Three-Dimensional Ocean Circulation in Long Bay of the Carolinas: Numerical Modeling Results of the Year 2009

ABSTRACT

The economies of states like North and South Carolina are heavily dependent on the security of their natural resources, such as the beaches along the Grand Strand. These beaches provide critical environments for the tourism industry in the southeastern region of the United States. However, in Long Bay of the Carolinas, coastal erosion is severe and sediment supply from nearby rivers is minimal. Thus, it has become increasingly necessary to study the oceanographic processes that affect the coastline and surrounding waters in order to protect the local and state economies. This study provides 3-D modeling simulations of sea water salinity, temperature, and currents in Long Bay, as created by a numeric model. These model simulations are a first step in understanding how the ocean circulates throughout Long Bay, which is an important factor controlling sand erosion on the beaches and sediment transport in the inner continental shelf. Preliminary results show that small river dispersal in Long Bay is localized but seasonally variable. Ocean circulation patterns are both spatially and temporally variable; the dominant circulation in Long Bay is along shore, which is considerably stronger than cross-shore currents. In addition, upwelling and stratification are strongest in Long Bay in the spring and summer. Our model is being used to simulate sediment transport and deposition in Long Bay to benefit beach erosion and nourishment studies.

Introduction

The east coast of the United States is home to an abundance of both natural and economic resources. Infrastructure and population in coastal areas is continually growing, and the southeastern U.S. has experienced a faster growth in population than any other coastal region since 1980 (Crosset et al., 2004). South Carolina's eight coastal counties are within this rapidly expanding area and will surely experience the effects of further population increase in the future. The Grand Strand in the Carolinas spans a 100 km arc of shoreline from Winyah Bay at the southern end to Cape Fear Estuary in the north, and the body of water bounded by this stretch of coastline is known as Long Bay (Figure 1). Along the Grand Strand are a number of major tourist attractions, including the cities of Myrtle Beach, North Myrtle Beach, Surfside Beach, and Murrels Inlet. The significance of tourism in the state's economy and infrastructure makes the beaches in these areas important natural resources to not only the states of North and South Carolina but the entire southeastern region. Because of the economic importance of these areas, it has become increasingly necessary to study the coastal oceanographic processes that affect the coastline.

Beaches and barrier islands are the two primary sedimentary environments along the Grand Strand, with some smaller tidal inlets and swashes in between (Ma, et al., 2010). Barrier spits in this area indicate that the predominant direction of longshore drifting is to the southwest. Previous work on similar coastlines near Sarasota, Florida and Long Island, New York, however, has shown that the rate and direction of transport of coarse and fine-grained sediment can vary significantly in time and space (Schwab et al., 2000, Twichell et al., 2003). Studies focused on the Grand Strand have found that longshore sediment transport is often disrupted by seaward transport events near locations of paleo-river channel-filled sands (Park et al., 2009).

Denny, et al. (2005) characterized four general sea-floor environments identified on the South Carolina inner shelf: inlet shoal complexes, shoal-detached shoals, hardbottoms, and mixed zones. The Pee Dee River system drains the Peidmont and coastal plain to Winyah Bay, but little modern fluvial sediment is deposited in Long Bay (Ma et al., 2010; Baldwin et al., 2004).

Long Bay is a mixed-energy, wave-dominated environment (Denney et al., 2005) with a tidal range of only ~1.4 to 1.6m (Slovinsky, 2001) and small riverine fluxes in the area. The sediment transport patterns in Long Bay are heavily controlled by the physical oceanographic processes occurring on the shore/inner shelf interface and further off shore.

The curved shape and bathymetry of Long Bay (Figure 2) may also play a key role in the sediment transport and coastal circulation processes. Sanay et al. (2008) found that the oscillatory nature of upwelling- and downwelling-favorable conditions, primarily controlled by wind and storm patterns, plays an important role in keeping the inner shelf stratified, and the curved shape of the coastline influences inner shelf circulation.

In order to counteract the severe erosion of the beaches, the state has adopted a nourishment program that transfers inner shelf sand onto the beaches and monitors the near-shore processes affecting sediment transport onshore and on the inner shelf. The 3-D ocean circulation patterns and the limits on how far the new sediment can be dispersed, however, are still poorly understood.

The objective of this study is to observe coastal circulation patterns near the Grand Strand, as simulated by a 3-D numerical model. Upon model validation, the results of this study can be used to predict sediment dispersal patterns and contribute to estimating the sediment budget in Long Bay. Such tasks are extremely necessary for economically-important areas such as the Grand Strand and will provide information useful for the conservation of the coastline and protection of South Carolina’s infrastructure. Specific objectives include (1) identifying longshore and cross-shore ocean circulation patterns and (2) analyzing model output for signs of upwelling and downwelling in Long Bay.

Hypotheses

The following four hypotheses were made in this study:

Hypothesis 1: The riverine dispersal from Winyah Bay and Cape Fear Estuaries are highly localized. Both estuaries are included in the model domain. Winyah Bay is the confluence of the Waccamaw, Pee-Dee, Black, and Sampit rivers. The Cape Fear River empties into the Cape Fear estuary (Figure 1).

Hypothesis 2: Despite the small magnitude, the river discharge from the two estuaries is seasonally variable, with the highest of riverine fluxes occurring during the spring. This will be made evident by significant longshore transport of fresh water from two estuaries.

Hypothesis 3: Ocean circulation in Long Bay will not be uniform in space nor time. Circulation along the shoreline will be considerably stronger than offshore currents, but will seasonally change direction. Mainly driven by the winds, transport along the coast in the spring should be to the Northeast, while during the fall it is typically to the Southwest.

Hypothesis 4: An increase in the riverine flux during the spring-summer season, in combination with the seasonal reversal of wind direction and longshore drift, should result in strong upwelling and stratification in the water column.

Modeling and Methods

A 3-D numerical model of the Grand Strand that is in development was used to conduct this research. The model, created through the Regional Ocean Modeling System (ROMS) (http://www.myroms.org), can be used to simulate ocean circulation and sediment transport in a three-dimensional model grid. ROMS is an open source code, and because of its numerical efficiency and robustness, this modeling system has arguably become the standard for coastal numerical studies (Ma et al., 2010). The physical-sediment coupled model has been used successfully for studies in the Adriatic Sea (Harris et al., 2008), Gulf of Mexico (Xu et al., 2008), Massachusetts Bay (Warner et al., 2008), and southwestern tropical Atlantic (Silva et al., 2009). This study was focused on the ocean circulation problem only, and more details of sediment transport can be found in Ma et al. (2010). For this study, the model domain covers the area of North and South Carolina coastline between Winyah Bay in the southwest and Cape Fear Estuary in the northeast (Figure 1).

ROMS takes in a series of inputs including river discharge, winds, waves, sea bed sediment, and others (Ma et al., 2010). From these inputs, simulations can be created showing the spatial variability of numerous physical properties. Salinity, temperature, and current velocity data was simulated over the entire model domain for the year 2009. These figures were created using the computer application and programming language MATLAB (Matrix Laboratory), a command-based mathematical computation and simulation tool (Sen et al., 2009).

Results

The model showed that the long term surface salinity mean varies both along and cross shore in Long Bay (Figure 3). Both Winyah Bay and Cape Fear estuaries influence the local dispersal of freshwater, with the strongest effect shown near the northeast and southwest boundaries of the coastline. The highest current velocities are shown offshore of Cape Fear estuary, near the apparent formation of a gyre. Also, current near the coastline tends to be in the southwest direction. The range of salinity in Figure 3, however, was only between 34 and 36 ppt. Figure 4 shows a more detailed spatial variability of salinity throughout each estuary from 0 to 36 ppt.

Model runs for temperature yielded similar results (Figure 5). The long term mean ranges only from 21°C to ~24°C, with the lowest temperatures near the mouths of two estuaries. The temperature increases with distance from the shore. The highest surface currents are near the mouth of each estuary, ranging from ~0.05m/s to ~0.15 m/s.

