



Centennial Changes of Salt Marsh Area in Coastal Georgia (USA) Related to Large-Scale Sediment Dynamics by River, Waves, and Tides

G. Mariotti^{1,2} · G. Ceccherini³ · C. R. Alexander^{4,5} · A. C. Spivak⁵

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Abstract

Marsh lateral expansion and retreat are often attributed to sediment availability, but a causal link is difficult to establish. To shed light on this problem, we analyzed changes in salt marsh area along the ~200-km-long Georgia coast (USA) from the 1850s to 2010s in relation to total suspended sediment (TSS) and to proxies for river sediment input and local sediment resuspension. Marsh area is characterized by large gains and losses (up to 200 m²/m/yr), but relatively small net change (-50 to 50 m²/m/yr or -0.1 to 0.1%/yr). This has resulted in a general loss of marsh area, except close to the mouths of major rivers, where there is net gain. Net expansion rates decreased in the Savannah Estuary but increased in the Altamaha Estuary from the 1850s–1930s period to the 1930s–2010s period, which are consistent with observed decreases and likely increases in sediment discharge in the two estuaries, respectively. To explain the spatial patterns in the 1930s–2010s marsh area change, we estimated TSS from satellite measurements (2003 to 2020). Along the northern part of the Georgia coast, net marsh gain is positively correlated to the average TSS within the estuarine region. However, this correlation breaks down in more southern areas (Cumberland Sound). Coast-wide, there is a better correlation between TSS associated with new input from the rivers, estimated as the TSS difference between high-discharge (Jan–Mar) and low-discharge (Sept–Nov) months. To identify the effect of wave resuspension in the nearshore, we consider the TSS difference between high-wave, low-discharge (Sept–Nov) and low-wave, low-discharge periods (Jun–Aug). Wave resuspension is relatively uniform along the coast and does not explain spatial patterns of marsh area change. Sediment input from the nearshore is likely contributing to the estuarine sediment budget in Georgia, but it is not sufficient to prevent marsh lateral retreat. To identify the role of tidal resuspension and advection, we consider differences in TSS between low and high tide. This differential is relatively constant along most of the coast, but it is much lower in the southern part of the coast, suggesting a lower tidal action in this region. Sediment resuspended by tides is likely originating from internal recycling (i.e., erosion) within the estuary, and thus does not contribute to marsh lateral expansion. The proposed approach to partition TSS is a general demonstration and could be applied to other coastal regions.

Keywords Marsh loss and gain · Sediment dynamics · Remote sensing · River discharge · Wave

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✉ G. Mariotti
gmariotti@lsu.edu

¹ College of the Coast and Environment, Louisiana State University, Baton Rouge, LA, USA

² Center for Computation and Technology, Louisiana State University, Baton Rouge, LA, USA

³ Joint Research Centre, Bioeconomy Unit, European Commission, Ispra, Italy

⁴ Skidaway Institute of Oceanography, University of Georgia, Savannah, GA, USA

⁵ Department of Marine Sciences, University of Georgia, Athens, GA, USA

Introduction

Sediment supply is a key driver for the morphodynamic evolution of coastal marshes over long timescales (> 50 years). For example, a study of marsh area change at different locations along the UK Coast found that sediment supply explains long-term and large-scale patterns in salt marsh lateral expansion and retreat (Ladd et al. 2019). Along the same lines, a worldwide analysis found that suspended sediment and tidal range explain 70% of marsh vertical accretion rates (Coleman et al. 2022).

Marsh evolution models predict that sediment input is needed to sustain coastal marshes (Kirwan and Guntenspergen 2010; Mariotti and Canestrelli 2017;

Fagherazzi et al. 2020; Mariotti 2020). The source of this sediment could be diverse, thus complicating the relationship between sediment dynamics and marsh morphodynamics. New sediment is generally supplied from rivers, hence explaining why river deltas are often filled with extensive marshes and why these marshes retreat when the river sediment supply decreases (Blum and Roberts 2009). Sediment can also be supplied from the continental shelf, which can be considered new input for the marsh system (Castagno et al. 2018). A clear example of this scenario is found in the Yangtze Delta, where sediment reworking on the delta-front by tidal currents and ocean waves has been sustaining the deltaic marshes since the river was extensively dammed in the 1980s (Yang et al. 2020, 2021).

Sediment can also be recycled within the marsh system through erosion of marsh edges, marsh channels, and adjacent mudflats. This released sediment contributes to marsh vertical accretion, but does so at the expense of marsh lateral retreat (Mariotti and Carr 2014; Hopkinson et al. 2018; Luk et al. 2021). A marsh could thus experience high TSS (total suspended sediment) and vertical accretion, yet lose area by lateral retreat (Mariotti and Fagherazzi 2010; Tambroni and Seminara 2012; Mariotti 2020). This indicates that TSS is not always a good indicator for whether marshes will retreat or expand laterally (Ganju et al. 2015, 2017). Sediment budgets are needed to resolve this uncertainty and have been successfully used as an indicator for marsh evolution (Ganju et al. 2015). Unfortunately, sediment budgets require direct measurements of sediment fluxes that are difficult to quantify accurately and thus are only available at few sites.

Remote sensing products offer tools to measure TSS over broad spatial scales. This has been done in a variety of ways, such as estimating river sediment discharge (Espinoza Villar et al. 2012; Evan N. Dethier et al. 2022), and spatio-temporal distribution of TSS in coastal (Miller and McKee 2004), deltaic (Park and Latrubesse 2014), and estuarine water (Balasubramanian et al. 2020; Mariotti et al. 2021). Although remotely sensed TSS cannot be used to develop complete sediment budgets in coastal areas, it can be combined with hydrographic data to gain insight about sediment transport processes. For this purpose, we developed a simple method to separate TSS measurements from satellite into proxies for river input, wave resuspension, and tidal resuspension. We hypothesize that these proxies might better explain spatial patterns of marsh changes than simple TSS measurements.

We applied this method to the coast of Georgia, which has extensive marsh area that receives different amounts of sediment inputs from rivers (Dame et al. 2000), making it well suited for a comparative study. Long-term marsh area changes in coastal Georgia have been previously quantified (Burns et al. 2020, 2021), but at a relatively small scale (i.e., 5–10 km). In order to identify regional drivers of marsh area change, we considered the whole coastal zone of Georgia

(~200 km) for a period of 160 years. We then compared the changes in marsh areas to the TSS proxies associated with riverine input, tidal resuspension, and wave resuspension.

Methods

Settings of Coastal Georgia

The Georgia coast is tide-dominated, with a mesotidal spring tide range of 3 m (Blanton et al. 2004) (Fig. 1). The region is characterized by a low-gradient, shallow shelf, short and wide Holocene and Pleistocene barrier islands, closely-spaced inlets, and large ebb-tidal deltas (Hayes 1994). These inlets are deeply scoured into older geologic units by swift, ebb-tidal currents (Blanton et al. 1999; Defne et al. 2011).

Fluvial sediment supply to the Georgia coast is dominated by two rivers which have their headwaters in the upland Piedmont, the Savannah and the Altamaha, which discharge along the northern and central coasts, respectively (Meade 1969). Several smaller rivers that have headwaters in the coastal plain also enter the ocean along the Georgia coast: the Ogeechee, Satilla, and St. Mary's.

Historical supply of sediment to the coast was enhanced by early farming practices and land clearing in the eighteenth and nineteenth centuries, leading to the release of great amounts of sediment that aggraded river channels (Trimble 1975; Trimble and Goudie 2008). Recent estimates that represent conditions after dam building on the Savannah in the 1950s document that the Savannah River supplies 0.201 MT/y of suspended sediment to the coast, whereas the Altamaha supplies 0.414 MT/y (Windom and Palmer 2022). The coastal plain rivers deliver an order of magnitude less: the Ogeechee delivers 0.041 MT/y, the Satilla delivers 0.047 MT/y, and the St. Mary's provides less than 3% of the suspended sediment delivered to the coastal ocean in Georgia. In the past 20 years, however, sediment supply from these rivers has declined by about 30% because of climate-change induced decreases in river flow (Weston 2013).

River discharge to the Georgia coast is relatively high during the winter, whereas waves and winds are higher during both fall and winter (Fig. 2) (Oertel and Dunstan 1981; Di Iorio and Castelao 2013). Suspended sediment discharged to the coast is largely constrained within ~10 km of shore by the coastal boundary zone, which restricts cross-shelf transport of suspended sediment, and brings suspended materials southward (Blanton et al. 1999). Less than 10% of this material escapes to the continental shelf (Windom and Gross 1989). Material within this zone, which is swept into the backbarrier system with every flood tide, is the major source of sediment that enables the extensive salt marshes of Georgia to accrete (Alexander et al. 2017; Windom and Palmer 2022). Several studies have documented that import of suspended sediment from the coastal ocean, as opposed to delivery from upland

