Horrible, horrible things: Numerical modeling of oil spills in Narragansett Bay

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Abstract. Numerical modeling is an important tool in the study of geophysical fluids. This methodology is particularly powerful because the response of natural systems to a range of parameters can be examined, which is not possible in "real world" experiments. Modeling estuarine circulation allows the prediction of the transport of materials that are in the water column such as pollutants, larvae, or other biological organisms. We use a three dimensional model of Narragansett Bay to perform numerical experiments on the dynamics of oil spills. We study the significance of different surface wind directions and magnitudes, as well as the significance of including variable salinity in the model. Most models only look at oil at the surface, but oil that mixes down into the water might behave differently than surface oil. We examine the difference in the spread of oil at the surface and oil that mixes down into the water. Our results suggest the direction and magnitude of surface winds provide a large constraint on the path of the oil spill and including variable salinity drastically changes the extent of oil dispersion within both surface and bottom waters.

1. Introduction

The physical dynamics of an estuary determine the transport of nearly all materials in the estuary. These materials include pollutants, biological organisms, and nutrients. Therefore, the ability to predict the velocity field of an estuary is an important tool in understanding the biology and chemistry of the estuary. There have been various numerical studies of estuarine circulation (e.g., Gordon and Spaulding, 1987). They are useful tools for studying the transport of these kinds of tracers because they predict the velocity field.

In this study we examine the dynamics of oil spills in Narragansett Bay. Narragansett Bay is a weakly stratified estuary in Rhode Island. The three important forces that act on this estuary are tidal forces, surface wind stress, and density effects caused by the salinity gradient. We examine the effect of these forces on the spread of oil in the Bay.

Oil spill modeling aids in the timely containment of spills and minimizing their damage. Most oil spill models only look at the spread of oil at the surface and assume that this will give an accurate representation of the total oil spreading. This may not be the case if the oil mixes down into the water column. We study the transport of oil at the surface as well as oil that mixes downward into the water column.

2. Model Description

The model we use is the Regional Ocean Modeling System (Haidvogel et al., 2000). It is a three-dimensional, free-surface, hydrostatic, primitive equation ocean model that uses stretched, terrain-following coordinates in the vertical and orthogonal cartesian coordinates in the horizontal. The primitive equations are:

$$\partial u / \partial t + \overset{r}{u} \cdot \nabla u - fv = - \partial \phi / \partial x + F_u + D_u \qquad (1)$$

$$\partial v / \partial t + \overset{r}{u} \cdot \nabla v + fu = - \partial \phi / \partial y + F_v + D_v \qquad (2)$$

$$\partial T / \partial t + \overset{r}{u} \cdot \nabla T = F_T + D_T \qquad (3)$$

$$\partial S / \partial t + \overset{r}{u} \cdot \nabla S = F_S + D_S \qquad (4)$$

$$\rho = \rho(T,S,P) \qquad (5)$$

$$\partial \phi / \partial z = -\rho g / \rho_0 \qquad (6)$$

$$\nabla \cdot \overset{r}{u} = 0 \qquad (7)$$

Equations (1) and (2) are the conservation equations of momentum for the x and y directions. Equations (3) and (4) are the advection-diffusion equations for potential temperature and salinity. Equation (5) is the equation of state. Equation (6) is the hydrostatic balance with the Boussinesq approximation. Equation (7) is the incompressible continuity equation.

We run this model on a domain from the Providence River as the north boundary and Rhode Island Sound as the south boundary. We force the open boundaries with tidal heights and amplitudes we obtained from the Adcirc circulation model run by the USGS and force the surface with analytical wind stresses.

We use 90 grid boxes in the zonal direction, 150 grid boxes in the meridional direction, and 20 grid boxes in the vertical direction. The vertical "sigma" coordinate is stretched and terrain-following. Since there are 20 vertical levels at all points in the bay, shallower points will have shorter grid boxes and deeper points will have taller grid boxes. Also, any vertical level will be at different depths at different points in the bay, depending on the total thickness of the water at that point.