The model also illustrated significant seasonal variability in the distribution of surface salinity and surface temperature. In the areas surrounding each estuary mouth, salinity is high during the winter (January through March), summer (July through September), and fall (October through December) of 2009 (Figure 6). In the spring (April through June), however, estuarine influence appears to be greater, and fresher water is dispersed further offshore and along the coastline.

Depth-averaged current velocity indicates a net transport to the northeast during the spring and to the southwest during fall. Mixed currents with varying directions are shown during winter and summer. During all four seasons, current velocities along shore are higher than cross-shelf velocities.

Mean surface temperatures also vary seasonally; however, there is little change in temperature offshore. Even smaller variability is observed along the coastline (Figure 7). Surface currents support the transport direction indicated by salinity dispersal and mean current. Figure 7 shows strong southwest transport in the fall and northeast transport in the spring. Again, for all four seasons, the longshore circulation is stronger than offshore movement. The strongest surface current velocities (~0.025 m/s to ~0.05 m/s) are observed near both estuaries.

Myrtle Beach Transect

The model was run to simulate data along three transects throughout Long Bay, but here only the transect offshore of Myrtle Beach is shown in Figure 8. This transect was relatively far from two estuaries. The long term salinity is distributed rather evenly across the inner shelf, with the freshest water near the coast and saltiest farther offshore (Figure9). The variability is low, however, only ranging from ~35.5 psu to ~36 psu. Current velocity is variable but tends to be directed onshore near the bottom of the water column and offshore at the surface (Figure 9, top panel).

The temperature is relatively uniform with the exception of warmer water near the surface offshore and an evident thermocline starting at about 10 meters depth and extending offshore along the sea bed to the shelf edge 100 km offshore (Figure 9, bottom panel).

The areas farthest offshore have a uniform salinity throughout the entire calendar year of 2009; however, seasonal variations are evident near shore (Figure 10 and Figure 11). Within about 60 km of the coast, the salinity distribution and current velocities vary greatly from season to season. During the winter, offshore surface currents overwhelm a weak bottom current moving onshore near the coast, with water fresher than ~35 psu extending nearly 15 km out. Further offshore, current velocity is seaward and fairly uniform at all depths (Figure 10). Similar salinity distribution and current velocities can be seen in fall 2009 (Figure 11). A similar salinity pattern is also seen in the summer of 2009, but the currents are very different than those found in winter and fall. The model shows strong landward currents ~90 km offshore. Near the coast, strong onshore currents are seen below the surface.

The model results for salinity in spring 2009 are different than what is seen during the other three seasons (Figure 10, bottom panel). During spring, water fresher than ~35 psu extends out to over 25 km offshore. This condition is complimented by high current velocities pointing seaward at the surface in the same location. Under the surface, strong currents move water up the slope and toward the shore.

Temperature offshore Myrtle Beach varies seasonally, with the warmest temperatures in the summer and fall, and colder temperatures during winter and spring (Figure 12 and Figure 13). Similar to salinity, temperature varies with depth as well as distance offshore. In the spring, a quick change can be seen from warm surface waters to cooler bottom water aligning the sea bed (Figure 12, bottom panel). Similar results are shown during summer of 2009.

The temperature tends to change more with distance offshore in the fall and winter. During spring and summer, temperature is more variable with water depth than distance offshore.

Discussion and Conclusions

Hypothesis 1 – Localized river dispersal

The model results for long-term salinity and temperature averages indicate a riverine influence from Winyah Bay and Cape Fear estuary. The area near the mouth of each estuary shows a localized dispersal of water that is fresher and cooler than the water in the surrounding areas (Figure 3 and Figure 5). Although the dispersal of surface salinity near the mouths in Figure 3 suggests a prominent flux of estuarine water, the riverine flux is, in fact, relatively small. Figure 4 provides an accurate illustration of the riverine and estuarine influences that Winyah Bay and Cape Fear estuary have on the surrounding salty sea water. In this figure, it is easier to see that the dispersal of estuarine water into the ocean is highly localized and restricted to a small area.

Hypothesis 2 – Seasonal variability

The magnitude of riverine influence to Long Bay as well as direction of net transport was seasonally variable in the model runs. The seasonal averages for surface salinity illustrate varying dispersals of estuarine water entering Long Bay from both estuaries, with the highest impact observed during the spring season when river discharge is high. This is consistent with the hypothesis proposed. Increased precipatation leads to a higher freshwater flux in the spring than during other seasons.

Hypothesis 3 – Ocean circulation is variable and mainly along the coast

A seasonal reversal of net water transport was also detected in Long Bay. In the spring, both mean and surface currents appear to produce a net movement to the northeast of Long Bay. By the fall of 2009, the transport is reversed; mean and surface currents result in a southwest transport of water. Similar results were identified by a recent observational study to monitor beach nourishment along the Grand Strand (Park et al., 2009). The Park study had anticipated a net southerly transport of sediment, but observed that the net downdrift alternates direction along the shoreline. For the model, during winter and summer, the current velocities and directions are mixed and the net direction of transport is not evident. This result could be caused by an interaction with cross-shore currents that was also observed in the beach nourishment monitoring project (Park et al., 2009).

In all cases, the transport of water in Long Bay was mainly longshore transport. Offshore movement of water was comparably small. The only instances that the longshore drift was not significantly bigger than cross shelf motion were during seasons when there were mixed currents throughout most of or the entire model domain. Transect figures for summer and winter salinities show a strong landward current at depth, but on a smaller scale than the longshore drift observed by surface and mean currents.

In the summer transect for Myrtle Beach (top panel of Figure 11), current velocity was very high along the offshore edge. This fact might be attributed to an effect caused by the nearby Gulf Stream, which tends to alternate between two positions off the South Carolina coast: (1) onshore, flowing over the Charleston bump and along the shelf break, or (2) offshore, flowing up to 100km east of the shelf break (Lee et al., 1989).

Hypothesis 4 – Upwelling and Stratification

Salinity and temperature averages for 2009 are suggestive of upwelling at all three transect locations. This is consistent with the hypothesis and consents with the results that indicate a high freshwater flux during the spring. Stronger less-dense riverine inputs to Long Bay in the spring move surface sea water offshore and allow cooler bottom water to move to shallower depths and near shore. The seasonal extension of estuarine water into the bay appears to lead to stratification of the water column at some locations on the inner shelf, but this observation cannot be validated without supporting density data from the water column. Sanay and Voulgaris (2008) do, however, identify an oscillation of upwelling-favorable and downwelling-favorable conditions in Long Bay that lead to some inner shelf stratification.

Future Work

In the model analysis presented by this project, general trends were used to validate the results presented by the 3-D numerical model. Although this study provided valuable information, the results presented here must be validated by oceanographic observational data. Continued work on this product should include a model-observational comparison.

Two quadrapods were deployed on the inner shelf of Long Bay in 2008 and 2009 as a part of an ongoing South Carolina Sea Grant project by Dr. Ansley Wren at Coastal Carolina University. Instruments on the two quadrapods collected data for waves, current velocity, temperature, salinity, and sediment concentration along the bottom boundary layer. With permission, the data collected for the SC Sea Grant project can be compared with the results of this ROMS numerical model. Additional observational data have been collected by Palmetto Wind Research Project by Coastal Carolina University. If the results of the model match these observations, the 3-D numerical model developed here can then be used in the future to predict changes in physical properties, near-shore ocean circulation, and sediment transport in Long Bay.

