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The Dynamical Response of Salinity to Freshwater Discharge and Wind Forcing in Adjacent Estuaries on the Georgia Coast

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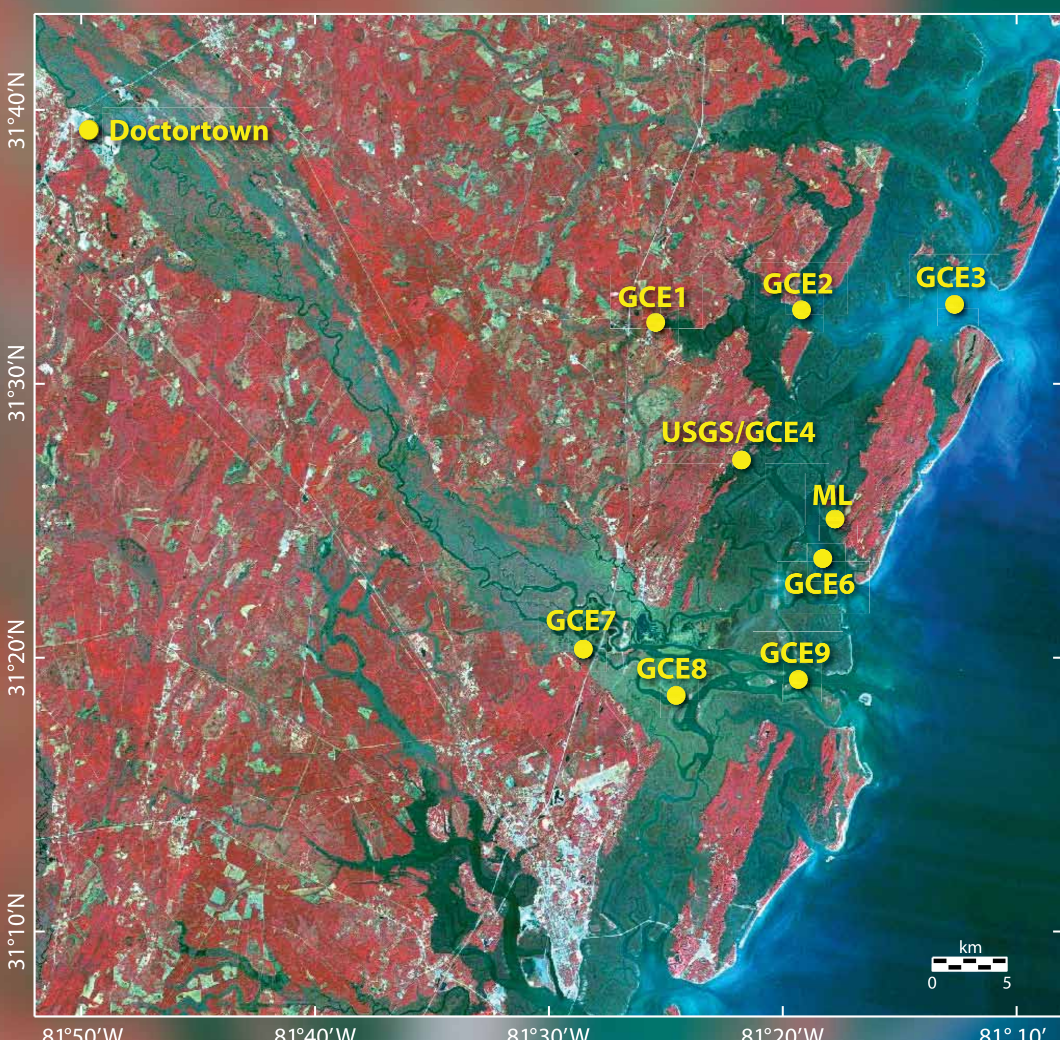

Figure 1. Infrared imagery of the Georgia Coastal Ecosystems (GCE) domain on the Georgia coast, with long-term monitoring sites marked in three adjacent estuaries: Altamaha River (Doctortown, GCE7, GCE8, GCE9), Doboy (USGS/GCE4, GCE6, ML), and Sapelo (GCE1, GCE2, GCE3). The National Data Buoy Center (NDBC) 41008 is located approximately 25 km offshore Sapelo Island at the 20 m isobaths (not shown).

