Limnol. Oceanogr., 52(3), 2007, 1231–1238

Hurricane signals in salt marsh sediments: Inorganic sources and soil volume

R. Eugene Turner[1], *Erick M. Swenson, Charles S. Milan and James M. Lee*
Coastal Ecology Institute, School of the Coast and Environment, Louisiana State University, Baton Rouge, Louisiana 70803

Abstract

The inorganic content of 51 dated sediment cores from Mississippi River deltaic plain salt marsh wetlands peaks with the landfall of hurricanes. Variations in the inorganic sediment content demonstrate no temporal coherence with changes in either the Mississippi River suspended matter concentration or discharge, or with wetland losses on this coast. The inorganic matter brought to wetlands during hurricanes is sufficient to account for the accumulated inorganic sediment, and the volume averages 9% of the soil volume. A "sediment deficit" hypothesis, which makes a causal connection between a changing inorganic supply and the dramatically high wetland losses on this coast, is therefore rejected. Our results support the hypothesis that wetlands of an undeveloped coast receive the majority of their inorganic sediments from offshore and not from overbank flooding or through crevasses. Restoration and wetland maintenance (prevention) goals should be implemented with this in mind: the coastal wetland losses of the last century along this coast appear to be a consequence of the diminished accumulation of organic matter and not from variations in inorganic sediment loading.

Coastal wetland sediments are composed primarily of inorganic matter, organic matter, water, and pore space. The soil volume is reduced as organic matter decomposes, pore spaces are compressed, as water is squeezed out when these soils are overlain by newer material, and as they age. Plants add to the volume of the deposited soils by way of their root and rhizome production. These soil volume changes affect the relative vertical position of plants rooted in the soil structure, which has consequences for plant physiology. Plant toxins, for example, sulfides, may accumulate when soils are flooded, killing the plant (Mendelssohn et al. 1981). The elevation of the plant relative to sea level is thus dependent on both biological and physical factors within the soil profile.

The inorganic material of coastal wetlands, because it is dense and relatively stable, will not compress much in the upper 2 m of soil. Inorganic matter thereby provides some volumetric stability to the soils, whereas organic material may oxidize and root production varies seasonally and annually. Changes in the suspended sediment supply to coastal zones are, therefore, of potential consequence to the long-term stability of coastal wetlands. The underlying causes for the precipitously reduced area of coastal wetlands in the northern Gulf of Mexico in the last century are related to changing stressors on the soil structure, but there is some dispute about which stressor is most important (Turner 1997).

One of these potential stressors is an "accretion deficit" of inorganic materials deposited on the wetland surface. Three factors may contribute to this deficit: (1) the 50% decline in suspended sediment concentration in the Mississippi River in the late 1950s following major dam construction, principally on the Missouri River (Meade and Parker 1984), (2) the general construction of local levees from Baton Rouge to New Orleans along the Mississippi River after the 1850s, and the completion of flood protection levees in the early 1930s as the U.S. responded to the disastrous 1927 flood in the lower Mississippi River (Barry 1998), and (3) diversion of the Mississippi River into the Atchafalaya Basin, where it enters the Gulf of Mexico west of the mouth of the Mississippi River delta. About 30% of the freshwater flow near St. Francisville is diverted westward into the Atchafalaya Basin to join with the Red River and to become the Atchafalaya River near Simmesport, Louisiana (Reuss 1998). The first two factors reduced the potential supply of suspended sediments to the deltaic plain, and the third changed the distribution of the sediments flowing through the landscape.

Not all sediments, however, flow into deltaic wetlands from an inshore to offshore direction. Inorganic sediments also originate in the offshore zone and move inshore through tidal passes as the result of large, episodic storms (Turner et al. 2006*a*) and with tidal mixing. Estuarine salinity in the Mississippi River deltaic plain is strongly influenced by the amount of river water moving along the coast and mixing with estuarine waters during tidal cycles (Wiseman et al. 1990). When salt water enters the estuary, suspended sediments may also be transported inward. The temporal variations in the concentration of suspended sediments in coastal waters entering estuaries through tidal passes are presumably linked to the same variance in the riverine source concentration and load.

---

[1] Corresponding author (euturne@lsu.edu; tel: 225-578-6454; fax: 225-578-6326).

Acknowledgments

We thank A. Bass, I. Hesse, G. Holm, D. Justic, S. Nesbitt, T. Oswald, G. Peterson, and P. Roberts for assistance in the field sampling.

Support for data analysis and manuscript preparation was provided by the National Oceanographic and Atmospheric Administration (NOAA) Coastal Ocean Program MULTI-STRESS award NA16OP2670 to Louisiana State University. The data collection was supported by the Environmental Monitoring and Assessment Program administered by the Environmental Protection Agency's Office of Research and Development (K. Summer, contract officer).

Hypothesis testing—The question we address here is whether the inorganic density of coastal wetland sediments reflects changes in the supply of inorganic materials potentially available from rivers and overbank flooding, through tidal passes and into tidal channels, or from what Stumpf (1983) described as the more "democratic" flooding of the coastal zone during hurricanes, when most wetlands are temporarily submerged. Our approach was to estimate the inorganic concentrations in sediments dated circa 1879 to 1990, and to compare and contrast the results with the outcomes anticipated if various hypotheses about the supply of potential source materials are true.