FIGURES

Fig. 1:

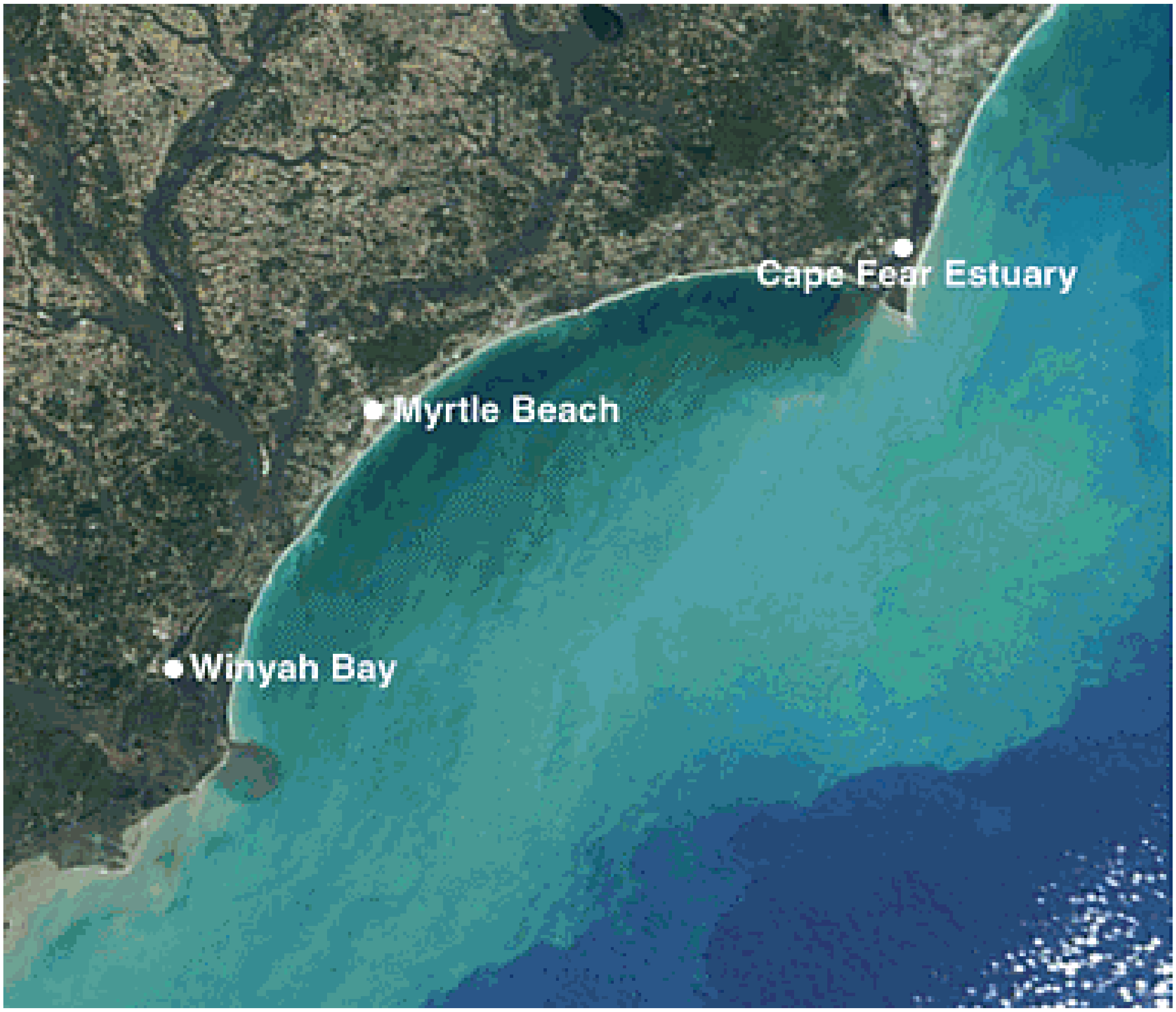

Figure 1—Map of Long Bay.
(The locations of Winyah Bay, Myrtle Beach, and Cape Fear Estuary are indicated.)

Fig. 2:

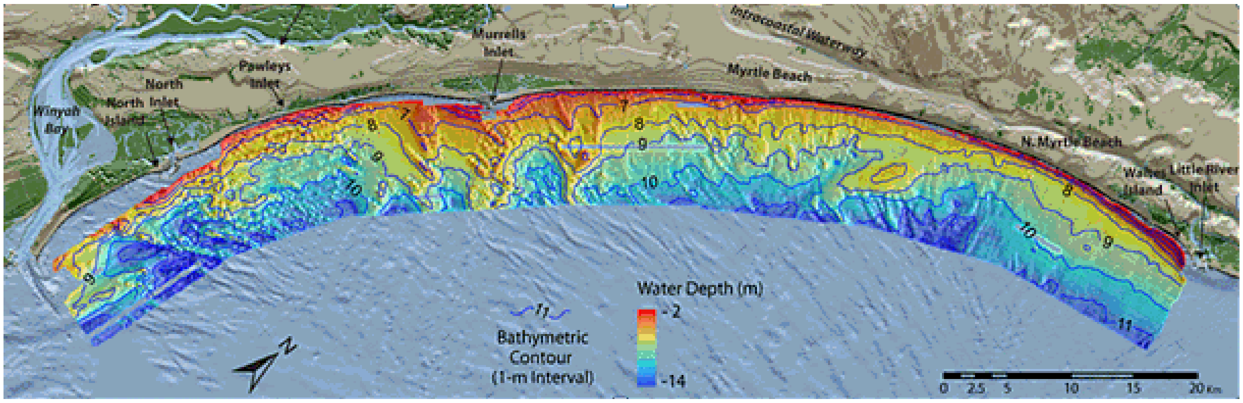

Figure 2--Inner-shelf Bathymetry of Long Bay, Spanning from Winyah Bay on the Southern End to Little River Inlet in the North. Base maps from Denny, et al (2005).

Fig. 3:

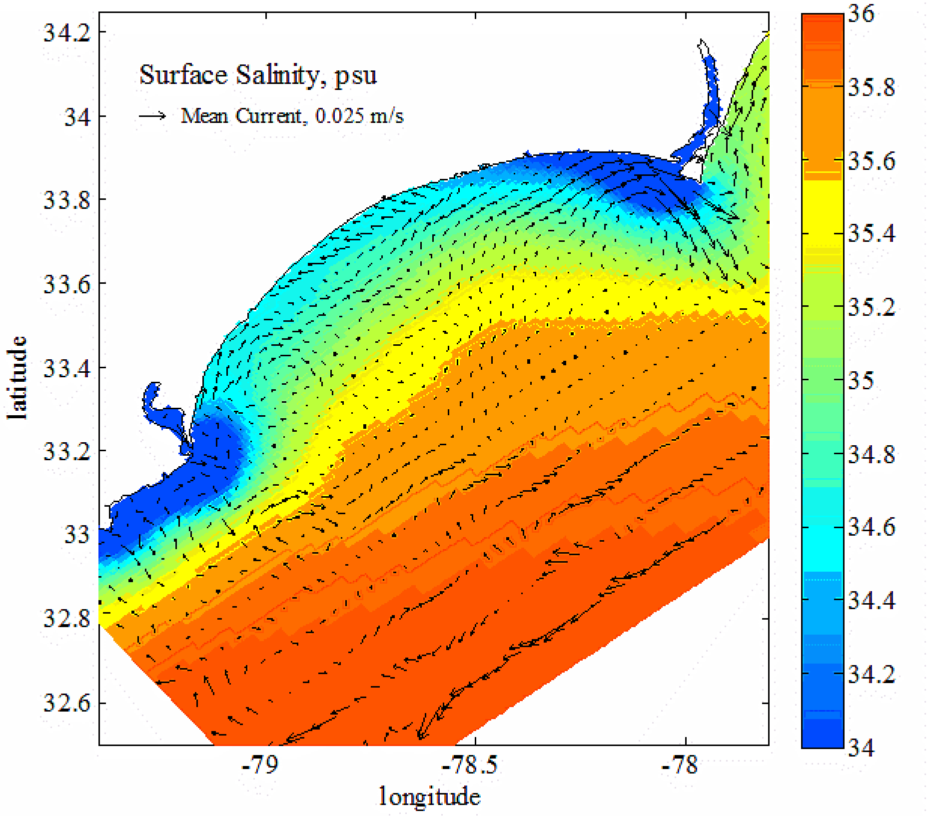

Figure 3--Long-term Mean Surface Salinity (psu) of Long Bay for the Year 2009. (Mean depth-averaged current is indicated by black arrows.)

