Model of Stratification in

The Elizabeth River

The Elizabeth River Project

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ABSTRACT: The Elizabeth River is known for having high levels of pollutants in it due to the industrialized area around the river. Pollutants tend to associate with fine-grained sediments, so the transportation of these pollutants can be examined by looking at the processes that transport these sediments. Conductivity-Temperature-Depth and Acoustic Doppler Current Profiling observations will allow the long-term patterns of net contaminant transport to be examined more fully. This paper looks at the background of estuaries, the effect that tides have on the circulation of estuaries, and the Doppler shift which is a key concept of the Acoustic Doppler Current profiler. It also describes the fieldwork that was done on the Elizabeth River using a CTD recorder and an ADCP. Graphs of the CTD data from the spring cruises were generated in order to see the stratification during the spring and neap tidal cycles. Finally, it examines the Potential Energy Anomaly that becomes a model that is used for the Elizabeth River in order to investigate the difference in stratification between the spring and neap tides from the late spring of 1999, and then applies it to the Elizabeth River.

INTRODUCTION

The Elizabeth River subestuary of Chesapeake Bay in Virginia is continuously contaminated with both polycyclic aromatic hydrocarbons (PAHs) and trace metals due to three centuries of human activity along the river, in addition to more recent industrial industry along its shores [8]. A major source of PAHs in the river is when in the 1960s, a wood preservative, creosote, was spilled into the estuary on two different occasions. There are especially high sediment loads of PAHs in the Southern Branch of the Elizabeth River (Figures 1-2) due to these accidents [7]. Also, other sources of contaminants in the river are petroleum related. Extreme enrichments of trace elements have also been noted in the Elizabeth River [8].

In river systems, many contaminants tend to associate with fine-grained sediments; thus, the fate of these pollutants can be dictated by the processes that affect sediment transport in the river system [9]. In the Elizabeth River, the fine sediment and pollutant transport and fate will be the result of the physical processes in the River. As a whole, this project examines the transport and fate of the pollutants by evaluating particle and associated contaminated resuspension and transport along the Elizabeth River.

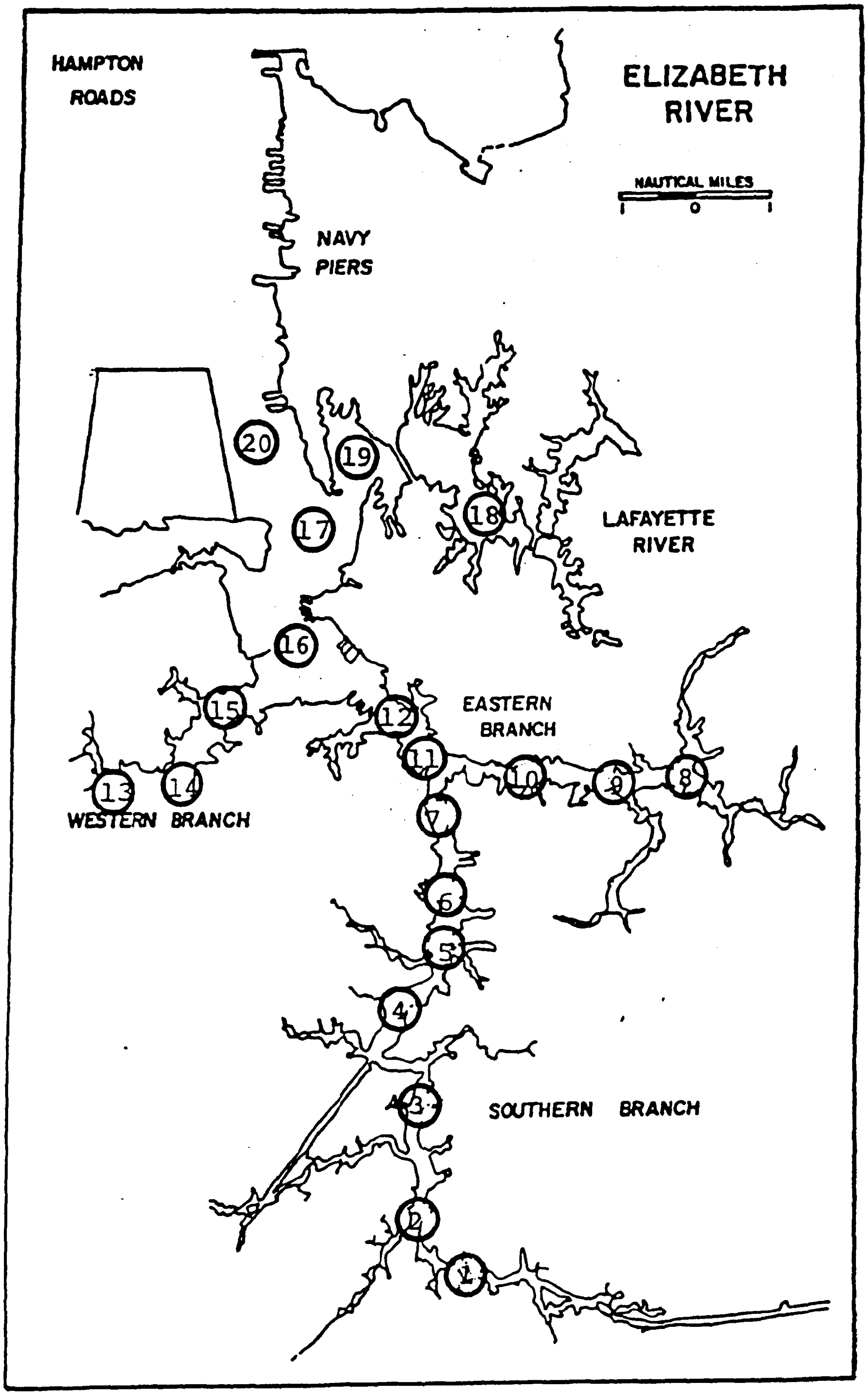


Figure 1. Map of the Elizabeth River. Circled areas show high level of pollutants in the River. [6]

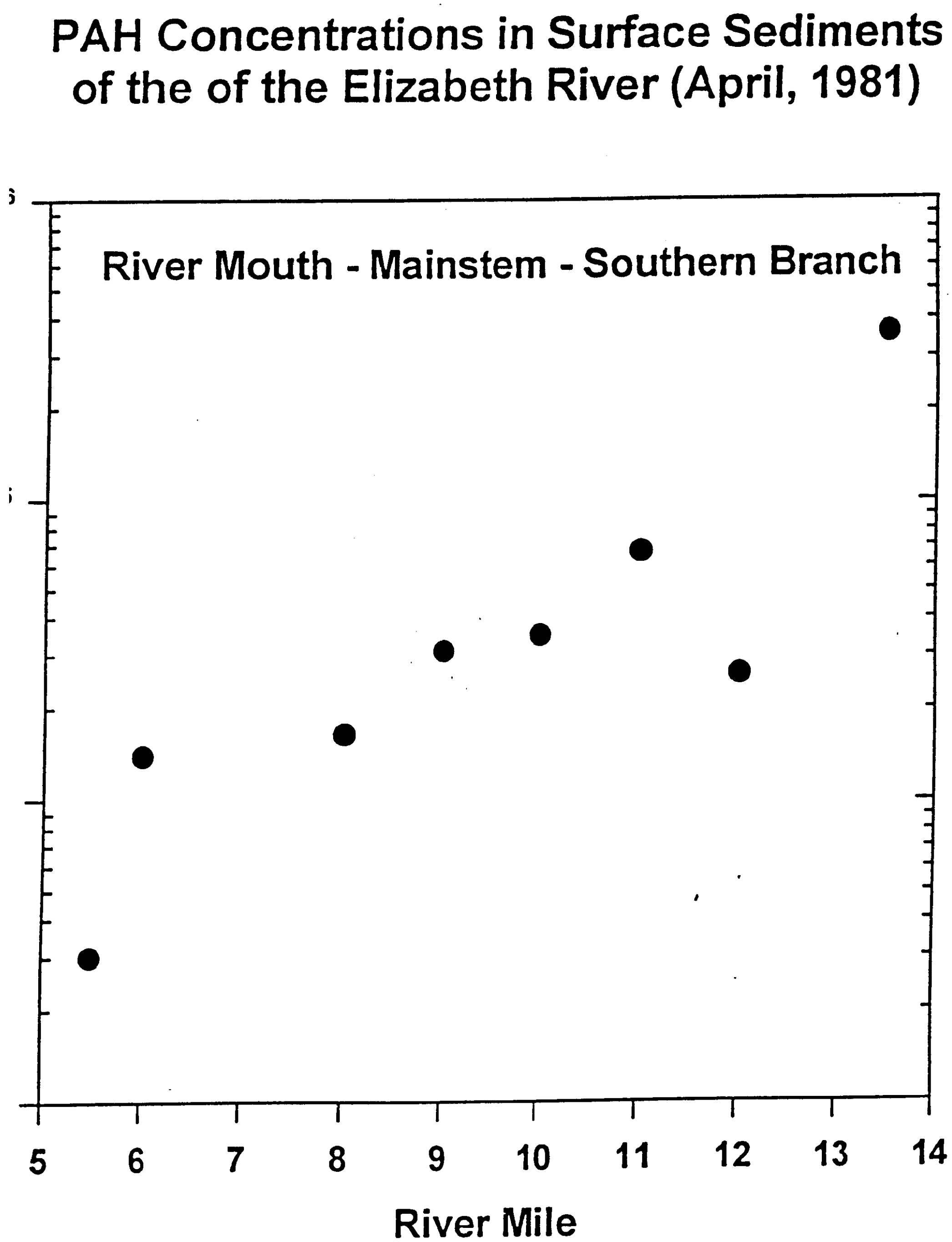


Figure 2. Level of PAH concentrations in surface sediments of the Southern Branch of the Elizabeth river. [1]

Through Conductivity-Temperature-Depth and Acoustic Doppler Current Profiling observations, the mean current shear and stratification can be monitored; therefore, the relative importance of density induced circulation versus tidal dispersion at spring and neap tides during the wet and dry season will be able to be investigated. Sampling under these conditions will allow the long-term patterns of net contaminant transport to be examined more fully [7].

