Freshwater Transport on the Continental Shelf of the Southeastern United States

Cheolsoo Kim
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FRESHWATER TRANSPORT
ON THE
CONTINENTAL SHELF OF THE SOUTHEASTERN UNITED STATES

by

Cheolsoo Kim
B.S. February 1974, Seoul National University, Seoul, Korea

A Dissertation Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY
OCEANOGRAPHY

OLD DOMINION UNIVERSITY
December, 1990

Approved by:

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ABSTRACT

FRESHWATER TRANSPORT
ON THE
CONTINENTAL SHELF OF THE SOUTHEASTERN UNITED STATES

Cheolssoo Kim
Old Dominion University, 1990
Director: Dr. Larry P. Atkinson

The circulation of water over the shelf of the southeastern United States was examined during the Fall Removal Experiment from late October to early November 1987. A steady state, two-dimensional analytical model of wind and density driven flow was used to study the relative importance of driving forces in shelf circulation, fate of freshwater and cross-shelf exchange processes. The inner and middle shelf mean circulation was found to be driven by four major components: 1) longshore wind, 2) longshore pressure gradient, 3) onshore wind and 4) cross-shelf density gradient including freshwater influx. Wind stress was the primary driving force for shelf circulation Southward wind stress produced a southward current with an embedded coastal jet, while weak wind stress reduced the jet strength and produced northward currents in the middle shelf. Strong southwestward wind events transported low salinity waters, from rivers in the central part of the South Atlantic Bight, southward to Cape Canaveral in a narrow baroclinic zone near the coast. Inner shelf fronts were produced by freshwater runoff. Downwelling favorable wind narrowed the baroclinic zone, inside of which a strong coastal jet developed. The runoff-induced residual circu-
lation made a generally weak contribution to the mean flow field. Freshwater was mainly advected through the inner shelf off Savannah and Brunswick by longshore transport and through the middle shelf between Brunswick and St. Augustine sections by cross-shelf transport. Freshwater transport estimates showed that about 10% of the freshwater input off Savannah arrived at the Cape Canaveral section and a major portion of the remaining freshwater left the shelf region by offshore transport. About 30% of the freshwater flowing into the region was temporarily stored there. Cross-shelf transport was especially important during weaker winds. Salinity was used as a conservative property for the calculation of the horizontal diffusion coefficient. The cross-shelf diffusion coefficient was estimated to be order of $10^5 - 10^6 \text{ cm}^2\text{s}^{-1}$ on the inner shelf, and $10^7 \text{ cm}^2\text{s}^{-1}$ on the middle shelf locations. Most shelf regions showed dominant advective cross-shelf transport, while in the frontal zone between Savannah and Brunswick sections there was an increase of diffusive cross-shelf transport. Current meter observations and surface distributions of tritium originating from the Savannah River confirmed the above analytical model and dynamical considerations.
Acknowledgements

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My special thanks go to Dr. Thomas N. Lee and Ms. Elizabeth Williams at University of Miami for providing the current meter data and Dr. Jackson O. Blanton and Ms. Julie Amft at Skidaway Oceanography Institute for providing the wind and sea level data etc. I also thank Mr. Bill Chandler for providing the hydrographic cruise data analysis and technical assistance. Again, I would like to express my sincere gratitude to all those individuals who provided assistance and encouragement during my academic years at the Department of Oceanography.

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Chapter 1
Introduction

Coastal ocean dynamics have received increased attention because of social and ecological problems. Since much of the ocean’s biological production and most of man’s pollution and their effects occur in continental shelf and adjacent ocean water, it is necessary to better understand the exchange processes between these waters. The characteristics of coastal waters are shallow depth, typically less than 100 m, the presence of a coastline and the influx of freshwater runoff from the land. In many coastal regions the freshwater runoff from rivers has a strong influence because of buoyancy additions that affect the dynamics and the contaminants that may affect the ecosystem. This thesis investigates the transport of runoff in the coastal ocean off Georgia and Florida.

In this chapter the general geography, wind climatology, runoff and tides are discussed. That is followed by a review of surface salinity distributions, nearshore processes including the coastal/nearshore front, storage of freshwater in the coastal boundary zone, general shelf currents, longshore pressure gradient, seasonal stratification and Gulf Stream forcing. A final part of this chapter reviews other coastal currents, modeling studies and introduces the objectives.
Geography

The continental shelf of the southeastern U.S. is often referred to as the South Atlantic Bight (SAB). Bumpus (1973) defined the SAB as the shelf region extending from Cape Hatteras to approximately West Palm Beach, Florida, where the shelf becomes very narrow. Figure 1 shows the location and bathymetry of the study region. The shelf is 120 km wide off Savannah, Georgia, the northern boundary of the study area, and decreases to a minimum of 40 km off Cape Canaveral, Florida. Shelf topography in this area is relatively simple with no significant canyons or reefs. The Georgia coast is a series of barrier islands and inlets behind which lie extensive salt marshes while the Florida coast is a nearly unbroken barrier island beach. The shelf slopes gently (about $4 \times 10^{-4}$) to a sharp shelf break that decreases in depth from 75 m to about 50 m from north to south. For descriptive purposes the study area may be divided into three cross-shelf zones: inner shelf (depths < 20 m), middle shelf (20 < depths < 40 m) and outer shelf (depths > 40 m). The approximate dimensions of the study area are 400 km x 100 km.

Wind climatology

Wind climatology in the SAB has been described by Weber and Blanton (1980), who used marine weather observations for the period 1945-1973 to compute monthly mean winds over the SAB in half degree grids. They described five seasonal mean wind regimes: 1) Winter (November - February) – southeastward winds, 2) Spring (March - May) – transition period from southward to northward winds, 3) Summer (June - July) – northwestward winds off southern Florida, northward off northern Florida and Georgia, and northeastward off the Carolinas, 4) Fall (August) – north-
Figure 1. Map of the study region and locations of the various observations. The small plus mark represents hydrographic stations.
Fort Pulaski
Savannah

Brunswick
Fernandina
Mayport
SAUF
St. Augustine
Marineland

Daytona
New Smyrna

Cape Canaveral

\[ \text{Longitude} \]

\[ \text{Latitude} \]

\[ \text{0} \quad 50 \quad 100 \text{ km} \]

\[ \text{82.0} \quad 81.5 \quad 81.0 \quad 80.5 \quad 80.0 \quad 79.5 \quad 79.0 \]

\[ \text{32} \quad 31 \quad 30 \quad 29 \quad 28 \]

\[ \text{\(\Delta\): Wind Station} \]
\[ \text{■: T,S Station} \]
\[ \text{\(\bullet\): Current Meter} \]
\[ \text{■: Sea Level Strn.} \]
ward winds and transition period, 5) Mariners’ Fall (September - October) – strong southward winds. Mariners’ fall season will be described in more detail because this thesis focuses on that time period. Mariners’ fall is so named because it has not been generally recognized by meteorologists and oceanographers as a major wind regime distinguishable from the winter and summer regimes. Sometime in September or October the prevailing northward winds of August and September switch to southward. These winds are the strongest of the year with monthly mean wind stress vector magnitude approximately 0.4 dyne cm$^{-2}$ at the coast and 0.7 dynes cm$^{-2}$ at the shelf break (Weisberg and Pietrafesa, 1982). Figure 2 shows the monthly mean winds for September, October and November (Weber and Blanton, 1980). Another peculiarity of mariners’ fall is an apparent region of wind stress maximum 100 km off the coast (Saunders, 1977). The strong and persistent southward winds are one of the most important forces in the SAB during the study period. The energy level of the wind variance field and its coherence structure vary seasonally since the most persistent direction and regularity of extratropical cyclone movement through the SAB is in fall and winter (Weisberg and Pietrafesa, 1983). Thus, fall and wintertime coherences show maxima while summertime coherence shows minimum because the wind field is most irregular.

**Rivers and runoff**

Many medium size rivers discharge about 50 km$^3$ annually into the SAB (Atkinson et al., 1983). Maximum inputs occurs along the coasts of Georgia and South Carolina (Figure 3). The Altamaha, Savannah, Pee Dee and Cooper/Santee Rivers provide over 80% of the total freshwater discharge (Atkinson et al., 1978) between
Figure 2. Mean monthly wind vectors for (a) September, (b) October and (c) November during 1945-63 (from Weber and Blanton, 1980).
Figure 3. Distribution of (a) annual river runoff concentration along the coast and (b) mean monthly flow. Arrows on chart show annual average river flow as $km^3$ of runoff per $km$ of shoreline. The $km$ of shoreline unit is calculated by summing one-half the distance to the adjacent gaged rivers. River flow is concentrated in the central portion of the SAB (from Atkinson et al., 1983).
Cape Romain, South Carolina, and Jacksonville, Florida. These rivers, combined with the flow of many smaller rivers, create what appears to be a line source of runoff into the SAB. There is essentially no runoff south of Jacksonville. The mean monthly distribution of runoff shows a peak in March and a minimum in October (Figure 3). Sometimes runoff during the fall is large because of hurricanes but the effect is not important to the mean value.

