Imperial River and Estero Bay Circulation: Estimation of Pressure Gradient and Frictional Forcing Based on Flow Monitoring

Key Words: Estuary, Estero Bay, Imperial River, Barotropic, Baroclinic, Navier Stokes Equation

Abstract

Estuaries are dynamic water bodies with numerous physical and chemical influences dominated by estuarine circulation. The ecosystem is highly sensitive to circulation changes, which itself is controlled by tides, wind, and river hydrology. Frictional drag and barotropic and baroclinic pressure gradient forces were quantified to determine the tidal dominance in driving circulation within Estero Bay, Florida and the lower reaches of the Imperial River that joins into the estuary. As freshwater input for this estuary is seasonal in nature, tides control the estuarine dynamics particularly during the dry season. The study made an attempt to evaluate the tidal circulation characteristics of this shallow estuary during spring and neap tidal conditions.

Introduction

Of the 2173 km coastline of Florida, approximately three quarters is comprised of estuaries. The Charlotte Harbor Estuarine system encompasses the southwestern coast of Florida and within it are several small estuaries. This estuary system spans an area of approximately 518 km of coastline. It is a key habitat for fish, birds, mangroves, oyster reefs, and various other marine and endangered species. Estuaries can originate in four different ways: drowned river valleys, fjords, bar-built estuaries and tectonic estuaries. The Estero Bay is a bar-built estuary, created when ocean-born sediments were transported and deposited as sandbars and barrier islands along the coast. Rivers empty freshwater and sediments into these protected water bodies blending freshwater with ocean water. Critically important is their function as nurseries for larvae and juvenile species (Vasconcelos et al. 2011). Since estuaries are able to provide for multiple species at one time, growth and survival is enhanced by the high productivity found in estuaries and their relatively turbid waters that prevent predation (Nagelkerken et al. 2000, Vasconcelos et al. 2011). In providing shelter and protection for many species, estuaries foster safe refuge from predators

and ample food sources generating large fish stocks and profitable fisheries along coastlines. Seagrass beds, mangroves, and oyster bars thrive in estuaries, adding to their high productivity.

Estuaries differ in characteristics including length, depth, tidal range, freshwater input rate, and their geometry. They are defined, not only geologically, but also by their circulation patterns. Estuarine circulation is critically important in nutrient cycling, sediment transport, temperature effects, dissolved oxygen content, current speeds and economic factors. A typical estuarine circulation pattern is the seaward current above a landward current. Estuarine circulation can be created by horizontal salinity gradients and wind-driven motions (Xie and Eggleston 1999). Shallow estuaries are greatly influenced by wind blowing over the surface, driving circulation patterns (Schoen et al. 2014).

In addition to the tide-generated water surface elevation gradient, the driving force of the estuarine circulation is the horizontal salinity gradient $\partial s / \partial x$, which induces a vertically varying pressure gradient (Geyer 2010). Mixing of freshwater and ocean water within the estuary determines the distribution of salty waters and the mixing process can be advective or dispersive (Snedden 2016). Through barotropic currents induced by gradients in water surface elevation such as those caused by wind or tidal forcing, advection occurs as salt is displaced by net flows produced by the tidal cycle. Advection also occurs via baroclinic currents induced by longitudinal density gradients, causing the more dense saline water to flow landward near the bottom. Dispersive processes occur when a net transport of salt occurs over a tidal cycle even though there is no net movement of water (Snedden 2016).

The estuary that we studied, Estero Bay, is a bar-built, shallow water estuary located in the Southwest Florida. During the dry season, or non-summer months, it exhibits characteristics of a lagoonal estuary where tidal influences are strong and the tidal range observed is less than 1m for most of the time. The estuary experiences a mixed tidal cycle that, as prefaced above, greatly impacts productivity (Kellmeyer and Salmon 2001). The purpose of this study is to quantify the effects of tide and horizontal gradient in salinity and temperature on estuarine circulation during spring and neap tides. Importance is placed on tidal influences and bottom friction as it has been found that the transverse structure of exchange flows in many estuaries is sensitive to friction, which is significantly affected by tidal forcing. Incorporation of this tidal forcing is crucial when properly simulating estuarine circulation (Guo and Valle-Levinson, 2007).

