CITATION

Fugate, D., and F. Jose. 2019. Forces in an estuary: Tides, freshwater, and friction. *Oceanography* 32(1):231–236, https://doi.org/10.5670/oceanog.2019.105.

DOI

https://doi.org/10.5670/oceanog.2019.105

FORCES IN AN ESTUARY

Tides, Freshwater, and Friction

By David Fugate and Felix Jose

PURPOSE OF ACTIVITY

The goal of this activity is to help environmental science students understand and compare hydrodynamic forces in an actual estuary. The interplay of physical forces in an estuary determines the currents and the amounts of mixing and stratification within the water column. The currents, in turn, are an important control on the distribution of phytoplankton, which form the base of the food web, and suspended sediments, which contain nutrients and pollutants. During this activity, students estimate the relative strengths of the key forces in an estuary, the barotropic and baroclinic pressure gradients, and friction. In addition, students estimate how these values change during flood and ebb and spring and neap tidal phases.

Another purpose of this activity is to provide students with experience in analyzing data using spreadsheets, in organizing and collaborating within a fieldwork team, and in producing a scientific report.

AUDIENCE

This field experiment was designed for an intermediate- to upper-level Introduction to Physical Oceanography class and is also appropriate for upper-level undergraduates or graduate students in marine or environmental studies.

TIME REQUIRED

In this activity, the class is split into four groups, each of which participates in a separate two- to three-hour field trip. In addition, the entire class meets for two two-hour class periods that involve analyses and syntheses, though this portion may be assigned as homework.

BACKGROUND

Estuaries are crucial environments for many aquatic species. Over 70% of commercial fish and shellfish utilize estuaries as spawning grounds and nurseries (US EPA, 1992), and these organisms depend directly and indirectly on estuarine currents and water-column mixing. Variations in currents and mixing in an estuary are critical to determining the transport of phytoplankton, sediment, pollutants, and nutrients, as well as the flux of O_2, CO_2, and other materials vertically and horizontally, through the estuary. Currents and mixing also help determine the location and strength of the estuarine turbidity maximum (ETM), which in many estuaries is an important habitat for phytoplankton and juvenile and larval fish (e.g., North and Houde, 2003).

Currents and mixing in an estuary are determined by the interaction of tides and freshwater discharge, as well as the estuary's geometry. A variety of mechanisms form subtidal currents, but for this activity we investigate the forces causing density-driven residual currents, which are often associated with salt wedge, partially mixed, and well-mixed estuarine types (Figure 1a–c). Other estuary types, such as fjord and inverse, are also recognized.

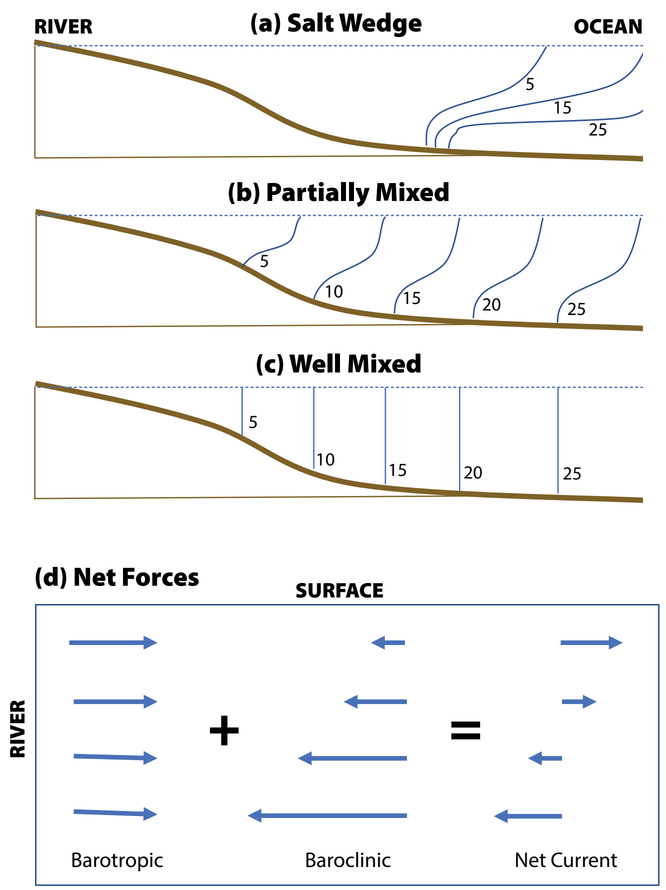


FIGURE 1. Diagrams of estuarine types and combinations of barotropic and baroclinic pressure gradients. Blue contours show isohalines. (a) Salt wedge. (b) Partially mixed (c) Well mixed. (d) Net forces in a partially mixed estuary.