ABSTRACT. Ten years of oceanic and meteorological monitoring data were collected in order to understand the spatial and temporal patterns of salinity distribution across three adjacent estuaries in the Georgia Coastal Ecosystems Long Term Ecological Research domain. Empirical orthogonal function analysis shows that 95% of the subtidal salinity variability can be explained by two principle modes. The first mode is dominated by river discharge, and causes system-wide freshening throughout the domain. The second mode, which explains 8% of the variability, is correlated with subtidal sea surface height and, hence, alongshore winds. The response in Sapelo and Doboy Sounds to this second mode, however, is out of phase with that of Altamaha Sound. During upwelling-favorable winds when coastal sea surface height decreases, Altamaha Sound freshens, and salinity increases in Doboy and Sapelo Sounds. On the other hand, freshening in Doboy and Sapelo Sounds and a salinity increase in Altamaha Sound accompany downwelling-favorable winds. A regional ocean model of a highly idealized coastal domain of three adjacent estuaries connected by the Intracoastal Waterway is consistent with the observations—river discharge and upwelling-favorable winds freshen the coastal domain so that when downwelling-favorable winds occur, the coastal freshwater originating in the Altamaha River is transported into Sapelo and Doboy Sounds. Model results suggest that the Intracoastal Waterway and the complex network of channels that connects the sounds play a dominant role in water exchange between the adjacent estuaries.

INTRODUCTION

The Georgia coast is a complex estuarine system, with sounds connected by a network of channels, creeks, and intertidal areas. Thus, the coastal domain is expected to present large spatial and temporal variability in water residence times because of the many pathways for water to flow. With population increases and development within the Altamaha River watershed, water demands and land use changes may result in decreased freshwater inflow and increased nutrient and pollutant inputs to the coast. Information on how freshwater and saltwater move through this system is critical for understanding long-term changes in ecosystem processes. In this paper, we address transport processes affecting subtidal salinity in three adjacent Georgia estuaries connected by both the Intracoastal Waterway and extensive intertidal marsh and creek channels, and also their connections to the coastal ocean.

Density-driven circulation, tides, and wind-driven currents are responsible for horizontal exchange between estuaries and the coastal ocean, which, in turn, have a major impact on the ecology, chemistry, water quality, and sedimentary processes in estuarine and coastal environments (Geyer and Signell, 1992). Circulation, mixing, and transport processes are evaluated in terms of freshwater discharge, ocean inundation, atmospheric forcing, and frictional effects over tidal, subtidal, and seasonal time scales. We currently have a good understanding of estuary/ocean exchange in isolated systems, but how buoyancy forcing from one estuary propagates into adjacent estuaries is not well known.

The Georgia Coastal Ecosystems Long Term Ecological Research (GCE LTER) site is located along three adjacent estuaries on the Georgia coast (Altamaha, Doboy, Sapelo), and it encompasses upland (mainland, barrier islands, marsh hammocks), intertidal (fresh, brackish, salt marsh), and submerged (river, estuary, continental shelf) habitats (see color infrared image of the domain in Figure 1). The Altamaha River is the largest source of freshwater to the GCE domain and provides a natural gradient of freshwater inflow to the estuaries. On the ocean side, the domain is bounded by the South Atlantic Bight, which extends from Cape Hatteras, NC, to West Palm Beach, FL. The broad expanse of the continental shelf in this area not only helps to protect the coast from wave and storm activity but also serves to channel the tides, which are semidiurnal and range in height from 1.8 m (neap) to 2.4 m (spring).

The primary focus here is to understand the spatial and temporal modes of variability in salinity and to identify some of the dominant forcing controlling variability and communication between estuaries. In a study of water exchange between two estuaries off South Carolina, for example, Traynum and Styles (2008) noted that wind-induced sea level rise (coastal setup) causes an increase in net flow toward Winyah Bay from North Inlet, while wind-induced sea level drop (coastal set down) causes a reversal of this exchange flow, moving water from Winyah Bay to North Inlet. Wind can produce substantial subtidal variability in these estuaries, and the differences in the responses of adjacent

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estuaries to wind forcing can produce large sea level differences at subtidal time scales. Zhao et al., (2010) showed that the modeled net water flux between Plum Island Sound and the Merrimack River estuary was dependent on discharge, tides, and wind forcing. Roegner et al. (2002) showed that the Columbia River plume was forced against the coast during downwelling conditions, allowing low-salinity water to be advected into Willapa Bay to the north. As the winds switched to upwelling-favorable conditions, the Columbia plume was replaced by salty water near shore. All of these processes potentially play an important role in water, nutrient, and plankton exchange in connected systems.