We restricted our analyses to salt marshes, rather than brackish and freshwater coastal marshes, for three reasons. First, the wetland loss rates on the Louisiana coast have been high in the last 50 yr (i.e., the loss of coastal wetlands from 1955 to 1978 was 111.2 km^2 yr^{-1}; Baumann and Turner 1990). These wetland-to-water conversions are thought to be linked to an insufficient supply of inorganic sediments, which various restoration initiatives are meant to redress (LCWCRTF 1998). Understanding why inorganic sediment storage in salt marshes varies is, therefore, of fundamental importance to wetland restoration efforts and the prevention of wetland losses. Second, salt marshes are the closest wetland habitats to the tidal entrance that receive the suspended sediments from offshore coastal currents. The temporal variances in coastal sediment supplies entering from offshore and through tidal passes, e.g., from Mississippi River suspended sediments or from offshore sources, are more likely to be detected in wetlands near the coast than further inland. Finally, the volume of inorganic material in salt marshes on the western Atlantic shoreline is $<10\%$ of the soil volume and nearly equal to the volume of organic matter, and it is higher than the more inland brackish and fresh marshes (Turner et al. 2001, 2006*b*). In other words, it may be possible to detect a signal of a relatively small change in the amount of inorganic accumulation amidst the noise arising from the background of spatial variance and sampling artifacts. A change in the relative rate of inorganic sediment accumulation over one year or longer should be much easier to detect when the organic content is large and when the average inorganic density is small than when the organic content is small and the mineral content is large. The advantage of the potentially higher signal : noise ratio in the salt marshes, compared to more inland marshes, was anticipated because of the substantial declines in source material supply delivered to coastal waters (discussed below).

There were two potentially confounding factors in this analysis: (1) a sedimentary signature of varying inorganic sediment accumulation might be undetectable if the signal were smeared by sediment mixing, and, (2) postdepositional changes arising from sediment compaction or organic matter decomposition may increase the concentration of mineral matter and blur, or even erase, the temporal variations in accumulation occurring after deposition. For example, a several-centimeter-thick layer deposited by Hurricane Andrew (1992) "was no longer readily obvious in the sediments two years after landfall" (Parsons 1998).

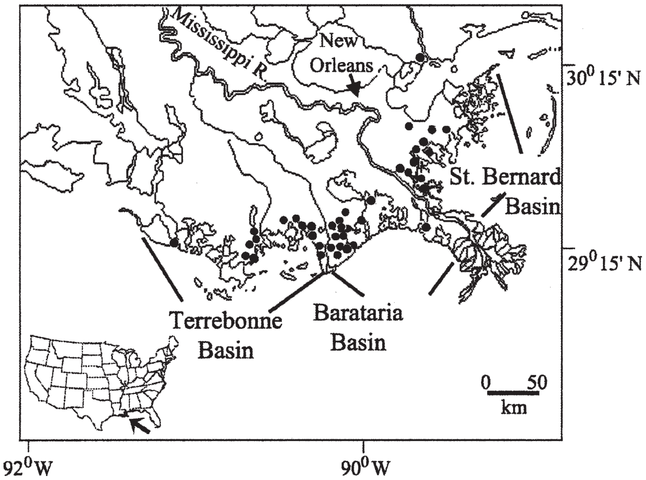

Fig. 1. The location of 40 samples sites where the 51 sediment cores were collected.

We collected 51 sediment cores from salt marshes in each of the three estuaries of the Mississippi River deltaic plain (Fig. 1). The uncommonly large sample size was designed to minimize the potential confounding effects of local hydrologic changes, uncertainties about the location and size of the area affected by hurricane storm surges, and the natural variance among estuaries. We compared the temporal patterns in the inorganic density in the dated sediment layers to the temporal variations in: (1) river sediment loading, (2) suspended sediment concentration in the Mississippi River, and (3) major hurricane events, in order to test various hypotheses about the source of inorganic sediments in salt marshes along this coast. The primary observational consideration was whether or not there was less or more inorganic material in sediments dated just before or during the period when high wetland losses occurred, which was from the late 1950s to the end of the 1970s (Turner 1997). If no changes in the inorganic density occurred downcore, then no further investigation was required because: (1) it was clear that the inorganic supply to the salt marsh had probably not changed in the last 100 yr, and therefore it had not contributed to a proposed sedimentary imbalance contributing to the observed wetland losses, or (2) sediment mixing had smeared the record. There are several hypotheses (H) that can be tested if variance in the inorganic concentration downcore is observed: (H1) if hurricanes are a significant source of inorganic sediments for the deltaic plain, then the peaks of inorganic density in dated sediments will be coincidental with the occurrence of hurricanes. (H2) If the variability in overbank flooding from river to estuary is relatively significant compared to other sources of inorganic sediments, then there will be a conspicuous and relatively large reduction of the inorganic density in the dated sediments: (1) beginning from the end of the 1800s to the present, or (2) coeval with completion of flood control and navigation levees, or (3) as the diversion of the Mississippi River into the Atchafalaya Basin increased to 30% of the main channel flow, but not after it reached 30%. (H3) If the 1927 flood were a significant event in salt marsh accretion, then a spike in inorganic sediment concentration might be evident in the layer dated circa 1927. (H4) If variance in the Mississippi River suspended sediment loads over many years were an important influence on the inorganic density of salt marsh sediments, then there may be a decline in the inorganic content of dated sediments that is coincidental with the precipitous decline of suspended sediments that began in the early 1950s.