The physical forces that dominate tidal and subtidal currents in most small estuaries are barotropic and baroclinic pressure gradients and bottom friction (e.g., Friedrichs and Aubrey, 1988; Geyer et al., 2000). Wind can also be an important factor (e.g., Scully et al., 2005; Wong and Moses-Hall, 1998), but is not addressed in this activity other than to make simple observations of wind strength and direction and to speculate about how they may affect our conclusions. Depending on the time and length scales of the physical properties, the Coriolis force may be relevant in some sections of larger estuaries such as Chesapeake Bay, but can be neglected in smaller estuaries. Advanced students may want to test whether the Coriolis force can be neglected in their estuary by researching and evaluating the Rossby number. The main analysis for this exercise is a very basic approach that treats the problem as a vertically averaged balance between acceleration, friction, and the pressure gradients. Nevertheless, it is a good starting point for students interested in learning about the play of forces in an estuary and is relatively easy to measure. The terms used to calculate these quantities are from the depth-averaged shallow water equations of momentum.

Friction Force

As water moves in an estuary, resistance from the bottom opposes the flow in the form of friction. Though the dynamics of friction in the bottom boundary layer can be complicated, we can get a reasonably good estimate of the degree of friction by using a simple quadratic drag formulation and vertically averaging over the water column:

$$\textit{Friction from the bottom} = -\frac{C_D u|u|}{H}, \qquad (1)$$

where u is the along channel current, C_D is the drag coefficient (set to a typical value for muddy estuaries of 0.003; e.g., Dyer, 1986; Trowbridge et al., 1999; Winterwerp and Wang, 2013), and H is the water depth. The value for u is conventionally the current speed one meter above the bottom, but in practice in shallow estuaries, the vertically averaged currents are often used (e.g., Li et al., 2004; Traynum and Styles, 2007).

Baroclinic Pressure Gradient Force

Horizontal differences in water density create a baroclinic pressure gradient that increases with depth in the water column (Figure 1d). Along a partially mixed estuary, the water is denser near the ocean at the saltier mouth of the estuary and least dense at the fresher head of the estuary. Combined with the barotropic pressure gradient (see below), this creates a two layered subtidal (i.e., tidally averaged) current in which saltier water moves up the estuary from the ocean at the bottom, and fresher water moves toward the ocean at the surface (Figure 1d). This residual current is not observable from shore or a boat. Instead, only the much stronger instantaneous flood and ebb currents can be observed.

Imagine a parcel of water near the bottom that moves upstream with the flood current for 10 km. During the subsequent ebb, the parcel of water may move downstream only 9.9 km. After many tidal cycles of moving up 10 km and moving back only 9.9 km, the net movement of the water parcel is upstream. This subtidal, or residual, current can be measured by tidally averaging time series of flow measurements. While the measurement of these currents is beyond the scope of this exercise, we will measure the force that causes them. It is also this current that is responsible for the classically formed ETM. At the upper extent of the salinity intrusion, the horizontal density gradient and its associated subtidal currents stop. This results in a near-bottom convergence of the landward-directed, density-driven current and the seaward-directed freshwater discharge. At this location, suspended sediments and weakly swimming organisms can be trapped and focused, creating a region of high turbidity. The force due to the vertically averaged baroclinic pressure gradient is

$$\textit{Force due to baroclinic pressure gradient} = -H\frac{g}{\rho_0}\frac{\partial \rho_x}{\partial x}, \qquad (2)$$

where H is the mean water depth, g is the force of gravity (9.8 m s^{-2}), ρ_0 is the mean density of the water, $\partial\rho_x$ is the horizontal difference in vertically averaged density, and ∂x is the distance along the estuary. Because of the relatively shallow depth of estuarine systems, pressure has a negligible effect on density. Students can then calculate the density of the water by measuring only the temperature and salinity. Instead of using the complex equation of state, students use a linear approximation that utilizes the thermohaline coefficients of expansion and contraction and ignores the effect of pressure. Densities can then be calculated using the equation

$$\rho = 1{,}000 - 0.15 * (T - 10) + 0.78 * (S - 35), \qquad (3)$$

where ρ is the density in kg m^{-3}, T is temperature in degrees centigrade, and S is salinity, and −0.15 and 0.78 are the thermohaline coefficients of expansion and contraction around 10°C and salinity of 35, respectively.