BACKGROUND

There are three types of estuaries: salt wedge estuaries, partially mixed estuaries, and well-mixed estuaries. The Elizabeth River is considered to be a partially mixed estuary which occurs where the river discharges into the sea with a moderate tidal current. Tidal currents are significant, so the whole water mass moves up and down the estuary with the flood and ebb tides. In addition to the current shear at the saltwater/ freshwater interface, friction at the estuary bed creates shear stress there, and generates turbulence, which causes even more effective mixing of the water column than that caused by the waves at the saltwater/freshwater interface. Not only is freshwater mixed upwards, but saltwater is mixed downwards. This two-way mixing across the halocline makes it much less well defined. The freshwater flowing seawards is now mixed with a relatively high proportion of saltwater so that the compensating landwards flow from the sea is much stronger than that in a salt wedge estuary [2].

In partially mixed estuaries, the landwards flow of the seawater along the bed is strong enough to move sediment up the estuary as far as the null point. Where transport ceases, a turbidity maximum is formed. The pattern of water circulation does much to

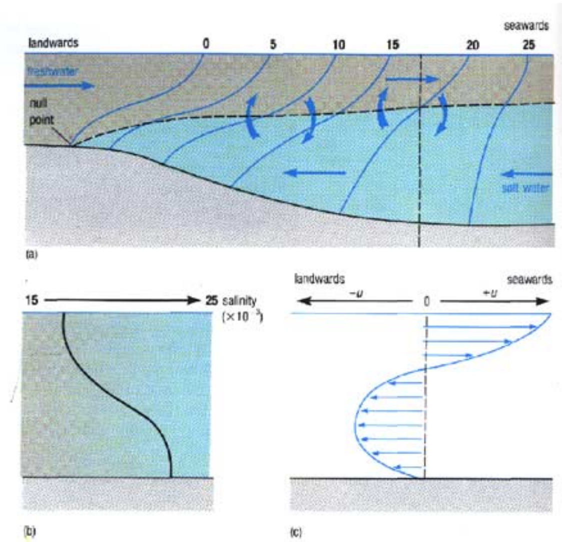


Figure 3. Diagrammatic representation of water circulation. (a) Longitudinal section to show water circulation and salinity gradient. (b) Salinity-depth profile along vertical line in (a). (c) Velocity-depth profile along dashed vertical line in (a). [2]

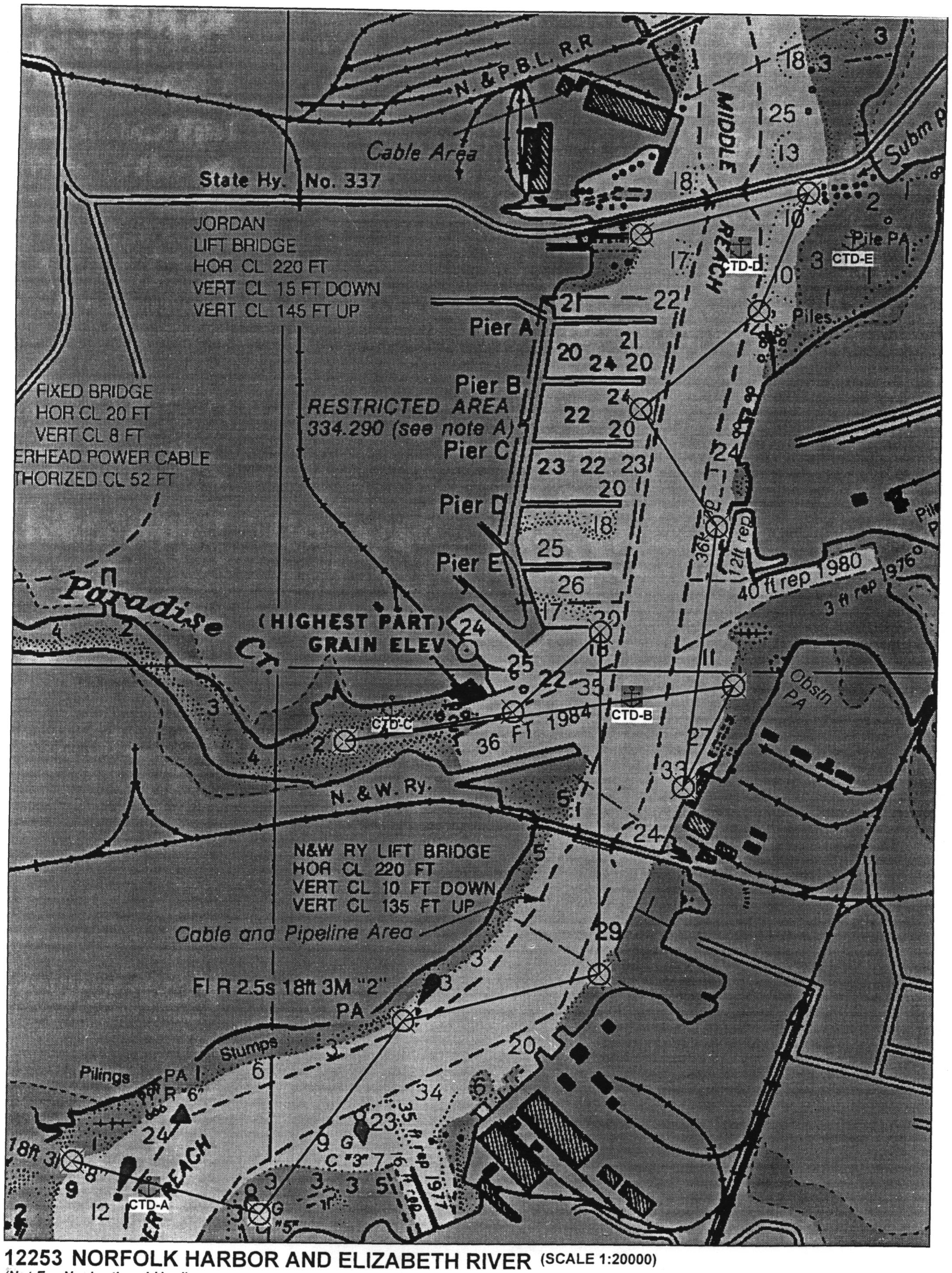
maintain the turbidity maximum. Suspended sediment is brought downstream by river transport to the head of the estuary. In the upper estuary, suspended marine sediments which are brought up-estuary by the landwards flow of seawater close to the bed, are mixed into the upper layers of the turbidity maximum [2]. A mixture of marine and river-borne sediment is carried back seawards until a point where the mixing of saltwater and freshwater is sufficiently reduced to allow sediment to settle. Some of it is then carried back landwards to the null point in the saltwater flow, along with new sediment being brought in by the sea. This form of circulation therefore acts as a sediment trap, which slows the escape of sediment to the open sea [2].

Another factor that plays an important role in the mixing of salinity in the estuary is tides. The rising tide is referred to as a flood, whereas the falling tide is called the ebb. The period in between the two is referred to as slack tide. The Sun and the Moon both play roles in producing tides. They both produce tractive forces and two equilibrium tidal bulges each. When the tide generating forces of the Sun and Moon are in the same direction, the solar and lunar tides coincide. This produces a spring tide, where the high tide is higher than usually, and the low tide is lower than usual, resulting is a larger tidal range. When spring tides occur, the sun and moon are said to be in conjunction with each other (with new moon) or in opposition (full moon). The term for both of these situations is the Moon and Sun are in syzgy.