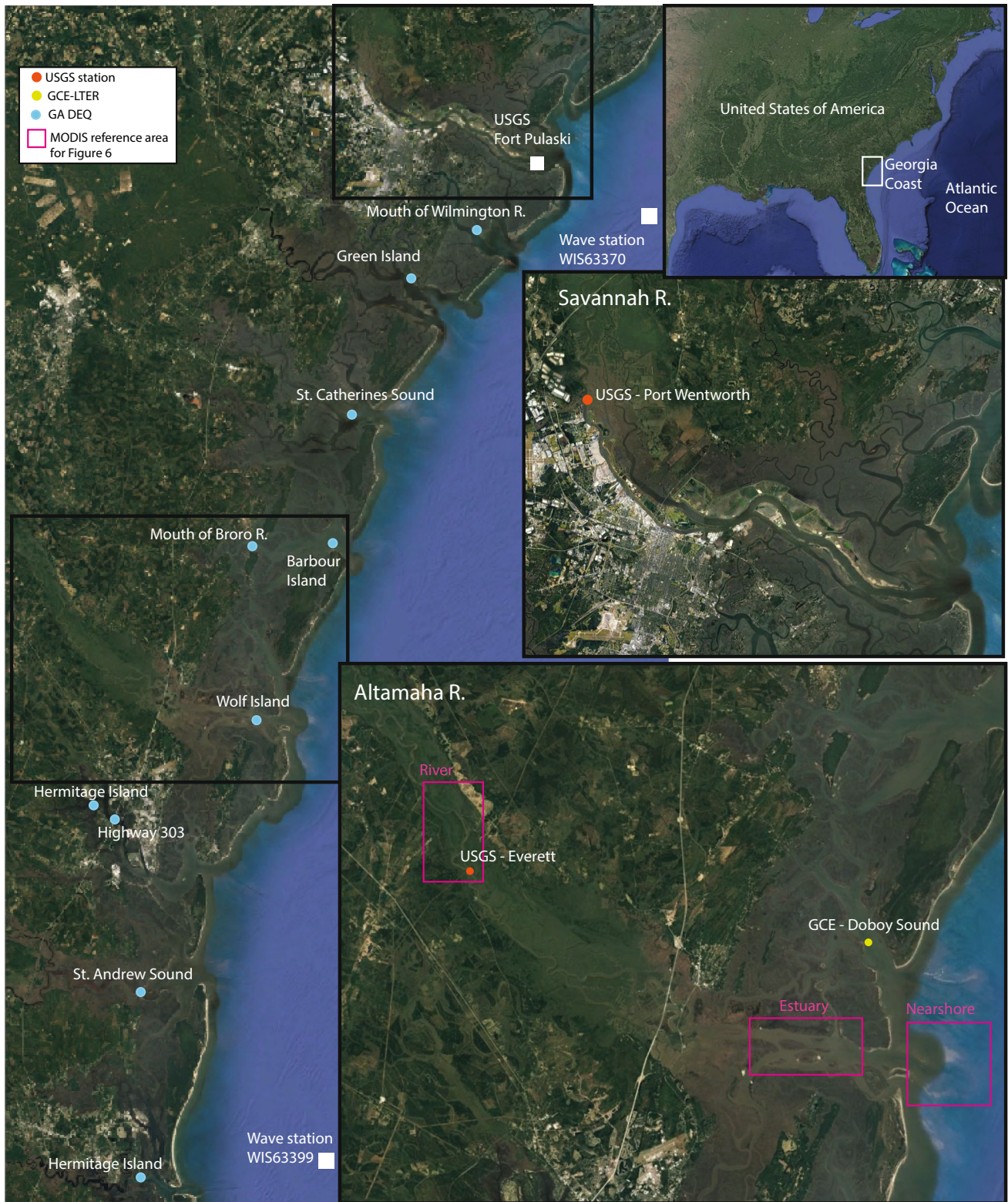
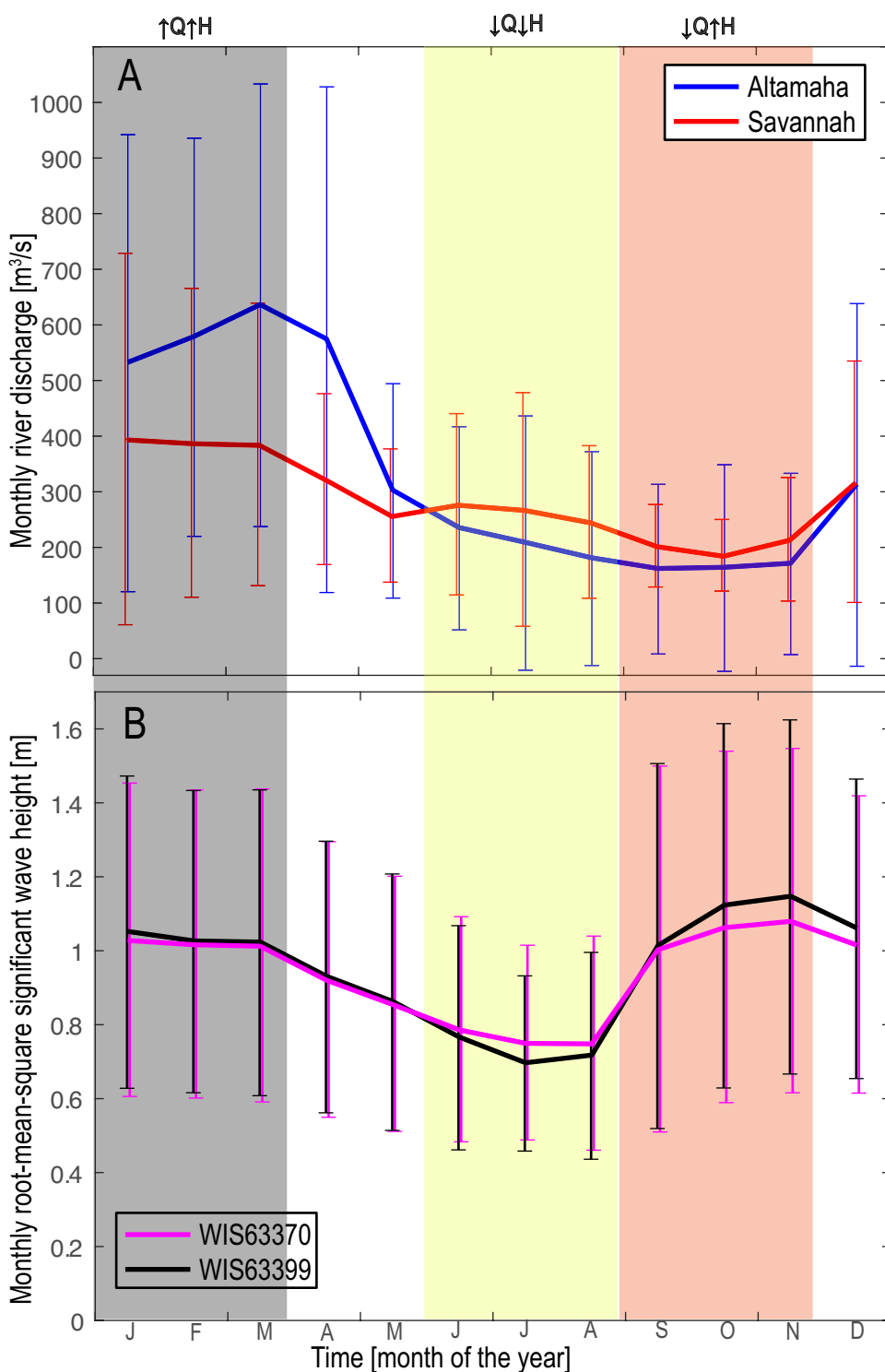


Fig. 1 Map of Coastal Georgia, showing the field sampling stations (Landsat/Copernicus, downloaded from GoogleEarth on December 2022). The insets show the details of the Savannah and Altamaha rivers. For specific descriptions of the stations, see text

Fig. 2 Monthly variability in river discharge and wave height in the Georgia coast. **A** Monthly river discharge “Q” (mean and standard deviation for the period from 2003 to 2020), for USGS station Altamaha River at Everett and Savannah River near Clio. **B** Monthly root-mean-square significant wave height “H” (mean and standard deviation for the period from 2001 to 2020), for two Wave Information Study stations located on the northern and southern ends of the Georgia coast (see Fig. 1)



sources, is the major source of material to the estuaries and marshes (Windom et al. 1971; Mulholland and Olsen 1992; Blanton et al. 1999).

Suspended sediment concentrations (TSS) within the coastal frontal zone range from 5 to 10 mg/L (Oertel and Dunstan 1981). TSS within the shallow Georgia estuaries vary greatly,

from 10 to 1000 mg/l (Oertel 1974; Oertel and Dunstan 1981), with resuspension most pronounced in the first 2 h after high slack tide, when dominant ebb-directed currents achieve velocities up to 1 m/s that resuspend bottom sediments (Blanton et al. 1999). Sediment in suspension is dominated by mud (i.e., material smaller than 64 μm) (Oertel 1974; Blanton et al. 1999).

Georgia's salt marshes are dominated by *Spartina alterniflora* grasses growing in organic-poor soils (Higinbotham et al. 2004; Loomis and Craft 2010). Riverine sediments are deposited along creekbanks, creating levees. Tall-form *Spartina* is abundant along creekbank levee edges with medium-form behind the levees and short-form in the higher-elevation marsh interior (Alexander et al. 2017). Infrequently flooded and higher elevation areas host *Juncus roemerianus* and, less commonly, *Distichlis spicata* (Higinbotham et al. 2004; Hladik and Alber 2014). Fiddler crabs and other burrowing invertebrates are common and marshes can be heavily bioturbated (Teal 1958).

Mapping Marsh Changes

We considered marsh area at three points in time: 1850s (first dataset available), 1930s (intermediate between our youngest and oldest dataset), and 2010s (last dataset available) (Fig. 3). These large time intervals reduce the signal to noise ratio by providing a longer time period over which to smooth out the effect of episodic events (Crowell et al. 1991; Jackson et al. 2012).

For the 1850s and 1930s, we used the T-sheets maps digitized by National Oceanic and Atmospheric Administration National Geodetic Survey (<https://shoreline.noaa.gov/data/datasheets/t-sheets.html>). For the 2010s, we used the national wetland inventory from the US Fish and Wildlife Service (<https://www.fws.gov/program/national-wetlands-inventory/wetlands-mapper>). All maps were resampled at a 10×10 m resolution for consistency. The domain ranges from the southern border of Georgia (30.7°N), located in the St. Mary's River, and just north of the northern border of Georgia (32.1°N), located in the estuary of the Savannah River.

In order to estimate the error associated with the marsh area change, we calculated the average number of shoreline cells (including both sides of each channel and any marsh facing a mudflat) at any given shore-perpendicular transect and found it equal to 40 ± 20 . Assuming that the shorelines have an error of 10 m, this gives an error of about 400 m²/m. Given that the marsh area changes have an interval of 80 years, this means that the marsh area change error is about 5 m²/m/yr.