Methods

Sediment core collection—We collected 51 sediment cores from Louisiana estuaries in 1991 and 1993 (Fig. 1), dated them with ^{137}Cs radioisotopic methods, and measured the inorganic density in all of the individually dated subsamples. These sediment cores were from salt marshes in the Terrebonne ($n = 16$), Barataria ($n = 19$), and St. Bernard estuaries ($n = 16$), and they were chosen at random as part of the U.S. Environmental Protection Agency EMAP (Environmental Monitoring and Assessment Program) Salt Marsh Program (Turner et al. 1995). Cores were collected at a center point located ~50 m from the shoreline to ensure that any "edge effects" did not influence interpretation of the data. The apparent amount of compaction was assessed during and after the core was removed from the ground. The cores were frozen upon return to the laboratory. The cores were extruded using a thawing box, measured, and kept frozen until sectioned at 1-cm intervals. The dishes with the core sections (each subsection has a volume of at least ~90 cm^3) were then weighed to the nearest 0.01 g, dried for 24 h at 60°C, and then weighed again. The salinity of these salt marshes, including porewater salinity, was less than 20 and the residue from evaporated salt was an inconsequential component of the total weight of the core subsections. The sections were homogenized using a Willey Mill (with a no. 20 mesh screen) and then placed into numbered and labeled containers. A subsample (~1.0 g) of each of the homogenized core sections was taken to estimate inorganic and organic content by loss on ignition at 550°C. These procedures allowed us to evaluate pre- and postcollection sediment compaction and to determine both wet and dry bulk densities. The surface layer was not dated if it was an unconsolidated flocculent layer.

Sediment dating—The dating methods, quality control criteria, and the counting statistics for all sediment cores dated with ^{137}Cs are those described in Milan et al. (1995) and Turner et al. (2001) who reported on the accretion rates for all of these samples. Briefly stated, the dried and ground samples were counted for ^{137}Cs using a 40% efficiency germanium detector. The radioisotope ^{137}Cs, a residual of nuclear bomb fallout, first appeared in measurable amounts in the early 1950s, peaked in the spring of 1963 with additional large amounts in early 1964, and has declined since with minor fluctuations, i.e., from the Chernobyl accident in some locations. The average ages of the individual subsections of the sediments were dated using the average accretion rate from the 1963–1964 layer to the surface. These sections were usually thick enough to be composed of sediments that had accumulated over more than one year. The constituent values for individual years were determined by interpolation, assuming a constant accumulation rate between the surface and the 1963–1964 horizon, and the same vertical accretion rate below the 1963–1964 horizon. This approach to dating means that dating precision decreases with depth beneath the 1963–1964 layer. The deepest layers, in other words, are the layers with the poorest chronology, assuming errors are propagated downward.

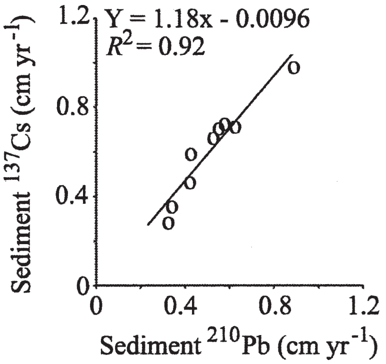

Fig. 2. The relationship between the accretion rate since 1963–1964 (determined using the ^{137}Cs method) and the accretion rate over the last 100+ yr (determined using the ^{210}Pb method). Adapted from data discussed in Turner et al. (2006*b*).

Extrapolation of the results obtained from using ^{137}Cs methodology to the deeper layers is justified on the basis of a strong and linear relationship between the vertical accretion rate using ^{137}Cs methodology and ^{210}Pb dating methods, which is generally the case for organic-rich salt marshes, including these marshes (Turner et al. 2006*b*). A linear regression of the relationship between the accretion rates determined by the two methods yields an adjusted R^2 value of 0.92 for these samples ($p < 0.01$; ±1 standard error [SE] = 0.13; Fig. 2). This constancy between the accretion rates estimated by the ^{137}Cs and ^{210}Pb dating techniques makes it possible to estimate an inorganic density for each year of the sediment profile using ^{137}Cs within the 150 yr that the ^{210}Pb dating technique is valid.

There is not a one-to-one correspondence with the estimated dates using each method. The date assigned using constant accretion rates from the surface to the 1963–1964 horizon and applied throughout the sediment profile underestimates the true age in the layers beneath the 1963–1964 horizon because of autocompaction (Turner et al. 2006*b*). The vertical accretion rates of salt marsh sediments dated before 1963–1964 using ^{137}Cs dating techniques average 118% of the accretion rate that occurred after deposition dated using ^{210}Pb dating methods for sediment accretion rates that vary by a factor of three (Fig. 2). A sediment layer deposited in 1900 or 1930 would be dated as being deposited circa 1911 or 1936, respectively, without correction for the autocompaction shown in Fig. 2.