Fig. 4

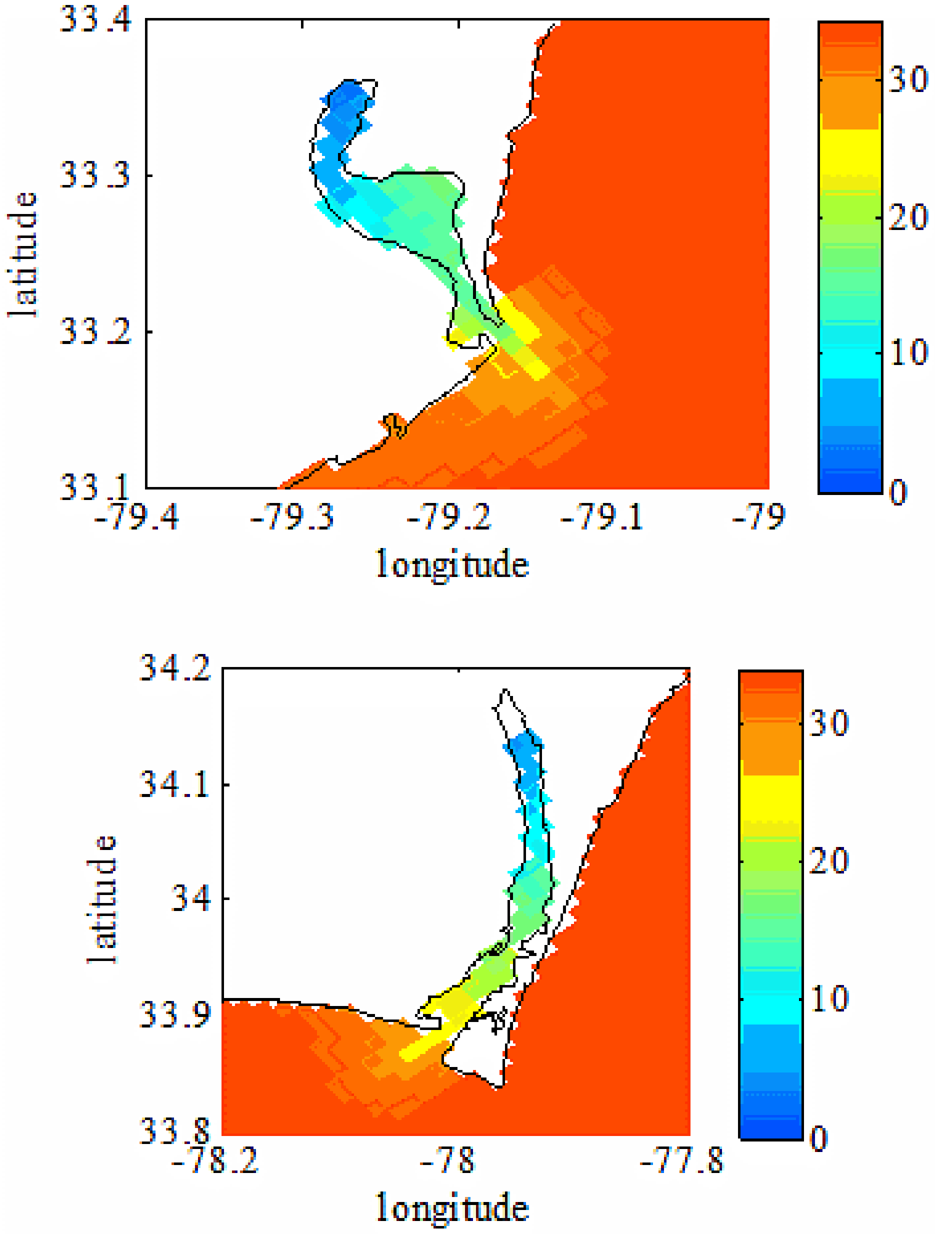

Figure 4--Long-term Mean Salinity (psu) for Winyah Bay (top) and Cape Fear Estuary (bottom).

Fig. 5

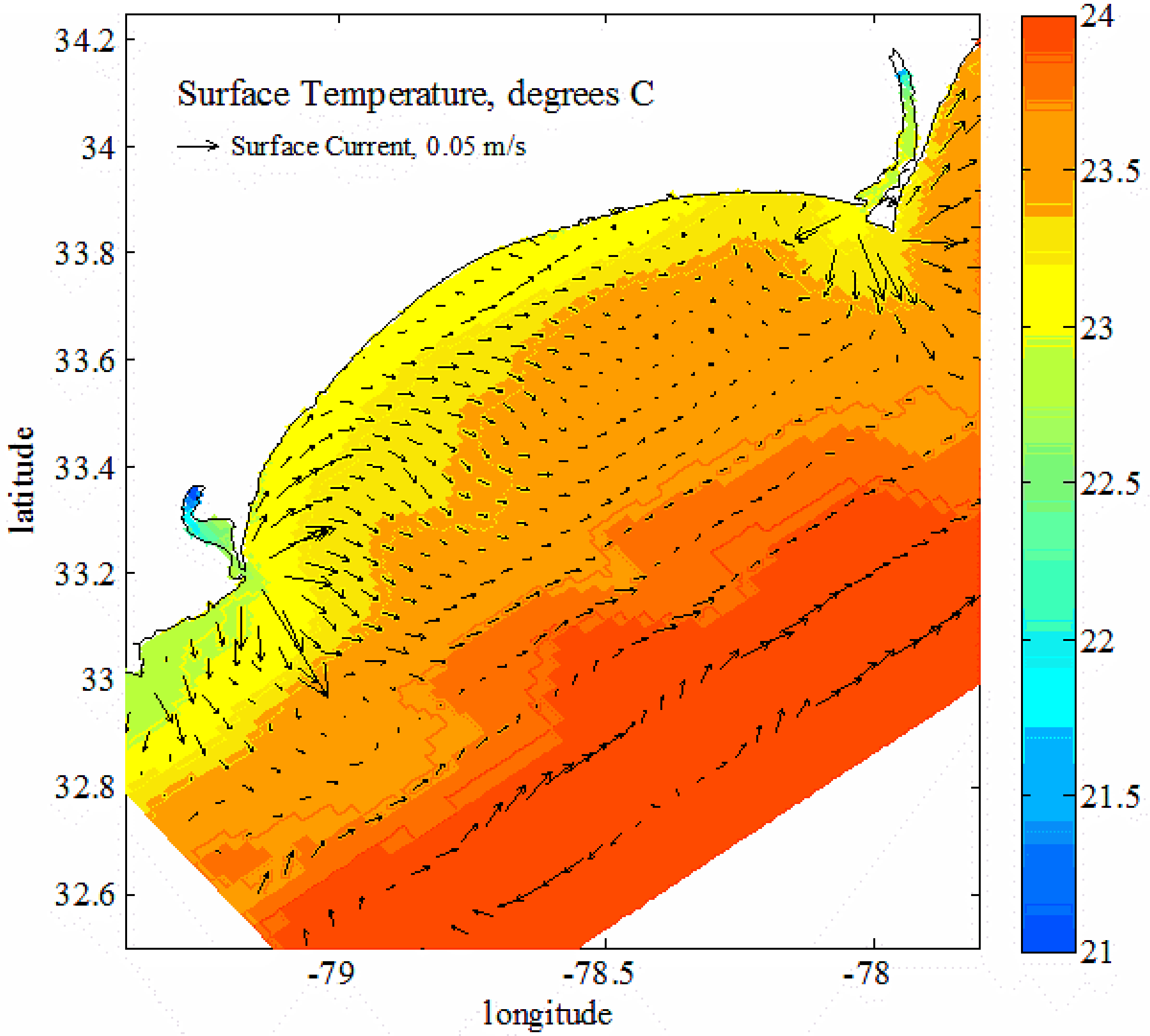

Figure 5--Long-term Mean Surface Temperature of Long Bay in Degrees Celsius for the Year 2009. (Surface current is indicated by black arrows.)