Barotropic Pressure Gradient Force

A slope in the sea surface creates barotropic pressure gradients. In estuaries, the slope is usually dominated by the differences in water height between the estuary and the open ocean caused by tides, but also includes a slope associated with the freshwater flow out of the estuary. The water is forced from higher pressure under the top of the slope to lower pressure regions where the water elevation is lower. The magnitude of this barotropic pressure gradient is the same at all depths in the water column (Figure 1d) and can be described as:

$$\textit{Force due to barotropic pressure gradient} = -g\frac{\partial \eta}{\partial x}, \qquad (4)$$

where $\partial\eta$ is the difference in height of the water column along the length, ∂x, of the estuary being measured. Surface slopes are particularly difficult to measure because of the very slight changes in elevation with distance and difficulties in establishing an equal geopotential reference level. Instead, we assume that the Coriolis effect is negligible in a small estuary and estimate the force due to surface slope using the force balance:

$$\text{Total Acceleration} = \text{Surface Slope force} + \text{Density Gradient force} + \text{Friction force}.$$

After calculating acceleration (described below), the density gradient force, and the friction force, the barotropic force can be calculated by subtraction, and the difference in water elevation along the measured transect can also be calculated.

Total Acceleration

An estimate of total acceleration is made by comparing the velocity measured at the beginning of each field trip with the last velocity measurement of that trip at a stationary site. The acceleration is the difference between the two velocities divided by the time interval between the measurements.

ACTIVITY

This activity allows students to measure and compare the relative size of estuarine forces described above through gathering the appropriate data in the field. Like a game of tug-of-war, in which the opposing forces may be strong but the net movement of the knot in the middle may be small, subtidal currents may also be small. The measurement of the density differences along the estuary and the resulting baroclinic force provides evidence for this force, which is not easily observed by our senses. Students may be surprised at the small change in water elevation that can cause substantial tidal currents.

A secondary aspect of this activity is the experience and learning acquired through coordinating and organizing results in a team-based approach. Students find that a relatively simple field experiment requires much effort to coordinate data, provide quality checks, and check units, among other activities, with their team. This is the reality of much of scientific research, but students get little taste of it in traditional lecture-based science classes.

Materials

- Small power boat such as skiff with depth meter and GPS
- Hand-held CTD (we use YSI Pro Plus) along with a weight to help the instrument sink to the bottom, if it is not provided
- Current meter (we use OTT MF Pro), or grapefruit drifters and stopwatch
- Spreadsheet software (MS Excel, or similar)
- High-frequency depth profiling CTD (we use a SBE 19plus; optional)
- Handheld anemometer (we use a Kestrel 1000; optional)
- Lead line or depth sounder if not available on boat

Setup

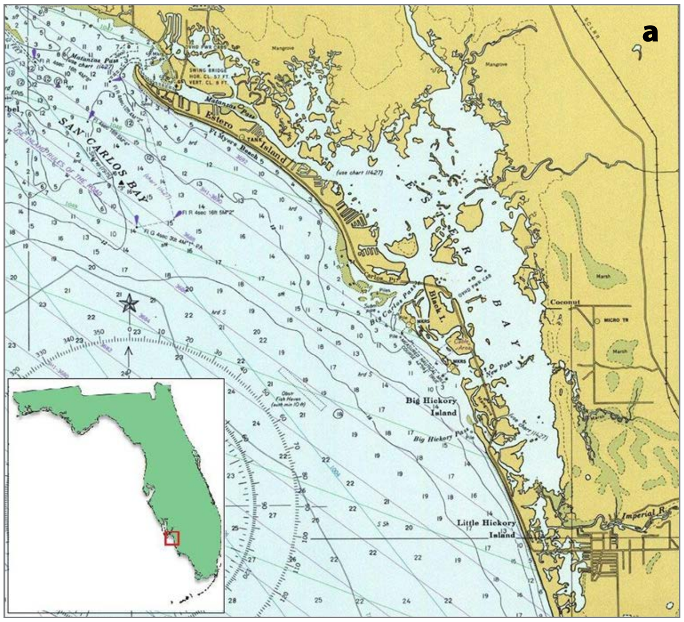
Instructors should first use the classroom to teach the concept of pressure and the relevant forces in an estuary from a qualitative and intuitive perspective. For example, most students have been in a swimming pool where, when diving to the bottom, their ears popped from the increased pressure due to the weight of the water above them. Barotropic pressure gradients are easily observed in a river moving down a mountain slope. Baroclinic pressure gradients can be observed in a tank that is separated into two sections, with freshwater and saltwater sides each dyed a different color. When the barrier is removed, the saltwater will be seen to move toward and under the freshwater region.

