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Time-Varying Rates of Organic and Inorganic Mass Accumulation in Southeast Louisiana Marshes: Relationships to Sea-Level Anomalies and Tropical Storms

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ABSTRACT

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Louisiana's coastal wetlands are complex systems that require a continuous input of organic and inorganic material to keep pace with relative sea-level rise. Coastal restoration projects such as sediment diversions are being implemented to mitigate land loss and increase availability of inorganic sediment to coastal wetlands, and marshes specifically rely on organic material to build soil volume and maintain surface elevation. Interannual-to-decadal sea-level anomalies such as hurricanes can affect marsh accretion, mineral deposition, and plant productivity. In this light, complex ecogeomorphic feedback controls whether a marsh surface is sustainable or eroded/drowns. This study performs some of the first differential vertical accretion rates (VARs) and organic and inorganic mass accumulation rates (MARs) over time in SE Louisiana marshes determined from the ²¹⁰Pb Constant Rate of Supply model, coupled with standard ¹³⁷Cs VARs. These accumulation rates over the past ~100 years were measured from a total of six brackish and salt marsh locations in Barataria Basin near the proposed Mid-Barataria Sediment Diversion. They were then related to interannual sea-surface elevations at Grand Isle, Louisiana, over the last ~60 years and recorded hurricane activity in the delta. Results show VARs range from 0.63 cm/y to 1.69 cm/y and total MARs range from 0.11 to 0.43 g/cm²/y. Temporally, VARs and MARs (total, inorganic, and organic) are characterized by gradual increases in rates with decreasing age along with episodic peaks in VARs and MARs. The findings of this study indicate that no relationship occurs between sea-level anomalies and VARs or organic and inorganic MARs; however, a strong relationship appears to occur between major hurricanes to VAR and MAR contributions. Furthermore, high water content (81 ± 8%) and organic-rich soils in the sediment cores highlight the significance of belowground biomass and associated pore volume in maintaining marsh elevation in the study area.

ADDITIONAL INDEX WORDS: *210-Pb chronology, vertical accretion, sediment accumulation, hurricane sedimentation.*

INTRODUCTION

The persistence of Louisiana tidal marshes against sea-level rise is dependent on the rate of vertical accretion, a process of organic and inorganic deposition that contributes to marsh elevation. Vertical accretion rates (VARs) may fluctuate depending on factors such as organic and inorganic material availability, vegetation production and decomposition rates, subsidence, and sea-level fluctuations (Day *et al.*, 2011; DeLaune, Baumann, and Gosselink, 1983; Morris *et al.*, 2016; Nyman *et al.*, 2006; Turner, Swenson, and Milan, 2002). Relative sea-level rise (RSLR; eustatic/geocentric sea-level rise plus subsidence) poses a major threat to Louisiana marshes and can result in marsh deterioration or conversion to open water (*i.e.* submergence) if RSLR rates exceed marsh surface-elevation gain (Boesch *et al.*, 1994; Reed, 2002). In Louisiana marshes, the rate in which surface marsh elevation increases or decreases is highly correlated to accretion rates.

More than 1100 square kilometers of wetland has been lost in Barataria Basin alone from 1932 to 2016 (Couvillion *et al.*, 2017). Louisiana has a \$50 billion, 50-year plan to combat wetland loss for coastal protection involving building and sustaining marshes in Louisiana (Coastal Protection and Restoration Authority of Louisiana, 2023); therefore, understanding the contributions of organic and inorganic material to marsh elevation growth is imperative. The contributions of organic and inorganic material to vertical accretion are complex because it is highly variable and often depends on marsh vegetation type, geographic location, local hydroperiod, and small-scale local topographic controls. For example, previous studies conducted in Louisiana found organic matter accumulation to be the primary driver of vertical accretion in inactive fresh to brackish marshes (marshes lacking regular fluvial input); however, mineral contributions increase in salt marshes where sediment is deposited and reworked via storms and tides (DeLaune *et al.*, 2013; Hatton, DeLaune, and Patrick, 1983; Nyman, DeLaune, and Patrick, 1990). Turner, Swenson, and Milan (2002) found organic matter accumulation, specifically belowground biomass, to be a greater factor in maintaining marsh elevation than inorganic accumulation in established salt marshes because of its

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larger contribution to soil volume. However, the right conditions are needed for organic matter to be preserved in the subsurface.

Factors such as salinity, hydroperiod, temperature, vegetation type, and redox potential influence organic matter deposition and decomposition, and thus preservation (Matzke and Eelsey-Quirk, 2018; Vaccare, Meselhe, and White, 2019; White *et al.*, 1978). Specifically, vegetation can become waterlogged during prolonged periods of inundation, resulting in reduced Eh potential and precipitation of metals and compounds such as nitrate, sulfate, iron, manganese, and acids. In salt marshes, high sulfide concentrations induced by inundation can be toxic to vegetation and increase decomposition rates (DeLaune and Pezeshki, 1994; Inglett, Reddy, and Corstanje, 2005; Pezeshki and DeLaune, 2012; Ponnampuruma, 1984). During storm events and cold fronts, salinity concentrations and coastal water levels increase as seawater encroaches landward, causing temporary inundation that can both benefit or harm marsh vegetation depending on the resiliency of each species to inundation and salinity (Hiatt *et al.*, 2019).

Vertical accretion in marshes is highly dependent on the inundation period (*i.e.* hydroperiod) to bring necessary sediments and nutrients for organic and inorganic accumulation and to flush toxic byproducts. Barataria Basin, located in SE Louisiana, has a microtidal regime (tide range < 1 m) and has been isolated from the fluvial influence of the Mississippi River since construction of flood-control levees; as a result, coastal sea-level fluctuations are primarily driven by low-frequency atmospheric and oceanic forcing associated with winter and tropical storms (Hiatt *et al.*, 2019; Maul and Hanson, 1991). In this region, winter storm (*i.e.* cold front) passages occur primarily between October and April, recur every 7–10 days, and typically increase water levels before the storm passage, followed by a rapid reduction in water level immediately after the storm's passage (fluctuations ~1 m; Chuang and Wiseman, 1983; Hiatt *et al.*, 2019; Li and Clarke, 2005). Several authors show that sedimentation in marshes is not a continuous process and that the passage of cold fronts can be a larger driver of sediment deposition—and thus vertical accretion—than regular tidal inundation (Cahoon and Turner, 1987; Georgiou, FitzGerald, and Stone, 2005; Reed, 1989; Roberts *et al.*, 2015).

The availability of sediment within the local waterbodies and the physical dynamics to deliver this sediment to the marshes are key factors. Previous studies have documented that tropical storms are another critical delivery mechanism of sediment to coastal Louisiana marshes (Cahoon *et al.*, 1995; Smith *et al.*, 2015; Turner *et al.*, 2006; Tweel and Turner, 2012, 2014). Over the last 15 years, 25 tropical cyclones or depressions have made landfall on or near the Louisiana coast, and the degree to which the coastal landscape is affected (erosion *vs.* accretion) is dependent on landscape topography, wetland type, soil shear strengths, and the duration/magnitude of wind stress and inundation (Morton and Barras, 2011). Storm surges induced by hurricanes and tropical cyclones can result in 1–5 m of water above mean water levels (Bianchette *et al.*, 2015; Guntenspergen *et al.*, 1995; McGee *et al.*, 2006), and because the Gulf of Mexico coast has a microtidal regime, even small-scale, sea-level

variations (± 10 cm) can cause drastic alterations to marsh systems, in particular hydroperiod and sediment delivery (Kearney and Turner, 2015).

Coastal sea-level variations in the Gulf of Mexico over longer-term (interannual-to-decadal) timescales are driven by atmospheric and oceanic forcing mechanisms spanning global and regional scales (Hiatt *et al.*, 2019; Woodworth *et al.*, 2019). Local alongshore wind stress has shown to be a valuable driver of interannual coastal sea-level anomalies north of Cape Hatteras to Nova Scotia (Andres, Gawarkiewicz, and Toole, 2013; Kenigson *et al.*, 2018). Coupling between the wind field in the region and the North Atlantic Oscillation has been proposed (Andres, Gawarkiewicz, and Toole, 2013), although the correlation is significant only going back to the late 1980s.