The GCE LTER project has been collecting data relevant for understanding ecosystem processes since 2000. Patterns and processes in this complex landscape vary on multiple scales, both spatially (longitudinally within and meridionally between sites) and temporally (tidal, diurnal, spring/neap, seasonal, and interannual). Salinity variability (at our long-term monitoring sites GCE1, 2, 3, 6, 7, 8, 9, and partner stations USGS/GCE4 shown in Figure 1) is likely to be influenced in many ways, such as by river discharge changes, oceanic inundation, and atmospheric forcing throughout the estuarine landscape. An idealized model can help shed light on the propagation pathways for freshwater to test the hypothesis that river and wind forcing affect coastal transport through sounds and through connecting channels.

This paper first describes the long-term data sets used in this study and the implementation of a highly idealized model of the domain. The results section compares observations and model output. The objectives are to understand the mechanisms controlling salinity variations in adjacent estuaries.

EXPERIMENTAL METHODS

Observational Data

The US Geological Survey (USGS) gage at Doctortown, GA, provides near-real-time data on river discharge into the Altamaha estuary. The Altamaha River, the largest source of freshwater to the GCE domain, drains a watershed of 36,700 km^2 and is Georgia's largest river system. Daily averaged river discharge from 2002–2012 shows a change from a wet period (2003–2005) to drought conditions (2006–2008) with a recovery in spring 2009 (Figure 2a). Afterward, the Altamaha River discharge was at its lowest ever recorded (since October 1931) in September 2011, falling below 35 $m^3 s^{-1}$. The median climatology for river discharge over the 10-year span ranges from a maximum of 600 $m^3 s^{-1}$ in March to a minimum of 60 $m^3 s^{-1}$ in August. Coastal precipitation is not necessarily indicative of river discharge, as afternoon thunderstorms in summer are very common. Seasonal climatology of coastal precipitation from the Marsh Landing weather station (ML; see Figure 1 for location) for the period 2002–2012 is greatest during the summer months from about June to October when the river discharge is at its lowest. The timing of this freshwater delivery could have important consequences for marsh processes during the active growing season when river flow is low.