Suspended matter concentration—The concentration of suspended matter at New Orleans was first measured in 1839 (Turner and Rabalais 2003). These earlier estimates counted sediment grains and used a conversion factor to estimate sediment concentration and are not included in this analysis. It was not until 1879 that a gravimetric method was first used in a systematic manner. The effects of land clearing and agricultural expansion in the Mississippi River watershed in the1800s increased sediment yields throughout the basin and were the reasons for the formation of the Soil Conservation Service in the 1930s. The estimates of suspended sediment concentrations in the river are, therefore, assumed to be at their peak in the late 1800s, compared to in earlier centuries.

Hurricane strength—Data on hurricanes ranked as a category three storm, and that have a tidal surge >3 m, were obtained from a variety of private and public agencies (Dunn and Miller 1964; USACOE 1972; Roth 1998; Jarrell et al. 2001). These data are in Turner et al. (2006*a*). Some hurricanes were not included, although they were listed as major storms on various lists. Hurricanes Ethel (1960), Edith (1971), and Carmen (1974) had maximum winds in excess of 240 km h^{-1}, but did not have a storm surge >3 m at landfall in Louisiana. Hurricane Elena (1985) was a category three storm, but the major damage and 3-m storm surge occurred in Florida before it arrived in Louisiana. Hurricane Juan, an unranked storm, had multiple landfalls, and the maximum storm surge was slightly less than 3 m (2.8 m at Cocodrie, Louisiana).

Inorganic sediment budget—The volume of inorganic and organic material in sediments was estimated using a mineral weight to volume conversion factor of 2.61 and 1.14 g cm^{-3}, respectively (DeLaune et al. 1983).

The average inorganic density for the dated sediments in three estuarine watersheds was computed for various intervals to investigate whether the concentration had changed over the approximately 100+ yr record represented in the dated sediments. The annual amount of accumulation in the Louisiana coastal wetlands was estimated by multiplying the area of wetland (Baumann and Turner 1990) by the average inorganic concentration in soils dated from 1900 to 1990. This accumulation was compared to the annual yield of suspended sediments carried by the Mississippi River at St. Francisville, Louisiana (Chakrapani 2005).

Land loss and canal area—The canal area and land loss rates are in Turner (1997), Morton et al. (2005), and from the permitting records of the Louisiana Department of Natural Resources for 1990 to 2000.

Results

Suspended matter concentration—The average annual concentration of suspended sediments in the Mississippi River at New Orleans from 1880 to 1950 was 580 ± 21.2 mg L^{-1} and 218 ± 18.9 mg L^{-1} from 1950 to 1990 (mean ± 1 SE; Fig. 3). This change represents a decline of 62% from one interval to the other.

Inorganic and organic content—The oldest sediments used here were dated circa 1880 using results from the ^{137}Cs method. The actual date of deposition for these oldest sediments was estimated to be circa 1865, based on the ^{210}Pb dating method used on a subset of sediment cores (Fig. 2). This temporal offset of 18% over the 98 yr since the 1963–1964 ^{137}Cs peak is important in the following discussion, in which the inorganic density of sediments dated using the ^{137}Cs method will be compared to events with known true dates, i.e., hurricanes.

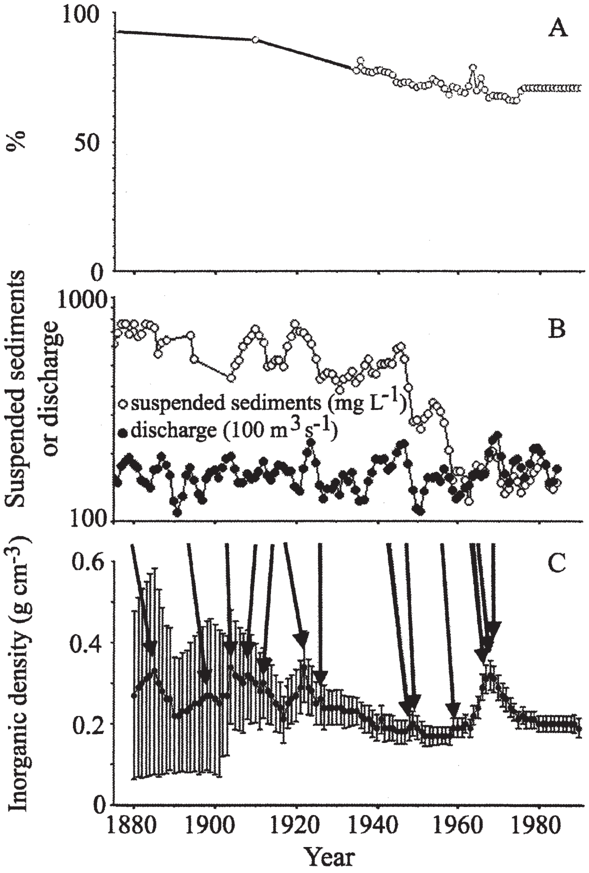

Fig. 3. Changes in suspended matter loading and storage in coastal wetlands. (A) The percent of the Mississippi River that goes directly into the modern mouth of the Mississippi River Delta. (B) The average annual concentration of suspended sediments (mg L^{-1}) at New Orleans (open circles) and the annual discharge of the Mississippi River at Vicksburg, Mississippi (closed circles; 100 m^3 s^{-1}). A 3-yr running average is depicted. (C) Inorganic density (g cm^{-3}) in dated sediments from the Mississippi River deltaic plain and the incidence of hurricanes in southeast Louisiana that had a storm surge >3 m. The arrows are suggested temporal linkages between hurricane events and peaks in inorganic density. The bars around each filled circle are ±1 SE. The dates for sediments layers are slightly older than depicted because the dates are not compensated for compaction, which may amount to 13 yr in 1890, and is 0 in 1963.