TSS Measurements and Analysis

We used MODIS satellite imagery (250 m resolution), analyzed through Google Earth Engine (GEE). Land was masked using a threshold over the normalized difference vegetation index and buffered by one cell to remove those that included partial land and partial water. MODIS images have been successfully used to estimate TSS in estuarine and coastal waters (Miller and McKee 2004; Espinoza Villar et al. 2012; Iles et al. 2020; Mariotti et al. 2021). Here, we

used a previously proposed formula (Mariotti et al. 2021), which predicts TSS [mg/l] based on the surface reflectance red band (620–670 nm) S :

$$TSS = \max [0, 13 \exp(2.9S) - 15] \quad (1)$$

The equation was calibrated for the river dominated environment of the Mississippi Delta (Mariotti et al. 2021). Because of the high turbidity of the water, we did not include any correction due to reflection from the bed.

We validated this relationship (Eq. 1) against TSS measured at thirteen locations in coastal Georgia (Figs. 1, S1). Ten stations were from the Georgia Environmental Monitoring and Assessment System (Wolf Island, Hermitage Island, Cumberland Sound, Green Island, Mouth of Wilmington River, Mouth of Broro River, Barbour Island, St. Catherines Sound, Turtle River and St. Andrews Sound). Two stations were from the USGS: the Altamaha River (USGS 02226160 Everett City) and the Savannah River (USGS 02198920 Port Wentworth). One station was sampled as part of the Georgia Coastal Ecosystems LTER, in Doboy Sound (GCE-LTER-DB03). Each station has between 50 and 200 samples, which were collected between 2003 and 2020. All samples were collected near the water surface.

Because only 2–8 MODIS images are available every month, depending on cloud cover, only a few % of the images and field samples were collected within 1 h of each other. Thus, in addition to the standard one-to-one comparison between field and satellite TSS, we used a time aggregation by calculating the median monthly values for both the satellite images (2–8 images per month) and field samples (usually ~1 sample per month), as well as the whole-time-series median at each station for both the satellite images and field samples.

TSS Associated with Riverine Input and Swell Wave Resuspension

Data were aggregated into three seasons differentiated by river discharge and wave regime. The river discharge categories were based on stations upstream of the tidal limit in the Altamaha (at Everett, ~30 km upstream of the mouth) and Savannah Rivers (at Clyo, ~50 km upstream of the mouth; Fig. 1). At both stations, discharge is higher from December to April than from May to November (Fig. 2). Wave regime was categorized based on significant wave height from 1980 to 2020 for two stations of the US Army Corps of Engineers Wave Information Studies (Fig. 1). In order to give more importance to larger waves, we calculated the monthly root-mean-square wave height. At both stations, the waves are higher (~1.1 m) from September to March than from April to August (~0.7 m). From these patterns, we identified a high-discharge and high-wave season (January to March), low-discharge and low-wave season (June

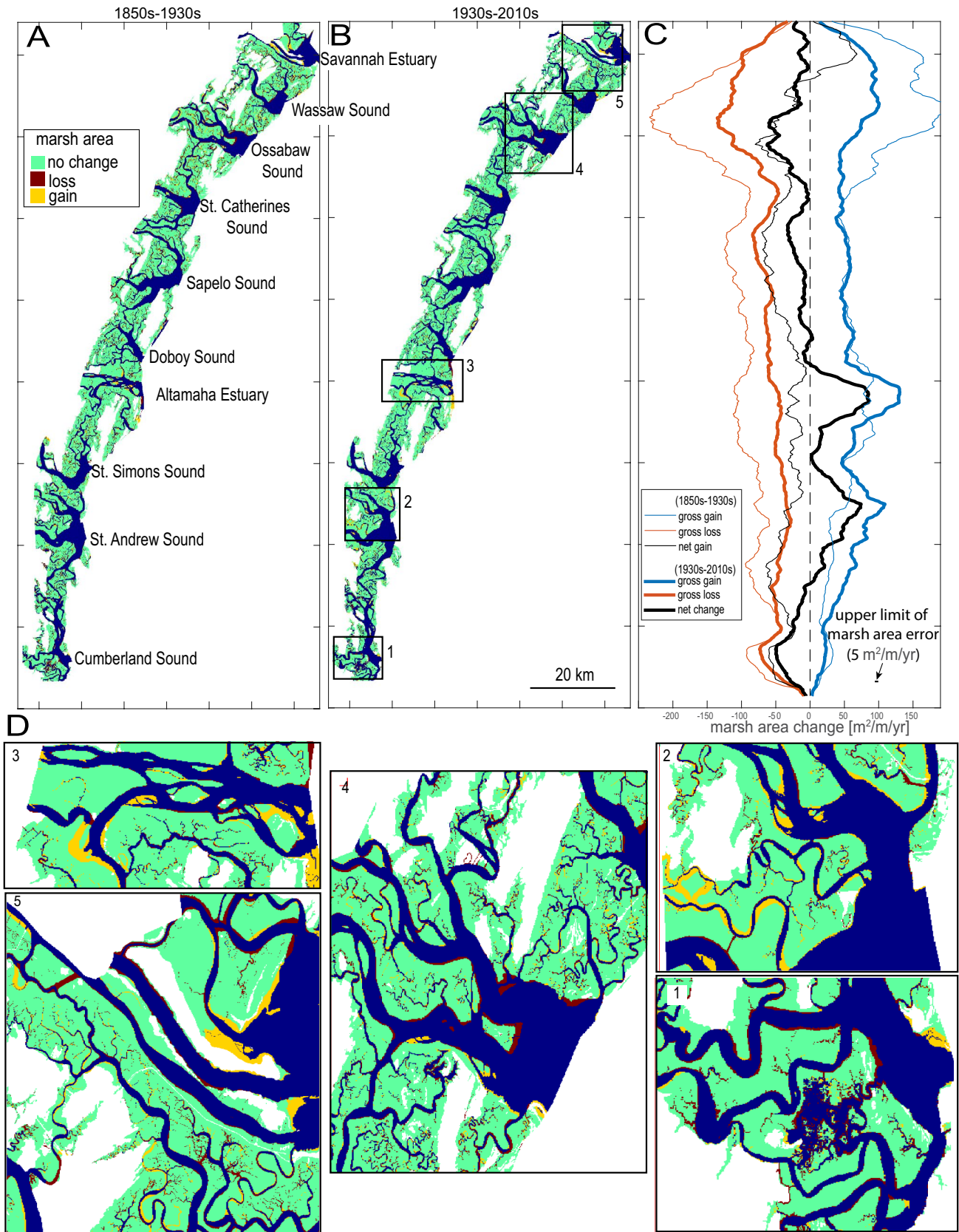


Fig. 3 **A, B** Marsh area change from 1850 to 2010s. **C** Marsh area change averaged in the cross-shore direction, with a moving average window of 20 km in the along-shore direction. **D** Detail of marsh change from 1930 to 2010s in five zones characterized by overall net marsh expansion (2,3) and net marsh loss (1,4), and net zero change (5)

to August), and low-discharge and high-wave season (September to November; Fig. 2).

As a proxy for the TSS associated with river input, we calculated the difference between MODIS-TSS averaged during the high-discharge high-wave season (Jan–Mar) and the low-discharge high-wave season (Sep–Nov), here referred to as $\Delta TSS_{\text{river}}$. As a proxy for the TSS associated with swell wave resuspension in the nearshore, we calculated the difference between TSS averaged during the low-discharge high-wave season (Jan–Mar) and the low-discharge low-wave season (Jun–Aug), here referred to as ΔTSS_{wave} .

TSS Associated with Tides

The contribution of tides to TSS is difficult to measure through remote sensing because fine sediment in the estuarine water of Georgia might constantly be resuspended, with little to no settling during slack tide (J. Blanton et al. 1999). Thus, the difference between periods of high and low tidal resuspension cannot be directly obtained as for the riverine and wave contribution.

As a proxy for tidal dynamics, we considered the difference in TSS between high and low water, ΔTSS_{tide} . This value does not directly quantify sediment resuspension, but rather quantifies sediment advection by tides. Low values of ΔTSS_{tide} can be obtained for two contrasting scenarios: if there is no tidal resuspension during high and low tides and if there is high (and similar) tidal resuspension during both high and low tide. As such, ΔTSS_{tide} cannot be directly compared to $\Delta TSS_{\text{river}}$ and ΔTSS_{wave} , but could be still considered an indirect proxy for the overall tide action in the region.

To calculate ΔTSS_{tide} , we divided all MODIS-TSS measurements in “low tide” (water level < -0.5 m MSL) and “high tide” (water level > 0.5 m MSL); calculated using the water level in Fort Pulaski, GA (NOAA station 8670870); and applied to the whole domain. For simplicity, MSL is assumed equal to the value during the epoch 1983–2001, given that MSL changes during the 20 years period are small (< 5%) compared to the tidal range. Similarly, we assume that water levels are spatially uniform and neglect lags in water levels in the along-shore (at most 30 min for the Georgia coast) and cross-shore directions (which is about one hour within 10 km of the estuary reach). These assumptions only affect classifications of tidal stages close to MSL, and not how slack high and slack low tides are classified. Water levels close to MSL are less frequent than those close to high and low tides, and thus have low importance overall.