Fig. 6

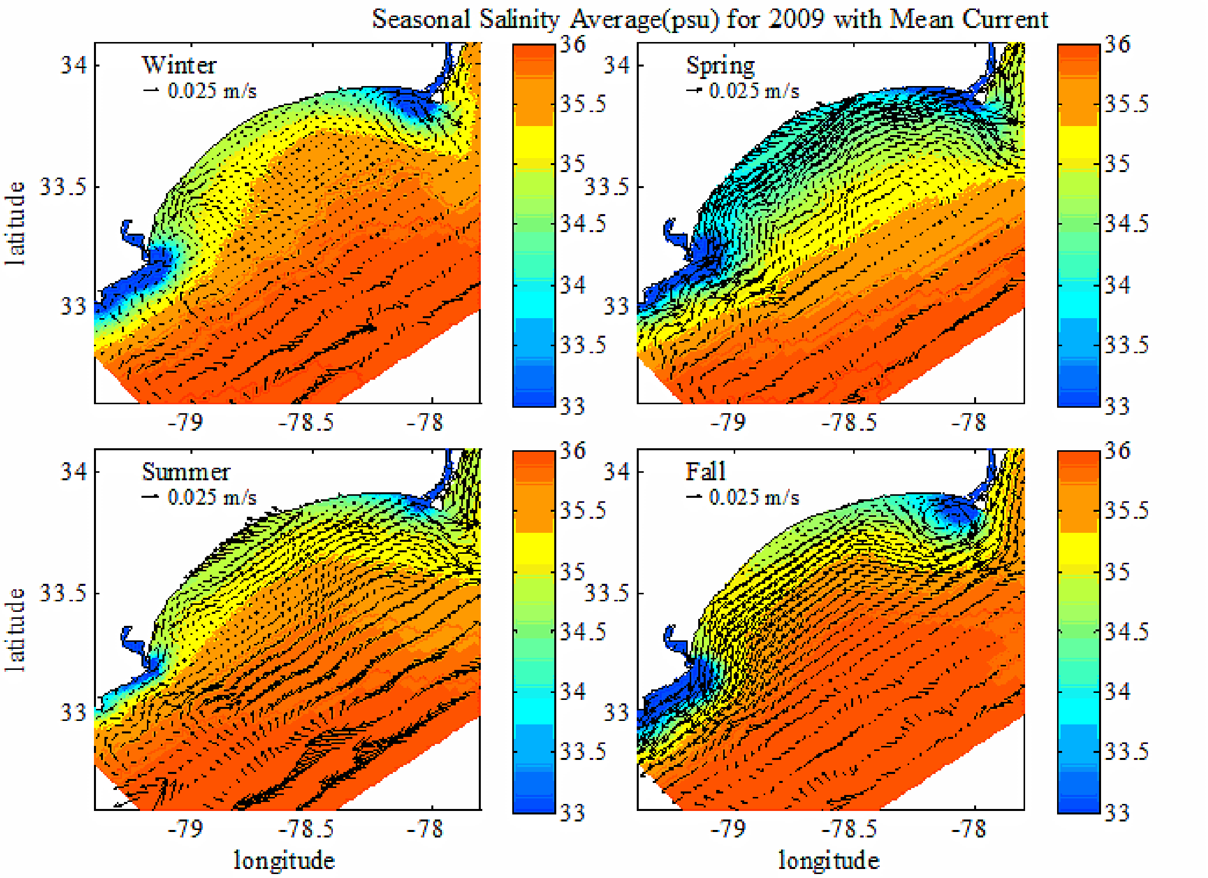

Figure 6--Seasonal Surface Salinity (psu) Means in Long Bay for the Year 2009. (Depth-averaged current is indicated by black arrows.)

Fig. 7

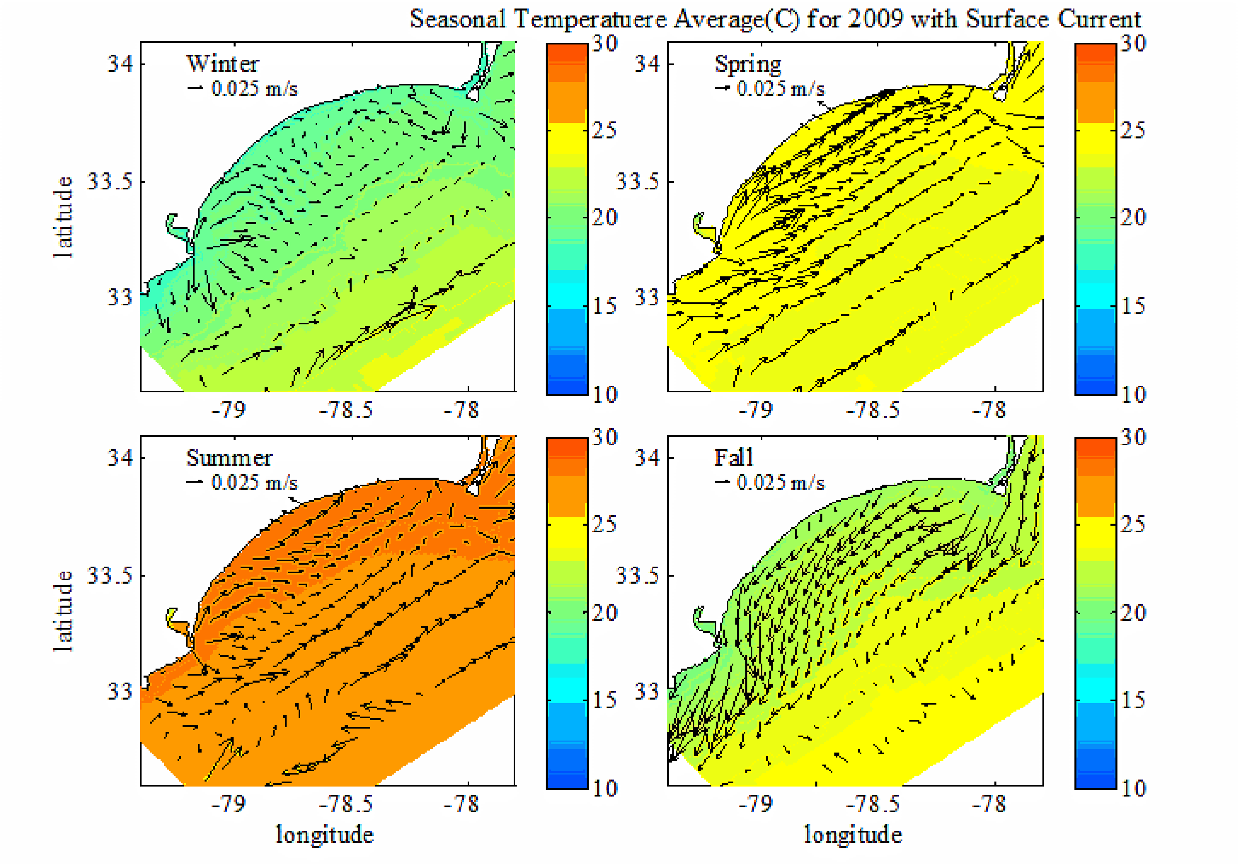

Figure 7--Seasonal Surface Temperature Means in Degrees Celsius in Long Bay for the Year 2009.
(Surface current is indicated by black arrows.)