When the Moon and Sun act in right angles to each other, than the solar and lunar tides are out of phase. This produces a neap tide, and the Moon is said to be in quadrature when neap tides occur. This tidal range is smaller than average, and occurs during the first quarter of the Moon and the third quarter of the Moon. Likewise, the regular changes in the declinations of the Sun and the Moon, and their cyclical variations in positions contribute to the tide at any particular time and place.

FIELD WORK

Data from the Elizabeth River was collected at two different times during the year. The first was during the days of May 24 and June 11 of 1999, and the second was in November of 1999. During each of these times, data was collected during spring and neap tides. Part of the project consisted of surveying the river by using an Acoustic Doppler Current Profiler (ADCP) that was mounted on the front of the research vessel looking down into the river. The boat surveyed the exact same path of the river during a day in the spring tidal cycle and the neap tidal cycle. In May and June, the surveying took place over two full tidal cycles, each day lasting about 25 hours. The surveying in May was the neap tide, and the day in June was the spring tide. During the surveying that took place in November, 13 runs were made of the river during the neap tide, and 14



12253 NORFOLK HARBOR AND ELIZABETH RIVER (SCALE 1:20000)

(Not For Navigational Use!)

Figure 4. Survey track for the field work of the Elizabeth River. The CTD stations are marked in the white boxes denoted by the symbol CTD and then followed by the station number. The circled points show where the survey boat made exact turns each time.

surveys were taken on the day of the spring tide. (Figure 4) This took about 13 hours for each day. The Global Positioning System (GPS) allowed the same path of the river to be traced each time. Conductivity-Temperature-Depth (CTD) readings were taken on every other survey run each day by a CTD recorder which allows the change in salinity and temperature to be looked at during the flood, ebb, and slack tides. These CTD readings occurred at 5 stations on the river. Stations A, B, and D were in the main channel, station C was in Paradise Creek, and station E was in another area of the river which was off the main channel. Both stations C and E were much shallower than the others, averaging about 2 meters deep. (Marked on Figure 4) The CTD recorder was slightly submerged in the water for a few seconds at the beginning of each station in order to allow the sensors to calibrate. Once it had been calibrated, it was then pulled back to the surface, and then lowered slowly through the water column. The goal was to get at least three readings per meter from the surface to the bottom for each station. (i.e. 2.23, 2.56, 2.89 meters) The data was collected and fed into a computer using a program called slacko.dat, and then converted to a viewable file by a program called slacko.rel.

The ADCP measures current velocity profiles. It uses the Doppler effect by transmitting sound at a fixed frequency and listening to echoes returning from sound scatters in the water. The sound scatters are small particles or plankton that reflect the sound back to the ADCP. When sound scatterers move toward the ADCP, the sound heard by the scatterers is Doppler-shifted to a higher frequency. The amount of shift is proportional to the relative velocity between the ADCP and the scatterers. Part of this sound is reflected back to the ADCP. Thus, the ADCP hears the back-scattered sound Doppler shifted a second time (See Figure 5) [10]. If the tone is higher than the one sent out by the ADCP, the scatters that reflected the sound must have had an along- beam velocity component towards the ADCP, and if it was lower then the scatters had an along-beam current away from the ADCP [10].

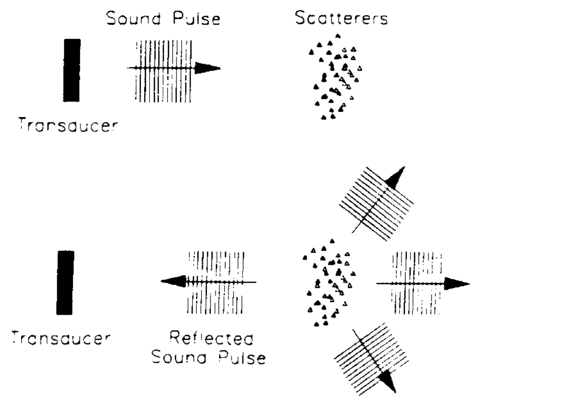


Figure 5. Diagram representing the Doppler shift. [10]

The Doppler shift only works when sound sources and receivers get closer to or further from one another. If both move relative to the earth but stay at a fix position relative to each other, there is no Doppler shift. This means that the Doppler shift results from the velocity component in the direction of the line between the source and the receiver [10].

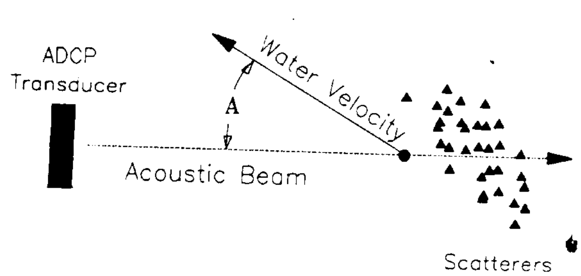


Figure 6. Diagram showing the angle of the water velocity with respect to the scatterers that is used in the Doppler Shift equation. [10]

$$F_D = 2\ F_s\ (V/C) \cos(A)$$

Where F_D is the Doppler frequency shift, F_s is the frequency of sound when everything is still, V is the relative velocity between the sound source and the sound receiver (m/s), C is the speed of sound (m/s), and A is the angle between the relative velocity vector and the line between the ADCP and the scatterers

The ADCP consists of four beams, each that measure a different velocity component. One pair of beams produces one horizontal component and the vertical velocity component. The second pair produces a second, perpendicular horizontal component as well as a second vertical velocity component.

The ADCP measures current profiles by breaking up the velocity profile into uniform segments called depth cells, or bins. In this experiment the bins were .25 meters. Each of these depth cells is comparable to a single current meter [10]. The ADCP does not measure currents in small, localized volumes of water, but they average the velocity over the full range of the depth cell.

The ADCP sent pings out of each of the four beams. Each ping that was sent out had a frequency of 1200 kHz. However, the single-ping velocity measurement uncertainty is too large to meet most measurement requirements. Therefore, the data is averaged to reduce the measurement uncertainty to acceptable levels. This project used an averaging of 12 seconds and 20 seconds in the field to reduce the error and noise. These are the processed data files. Also, the raw data was recorded in four ping averages every one and a half seconds. This allows further averaging to take place over any period of time.

The data was acquired by the ADCP using a program called *Transect*. This program lets the researcher see the data as it is being processed using different views such as bottom tracking, relative velocity magnitudes, or the backscatter intensity of the four beams. Also, it allows the raw data to be averaged over different time intervals after the data has been collected. Below is the bottom track of the first survey from May using the program *Transect.* It shows that the river is in ebb tide. (The water velocity direction is north emptying into the Chesapeake Bay) The red line is the track of the ship, and the blue lines are the magnitude and the direction of the water velocity.

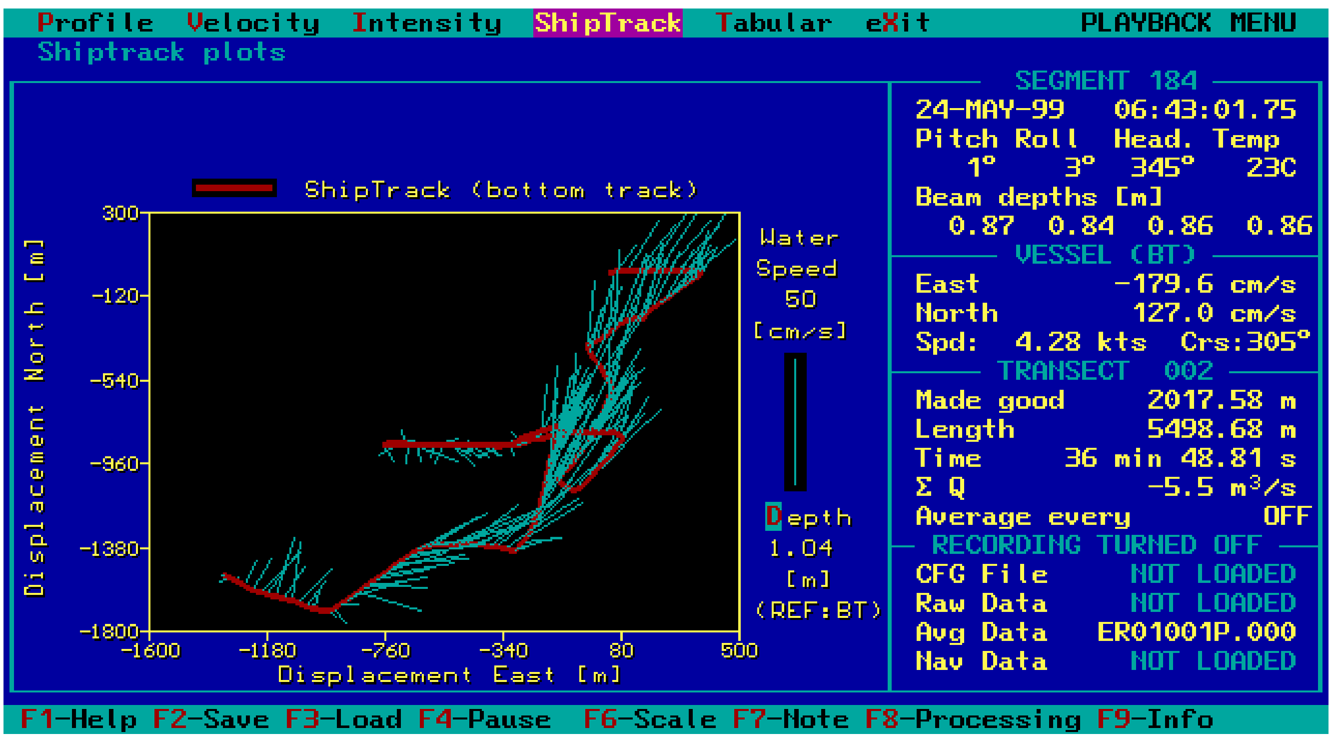


Figure 7. View of the program *Transect*. The water at this time is in ebb tide because the velocity is in a northerly direction meaning it is flowing into the Elizabeth River. The red line represents the bottom track of the ship, and the blue lines show the velocity of the water. This is data from the ADCP.