Additionally, previous studies have found a relationship between interannual Atlantic (Florida to Delaware) coastal sea-level variations to zonal transport variations into the western boundary region induced by Rossby wave interaction with the boundary current (Hong, Sturges, and Clarke, 2000). Rossby waves are generated by wind-stress curl anomalies and propagate westward at a month-to-year time scale depending on latitude (Chelton and Schlax, 1996). These Rossby wave/boundary current interactions induce accelerations in Gulf Stream transport and subsequent geostrophic adjustment changes the cross-shore, sea-surface slope between the boundary current and the Atlantic coast, which inherently causes sea-level variations (Hong, Sturges, and Clarke, 2000). Some of the water mass associated with Rossby wave propagation passes through the Gulf Stream and into boundary regions, increasing the sea level along the coast (Thompson and Mitchum, 2014). Meridional variations in Florida Current and Gulf Stream transport have implications for heat transport from the Gulf to subpolar regions and can lead to thermocline adjustment of sea level (Volkov *et al.*, 2019; Yin, 2023).

Although it is generally accepted that the deteriorating organogenic marshes of SE Louisiana are highly susceptible to RSLR, inundation from cold fronts, tropical storms, and/or longer-term sea-level anomalies (and the associated sediment supplied to them), the relationships remain poorly resolved. To fill these knowledge gaps, this study uses long-term (~100–120 years) VARs from ^{137}Cs and ^{210}Pb chronologies to quantify the first differential VARs over time in Louisiana marshes determined from the ^{210}Pb Constant Rate of Supply (CRS) model. This methodology was employed by Kolker *et al.* (2009) in salt marshes of a Long Island estuary (New York), where differential VARs in those low tidal range marshes were attributed to short-term (2–5 years), dynamically driven changes in sea level (from low atmospheric pressure and high wind field anomalies). This study investigates whether interannual-to-decadal sea-level fluctuations have an effect on VARs—and thus mineral and organic accumulation—in Barataria Basin, an intertributary basin in SE Louisiana. The study uses these efforts to investigate the relationship between mass accumulation (organic and inorganic) and interannual sea-level anomalies and the passage of major storms (*e.g.*, hurricanes) to gain a better understanding of the relative contributors to marsh elevation and sustainability in Mississippi Delta marshes.



Figure 1. Map displaying study area and location of Coastwide Reference Monitoring System (CRMS) core sites in relationship to the proposed Mid-Barataria Sediment Diversion. Blue arrow represents the location and flow direction of the diversion; yellow circles represent sites classified as brackish marsh and red circles represent sites classified as salt marsh; white star represents the location of the Grand Isle National Oceanic and Atmospheric Administration (NOAA) tide gauge.

METHODS

Barataria Basin is an interdistributary basin characterized by marshes and open water with salinity increasing seaward and a chain of barrier islands separating the bays of the lower basin from the Gulf of Mexico. It is estimated that 1100 km² of land has been lost in Barataria Basin since the 1930s (Couvillion *et al.*, 2017). The study area for this project is located within the basin, south of the proposed Mid-Barataria Sediment Diversion and bounded by Barataria Bay to the south, Little Lake to the west, and the Mississippi River to the east (Figure 1). The marshes of the study area are inundated 60%–75% of the time and are populated with brackish and salt marsh vegetation, including herbaceous plants such as *Spartina alterniflora* and *Spartina patens* (grasses), *Schoenoplectus americanus* (sedges), and *Juncus roemerianus* (rushes; Coastal Wetlands Planning, Protection and Restoration Act, 2023).

Barataria Basin is a remnant of the previously active St. Bernard (~3.5–1.7 kya), Lafourche (~1.7–0.5 kya), and Plaquemines-Balize (~1.4 kya–present) delta complexes (Chamberlain *et al.*, 2018; Hijma *et al.*, 2017; Törnqvist *et al.*, 1996). The basin is currently in the latter phases of deltaic transgression, characterized by landward migration of barrier islands and subsidence-driven wetland deterioration (Penland *et al.*, 1988; Roberts, 1997). The basin is no longer fluviually influenced by the Mississippi River since the addition of man-made levees in the early 20th century, although small quantities of river inputs occur through the Gulf Intracoastal Waterway, Davis Pond Freshwater Diversion, and two siphons (Naomi and West Pointe a la Hache; Connor and Day, 1987; Mariotti *et al.*, 2021). Barataria Basin experiences ~30 km² of land loss per year dominantly caused by a combination of RSLR (eustatic sea level plus subsidence; 2–12 mm/y) brought on by compaction of organic-rich Holocene strata and

marsh-edge erosion induced via wind-driven water fluctuations (Couvillion *et al.*, 2017; Jankowski, Törnqvist, and Fernandes, 2017; Morton, Bernier, and Kelso, 2009; Morton *et al.*, 2005; Sapkota and White, 2019; Törnqvist *et al.*, 2008; Valentine and Mariotti, 2019; Wilson and Allison, 2008).

Sea-Level Rise and Hurricane Data

Monthly sea-level data at Grand Isle, Louisiana, from 1947 (oldest available data) to 2020 were downloaded from the National Oceanic and Atmospheric Administration (NOAA, 2024b; see Figure 1 for location). A 5-month running average was applied to the monthly sea-level data along with removal of seasonal cycles and linear sea-level trends to better view interannual sea-level anomalies and variations. Hurricane data (years, categories, and paths) used in this study were also collected from NOAA (2024a). Major hurricanes (category 4 or greater) that made landfall in Louisiana and Mississippi over the last ~100 years were chosen for analysis.

Core Acquisition and Sampling

Twelve marsh cores were extracted to 1-m depth with a Russian peat-auger during fall 2020 from six Coastwide Reference Monitoring System (CRMS) sites in Barataria Basin near the proposed Mid-Barataria Sediment Diversion (Figure 1). At each site, cores were sampled into 2-cm depth increments, with one core sampled for bulk density, grain size, and organic content analyses and a duplicate core sampled for radiochemical analyses. The CRMS database integrates vegetation cover and composition to assign a marsh classification to each CRMS site; three sites are classified as brackish marsh and three as salt marsh (Figure 1).

Organic Matter Content

Organic matter content was determined using loss on ignition (LOI), a process that uses high temperatures (550°C) to remove organic matter from a sample and subsequently estimates organic content by subtracting sample weights before and after burning (Heiri, Lotter, and Lemcke, 2001). Equation (1) was used to calculate the percentage of organic matter (% OM) per sample:

$$\%OM = \frac{W_i - W}{W_i} \cdot 100 \quad (1)$$

where, W_i is the sample dry weight pre-LOI and W is the dry weight post-LOI in grams.

Bulk Density and Water Content

Bulk density was estimated via volume measurements that were taken using an open-ended syringe. The dry weight was recorded, and Equation (2) was used to estimate dry bulk density (ρ ; g/cm³):

$$\rho = \frac{\text{dry weight}}{\text{sample wet volume}} \quad (2)$$

Water content was expressed as a percentage and estimated using the following equation:

$$\%H_2O = \frac{W_i - W}{W_i} \cdot 100 \quad (3)$$

where, W_i is the wet weight and W is the dry weight in grams.

Granulometry

Because of the organic-rich and muddy nature of the sediment, deflocculation was performed by adding sodium hexametaphosphate (NaPO₃)₆ to the sample. Samples were then sieved to remove any large organic particles and subsequently centrifuged. Hydrogen peroxide was then added and placed in a hot bath for organic digestion, and grain size was determined using a Beckman-Coulter laser diffraction particle size analyzer that can measure grain sizes from 4 μm (clay) to ≤2 mm (sand).

