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**SHORT COMMUNICATION**

# OBSERVATIONS OF LATERAL SALINITY VARIABILITY AT A DELTAIC—BAY TRANSITION ZONE, MOBILE BAY, ALABAMA§

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KEY WORDS: Estuaries, Estuarine geomorphology, Ship channel, River discharge, Bathymetry modifications

## INTRODUCTION

Estuaries are complex systems in which freshwater and saltwater interact. In a typical estuary, stratification is dictated by salinity, where freshwater overlays saltwater. Salinity is a critical environmental characteristic that influences estuarine habitats because flora and fauna have salinity tolerances beyond which they are unable to survive (Elliot and Quintino 2007). Therefore, salinity exposure across estuarine regions can alter the habitats and ecosystems in these areas.

Salinity distribution is typically controlled by estuarine circulation and accompanying mixing (Valle—Levinson 2011). Typical drivers of estuarine circulation and mixing are river discharge, tides, and wind forcing (MacCready and Geyer 2016). However, the response of different estuaries to these drivers is very sensitive to the geomorphology of the estuary (Wong 1994, Lerczak and Geyer 2004). For example, wide estuaries relative to the Rossby radius of deformation, i.e., large Kelvin number systems, can have significant lateral salinity variability with fresher conditions on the left side of a given cross—section (from an inward—looking perspective). Salinity changes can also be associated with the complexities of multiple freshwater pathways, i.e., distributary rivers, in deltaic regions and/or construction of ship—channels (e.g., Chubarenko and Tchepikova 2001). Consequently, natural and anthropogenic bathymetric features may alter salinity distributions in estuaries.

Salinity variation and the associated distance that salinity moves inland, i.e., salt intrusion, result from the combination of river discharge, water depth, and estuarine circulation (Cook et al. 2023). Specifically, stronger river inflow will reduce salinity intrusion, yet it will also amplify the estuarine circulation, which in turn will lead to a stronger bottom return (shoreward) flow of oceanic water up the thalweg of a system. These interactions are modified by ship channels as the deepening of the system typically allows salt to penetrate further inland due to the enhanced baroclinic forcing, e.g., Savanah River channel deepening (Mendelsohn et al. 1999).

As a result, natural and anthropogenic modifications complicate our understanding of expected salinity dynamics within a typical estuary. To add a perspective on this issue, salinity patterns at 2 geomorphically complex water quality stations within the Mobile Bay estuary, AL were investigated under a range of forcing conditions. Clear lateral differences in the system were observed and these differences are speculated to be attributed to a specific system feature, i.e., proximity to a ship channel.

## MATERIALS AND METHODS

### Study Site

Mobile Bay provides an excellent location to investigate the role of geomorphology in estuarine salinity patterns (Figure 1).