At the end of the topic lecture, students are introduced to the relevant terms of the momentum equations, which are shown to only be "shorthand" notation for what they have already learned qualitatively. In addition to expressing the relationships precisely, the terms allow us to quantify the pressure and forces (per unit mass). Students are given a few practice calculations and questions from some realistic examples, for example, contrasting the barotropic pressure gradient in an oceanic gyre with that from a tidal height gradient along an estuary.

Students are divided into four groups for their work both in the field and during the analysis and report writing. Our classes typically have about 36 students, so four groups provide enough students to accomplish the primary tasks should a few not be able to make the field trip. Each group attends only one of four field excursions (completed in two different days about a week apart) that are planned to provide for sampling during flood and ebb of both a neap and a spring tidal cycle. This sampling schedule then requires that the instructor be present for two days, and that each student attends only one two- to three-hour field trip. Students have pre-prepared log sheets that they bring with them. For more advanced classes, the students may be given the preparation of log sheets ahead of time as an exercise.

Fieldwork

In the field, we establish one or two subgroups to be responsible for collecting current data (usually two students in a canoe for each subgroup), depending upon the number of students available, at one or two stationary sites. The sites are best positioned along relatively straight lengths of the estuary. The rest of the students perform a longitudinal transect with the skiff. At the stationary sites, the students measure the current velocity at regular intervals; about every 15 minutes usually works well. If a flow meter is available, they measure a vertical profile of velocity at near bottom (about 0.2 m above bottom), mid-level, and surface (about 0.2 m below surface) depths. This profile is taken in the center channel and in the shoal areas on both sides of the channel. If only a drifter (usually a grapefruit) is



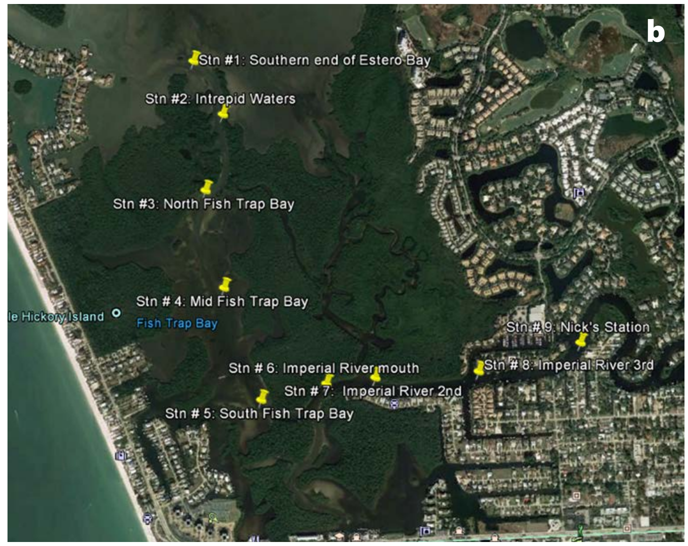


FIGURE 2. Site maps. (a) Location of Estero Bay (adapted from Florida Center for Instructional Technology), and (b) student example showing their sampling stations.

FIGURE 3. Students near the bow are measuring temperature and salinity with a YSI Pro Plus hand-held CTD. Near the stern, students are measuring the current speed with an OTT MF Pro. A student in the middle is measuring wind speed with a Kestrel 1000. The other students are logging data from the instruments, or GPS coordinates and depth measurements from the boat console. *Photo credit: FGCU photographer James Greco*

available, they measure surface currents using a stopwatch and GPS. The students usually measure out and mark a known distance and then time how long it takes the drifter to transit. The times and distances are adjusted for the relative speed of the current to get an accurate estimate of the velocity and to obtain multiple measurements over about one and a half hours for a semidiurnal tide.