²¹⁰Pb and ¹³⁷Cs Chronology

Gamma spectroscopy was used to estimate ²¹⁰Pb and ¹³⁷Cs inventories in all sediment cores. A Canberra SAGE (germanium) well gamma detector was used to measure the radionuclides of interest: ¹³⁷Cs and ²¹⁰Pb (photopeaks at 661.7 keV and 46.5 keV, respectively) and their necessary parent isotopes (²³⁴Th, 63 keV; ²¹⁴Pb, 295 keV; ²¹²Pb, 238.6 keV; and ²¹⁴Bi, 352 keV). Before analysis, once pulverized, the samples were sealed and left undisturbed for at least 3 weeks to allow short-lived radioisotopes to reach secular equilibrium with their parent isotopes (Bush, 1981). After secular equilibrium was reached, each sample was analyzed in the gamma detector for 24 hours. The ²¹⁰Pb CRS model assumes a constant ²¹⁰Pb atmospheric flux but allows for time-varying accretion rates and accounts for changes in initial specific activity (Appleby and Oldfield, 1978), making the model an ideal candidate for calculating sediment accumulation and accretion changes over time. This model has been employed in other marsh systems in the United States, but this is the first application to marshes in Louisiana and is briefly described here (Kolker, 2005; Kolker *et al.*, 2009). The ²¹⁰Pb_{xs} activity was determined by subtracting supported ²¹⁰Pb activities from the total ²¹⁰Pb activity. The ²¹⁰Pb excess inventory is calculated using the following equation:

$$I_0 = \sum (^{210}\text{Pb}_{\text{xs}i} \cdot \rho_i \cdot \ell_i) \quad (4)$$

where, ²¹⁰Pb_{xs}_{*i*} is the excess ²¹⁰Pb activity at depth *i*, ρ_i is the bulk density at depth *i*, and ℓ_i is the interval thickness (Kolker, 2005). The sum of ²¹⁰Pb inventory (I_0) is subtracted from an interval's activity, and all activity above it is used to calculate residual ²¹⁰Pb at depth (I_z). Time (*t*) in years can then be calculated using the following equation:

$$t = \frac{1}{\lambda} \ln \left(\frac{I_0}{I_z} \right) \quad (5)$$

where, λ equals 0.03114 y⁻¹ and represents the ²¹⁰Pb decay constant. Time is then subtracted from the collection year to determine the deposition year at each sample interval. The VAR (ω) is calculated for each interval using the following equation:

$$\omega = \frac{x_i - x_{i-1}}{t_i - t_{i-1}} \quad (6)$$

where, x_i is the interval depth, x_{i-1} is the interval depth above x_i , t_i is the age of the interval, and t_{i-1} is the age of the interval above x_i (Kolker *et al.*, 2009). The mass accumulation



Figure 2. Sediment core image of Coastwide Reference Monitoring System (CRMS) site 4690 from 15–30 cm displaying organic-rich mud with roots. A large *Spartina alterniflora* root can be seen in the bottom core.

rate (MAR) is calculated and can be further parsed into organic mass accumulation (OMA) and inorganic mass accumulation (IMA) with the following equations:

$$\begin{aligned} MAR &= \rho_i \cdot \omega_i \\ IMA &= \rho_i \cdot \omega_i \cdot (1 - LOI_i) \\ OMA &= \rho_i \cdot \omega_i \cdot LOI_i \end{aligned} \quad (7)$$

where, ρ_i is the bulk density at depth i , ω_i is the VAR at depth i , and LOI_i is the organic fraction at depth i .

For comparison and corroboration, a standard average VAR using ^{137}Cs was also obtained for each core by dividing the depth of peak ^{137}Cs activity (D_m) by the collection year (in this case, 2020) minus the year of maximum cesium fallout (1963; Corbett and Walsh, 2015; Ritchie, Hawks, and McHenry, 1975):

$$^{137}\text{Cs VAR} = \frac{D_m}{2020 - 1963} \quad (8)$$

The ^{137}Cs MAR was calculated by multiplying the ^{137}Cs VAR (cm/y) by the core averaged bulk density (g/cm^3).

RESULTS

All six sediment cores had similar characteristics and were abundant in organic matter. The lithology was consistently silt from the top to base of the cores, with root and rhizome abundances increasing with depth except for CRMS 225, which had the highest organic abundance from 48–78 cm. Roots and rhizomes were identified as a combination of *S. alterniflora*, *S. patens*, and *Schoenoplectus* sp. (Figure 2).

Geotechnical Properties

A total of 122 samples were analyzed for organic content, water content, bulk density, and grain size. Depth profiles of the soil properties can be found in Figures 3 and 4. The

LOI results indicate that the uppermost meter of the sub-surface in Barataria Basin is organic rich (average organic content > 30%). Organic content increased ~10%–20% beneath 50–60 cm depth in four (three brackish, one saline) of the six marsh cores (Figure 3). Average water content ranged from 77%–87% and increased by ~10%–20% with depth at three CRMS sites (224, 225, 237), whereas the other three sites remained relatively constant with depth. Bulk density ranged from 0.16 to 0.27 g/cm^3 and decreased slightly with depth (~0.1–0.2 g/cm^3), although a few punctuated increases are seen in CRMS cores 237 and 4690 (Figure 3). The median grain size (D_{50}) of the sediment ranged from fine to coarse silt (8–62 μm ; Figure 4), which is consistent with findings in surrounding brackish and saline marshes in Barataria Basin (Bomer *et al.*, 2019; DeLaune, Patrick, and Buresh, 1978; Hatton, DeLaune, and Patrick, 1983). The average grain size in brackish and saline sites was $23.97 \pm 13.58 \mu\text{m}$ and $27.96 \pm 11.78 \mu\text{m}$, respectively. No distinct vertical patterns were seen within the grain-size data; however, occasional brief transitions to very fine sand (63–125 μm) are seen in CRMS 224 and 225 (Figure 4).

^{210}Pb and ^{137}Cs Inventories and Profiles

Downcore profiles of $^{210}\text{Pb}_{\text{xs}}$ and ^{137}Cs activity can be seen in Figure 5. The $^{210}\text{Pb}_{\text{xs}}$ activities ranged from 0 to 21.49 dpm/g. On average, $^{210}\text{Pb}_{\text{xs}}$ inventories of the northern brackish sites were 59% higher than southern saline sites, commensurate with slightly finer grain-size data discussed previously. Although $^{210}\text{Pb}_{\text{xs}}$ profiles generally decayed with depth as expected, the decay pattern of the $^{210}\text{Pb}_{\text{xs}}$ profiles was highly variable rather than purely exponential (Figure 5). This is common in sediments with varying grain size and organic content (Kolker *et al.*, 2009). None of the profiles reached supported ^{210}Pb levels; however, most were less than 3–5 dpm/g from supported activities at the base of the cores.

The ^{137}Cs peaks ranged from 0.41 to 1.63 dpm/g. Similar to $^{210}\text{Pb}_{\text{xs}}$, ^{137}Cs inventories were 77.5% higher in brackish sites than saline sites. Similarly, ^{137}Cs peaks greater than 1 dpm/g are present only in the brackish sites, ^{137}Cs peaks in saline sites were less than 1 dpm/g, and only slightly defined peaks are seen in CRMS 224 and 3617.

VARs and Geochronology

The ^{210}Pb chronology via the CRS model indicates that the sedimentary record of the 1-m marsh cores extends to the late 19th and early 20th century. The CRS VARs calculated over time ranged from 0.12 to 8.04 cm/y (Figure 6). Over time, large variations in rates of vertical accretion are found, with several commensurate peaks at the same time in different cores (Figure 6), which supports the methodology and resultant ages. As sediment age became younger, all CRMS sites followed a pattern of gradual increases in VARs and one to three brief anomalous peaks indicative of punctuated sedimentation events. Among the six marsh cores, maximum VARs ranged from 2.7 to 8.04 cm/y. The quantity, magnitude, and timing of the peaks varies between sites, although four