Wind forcing off Georgia is

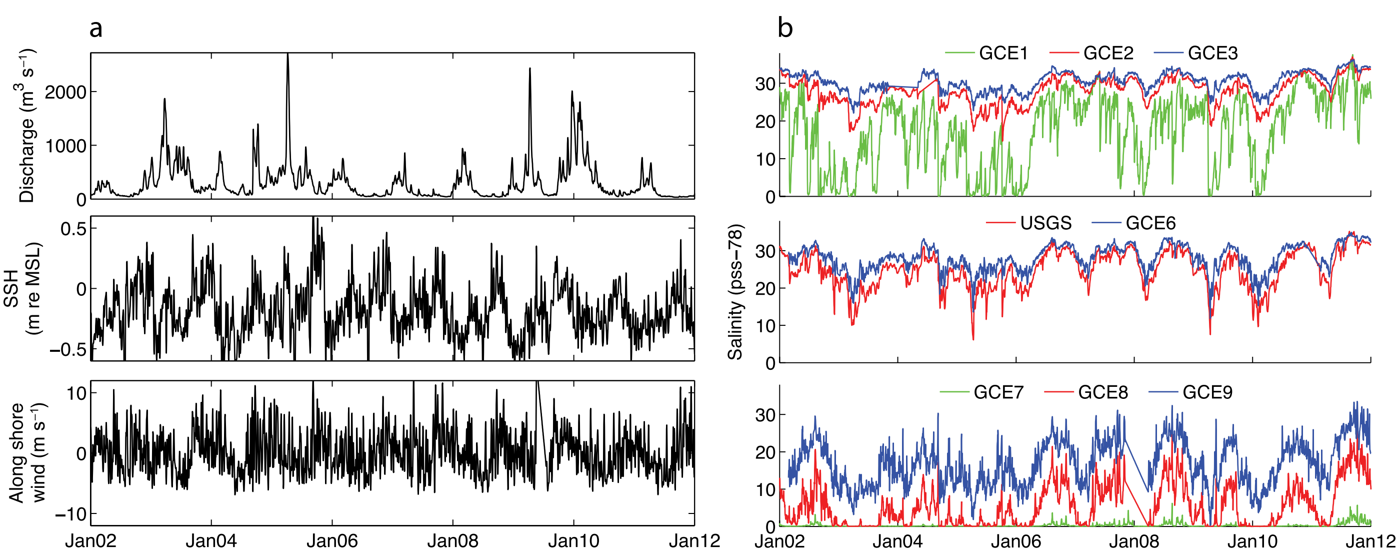

Figure 2. (a) Forcing within the domain is shown as river discharge and sea surface height (SSH, relative to mean sea level) associated predominately with the alongshore winds. (b) Salinity is shown along the longitudinal and meridional gradients within the GCE domain. See Figure 1 for station locations.

characterized by strong seasonal variability (Weber and Blanton, 1980). Hourly wind data from the offshore National Data Buoy Center (NDBC 41008) located at Grays Reef National Marine Sanctuary was collected for the period 2002–2012 and daily averaged quantities were binned into seasonal time frames. Strong Nor'easter storms dominate in the fall (September/October/November), with winds blowing predominantly alongshore, causing downwelling-favorable conditions and onshore transport (Figure 3). In winter (December/January/February), westerly winds are strengthened, but strong storms from the northeast are still relatively frequent. Spring (March/April/May) and summer (June/July/August), on the other hand, are characterized by winds predominantly from the southwest, which are upwelling favorable and promote offshore transport. Throughout the year, alongshore winds dominate over cross-shore winds.

Subtidal sea surface height (SSH) from the USGS station at Meridian, GA, is positively correlated (r = 0.53) with alongshore winds (positive winds from the NNE) and negatively correlated (r = –0.37) with cross-shore winds (positive winds from the WNW) both with p-values < 0.05. The change in inundation in the estuary as a result of changing prevailing winds can be as much as 0.6 m (Figure 2a). During the fall and winter seasons, Nor'easters create downwelling-favorable conditions that promote onshore transport and, hence, inundation in the estuaries. These conditions could cause the Altamaha River plume to thicken and converge on the Georgia coast and move southward. During spring and summer, winds are primarily from the southwest and promote offshore transport and thus reduced sea surface heights. The offshore transport during spring could also be enhanced because of increased river discharge during this time. During these upwelling-favorable winds, the Altamaha River plume could thin and move northward off the Georgia coast. In fact, Blanton and Atkinson (1983) showed that the river-generated low-salinity plume is carried offshore in spring and alongshore and southward in autumn. Winter storms from the west bring the most significant cross-shore winds, and the negative correlation seems to imply that water is forced out of the estuary, causing decreased sea surface heights. In shallow waters where friction is important, cross-shelf winds can result in cross-shelf velocities in the upper few meters of the water column that are similar in magnitude to those generated by alongshelf winds (Tilburg, 2003; Fewings et al., 2008).

Figure 2b shows daily averaged salinity over the GCE domain at each of the long-term monitoring sites. GCE1 in the headwaters of Sapelo Sound shows large changes in salinity that are mainly due to local rain and groundwater input, which is presumably recharged by precipitation. GCE7 in the Altamaha River, located approximately 20 km upstream from the ocean, is almost always fresh except for times of drought conditions.