Fig. 8

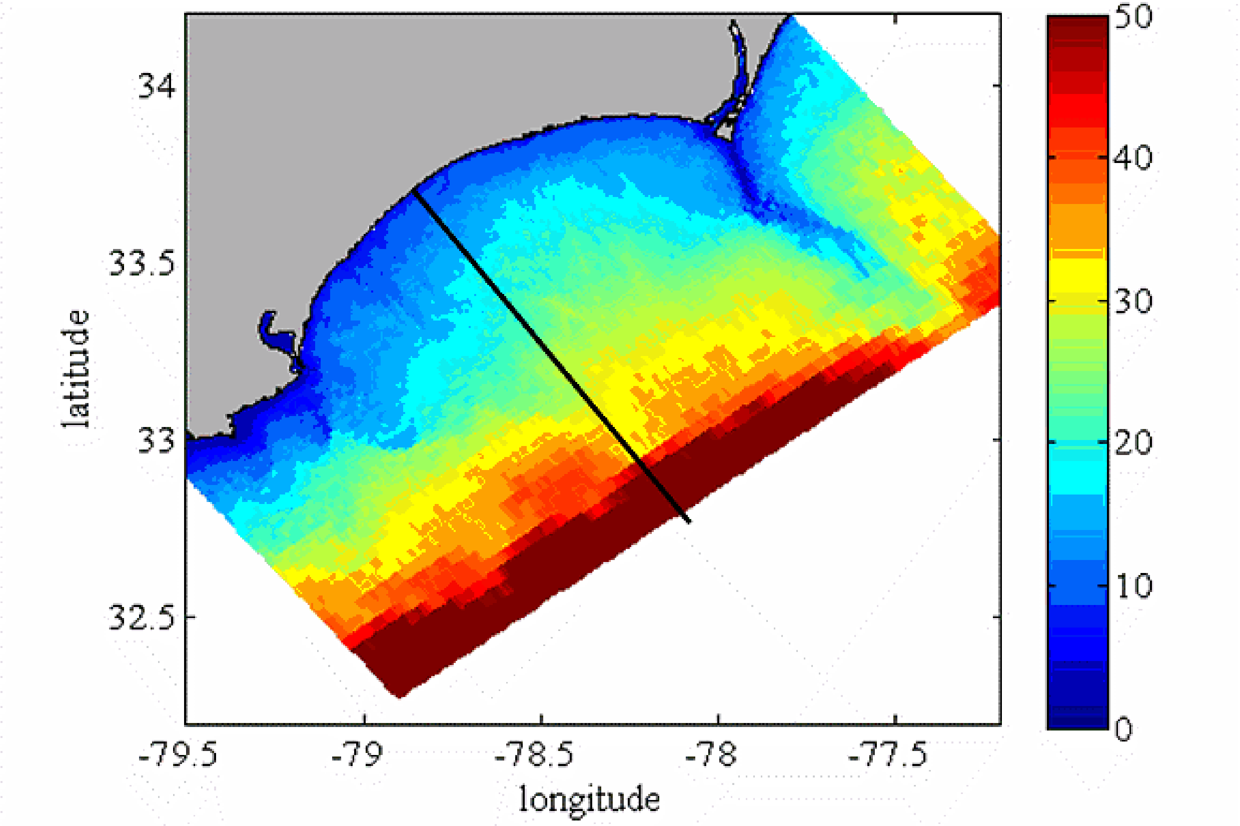

Figure 8--Water Depth in Meters in Long Bay With the A-Transect Offshore of Myrtle Beach Illustrated by a Black Line

Fig. 9

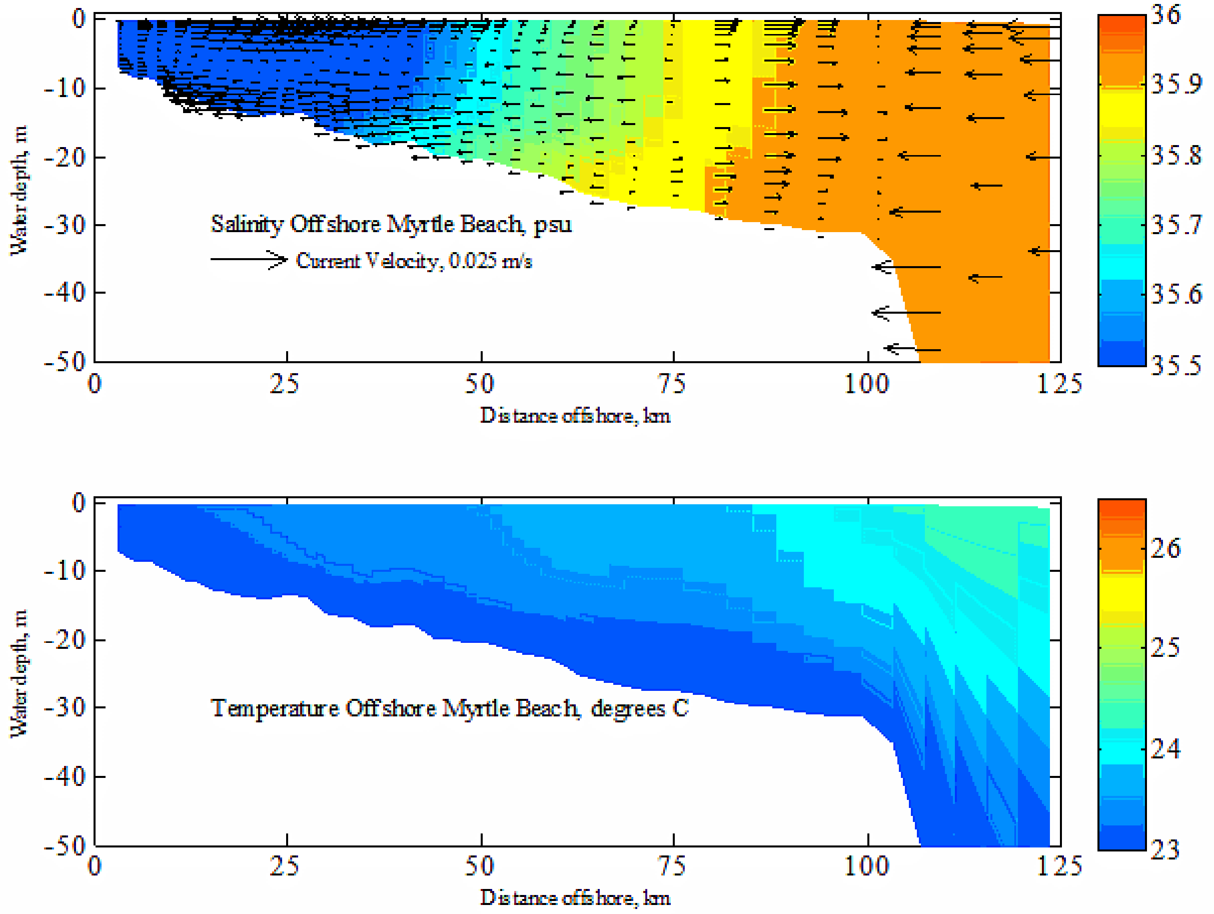

Figure 9--Long-Term Means of Salinity (psu) and Temperature (in Degrees Celsius) at Depth Offshore of Myrtle Beach for the Year 2009.
(Mean current is indicated by black arrows.)