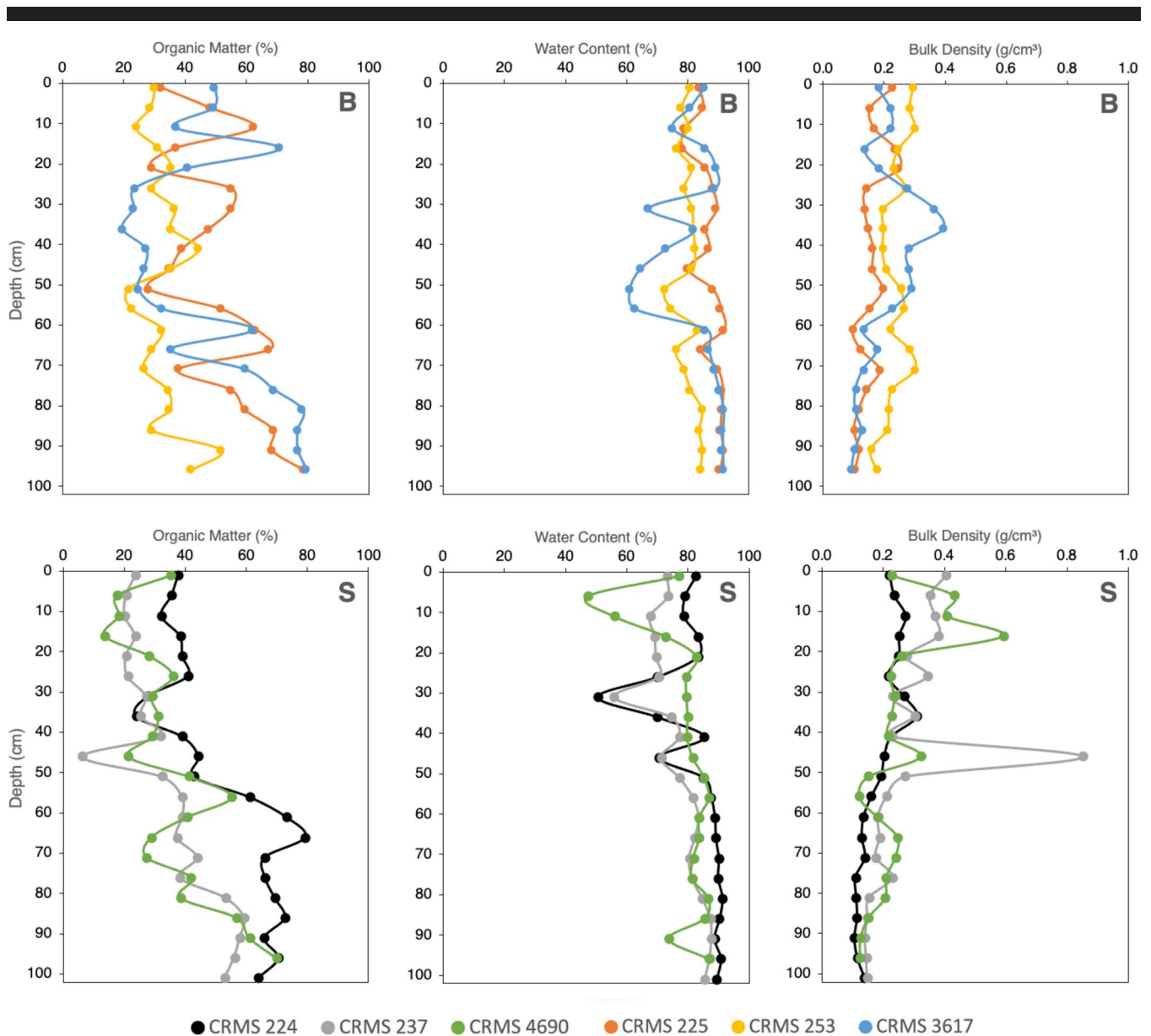


Figure 3. Variations of percentage of organic matter (left top and bottom), percentage of water content (center top and bottom), and bulk density (right top and bottom) with depth of all six Coastwide Reference Monitoring System (CRMS) sites. The top three figures represent the brackish sites (B), and the bottom three figures represent the saline sites (S).

distinct accretion events occurred in the early 1980s, mid-1990s, late 1990s/early 2000s, and early to mid-2010s.

For comparison, ^{137}Cs VARs (which provide one average rate per core) ranged from 0.63 to 0.98 cm/y (Table 1). The ^{137}Cs VARs are consistently lower than core-averaged CRS VARs from ^{210}Pb shown in Table 1, with the exception of CRMS 253, which is statistically very similar.

Mass Accumulation Rates

The CRS total MARs ranged from 0.01 to 1.86 $\text{g}/\text{cm}^2/\text{y}$ (Figure 6). The MARs followed a similar trend as accretion: a gradual increase with decreasing age with one to three peaks

over the century of data captured (Figure 6). These higher-than-average MAR peaks ranged from 0.3 to 1.86 $\text{g}/\text{cm}^2/\text{y}$. When MAR was parsed into organic and inorganic constituents (Figure 7), organic MARs ranged from 0.01 to 0.57 $\text{g}/\text{cm}^2/\text{y}$ and inorganic MARs ranged from 0.01 to 1.43 $\text{g}/\text{cm}^2/\text{y}$. Inorganic MARs are consistently greater than organic MARs except at CRMS 225 during the 1960s and early 1970s (Figure 7). Chronologically, peaks in MAR co-occur with vertical accretion peaks; however, when parsed into organic and inorganic constituents, occasional decoupling of organic mass accumulation and inorganic mass accumulation occurs when compared with total MARs. For example, during the mid-

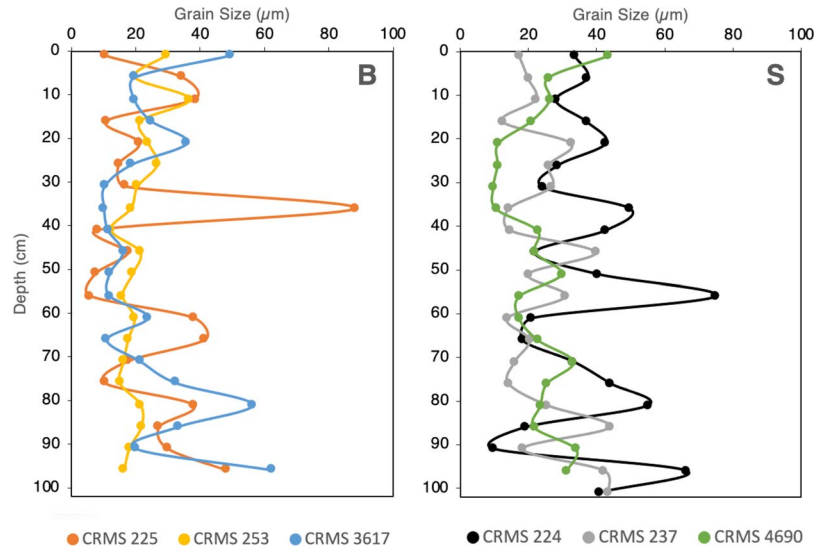


Figure 4. Median (D_{50}) grain size with depth of the six Coastwide Reference Monitoring System (CRMS) sites, showing silt as the predominant grain size. Left figure represents brackish sites (B); right figure represents saline sites (S).

1980s, inorganic mass accumulation and vertical accretion at CRMS 237 appear to have an inverse relationship with organic mass accumulation (Figures 6 and 7). The ^{137}Cs MAR ranged from 0.11 to 0.24 $\text{g}/\text{cm}^2/\text{y}$ and is consistently lower than the averaged CRS MAR (Table 1). Because CRS MAR varies through time, averaged values are larger than ^{137}Cs because of the presence of punctuated MAR peaks (Figure 6), which results in the CRS MAR appearing higher than it would be if peaks were removed from the average (Table 1).

DISCUSSION

Successfully applying the CRS radioisotope dating model to Louisiana marshes for the first time reveals that rates of vertical accretion, total mass accumulation, and organic and inorganic components of mass accumulation have markedly varied over the last ~ 100 years. This section (1) discusses temporal trends in MARs and soil volume dynamics in organic-rich Louisiana marshes, (2) discusses the complexity of hurricane-induced deposition and erosion and the way in which it is expressed in the stratigraphic record, and (3) assesses the linkage between interannual sea-level anomalies and rates of vertical accretion and mass accumulation.