This study was conducted during fall 2017, as a class project during the Physical Oceanography course (OCP 3002C) at Florida Gulf Coast University. The objective of the study was to introduce Marine Science Undergraduate students to various hydrodynamic forcings that drive estuarine circulation; by measuring salinity, temperature, current speed & direction, etc. from multiple locations along a stretch of the estuary. Study also would help to understand the effect of spring-neap tidal cycles on the tidal currents and mixing processes in a shallow partially mixed estuary

Materials and Methods

Field data collection for this study was conducted on the Imperial River and southern reaches of the Estero Bay, located in Bonita Springs, Florida (see Figure 1). Observations were made from none sites along the estuary and the river; beginning at the southern end of Estero Bay and proceeding up in the Imperial River (see Figure 1 for the station locations). At each site, geographical coordinates were recorded using a GPS system mounted on the vessel. A hand-held YSI meter was then lowered into the water to collect data from top of the water column (0.15 m below surface) and near bottom (0.15 m above bed). The YSI meter was used to obtain: temperature (°C), dissolved oxygen (mg/L), and salinity (ppt). After the YSI readings were recorded into lab notebooks, an acoustic current meter was lowered into the water column to collect current speed and direction from the two corresponding water depths. Water depth was collected using SONAR mounted on the boat. Wind speed was measured using a digital hand-help anemometer and direction was visually estimated.

Figure 1: Marked locations where measurements were gathered in Estero Bay and the Imperial River. Red dots represent study area section 1 (sites 1-5) and green dots represent study area section 2 (sites 5-9).

These procedures were repeated at all nine sites over the course of 4 field trips, two during a Neap tide, and two during a Spring tide. Approximately 7 students went out on the research boat during each trip to collect the measurements. In order to compare the circulation dynamics of the estuarine environment with that of the lower reaches of the river, study area has been divided into two sections. Stations 1-5 represent the estuarine environment and stations 5-9 represent the lower reaches of Imperial River (see Figure 1).

Using the collected temperature and salinity data, density of the water was calculated using equation (1), Knauss (1997). Salinity, temperature, density, flow velocity and DO were compared between the surface and bottom during the ebbing and flooding phases of spring tide and neap tide. Also, the data were further processed to solve a simplified version of Navier Stokes Equation to estimate the barotropic and baroclinic pressure gradient forces and thereby the elevation difference (head) for the two aforementioned sections of the study area that represent estuarine and riverine dominance.

$$\rho = 1000 - 0.15 * (T-10) + 0.78 * (S-35) \qquad\qquad 1$$

where 'T' is temperature (°C) and 'S' is salinity (psu).

To calculate baroclinic density gradient, aerial distances between stations 1&5 and 5&9 were calculated using ruler tool in Google earth.

$$\textbf{Baroclinic pressure gradient force} = -H(g/\rho_0)(\Delta\rho_x/\Delta x) \qquad\qquad 2$$

where 'H' is the average depths of the two stations, 'g' is gravity (9.8 m/s^2), 'ρ_0' is the mean of all four density measurements (top and bottom at both stations), '$\Delta\rho_x$' is the difference in the vertically averaged densities between both stations, and 'Δx' is the measured distance between the two stations.

Friction from the bottom due to the current was estimated using equation (3)

$$\textbf{Vertically averaged frictional drag on flow} = C_d * (u^2/\text{depth}) \qquad\qquad 3$$

where the 'u' is the average current speed from top and bottom of the water column and drag coefficient (C_d) is assumed to be 0.003, for a fine sand bottom substrate.

Barotropic pressure gradient force is due to a sloping sea surface from wind, tidal convergence etc. Dye et al. (2018) reported that wind contribution in the Estero Bay circulation is less than 5% on average. So the barotropic forcing is entirely due to the tidal convergence and their relaxation at the inlet entrances. Because surface slopes change in elevation very slightly over short distances, slope is estimated by assuming the water body is at a relatively steady state and thus having no acceleration: total Acceleration = 0 = Surface Slope force + Density Gradient force + Friction force

$$0 = -g\frac{\partial\eta}{\partial x} + -H\frac{g}{\rho_0}\frac{\partial\rho_x}{\partial x} + -C_d\frac{(u^2)}{depth} \qquad\qquad 4$$

where dx is distance along estuary, g = 9.8 ms$^{-2;}$ H is average depth from the two terminal stations of the study sections; ρ_0 is average density between the two corresponding stations; u is the current velocity from top and bottom (four measurements were averaged); and $\partial\rho_x$ is the horizontal change in density between the two stations. Solve for $\partial\eta$ to find difference in water level elevation between the terminal stations of the two separate sections of the estuary that has been monitored.