**Tides**

The tidal currents are almost spatially uniform with the larger amplitudes occurring in the region where the shelf is widest (between Savannah and Jacksonville). Maximum tidal range of 2.5 m is found in the Savannah area, and the minimum is 1.1 m at Cape Canaveral. Tidal motions account for 75-90% of the total kinetic energy of inner shelf waters throughout the year (Pietrafesa et al., 1985). The M$_2$ component ($T_2 = 12.42$ h) dominates sea level and current fluctuations accounting for roughly 80% of the tidal variations. Tidal residual currents are directed northward along isobaths with maximum speeds of 3.5 cm s$^{-1}$ (Wang et al., 1984). While variance in longshore currents is mainly subtidal the variance in cross-shelf current is mainly tidal. Tidal currents account for about 20-40% of the longshore current variability in the middle shelf region, and the variance for cross-shelf current ranges from 80-90% on the shelf to 50-70% at the shelf edge (Lee and Brooks, 1979; Lee et al., 1989).

**Mean surface salinity distributions**

Lowest surface salinities are observed in April and May during or just after
periods of highest runoff (Figure 4). The lowest salinities are found off Georgia where runoff is concentrated. However, during October low salinities are found off the Florida coast. This is because strong southward winds associated with Mariners’ Fall cause strong southward transport (Atkinson et al., 1983). This was the focus of the experiment.

The coastal front/inner shelf

The influx of runoff causes the formation of a frontal zone with persistent southward baroclinic flow (Blanton, 1981). Blanton and Atkinson (1983) describe the nearshore frontal zone as a storage zone for freshwater discharge. The offshore pressure gradient induced by low density water in the frontal zone turns water to the right within a Rossby radius of about $5 \text{ km}$, in the absence of wind forcing (Blanton and Atkinson, 1983). In the fall a combination of offshore pressure gradient and strong southward winds advect water southward towards Cape Canaveral (Blanton, 1981). As a result, anomalously low salinity water is found in the coastal zone off Florida during the fall (Atkinson et al., 1983), even though there is no known local source of freshwater (Figure 4).

Storage of freshwater in the coastal waters

Seasonal processes may accelerate the removal or storage of low salinity water within the frontal zone, and the storage process has been parameterized by the change in time of the freshwater content (Blanton and Atkinson, 1983). Commonly, storage takes place during positive variation of the freshwater content. Northward winds in the spring cause the removal of low salinity water from the nearshore zone while this
Figure 4. Monthly mean surface salinity (from Atkinson et al., 1983).
water is effectively stored within the frontal zone during light winds of summer (Blanton and Atkinson, 1983).

**Shelf currents**

The existence of mariners' fall in the SAB area was noted earlier (Green, 1944) and was used in the classic circulation discussion by Bumpus (1973) who used drift bottle and sea-bed drifter data. Another drift bottle experiment during the fall indicated southward flow with velocities greater than 20 km day$^{-1}$ in the Georgia Bight (Atkinson, 1978). The northeast winds would tend to send drifters southward and shoreward producing the well-defined surface circulation shown by Bumpus (1973). Middle shelf currents are principally affected by the longshore wind and pressure gradients (Lee et al., 1984). Analysis of long term mean flows at middle shelf suggests the longshore momentum balance is between a longshore pressure gradient forcing the flow northward and an opposing bottom stress (Lee and Brooks, 1979; Atkinson et al., 1983). The longshore pressure gradient may result from the slope of sea level downward to the north in the Gulf Stream (Sturges, 1974) and plays a role similar to that found for the open ocean along the Middle Atlantic Bight (Csanady, 1978; Beardsley and Winant, 1979). However, subtidal frequency flow in middle shelf is primarily dependent on local wind forcing (Klinck et al., 1981; Lee and Atkinson, 1983) through an Ekman frictional equilibrium process.

**The longshore pressure gradient**

The longshore pressure gradient appears to be an important force in the circulation of the SAB. A longshore slope of order $-10^{-7}$ is needed to balance the mean
longshore momentum in the outer shelf of study area during winter and summer (Blanton, 1981; Lee et al., 1984; Lee and Pietrafesa, 1987; Lee et al., 1989). Pattullo (1963) showed that large positive sea level deviations from the annual mean elevation occurs in September along the southeastern United States using the International Geophysical Year 1957-1959 sea level data. Pattullo used five factors to explain the variations in sea level: a) fall in local atmospheric pressure; b) increase in heat content of water; c) decrease in salinity of water; d) increase in speed of onshore component of wind; e) increase in speed of longshore component of current. Sturges (1974) found a similar slope ($-2 \times 10^{-7}$) in the Gulf Stream adjacent to the SAB shelf from both steric and geostrophic leveling, indicating a possible Gulf Stream origin for the slope. Beardsley and Winant (1979) show that the physical mechanism which creates the longshore pressure gradient thought to drive the longshore flow must be of oceanic origin. The largest monthly deviation of pressure gradient occurs in October (Sturges, 1974). In the Middle Atlantic Bight, analyses of coastal sea level variations (Chase, 1979) have shown a wind stress related component of the longshore slope along the Long Island coast (Csanady, 1979).

Stratification

The shelf area exhibits seasonal changes in stratification with homogeneous conditions prevailing during the fall and winter seasons because of cooling and intensified wind mixing. Vertically stratified waters are typifying spring and summer periods because of increased runoff, heating and decreased wind mixing (Atkinson et al., 1983; Lee et al., 1984). During the winter, water with reduced salinity is generally held against the coast by southward winds and the resulting geostrophic effects. Pre-
vailing northward winds and Gulf Stream perturbations during summer cause upwelling off north Florida (Blanton et al., 1981). Gulf Stream water intrudes along the bottom to replace the upwelled water causing more stratified hydrographic conditions during summer over the shelf area (Blanton et al., 1981).

**Gulf Stream effects**

The western edge of the Gulf Stream tends to follow the shelf break in the SAB and exhibits considerable influence over the adjacent shelf waters. Low-frequency (\( f < 0.6 \; \text{cpd} \)) current and temperature variability in the outer shelf (depths > 40 m) is dominated by northward propagating Gulf Stream meanders and eddy events in the period band of 2 days to 2 weeks with no apparent relation to wind forcing (Lee and Brooks, 1979; Lee and Atkinson, 1983).

However, the effect of Gulf Stream forcing is considerably reduced only 25 km from the shelf break (Lee and Brooks, 1979). It appears that the relatively wide and shallow shelf effectively isolates a large portion of the shelf from disturbances at the shelf-break. Thus, it may be possible to use simplified models that ignore Gulf Stream forcing to predict the fall and winter shelf circulation. Nevertheless, the forcing dynamics of longshore current variability over the outer shelf are complicated. As the shelf break is approached, the effects of Gulf Stream wavelike meanders and frontal eddies become stronger and relatively more important (Lee and Atkinson, 1983; Li et al., 1985).

**Coastal ocean models**

Over the years many models have been developed to investigate coastal ocean
dynamics. Stommel and Leetmaa (1972) have shown a steady-state, two dimensional theoretical model for the mean wintertime shelf circulation driven by steady, uniform wind and freshwater. The model incorporated linear Ekman dynamics with constant vertical friction and diffusion coefficients, while the cross-shelf salt balance is maintained by an advective-diffusive shear dispersion mechanism. Csanady (1976) proposed decoupling the diffusion equation from the momentum equations and treated the density variation as an external forcing term through the dynamic height gradient. The model then reduces to the Ekman model with pressure gradient. It also includes a coastline, and it assumes zero net cross-shelf transport. Both Stommel and Leetmaa (1972) and Csanady (1976) suggest the need for a longshore pressure gradient to drive the flow on the Middle Atlantic Bight against the wind stress which is taken to be eastward during winter.

Csanady (1978) presented a simple linear model for the frictionally damped steady-state, depth-averaged flow driven over a sloping shelf by a uniform longshore pressure gradient externally imposed at the shelf break. A similar dynamical model was used by Beardsley and Hart (1978) to study the shelf circulation driven by a large concentrated buoyancy source. These models do not couple the density equation with the momentum equations, although both give additional insights into portions of the physical mechanisms involved in the shelf circulation problem. Johnson et al. (1984) investigated a local model of wind driven currents on the continental shelf with vertical decoupling at the pycnocline. They included a longshore sea surface slope and a horizontal pressure gradient as additional driving forces. The results indicate that these models are useful to determine the mean circulation over the east coast shelf for the vertically homogeneous water condition.
Most of theoretical understanding on shelf water behavior is based on some form of the Ekman model. The cross-shelf transport of buoyant water must play a significant role in the nature of the cross-shelf circulation and the establishment of the density structure. The research efforts in this study were focused on the inner shelf and middle shelf regions where effects of local wind forcing, bottom friction, riverine freshwater discharge and pressure gradient, which are small scale processes, are important. A steady-state, two-dimensional analytical model was adapted for the study of the wind and density driven flow on this study area during FLEX period. Wind and hydrographic data were used as an input to the model and current observations were used to verify the model results. The model results were used to calculate the freshwater volume transport.