The density of inorganic material in sediments dated for the same year and for the entire 1880 to 1990 depth profiles, ranged from 0.17 to 0.34 g cm^{-3}, with a mean value of 0.239 ± 0.004 (μ ± 1 SE). The volume of inorganic material determined using this mean value and a weight to volume conversion factor of 2.61 g cm^{-3} is 9.2%.

Table 1. The average inorganic density (g cm^{-3}, ±1 SD), change, and volume for sediments from salt marshes in the Terrebonne, Barataria, and St. Bernard estuaries.

Time interval	Barataria density	Terrebonne density	St. Bernard density
1990 to 1963	0.15 (0.09)	0.23 (0.12)	0.29 (0.17)
1990 to 1930	0.13 (0.09)	0.19 (0.10)	0.27 (0.17)
1990 to 1900	0.14 (0.11)	0.19 (0.10)	0.28 (0.18)
1962 to 1930	0.11 (0.11)	0.15 (0.10)	0.26 (0.19)
1962 to 1900	0.12 (0.14)	0.16 (0.09)	0.29 (0.20)
1929 to 1900	0.16 (0.24)	0.16 (0.05)	0.34 (0.26)
Change in inorganic content 1900–1929 to 1963–1990			
	–6.3%	+44%	–15%
Average inorganic volume from 1990 to 1900			
	5.3%	7.4%	10.9%

There is a statistically significant decline in inorganic sediment concentration from 1880 to 1990 of –0.0008 g cm^{-3} yr^{-1} ± 0.0001 ($\mu \pm 1$ SE; $p < 0.001$; adj. $R^2 = 0.32$). This rate of change was accompanied by a decrease in inorganic density of 0.33% yr^{-1} when measured against the average value for all samples, resulting in a change from 0.28 to 0.19 g cm^{-3} from 1880 to 1990, respectively. This average rate of change in inorganic density compares to a value of 0.38% yr^{-1} for a larger number of sediment cores taken along the same coast, which included most of these cores (Turner et al. 2006*b*). The average relative change in inorganic concentration in these cores is matched by an equal change in the average organic concentration, and the volumetric change in each is best explained as resulting from compaction, but not from organic oxidation or from changes in sedimentation rate (Turner et al. 2006*b*).

The average organic content in all samples was 36.7% ± 0.6% (dry weight; $\mu \pm 1$ SE), which is about 6.5% of the soil volume.

The average inorganic density in different time periods for the three different estuaries is listed in Table 1. The highest inorganic density is in sediments collected from the St. Bernard estuary, and the lowest values are in sediments collected from the Barataria Basin. The mean inorganic density decreased from the surface to bottom layer for sediments from the Terrebonne Basin, remained about the same for sediments from the Barataria Basin, and increased for sediments from the St. Bernard Basin. However, the variations among dated segments were high enough so that there were no statistically significant differences in inorganic density detected among sediment layers collected from one estuary. The same temporal and spatial patterns emerge for the percent volume that the inorganic material occupied, because of the constant weight to volume conversion factor that was applied.

Hurricanes—There were 14 hurricanes from 1879 to 1990 with tidal surges estimated to be >3 m at landfall on the Mississippi River deltaic plain (Turner et al. 2006*a*). This frequency is equivalent to an average occurrence of a major hurricane every 7.9 yr. The two longest periods between category three hurricanes were from 1969 to 1990 (21 yr) and from 1926 to 1943 (17 yr). There were several periods when category three hurricanes clustered together: 1906 to 1909 (2), 1915 to 1918 (3), and 1964 to 1969 (3).

A peak in inorganic density is associated with each of these 14 hurricanes, with a slight offset because of the compaction described above, which results in an underestimation of the true age of the sediments by up to 13 yr in 1890, but 0 yr in 1963–1964 (Fig. 2). The clusters of the multiple hurricanes are coincidental with the largest peaks in inorganic density. There is a downward decline in inorganic concentration for the five decades after the 1915–1918 cluster of hurricanes, and then a rise that is coincidental with the passage of three hurricanes in 1964 (Hilda), 1965 (Betsy), and 1969 (Camille). The minor peaks between these conspicuously larger peaks are coincidental with the hurricanes of 1926, 1943, 1947, and 1956. The two rises in the concentration of inorganic matter before 1900 are coincidental with the 1879 and 1893 hurricanes (Fig. 3).

The mobilization and/or remixing of sediments after the cluster of multiple hurricanes does not appear to be enough to smear the record, because peaks are clearly coincidental with the occurrence of multiple hurricanes within a few years of each other. The peaks associated with the hurricanes spaced further apart, however, are disproportionately lower than the sum anticipated from one-third of the cluster of three hurricanes. This suggests that remobilization or mixing of sediments can be significant.