Mass Accumulation in the Subsurface *vs.* Volume

Collectively, the results highlight the significance of inorganic material to mass accumulation in brackish and salt marshes in Barataria Basin (Figures 6 and 7). On average, inorganic matter composed 68% of mass accumulation and organic matter composed 32%. These results agree with previous investigations finding that inorganic mass accumulation can account for up to $\sim 74\%$ total mass accumulation in the upper 24 cm along coastal Louisiana (Sanks, Shaw, and Naitani, 2020). The core-averaged inorganic and organic mass accumulation in the Barataria Basin (excluding anomalously high accumulation peaks) ranged from 0.1 to 0.26 $\text{g}/\text{cm}^2/\text{y}$ and

0.05 to 0.09 $\text{g}/\text{cm}^2/\text{y}$, respectively, which is consistent with previous brackish and salt marsh studies along the Gulf Coast (Callaway, DeLaune, and Patrick, 1997; Shrull, 2018; Smith, Osterman, and Poore, 2013; Turner, Swenson, and Milan, 2002).

Similar to rates of vertical accretion, MARs increase through time, and inorganic MARs tended to increase more than organic MARs, particularly in the saline sites (Figure 7). Thus, even though Barataria Basin does not receive significant fluvial inputs, mineral matter is still the larger contributor to mass accumulation; however, visual observation of the sediment cores (Figure 2) suggests water and organic matter compose the majority of the subsurface volume, which is further supported by the data shown in Figure 3. By mass, $81\% \pm 8\%$ of the core composition is water that is contained in pore spaces between sediment grains and interstitial pore space within belowground biomass (*i.e.* plant material such as roots and rhizomes; Figure 3). The dry mass, comprising organic and inorganic matter, is only $\sim 19\%$ of the total mass. Organic plant growth is crucial to increasing soil volume in sediment-starved marshes because several aquatic species, *S. alterniflora* specifically (an abundant species within the study area), contain large rhizomes with plentiful aerenchyma that not only allow gas transport throughout the live plant but also create ample pore space volume (Gleason and Ziemann, 1981; Turner *et al.*, 2004). This allows these wetlands to maintain elevation until the plants die and the roots lose turgor pressure and dehydrate, resulting in soil volume decrease (Day *et al.*, 2011; Kaye and Barghoorn, 1964; Niering and Warren, 1980; Nyman, DeLaune, and Patrick, 1990; Turner, Swenson, and Milan, 2002).

These findings are supported by previous microtidal marsh studies that report 85% of marsh soil volume is pore space and marsh elevation maintenance is more reliant on organic material than mineral matter (Craft, Seneca, and Broome,

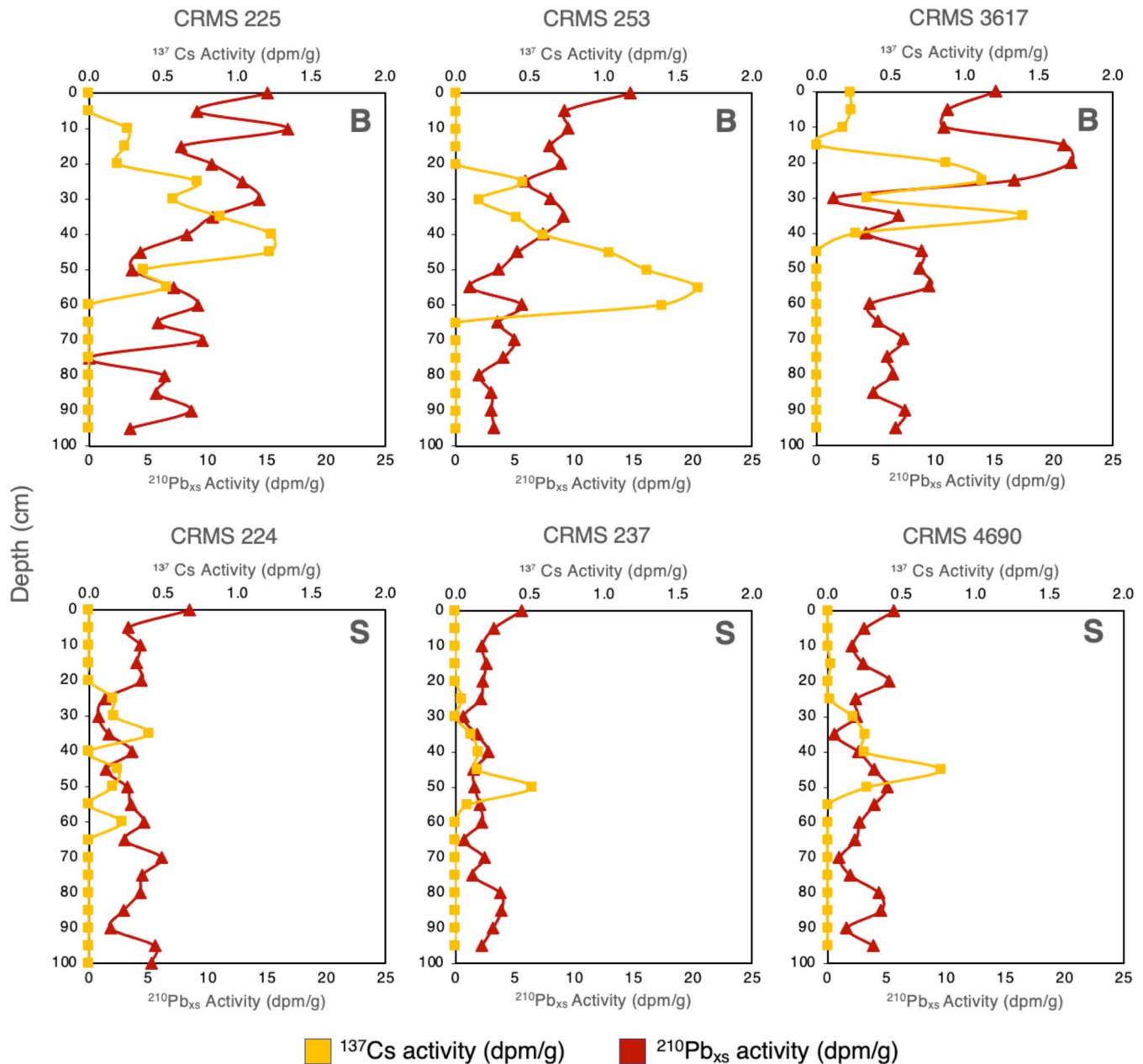


Figure 5. The ^{137}Cs and $^{210}\text{Pb}_{\text{xs}}$ activities with depth for brackish (B, top) vs. salt marsh (S, bottom) sites. Yellow represents ^{137}Cs activity; red represents $^{210}\text{Pb}_{\text{xs}}$ activity.

1993; Morris *et al.*, 2016; Nyman *et al.*, 1993). Here, organic content increases by $\sim 20\%$ – 50% with increasing depth at five sites (except CRMS 253), yet bulk density remains relatively constant. When visually observing the sediment cores, evidence of organic-rich soil and increased presence of plant roots was prevalent below ~ 50 – 60 cm depth in five of the six cores. Peat, defined as organic content $>75\%$, may form through a number of biological, chemical, and physical processes such as organic decay due to microbial activity, oxidation of labile organic material (leaving only recalcitrant

material remaining), and compaction due to sediment loading (Huat *et al.*, 2014; Kelsall *et al.*, 2023; Van Asselen, Stout-hamer, and Van Asch, 2009). Peaty or highly organic soils are most susceptible to compaction with depth because of high porosity and propensity to organic decay (Van Asselen, Stout-hamer, and Van Asch, 2009); however, if an organic-rich marsh is inundated regularly, uncompacted peat and organic rich soil will expand as it absorbs water, contributing to soil volume and elevation (Reyes and Chmura, 2022; Turner *et al.*, 2004).