Using the data that was collected in the spring, ASCII text files were made from *Transect* and then read into *Matlab*. From these *Matlab* files, a computer program was written that took the data and plotted the track of the river showing the different magnitudes and directions of the velocity (Figure 8). These graphs were used in order to find a spot in the Elizabeth River that had fairly constant velocities throughout the two data sets in the spring.

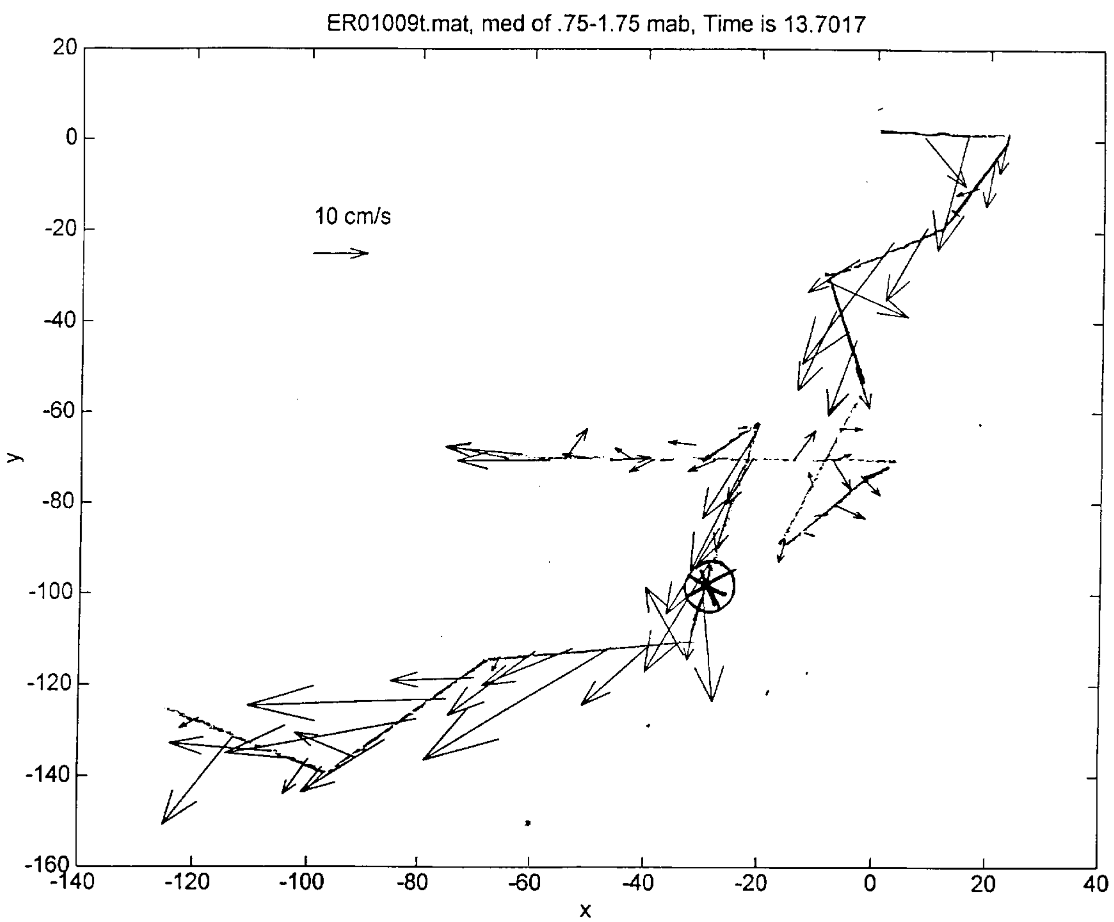


Figure 8. Output of the *Matlab* program which plotted the bottom track of the ship for each run, and then the water velocities and directions. The circled area shows the area of the river which had consistent data over the two surveys taken in the spring.

RESEARCH

The part of the project that this semester's research has focused on has been the difference in stratification between the spring and neap tides during the May and June cruises. The station locations are marked on Figure 4. Using *Matlab* and the data from the CTD, graphs were plotted of the temperature vs. depth, salinity vs. depth, and density vs. depth. All data from the five stations were plotted on the same graph, and there was a graph made for each run that had CTD data taken on it. However, only graphs from Station A, B, and D are shown since they were in the main channel, and those were the areas that were focused on. Examples of these graphs can be seen in Figure 9, which was from the first run on May 24, and also on Figure 10, which was from the first run on June 11.

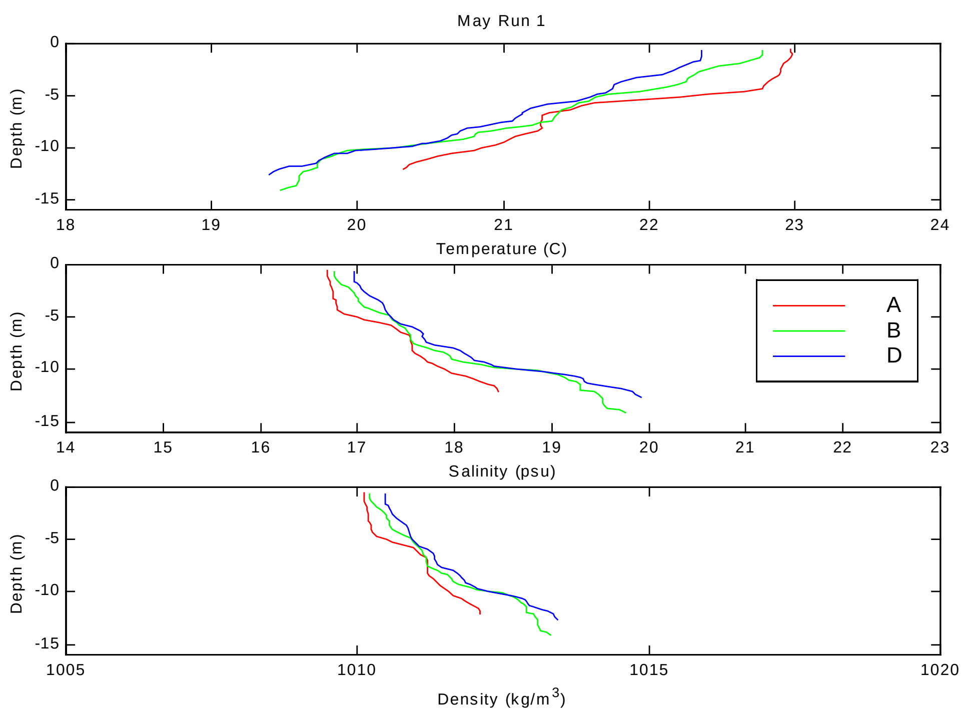


Figure 9. Graphs of the CTD data from the first run in May. Red is data from Station A, green is data from Station B, and blue is data from Station D. The data used for the density graph was calculated from the data for the temperature and salinity. It can be seen that there is vertical stratification.

The red line represents the data at station A, the green line is station B, and the blue line is station D. The same color legend is used in Figure 7 below.