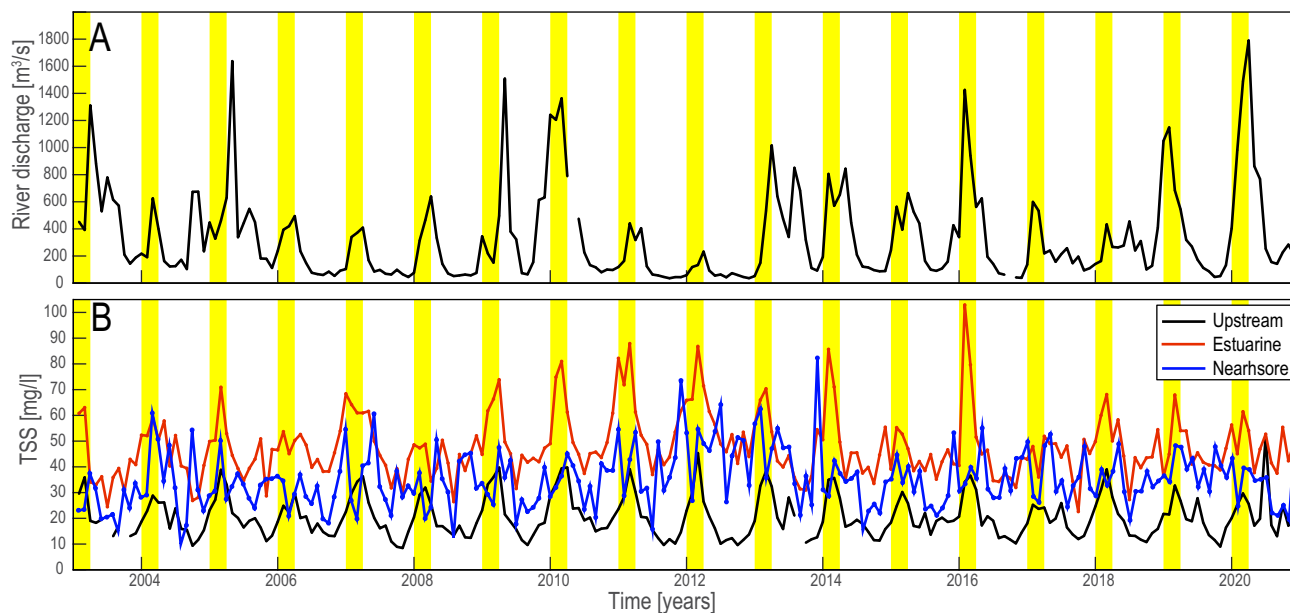


Fig. 4 Example of discharge and TSS time series from 2003 to 2020. **A** River discharge in the Altamaha River, from USGS station at Everett. **B** Monthly TSS estimated from MODIS at three points of interest in the Altamaha Estuary (see Fig. 1 for locations). The yellow

rectangles identify the January–March period for each year. Note a large seasonality in the upstream region and a low seasonality in the nearshore region

Along-Shore Variability in Marsh Area Change and TSS Proxies

To identify along-shore variability, we considered the total amount of marsh loss integrated in the cross-shore direction up to the tidal limit (i.e., the amount of marsh loss per unit of along-shore length in $\text{m}^2/\text{m}/\text{yr}$). A rate of actual marsh area change was considered to be more indicative of changes in lateral marsh extent, as opposed to normalizing by marsh area (i.e., a percentage), based on (Ladd et al. 2019). This measurement was spatially smoothed using a moving window of 20 km in the along-shore direction.

To provide an indicator for the sediment availability to the marshes, we calculated the cross-shore averaged TSS and $\Delta\text{TSS}_{\text{river}}$ within the estuarine region, defined as the area from the barrier islands to 20 km landward (see Fig. 5). We also calculated the cross-shore averaged $\Delta\text{TSS}_{\text{wave}}$ and $\Delta\text{TSS}_{\text{tide}}$ within the nearshore region, defined as the area from the barrier islands to 5 km seaward (see Fig. 5). The value obtained from $\Delta\text{TSS}_{\text{wave}}$ is considered a proxy for sediment import from the nearshore (i.e., the South-Atlantic Bight). The value obtained for $\Delta\text{TSS}_{\text{tide}}$ requires a more complex interpretation. Because $\Delta\text{TSS}_{\text{tide}}$ in the nearshore of Georgia is caused by the advection of sediment in and out of the estuary and it is minimally affected by tidal resuspension directly in the nearshore (Oertel and Dunstan 1981), $\Delta\text{TSS}_{\text{tide}}$ is considered a proxy for sediment resuspension in the estuary. As for the marsh area change, all the TSS metrics were smoothed in the along-shore direction considering a moving window of 20 km.

Results

Marsh Area Changes

Spatial patterns of marsh lateral expansion and retreat vary along the Georgia coast (Fig. 3). As previously observed (Burns et al. 2020, 2021), there is a large gross change in marsh area on multi-decadal time scales, mostly due to channel migration. The net change is generally small, and in some areas close to zero, as in Sapelo Sound between 1930 and 2010s (Fig. 3C).

Across the whole Georgia coast, there are regions with net loss or gain. This latter is particularly relevant, since expansion is relatively uncommon in coastal marshes on the US East Coast and more generally worldwide (Murray et al. 2022). New marsh formation is generally present at the mouths of the Altamaha and Savannah Rivers (Fig. 3D). Interior marsh loss was also present in some cases, especially in Cumberland Sound (Fig. 3D).

During the first time period (1850s to 1930s), there was a net loss of marsh in most areas (with a maximum value of $80 \text{ m}^2/\text{m}/\text{yr}$), except close to the Savannah Estuary, where there was a net gain of about $60 \text{ m}^2/\text{m}/\text{yr}$. During the second period (1930s to 2010s), the rate of net change in marsh area decreased in the Savannah Estuary, becoming a loss of about $10 \text{ m}^2/\text{m}/\text{yr}$, but increased in the Altamaha Estuary and St. Simons/ St. Andrew Sound.

TSS Estimates from Satellite

TSS estimated from satellite captures the main temporal trends observed at the thirteen stations where it was directly measured (Fig. S1). For example, satellite images capture the TSS seasonality (i.e., regular temporal pattern throughout the year) measured in the Altamaha River-Estuary, with higher levels during the high-discharge months than in low-discharge months (Fig. S1). The satellite images also capture a less prominent TSS seasonality measured in the Savannah River Estuary (Fig. S1). The satellite images also capture the relatively uniform and large TSS values ($50\text{--}100 \text{ mg/l}$) measured in stations located in estuarine backbarrier waters, such as those in Doboy Sound, in the Altamaha Estuary at Wolf Island, and at St. Andrew Sound (Fig. S1).

When comparing the monthly values, the correlation between TSS measured in the field and estimated from MODIS is relatively poor ($R^2=0.12$), and only slightly better ($R^2=0.17$) if measurements $> 150 \text{ mg/l}$ are removed (Fig. S2A). As described above, this is not a one-to-one comparison. TSS from satellites is the median over 2–8 images per month and biased toward fair weather (i.e., when cloud coverage is absent). As such, remotely sensed TSS filters out the short-term temporal variability and captures sediment dynamics that are slowly changing. Field samples were collected about once per month, and can capture both baseline and episodic short-lived resuspension events (e.g., waves, tides, boat traffic). Thus, TSS from field sampling would inevitably have more variability than from satellites. In addition, TSS field measurements might include small amounts of sand, which increases the mass without creating a significant optical response.

The direct comparison of individual MODIS TSS and field TSS that were near synchronous (i.e., with a maximum lag of 1 h) reduced the number of datapoints by more than an order of magnitude (Fig. S2C), but increased the R^2 value to 0.52. Some of the unexplained variability is likely due to the fact that TSS in the field is still highly variable at hourly time scales. For example, surface TSS in the Satilla Estuary has been shown to change from 40 to 400 mg/l within an hour (Blanton et al. 1999).

When comparing MODIS and field TSS averaged for the whole period (2001 to 2020) at each of the thirteen locations (Fig. S2B), R^2 increased to 0.63. This provides a strong indication that the method is capable of predicting the large scale variability in TSS.