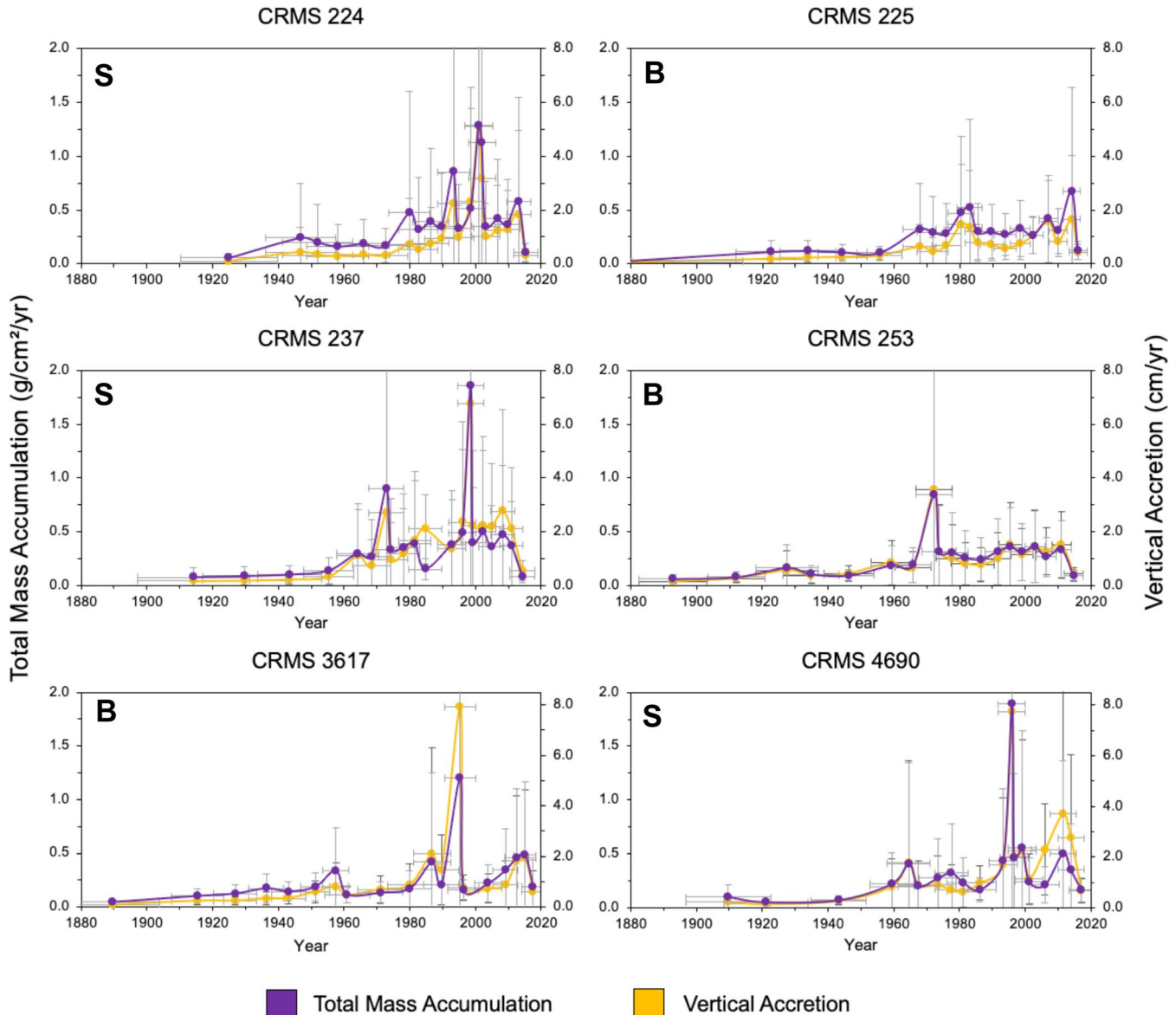


Figure 6. Total mass accumulation (purple) and vertical accretion (yellow) viewed through time using the ^{210}Pb Constant Rate of Supply dating model. Vertical and horizontal error bars are reported as standard error. Saline site graphs = S; brackish site graphs = B.

Historically, bulk density of mineral-rich marshes increases with depth in response to compaction (Turner, Milan, and Swenson, 2006). This statement is true for organic-rich marshes as well; however, organic-rich soils have a lower bulk density than mineral sediment. Therefore, when compacted, peat and organic-rich soil may have a similar bulk density as uncompacted mineral soil (Jepsen, Roberts, and Lick, 1997; Van Asselen, 2011; Van Asselen, Stouthamer, and Van Asch, 2009). Therefore, it is likely that bulk density remaining relatively constant with depth in this study is because of the similar densities of silt and compressed organic material and peat (Figure 3). Previous studies using computed tomography scans on belowground biomass in Atlantic coast marshes show that

the volume of roots and rhizomes can be considerable, particularly at shallow depths ($125\text{--}250\text{ cm}^3$ in the upper 10 cm; Miller, 2019; Wigand *et al.*, 2015). Thus, although mineral MARs are greater than organic MARs in the study area, accumulated live and dead below-ground biomass is the major contributor to the volume (and hence, elevation) of the marshes.

Hurricanes and Sediment Deposition and Erosion

A common trend seen among the CRMS marsh sites within this study is a contemporaneous increase in organic and inorganic MARs during punctuated vertical accretion events. Figure 7 shows many accumulation peaks co-occur (within CRS age error range) with major hurricanes (category 4 or greater) that have

Table 1. The ^{137}Cs and ^{210}Pb CRS VARs and MARs determined from activity with depth (Figure 5). Note that the CRS model VARs and MARs reported are core-averaged values, whereas the ^{137}Cs VARs and MARs are singular values based on peak Cs activity. The CRS VARs and MARs with “peaks excluded” indicate that accretion and accumulation peaks were excluded from the average. Error reported as standard deviation.

CRMS Site	CRS VAR cm y^{-1}	CRS VAR (peaks excluded) cm y^{-1}	^{137}Cs VAR cm y^{-1}	CRS MAR $\text{g/cm}^2/\text{y}$	CRS MAR (peaks excluded) $\text{g/cm}^2/\text{y}$
224	1.69 ± 1.29	1.22 ± 0.58	$0.63 \pm 0.02^\dagger$	0.3 ± 0.31	0.22 ± 0.17
225	1.13 ± 0.65	0.92 ± 0.45	0.72 ± 0.02	0.18 ± 0.12	0.13 ± 0.09
237	1.61 ± 1.57	1.18 ± 0.59	0.89 ± 0.02	0.43 ± 0.37	0.36 ± 0.22
253	1.04 ± 0.7	0.91 ± 0.42	0.98 ± 0.02	0.25 ± 0.19	0.22 ± 0.11
3617	1.17 ± 1.09	0.95 ± 0.55	$0.63 \pm 0.02^\dagger$	0.28 ± 0.41	0.2 ± 0.14
4690	1.54 ± 1.69	1.18 ± 0.63	0.81 ± 0.02	0.39 ± 0.41	0.28 ± 0.19

CRS = Constant Rate of Supply; MARs = mass accumulation rates; VARs = vertical accretion rates

† Only a slightly defined Cs peak.

made landfall in Louisiana or Mississippi. The findings of this study indicate that, on average, vertical accretion was nearly four times greater during years of hurricane events than years without hurricane events (Figure 7). Further, inorganic and organic MARs were 4.9 and 4.1 times higher, respectively, during years with hurricane landfalls (category 4 or higher; Figure 7). Inorganic sediment is likely sourced from wave resuspension in local bays during the storm event, but inorganic and organic material could be sourced from lateral erosion of marsh edges (a phenomenon referred to as marsh cannibalization; Elsey-Quirk *et al.*, 2019b; Mariotti *et al.*, 2021; Wilson and Allison, 2008). In addition, no distinct changes in grain size during sedimentation (storm) events were observed, further indicating that sediment deposition via storms is likely sourced locally within Barataria Basin or surrounding areas.

Hurricane-induced mineral mass accumulation is found to be highly variable, ranging from 0.21 g/cm^2 to 1.43 g/cm^2 , which supports previous findings from hurricane sedimentation within wetlands of the Mississippi River delta plain (Smith *et al.*, 2015). Although previous studies noted vegetation death and land loss of fresh to saline marshes after storm events in Louisiana, the results from this study suggest storm events contribute to sediment accumulation rather than reducing it in several instances (Guntenspergen *et al.*, 1995; Tweel and Turner, 2012). The concurrent increase in organic mass accumulation during or immediately following storm events may be caused by vegetation uplift and deposition from adjacent marshes, increased productivity following nutrient-rich sedimentation, or a combination of these factors (Chabreck and Palmisano, 1973; McKee and Cherry, 2009; Nyman, Crozier, and DeLaune, 1995). For instance, marsh vegetation along marsh edges is often uprooted during hurricanes and subsequently deposited at nearby marsh or pond locations (Chabreck and Palmisano, 1973). Alternatively, if marsh vegetation remains intact during storm events, it may deteriorate because of burial by excessive sediment deposition, vegetative wrack, or salt burn from saline water transported inland from the Gulf of Mexico during storm surges, resulting in a decrease in organic accumulation (Guntenspergen *et al.*, 1995).