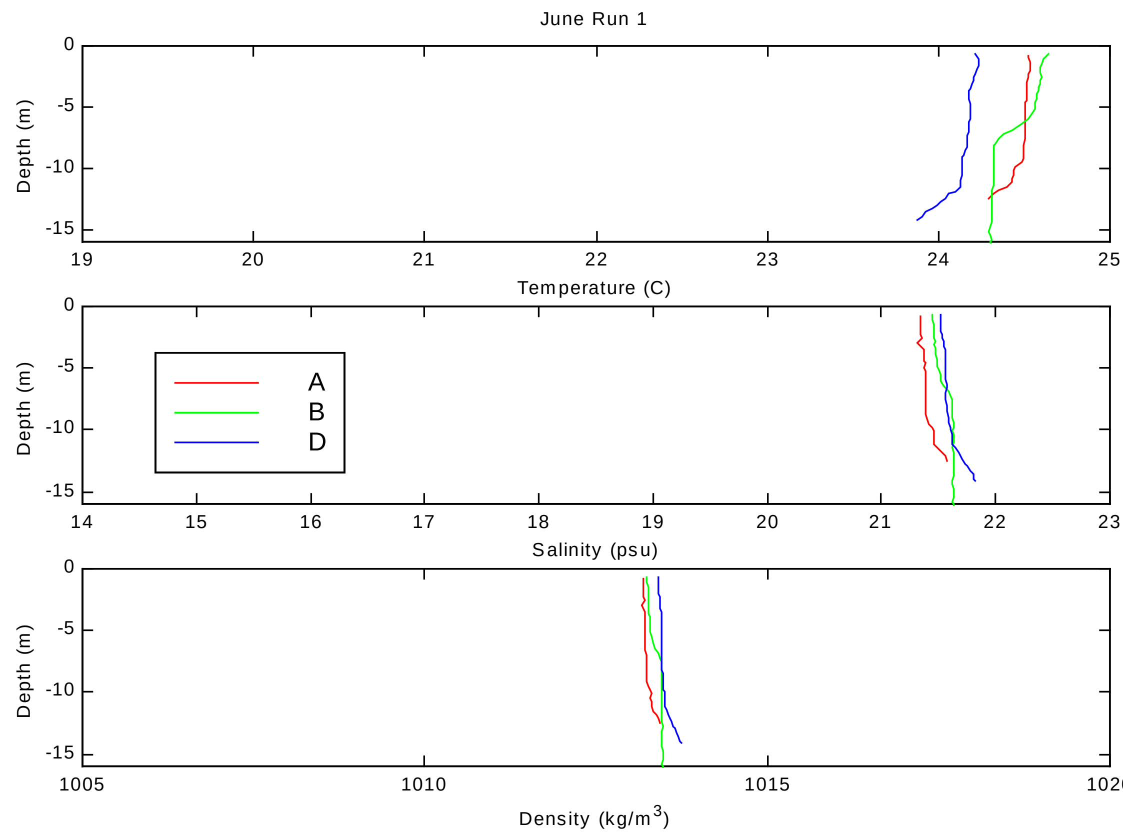
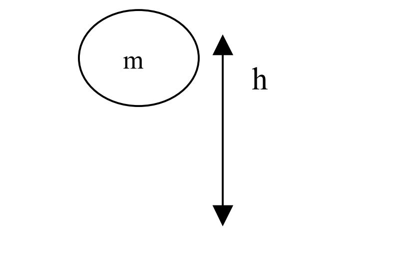


Figure 9. Graphs of the CTD data from the first run in June. Red is data from Station A, green is data from Station B, and blue is data from Station D. The data used for the density graph was calculated from the data for the temperature and salinity. It can be seen that there is very little stratification for this run.

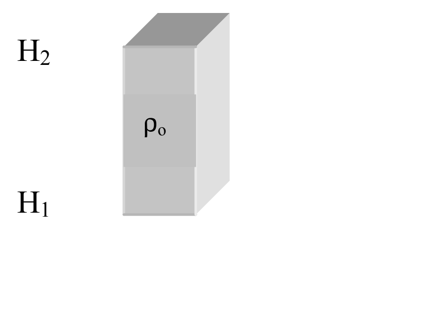
It can be seen by looking at the two salinity versus depth graphs that there is very little vertical stratification from the data in June, whereas the data from May does show stratification. This was a continuous pattern that was seen in the graphs from May and June. As a reminder, the June cruise was during the spring tide, and the May cruise was during the neap tide. The next question that was asked was what could cause these patterns, and how much of an effect do the various estuarine processes have on stratification in the Elizabeth River. This was examined using the model of the Potential Energy Anomaly (PE Anomaly), which expresses the strength of stratification in terms of energy, and the intensity of the various mixing processes in terms of rate of working or rate of generation of turbulent kinetic energy (TKE) [3].

The PE Anomaly is analogous to the simple equation for potential energy, where



potential energy (PE) = mgh.

g is the acceleration of gravity, h is the height, and m is the mass of an object. But, for a column of water or air, there equation changes slightly.



$P = mgh_{cm} = \rho_o(H_2-H_1)Ag[(H_2+H_1)/2)]$

The column has an area of A in a horizontal plane, and a height of $h = (H_2-H_1)$. ρ_o is the density, and the mass of the column is $\rho_o V$, which is $m=\rho_o hA$. The height of the center of mass above the reference level is $h_{cm}=[(H_2+H_1)/2)]$. So, $P = mgh_{cm} = \rho_o(H_2-H_1)Ag[(H_2+H_1)/2)]$

The convention that will be used mostly is the potential energy per unit area, so this will be implied by $PE = \rho_o(H_2-H_1)g[(H_2+H_1)/2)]$.

If the water column has a non-constant density function ρ(z), then the potential energy is

$$PE = \int_{-h}^{0} \rho(z) gz dz$$

If it becomes well-mixed, then the water column would have a constant density of $\hat{\rho}$ where $\hat{\rho}$ is the vertically averaged density,

$$\hat{\rho} = \frac{1}{h}\int_{-h}^{0} \rho(z) dz$$

and the potential energy of the mixed column would be

$$PE_{mixed} = \int_{-h}^{0} \hat{\rho} gz dz$$

The stratification represented by the PE Anomaly is

$$\phi = \frac{PE_{mixed} - PE}{h} = \frac{1}{h}\int_{-h}^{0} (\hat{\rho} - \rho(z)) gz dz$$

An example of the PE Anomaly can be seen when looking at a two-layer density structure. The Potential Energy of a stratified column (per unit area and relative to bottom level) is: (Illustrated this is Figure 10)

$$PE_{2L} = \rho_o (h - \Delta h) g \frac{1}{2}(h - \Delta h) + (\rho_0 - \Delta\rho)\Delta h g (h - \frac{\Delta h}{2})$$

$$= \frac{1}{2}\rho_o g (h - \Delta h)^2 + g\Delta h(\rho_o - \Delta\rho)\left(h - \frac{\Delta h}{2}\right)$$

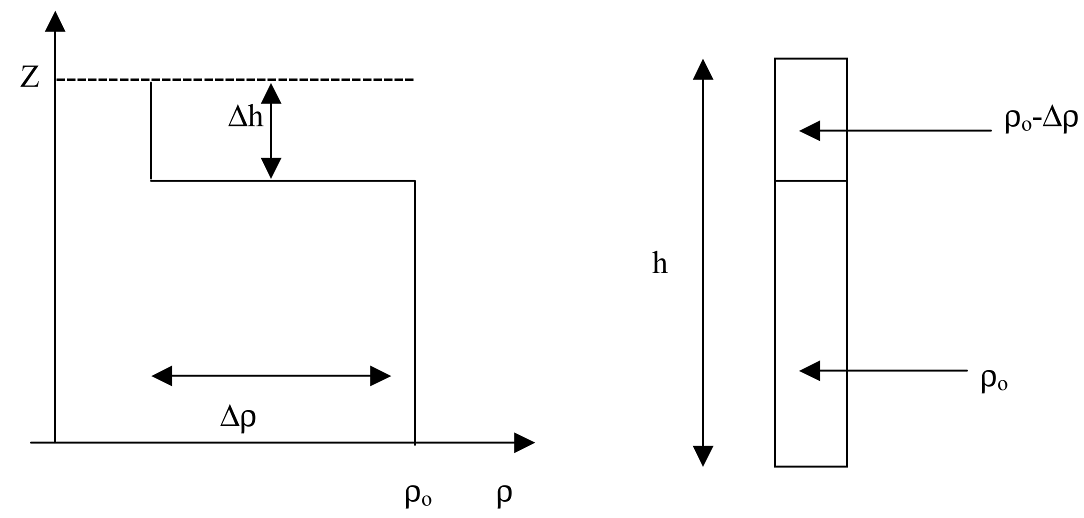


Figure 10. Diagram representing the 2-layer potential energy anomaly before the water column is mixed.