The rest of the students on the motorized skiff measure temperature and salinity at the surface and near bottom at five to nine evenly spaced stations along the transect. The upstream location of the first transect station is where the water is nearly fresh. The downstream location is determined by the closest logistically available site near the ocean. Our downstream transects are located at the end of Fishtrap Bay, which opens into the southern portion of Estero Bay, Florida, about 3–4 km from the upstream transect (Figure 2). During the dry season, salinity reaches farther up the estuary and requires more stations than during the wet season. At each station, the students record latitude and longitude, depth, surface and bottom temperature, and salinity (Figure 3). The students log the data onto their prepared data sheets.

Analysis and Report

Each of the four groups writes a collaborative report that includes the measurements and analyses of the data that they collected. The analysis and plot generation are usually done with Microsoft Excel software, although we allow them to use whatever software they prefer. The students are also provided with the results from the other groups so that they can make comparisons over tidal phases. Within the groups, students choose roles for themselves according to the instructions:

"Each student will take on one or more of the following roles: raw data preparation, data analysis and interpretation, background information writer, liaison to collaborate with other groups and to coordinate efforts within their own group, first draft writers (more than one), proofers and editors (more than one), and figure editors (legends, captions). Remember, ultimately you will be working together. If you are finished with one of your tasks, or waiting, volunteer to help with something else. At the end of the project, you will fill out peer assessment forms."

Learning to work together is an important aspect of this activity, and a skill that students will need if they pursue careers in science. The peer assessment helps provide incentive for the members to participate and allows the instructor some flexibility in assessment should one of the members prove to be especially weak or strong in their participation. The peer assessments are ratings from 5 (superior) to 1 (weak) on each of the following attributes:

- Participated in group discussions
- Helped keep the group on task
- Contributed useful ideas
- Amount of work done
- Quality of completed work

Basic Report Instructions and Overreaching Questions

Your written field report should include:

1. Short background of estuarine circulation and a description of the study site
2. Site map with transect location indicated
3. Materials and methods section
4. Results section which should include:
   - Plots of along-transect salinity, temperature, and density for your transect; for each parameter, there should be two lines on the graph, one showing surface values and the other showing bottom values
   - Time series plots of current speeds, both surface and bottom, from the stationary site
   - Any other relevant results or observations that were made
   - The calculations of the acceleration; the baroclinic, barotropic, and friction forces; and differences in water elevation along the transect.
   - The values for the above forces calculated by the other groups (but it is not necessary to show all the calculations from the other groups)
   - Your data in a table form in an appendix.
5. Discussion and conclusions
   - Your report should be written in a cohesive manner and should at a minimum address the following questions:
   - Which force(s) were the most important to determining the current in the estuary? Typically, we are comparing the order of magnitude of the forces in question, so small errors in measurement should not make much difference to your conclusions.
   - Do you see changes in stratification (the difference between surface and bottom density) between ebb and flood phases?
   - Is density variability caused mostly by salinity or temperature? How do you know?
   - Describe any spring neap variations in any of the above processes that you observed.

EXAMPLE RESULTS

Students calculate the distance between stations using the GPS coordinates that they recorded and the Ruler tool in Google Earth. In the baroclinic pressure gradient calculation, H is the mean depth of the first and last stations. For friction calculations, the mean of the surface and bottom currents from all the stations is used. Some example results from a recent class and their captions are shown in Figure 4 and in Table 1. During this transect, the water was well mixed and the students unnecessarily went well past the extent of the salinity intrusion. For this reason, their calculations of the forces (Table 1) are based upon the first five stations. Though the Imperial River is relatively shallow,