Hurricane deposition and erosion can be spatially variable in Louisiana (Tweel and Turner, 2012, 2014). Within this study, even though the coring sites were within ~ 10 miles of one another, the timing of sedimentation events varied among the sites. For example, CRMS 224, 237, 3617, and 4690 exhibit the highest VARs throughout the ~ 100 -year

record in the mid- to late 1990s; however, an increase in vertical accretion is not seen during this time at CRMS 225 and 253. Additionally, hurricane intensity did not fully explain temporal variations in VARs. For example, the sedimentation peak seen in the mid- to late 1990s coincides with Hurricanes Andrew and Lili, which made landfall as categories 4 and 3, respectively. On the other hand, Hurricane Katrina, which made landfall as a category 5 in 2005, is not reflected in the sedimentation record at any of the CRMS sites within this study.

Hurricane Katrina is the only category 5 hurricane that made landfall within ~ 100 miles of Barataria Basin since the 1960s, and the study sites are located on the western side of the storm track. Therefore, it is possible that the hurricane's proximity to the study area, intensity, and trackline orientation resulted in erosion rather than sediment deposition in the study area. However, evidence of erosion was not seen in the ^{210}Pb chronologies, indicating either erosion did not occur, or more likely, sediment of similar age was uplifted and transported from a nearby marsh edge or bay bottom and deposited in the study area during Hurricane Katrina (Wilson, Perillo, and Hughes, 2021). Five category 4 or 5 hurricanes have made landfall within 100 miles of Barataria Basin before 1970 (*i.e.* Hurricanes Betsy, Camille, and three unnamed, with three occurring west of the study site and two occurring east of the study site). Figure 7 shows that sedimentation peaks were not always present for these five major hurricanes before 1970. For CRMS sites 224, 225, and 3617, which had no peaks in sedimentation before the 1970s, it is likely these events were not preserved in the sediment record.

Sea-Level Anomalies

The sea-level anomaly record since 1947 can be characterized by a period of an anomalously low sea level (-5 cm) from the early 1950s to the late 1960s, followed by a period of an anomalously high sea level ($+5 \text{ cm}$) from the 1970s to late 1990s, another low stand from the late 1990s to mid-2010s (-5 to -7 cm), after which it steadily increased to present-day conditions around $+4 \text{ cm}$ (Figure 8). These decadal changes in sea-level anomalies are induced by atmospheric and climatic changes sourced both locally and globally. Locally and seasonally, cold fronts can cause the sea level to fluctuate up to $\sim 1 \text{ m}$ because of local wind stress, atmospheric pressure changes, and approximately 30–50 cold fronts pass each year (Hiatt *et al.*, 2019; Roberts *et al.*, 2015).

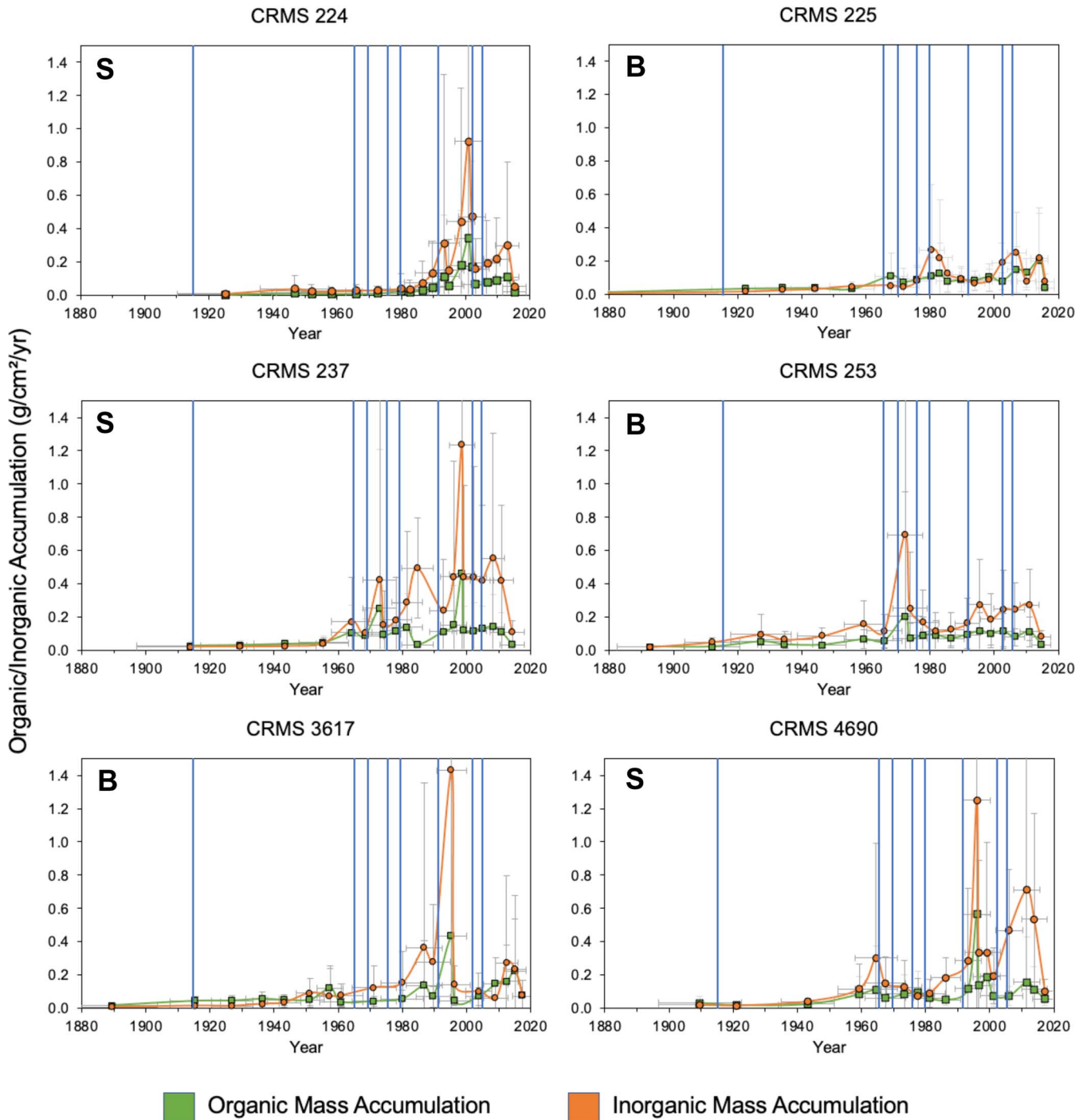


Figure 7. Organic and inorganic mass accumulation over the last ~100 years. Blue lines represent years of major hurricanes (category 4 or greater) that made landfall in Louisiana or Mississippi. Saline site graphs = S; brackish site graphs = B.