Past studies (Blanton and Atkinson, 1983; Lee and Atkinson, 1983; Li et al., 1985; Lee et al., 1989) have demonstrated that major transport processes on the outer to middle shelf are driven by wind events and Gulf Stream fluctuations. On the inner shelf, transport is controlled by wind events, tidal exchanges and the presence of low salinity water from river runoff. Theoretical models need various driving forces as input values. Some of them come from the field observations, and others come from the literature.

Summary of Thesis

Data used in this study are from the Fall Removal Experiment (FLEX). In October 1987 FLEX was conducted on the continental shelf between Savannah, Georgia and Cape Canaveral, Florida. The purpose of FLEX was to investigate processes involved in the transport of freshwater southward along the SAB coast from Savannah
to Cape Canaveral, where it is apparently removed from the shelf and entrained in the Gulf Stream. Such processes of transport and removal are of particular interest in determining the fate of pollutants introduced into shelf waters via freshwater discharge.

The important processes affecting the transport and fate of materials on the SAB shelf area are strongly dependent on the timing and magnitude of specific physical or meteorological events. The strength and occurrence of these events vary markedly on time scales ranging from several days to seasons. Comparison of model results and observations indicated that current variability was primarily friction response to local wind forcing.

The specific objectives of this study were:

- to identify the physical processes responsible for the southward and eventual offshore transport of low salinity water.
- to quantify driving forces in shelf circulation.
- to calculate freshwater volume transport (longshore and cross-shelf) and flow rates during the various wind events.
- to determine the importance of cross-shelf mixing and exchange processes during the various southward wind regimes.
Chapter 2
Methods

2.1 Wind data

Two Coastal Marine Aids to Navigation (C-MAN) stations (SNLT and SAUF) wind data were used in this study (Figure 1). C-MAN stations are located either on ocean towers or on piers of varying heights. They are operated by the National Oceanic and Atmospheric Administration.

The following method was used to calculate wind stress. The method assumed neutral air stability, and the measured wind speeds were adjusted to a 10 m height above the sea surface using an iterative technique (Blanton et al., 1989a). The 10 m wind speed, $u(10)$, was calculated from the logarithmic profile law:

$$u(10) = u(z) \frac{\ln [10/z_0]}{\ln [z/z_0]}$$

(2.1.1)

where $u(z)$ was the measured wind speed at height $z$. The roughness length, $z_0$, describes the surface as seen by the turbulence and it is a function of sea surface parameters (Burling and Stewart, 1967). From the neutral drag coefficient formula (Large and Pond, 1981):

$$C_{dn} = [0.49 + 0.065u(10)] \times 10^{-3}$$

(2.1.2)

Corresponding $z_0$ was computed from the definition of $C_{dn}$ and the logarithmic wind profile law:
\[ C_{dn} = u_*^2 / [u(10)]^2 \]  
\[ \frac{u(z)}{u_*} = \frac{1}{\kappa} \ln \left[ \frac{z}{z_0} \right] \]

where \( u_* \) is the friction velocity defined by \((\tau/\rho)^{1/2}\), \( \kappa \) is the von Kármán constant, \( \tau \) is the surface wind stress, and \( \rho \) is seawater density. Measured values of \( \kappa \) range from 0.35 to 0.42 (Busch, 1977). This constant was assumed to have the value of 0.40.

The \( z_0 \) obtained in this way can be reentered in equation (2.1.1) and a new \( u(10) \) speed computed. The value for \( u(10) \) converges on a final value after a few iterations and is independent of the initial assumption for \( z_0 \). It was specified that if the computed value for \( u(10) \) is less than 11 m s\(^{-1}\), \( u(10) \) is set as:

\[ u(10) = \frac{11.55 u(z)}{\ln \left[ \frac{z}{z_0} \right]} \]  

where \( z_0 = 9.67 \times 10^{-5} \) m. Using the value for \( u(10) \), wind stress components \( \tau^x \) and \( \tau^y \) were calculated as follows:

\[ \tau^x = \rho_a C_{dn} u(10) x(10) \]  
\[ \tau^y = \rho_a C_{dn} u(10) y(10) \]

where \( \rho_a \) is air density which is taken to be 1.225 kg m\(^{-3}\), \( x(10) \) and \( y(10) \) are the east, north components of \( u(10) \), and \( C_{dn} \) is the neutral drag coefficient calculated by Large and Pond (1981) as:

\[ C_{dn} = [0.49 + 0.065 u(10)] \times 10^{-3} \quad u(10) \geq 11 \text{ m s}^{-1} \]  
\[ C_{dn} = 1.14 \times 10^{-3} \quad u(10) < 11 \text{ m s}^{-1}. \]

**SNLT**

Wind speed and direction (33 m height), air temperature (5 and 20 m height),
water temperature (4 m depth), barometric pressure, and water level were obtained from the Savannah Navigational Light Tower (SNLT). SNLT is located at 31° 56.9' N, 80° 40.8' W. The mean depth of tower position is 16 m at mean low water.

SNLT wind data were used in calculations involving the Savannah and Brunswick sections. \( u \) and \( v \) components of wind field were rotated clockwise for each section so that the coordinates are parallel to the coast (i.e. 47° for Savannah, 14° for Brunswick).

**SAUF**

SAUF (St. Augustine, Florida) is located at 29° 54' N, 81° 18' W, and the sensor height is 16.4 m. SAUF wind data were used for St. Augustine and Cape Canaveral section and components of wind field were rotated counterclockwise by 14° along St. Augustine and 13° along Cape Canaveral section.
2.2 Current meter data

Locations of the current meter arrays are shown in Figure 5. Twelve current meters were moored from July through December 1987 by University of Miami and Skidaway Institute of Oceanography. The array consisted of moorings at 10 and 20 m isobaths along the Brunswick (B1, B2), St. Augustine (A1, A2) and Cape Canaveral (C1, C2) sections. Only four current meter records were used in this study due to the failure of some current meters or the short recording period of others (i.e. do not cover the FLEX cruise experiment period). No data were recovered from St. Augustine section mooring.

Table 1 shows current meter performance. Two different current meter types were used in this experiment: Aanderaa and Niskin Wing Current Meters (NWCM). The NWCM data were recorded in vector averaging mode every 20 minutes and instantaneous value of current direction every 20 minutes. The Aanderaa current meter speed was averaged over 20 minutes. The direction was recorded instantaneously every 20 minutes. Temperature was measured as an instantaneous value every 20 minutes. The current speeds were treated by 10 hour lowpass for the NWCMs and 3 hour lowpass for the Aanderaas.

Final low-frequency \((f < 0.6 \text{ cpd})\) time series of data sets were obtained by filtering with a 40 hour lowpass Lanczos filter kernel to remove variance associated with tidal and inertial motions. After filtering, the time series of current meter data was subsampled every 6 hours and rotated to align with the local topography, such that the velocity components \((u, v)\) were positive in the offshore and northward longshore directions, respectively.
Figure 5. Current meter positions. The notation used to identify mooring sites consisted of a letter to indicate the section followed by numbers to indicate the mooring depth (the numbers 1, 2 represent the 10, 20 m isobath) and instrument depth (01, 02 represent the upper, lower layer).
Table 1. Current meter mooring performance.

<table>
<thead>
<tr>
<th>Station</th>
<th>Instrument type</th>
<th>Water depth (m)</th>
<th>Mooring depth (m)</th>
<th>Data quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>C101</td>
<td>NWCM</td>
<td>10.5</td>
<td>4.6</td>
<td>good: short - about 6 days</td>
</tr>
<tr>
<td>C102</td>
<td>NWCM</td>
<td>7.3</td>
<td></td>
<td>good</td>
</tr>
<tr>
<td>C201</td>
<td>NWCM</td>
<td>20.4</td>
<td>6.0</td>
<td>no data: internal constants wrong</td>
</tr>
<tr>
<td>C202</td>
<td>AACM</td>
<td>15.0</td>
<td></td>
<td>good</td>
</tr>
<tr>
<td>A101</td>
<td>NWCM</td>
<td>10.2</td>
<td>4.6</td>
<td>no data: instrument flooded</td>
</tr>
<tr>
<td>A102</td>
<td>NWCM</td>
<td>7.3</td>
<td></td>
<td>good: short - about 55 days</td>
</tr>
<tr>
<td>A103</td>
<td>NTG</td>
<td>9.7</td>
<td></td>
<td>no data: lost on recovery</td>
</tr>
<tr>
<td>A201</td>
<td>NWCM</td>
<td>20.7</td>
<td>6.0</td>
<td>good: short - about 16 days</td>
</tr>
<tr>
<td>A202</td>
<td>NWCM</td>
<td>15.0</td>
<td></td>
<td>no data: battery exploded inside</td>
</tr>
<tr>
<td>A203</td>
<td>NTG</td>
<td>19.7</td>
<td></td>
<td>sensor leaked after Oct. 18</td>
</tr>
<tr>
<td>B101</td>
<td>NWCM</td>
<td>11.0</td>
<td>4.6</td>
<td>not reliable</td>
</tr>
<tr>
<td>B102</td>
<td>NWCM</td>
<td>7.3</td>
<td></td>
<td>good: short - about 8 days</td>
</tr>
<tr>
<td>B103</td>
<td>NTG</td>
<td>9.7</td>
<td></td>
<td>no data: lost on recovery</td>
</tr>
<tr>
<td>B201</td>
<td>NWCM</td>
<td>20.7</td>
<td>6.0</td>
<td>fair: many gaps</td>
</tr>
<tr>
<td>B202</td>
<td>AACM</td>
<td>15.0</td>
<td></td>
<td>good</td>
</tr>
<tr>
<td>B203</td>
<td>NTG</td>
<td>19.7</td>
<td></td>
<td>good</td>
</tr>
</tbody>
</table>

Instrument types
- AACM - Aanderaa Current Meter
- NWCM - Niskin Mark IIa Current Meter (vector averaging mode)
- NTG - Niskin Tide gauge (measures bottom pressure)
2.3 Hydrographic data

Two ships, the R/V Columbus Iselin and the R/V Blue Fin, participated in the FLEX field experiment to monitor temporal and spatial changes in the continental shelf of the southeastern United States.