Fig. 10

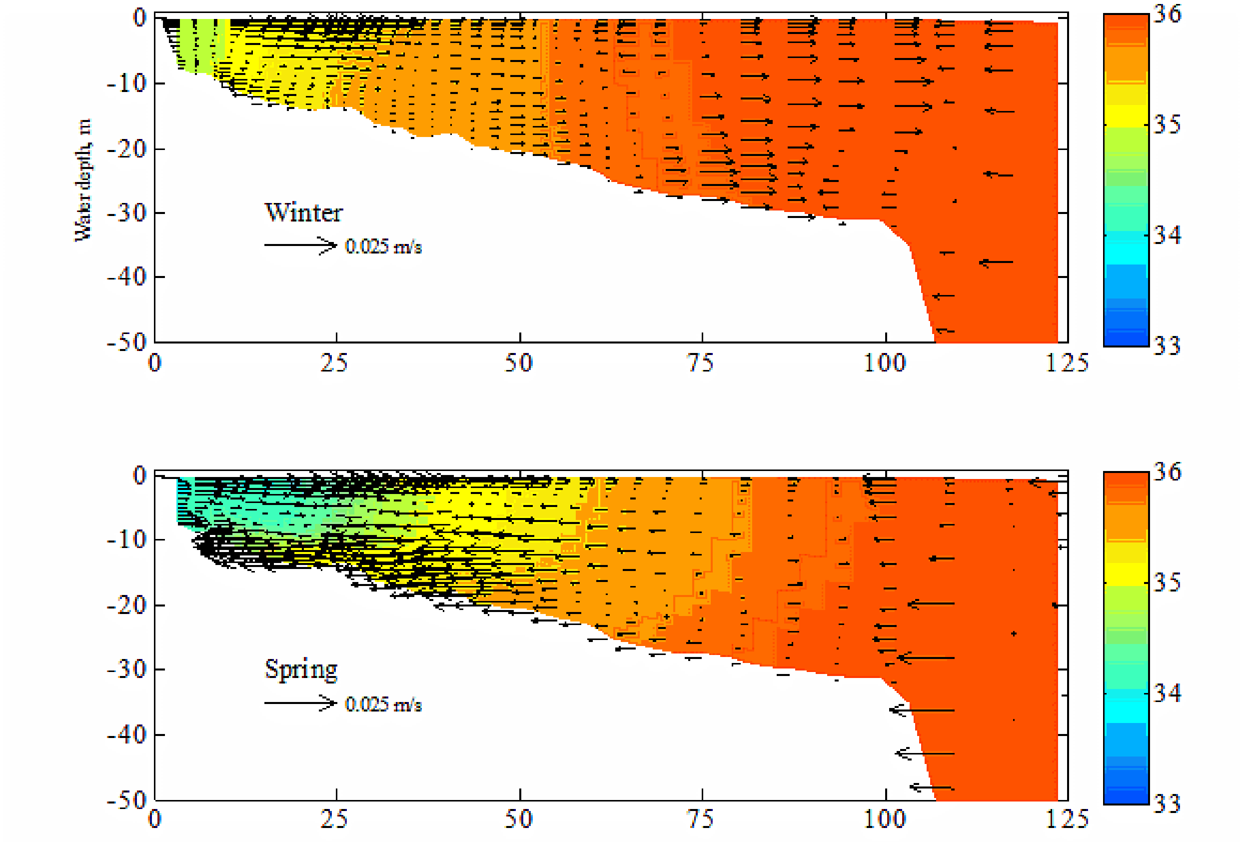

Figure 10--Winter and Spring Mean for Salinity (psu) Offshore of Myrtle Beach for the Year 2009.
(Mean current is indicated by black arrows.)

Fig. 11

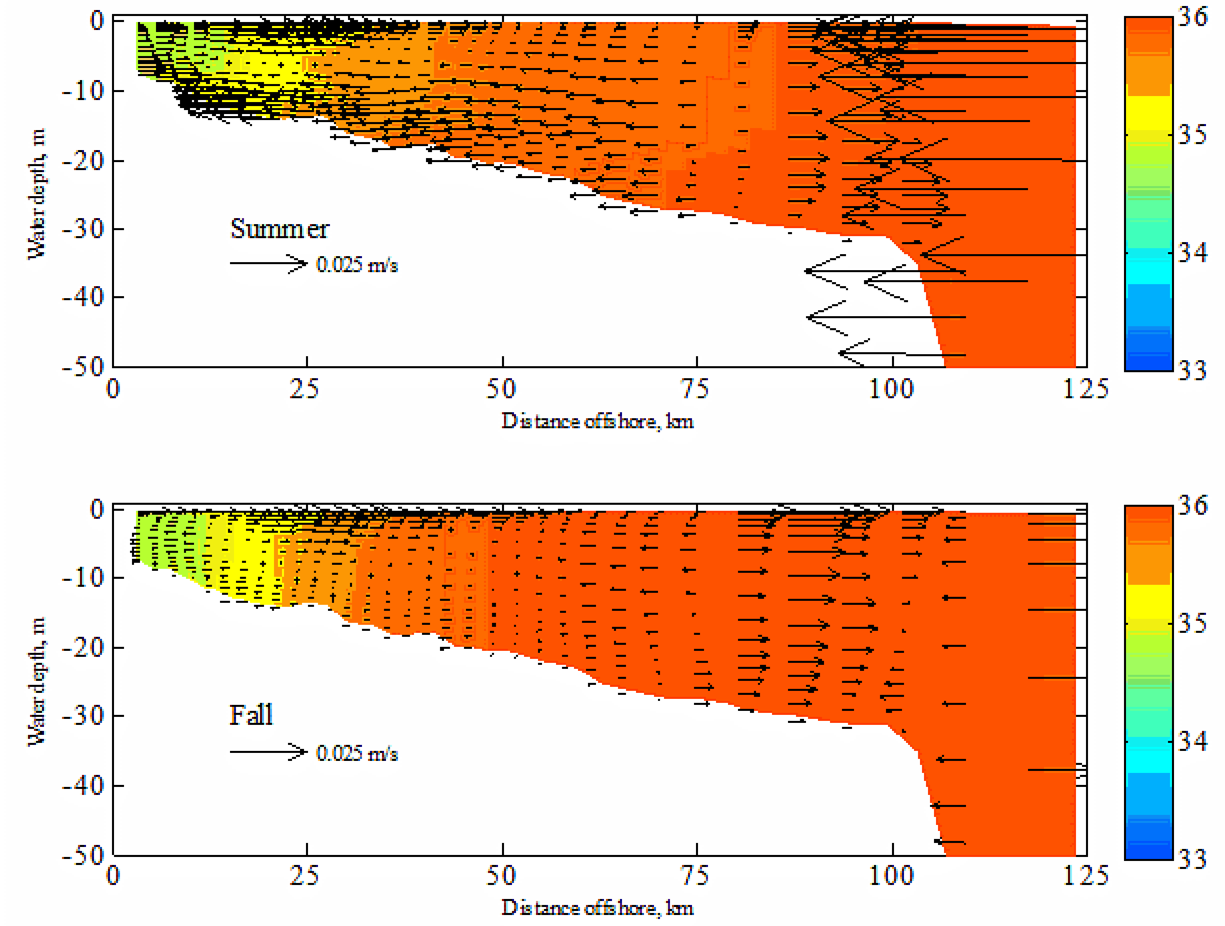

Figure 11--Summer and Fall Means for Salinity (psu) Offshore of Myrtle Beach for the Year 2009.
(Mean current is indicated by black arrows.)