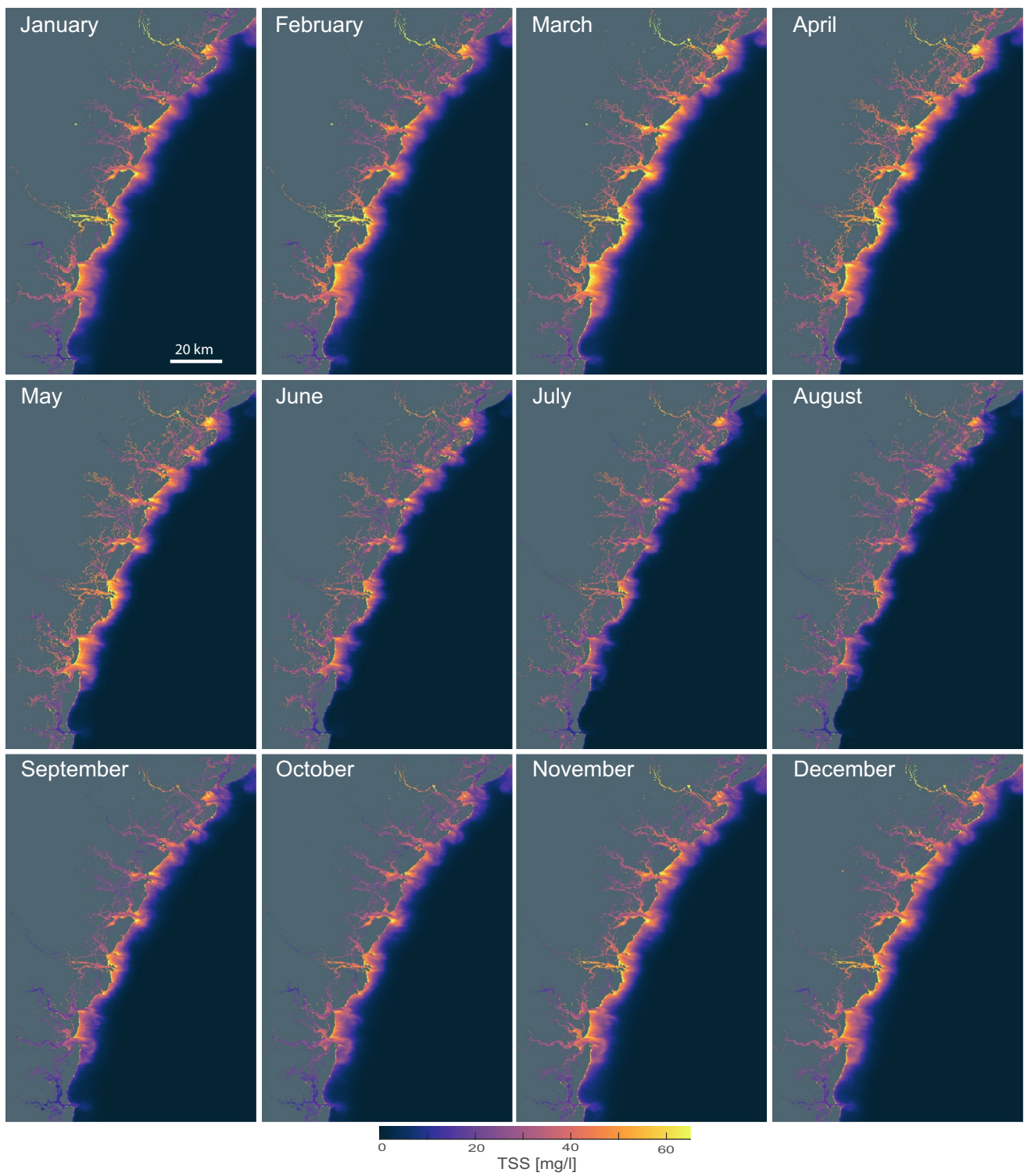


Fig. 5 Median monthly MODIS-TSS for the period 2003–2020

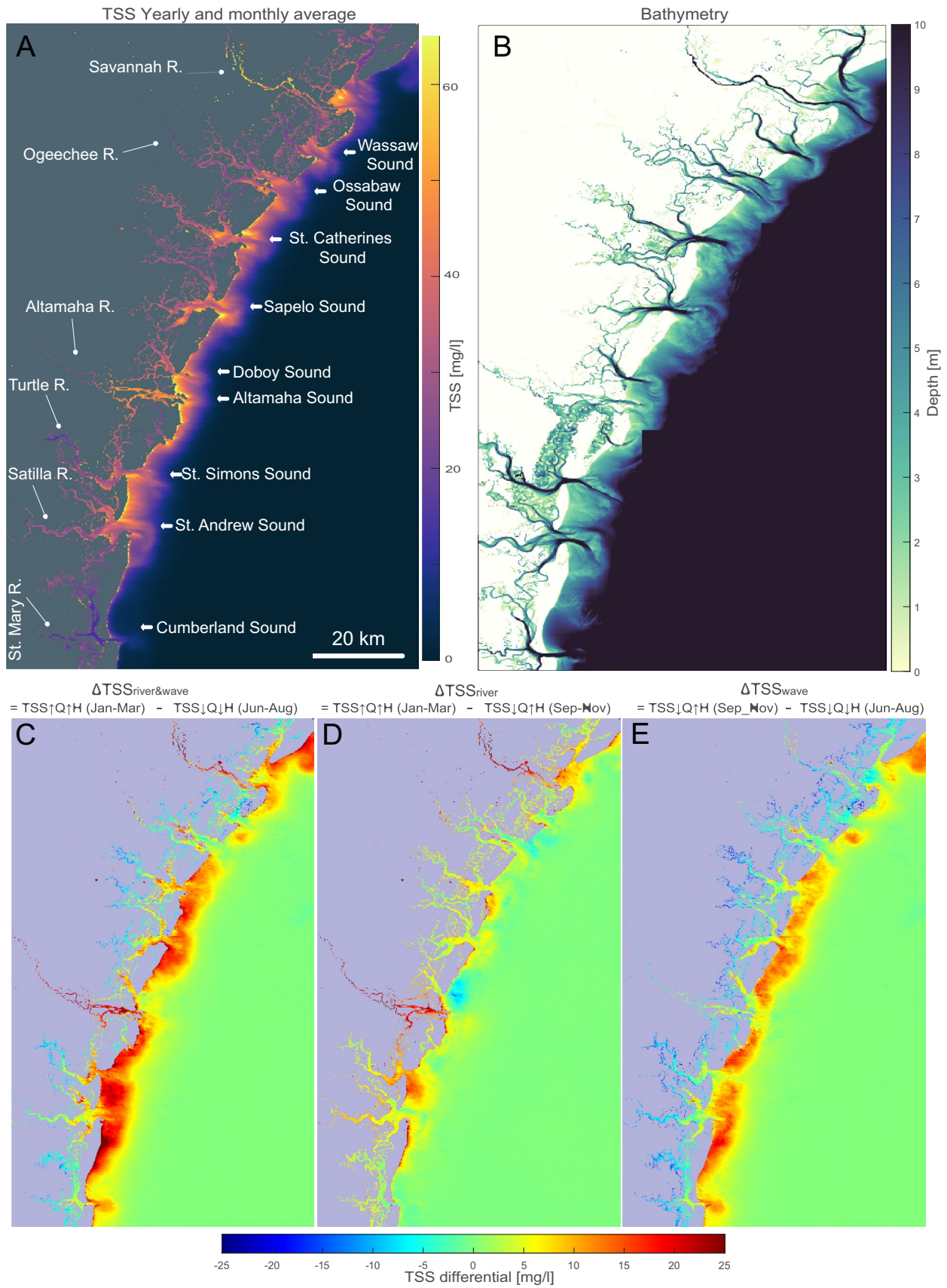


Fig. 6 **A** TSS averaged for all years and all months. **B** Bathymetry. **C** TSS difference between high-discharge high-waves (Jan–Mar) and low-discharge low-waves (June–Aug) months averaged for all years. **D** TSS difference between high-discharge high-waves (Jan–Mar) and low-discharge high-waves (Sept–Nov) months averaged for all years. **E** TSS difference between low-discharge high-waves (Sept–Nov) and low-discharge low-waves (June–Aug) months averaged for all years

TSS Spatio-temporal Variability Along the Georgia Coast

When considering the whole Georgia coast, median TSS values for every month between 2003 to 2020 show two major spatio-temporal patterns (Fig. 5, 6, S6). First, TSS is the highest (up to 100 mg/l) in Altamaha and Savannah Estuaries (Figs. 5, 6A). Second, TSS is higher in winters and early spring than in the summer (Fig. 5, S6).

TSS in estuarine and coastal waters displays strong variability in the cross-shore direction. As an example, we considered three regions within the Altamaha system (Figs. 1, 4): an upstream non-tidal location, a backbarrier estuarine location, and a nearshore location. The upstream location has the most seasonal variability, with TSS levels in the high-discharge period about double those in the low-discharge period. TSS is higher in the estuarine location than in the

upstream location, likely reflecting tidal resuspension and the formation of an estuarine turbidity maximum. Seasonal variability in TSS is also smaller in the estuarine location than upstream, reflecting a lower importance of riverine inputs. In the nearshore region, there is little seasonal variability and generally a lower TSS than in the estuary.

TSS Associated with River Input, Wave Resuspension, and Tide Resuspension

As described above, we calculated TSS proxies for riverine sediment input, sediment resuspension by waves, and sediment resuspension/advection by tides (Figs. 6, 7, and 8). The proxy for TSS associated with river ($\Delta\text{TSS}_{\text{river}}$) is largest (~ 20 mg/l) in the Altamaha and Savannah Estuaries, as expected given the size of these rivers (Fig. 6D). Slightly lower levels (~ 10 mg/l) are found in St. Andrew and St. Simons Sound, as well as in the ebb-tide delta shoals facing the barrier islands. Everywhere else, including other estuaries and the nearshore, values are small (0–5 mg/l).

The proxy of TSS associated with swell waves ($\Delta\text{TSS}_{\text{wave}}$) is higher in the nearshore than in estuarine areas and upper river reaches. The values are especially high on the shoals seaward of the barrier islands (0–5 km offshore) (Fig. 6E),