**R/V Columbus Iselin (Oct. 22 - Nov. 7, 1987)**

The R/V Columbus Iselin was used to map the extent of low salinity water by repeatedly occupying four transects from Savannah, Georgia to Cape Canaveral, Florida (Figure 1). There were 13 hydrographic sections (2 Savannah, 5 Brunswick, 4 St. Augustine and 2 Cape Canaveral). Each section comprised CTD observations of temperature, salinity and density from near surface to near bottom. A Neil Brown Mark III B CTD with attached Q-Fluorometer and General Oceanics Rosette supporting 5 and 10 liter Niskin Bottles were used for these observations. The rated accuracy of this system was $\pm 0.005 \text{ mmho cm}^{-1}$ in conductivity and $\pm 0.005^\circ\text{C}$ in temperature. The distance between the stations was about 2.5 km over the inner shelf and about 10 km over the middle shelf. The shipboard observations were from October 22 to November 7, 1987.

**R/V Blue Fin (Oct. 17 - 18, Oct. 22 - Nov. 9, 1987)**

A preliminary survey of the coastal waters from Brunswick to Savannah, Georgia was performed from October 17-18, 1987 by R/V Blue Fin. After that, a series of cruises were conducted from October 22 to November 9, 1987 in the area of the Savannah transect. These cruises monitored the changes in the inner shelf frontal zone and helped to determine the approximate configuration of the Savannah River plume.
In this study, our main interest of research focused on the whole shelf area so the R/V Blue Fin hydrographic cruises were not discussed in detail.

**Beach temperature and salinity data (Marineland and New Smyrna)**

Temperature and salinity data were collected at high tide every three days from August 1986 to December 1987 at the Marineland and the New Smyrna Beach. At Marineland a lab thermometer was used at the inflow point to their aquariums. The water was pumped from an intake 100 feet off of the beach. Salinity bottle samples were drawn from the same place. At New Smyrna Beach a bucket thermometer was used by wading into the surf at the street approach to the beach. Salinity bottle samples were drawn from the same place. The salinity bottles were transported to Old Dominion University where an A.G.E Minisal was used to determine salinity. Times of high tide were determined from the local Tide Tables of Mayport, Florida for Marineland beach and New Smyrna Beach for New Smyrna.
2.4 Tritium data

Water samples for tritium analysis were taken at 72 stations from the CTD surface Niskin bottle during the R/V Columbus Iselin hydrographic cruise. An additional 28 samples were collected at the mouth of the Savannah River and near the Savannah section during the R/V Blue Fin hydrographic cruise. All tritium samples were analyzed at the Tritium Laboratory of the Rosenstiel School of Marine and Atmospheric Science.

The Savannah River is one of the major riverine freshwater sources to the SAB and has a uniquely high tritium concentration because of operations at the Savannah River Plant, in Aiken, South Carolina, about 140 km upstream from the mouth of the river. Nuclear reactors of the Savannah River Plant are the main source of tritium. Tritium released from the Savannah River complex is produced from neutron activation of heavy water, from irradiation of lithium and from uranium fission. The tritium is released at a controlled rate into five surface streams that eventually flow into the Savannah River (Bush, 1988).

Tritium ($^3H$), a radioactive isotope of hydrogen with atoms of 3 times the mass of ordinary light hydrogen atoms, is a weak (0.018 MeV) beta emitter. It is produced naturally in the upper atmosphere by cosmic ray interaction with atmospheric nitrogen and oxygen. Tritium concentrations are expressed in $TU$, where 1 $TU$ indicates a $T/H$ ratio of $10^{-18}$. This value refers to the internationally-adopted scale of the U.S. National Bureau of Standards (NBS), which is based on their tritium water standard #4926 as measured on Sept. 3, 1961 (Mann et al., 1982) and age-corrected with the half-life of 12.43 years, i.e., the decay rate for tritium $\lambda = 5.576 \% \text{year}^{-1}$. In this
scale, 1 TU is equivalent to 7.088 dpm (kg H₂O⁻¹) or 3.193 pCi (kg H₂O⁻¹).
Here, dpm means disintegration per minute, and pCi is the pico Curie. Tritium concentration values were corrected for date of sample collection and analyzed by direct run, i.e. without electrolytic enrichment.
2.5 Analytical current models

Two analytical models, density driven and wind driven, were adopted for the understanding of shelf mean circulation. The mean circulation was defined as the non-tidal or residual flow obtained by averaging currents for a longer period than tidal and weather cycles. Although this kind of model is not new, when applied in shallow water and with imposed density and sea level gradients, some interesting and complex features are seen in the shelf circulation patterns during specific conditions (e.g. freshwater inflow rate and various wind events). A wind driven current model was used to calculate longshore transport. This model and a density driven current model were used to examine the forces causing the longshore flow. I described the basic equations, assumptions, boundary conditions and solutions for these analytical models in this section.

2.5.1 Density driven current model

Along many coasts there is an influx of river discharge, producing a zone of low salinity water that mixes gradually with higher salinity offshore. The mixing of riverine freshwater and seawater gives rise to characteristic patterns of coastal circulation and salinity distribution. The presence of a density gradient, with the density increasing from the shoreline to offshore, produces pressure gradients within the water.

The idealized case of flow bounded by a straight coast is considered for this study region. The $x$-axis is taken perpendicular to the coast, the $y$-axis along the shoreline and the $z$-axis vertically upwards. As a result of a uniform influx of river discharge from the coast, it is assumed that the density of the inner shelf water increases in the
offshore direction, the isopycnals running parallel to the coast. Also, it is assumed that at any position the water column is vertically well mixed. Conditions are assumed to be uniform in the \( y \)-direction, so that \( \partial / \partial y = 0 \) for any physical property.

The basic equations of momentum, hydrostatic and continuity for a steady state are

\[
-f v = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{1}{\rho} \frac{\partial \tau^x}{\partial z} \quad (2.5.1)
\]

\[
f u = \frac{1}{\rho} \frac{\partial \tau^y}{\partial z} \quad (2.5.2)
\]

\[
\frac{1}{\rho} \frac{\partial p}{\partial z} + g = 0 \quad (2.5.3)
\]

\[
\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \quad (2.5.4)
\]

where \( u, v \) and \( w \) are the \( x \)-, \( y \)- and \( z \)-direction velocities, respectively, \( f \) the Coriolis parameter, \( \rho \) density, \( p \) pressure, \( \tau^x \) and \( \tau^y \) surface wind stresses, and \( g \) gravity constant. It is convenient to represent the current by the complex variable

\[
W = u + iv
\]

where \( i = (-1)^{1/2} \). Introducing the coefficient of eddy viscosity \( (A_z) \), assumed to be independent of \( z \), the shear stress terms can be written

\[
\tau^x = \rho A_z \frac{\partial u}{\partial z}, \quad \tau^y = \rho A_z \frac{\partial v}{\partial z} \quad (2.5.5)
\]

After solving equations (2.5.1) and (2.5.2) using equation (2.5.3), complex variables and coefficient of eddy viscosity, the solution may be written

\[
W = W_1 + W_2 + W_3 \quad (2.5.6)
\]

where \( W_1 = \frac{ig}{f} \frac{\partial \zeta}{\partial x} \), \( W_2 = -\frac{ig}{\rho f} \frac{\partial p}{\partial x} \), \( \frac{\partial^2 W_3}{\partial z^2} - \frac{if}{A_z} W_3 = 0 \), \( i \) is the imaginary unit, and \( \zeta \) the surface elevation. Thus
\[ u_1 = u_2 = 0 \]  
(2.5.7)

\[ v_1 = \frac{g}{f} \frac{\partial}{\partial x}, \quad v_2 = -\frac{g}{\rho f} \frac{\partial \rho}{\partial z} \]  
(2.5.8)

and \( W_3 \) has the solution

\[ W_3 = ae^{kz} + be^{-kz} \]  
(2.5.9)

where \( k = (1 + i)(DE)^{-1} \), \( D_E = (2\Lambda_z f)^{1/2} \), and \( a \), and \( b \) are constants.