Results

Time series of measured data on salinity, current speed (from top & bottom), water temperature, Dissolved Oxygen are provided below. The morning trip during the Neap tide (10/19/2017) had the lowest salinity values all along the study area; while the morning survey during the Spring tide (11/7/2017) had the highest salinity measurement of 8.52 ppt at station 1 (see Figure 1 for station locations). There is an obvious decrease in salinity from station 1 to station 9 as data was collected from Estero Bay into the upper reaches of the Imperial River. At station 4, there is a significant variability in salinity values observed as this can be seen as the transitional point between estuarine and river environments. Also, this shallow station is located at the middle of the Fish Trap Bay, which is being influenced by wind-induced turbulence and mixing processes.
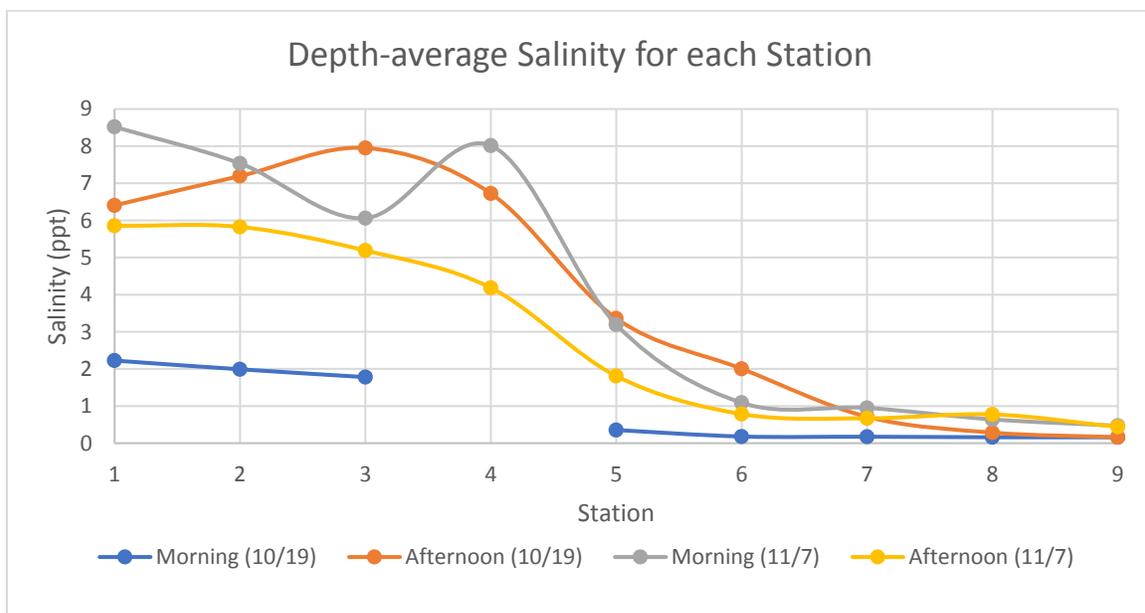

Figure 2: Salinity data collected from the study area during the four surveys. Please note the decreasing trend in salinity from the mouth of the Estero Bay moving up the Imperial River. Data were collected during Spring tide (10/19) and neap tide (11/7).

Current measurements are provided as separate plots for the spring and neap tide surveys. Surface and bottom currents are observed to be very strong at stations 2 during the ebbing and flooding phases of the neap tide on 10/19 (Figure 3). This station is located at the middle of a narrow creek, which amplified the flow to maintain the flow continuity in the estuary. Also, station 7, which is located near the confluence of two creeks, shows stronger currents during the ebbing phase of the neap current. Current speed measured from the Imperial River segment of the study area, both from the surface and the bottom, shows no particular trend, with higher values observed at the surface. River is deeper at stations 8 and 9, which also resulted in a uniform trend in the flow dynamics.