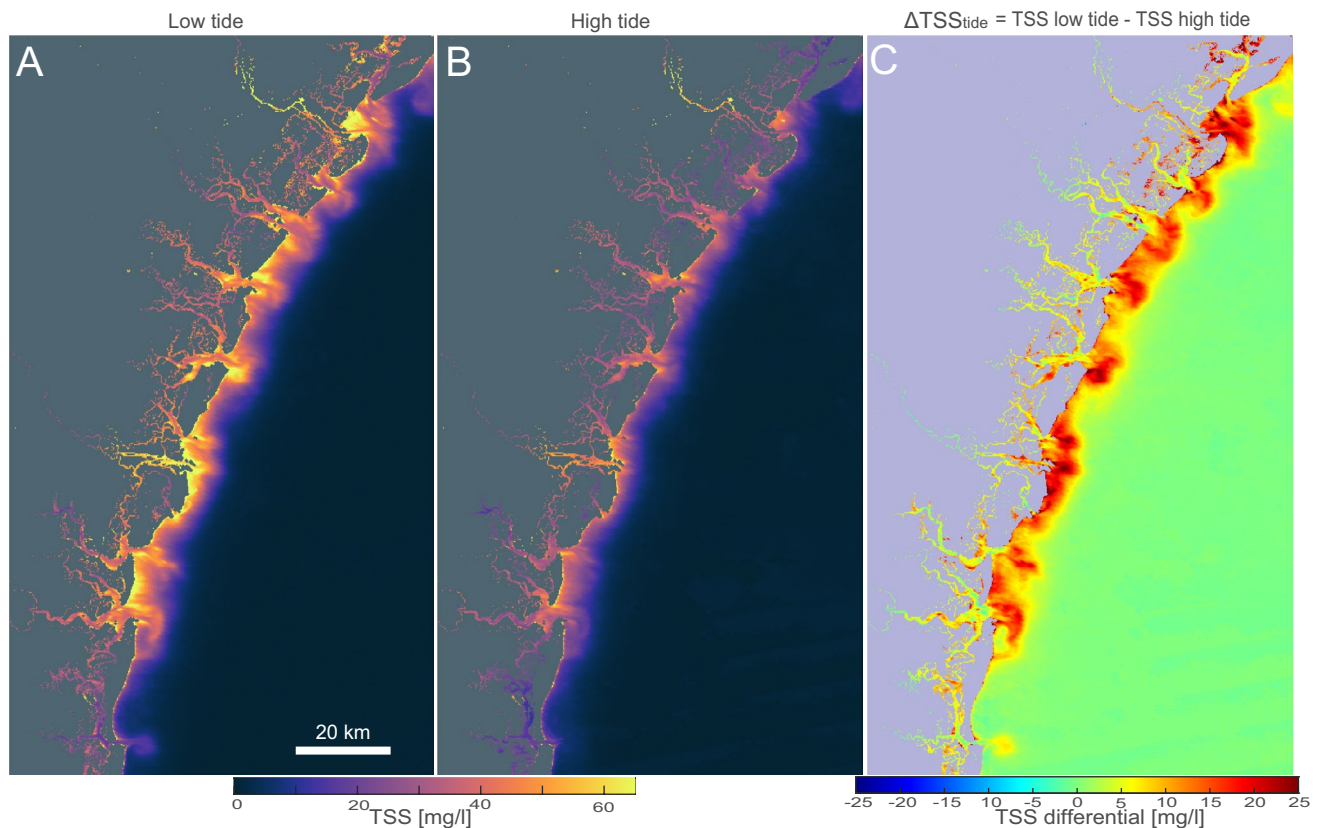


Fig. 7 Average TSS for all years and all months. **A** Low tide (water levels < -0.5 m above MSL), **B** high tide (water levels > 0.5 m above MSL), **C** difference between low and high tide during all months

likely because the higher bed shear stress associated with shallow water depths. ΔTSS_{wave} is relatively uniform in the along-shore direction, even though it is slightly smaller outside of Wassaw and Ossabaw Sounds in the north and outside of Cumberland Sound in the south (Fig. 8).

TSS is always greater at low tide than at high tide (Fig. 7), except for a few areas (<1% of the domain) in the upper reaches of the Altamaha and Savannah Rivers where TSS at high tide is a few mg/l greater (~5–10%) than at low tide. As a result, ΔTSS_{tide} is almost always positive. The largest ΔTSS_{tide} (~30 mg/l) is found in the nearshore region (0–5 km from the coastline) and mostly delineate the offshore limit of advection during ebb tide (Oertel and Dunstan 1981; Blanton et al. 1989). In the estuarine

water landward of the barrier islands, ΔTSS_{tide} is close to zero (i.e., TSS is similar for high and low tides), likely because tidal currents are always strong enough to resuspend sediment. The ΔTSS_{tide} is generally larger in the nearshore region just seawards of the inlets, in contrast to ΔTSS_{wave} , which tends to be larger in front of the barrier islands. ΔTSS_{tide} is relatively uniform in the long-shore direction, except near Cumberland Sound (Fig. 8). The difference is similar when calculated considering all months of the year, or when calculated at different times of the years (high-discharge high-waves, low-discharge low-waves, low-discharge high-waves) (Fig. S3), suggesting that the difference in wave-induced sediment resuspension between high and low tides does not play a strong role.

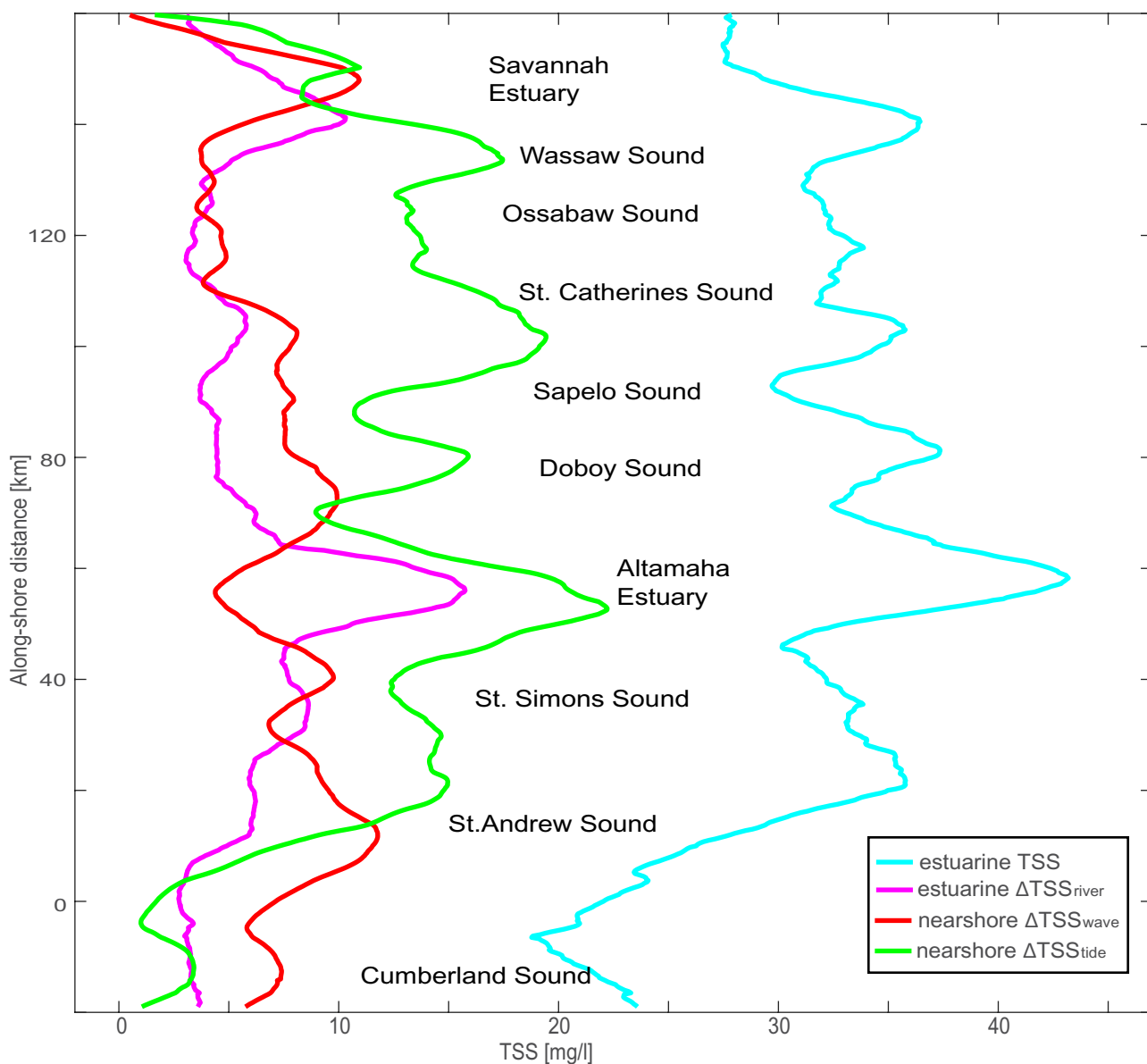


Fig. 8 Along-shore variability in TSS metrics. TSS and ΔTSS_{river} are calculated within the estuarine region, i.e., from the barrier islands to 20 km landward; ΔTSS_{wave} and ΔTSS_{tide} are calculated in the nearshore region, i.e., from the barrier islands to 5 km seaward

Discussion

Study Limitations

Our estimates of marsh area change are affected by the uncertainty of 1850s and 1930s map digitization. Because of the coarse spatial resolution (10 m) of the maps, changes associated with small channels (< 10 m) and rates smaller than about 0.1 m/yr cannot be resolved. Nevertheless, the analysis provides a first-order estimate of marsh area changes that are comparable to more detailed studies (Burns et al. 2020, 2021). For example, the net marsh change in Sapelo Sound between 1930 and 2010s was close to zero (Fig. 3C), which is consistent with a previous analysis performed at a finer spatial resolution (Burns et al. 2021) (Fig. S4). In addition, the same method (i.e., T-sheet historical maps analyzed at 10 m) has been successfully used to estimate long-term marsh area change in the Mississippi Delta (Valentine and Mariotti 2019) and in the Delaware Bay (Else-Quirk et al. 2019).

The algorithm to convert satellite data to TSS (Eq. 1) was previously calibrated using relationships developed in a study from the Mississippi River (Mariotti et al. 2021), which could in theory have different water characteristics than the rivers in Georgia, some of which have a relatively high amounts of tannins. A classification of optical properties using the LANDSAT satellite clustered the Mississippi River and Georgia rivers in two different—but relatively close—groups (Dethier et al. 2020). The Georgia rivers had higher particulate organic matter content than the Mississippi River, but lower than extremely organic rivers, such as those in Florida (Dethier et al. 2020). Given the temporal mismatch between satellite data and field measurements, we did not attempt to recalibrate the TSS conversion for the Georgia coast. Rather, we used the field measurements as a fully independent validation of the assumed TSS conversion.

The TSS considered in this analysis, both from satellite and from field sampling, represents the value at the water surface (generally the top 1 m). Despite fine sediment being relatively uniformly distributed in the water column compared to sand, vertical gradients in TSS could still be present, especially in deeper areas. For example, field measurements in the estuarine portion of the Satilla River found, during the peak ebb tide, TSS was 8000 mg/l in the bottom 2 m of the water column and 2000 mg/l in the top 10 m of the water column (Blanton et al. 1999; Alber 2000). While these gradients are important to quantify sediment fluxes and budgets, they can be neglected when comparing different areas along the Georgia Coast (for which surface TSS is always considered). Also, these large gradients are likely to occur during peak tidal currents, which are already filtered out by the method used to analyze the satellite images.

Despite the limitations, the TSS predicted from the MODIS images captures the TSS order of magnitude at every station (Fig. S1), which generally ranges between 20 and 100 mg/l. Values in the range of 30–50 mg/l within the estuaries are consistent with previous field studies from the same area (Windom et al. 1971; Oertel 1974; Alber 2000; Dethier et al. 2022). Lower TSS values (~ 20 mg/l) in the southern portion of the coast, toward Cumberland Sound, are also consistent with previous work in that area (Radtke 1985).