\( W_1 \) represents a gradient current, proportional to the slope of the surface and independent of depth \( z \). \( W_2 \) represents a density current, proportional to the density gradient and varying linearly with \( z \). While \( W_3 \) is an Ekman spiral type of solution.

**Currents for frictionless flow**

First, consider the case of negligible internal friction, i.e. \( A_z = 0 \) and hence \( W_3 = 0 \). Then, from equations (2.5.7) and (2.5.8),

\[ u = u_1 + u_2 = 0 \]  
(2.5.10)

\[ v = -\frac{g}{\rho f} \frac{\partial \rho}{\partial z} (h + z) \]  
(2.5.11)

The surface flow for increasing density toward offshore is in the negative \( y \)-direction and the speed of the current decreases linearly from surface to bottom.

**Currents allowing for friction**

To allow for internal friction the solution \( W_3 \) must be added to \( W_1 \) and \( W_2 \) so that

\[ W = \frac{ig}{f} \left[ \frac{\partial \zeta}{\partial x} - \frac{1}{\rho} \frac{\partial \rho}{\partial x} \right] + ae^{kz} + be^{-kz} \]  
(2.5.12)
The boundary conditions have to be applied to the combined solution:

\[
\frac{\partial W}{\partial z} = 0 \quad z = 0 \tag{2.5.13}
\]

\[
A_z \frac{\partial W}{\partial z} = rW \quad z = -h \tag{2.5.14}
\]

\[
\int_0^h u \, dz = R \tag{2.5.15}
\]

where \( r \) is bottom friction coefficient, and \( R \) is the rate of freshwater influx per unit length of coastline. A solution in a form suitable for application to a practical case is given at Appendix A.

From the continuity equation (2.5.4) and calculated distribution of cross-shelf velocities \( u(x, z) \) the stream function \( \psi(x, z) \) in the cross-shelf plane is

\[
u = \frac{\partial \psi}{\partial z}, \quad w = -\frac{\partial \psi}{\partial x} \tag{2.5.16}
\]

taking the bottom as the \( \psi = 0 \) streamline. This calculation also determines small vertical velocities.

### 2.5.2 Wind driven current model

A more complex wind driven current model is used to estimate currents for transport studies and effects of various driving forces in shelf circulation. An approach using local Ekman dynamics was adopted, in which the wind stress was included in the equations governing the water movements. The model requires as inputs: 1) the wind stress field, 2) longshore pressure gradient, 3) cross-shelf density gradient, 4) frontal zone distance, 5) freshwater inflow rate and 6) latitude of the section.
Equations of motion

The two horizontal steady state momentum equations in a vertically well mixed shallow sea are written as

\[-fv = -g \frac{\partial \zeta}{\partial x} + \frac{g}{\rho_0} \frac{\partial \rho}{\partial x} + A_z \frac{\partial^2 u}{\partial z^2} \]  \hspace{1cm} (2.5.17)

\[fu = -g \frac{\partial \zeta}{\partial y} + A_z \frac{\partial^2 v}{\partial z^2} \]  \hspace{1cm} (2.5.18)

Here, \( \zeta \) is surface elevation, \( \rho_0 \) reference density, \( A_z \) vertical eddy viscosity. The coordinate system and notation are the same for the previous subsection 2.5.1. The density is a function of \( x \) alone, i.e. \( \partial \rho / \partial y = 0 \). Also, these momentum balances are supplemented by the continuity equation.

Assumptions

- Time scale (period, \( T \)) was longer than tidal or weather cycles. Frictional adjustment time scale was assumed to be less than 12 hours.

- A value of \( -2.0 \times 10^{-7} \) was chosen for longshore sea surface slope. This value was in the \( -1.0 \times 10^{-7} \) to \( -3.0 \times 10^{-7} \) range of previous observations and sea level observations made during FLEX.

- The water column was assumed to be vertically homogeneous. Horizontal density gradients were calculated from hydrographic observations.

- Friction:

  Vertical friction — Vertical eddy viscosity (Austach) in water shallower than 0.1\( u_* f^{-1} \) (depth of a turbulent Ekman boundary layer) is

  \[ A_z = u_* h / 20 \]  \hspace{1cm} (2.5.19)
In deeper layers of fluid (deeper than 0.1u* f^{-1}),

\[ A_z = \frac{u_*^2}{200f} \quad (2.5.20) \]

where \( u_* \) (friction velocity) is \( \sqrt{\frac{\tau}{\rho}} \).

Ekman depth is defined as \( D_E = (2A_z/f)^{1/4} \). In this calculation the typical value of Ekman depth was about 12 m.

**Horizontal friction** — In a study of the flow of an estuary onto the continental shelf, Beardsley and Hart (1978) produced a simple estimate of the effect of horizontal friction and they concluded that horizontal friction is not important at distances from the source greater than \( L_c \) where

\[ L_c = \frac{4 |\alpha| A_h}{C_B u_{*b}} \quad (2.5.21) \]

\( \alpha \) is a linear bottom profile of small slope, \( A_h \) is the horizontal mixing coefficient, and \( C_B \) is the bottom drag coefficient and \( u_{*b} \) is the bottom friction velocity. Using a representative \( A_h \) value of \( 2 \times 10^6 \ cm^2 s^{-1} \), \( L_c \) is less than 1 km.

The principal source of horizontal friction is the coastline. But more than 1 km offshore, the water is still so shallow that bottom friction tends to dominate, as implied in the Beardsley and Hart (1978) analysis. For this reason, horizontal friction was neglected in this study.

**Bottom friction** — Classic Ekman theory shows that water depth affects the character of a steady barotropic current on the continental shelf and its bottom stress (Csanady, 1982). The bottom stress is determined by the near bottom velocity and is represented by a quadratic friction law (Csanady, 1982):
\[ B_x = C_d u_b q, \quad B_y = C_d v_b q \quad z = -h \quad (2.5.22) \]

where \( q = (u_b^2 + v_b^2)^{1/2} \), \( u_b \) and \( v_b \) are components of the bottom velocity, and \( C_d \) is a dimensionless drag coefficient. The above equation (2.5.22) can be rewritten using depth-average velocities as follows:

\[ B_x = ru, \quad B_y = rv \quad z = -h \quad (2.5.23) \]

where \( r \) is a bottom resistance coefficient with dimensions \([\text{length}/\text{time}]\). The empirical value of \( r \) was the order of \( 10^{-1} \text{ cm s}^{-1} \) (Csanady, 1982; Blanton et al., 1989b; Lee et al., 1989). Winant and Beardsley (1979) found that drag coefficients and bottom resistance coefficients were notably larger for daily averaged measurements made closest to the bottom (about 3 m above the bottom). The bottom resistance coefficient \( (r) \) value used in this study was 0.16 \( \text{cm s}^{-1} \).

**Boundary conditions**

Boundary conditions at the surface and bottom are

\[ A_x \frac{\partial u}{\partial z} = \tau_0^x, \quad A_x \frac{\partial v}{\partial z} = \tau_0^y \quad z = 0 \quad (2.5.24) \]

\[ A_x \frac{\partial u}{\partial z} = ru, \quad A_x \frac{\partial v}{\partial z} = rv \quad z = -h \quad (2.5.25) \]

where \((\tau_0^x, \tau_0^y)\) are surface wind stresses.

The vertically integrated transport at the open boundaries are

\[ \int_{-h}^{0} u \ dz = U \quad \int_{-h}^{0} v \ dz = -V \quad (2.5.26) \]

where \( U \) is the freshwater influx from the coastline.

**Solution**

From the equations of motion, the \( y \)-component equation (2.5.17) was multiplied
by $i$ and added to the $x$-component equation (2.5.18) to form,

\[
\frac{\partial^2 w}{\partial z^2} - \frac{i f}{A_z}w = \frac{g}{A_z} \left[ \nabla \eta - \frac{z}{\rho_0} \frac{\partial \rho}{\partial x} \right]
\]  
(2.5.27)

where $w = u + iv$, $\nabla \eta = \frac{\partial \zeta}{\partial x} + i \frac{\partial \zeta}{\partial y}$.

The solution to this equation is

\[
w = ae^{kz} + be^{-kz} + \frac{ig}{f} \left[ \nabla \eta - \frac{z}{\rho_0} \frac{\partial \rho}{\partial x} \right]
\]  
(2.5.28)

where $k = (1 + i)(f/2A_z)^{1/2}$ and $a, b$ are complex constants, to be determined from the surface and bottom boundary conditions. The last term of equation (2.5.28) is the geostrophic velocity component. The streamline pattern $\psi(x, z)$ was introduced from the calculated distribution of cross-shelf velocities $u(x, z)$, as in equation (2.5.16).
Chapter 3
Results

3.1 Wind field observations

Winds during the fall 1987 observations were mainly southwestward which is typical of mariners' fall. In this section, wind observations from the Savannah Navigational Light Tower (SNLT) and St. Augustine Florida (SAUF) stations are presented.