Data from the spring tide surveys (11/7) again demonstrated that currents were stronger at station 2, middle of the narrow creek that connects Fish Trap Bay with the Estero Bay. Also, except for the afternoon survey, strong currents were measured from station 5, southern end of the Fish Trap Bay, which can be attributed to its location at the entrance to a restricted section of the Bay that connects the Fish Trap Bay with Imperial River. Also, wind induced drag over the open waters of the Fish Trap Bay could amplify the currents in this shallow section of the estuary.
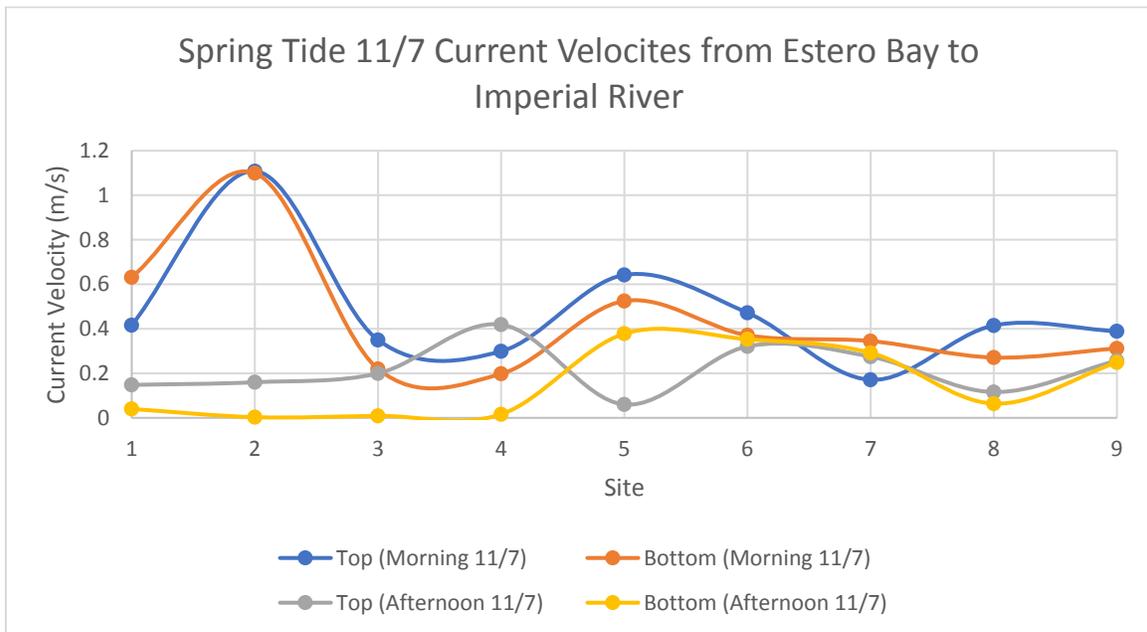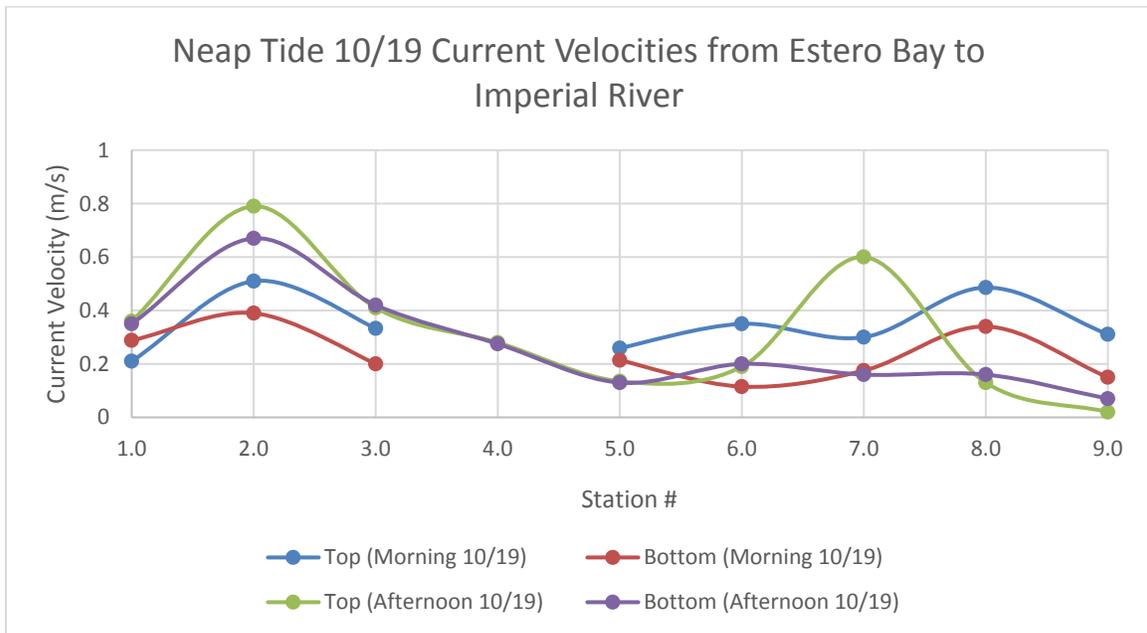
Figures 3 and 4: Current velocity comparisons are made between neap and spring tides along the entire study area; from the mouth of the Estero Bay to a location up the Imperial River.