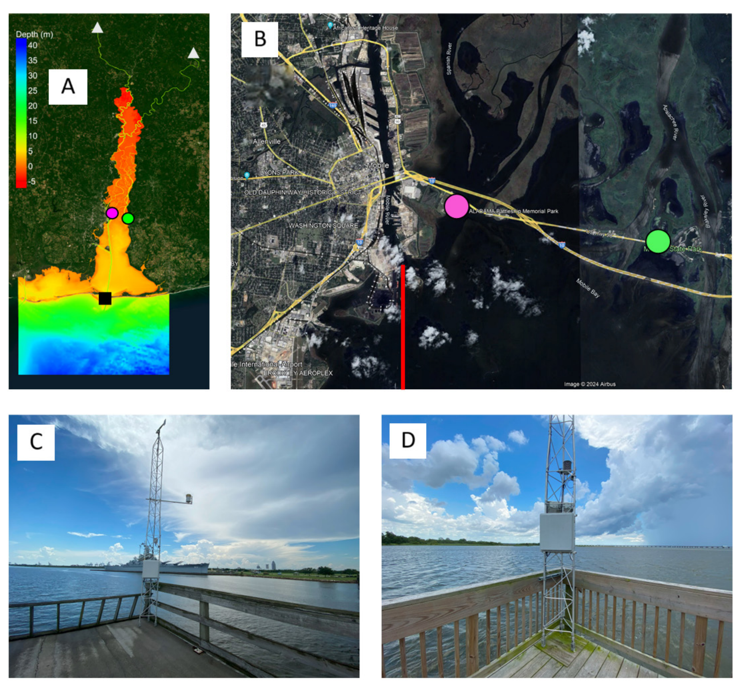


***FIGURE 1.*** *Area of study in the Mobile Bay and lower Mobile-Tensaw Delta, AL. A. Entire Mobile Bay and lower Mobile-Tensaw Delta with the associated bathymetry, showing USGS gage stations Alabama's Real-Time Coastal Observing System (ARCOS) (▲), Battleship Park (BSP) (30°40′ 57.65″ N) (●), Meaher Park (MP) (30°40′ 22.76″ N) (●), and Dauphin Island water level station (■). B. Enlarged view of upper Mobile Bay showing shipping channel (red line) relative to BSP and MP stations. C. Specific EXO2 sonde data collection site at BSP. D. Specific EXO2 sonde data collection site at MP. Satellite image from Google Earth Pro.*

§ *The first author conducted this research as part of the Dauphin Island Sea Lab's Research Experience for Undergraduates in the coastal and nearshore marine science program.*

The system is considered a drowned river valley estuary located in the northern Gulf of Mexico with an average depth of 3 m. However, there is a narrow (120 m wide) and deep (12—15 m) ship channel that runs the length of this system leading into the Mobile River on the western side of the head of the bay. The head of the bay is defined by a transition region where the relatively wide, open expanse of Mobile Bay shifts into a complex network of interconnected freshwater rivers, creeks, lakes, wetlands, and bayous that make—up the Mobile—Tensaw Delta. This transition zone of the lower Mobile—Tensaw Delta is impacted by 5 rivers, namely the Mobile, Spanish, Tensaw, Apalachee and Blakeley Rivers, and thus provides freshwater into the bay from multiple river channels. The system is impacted by diurnal, micro—tidal conditions with a tidal range varying from ~0.0 to 0.6 m and large river discharge with an annually averaged daily value of 1,866 $m^3/s$ (Dykstra et al. 2022). There is significant seasonality in the river flow with late winter and early spring being the peak discharge period. Overall, the geomorphological features at the head of Mobile Bay might be expected to generate large lateral differences in salinity characteristics and responsiveness to different forcing conditions.

**Data Collection**

Data on the physical conditions in Mobile Bay were collected at multiple locations from February 2023 to June 2024. Two Alabama Real—Time Coastal Observing Systems (ARCOS) stations in upper Mobile Bay with about the same latitude (30°40' 40.00" N) collected salinity data every 30 min during the study period (Figure 1A). Site 1, Battleship Park (BSP) (30°40' 57.65" N), is located closer to the shipping channel and Site 2, Meaher Park (MP) (30°40' 22.76" N), is located further from the shipping channel (Figure 1B). These data were collected by YSI/Xylem EXO2 sondes with conductivity, temperature and pressure probes. The EXO2 sondes were 0.5 m above the bottom in ~4.0 m and 3.8 m of water for BSP and MP, respectively. These data were recorded internally as well as delivered in near real—time to a cloud—based server via cellular telemetry package. The data were reported using the Practical Salinity Scale (conductivity ratio), which is unitless. The study period was selected as this was the longest duration over which sampling at these 2 stations overlapped.

Forcing data that would be expected to impact salinity conditions in the bay were also collected. River discharge data was acquired from 2 USGS gauging stations: the Claiborne Lock and Dam (USGS station 02428401) on the Alabama River and Coffeeville Lock and Dam (USGS station 02469762) on the Tombigbee River. Water level data were acquired from a NOAA tidal station (NOAA station 8735180, Dauphin Island, AL; Figure1A). While wind forcing is known to be important in Mobile Bay (Coogan and Dzwonkowski 2018), the system response is beyond the scope of this note.

**Methods and Analysis Tools**

Time series and regression analyses were conducted to better understand patterns in the salinity and their associated drivers. Standard quality control flags were associated with each data parameter from which only the highest level of data were selected. Visual inspection of the data was conducted to assess the overall patterns in the dataset. For salinity data, 3 short anomalous drops to zero were removed during the saltiest period (durations of 0.5 h in September, 5.5 h in early November, and 0.5 h in mid—November) at the BSP site and were filled using linear interpolation. Daily averages were calculated to match the discharge data. Investigation of the monthly variability in the salinity data was conducted using monthly means and associated standard errors.