3. Description of Numerical Experiments

We modeled an oil spill at Brenton Reef in Narragansett Bay (Figure 1) and represented the oil spill by adding lagrangian "floats". These floats move along lines of constant geopotential by horizontal advection. It is important to note that we are ignoring the effect of horizontal diffusion or any other sinks for the oil, such

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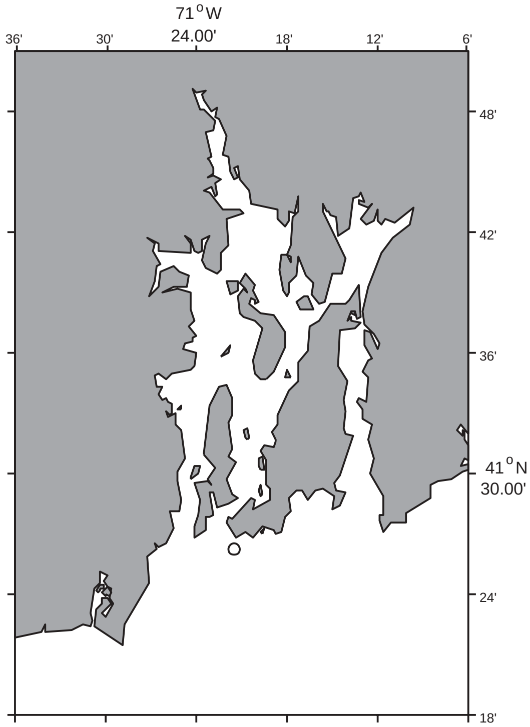

Figure 1. Brenton Reef. Site of oil spill (circle).

as loss to the bottom or air. We account for vertical diffusion by placing floats at the top, middle, and bottom sigma level. Finally, the simplifying assumption is made that much of the important dynamics are advection based and that we may still capture many of the important features of the oil spill while ignoring other terms in the transport equation.

All runs are forced with tidal components M2, M4, M6, S2, N2, K1, and O1 obtained from the Adcirc circulation model run by the USGS. We examined the effects of different wind speeds and directions and the effects of salinity. We used four different surface wind directions and three different surface wind speeds. The control run had no wind and subsequent trials had winds of 5, 7, and 9 m/s out of the north, east, south, and west. We ran the model without variable salinity for each case and then ran the 5 m/s cases with variable salinities and fresh water input at the Providence River of 50 cubic meters per second. The initial condition for the salinity runs was a simple linear meridional gradient, starting at 30 PSU at the south boundary and ending at 0 at the Providence River. (In order for the numerics to work properly, we included a very small sine wave perturbation to this salinity field in the zonal direction in the). A constant temperature was applied throughout the bay in all runs.

The duration of all experiments was five days. Initial wind speed was zero and ramped up over three hours to the final wind speed. After three days, speeds were ramped down over three hours. The final two days had no wind. Ten floats were put in at each of the top, middle, and bottom layers. The first float at each level was added 12 hours into the run in order to give the model time to “spin up”. Every additional six hours, a float was added at each level.

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4. Results

4.1. Without variable salinity

The positions of floats over time mark dispersion patterns, or pathways, for oil introduced to the system. These particle paths also provide a glimpse into both tidal and non-tidal circulation patterns as a function of different forcing conditions. Results are presented for simple cases first and then for cases with increasing complexity.

Figure 2 shows the partical trajectories of the oil floats with no wind or salinity in the top, middle, and bottom levels. The oil does not go very far in this run. The prevailing pattern is characterized by the floats moving northward along the east side of the east passage and then moving southward along the west side of the east passage.

Figure 3 shows the partical trajectories for the runs with winds out of the north and no salinity. It shows the top, middle, and bottom levels for a 5, 7, and 9 m/s surface wind. In the 5 m/s run, only the surface floats seem to be influenced by the wind. The surface floats go to the south. For stronger wind speeds, the bottom and middle floats go further north. This is reasonable, because conservation of mass dictates that if the surface water is flowing south, there must be a return flow going north.

Figure 4 shows the same plots with winds out of the south. Like with the southerly winds, the surface water flows in the direction of the wind. Interestingly, at higher wind speeds there is basically no flow opposite the wind by the bottom floats and only a very small return flow by the middle floats.