Vertically averaged water temperature data is provided in Figure 5. It is interesting to note that the vertically averaged temperature shows uniform values along the entire stretch of the study area, with a maximum variability of 0.5^0C from the mean. Also, when comparing all the four surveys, the mean temperature varied ~ 3^0C between the highest and lowest values. Highest temperature was recorded during the afternoon survey on 10/19 while the lowest temperature was recorded during morning of 11/7 spring tide survey. This temperature distribution data clearly indicates that water is sufficiently mixed in this shallow estuary and that tide is the dominating force that drives the estuarine circulation.
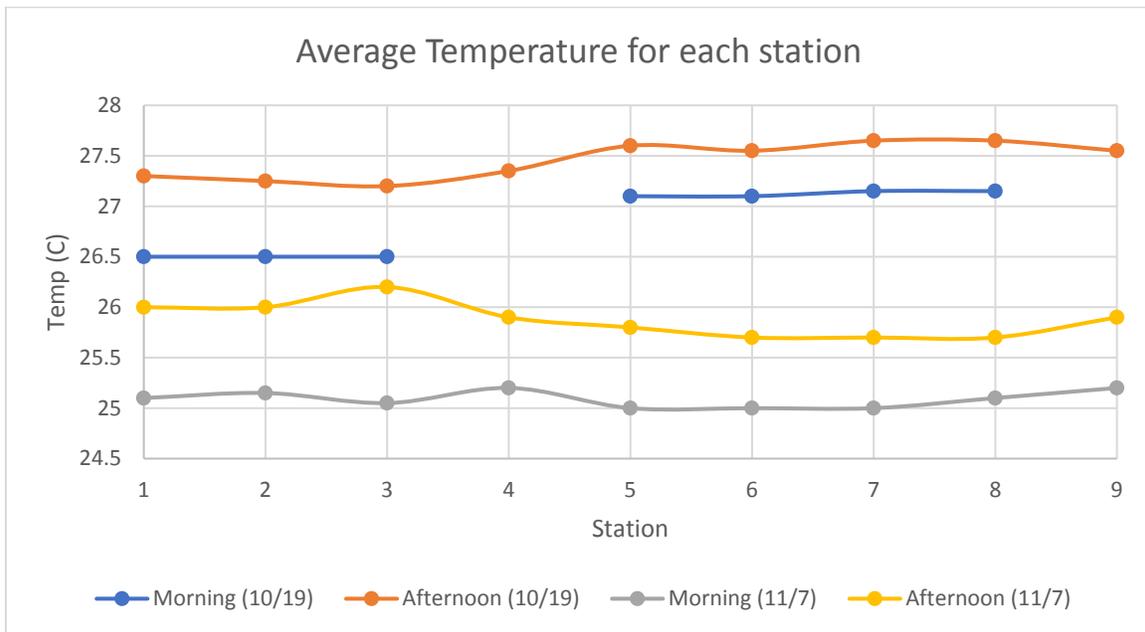

Figure 5: Time series of vertically averaged water temperature along the study area. Highest and lowest measured temperatures, corresponding to different phases of spring and neap tide, varied only by 3ºC.