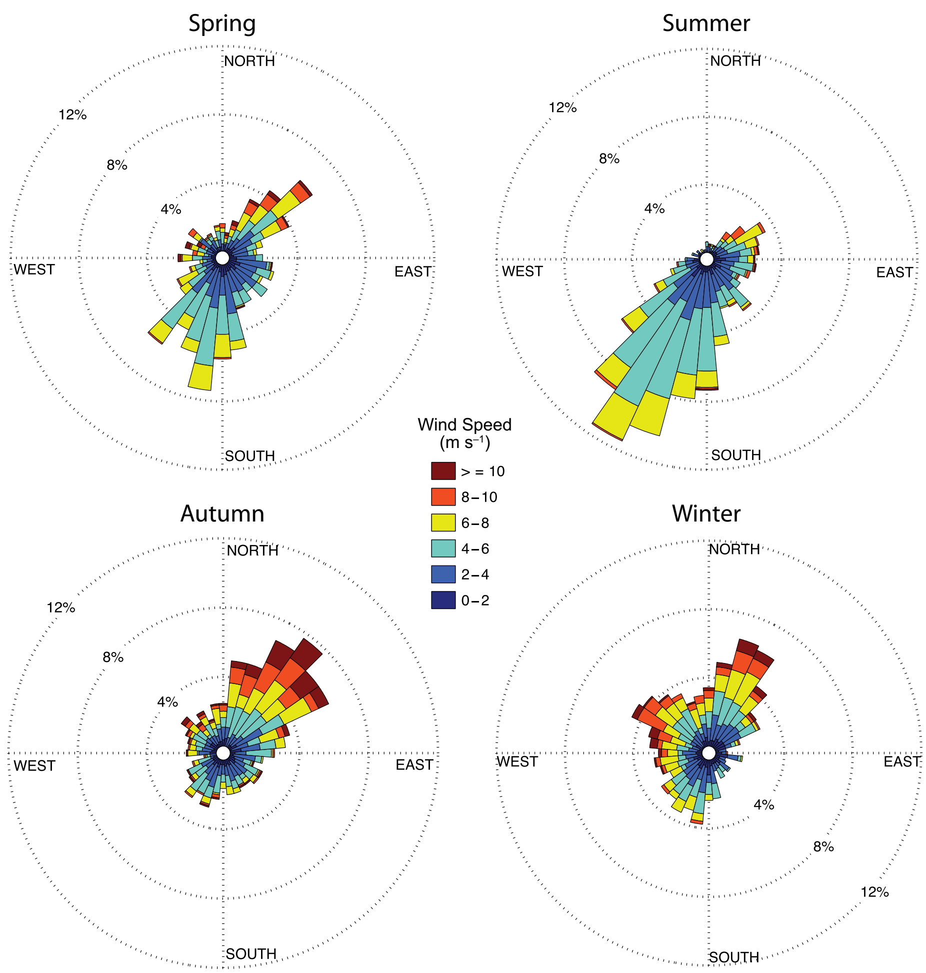

Figure 3. Seasonal offshore wind climatologies for data collected at the NDBC 41008 buoy from 2002–2012. The meteorological convention is used to show the direction from which the winds come.

The remaining stations are also strongly influenced by freshwater and oceanic input and show strong seasonal variability. Significant drought in 2011 and 2012 has caused some of the highest tidally averaged salinities recorded throughout the domain, exceeding 36 at our most oceanic site (GCE3) and approaching 6 at our most freshwater site (GCE7).

Model Setup

We use a periodic implementation of the Regional Ocean Modeling System (ROMS; Haidvogel et al., 2008), with a domain extending 96 km offshore and 52 km alongshore. The grid resolution varies from 50 m in the narrowest channels to approximately 800 m at 80 km from the coast. Over the shelf, the bottom slope $\alpha = 5 \times 10^{-4}$ is constant. Two different representations of the estuarine region are used (see Figure 6), one in which the sounds are connected by multiple channels and one in which a single channel representing the Intracoastal Waterway is used. In all cases, a constant inflow of 200 $m^3\ s^{-1}$ is imposed at the head of the Altamaha River throughout the simulation, except for days 10–17 when it varies gradually in a pulse reaching 700 $m^3\ s^{-1}$. Results are qualitatively similar if the inflow is kept constant at 200 $m^3\ s^{-1}$. For simplicity, no river inflow or groundwater discharge is imposed at Doboy and Sapelo Sounds. The model is forced by tides following Battisti and Clarke (1982) and by alongshore winds at 0.03 Pa oscillating in direction sinusoidally between upwelling and downwelling favorable with a period of 12 days.

RESULTS

Observational Patterns

Empirical orthogonal function (EOF) analysis is used to study the salinity variability using six spatially separated measurements, following the method of Burd and Jackson (2002) who used EOF analysis to understand the modes of variability in nutrient data collected in Florida Bay. GCE1 and GCE7 are excluded from the analysis because variability at those stations is dominated solely by river discharge and/or local rain and groundwater input. For the six remaining sites, two modes explain 95% of the salinity variability, of which the first mode explains 87% (see Figure 4).