The potential energy after mixing the stratified column is:

$$PE_m = \rho_m hg\frac{h}{2} = \frac{1}{2}\rho_m gh^2$$ (Illustrated in Figure 11)

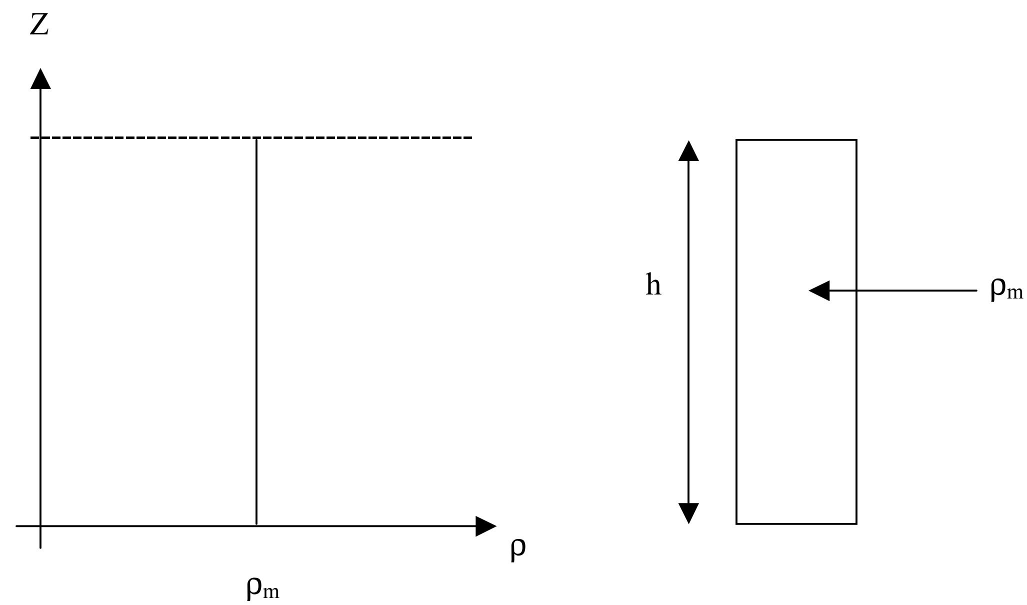


Figure 11. Diagram representing the 2-layer PE Anomaly after mixing the water column.

By conservation of mass, the mass when stratified is the same as the mass after mixing.

$$\rho_o(h-\Delta h)+(\rho_o-\Delta\rho)\Delta h=\rho_m h$$

Solving for ρ_m gives

$$\rho_m=\rho_o-\frac{\Delta h}{h}\Delta\rho\,.$$

Then the potential energy of the mixed column is:

$$PE_m=\frac{1}{2}\rho_m g h^2=\frac{1}{2}g(\rho_o h-\Delta\rho\Delta h)$$

In order to mix the 2-layer column, the difference in PE must be supplied

$$PE_m-PE_{2L}=\frac{1}{2}g\Delta\rho\Delta h(h-\Delta h)$$

By convention, the "PE Anomaly" is the difference divided by h:

$$\phi_{2L}=\frac{1}{2}g\Delta\rho\Delta h\left(1-\frac{\Delta h}{h}\right).$$

Phi is a measure for stratification. A phi of 0 means that there is no stratification (the water is well-mixed), a relatively small phi corresponds to weak stratification, and a large phi indicates highly stratified water. There are three main processes in estuaries that have an effect on phi. They are tidal straining, tidal stirring, and the influence of estuarine circulation. The influence of tidal straining reverses within every tidal cycle. During ebb, all the water at a given location is getting fresher (lighter), but a faster velocity in the upper part of the water column causes more of a change there in the deeper water so stratification and phi increase. During flood, all the water at a given location is getting saltier (heavier), but again, the faster velocity in the upper part of the water column causes more of a change there and stratification and phi decrease [3]. This concept of the upper part of the water column moving in the same direction as the lower part, but at a different velocity, is known as differential advection. This advection can lead to changing stratification over a tidal cycle as described above, and this is also known as strain-induced periodic stratification, or "SIPS". If the density structure of the water column changes with time, so will phi at a rate of

$$\frac{\partial \phi}{\partial t} = \frac{g}{h}\int_{-h}^{0}\left(\frac{\partial \hat{\rho}}{\partial t} - \frac{\partial \rho}{\partial t}\right) z dz .$$

The density change in association with the salinity change is

$$\frac{\partial \rho}{\partial t} = \frac{\partial \rho}{\partial S}\frac{\partial S}{\partial t} = \frac{\partial \rho}{\partial S}\left(-u\frac{\partial S}{\partial x}\right) = -u\frac{\partial \rho}{\partial S}\frac{\partial S}{\partial x} = -u\frac{\partial \rho}{\partial x}$$, where u is the tidal current.

It is assumed that the change in density with respect to x is constant. If the equation above is vertically averaged, then

$$\frac{\partial \hat{\rho}}{\partial t} = -\hat{u}\frac{\partial \rho}{\partial x}$$ leading to $$\frac{\partial \phi}{\partial t} = \frac{g}{h}\frac{\partial \rho}{\partial x}\int_{-h}^{0}\left(u(z) - \hat{u}\right) z dz .$$

$\hat{u}$ is the depth averaged tidal current. The equation above expresses the influence of SIPS due to the velocity profile u(z) on stratification [3]. Following an example from Simpson et al. 1990, take a tidal current profile

$$u(z) = \hat{u}\left[a - b\left(\frac{z}{h}\right)^2\right]$$, where a=1.15, and b=0.425.

$$\left(\frac{\partial \phi}{\partial t}\right)_{stra} = \frac{g}{h}\frac{\partial \rho}{\partial x}\hat{u}\int_{-h}^{0}\left[a - b\left(\frac{z}{h}\right)^2 - 1\right] z dz = .031 g h \hat{u}\frac{\partial \rho}{\partial x}$$ [11].

This represents the effect that tidal straining has on stratification.

Another process that affects stratification is estuarine circulation. It tends to make the surface water fresher (lighter and a smaller density) and the deeper water saltier (heavier and a greater density). This increases stratification and therefore, it also increases phi. The contribution of this flow to phi can be determined as follows. The derivative of phi with respect to time is

$$\frac{\partial \phi}{\partial t} = \frac{g}{h}\frac{\partial \rho}{\partial x}\int_{-h}^{0}(u(z) - \hat{u})zdz \, .$$

To represent the velocity shear due to estuarine circulation, the steady state flow is used in which the pressure gradient is balanced by frictional forces.

$$u(\zeta) = \frac{gh^3}{48A_z\rho}\frac{\partial \rho}{\partial x}(1 - 9\zeta^2 - 8\zeta^3), \zeta = \frac{z}{h}$$

Substituting into the above equation:

$$\frac{\partial \phi}{\partial t} = \frac{g^2h^4}{48A_z\rho}\left(\frac{\partial \rho}{\partial x}\right)^2\int_{-1}^{0}(1 - 9\zeta^2 - 8\zeta^3)\zeta d\zeta$$. Simplified this becomes

$$\left(\frac{\partial \phi}{\partial t}\right)_E = \frac{1}{320}\frac{g^2h^4}{A_z\rho}\left(\frac{\partial \rho}{\partial x}\right)^2 \text{ [11].}$$

A_z is the eddy viscosity term. It cannot properly be treated as a constant because of the very large changes in tidal currents and therefore, the intensity of turbulence and vertical mixing over the tidal cycle. The variation can be described as $A_z = \gamma|\hat{u}|h$, where γ is a proportionality constant that indicates the strength of the dependence [4]. $|\hat{u}|$ is the depth mean speed of the current.

The third process that has an effect on ϕ is tidal stirring due to the generation of TKE by the bottom stress associated with the tidal current. The influence of stirring is to mix the water, reduce stratification, and therefore, reduce phi towards 0. There is a restrictive assumption that wind stirring and any non-tidal motion are negligible and therefore neglected for this model. The rate of working, or tidal stirring power is $P_t = \varepsilon \rho c_d |\hat{u}|^3 / h$. ε is the fraction used for the efficiency of mixing, and c_d is the bottom drag coefficient. The average stirring power over a tidal cycle is

$$\frac{1}{T}\int_0^T |\hat{u}|^3 \, dt = \frac{4}{3\pi} U^3, \text{ if } |\hat{u}| = U \sin \omega t \quad (T=2\pi/\omega).$$

So, the average available stirring power is $\frac{4\varepsilon c_d U^3 \rho}{3\pi h}$. However, this model uses the more general form for the contribution of tidal stirring on stratification, which is

$$\left(\frac{\partial \phi}{\partial t}\right)_{stir} = -\varepsilon \rho c_d \frac{|\hat{u}|^3}{h}.$$

The equation governing the rate of change of stratification is just the sum of the three individual processes.

$$\frac{\partial \phi}{\partial t} = \left(\frac{\partial \phi}{\partial t}\right)_{stra} + \left(\frac{\partial \phi}{\partial t}\right)_{E} + \left(\frac{\partial \phi}{\partial t}\right)_{stir.}.$$

And together, this becomes

$$\frac{\partial \phi}{\partial t} = .031 gh |\hat{u}| \frac{\partial \rho}{\partial x} + \frac{1}{320} \frac{g^2 h^4}{\rho A_z} \left(\frac{\partial \rho}{\partial x}\right)^2 - \varepsilon \rho c_d \frac{|\hat{u}|^3}{h}.$$

This equation can be integrated in time to determine ϕ(t) (J m^{-3}), that is, the variation of the strength of stratification with time [3].