Figure 5 shows the same plots with winds out of the east. The surface water flows with the wind. At higher wind speeds, the middle and bottom floats do not go against the wind, but in some cases go slightly more north and south.

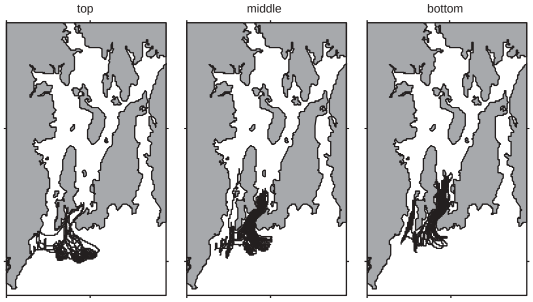

Figure 2. Path of oil spill. No wind. No salinity.

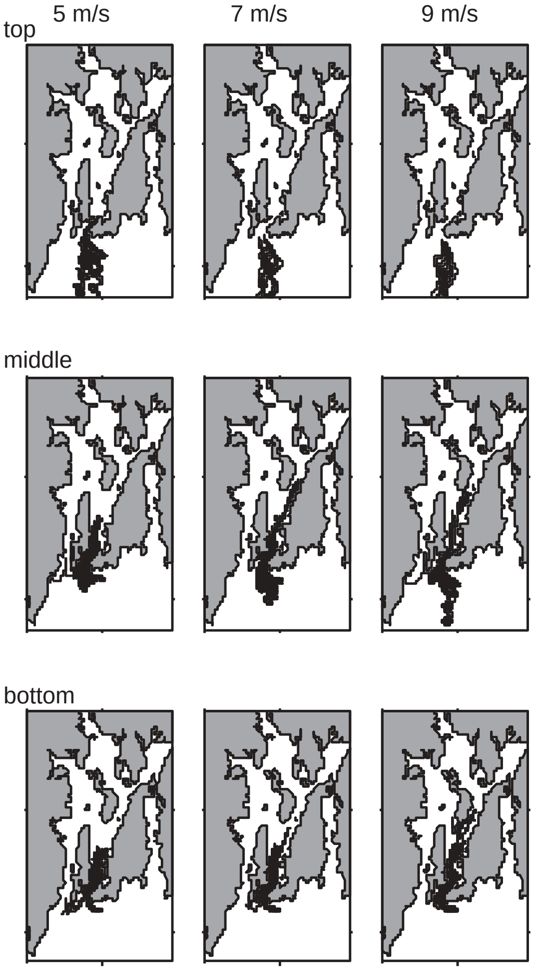

Figure 3. Path of oil spill. Northerlies. No salinity.

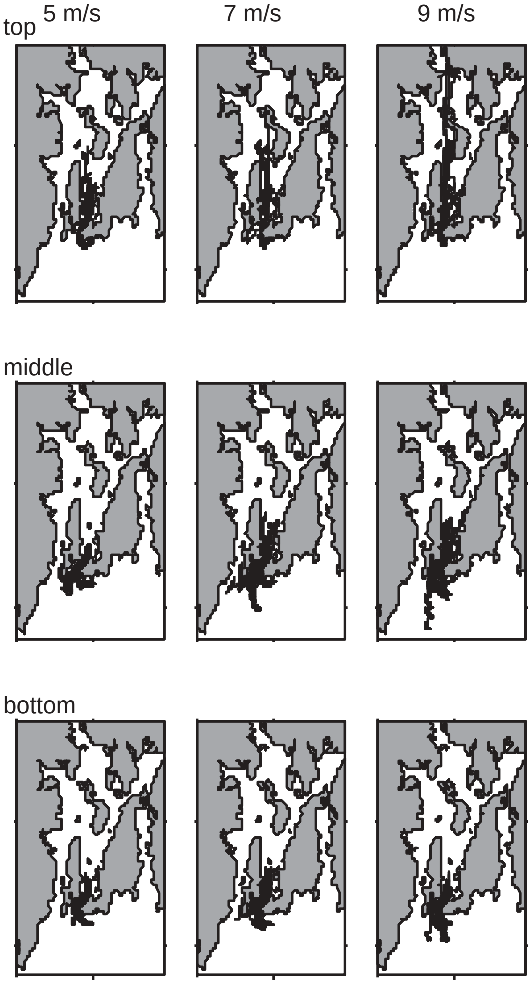

Figure 4. Path of oil spill. Southerlies. No salinity.