Figure 6 provides the computed water density from the study area. It is evident that water density follows the measured salinity pattern as the water temperature shows no spatial variability. Brackish water is getting into the lower reaches of Imperial River through the narrow Creek, represented by stations 1,2 and 3. Water salinity and density in the Fish Trap Bay also shows comparable values as that in the estuarine environment. However, water density from stations 5-8 shows the dominance of freshwater influence. Figure 7 provides the vertically averaged dissolved oxygen (DO) concentration in the study area during the spring and neap tidal phases. It is to be noted that DO is generally higher in the estuarine side than the fresh water section of the River. DO concentration varies significantly during the flooding ebbing phases of the spring tide, in comparison with that of the neap tide. This can be attributed to the sheer volume of well mixed marine water from the west Florida Shelf, getting into the estuary during a spring tide. Even though

fresh water could hold more DO than salty water, vertical mixing of oxygenated surface water happens more often in the open estuaries and bays than in the constricted river channels.
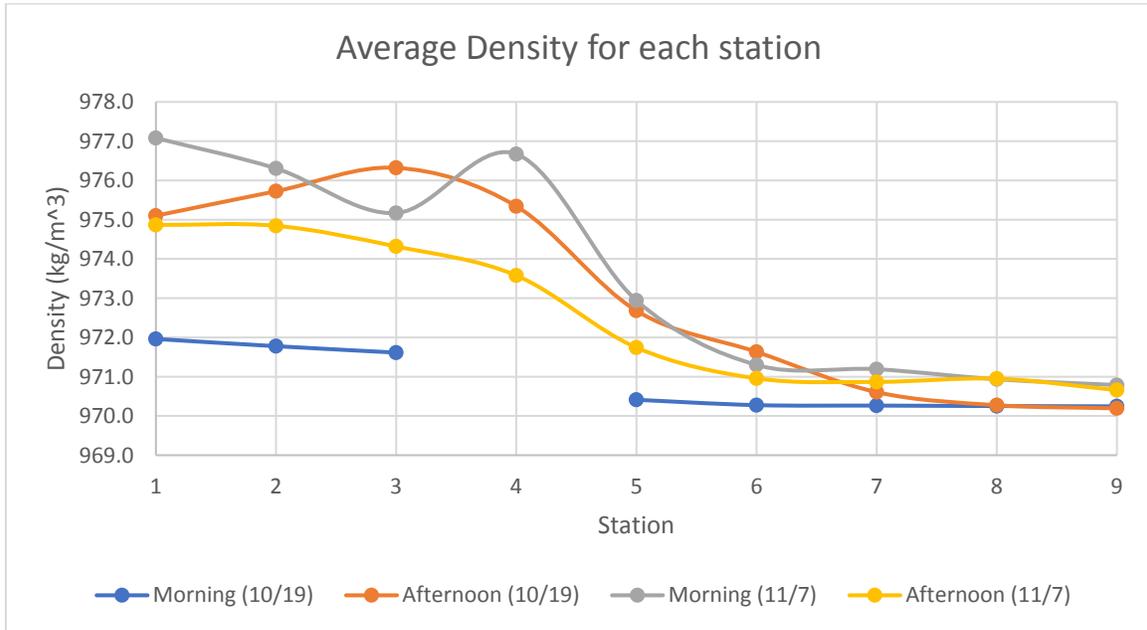
Average Density for each station

Figure 6. Density changes along a study area reflects the salinity pattern with high density for the estuarine environment and diluted water for the Imperial River section. Tidal influence on the water density can also be noticed during the spring and neap tides.
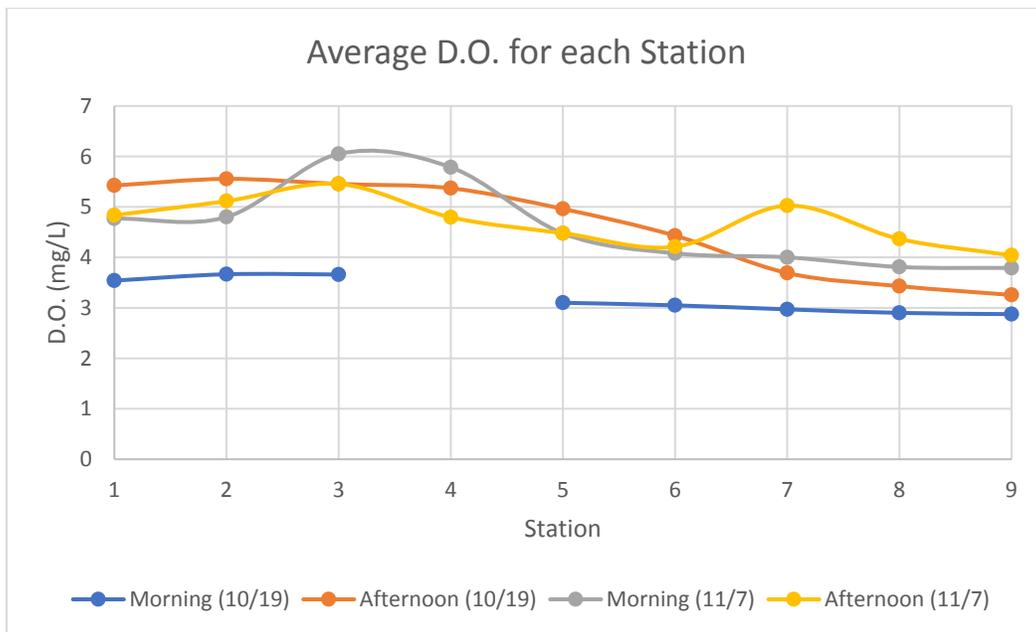
Average D.O. for each Station