The first principal component time series (Figure 4a, top) shows the level of salinity variability throughout the domain when scaled by the spatial components (Figure 4a, bottom). This mode is negatively correlated with river discharge (r = –0.75). The spatial pattern for the first EOF mode shows that the eigenvectors are positively distributed over the whole domain. This result implies that salinity variability throughout the domain is dominated by river discharge, and that increased discharge causes system-wide freshening. Spatial EOF values are higher in the Altamaha River and in the headwaters of Doboy Sound, indicating that river discharge has a greater effect in these locations compared to the more oceanic waters of Sapelo Sound and the mouth of Doboy Sound where EOF spatial values are less.

Because river discharge is the dominate forcing for salinity variability, correlations between the discharge at Doctortown and the full salinity record throughout the domain show average time lags ranging from four days in the Altamaha estuary at GCE8 and GCE9 to 12 days in Sapelo Sound at GCE2 and GCE3. Sheldon and Alber (2005) compute transit time through the Altamaha River using a one-dimensional SqueezeBox model with varying discharge rates and show that Altamaha transit times range from 1–10 days over 54 km of the lower river.

For the second EOF mode, eigenvectors for Sapelo and Doboy are out of

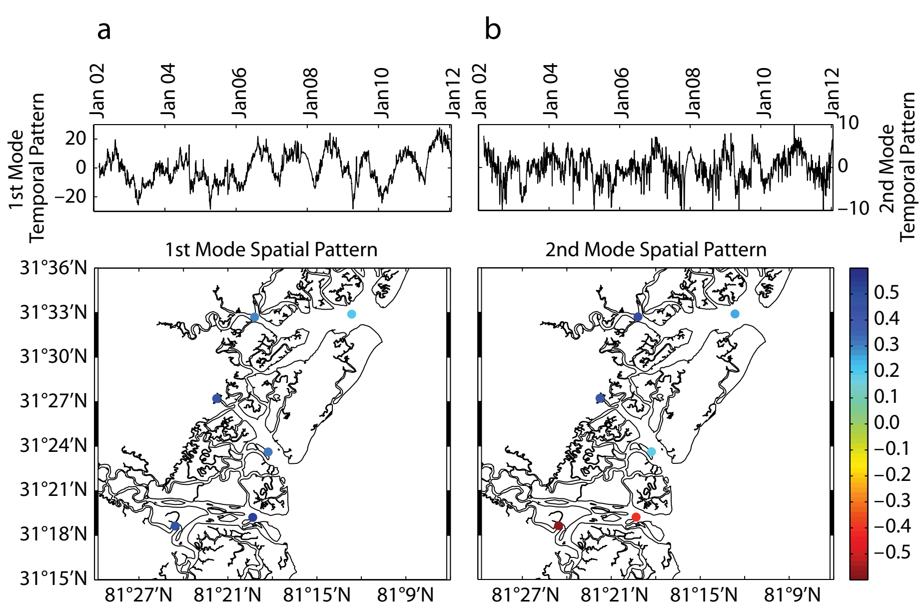

Figure 4. Empirical orthogonal function (EOF) time series and spatial patterns for the (a) first and (b) second salinity modes.

phase with that of the Altamaha River (Figure 4b, bottom). The principal component in this case (Figure 4b, top) is correlated with SSH (r = ±0.4). For the Altamaha River, the results indicate that when SSH increases, salinity increases (positive correlation), whereas in Doboy and Sapelo Sounds, when SSH increases, they freshen (negative correlation). When the SSH increases during Nor'easters, Altamaha River water may be forced through the Intracoastal Waterway or other channels moving freshwater north or may recirculate back in through the sounds from the coastal ocean, freshening the waters in Doboy and Sapelo Sounds. When SSH decreases during upwelling-favorable conditions or during westerly winter storms, Altamaha estuary would freshen as a result of increased offshore transport, and salinity would increase in Doboy and Sapelo Sounds.

Modeling Results

Results from a highly idealized model representation of the Altamaha-Doboy-Sapelo estuarine complex and the adjacent coastal ocean are consistent with those described above. An EOF decomposition of the resulting surface salinity field (Figure 5) reveals a picture that is consistent with the variability observed in the moorings. The first EOF, which explains 82% of the total variance, has the same sign over most of the domain and represents the system-wide freshening caused by the continuous supply of freshwater from the Altamaha River. The second EOF mode explains 12% of the total variance, and it reveals an out-of-phase salinity response between the Altamaha River and Doboy and Sapelo Sounds, again agreeing with the mooring observations (compare to Figure 4).