Figure 6 shows the same plots with winds out of the west. The surface water flows with the wind, and interesingly at higher wind speeds, the middle floats go with the wind and with a 9 m/s wind even the bottom floats go with the wind.

In the runs with no salinity, the winds did not have a very large influence on the floats in the middle and bottom layers. With the northerlies and southerlies, the bottom floats typically traveled opposite the wind direction. With the easterlies and westerlies, the middle and bottom floats sometimes moved orthogonal to the wind and sometimes traveled with the wind.

4.2. With variable salinity

Long term transport in estuaries is clearly influenced by background density gradients. In natural systems like the Bay, density is related to both temperature and salinity. In order to begin simply, we start by considering the role of salinity on non-tidal dispersion patterns.

Figure 7 shows the particle trajectories of the oil floats with no wind, including variable salinity and a freshwater source from the Providence River. Clearly, including variable salinity and adding mass at the Providence River makes a substantial difference. As expected because of the freshwater from the Providence River the surface floats travel further south than they did without salinity. Also, because of the density effects, the middle and bottom floats go much further north. The oil floats also spread more with salinity than without salinity.

Figure 8 shows the particle trajectories of the floats for 5 m/s winds out of the north and south while including variable salinity. For the northerly wind, the surface floats travel further to the south and less to the east and west than without wind. The middle and bottom floats travel further north and the bottom floats move less to the east than without any wind. With the southerly wind, some of the surface floats travel much further north and the floats do not move southeast as in the no wind case. The middle floats do not move as far north and more floats move to the south and east as in the no wind case. The bottom floats move further to the south and less to the east than with no wind.

Figure 9 shows the trajectories for 5 m/s winds out of the east and west with variable salinity. For the easterly wind, the surface floats all move southwest instead of some of the floats moving southeast as in the run with no wind. The middle floats travel further north, and

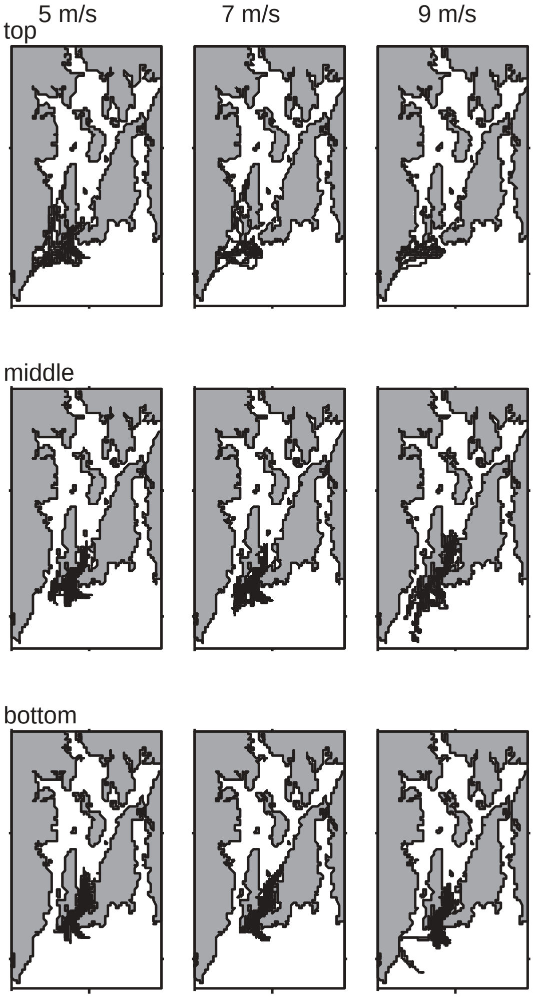

Figure 5. Path of oil spill. Easterlies. No salinity.