The analysis of TSS from satellite and field measurements also revealed two unexpected trends at the Port Wentworth station on the Savannah Estuary. First, TSS is less seasonally variable than in the Altamaha Estuary (Fig. S1). This likely occurs because the Savannah system is much more modified by human activities, such as damming to control flow, channel dredging, and boat resuspension, all of which cause an irregular modulation of TSS throughout the year. Second, TSS field measurements are more variable between 2011 and 2020 than 2003 and 2010. For example, TSS might change by 100 mg/l between measurements taken a few days apart. This change in variability is also qualitatively captured by the satellite images (Fig. S1). This trend might indicate a change in dredging activity or boat traffic (Mariotti and Boswell 2023); for example, a marina located ~ 50 m from the measuring station was expanded in 2011.

Riverine Sediment Input Is Required for Marsh Net Expansion

We considered TSS measured from 2002 to 2020 to gain insight into changes in marsh area from 1930 to 2010s. Given the difference in the two intervals, the comparison is characterized by a high uncertainty and should be interpreted with caution.

Net marsh gain is correlated to estuarine TSS, which is generally higher around the Altamaha and the Savannah Estuaries (Fig. 9) and expected given the large discharge of these rivers (Meade 1969). Noticeably, the correlation between net marsh area changes and estuarine TSS is poor ($R^2 = 0.27$) when considering the whole coast. The poor correlation is mostly evident in southern portion of the Georgia coast (Cumberland Sound). This area is experiencing fast rates of marsh loss, mostly in the interior (Fig. 3D), which is consistent with nearly absent river inputs.

The overall poor correlation between TSS and marsh area change demonstrates that this variable alone is not a good indicator for long-term trajectories. One potential reason is that it does not distinguish new sediment input from internal recycling. Using $\Delta TSS_{\text{river}}$, we found stronger correlations between marsh area change and TSS associated with river input ($R^2 = 0.59$; Fig. 9). This confirms previous theories

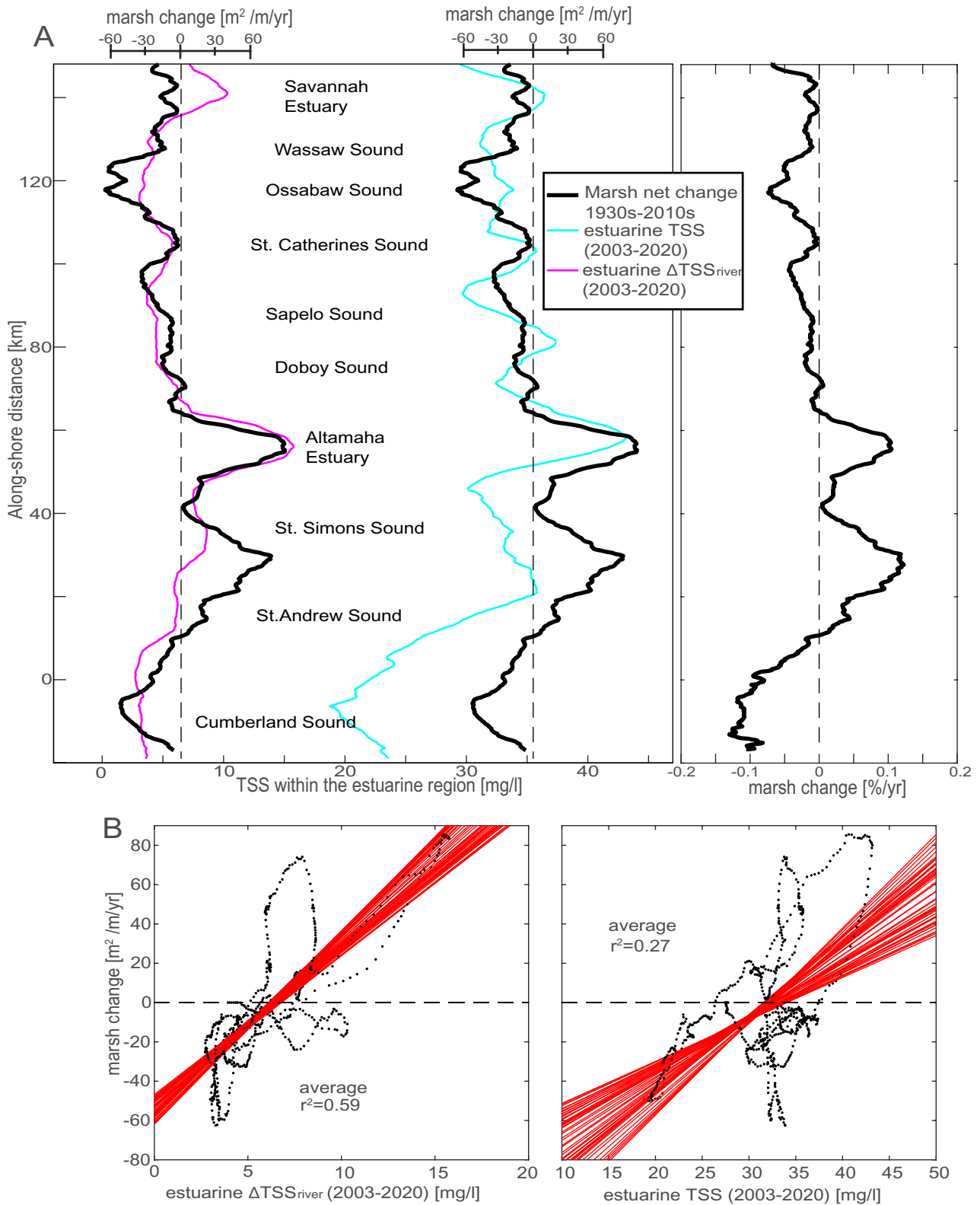


Fig. 9 **A** Cross-shore averaged and yearly-averaged TSS and ΔTSS_{river} (as in Fig. 4). The black lines are the net marsh area change for the 1930s–2010s period (as in Fig. 2B). For all values, a moving average window of 20 km in the along-shore direction is used to smooth the patterns. TSS is calculated within the estuarine region, i.e., from the barrier islands to 20 km landward. **B** Correlation

between marsh area change, TSS, and ΔTSS_{river} . Because the marsh area change is autocorrelated (up to a distance of about 12.5 km, equivalent to 50 cells), the regression was performed on a 1/50th subset of the data and was repeated 50 times by changing the starting point of the subsampling. The average R^2 value was then reported

that sediment imported from outside of the system is needed to promote net marsh expansion and prevent retreat (Mariotti and Carr 2014; Ganju et al. 2015) and suggests that riverine input is crucial for these marshes.

The clearest link between $\Delta TSS_{\text{river}}$ and marsh expansion is in the Altamaha Estuary. This is expected, given that the Altamaha has only three dams that were constructed on its tributaries between 1910 and 1980 and there is no dredging in its channel (Windom and Palmer 2022; Fig. S5). $\Delta TSS_{\text{river}}$ does not however predict the patterns of marsh change at every location. For example, $\Delta TSS_{\text{river}}$ is similar in Savannah Estuary and in the St. Simons Estuary, but the marsh is slightly retreating in the former but prograding in the latter. We suggest that some other human activity (e.g., damming and other river management activities) in the Savannah system might explain this difference.

TSS Due To Nearshore Wave Resuspension and Estuarine Tide Resuspension

River sediment input is crucial for net marsh expansion with sea-level rise (Blum and Roberts 2009), but sediment input by waves and tidal resuspension could also have important roles in lateral and vertical marsh dynamics (Yang et al. 2021). We developed proxies for wave and tide resuspension which, although lacking the accuracy of in situ measurements (e.g., Blanton et al. 1999), provide a first-order coast-wide characterization.

ΔTSS_{wave} does not reflect the full amount of wave sediment resuspension. This is because the seasonal period used as reference for low wave resuspension (June–Aug, Fig. 6E) still has relatively large waves (Fig. 2). Nonetheless, ΔTSS_{wave} is useful to detect relative changes in wave resuspension in the nearshore, and hence potential for sediment input into the estuary. For example, ΔTSS_{wave} is slightly smaller in the nearshore off Wassaw and Ossabaw Sounds (Fig. 8), partly explaining high rates of marsh loss between 1930 and 2010s, and it is slightly larger in the nearshore off St. Andrew Sound, partly explaining high rate of marsh gain between 1930 and 2010s. On the other hand, ΔTSS_{wave} is relatively uniform compared to $\Delta TSS_{\text{river}}$ along the ~200 km coast (Fig. 8), and thus cannot fully explain the along-shore variability in marsh area change (Fig. 3C), such as considerable expansion in the Altamaha Estuary compared to other areas. Instead, we suggest that wave resuspension in the nearshore constitutes a relatively uniform input of sediment to Georgia's estuaries and marshes.

Previous studies in coastal Georgia indicate that nearshore sediment import largely contributes to the estuarine sediment budget (Meade 1969; Windom et al. 1971; Meade 1982; Mulholland and Olsen 1992; Blanton et al. 1999). Similarly, nearshore sediment import contributes to marsh lateral expansion in the Yangtze Delta (Yang et al.

2020, 2021). The magnitude of wave-driven sediment imported from the nearshore cannot be estimated with our remote sensing methods. Despite this limitation, we conclude that nearshore sediment import alone is not enough to prevent marsh lateral retreat in Georgia because marshes located away from riverine sediment input are retreating.

ΔTSS_{tide} is more difficult to interpret than ΔTSS_{wave} . As described in Section "Along-Shore Variability in Marsh Area Change and TSS Proxies", we suggest that ΔTSS_{tide} in the nearshore area is a proxy for sediment resuspension in the estuary. Given that sediment resuspension of the estuary is due to erosion of the channels, tidal flats, and marsh edges, nearshore ΔTSS_{tide} should not be considered a proxy for new sediment input for the estuary, but rather a proxy for internal sediment recycling within the estuary. Sediment from internal recycling should be important for marsh vertical accretion—consistent with the observation that marsh vertical accretion is correlated to TSS (Coleman et al. 2022)—but likely does not contribute to marsh lateral expansion (Mariotti and Carr 2014).