SNLT: Figure 6a shows the stick plot for the 3 hour averaged winds during the FLEX cruise period (Oct. 20 - Nov. 10, 1987). Mean wind speed and prevailing direction were 7.9 m s\(^{-1}\) towards the southwest. Figure 7 shows the calculated wind stress components during the same period. Wind stress exhibited strong variability on synoptic time scales. Mean east (\(x\)) and north (\(y\)) wind stress components were \(\bar{\tau_x} = -0.65\), \(\bar{\tau_y} = -0.62\) dyne cm\(^{-2}\). Wind stress directional steadiness was 0.89 for east, 0.80 for north component of wind stress indicating persistent southwestward winds. The wind stress directional steadiness is the magnitude of vector average wind stress divided by the scalar average wind stress magnitude (Chelton et al., 1990). The spectrum for SNLT winds from October 20 to November 10, 1987 is shown in Figure 9a. This power spectrum (computed from 176 measurements, no smoothing and 2 degrees of freedom) was dominated by large peaks occurring at frequencies of 0.14 (corresponding to the period 7.3 days) and 0.23 \(cpd\) (4.4 days) with a minor peak at 0.36 \(cpd\) (2.7 days).
Figure 6. Stick plots for the wind field at (a) SNLT and (b) SAUF stations.
Figure 7. Wind stress components (in dyne cm$^{-2}$) at SNLT during the FLEX experiment.
SNLT

(a) \( \tau_x \)

(b) \( \tau_y \)

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**SAUF**: The stick plot for the 3 hour averaged winds at SAUF during the FLEX cruise period is illustrated in Figure 6b. Mean wind speed was 6.3 m s\(^{-1}\) and prevailing wind direction was southward. Figure 8 shows the calculated wind stress. Mean east and north components of wind stress at this pier station were \(\bar{\tau}_e = -0.21\), \(\bar{\tau}_n = -0.43\) dyne cm\(^{-2}\). The wind stress directional steadiness were 0.72 for east and 0.93 for north component of wind stress indicating persistent southward winds. The spectrum for SAUF wind observations (176 measurements, no smoothing and 2 degrees of freedom) is shown in Figure 9b. It showed the two major peaks occurring at frequencies, 0.32 (3.1 days) and 0.14 cpd, and a minor peak at 0.64 cpd (1.6 days).

Winds at SNLT were stronger than at SAUF, however, they were steadier at SAUF. The direction at SNLT was southwestward compared to the southward mean at SAUF. The wind speed variability at both stations peaked in the 2 - 7 days range which are typical storm periods.

Three types of wind events were chosen for specific analysis by considering the times when the hydrographic sections were occupied and the strength of the winds. The three chosen events were the moderate wind event on October 24, the strong wind event on October 26, and the weak wind event on October 29 (Figures 7 and 8). The wind strength for these wind events and other information are summarized in Table 2. The periods of wind relaxation or reversal between these events were typically only few days long (Figures 7 and 8). The wind stress fluctuations were strongly polarized in the longshore direction with the wind stress decreased to the south.
Figure 8. Same as in Figure 7, except for SAUF.
(a) $\tau_x$

(b) $\tau_y$
Figure 9. The spectrums of (a) SNLT and (b) SAUF wind velocity observations from October 20 to November 10, 1987.
Table 2. Density gradient, frontal zone distance and wind stress values for the hydrographic sections. Frontal zone starts from the first station of each hydrographic section. Wind stress values are rotated along each section and average of 24 hours (dyne cm\(^{-2}\)). The last term shows the wind event (i.e. M: moderate, S: strong and W: Weak).

<table>
<thead>
<tr>
<th>Section</th>
<th>Density gradient</th>
<th>Frontal zone (km)</th>
<th>Wind stress (\tau^x)</th>
<th>Wind stress (\tau^y)</th>
<th>Wind Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>C01</td>
<td>(6.0 \times 10^{-10})</td>
<td>(-2.7 \times 10^{-10})</td>
<td>10</td>
<td>-0.83</td>
<td>-0.81</td>
</tr>
<tr>
<td>A01</td>
<td>(5.3 \times 10^{-10})</td>
<td>(-8.3 \times 10^{-11})</td>
<td>15</td>
<td>-0.48</td>
<td>-0.71</td>
</tr>
<tr>
<td>B01</td>
<td>(6.7 \times 10^{-10})</td>
<td>(-1.7 \times 10^{-11})</td>
<td>18</td>
<td>-0.73</td>
<td>-1.21</td>
</tr>
<tr>
<td>S01</td>
<td>(4.0 \times 10^{-10})</td>
<td>(-1.7 \times 10^{-10})</td>
<td>35</td>
<td>0.09</td>
<td>-0.92</td>
</tr>
<tr>
<td>B02</td>
<td>((7.0 \times 10^{-10}))</td>
<td>(-2.0 \times 10^{-11})</td>
<td>20</td>
<td>-1.01</td>
<td>-1.80</td>
</tr>
<tr>
<td>A02</td>
<td>(7.5 \times 10^{-10})</td>
<td>(-1.2 \times 10^{-10})</td>
<td>20</td>
<td>0.04</td>
<td>-0.23</td>
</tr>
<tr>
<td>C02</td>
<td>(5.0 \times 10^{-10})</td>
<td>(-2.9 \times 10^{-10})</td>
<td>12</td>
<td>0.03</td>
<td>-0.23</td>
</tr>
<tr>
<td>B03</td>
<td>(8.0 \times 10^{-10})</td>
<td>(-1.7 \times 10^{-11})</td>
<td>20</td>
<td>-0.12</td>
<td>-0.43</td>
</tr>
<tr>
<td>S02</td>
<td>(1.04 \times 10^{-9})</td>
<td>(-1.3 \times 10^{-10})</td>
<td>25</td>
<td>0.08</td>
<td>-0.24</td>
</tr>
<tr>
<td>B04</td>
<td>(6.0 \times 10^{-10})</td>
<td>(-3.3 \times 10^{-11})</td>
<td>25</td>
<td>-0.47</td>
<td>-0.84</td>
</tr>
<tr>
<td>A03</td>
<td>(5.5 \times 10^{-10})</td>
<td>(-2.2 \times 10^{-10})</td>
<td>20</td>
<td>-0.44</td>
<td>-0.32</td>
</tr>
<tr>
<td>A04</td>
<td>(6.0 \times 10^{-10})</td>
<td>0.0</td>
<td>20</td>
<td>-0.29</td>
<td>-0.04</td>
</tr>
<tr>
<td>B05</td>
<td>(4.4 \times 10^{-10})</td>
<td>0.0</td>
<td>50</td>
<td>-0.15</td>
<td>-0.53</td>
</tr>
</tbody>
</table>
3.2 Current observations

There were four acceptable current meter observations during FLEX and all were analyzed for this study. Current meter statistics during the experiment period are shown in Table 3. Mean longshore currents were southward at 3.8 to 6.8 cm s$^{-1}$ while cross-shelf currents ranged from 0.4 to 4.1 cm s$^{-1}$. Mean surface cross-shelf currents at the Brunswick offshore mooring (B201) were offshore (about 2.2 cm s$^{-1}$), and mean bottom cross-shelf currents were offshore at 0.4 to 4.1 cm s$^{-1}$. The velocity component fluctuations of these current meters during the FLEX cruise period are given in Figures 10 and 11.

Analysis of the moored current data at the Brunswick 20 m isobath (B201 and B202) indicated that shelf currents correlated with local wind stress fluctuation (Figure 10). There was a clear relationship between strong southwestward wind stress events and negative longshore current velocity, followed by wind relaxation events and positive longshore current velocity. The time lag between wind and longshore current changes was estimated to be much less than 6 hours by comparing the time delay between wind and current changes. The typical frictional adjustment time for 20 m depth and moderate wind stress (1.0 dyne cm$^{-2}$) is about 6 hours. Clearly, the longshore currents are in frictional equilibrium with adjustment times of less than 6 hours. Cross-shelf current components were weak and did not correlate with the local wind stress.

Current meter observations at the Cape Canaveral 11 and 20 m isobaths showed similar relationship between the southwestward wind stress events and southward longshore current. The time lag was nearly zero for the moderate longshore wind...
Table 3. Current meter statistics. Velocity components are rotated along each section and filtered with a 40 hour lowpass filter. U and V refer to the component and T to temperature. Current meter locations are shown in Figure 5. Units of $u$ and $v$ are $\text{cm s}^{-1}$, and temperature is °C.