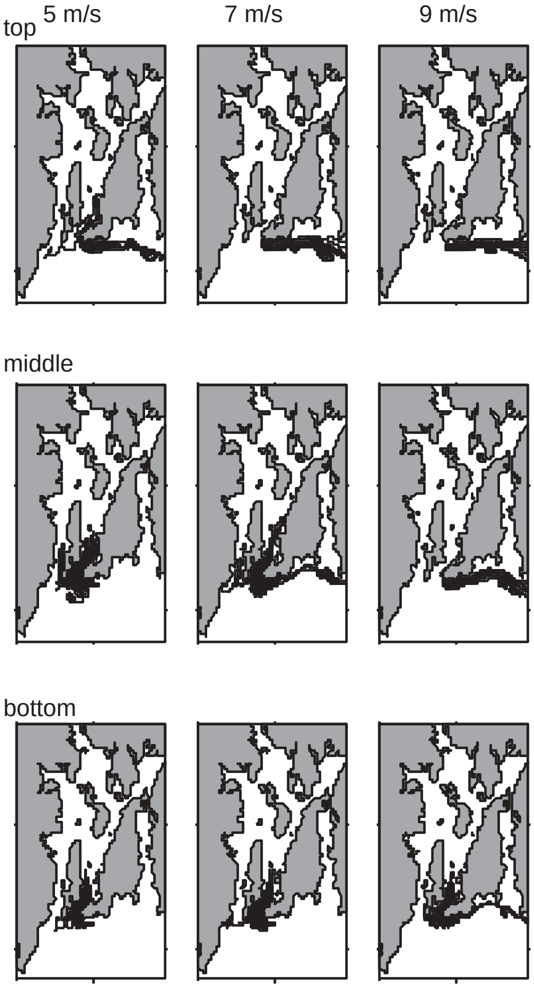

Figure 6. Path of oil spill. Westerlies. No salinity.

some floats travel up the west passage. The bottom floats move less to the east. For the westerly wind, the surface floats go much more to the east than with no wind. The middle floats move further north and south and the bottom floats move further north.

The runs that include variable salinity show the oil spreading out much more than the runs without variable salinity. Also, the wind influences the flow at the bottom and middle levels more than without salinity and the bottom and middle level floats move much further, especially to the north.

4.3. Effects of different magnitudes of wind speed

A number of studies (eg., Weisburg and Sturges, 1976) have shown that wind forcing is of equal magnitude to tides in terms of kinetic energy for estuarine systems. A set of experiments were run to quantify how the magnitude and direction of wind speed modulates surface versus bottom dispersion patterns.

Figure 10 shows the maximum latitude reached by the floats as a function of wind speed; these runs have no variably salinity. The four panels show the four wind directions, each with a separate curve for the top middle and bottom levels.

With the easterlies, at moderate wind speeds the surface floats move much further north than with no wind or at extreme wind speeds. The curve for the middle floats initially decreases and subsequently increases at very high wind speeds. The bottom curve does exactly the opposite, initially increasing and then decreasing at very high wind speeds. With the westerlies, the surface curve increases from no wind to the 5 m/s wind and then decreases. The middle curve is erratic, and the bottom curve decreases at a steady, slow rate.

The southerlies show the surface curve increasing very rapidly with wind speed. The middle and bottom curves are fairly flat. With the northerlies, the surface curve decreases, while the middle and bottom curves increase.

Figure 11 shows the minimum latitude reached by the floats as a function of wind speed. Once again, these runs do not include variable salinity.

With the easerlies, all of the curves initially increase and then decrease. However, the surface curve is fairly constant. With the westerlies, all the curves increase.

With the southerlies, the surface curve increases, while the middle and bottom curves increase and then decrease. With the northerlies, the surface curve

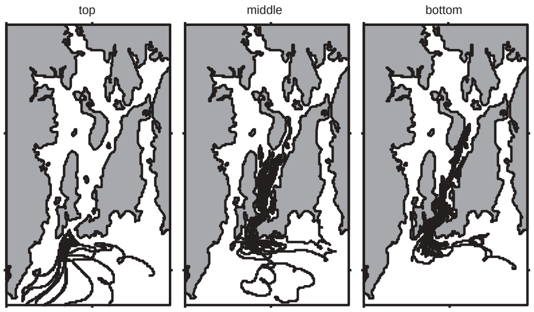

Figure 7. Path of oil spill. No wind. With salinity.