Figure 7: Dissolved oxygen values showed more variation within the spring tide than the neap tide. Also, as a general trend, higher DO is observed at the estuarine side of the study area.

Forcing Functions

Barotropic pressure gradient force was higher in the estuarine section of the study area (stns 1-5) during the neap tide and the beginning of the ebbing cycle during spring tide (see Table 1). However, towards the end of the ebbing cycle, on the same day, barotropic pressure gradient was slightly higher in the river section (stns 5-9). Baroclinic conditions shows higher values for the estuary section during the neap tide and towards the end of ebbing phase of the spring tide; while, during the beginning of the spring ebbing cycle, higher values were estimated for the river section. Frictional drag from the bottom also shows higher values when the water level in the study area was higher.

Table 1: Calculated Tidal forcings during Neap and Spring tides

Tide	Station	Force due to density gradient (baroclinic)	Vertically averaged frictional drag	Surface slope force (barotropic)	Elevation Difference $\partial\eta$ (difference in tidal height b/w mouth and head)
Neap (afternoon)	1 to 5	-9.26E-06	2.91E-04	-2.82E-04	0.0459
	5 to 9	-1.07E-05	3.74E-05	-2.67E-05	0.0041
Spring (morning)	1 to 5	-1.19E-05	1.98E-03	-1.97E-03	0.3206
	5 to 9	-8.59E-06	1.10E-03	-1.09E-03	0.1663
Spring (afternoon)	1 to 5	-8.58E-06	3.62E-03	-3.61E-03	0.5883
	5 to 9	-3.32E-06	3.67E-04	-3.64E-04	0.5550

Discussion

Estero Bay is a shallow water estuary with its circulation dynamics dominated by the tidal forcing. The study area, being far away from any of the 4 tidal inlets of the Bay, is known for its brackish water environment, with dilution from the Imperial River discharge, especially during the summer wet season. Measured salinity values range from 8.5 ppt to almost fresh conditions during the four hydrographic surveys conducted in October/November 2017. A sudden decrease in salinity was observed when transitioning from Fish Trap Bay into the Riverine environment (see Figure 2). Higher salinity was observed from the northern end of the Fish Trap Bay in the afternoon of 10/19, when the ebbing reached its lowest point. Similarly, higher salinity was observed from the middle of the Fish Trap Bay during the ebbing phase on 11/7. These observed higher salinity values from the Fish Trap Bay could be attributed to localized evaporation from this shallow estuary, as reported by Sumner and Belaineh (2005) from the Indian River lagoon. Mean density variability during neap and spring tides shows similar trends although there is greater variability during the spring tide (Figure 6). This can be attributed to the dominance of tide and the sheer volume of salt water entering the estuary and intruding further upstream into the Imperial River during a dry season. Data from previous observations (not provided here) shows that during rainy season water becomes fresher along the lower reaches of the Imperial River.

Surface currents were observed to be stronger than bottom currents due to the drag from the bed friction. Highest contrast in surface and bottom currents were observed from stations 2 and 7. Station 2 is in the middle of a narrow Creek, where the current speed was always strong to satisfy the continuity. Station 7 is in the lower reaches of the River and having a deeper depth. Stations 5 and 7 shows an inversion in current speed during the afternoon and morning surveys of 11/7 spring tide. Station 5 is located towards the southern end of the Fish Trap Bay which is exposed to added shear from the flow during the final ebbing phase of the spring tide. However, the inversion observed at station 7 can be attributed to the flow dynamics within the riverine system.