Estimates of sediment storage and source material size—We estimate that there was no more than 15.9 × 10^9 kg of inorganic material stored in Louisiana's coastal wetlands each year by using the average vertical accretion rate (0.66 cm yr^{-1}), the average inorganic content (0.24 g cm^{-3}) for these cores, and the area of all wetland types in 1978 (10,093 km^2; Baumann and Turner 1990). We estimate that there was no more than 49.7 × 10^9 kg of inorganic material stored in coastal open-water bodies each year by assuming the vertical accretion rate equaled relative sea-level rise (0.23 cm yr^{-1}), an average inorganic content of 1 g cm^{-3}, and the area of all open water in 1978 (21,628 km^2; Baumann and Turner 1990). These two estimates are an upper limit, because the inorganic concentration and accretion rate for wetlands and open-water bodies increase going from freshwater to seawater. If sediments are deposited in open-water areas at the same rate as in wetlands as a result of hurricanes, then the pro-rata deposition for open-water and marsh areas equals 26.1 × 10^9 kg yr^{-1} (Turner et al. 2006*a*), which is about half of the sediments estimated to be stored each year. These annual accumulations are about 4% and 8.5%, respectively, of the suspended sediment load presently delivered to the coastal zone by the Mississippi River each year (210 × 10^9 kg yr^{-1}; Chakrapani 2005). Although these estimates of sediment accumulation and hurricane delivery are gross estimates, they indicate that hurricanes are an important part of the coastal wetland inorganic sediment budget. Furthermore, the average annual accumulation of sediment within these salt marsh wetlands is 0.18 g cm^{-2} yr^{-1}. This compares with the 0.17 g cm^{-2} yr^{-1} from hurricanes on the deltaic plain salt marsh wetlands (Turner et al. 2006*a*). Hurricanes can, therefore, be the dominant source of inorganic material for these coastal marshes.

Hypothesis testing—Hypothesis H1 is not rejected, because there is a rise in the inorganic content of dated sediments from 1880 to 1990 that is coincidental with the occurrence of strong hurricanes, and particularly when the hurricanes are clustered so that they arrive within a few years of each other. These peaks persist for 100 yr, indicating that mixing is not sufficiently large to completely obliterate a signal arising from a storm of this size.

The changes in the inorganic content in the three basins from dated sediments from the 1900 to 1929 interval compared to 1963 to 1990 were –15%, –6%, and 43% (Table 1), average of 21%. This result is *inconsistent* with what should happen if the 67% decline in suspended sediment concentration in the Mississippi River from 1880 to 1990 were an important factor directly controlling the accumulation of inorganic matter in these soils. There was also no peak in the inorganic content of these sediments dated circa late 1920s, and there was no significant decline in inorganic content in the late 1950s when the concentration of suspended sediments in the Mississippi River dropped precipitously (Fig. 3). Further, there is a peak, not a trough, in the inorganic content of sediment dated to be deposited in the late 1960s, when the conversion of coastal wetlands to open water was at a peak. Hypotheses H2, H3, and H4 are rejected because of these results.

Discussion

Two simple observations arising from these data are clear and lead to at least one major conclusion about the source of inorganic sediments on this coast. The first observation is that there was no apparent difference in the inorganic density of dated subsamples of salt marsh sediment cores: (1) for several decades before and after the decline in suspended sediments in the Mississippi River, (2) at the time of the 1927 flood, or after the 1927 flood when the flood and navigation levee system was extended, heightened, and strengthened, or (3) as the percentage of Mississippi River water diverted westward through the Atchafalaya Basin reached 30%. The variability in riverine inorganic sediment supply cannot be invoked, therefore, to explain general patterns in the inorganic content of these coastal wetlands for the period examined.

The second observation is that the increases in inorganic density in these salt marshes are coincidental with the occurrence of major hurricanes. These peaks in inorganic density persist longer when multiple strong hurricanes occur within a few years of each other and are evident after many decades. Some smearing of the signal appears likely and is probably most significant within a few years after the hurricane, as others have indicated at individual sites (Parsons 1998).

These two observations and the sediment budgets lead to the conclusion that the inorganic materials for these salt marsh sediments are delivered from sea to inland and not from river over or through levees to wetlands. The amount of sediments introduced to estuarine wetlands by overbank flooding in unconfined channels has not made as significant a contribution as hurricanes to the increases in soil volume of salt marshes on this coast for the last 100 yr, and likely for centuries (Turner et al. 2006*a*). Storms smaller than hurricanes are probably a significant additional source of inorganic material that arrives more frequently, but in lesser amounts per episode, and the cumulative amount does not overwhelm the significance of hurricane events. These smaller events may redistribute previously deposited materials or lead to a smearing of the hurricane signal.

The appearance of storm-derived inorganic materials in salt marsh sediments may be easiest to detect where these environments are relatively organic-rich, where storm surges intrude further inland, where the elevation gradient is relatively slight, and if storms suspend more and heavier sediments than in the ordinary microtidal currents. A hurricane signal may not be as evident in macrotidal marshes fringing steep coastlines.