<table>
<thead>
<tr>
<th>Station</th>
<th>Period Starts</th>
<th>Ends</th>
<th>Mean</th>
<th>Std dev</th>
<th>Min</th>
<th>Max</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>C102U</td>
<td>871020 0000</td>
<td>871110 1800</td>
<td>3.6</td>
<td>4.5</td>
<td>-2.9</td>
<td>12.3</td>
<td>15.2</td>
</tr>
<tr>
<td>C102V</td>
<td>871020 0000</td>
<td>871110 1800</td>
<td>-6.5</td>
<td>10.2</td>
<td>-26.5</td>
<td>12.3</td>
<td>38.8</td>
</tr>
<tr>
<td>C102T</td>
<td>871020 0000</td>
<td>871110 1800</td>
<td>22.4</td>
<td>0.8</td>
<td>21.2</td>
<td>24.1</td>
<td>2.9</td>
</tr>
<tr>
<td>C202U</td>
<td>871020 0000</td>
<td>871110 1800</td>
<td>4.1</td>
<td>8.5</td>
<td>-16.9</td>
<td>15.6</td>
<td>32.5</td>
</tr>
<tr>
<td>C202V</td>
<td>871020 0000</td>
<td>871110 1800</td>
<td>-6.8</td>
<td>16.2</td>
<td>-31.7</td>
<td>24.9</td>
<td>56.5</td>
</tr>
<tr>
<td>C202T</td>
<td>871020 0000</td>
<td>871110 1800</td>
<td>24.2</td>
<td>0.5</td>
<td>23.4</td>
<td>25.1</td>
<td>1.7</td>
</tr>
<tr>
<td>B201U</td>
<td>871020 0000</td>
<td>871107 1200</td>
<td>2.2</td>
<td>2.6</td>
<td>-3.4</td>
<td>6.6</td>
<td>10.1</td>
</tr>
<tr>
<td>B201V</td>
<td>871020 0000</td>
<td>871107 1200</td>
<td>-6.8</td>
<td>8.3</td>
<td>-24.0</td>
<td>6.9</td>
<td>30.8</td>
</tr>
<tr>
<td>B201T</td>
<td>871020 0000</td>
<td>871107 1200</td>
<td>20.8</td>
<td>0.7</td>
<td>18.3</td>
<td>20.1</td>
<td>1.9</td>
</tr>
<tr>
<td>B202U</td>
<td>871020 0000</td>
<td>871107 1200</td>
<td>0.4</td>
<td>1.2</td>
<td>-2.7</td>
<td>3.3</td>
<td>5.9</td>
</tr>
<tr>
<td>B202V</td>
<td>871020 0000</td>
<td>871107 1200</td>
<td>-3.8</td>
<td>4.8</td>
<td>-13.9</td>
<td>3.4</td>
<td>17.2</td>
</tr>
<tr>
<td>B202T</td>
<td>871020 0000</td>
<td>871107 1200</td>
<td>21.1</td>
<td>0.7</td>
<td>20.2</td>
<td>22.5</td>
<td>2.4</td>
</tr>
</tbody>
</table>
Figure 10. Wind stress and observed current velocity components (in $cm \, s^{-1}$) at Brunswick section (B2).
Figure 11. Same as in Figure 10, except for Cape Canaveral section (C102, C202).
(a) Wind stress

![Wind stress graph](image)

- **SAUF**
- $\tau_x$, $\tau_y$

(b) C102 (7.3/11 m)

![Velocity graph](image)

- $u$, $v$

(c) C202 (15/20 m)

![Velocity graph](image)

- $u$, $v$

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stress and about 6-10 hours for the strong wind stress (Figure 11). The lower layer at
the offshore mooring (C202) had a longer adjustment time than the lower layer at the
inshore mooring (C102). This is expected according to the frictional adjustment
theory. Measurements in the lower layer clearly exhibited adjustment to surface
Ekman drift caused by the southward winds. There were exceptions to this, however.
For example, on November 3-5 currents were strong but winds were weak. The strong
currents may have been caused by Gulf Stream or pressure field forcing. Cross-shelf
currents were correlated with the cross-shelf wind stress. However, the cross-shelf
wind stress contributed less to producing currents than the longshore wind stress.
3.3 Sea level differences

Sea level fluctuations along the shoreline from Charleston, South Carolina to Mayport, Florida are shown in Figure 12. These data came from National Ocean Service tidal stations and were filtered with a 40 hour lowpass filter to remove the tidal effect. After barometric pressure correction and mean sea level adjusting (Sturges, 1974; Chase, 1979), departure estimation between these four tidal stations were calculated. The Charleston tidal station was used as the reference station to calculate sea level differences. The adjusted sea level differences between Charleston and Fort Pulaski, Fernandina, and Mayport are shown in Figure 13. During the FLEX observation, adjusted sea level at Fort Pulaski was 2.8 cm higher than Charleston, while at Fernandina and Mayport it was 8.3 and 6.4 cm higher, respectively. These sea level departures correspond to longshore pressure gradient from $-2.26 \times 10^{-7}$ to $-3.01 \times 10^{-7}$ and agreed with slopes found by Pattullo (1963) and Sturges (1974).
Figure 12. Sea level fluctuation along the shoreline tidal stations. Vertical dashed lines show the period of FLEX. All sea level data were filtered by 40 hour lowpass.
Figure 13. Sea level differences between (a) Charleston - Fort Pulaski, the mean departure during FLEX was $-2.80 \text{ cm}$. (b) Charleston - Fernandina, the mean departure was $-8.32 \text{ cm}$. (c) Charleston - Mayport, the mean departure was $-6.38 \text{ cm}$. Vertical dashed lines show the period of FLEX. Each tidal station sea level data was adjusted by the mean sea level and corrected for the barometric pressure.
3.4 Hydrographic observations

Waters in the SAB ranged from well-defined Gulf Stream water to highly variable and modified shelf waters. The study area has a broad and shallow shelf and responds quickly to atmospheric conditions, especially on the extremely shallow inner shelf. Inner shelf water temperatures quickly respond to air temperature while the outer shelf is modulated by the Gulf Stream. In this section the horizontal and vertical distributions of temperature, salinity and density are presented and discussed. The distribution of freshwater and a T-S diagram are also included. The hydrographic section observation time and other information are given in Table 4. The freshwater fraction at any hydrographic section was determined by using a reference salinity of 36.2 psu. This mixing salinity represented the value of outer shelf or proximity of the Gulf Stream. It is seldom that Gulf Stream surface salinities are less than 36.2 psu and the salinity of subsurface water that might be advected onto the shelf region is higher than 36.2 psu.

R/V Columbus Iselin (Oct. 22 - Nov. 7, 1987)

As was noted in the Introduction, the historical mean data (Figure 4) show a band of low salinity water along the coast from Georgia to Florida in October. The horizontal distributions of surface salinity during the FLEX observation also showed a narrow low salinity band along the coastline (Figure 14). The 35 psu isohaline stretched toward Cape Canaveral, and the 32 and 33 psu isohalines reached 30.5°N (Figure 14d). In the middle shelf region, intrusions of the Gulf Stream water were observed as evidenced by the 36.2 psu isohaline (Figure 14). The surface temperature fields are given in Figure 15. Cold waters (about 19-22°C) were nearshore, and
Table 4. Hydrographic section data.

<table>
<thead>
<tr>
<th>Section</th>
<th>Observation</th>
<th>24 Hr. mean</th>
<th>Rotated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
<td>$\tau^x$</td>
</tr>
<tr>
<td>C01</td>
<td>871023 0800</td>
<td>871023 1400</td>
<td>-0.630</td>
</tr>
<tr>
<td>A01</td>
<td>871024 0000</td>
<td>871024 1100</td>
<td>-0.293</td>
</tr>
<tr>
<td>B01</td>
<td>871024 1800</td>
<td>871025 0400</td>
<td>-1.006</td>
</tr>
<tr>
<td>S01</td>
<td>871025 1400</td>
<td>871025 2200</td>
<td>-0.615</td>
</tr>
<tr>
<td>B02</td>
<td>871026 1300</td>
<td>871026 2300</td>
<td>-1.419</td>
</tr>
<tr>
<td>A02</td>
<td>871027 1500</td>
<td>871028 0200</td>
<td>0.095</td>
</tr>
<tr>
<td>C02</td>
<td>871028 1400</td>
<td>871028 2000</td>
<td>0.076</td>
</tr>
<tr>
<td>B03</td>
<td>871029 1700</td>
<td>871030 0400</td>
<td>-0.219</td>
</tr>
<tr>
<td>S02</td>
<td>871031 1700</td>
<td>871101 0100</td>
<td>-0.115</td>
</tr>
<tr>
<td>B04</td>
<td>871101 1400</td>
<td>871102 0100</td>
<td>-0.663</td>
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<tr>
<td>A03</td>
<td>871102 1600</td>
<td>871103 0200</td>
<td>-0.347</td>
</tr>
<tr>
<td>A04</td>
<td>871105 0000</td>
<td>871105 0400</td>
<td>-0.273</td>
</tr>
<tr>
<td>B05</td>
<td>871105 1400</td>
<td>871106 0300</td>
<td>-0.270</td>
</tr>
</tbody>
</table>

Notes:

Rotation angle along section.