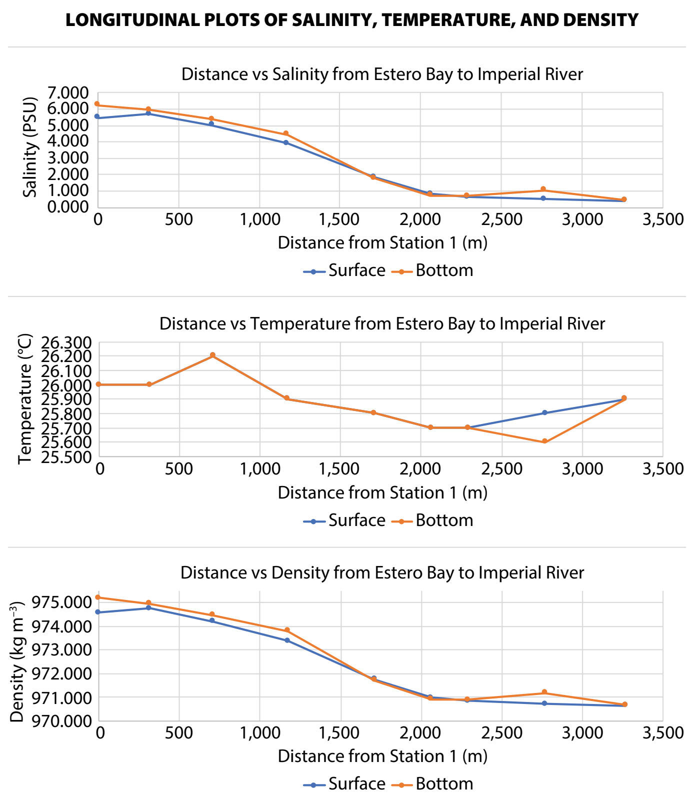


FIGURE 4. Example results and captions from student report. (a) Salinity decreases from Estero Bay into the Imperial River. Bottom water is slightly saltier than surface water. (b) Temperature remained the same for top and bottom water at each location for sites 1–7 as well as site 9. Site 8 has a slight variation in temperature as the surface water is slightly higher in temperature. (c) The density decreases gradually from Estero Bay into the Imperial River. Surface water (blue curve) is slightly lighter than the bottom water.

TABLE 1. Example of student estimates of the hydrodynamic forces in the Imperial River, Florida.

TERM	VALUE
Friction	2.06×10^{-4} N kg^{-1}
Baroclinic Pressure Gradient	-6.89×10^{-6} N kg^{-1}
Barotropic Pressure Gradient	-2.1×10^{-4} N kg^{-1}
Change in Elevation along Estuary	0.036 m

with depths usually 2 m or less, the water column often becomes much more stratified. Despite the many assumptions and simplifications of this approach, their estimates of the forces and the elevation of the water column are realistic. Future implementations of this activity will include a discussion of the assumptions and simplifications, such as the assumptions of relatively similar width and depth of the channel, and the effects of non-simultaneous measurements.

ALTERNATE APPROACHES AND EXTENSIONS

- Use grapefruit drifters if flow meters are not available.
- Use a nautical map and choose sites at channel markers if depth meter and/or GPS are not available.
- If no powerboat is available for transects, the force measurements can be made from canoes positioned at each end of the estuary. Before deployment, each canoe group can establish a sampling routine, then take measurements at the same time at each site, for example, every half hour.
- Deployment of a fixed current meter, or current data from the one or two stationary sites, allows discussion of flood and ebb asymmetry and likely directions of net sediment transport.
- If a turbidity meter is available, students can also examine variations in turbidity and whether there is a classical ETM. If a classical ETM is not observed, what other processes can create turbidity maxima?
- How sensitive are the force calculations to the estimate used for the drag coefficient?
- A further preparation exercise is to have each group prepare their own log sheets ahead of time. This activity helps them focus on exactly what information they need to complete the analysis and how to organize it.
- Further analysis for more advanced students can include log layer estimations of friction from higher spatial resolution profiles of currents at the stationary sites. Cross-sectional variations can also be examined, and the effect of friction along the sides of the estuary can be discussed.
- Further discussion for more advanced students could include the effects of asymmetries in mixing and how they can also drive subtidal currents (e.g., see Geyer et al. 2000).
- Depending upon availability, we also take vertical profiles of temperature, salinity, and turbidity with an SBE 19plus CTD. Data from this instrument are processed by the instructor and provided to the undergraduates to compare their results with the higher vertical resolution obtained from the instrument. Graduate students may be assigned the task of processing the Sea-Bird CTD data as well.
- A quantitative approach to evaluating the stratification can easily be accomplished with this data by researching and calculating the Brunt–Väisälä frequency at one or more sites and times.

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ACKNOWLEDGMENTS

We thank the students in OCP 3002C who participated in these field experiments and Florida Gulf Coast University (FGCU) and the Vester Marine station for providing boats and captains.

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ARTICLE CITATION

Fugate, D., and F. Jose. 2019. Forces in an estuary: Tides, freshwater, and friction. *Oceanography* 32(1):231–236, https://doi.org/10.5670/oceanog.2019.105.