Water surface elevation difference computed separately for the estuarine and river section shows that higher values are always found for the estuarine segment, which also can be attributed to the stronger currents measured from the estuary section of the study area. Also, Spring tides have the largest variation between high and low tides indicating that elevation in sea surface would have the greatest difference. Spring tides also cause more mixing, which would cause baroclinic conditions to be less prevalent, as the mixing would make the water column more uniform and there would be less salinity difference throughout the estuary; therefore less density difference.

Conclusion:

Circulation dynamics of Estero Bay has been studied using hydrographic and current monitoring during a spring and neap tidal phases, as part of a Physical Oceanography class project. Lower reaches of the Imperial River and the southern end of the Estero Bay experience low salinity due to their remoteness from the tidal inlets. Barotropic pressure gradient force is at least 2 order of magnitude higher than the baroclinic pressure gradient in this section of the bay, which means that water column is more mixed. Our field data also validated this observation. Bottom frictional drag was higher during the late ebbing phase of spring tide, when the water level was at the lowest.

References:

Dye, B., Jose, F. and Allahdadi, M.N., et al, 2018. Hydrodynamic Model study of a shallow estuary in southwest Florida, Journal of Coastal Research (in preparation).

Geyer, W. R. (2010). Estuarine salinity structure and circulation. *Contemporary issues in estuarine physics*, 12-26.

Geyer, W. (1997). Influence of Wind on Dynamics and Flushing of Shallow Estuaries. *Estuarine, Coastal and Shelf Science,* 44(6), 713-722.

Guo, X., & Valle-Levinson, A. (2007). Tidal effects on estuarine circulation and outflow plume in the Chesapeake Bay. *Continental Shelf Research*, *27*(1), 20-42.

Kellmeyer, K. & Salmon, M. (2001) Hatching rhythms of Uca thayeri Rathbun: timing in Semidiurnal and mixed tidal regimes. *Journal of Experimental Marine Biology And Ecology,* 206(2), 169-183.

Kleppel, G.S., Christie, D.R., Milon, J.W., Smith, N.P. & Vargo, G.A. (1996) *The state of Florida's estuaries and future needs in estuarine research: Part 2. an academic research agenda (review draft).* Gainesville, FL, Florida Sea Grant College Program, (Florida Sea Grant College Technical Paper, 86)

Knauss, J.A., 1997. Introduction to Physical Oceanography, Waveland Press Inc., pp309.

Nagelkerken, I., Van der Velde, G., Gorissen, M., Meijer, G., Van't Hof, T., & Den Hartog, C. (2000). Importance of Mangroves, Seagrass Beds and the Shallow Coral Reef as a Nursery for Important Coral Reef Fishes, Using a Visual Census Technique. *Estuarine, Coastal and Shelf Science*, *51*(1), 31-44.

Qiu, C., Zhu, J., & Gu, Y. (2012). Impact of seasonal tide variation on saltwater intrusion in the Changjiang River estuary. *Chinese Journal of Oceanology and Limnology,* 30(2), 342-351.

Schoen, J. H., Stretch, D. D., & Tirok, K. (2014). Wind-driven circulation patterns in a shallow estuarine lake: St Lucia, South Africa. *Estuarine, Coastal and Shelf Science*, *146*, 49-59. doi:10.1016/j.ecss.2014.05.007

Snedden, G. A. (2016). Drivers of Barotropic and Baroclinic Exchange through an Estuarine Navigation Channel in the Mississippi River Delta Plain. *Water*, *8*(5), 184.

Sumber, D.M. and Belaineh, G., 2005. Evaporation, precipitation and associated salinity changes at a humid, subtropical estuary, Estuaries, 28(6), 844-855.

Vasconcelos, R., Reis-Santos, P., Costa, M., & Cabral, H. (2011). Connectivity between estuaries and marine environment: Integrating metrics to assess estuarine nursery function. *Ecological Indicators, 11*(5), 1123-1133.

Xie, L., & Eggleston, D. (1999). Computer Simulations of Wind-induced Estuarine Circulation Patterns and Estuary-shelf Exchange Processes: The Potential Role of Wind Forcing on Larval Transport. *Estuarine, Coastal and Shelf Science*, *49*(2), 221-234.