We further use the idealized model to investigate how freshwater from the Altamaha River is transported to the different estuaries and the coastal ocean by tracking the transport of a passive tracer in the system. The initial dye concentration is set to one in the Altamaha River, and to zero everywhere else in the domain. Additional dye is introduced at the head of the Altamaha River. As such, the dye serves as a tracer of Altamaha River water in the system. Results indicate that the Intracoastal Waterway and other channels connecting the Altamaha River and Doboy Sound play a crucial role in the connectivity between the estuaries. In a simulation where a network of channels connects the estuaries, most of the dye is transported from the Altamaha River into Doboy Sound via those channels (Figure 6, left). As a result, the concentration of the tracer in the coastal ocean is relatively small. In a second idealized simulation, where the same dye flux is imposed at the Altamaha River, but in which the Altamaha River and Doboy Sound are connected by a single channel, most of the dye ends up in the coastal ocean, with much less transport into Doboy Sound (Figure 6, right).

In either case, the exchange of Altamaha River water between the coastal ocean and Doboy Sound via its mouth at subtidal time scales is related to sea level variability at the coast. Analysis of the subtidal total dye flux at the mouth of Doboy Sound reveals a

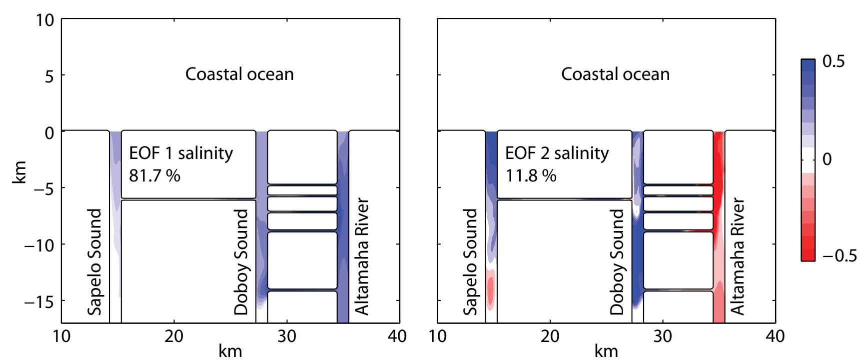

Figure 5. Surface salinity EOF for multiple channels simulation.

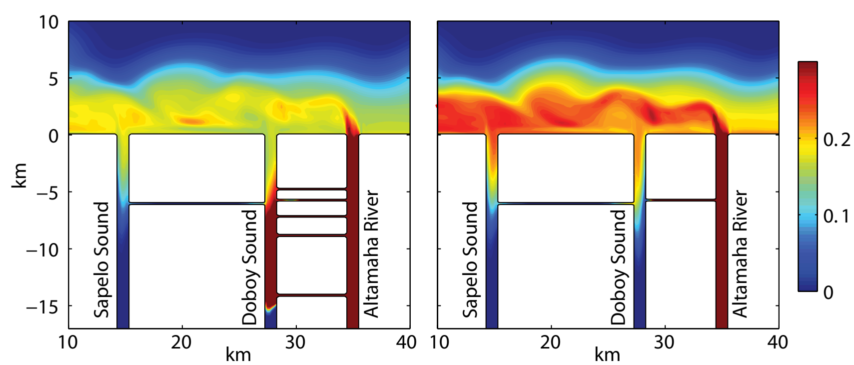

Figure 6. Dye concentration after several days of model simulation. Dye was released at the Altamaha River. Run shows that channels and the Intracoastal Waterway play crucial roles in the connectivity between the estuaries, at least in the idealized model.

