptible to wind and wave erosion than those along the narrow, meandering upper river channel. Notably, there are few main channel marshes south of Benedict while they are the dominant feature of the upper river (Figure 2).

Sediment elevations at the Patuxent River mudflat sites also showed divergent behaviors (Figure 8c). The upper river mudflat [in Jug Bay], densely vegetated by emergent aquatic vegetation in the summer and fall, showed large negative changes in sediment elevation in the winter and spring and a negative annual average rate of change (Figure 4). These data suggested that the upper river [Jug Bay] mudflat was not an efficient sediment trap. In contrast, the extensive main channel *Phragmites* marshes south of Jug Bay (represented by the middle river location) appeared to be major sediment sinks. Elevations at both marsh and mudflat sites at our middle river location increased at high rates, and positive relationships with seasonally-averaged Patuxent River discharge explained 69% and 33% of the seasonal variability in observed marsh and mudflat $\Delta h/\Delta t$ values, respectively. In five of seven seasons, these adjacent marsh and mudflat sites had opposite $\Delta h/\Delta t$ values, suggesting a potential reworking of sediments similar to that implicated in the North Inlet Bly Creek data.

The lack of any relationship between seasonal changes in sediment elevation from the Muddy Creek brackish marshes and tidal inundation regime was not surprising. JORDAN *et al.* (1986) reported that most high marsh accretion in Muddy Creek was due to the accumulation of organic matter produced *in situ*, rather than to the import of mineral sediment. We installed the sites randomly with respect to the forest boundary, the tidal creek, and local conditions (such as macrophyte biomass and sediment characteristics). At each Muddy Creek site, we had only two SET arm orientations to represent ambient conditions, thus the site data in Figure 9 are means of only two arm orientation [population] means (each based on nine pin measurements). In contrast, North Inlet and Patuxent River habitat-level data were calculated as means of four arm orientation [population] means. Thus, the large differences in sediment elevations observed in the Muddy Creek estuary were probably a combination of the effects of one highly variable site, smaller sample sizes at these sites, and inherent natural variability in brackish marsh sediment elevations on small spatial scales (0.25 ha).

CONCLUSIONS

These 2.5 years of sediment elevation data confirmed the spatial complexity of long-term sediment dynamics and have proven useful for generating hypotheses and guiding future research. They should not be viewed as conclusive, however. The three estuaries studied had significantly different sediment elevations at the coarsest spatial analysis (the estuary), but not at the habitat level. Both North Inlet and Patuxent River sediment elevations appeared to be sensitive to landscape inputs (runoff, river flow) and geomorphic features (geologic age at North Inlet, river morphology at the Patuxent River). Muddy Creek elevation data demonstrated the high degree of variability at the habitat-level spatial scale ($\approx$0.25 ha) that may characterize brackish marshes. The range of average annual changes in sediment elevations reported here was comparable to sediment accretion rates measured in a number of other estuaries with a number of techniques (see Table 1). As we continue to measure sediment elevations in these estuaries, we will continue to investigate reasons for the patterns and differences shown here. The SET technique is also being used in Louisiana and Georgia (R. BOUMANS, Louisiana State University, *personal communication*), and we hope to install and monitor SET sediment elevation sites in Florida, North Carolina, and Virginia estuaries in the near future. Ultimately, the consistent use of this accurate, repeatable technique to quantify estuarine and wetland sediment elevation dynamics in a number of systems will result in a long-term data set critical to future regional scale comparisons of Atlantic and Gulf Coast estuaries.

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