To minimize the impact of serial correlations in the standard error calculation, a decorrelation factor of 5 days was used. The decorrelation factor was qualitatively estimated considering weather band (~2—15 days) and tropic—equatorial tidal cycle (~14 days) time scales. The decorrelation time scale is generally consistent with the analysis of Dzwonkowski et al. (2011), which used a minimum decorrelation time scale of 2 days for 40 h low—pass filtered data in the study region. As such, a 5 d decorrelation time scale is expected to be a reasonable first order estimate for this factor. Degrees of freedom were determined by dividing the total daily measurements within a monthly average by 5 days.

All time—series analyses were conducted using MATLAB. To analyze the salinity response to discharge conditions, power regression analysis of salinity and river discharge were calculated using Excel. This analysis was conducted with a 2 d lag time between the discharge and salinity data to account for the transit time from the river gauges to the water quality stations. For tidal forcing, daily maximum tidal heights were extracted from the hourly harmonic prediction at the NOAA tide gauge and then visually compared to daily salinity patterns to identify potential response patterns.

## Results

**Salinity Variability**

During the 17—month observation period, salinity ranged from 0 to 30 at BSP and 0 to 15 at MP. There were similar patterns in daily average salinity at both BSP and MP from February 2023 to June 2024 (Figure 2A). Both stations displayed clear seasonal patterns with lower salinities from mid—winter to early summer and higher salinities from late summer to late fall. Though these patterns were relatively similar, there were some notable differences. There was a clear magnitude difference, with higher salinity values at BSP. In addition, BSP had greater short—term variability, with much larger multi—day oscillations. For example, there was a difference in the short—term salinity variability from August through September 2023 and December 2023 through January 2024; salinity fluctuations of 5—10 were observed at BSP that were not present at MP.

Mean salinity levels were notably different between BSP and MP in every month except January 2024, where there was overlap in the standard errors (Figure 2B). These differences between BSP and MP indicated that there was lateral salinity variability between these 2 sites, with the site closest to the shipping channel (BSP) having higher levels of salinity.