This interpretation provides an explanation for the poor correlation between TSS and marsh loss (Fig. 9). As pointed out in Section "Riverine Sediment Input Is Required for Marsh Net Expansion", both Ossabaw and Cumberland Sounds have relatively high rates of net marsh retreat (60 m²/m/yr), but TSS is higher in the former (~30 mg/l) than in the latter (~20 mg/l). Similarly, nearshore ΔTSS_{tide} is higher in Ossabaw (~15 mg/l) than in Cumberland (~5 mg/l). This supports the idea that sediment from internal recycling in the estuary does not contribute to marsh lateral expansion.

Even though internal recycling does not contribute to marsh expansion, it is worth asking why it does vary along the Georgia Coast, i.e., why ΔTSS_{tide} is lower in Cumberland Sound than in the other areas. This could be partly explained by the tidal range, which decreases from 2.3 m at Fort Pulaski (within the Savannah Estuary) to 2.0 m at Fernandina Beach, Florida (just south of Cumberland Sound). Furthermore, even if tidal currents were able to resuspend sediment, the minimal amount of river-delivered sediment in the southern 30 km of coastal Georgia might limit the amount of sediment to be resuspended by tidal currents.

Classification of the Georgia Coast into Distinct Regions: Observations and Future Research

We identified five regions in the Georgia coast with similar sediment and marsh dynamics. This classification does not explain all aspects of these regions, but rather highlights key characteristics, facilitates comparison to sites outside of Georgia, and points to future research questions. For example, it could help to guide more detailed investigations such as numerical modeling of hydrodynamic and sediment

transport, sampling of the sedimentary record in the floodplains and marshes, and accounting of sediment dredging and disposal.

Large Riverine Alteration

The Savannah River-Estuary is one of the largest on the US East Coast and is highly altered by humans. Several large dams for hydropower, flood control, and recreation have been built since the 1950s and sharply reduce the sediment load to the coast (Meade 1982). This trend has been experienced by many rivers in the US (Weston 2013) and worldwide (Dethier et al. 2022). In addition, dredging of the channel (Fig. S5) and off-site disposal of the sediment represents a loss of potential fine sediment to the Savannah estuary system, and its effect should be included in the overall sediment budget. Field and satellite data demonstrate that TSS and sediment discharge decreased in the Savannah River from 1974 to 1994 (Weston 2013; Windom and Palmer 2022) and 1984 to 2021, respectively (Dethier et al. 2022). These trends could explain the decrease in net marsh growth rate from the 1850s–1930s period to the 1930s–2010s period. This trend is similar to that in the Mississippi Delta, where lost marsh area has been associated with decreased riverine sediment input (Tweel and Turner 2012).

Low Sediment Supply Without Major River Alteration

Ossabaw and Wassaw Sounds are relatively undisturbed systems, which have experienced net marsh loss during both the 1850s–1930s and the 1930s–2010s periods. A low sediment supply from the watershed (the Ogeechee River), as demonstrated by low $\Delta\text{TSS}_{\text{river}}$, likely explains this pattern. A lower input from the nearshore, as evidenced by a low $\Delta\text{TSS}_{\text{wave}}$, is another possible cause, and should be further studied, for example, through modeling of nearshore waves. St. Catherine's, Sapelo, and Doboy Sounds are also relatively undisturbed systems with low sediment supply, similar to Ossabaw and Wassaw Sounds. In contrast, however, marsh retreat was larger in the 1850s–1930s period than in the 1930s–2010 in these three systems. Whether this change is related to more riverine sediment input, to more nearshore sediment input, or anthropogenic alteration of the system to create the Atlantic Intracoastal Waterway should be further investigated.

High Riverine Sediment Supply

The Altamaha Estuary experienced a large increase in marsh area change from the 1850s–1930s period ($-20 \text{ m}^2/\text{m}/\text{yr}$) to the 1930s–2010s period ($80 \text{ m}^2/\text{m}/\text{yr}$), which

suggests an increase in sediment delivery. This result is puzzling, in light of a previous study that suggested a decrease in sediment load in the Altamaha River from 1910 to 1970 (Meade and Trimble 1974), even though this decrease ($\sim 40\%$) was smaller than that in the Savannah River ($\sim 80\%$). On the other hand, a recent study based on analysis of field measurements showed that the TSS in the Altamaha River slightly increased from 1977 to 2011 (Weston 2013), whereas a study based on satellite analysis from 1980 to 2020 showed that TSS remained nearly constant (Dethier et al. 2022). It is possible that the land use change in its watershed from the 1960s—a nearly 100% increase in population but a 34% decrease in agricultural land (Weston et al. 2009)—combined with the absence of dredging and the paucity of dams has been sufficient to cause a sediment pulse to the estuary. Alternatively, an increase in sediment supply to the estuary in the last century might have been associated with floodplain sediment dynamics. Specifically, the pulse in sediment supply from the watershed during colonial times (seventeenth to nineteenth centuries) might have been temporarily stored in the river floodplain (Walter and Merritts 2008), and only in the last century been delivered to the estuary. These ideas require further investigation, and a better characterization of sedimentary records in the floodplains and estuary of the Altamaha. Also, a comparison with other sediment-rich and tidally influenced deltas, such as that associated with the Santee River, the fourth largest river in terms of discharge on the eastern coast, could give useful insights (Long et al. 2021).

Sediment Import from Lateral Transport

St. Andrew and St. Simons Sounds experience a rate of marsh gain as high as in the Altamaha Estuary ($60\text{--}80 \text{ m}^2/\text{m}/\text{yr}$, Fig. 11A). As mentioned in Section "TSS Due To Nearshore Wave Resuspension and Estuarine Tide Resuspension", this might be associated with enhanced sediment import from the nearshore, as suggested by a slightly higher value of nearshore $\Delta\text{TSS}_{\text{wave}}$ (Figs. 6, 8). A more likely explanation is found in the observation of relatively large $\Delta\text{TSS}_{\text{river}}$ ($\sim 15 \text{ mg}/\text{l}$) within the estuary and nearshore region between St. Simons and St. Andrew Sounds, which is not present in other nearshore regions of Georgia (Figs. 6D, 8, and 9). It is possible that this sediment originates from the Satilla and Turtle Rivers (Alber 2000), which discharge in St. Andrew and St. Simons Sounds, respectively. Alternatively, we suggest that the relatively high $\Delta\text{TSS}_{\text{river}}$ in St. Simons Sound, and to a lesser extent St. Andrew Sound, is associated with import of riverine sediment from outside the estuary. The sediment plume from the Altamaha River might be advected southward by longshore currents and then imported into the estuary during flood tides or

upwelling-favorable winds (Di Iorio and Castelao 2013), and the Altamaha River might directly deliver sediment into St. Simons Sound through one of its major tidal channels. This site exhibits unusually rapid accumulation of fine-grained sediment, leading to shoaling of the Atlantic Intracoastal Waterway, and the need for frequent dredging. These hypotheses could be tested with fine-scale modeling of estuarine and nearshore hydrodynamics, or possibly through remote sensing at a finer spatial resolution than the 250 m used in this study.

Extremely Low Sediment Supply

Cumberland Sound is distinct from the rest of coastal Georgia because it is sediment starved. It has low TSS values overall and little sediment resuspension by tides and waves. It is also more closely related to the geology of Florida, with no major river and a carbonate substrate. Although significant quantities of sand are present in the inshore and nearshore areas, little new sediment is supplied to the coastal zone by the St. Mary's River, which has its headwaters in the Okefenokee Swamp. Limestone outcrops in many places along the bed of the St. Mary's River demonstrate the lack of sediment supply from the uplands (Veatch and Stephenson 1911). Further, the turbidity in the coastal frontal zone decreases from north to south along the Georgia coast, and thus little material is available to import from the nearshore.

Conclusions

We provided a large-scale (~ 200 km) and long-term (160 years) analysis of marsh change for the Georgia coast and identified large variability in the along-coast direction. A first-order estimate of TSS spatial and temporal patterns were inferred from satellite measurements over 18 years and showed that net marsh area gain (~ 50 m²/m/yr or ~ 0.1% yr⁻¹) is associated with regions with relatively high TSS, which are generally found near large rivers. A better correlation was found when considering TSS specifically associated with rivers, ΔTSS_{river} , confirming that river sediment input is crucial for marsh lateral expansion.

We identified two major temporal changes from the 1850s–1930s period to the 1930s–2010s period: marsh net expansion increased in the Altamaha Estuary and decreased in the Savannah Estuary. We suggest that a decrease in sediment input from the Savannah River to its estuary triggered a decrease in net marsh growth, whereas an increase in sediment input from the Altamaha (whose cause remains unclear, but is most likely related to anthropogenic activities in the drainage basin) fed an increase in net marsh growth in the area.

Wave resuspension is relatively uniform along the Georgia coast, whereas tidal resuspension is lower in the southern portion of the Georgia coast. Wave resuspension is important to supply sediment to the estuary from the nearshore, but it is not enough to prevent marsh lateral retreat. Sediment resuspended by tidal currents is likely originating from estuarine sediment recycling, and does not contribute to marsh lateral expansion. This sediment could however be important to accrete the marsh vertically.

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Data Availability Total suspended sediment data are accessible at Georgia Environmental Monitoring and Assessment System (<https://gomaspublic.gaepd.org/>) and at USGS (<https://waterdata.usgs.gov/>). MODIS data are accessible at Google Earth Engine Code Editor (<https://developers.google.com/>).

Declarations

Disclaimer All views, opinions, findings, conclusions, and recommendations expressed in this material are those of the author(s) and do not necessarily reflect the opinions of the Georgia Sea Grant College Program or the National Oceanic and Atmospheric Administration.

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