The inorganic matter accumulating in these coastal marshes and open waters represents about one-tenth of the annual inorganic sediment load of the Mississippi River. Kesel (1988) estimated that 2.6% of the river's sediment load would flow through an unconfined channel if the levees were not there. Kesel's estimate is actually an overestimate of the amount available to all coastal wetlands because the artificial constriction of the river channel throughout the basin has raised the flood stage for the same-sized discharge event (Belt 1975), and the sediments tend to fall out near the river, hence the formation of the natural levees and the progradation of river deltas. The regional supply of materials over river banks and into these coastal wetlands appears much less important than the transport of inorganic sediments landward from offshore by storms. Further, it seems that the storage capacity of the offshore sediment sources is enough of a buffer to overwhelm the decade- or centuries-long variations in riverine inorganic sediment loading.

The majority of sediments deposited on the marshes during hurricanes is from the Mississippi River, but the deposited river sediments make their way to coastal waters before being suspended by hurricanes and carried inshore during strong storms. The imposition of flood protection levees on the landscape was therefore not a major alteration of the inorganic supply to coastal salt marshes, and perhaps brackish and freshwater marshes, because of the dominant role of storms compared to what once flowed over the river banks of the unconfined channel.

An implication of these conclusions is that the formerly dramatically high wetland losses along this coast (Fig. 4) were not a consequence of reduced inorganic sediment supply, but rather the result of other factors. There are other ways to explain the wetland losses of the last several decades that can be tested experimentally. One alternative explanation is based on the lack of organic accumulation belowground, which is principally from roots and rhizome production and not aboveground biomass (Turner et al. 2004). Results of sediment dating of a Terrebonne wetland by Nyman et al. (1995) and several Gulf of Mexico salt marshes by Callaway et al. (1997) have shown the significance of organic accumulations in controlling vertical

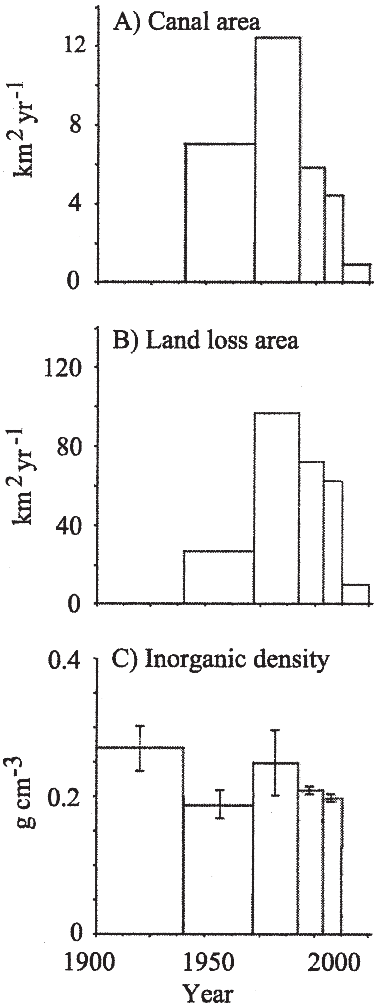

Fig. 4. The annual area of (A) new dredged channels (km^2 yr^{-1}), (B) land loss rates (km^2 yr^{-1}), and (C) average inorganic density (g cm^{-3}) on the Louisiana coast for various intervals. The inorganic content is the average (±1 SD) for the cores described in the text.

accretion rates. The large body of evidence from studies of freshwater peat has shown how important small changes in hydrology are in influencing the balance of carbon storage and hence soil subsidence (Turner 2004). The indirect hydrologic impacts on plants induced by dredging and spoil bank formation (up to 2-m high within an estuary that has tidal range <0.3 m) can thus explain the well-documented correlations between dredging canals and variations in wetland fragmentation and loss in time and space (Fig. 4; Turner 1997; Turner and Rao 1990; Bass and Turner 1997).

The equilibrium of forces determining whether there is wetland maintenance or loss is very different from those that lead to wetland creation. There is an ecosystem phase shift when plants colonize a sufficiently shallow platform built on mostly inorganic matter to spread widely and form new landscapes dependent on organic accumulation. The new plant-soil ecosystem is dynamically poised in a way that maintains them for centuries, even while important driving forces fluctuate greatly. Redfield (1972), for example, demonstrated that Cape Cod salt marshes once survived rates of sea-level rise twice as high as they do currently. Some of this ability to resist sea-level rise and storms is embedded in plants, and their role in sustaining coastal wetlands has been underestimated to date. Restoration programs that restrict the underlying cause-and-effect relationships and remedies to a focus on inorganic sediment source and delivery may be fatally flawed.

References

Barry, J. 1998. Rising tide: The great Mississippi flood of 1927 and how it changed America. Touchstone.

Bass, A., and R. E. Turner. 1997. Relationships between salt marsh loss and dredged canals in three south Louisiana estuaries. J. Coastal Res. **13:** 895–903.

Baumann, R. H., and R. E. Turner. 1990. Direct impacts of outer continental shelf activities on wetland loss in the central Gulf of Mexico. Environ. Geol. Water Resour. **15:** 189–198.

Belt, C. M., Jr. 1975. The 1973 flood and man's constriction of the Mississippi River. Science **189:** 681–684.