Fig. 12

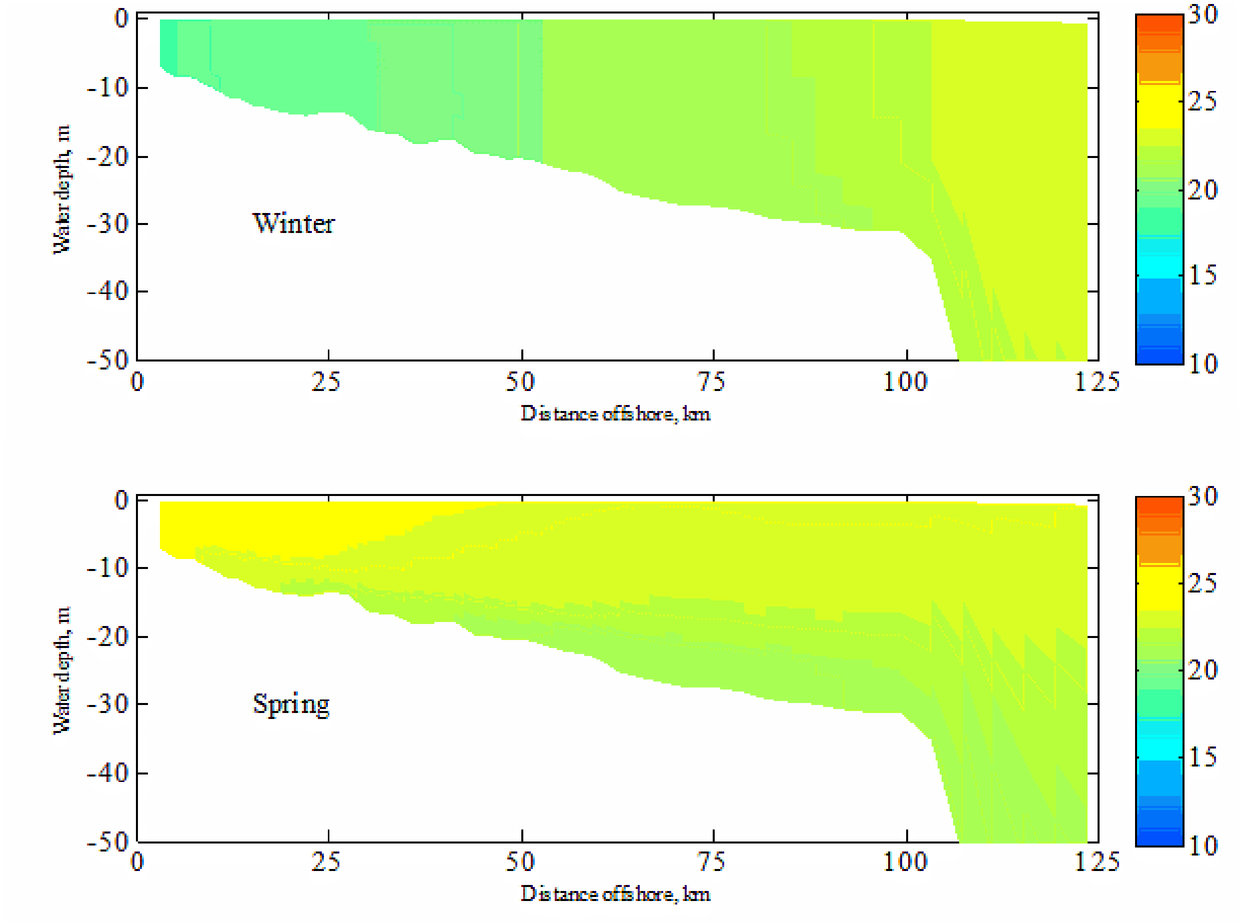

Figure 12--Winter and Spring Means for Temperature (Degrees Celsius) Offshore of Myrtle Beach for the Year 2009.

Fig. 13

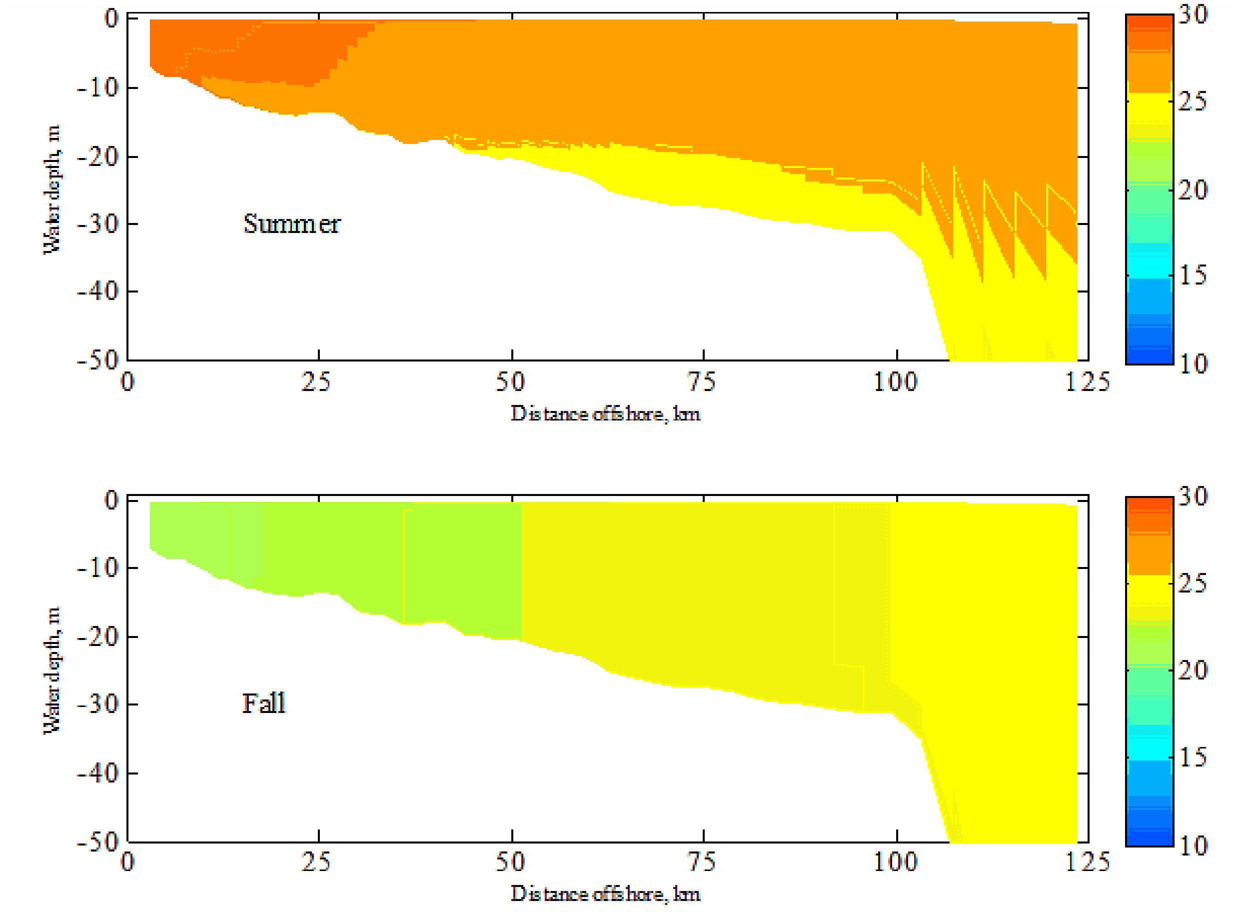

Figure 13--Summer and Fall Means for Temperature (Degrees Celsius) Offshore of Myrtle Beach for the Year 2009

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BIOGRAPHICAL NOTES

Brian Quigley was raised in Philadelphia, PA and will be graduating from Coastal Carolina University in May 2011 with a BS in Marine Science and a minor in Mathematics. At Coastal, he worked on ocean circulation of Long Bay as well as sediment dynamics and hypoxia in the northern Gulf of Mexico. His long-term goal is to pursue master's-level and Ph.D. degrees in oceanography with a focus on marine biology.

Dr. Kehui Xu (Assistant Professor) is a marine geologist whose research centers in the flux and fate of fluvial sediment from the land to the ocean. He has been involved in a range of interdisciplinary projects studying sequence stratigraphy, sediment transport, surficial processes, and numerical modeling. Besides the source-to-sink sedimentary study of Yangtze River and East China Sea, he is currently using the ROMS to study sediment transport processes on the Long Bay (SC) and the Texas-Louisiana Shelf.