RESULTS

A *Matlab* program [5] was used to make a model of phi for the Elizabeth River. The inputs for the program were three main tidal current components, the depth h, the change in density with respect to x, and the eddy viscosity (A_z). If A_z is entered as 0, the program then asks for γ and a floor for A_z, and then it generates the eddy viscosity. Else, if A_z is entered as a positive number, the program uses a constant A_z. The program also asked to input three values of tidal components. The value inserted for the principal lunar component was .55, and the value for the principal solar tidal component was .2. The values for these components gave the tidal currents amplitudes that matched those which were predicted for the Elizabeth River from the charts of the *Currents-Chesapeake, Southern Branch* (Figures 8 and 9). Again, the days of the cruises were May 24th, and June 11. The third tidal component, the larger lunar elliptical, was set to 0. This parameter allows the amplitude for the spring and neap tides to vary throughout the month; however, with its value being set to zero means that every spring tide will have the same current amplitude, and every neap tide will have the same amplitude during the month. The depth was set at 12 meters, and a constant A_z was used at a value of .0015 m^2/s. The parameter for the change in density with respect to the along channel distance From station A to station D is about three kilometers, or 3000 meters. So, the value for the change in density with respect to x was set at .4/30000 kg/m^4.

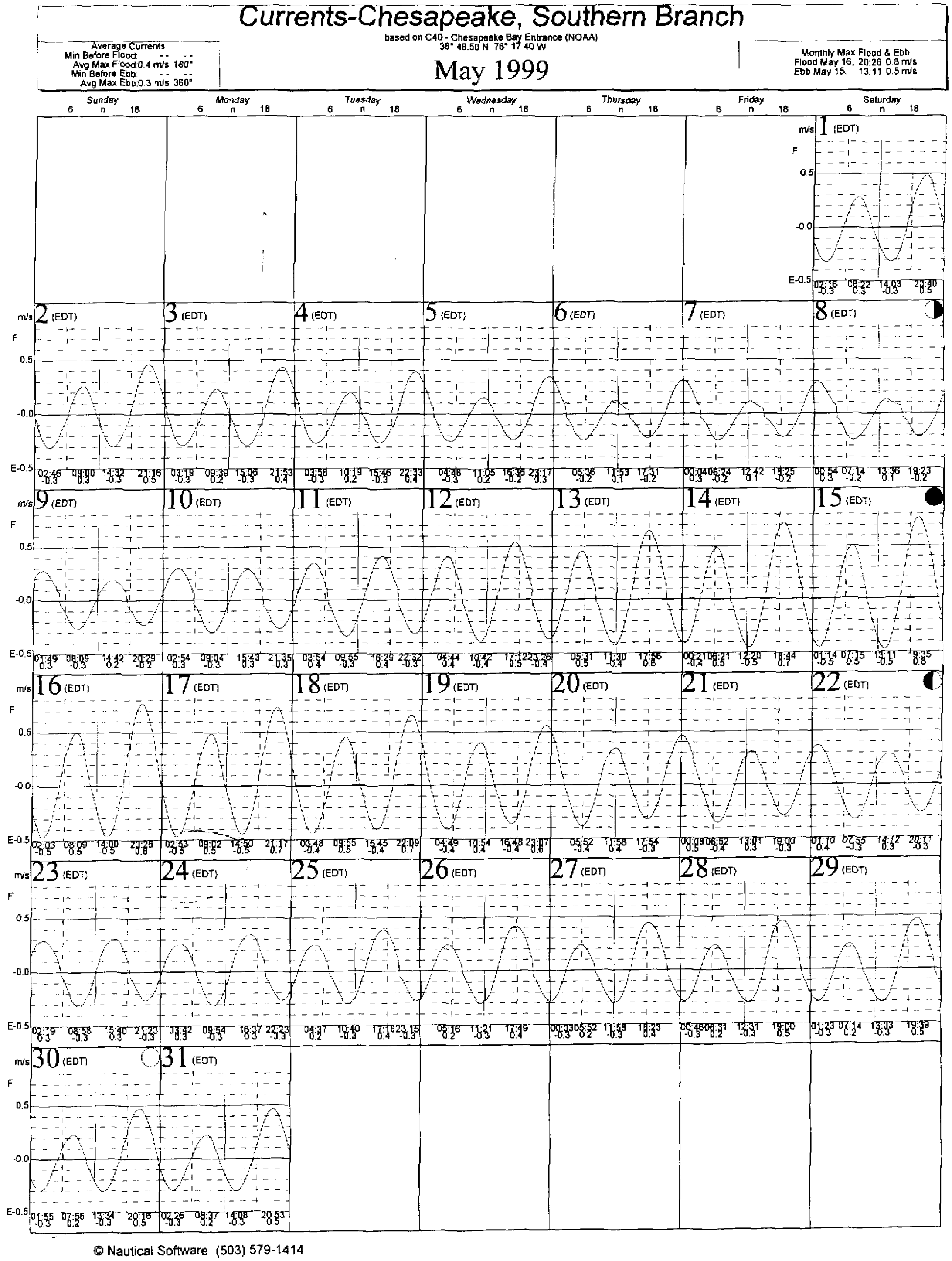


Figure 12. Tidal current predictions for the Southern Branch of the Chesapeake River for the month of May. The cruise was on the day of May 24, 1999, which shows the tidal current prediction had a maximum velocity of about .25 m/s.

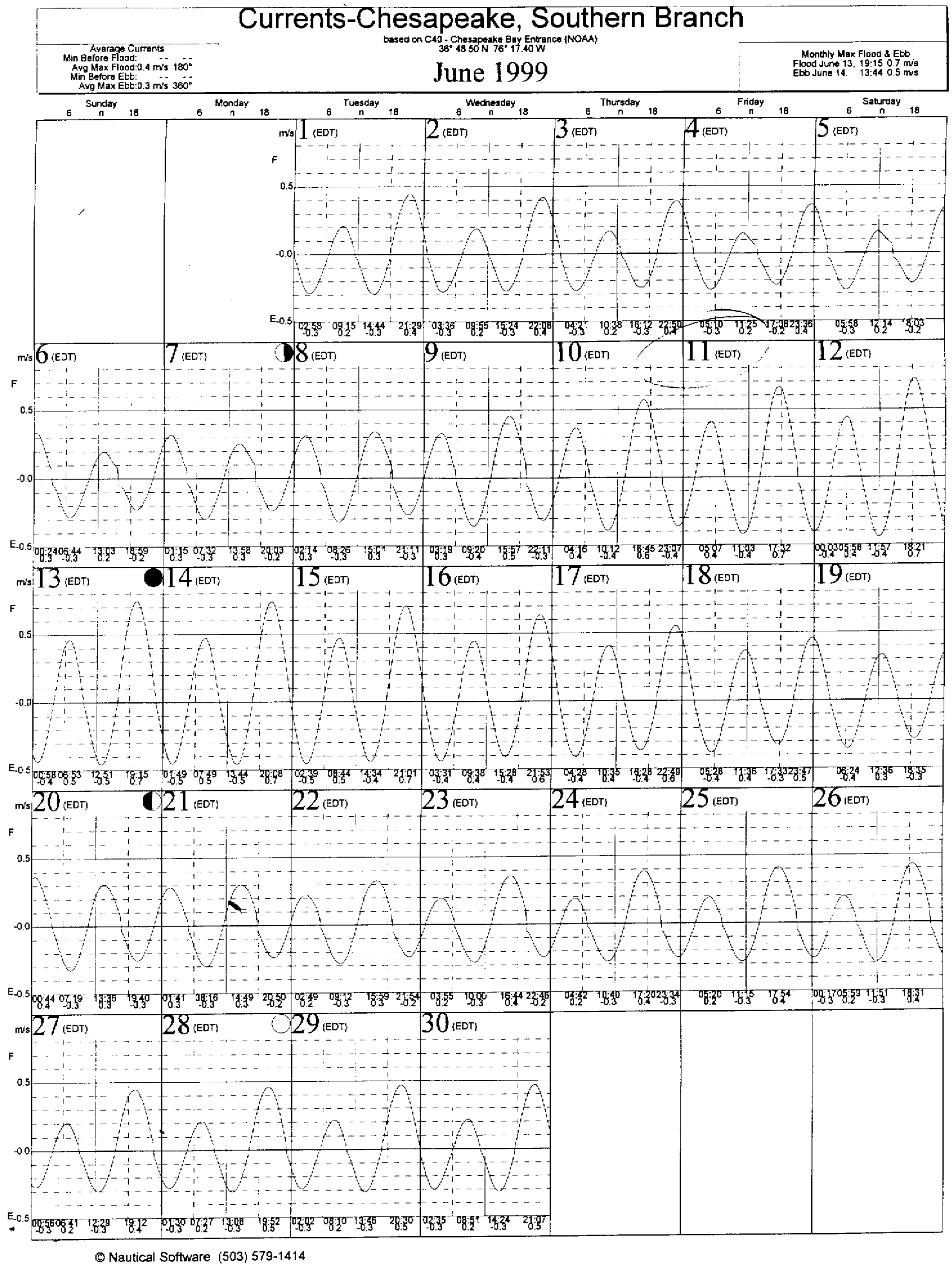


Figure 13. Tidal current predictions for the Southern Branch of the Chesapeake River for the month of June. The cruise was on the day of June 11, 1999, which shows the tidal current prediction had a maximum velocity of about .55 m/s.