Callaway, J. C., R. D. Delaune, and W. H. Patrick, Jr. 1997. Sediment accretion rates from four coastal wetlands along the Gulf of Mexico. J. Coastal Res. **23:** 181–191.

Chakrapani, G. J. 2005. Factors controlling variations in river sediment loads. Curr. Sci. **88:** 569–575.

Delaune, R. D., R. H. Baumann, and J. G. Gosselink. 1983. Relationships among vertical accretion, coastal submergence and erosion in a Louisiana Gulf Coast marsh. J. Sediment. Petrol. **53:** 147–157.

Dunn, G. E., and B. I. Miller. 1964. Atlantic hurricanes. Louisiana State Univ. Press.

Jarrell, J. D., M. Mayfield, and E. N. Rappaport. 2001. The deadliest, costliest, and most intense United States hurricanes from 1900 to 2000 (and other frequently requested hurricane facts). NOAA Technical Memorandum NWS TPC-1.

Kesel, R. H. 1988. The decline in the suspended load of the lower Mississippi River and its influence on adjacent wetlands. Environ. Geol. Water Sci. **11:** 271–281.

Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority (LCWCRTF). 1998. Coast 2050: Toward a sustainable coastal Louisiana., Louisiana Department of Natural Resources.

Meade, R. H., and R. S. Parker. 1984. Sediments in rivers of the United States. National Water Supply Summary. U.S. Geological Survey Water Supply Paper 2275.

Mendelssohn, I. A., K. L. McKee, and W. H. Patrick, Jr. 1981. Oxygen deficiency in *Spartina alterniflora* roots: Metabolic adaptation to anoxia. Science **214:** 439–441.

Milan, C. S., E. M. Swenson, R. E. Turner, and J. M. Lee. 1995. Accumulation rates estimated from ^{137}Cs activity: Variability in Louisiana salt marshes. J. Coastal Res. **11:** 296–307.

Morton, T. A., J. C. Bernier, J. A Barras, and N. F. Ferina. 2005. Rapid subsidence and historical wetland loss in the Mississippi Delta plain: Likely causes and future implications. U.S. Geological Survey Open-File Report 2005: 1215.

Nyman, J. A., C. R. Crozier, and R. D. Delaune. 1995. Roles and patterns of hurricane sedimentation in an estuarine marsh landscape. Estuar. Coast. Shelf Sci. **40:** 665–679.

Parsons, M. L. 1998. Salt marsh sedimentary record of the landfall of Hurricane Andrew on the Louisiana coast: Diatoms and other paleoindicators. J. Coastal Res. **14:** 939–950.

Redfield, A. C. 1972. Development of a New England salt marsh. Ecol. Monogr. **42:** 201–237.

REUSS, M. 1998. Designing the bayous: The control of water in the Atchafalaya Basin 1800–1995. Office of History, U.S. Army Corps of Engineers.

ROTH, D. 1998. Louisiana hurricanes [Internet]. National Weather Service, Lake Charles, Louisiana. Available from http://www.srh.noaa.gov/lch/research/lahur.htm. Accessed 18 November 1996.

STUMPF, R. P. 1983. The process of sedimentation on the surface of a salt marsh. Estuar. Coast. Shelf Sci. **17:** 495–508.

TURNER, R. E. 1997. Wetland loss in the northern Gulf of Mexico: Multiple working hypotheses. Estuaries **20:** 1–13.

———. 2004. Coastal wetland subsidence arising from local hydrologic manipulations. Estuaries **27:** 265–273.

———, J. J. BAUSTIAN, E. M. SWENSON, AND J. S. SPICER. 2006*a*. Wetland sedimentation from hurricanes Katrina and Rita. Science **314:** 449–452.

———, C. S. MILAN, AND E. M. SWENSON. 2006*b*. Recent volumetric changes in salt marshes. Estuar. Coast. Shelf Sci. **69:** 352–359.

———, AND N. N. RABALAIS. 2003. Linking landscape and water quality in the Mississippi River basin for 200 years. BioScience **53:** 563–572.

———, AND Y. S. RAO. 1990. Relationships between wetland fragmentation and recent hydrologic changes in a deltaic coast. Estuaries **13:** 272–281.

———, E. M. SWENSON, AND C. S. MILAN. 2001. Organic and inorganic contributions to vertical accretion in salt marsh sediments, p. 583–595. *In* M. Weinstein and K. Kreeger [eds.], Concepts and controversies in tidal marsh ecology. Kluwer.

———, ———, C. S. MILAN, J. M. LEE, AND T. A. OSWALD. 2004. Belowground biomass in healthy and impaired salt marshes. Ecol. Res. **19:** 29–35.

———, ———, AND J. K. SUMMERS. 1995. Coastal wetlands indicator study: EMAP—Estuaries Louisiana Province: 1991. Gulf Breeze, Florida: U.S. Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratory, EPA/620/R-95/005.

U.S. ARMY CORPS OF ENGINEERS (USACOE). 1972. History of hurricane occurrences along coastal Louisiana. Department of the Army.

WISEMAN, W. J., JR., E. M. SWENSON, AND J. POWER. 1990. Salinity trends in Louisiana estuaries. Estuaries **13:** 265–271.

Received: 1 September 2006
Amended: 18 January 2007
Accepted: 22 January 2007