Previous studies have documented increases in sedimentation and plant productivity due to increased inundation via cold fronts; however, the MARs and VARs analyzed here (1–2 year resolution over ~100 years; Figure 8) are not high enough to detect the seasonal sediment fluctuations brought

on by cold fronts and thus are not considered further here (Perez *et al.*, 2000; Roberts *et al.*, 2015). On a regional scale, heat and mass transport into and from the Gulf of Mexico are induced by water temperature and density changes occurring in the Atlantic Ocean (Muller-Karger *et al.*, 2015). Figure 8

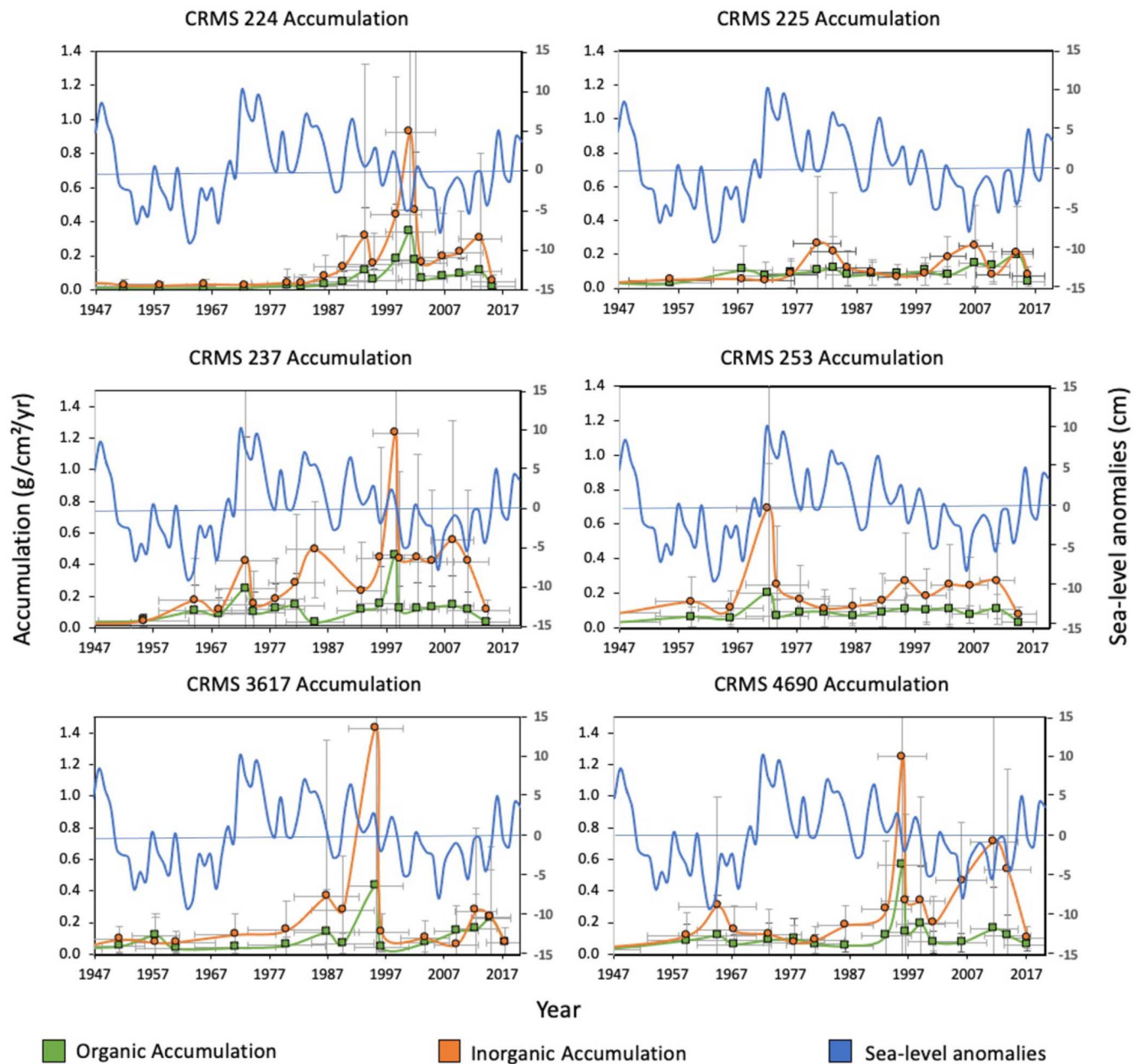


Figure 8. Graphs displaying organic and inorganic mass accumulation of the six Coastwide Reference Monitoring System (CRMS) sites in relation to the sea-level anomaly record since 1947.

indicates no relationship between sea-level anomalies and organic and inorganic mass accumulation ($r^2 < 0.1$). Therefore, these results support the notion that over the past 100 years, marshes within the study area have been able to maintain their elevation via sediment delivery and organic matter accumulation through processes other than decadal timescale sea-level fluctuations.

It is possible that interannual variations in sea-level influence elevation changes along coastal Louisiana; however, if so, the magnitude of elevation change was not great enough

to be quantified in the longitudinal mass accumulation or vertical accretion record collected in this study. Many studies have shown the significance of hurricanes and seasonal cold fronts to sediment delivery in Louisiana marshes (Bevington *et al.*, 2017; Hiatt *et al.*, 2019; Nyman, Crozier, and DeLaune, 1995; Payandeh *et al.*, 2019; Perez *et al.*, 2000; Smith *et al.*, 2015; Turner *et al.*, 2006)—supported by this study (Figure 7); it is likely these events are the main contributors to sediment delivery in the study area rather than sea-level anomalies.

Implications for the Mid-Barataria Sediment Diversion

Results from this study provide unforeseen insight to how brackish and salt marshes may respond to the Mid-Barataria Sediment Diversion, which is at present in the construction phase (Figure 1). A previous study in the basin by Bomer *et al.* (2019) found that subsidence will likely occur upon initial opening of the sediment diversion because of the highly compressible, organic-rich nature of the top 1–2 m of the marsh soil profile. The overburden pressure caused by the weight of water and sediment delivered by the diversion will cause belowground pore spaces to dewater and compress and fine-grain sediments to compact; however, those authors also found layers of low compressible deltaic sands and silts (~2–3 m deep) that reside beneath the 1–2 m thick organic-rich layers (Bomer *et al.*, 2019). Therefore, initial subsidence is likely; however, over time the organic-rich sediment will consolidate and decay and eventually attain maximum compaction that will decrease longer-term subsidence rates. In terms of initial diversion operation, Peyronnin *et al.* (2017) suggest a gradual increase in operation over the course of 5 to 10 years to allow distributary formation and to minimize flood risk with prime operation occurring during winter peaks to maximize sediment capture.

A previous mesocosm study found vegetation nutrient uptake decreased significantly with increasing salinities, suggesting salt marsh vegetation may not receive as many benefits from the diversion if the flow rate is not sufficient to reach marshes farther away from the diversion (Merino, Huval, and Nyman, 2010). On the other hand, if the diversion flow rate is too great, prolonged flooding will limit plant growth and productivity (Elsey-Quirk *et al.*, 2019a). According to the sea-level anomaly results from this study, the brackish and salt marshes within the study area have been able to withstand at least ± 10 cm of water-level fluctuations over the past 70 years (Figure 8). The duration of these sea-level anomalies warrants further investigation, particularly at each CRMS data site; however, it appears that at least over the time period analyzed here, these marshes have been able to maintain elevation with respect to local RSLR (0.92 ± 0.04 cm/y at the Grand Isle tide gauge) and interannual fluctuations in sea level. These results provide useful insight related to the amount of inundation that brackish and salt marshes may tolerate and are considerations for operation of the Mid-Barataria Sediment Diversion once constructed.

CONCLUSION

The goal of this project was to determine whether a relationship exists between organic or inorganic mass accumulation and sea-level anomalies in Louisiana marshes *vs.* major storm events. Findings from this study indicate no relationship exists between long-term total mass accumulation or vertical accretion and sea-level anomalies since 1947. Rather, major hurricanes (category 4 or greater) appear to be more significant contributors to both organic and inorganic mass accumulation and vertical accretion within brackish and salt marshes in Barataria Basin. No obvious grain size or lithology signatures were found in

storm event layers of the cores, suggesting hurricane deposition is likely sourced locally within Barataria Basin. Mineral matter comprised an average 68% of accumulated materials by mass; however, organic material was abundant in the sediment cores and $81 \pm 8\%$ of the cores were water and pore space (by mass), emphasizing the value of organic material (which houses extensive volumes of pore space and aerenchyma) in contributing to the elevation maintenance in these marshes. With respect to the outcome of the Mid-Barataria Sediment Diversion, introducing the freshwater and sediment slowly and moderately (≤ 10 cm above mean water levels upon opening, duration to be seasonally limited) into Barataria Basin may be one option to slow subsidence rates and prevent vegetation death due to extended inundation periods.

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