tendency for dye to be added to Doboy Sound during high sea level associated with downwelling-favorable winds, and for dye to be removed during depressed coastal sea level due to upwelling winds (Figure 7). These results demonstrate that during periods when coastal sea level is high, low-salinity waters found on the inner shelf and that originated in the Altamaha River flow into Doboy Sound. This leads to a relative decrease in salinity in Doboy Sound, which is consistent with the second EOF mode of salinity based on the mooring observations (Figure 4). It is clear, however, that the subtidal dye flux at the mouth of Doboy Sound is, on average, toward the estuary in the simulation where the Altamaha and Doboy Sound are connected by a single channel, while the average subtidal dye flux is offshore when the estuaries are connected by multiple channels (Figure 7). This is because in the multiple-channels scenario, dye is also transported into Doboy Sound via those channels. Once the dye concentration in Doboy Sound exceeds the concentration in the coastal ocean (e.g., Figure 6), the tracer begins to be exported offshore. In the single-channel scenario, on the other hand, only 4% of the water that originated in the Altamaha River and is found in Doboy Sound flows directly from the river through the Intracoastal Waterway. Most of the river water (~ 96%) first flows into the costal ocean before flowing into the sound by the tidal and exchange terms in the subtidal balance (Lerckzak et al., 2006). This leads to a positive averaged subtidal total dye flux at the mouth of Doboy Sound (i.e., toward the estuary; Figure 7).

DISCUSSION AND CONCLUSIONS

Long-term observations and highly idealized numerical model simulations reveal a large degree of water exchange between interconnected estuaries in the Georgia Coastal Ecosystem LTER domain. This highly complex estuarine system, with sounds connected by a network of channels, creeks, and intertidal areas, is expected to also present large spatial and temporal variability in residence time. The residence time—the average time a water particle spends within the estuary or in some portion thereof (Geyer and Signell, 1992)—is one of the most important factors influencing water contamination and nutrient levels, distributions of organics, and their spatiotemporal variations in bays and estuaries (Aikman and Lanerolle, 2004). In fact, model results show that the fraction of nutrients entering an estuary that is exported or denitrified can often be predicted from the freshwater residence time (Dettmann, 2001). Additionally, large residence times have been implicated in the outbreak of harmful algal blooms (Bricelj and Lonsdale, 1997). Processes that influence the transport of nutrient-rich riverine waters (approximately represented by the dye distribution shown in Figure 6) are crucial for understanding water quality in estuaries.

To date, several studies have quantified residence and flushing times in Altamaha Sound (Alber and Sheldon, 1999a; Sheldon and Alber, 2002), including low-frequency variability possibly associated with surface water withdrawal (Alber and Sheldon, 1999b). However, those studies did not address the potential for circulation to the Doboy and Sapelo estuaries. Recent estuarine modeling studies show that the exchange flux with the coastal ocean can be highly dependent on the exchange flux between interconnected estuaries, and that nonlinear tidal rectification can set up clockwise or counterclockwise exchange flow between estuaries and the coastal ocean (Zhao et al., 2010). The idealized modeling in the GCE suggests that if it weren't for multiple channels connecting the estuaries off Georgia (see Figure 1), most of the nutrients delivered by the Altamaha River would end up in the coastal ocean, with some small fraction recirculating back through the sounds. The multiple channels connecting the river and the adjacent sounds, however, strongly increase water exchange so that most of the nutrient-rich riverine waters get transported to Doboy Sound, thus increasing the residence time of the estuarine complex. In the GCE domain (Figure 1), connectivity is most likely somewhere between the two extreme cases represented by the idealized modeling.

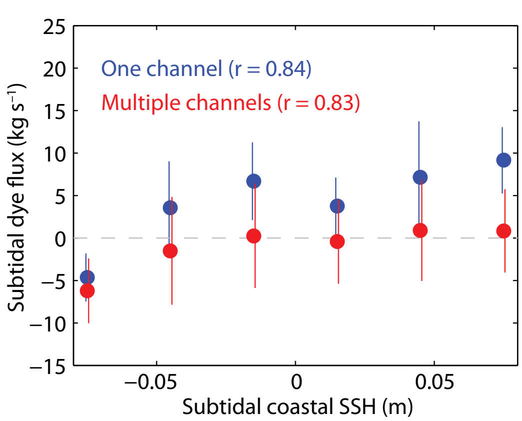

Figure 7. Binned scatterplot of subtidal total dye flux at the mouth of Doboy Sound as a function of subtidal coastal sea surface height (SSH). Positive values represent flux up the estuary.

Despite its great simplicity, it is encouraging to see that the idealized model of the GCE domain is able to capture the dominant modes of salinity variability in the system, including the out-of-phase response observed in the Altamaha River and Doboy and Sapelo Sounds. Further work in this region will involve the development of a realistic model of the domain together with seasonal measurements of the exchange flow with the coastal ocean that will be used to better constrain the dominant processes controlling connectivity in this complex system.

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