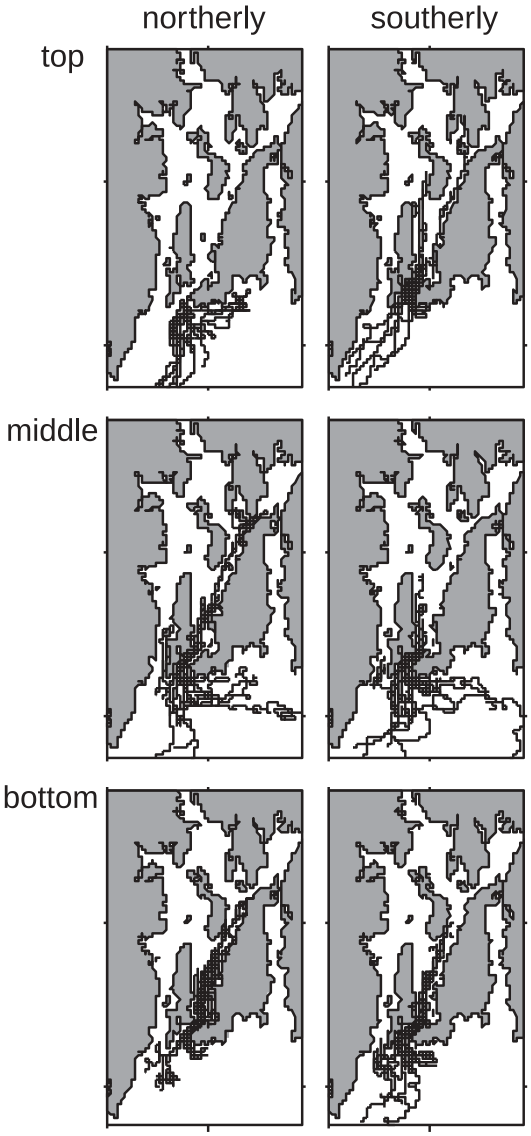

Figure 8. Path of oil spill. 5 m/s Northerly and Southerly. With Salinity.

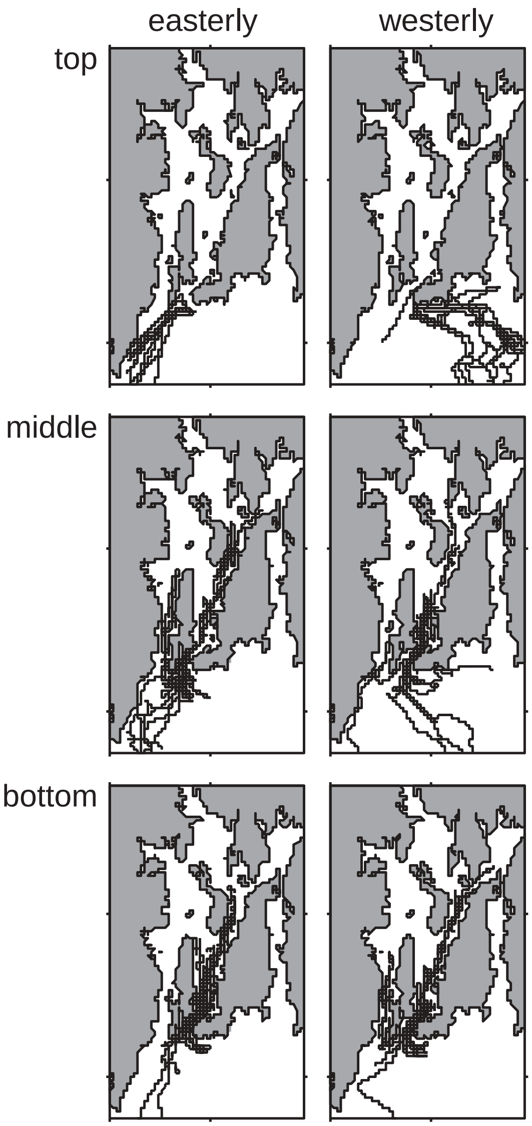

Figure 9. Path of oil spill. 5 m/s Easterly and Westerly. With Salinity.