**Salinity Drivers**

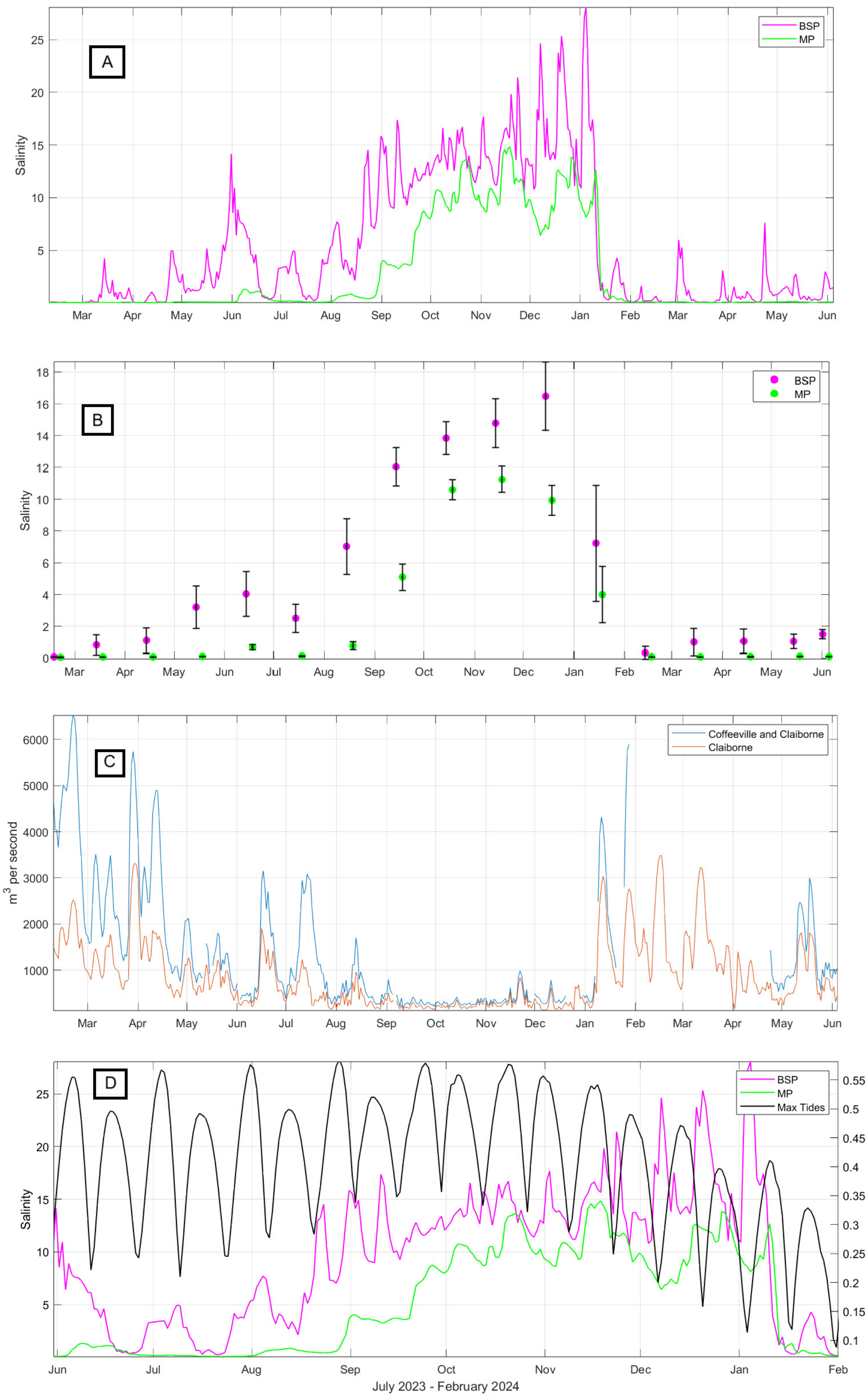


***FIGURE 2.*** *Salinity profiles at Battleship Park (BSP) and Meaher Park (MP) sampling stations. A. Daily average time series analysis of salinity. B. Mean (± se) monthly salinity at BSP and MP. C. Daily average timeseries analysis of river discharge ($m^3$ per second) from February 2023 to June 2024 from USGS gauging stations at the Claiborne lock and dam on the Alabama River and Coffeeville Lock and dam on the Tombigbee River. D. Daily average salinity at BSP and MP with daily maximum tides from July 2023-February 2024.*

To better understand the salinity variability at the 2 stations, river discharge into Mobile Bay was investigated as a first order driver of salinity dynamics. River discharge from February 2023 to June 2024 displayed notable variability with higher levels of discharge in the winter/spring and lower discharge in the summer/fall (Figure 2C). During periods of higher river discharge there were lower salinity levels at both BSP and MP. When levels of river discharge were lower, during August through December 2023, salinity levels were higher (Figures 2B, C).

To better quantify the inverse relationship between salinity and river discharge, a power law regression analysis was conducted (Figure 3). As suggested by the time series, both stations showed an inverse relationship with differing sensitivity to river discharge. While there were deviations around the power law fits, the $r^2$ values of 0.48 and 0.34 for BSP and MP, respectively, explain notable portions of the variance.

**Tidal Forcing**

To further understand other factors contributing to salinity variability, a potential second order interaction driven by tidal forcing was analyzed. The analysis focused on the period from July 2023 to February 2024 when the highest levels of salinity were observed at the sites (Figure 2D). During this time, there is a tropic—equatorial tidal cycle as expected in a diurnal system with high tidal height periods every ~14 days. This cycle is similar to the spring—neap tidal cycle in semi—diurnal systems. At the BSP site during mid—August to mid—September 2023 and late November through December 2023, water level height co—oscillated with the salinity.