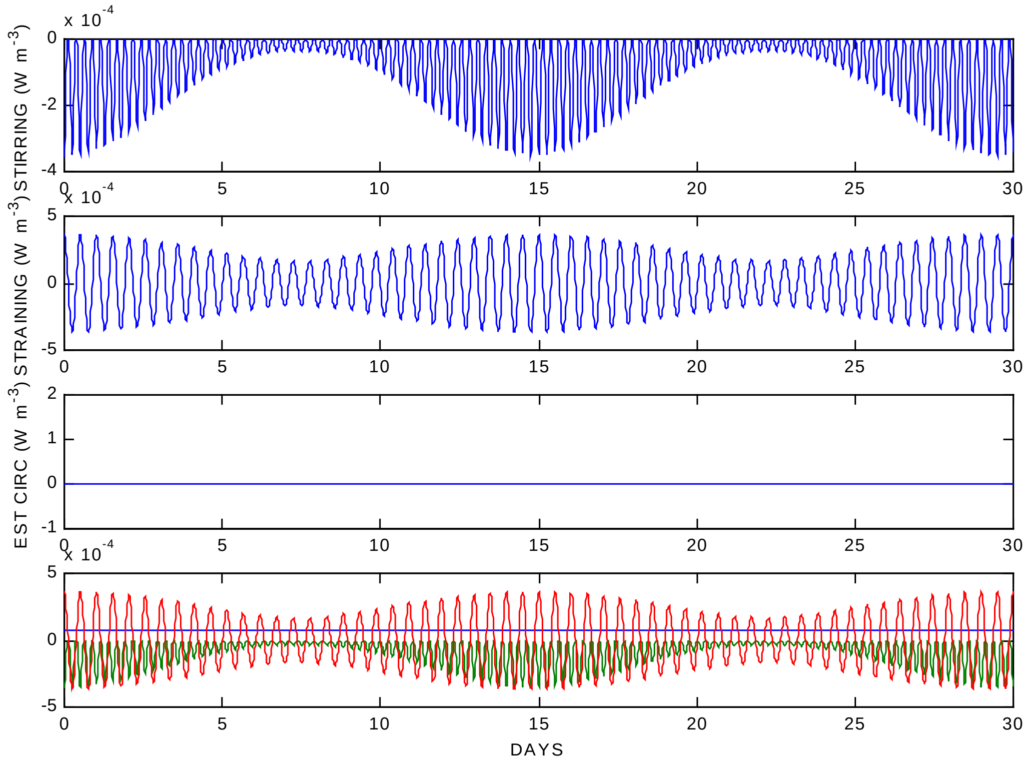


Figure 14. Graphs of the three processes which have an effect on phi. Top graph is the effect of tidal stirring, the upper middle graph is the effect of tidal straining showing SIPS, the lower middle graph is the effect of estuarine circulation, and the bottom graph shows the contribution of each process relative to one another.

The graphs in Figure 14 represent the effect of each of the separate process on the change of phi with respect to time. The top graph is the effect of tidal stirring; the second graph is the effect of straining on the rate of change of phi, and the third graph is the effect of estuarine circulation on the rate of change of phi with time. The graph on the bottom shows the effects of all three processes on the same scale. This allows the effects to be compared to each other. A note to make is that on the third graph, it appears that the effect due to estuarine circulation is zero. However, when placed on the bottom graph that has a smaller scale, it can be seen that the effect is in fact not zero.

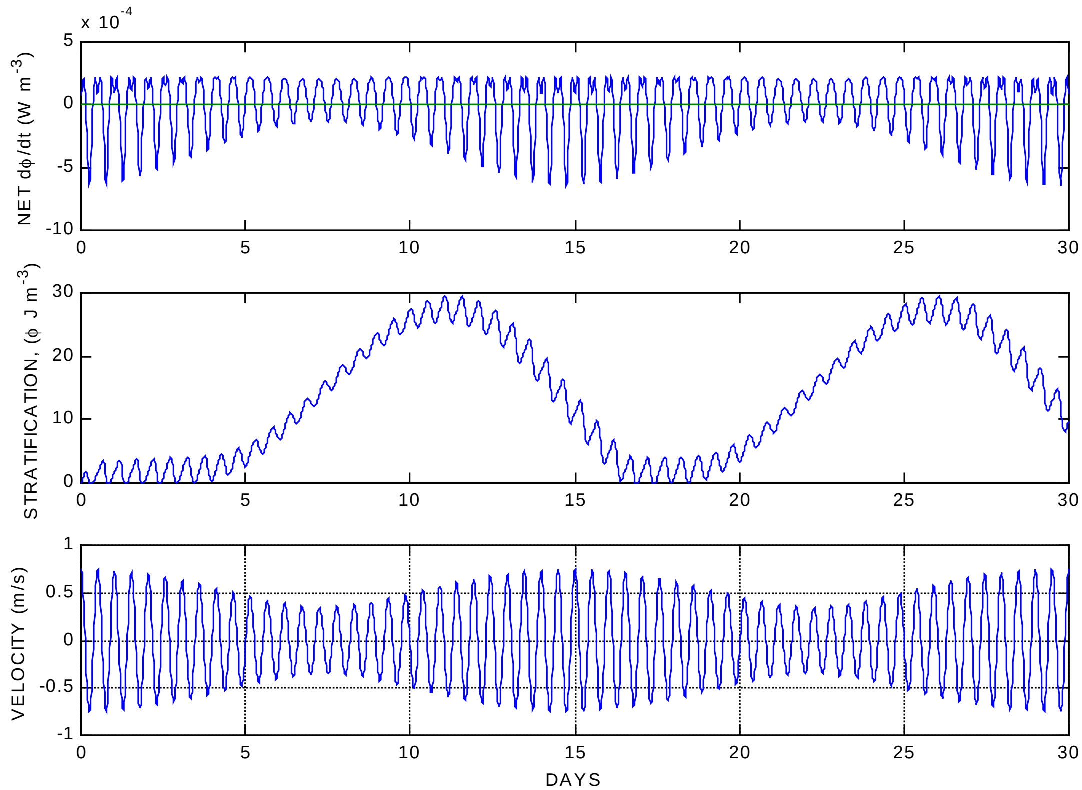


Figure 15. Model simulation of stratification over one month. Bottom graph represents the velocity overt the month, the middle graph represents the stratification over the month, and the top graph represents the net effect of all three processes on the rate of change of phi.

The first graph above represents the net effect of all three processes on the rate of change of phi. In other words, this is just the equation

$$\frac{\partial \phi}{\partial t} = .031gh|\hat{u}|\frac{\partial \rho}{\partial x} + \frac{1}{320}\frac{g^2h^4}{\rho A_z}\left(\frac{\partial \rho}{\partial x}\right)^2 - \varepsilon\rho c_d\frac{|\hat{u}|^3}{h}.$$

The middle graph is phi itself, and the last graph is showing the varying current velocity throughout a month. When comparing the graph of phi with the graph of velocity, it can be seen that when the current velocity starts to decrease, the stratification starts increasing. Then, as the current velocity starts to increase, the stratification starts to decrease back to phi equals zero. The influence of tidal straining is relatively small. It accounts for the small fluctuations that occur twice a day [4]. The variations in phi that occur over the longer time scale are mainly due to competition between estuarine circulation and tidal stirring. When the tidal currents are strong during spring tides, the tidal stirring wins over estuarine circulation, and it causes the water column to become well mixed, decreasing ϕ towards zero. Then, when the tidal currents are relatively small as they are during a neap tide, the tidal stirring decreases, and the estuarine circulation has more of an effect allowing more stratification in the water after a few days, therefore increasing phi. This competition is seen in the above graphs. During spring tides, phi is zero, and then with decreasing current velocity, phi builds up to be almost 30 Jm^{-3}.

CONCLUSION

After following the Potential Energy Anomaly and looking at the graphs of phi for the model of Elizabeth River, it is not surprising that there is a difference in the stratification for the data taken in the month of May and June. All the graphs of salinity versus depth for the day of June 11 show very little stratification, and June 11 was spring tide. The effect of tidal stirring was greater than that of the estuarine circulation causing the water column to become well mixed. And on May 24, the graph of salinity versus depth from the data collected shows that there is a greater stratification, meaning that tidal stirring was weaker so the estuarine circulation played a greater role. The next step would be to take ρ that was calculated from the salinity, temperature, and depth data recorded in the field, and then use that in the equation for phi. This would allow the real density profile of the Elizabeth River to be used in the Potential Energy Anomaly, and the exact strength of stratification for those two dates could be determined.

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