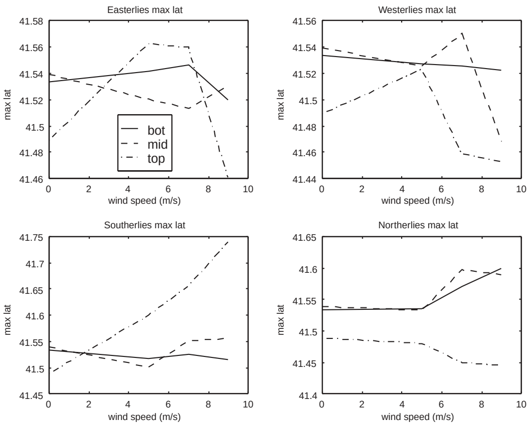

Figure 10. Furthest north floats reach vs wind speed.

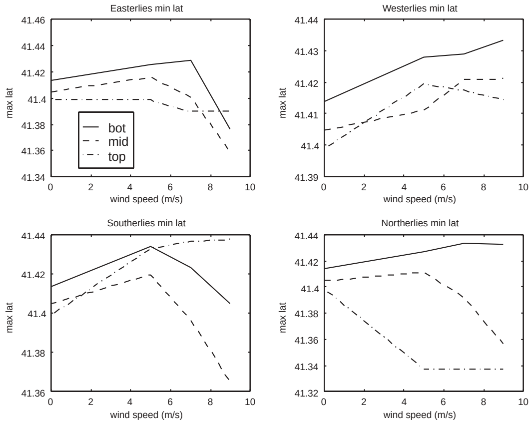

Figure 11. Furthest south floats reach vs wind speed.

decreases. (For all of the northerly winds, the floats reached the south boundary of the model.) The middle curve decreases, while the bottom curve increases slightly.

These plots show the nonlinear effects of surface winds. Few clear patterns were observed, but the middle and bottom curve behave fairly similarly.

5. Conclusions

It is clear that oil that mixes down into the water column behaves very differently than oil that remains at the surface. Models that only predict the spread of oil at the surface do not accurately predict the spread of oil if some oil mixes down into the water column. In order for the government to be able to respond better to an oil spill, models must be made that include deep water oil.

There is a drastic difference in the oil spill path and amount of spreading with and without salinity. This is due to the density difference induced by salinity, with fresh water at the surface moving out of the Bay and more saline, deeper water moving up into the Bay. Thus, hydrodynamical models that do not include density effects would predict far less deep transport.

The surface oil generally moves in the direction of the surface wind, while the deeper oil generally moves orthogonal to the wind if the wind is out of the east or west and opposite the wind if the wind is out of the north or south. The maximum opposite transport is at the middle level and not at the bottom. This could possibly be due to bottom friction.

6. Notation

D's	diffusive terms.
F's	forcing terms.
$f(x,y)$	Coriolis parameter.
g	gravitational acceleration.
P	total pressure.
$\phi(x,y,z,t)$	dynamic pressure, $\phi=(P/\rho_0)$.
$\rho(x,y,z,t)$	density.
$S(x,y,z,t)$	salinity.
$T(x,y,z,t)$	potential temperature.
u,v,w	(x,y,z) components of velocity vector $\vec{u}$.

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References

Gordon, R. B., and Spaulding, M. L., 1987. Numerical Simulations of the Tidal- and Wind-Driven Circulations in Narragansett Bay. *Estuarine, Coastal and Shelf Science,* **24**, 611-636.

Haidvogel, D. B., Arango, H. G., Hedstrom, K., Beckmann, A., Malanotte-Rizzoli, P., Shchepetkin, A., 2000. Model evaluation experiments in the North Atlantic Basin: simulations in nonlinear terrain-following coordinates. *Dynamics of Atmospheres and Oceans*, **32**, 239-281.

Weisburg, R., and Sturges, W., 1976. Velocity Observations in the West Passage of Narragansett Bay: A Partially Mixed Estuary. *Journal of Physical Oceanography*, **6**, 345-354.