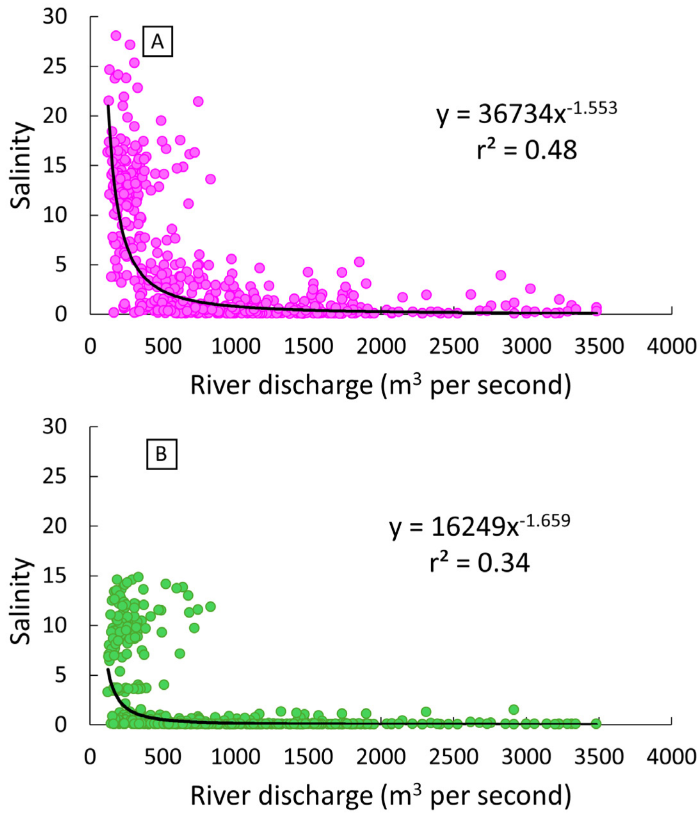


***FIGURE 3.*** *Power regression of daily average river discharge ($m^3$ per second) and salinity. A. Battleship Park station. B. Meaher Park station.*

During these periods, stronger tides coincided with lower salinity, and weaker tides coincided with higher salinity. However, this inverse relationship between tides and salinity was only seen at BSP.

## Discussion

### Potential Drivers of Lateral Variability

Observations from BSP and MP indicate that BSP had greater salinity variability than MP. Several geomorphological features of the system may contribute to this observation. The ship channel is an anthropogenic modification that creates a large conduit for salt intrusion, which can lead to an increase in salinity on the western side of Upper Mobile Bay (Schroeder et al. 1996). An additional complicating factor is the multiple sources of river discharge exiting into the head of the bay. Flow routing of freshwater through the delta is further complicated by the presence of the 'causeway', a low—lying roadway which modifies flows at the head of the bay. While salinity at the 2 parallel sites showed notable differences, the exact cause of these differences is difficult to isolate through observations alone.

The persistent salinity stratification that is maintained in the ship channel provides a source of salt to BSP, which is likely the primary driver of this lateral variability. Specifically, the deeper ship channel enhances the baroclinic pressure gradient, which in turn advects saltier water further into the estuary relative to conditions on the shallow shoals. This difference in the longitudinal advection of salt generates lateral gradients (i.e., lateral variability). In general, this increased salting from a ship channel is consistent with findings in other systems with ship channels, e.g., Savannah River Estuary (Mendelsohn et al. 1999) and Delaware Bay Estuary (Cook et al. 2023).

### Coupling of Salinity Intrusion and Discharge

Observations showed that river discharge was the main driver that influenced salinity variability at the 2 stations measured in this study. The relationship between salinity and river discharge displayed an inverse power relationship where salinity rapidly dropped in response to increasing discharge at both sites. These findings are consistent with the behavior of salinity intrusions, which have shown an inverse power relationship with discharge (Monismith et al. 2002, Ralston et al. 2008). Not surprisingly, the exponent defined in this study is different than that for salt intrusion length, e.g., $Q^{-1/3}$ from theory (Ralston et al. 2008) and $Q^{-1/7}$ from observations in this system (Coogan and Dzwonkowski 2018) as this study is focused on salinity at fixed stations and not the overall extent of salt into the system.

### Tropic—Equatorial Variability in Salinity Response

Despite Mobile Bay being a micro—tidal system, there is some evidence of tidal modulation of the low frequency salinity patterns. The inverse oscillations of the water level and salinity at BSP during several brief periods is consistent with the expected tidal forcing where enhanced (reduced) mixing during tropic (equatorial) tides should decrease (increase) the salt intrusion (e.g., Ralston et al. 2010). However, this relationship was not observed during the entire study period and was only observed at BSP. This finding suggests substantial spatial and temporal variability in the importance of tidal forcing on the salinity dynamics in this region of the bay. The inconsistency in these response patterns is likely due to along—estuary variability in the strength of salinity gradients, which can be influenced by a number of factors including wind forcing and/or coastal ocean conditions at the seaward boundary of the system.

## Conclusions

A time series analysis of salinity at 2 stations found notable spatial variability at the head of Mobile Bay where the system transitions from a deltaic river system into a more conventional estuary. While both sites responded similarly to river discharge, the site adjacent to the ship channel (BSP) was saltier and, at times, appeared to be influenced by tropic—equatorial cycles in the tides. Improving the understanding of salinity dynamics in such complex regions is of general importance but is of particular interest in Mobile Bay given its direct connection to the Mobile—Tensaw Delta, one of the most biodiverse locations in North America (Elliot 2020). Without such knowledge of salt intrusion, potential changes to this unique ecosystem will be difficult to anticipate from continued modification of the ship channel as well as from climate change.

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