- Savannah -47.40
- Brunswick -14.12
- St. Augustine 14.16
- Cape Canaveral 12.68
Figure 14. Surface salinity (in $psu$) map for (a) October 23 - 25, (b) October 25 - 28,
(c) October 30 - November 3 and (d) November 4 - 5, 1987.
Figure 15. Same as in Figure 14, except for temperature (in °C).
warm waters reflecting the Gulf Stream were seen over the outer shelf. The surface thermal gradients were constant (about $5 \times 10^{-2} \degree C \ km^{-1}$) over the shelf while salinity gradients were strong ($1.0 \times 10^{-1} \ psu \ km^{-1}$) over the inner shelf but less ($1.0 \times 10^{-2} \ psu \ km^{-1}$) offshore.

Vertical distributions of temperature, salinity and density for all sections are shown in Figures 16 through 19. Features to note include position of fronts, cross-shelf density gradients and the degree of stratification.

**Savannah**: These vertical sections showed the widest ranges for temperature and salinity, because of the proximity of the Savannah and other rivers farther north (Figure 16). Inner shelf waters varied from 31.6 to 36.0 psu and from 17.5 to 21.5°C, while the middle shelf salinities were greater than 36.0 psu and temperatures varied from 21.5 to 24.0°C. In near coastal surface layers, freshwater fraction was more than 10% because of the proximity of the Savannah River. Inner shelf vertically averaged freshwater fractions ranged from 5 to 10%. The middle shelf region freshwater fraction was less than 1%, because of the strong southward advection of freshwater along the coastline and influence of the Gulf Stream. Nearshore frontal zones were found near the 15 m isobath (40 km off the coast).

**Brunswick**: Brunswick sections exhibited smaller ranges for temperature and salinity than Savannah (Figure 17). Inner shelf waters varied from 32.0 to 35.6 psu and from 18.0 to 21.5°C, while the middle shelf salinities were higher than 35.6 psu and temperatures varied from 21.5 to 23.5°C. Nearshore freshwater fraction were greater than 10%, while the inner shelf varied from 3 to 10%. Middle shelf freshwater
Figure 16. Vertical profiles for Savannah section (a) S01 and (b) S02. Dates in figure show the observation ending time.
Figure 17. Vertical profiles for Brunswick section (a) B01, (b) B02, (c) B03, (d) B04 and (e) B05.
Figure 18. Vertical profiles for St. Augustine section (a) A01, (b) A02, (c) A03 and (d) A04.
Figure 19. Vertical profiles for Cape Canaveral section (a) C01 and (b) C02.
fraction was between 0.5 and 2\%, but middle shelf freshwater fraction was higher than the middle shelf off Savannah. Frontal zones were found about 15 m isobath (20 km off the shoreline).

**St. Augustine:** This section showed higher salinities and temperatures than those off Brunswick (Figure 18). Inner shelf waters varied from 33.4 to 36.0 \textit{psu} and from 19.5 to 22.5\textdegree C, while the middle shelf waters had higher salinities (36.0 \textit{psu}) and temperatures (22.5 to 24.5\textdegree C). Middle shelf waters were close to the characteristics of Gulf Stream water. Frontal zones were found about 20 m isobath (15 km off the coast). Nearshore freshwater fraction was about 6–8\%. There was essentially no freshwater in the middle shelf.

**Cape Canaveral:** Highest salinity and temperature were found over middle shelf off Cape Canaveral (Figure 19). The strong influence of Gulf Stream was clear except near shore. Inner shelf waters varied from 35.0 to 36.0 \textit{psu} and from 22.2 to 24.0\textdegree C, while the middle shelf had salinities higher than 36.0 \textit{psu} and varied from 24.0 to 26.5\textdegree C. Freshwater fraction was below 4\% over the whole shelf; this fraction was less than half that of farther north sections. Frontal zones were at the 15 m isobath (15 km off the coast).

Examination of all vertical hydrographic sections revealed the following: 1) a low salinity band persisted along the shoreline, 2) a nearshore frontal zone occurred 20–40 km off the coast at about 15 m isobath and 3) the temporal variation of hydrographic properties during FLEX was small.

The T-S diagram of all FLEX data (2848 points) are shown in Figure 20. The
Figure 20. T-S diagram during hydrographic cruise of R/V Columbus Iselin. The solid line show $\sigma_t$ values, and the thick line indicates the reference of Gulf Stream water (Atkinson, 1983). The dotted line shows the separation of Gulf Stream water and diluted Gulf Stream water with shelf water. Temperature is in °C, and salinity is in $psu$. 

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diagram shows that waters warmer than about 23°C were very similar to Gulf Stream water. Colder inner shelf waters were fresher and showing the lower salinities associated with the water off Brunswick.

**Beach temperature and salinity data (Marineland and New Smyrna)**

Salinities and temperatures measured at the two beach stations clearly showed the strong annual signals (Figures 21 and 22). Temperatures peaked in July and August after minima in February and March. Salinity was lowest (27.8 psu) in February, reached maximum values (36.5 psu) in June, July and August, then reached a secondary minimum (33.5 psu) in October during the observation period. Note the abrupt salinity decrease in September - October coincident with the onset of southward winds.

The spectrums of temperature and salinity data during a whole year of 1987 at two beach monitoring stations are given in Figures 23 and 24. The raw periodograms for Marineland station (computed from 113 observations) were dominated by large peak occurring at 1.07 cpy (corresponding to the period 342 days, i.e. annual cycle). Minor peaks occurred at the periods of 114 days and 49 days for temperature (Figure 23a) and 114 days and 57 days for salinity data (Figure 23b). The spectrums for New Smyrna Beach (119 observations) showed similar cyclical behavior (major peaks at 1.02 cpy) with Marineland Beach station. The periods of 118 days and 51 days for temperature and 118 days and 39 days were the minor peaks for this spectrum (Figure 24). Both beach temperature and salinity data showed strong annual and seasonal cycles.
Figure 21. Marineland (a) temperature, (b) salinity data during 1987.
Marineland Beach Station

(a)

Temperature (deg C)

(b)

Salinity (psu)

J  F  M  A  M  J  J  A  S  O  N  D

1987

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Figure 22. New Smyrna (a) temperature, (b) salinity data during 1987.
Figure 23. The spectrum of temperature and salinity data at Marineland beach station (a) temperature and (b) salinity during 1987. In the upper right corner of each plot, vertical component indicate the 95% confidence interval for the spectrum and horizontal element indicate the bandwidth of the spectrum estimation. The mean of each data were removed before the computation of periodogram.
Marineland Temperature 1987

Marineland Salinity 1987

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Figure 24. Same as in Figure 23, except for New Smyrna.
New Smyrna Temperature 1987

New Smyrna Salinity 1987

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3.5 Distribution of surface tritium

The Savannah River is the only source of tritium in the SAB (Bush, 1988). A tritium-salinity plot of all 100 samples taken during FLEX is shown in Figure 25. For comparison, the tritium-salinity plot obtained during the Spring Removal Experiment in 1985 is also shown (Figure 26). In both cases there is an obvious relationship between coastal water (about 10 $TU$) and Savannah River water (about 1000 $TU$). The linear salinity-tritium relationship suggests that tritium loaded Savannah River water mixed with low tritium shelf water. The other low salinity, low tritium values were taken very near the Altamaha or Ogeechee Rivers that contain little tritium; thus, the linear mixing line is different.

Surface distributions of tritium are shown in Figure 27, and the average for the whole experiment is shown in Figure 28. During the moderate wind event (October 23-25), the highest tritium concentration was nearshore (42 $TU$) in the St. Augustine section, and the lowest value was nearshore (9 $TU$) in the Cape Canaveral section along the shoreline (Figure 27a). Middle shelf of Savannah section showed no tritium distribution due to the longshore current advection. During the strong wind event (October 25-28), Brunswick section showed higher tritium concentrations offshore than during the moderate wind event (Figure 27b). In the weak wind event (October 28-31), Brunswick section revealed high tritium concentration (31 $TU$) at the inner shelf but did not show the cross-shelf transport of tritium at the middle shelf (map is not shown because only one section is available). This can be explained by the northward current at the middle shelf region during weak wind events while inner shelf currents were southward. In another wind relaxation event (November 4-5), St.
Figure 25. Tritium-salinity scatter plot for shelf sections.
Figure 26. Tritium-salinity scatter plot of all SPREX data. The solid squares indicate Ogeechee River data. Dashed line is linear regression line with Ogeechee River data excluded, with a regression coefficient of $r = 0.99$ (from Bush, 1988).
Figure 27. Surface tritium concentrations (in $TU$) for (a) October 23 - 25, (b) October 25 - 28, (c) November 1 - 3 and (d) November 4 - 5.
Figure 28. Average surface tritium concentrations (in $TU$) during experiment.
FLEX Surface Tritium
Cape Canaveral
Oct. 23 - Nov. 5 1987
Augustine section suggested cross-shelf tritium transport at the 20 m isobath (Figure 27d).

The maps all show a clear pattern of higher tritium values southward along the coast. Since the Savannah River is the only significant source of tritium the patterns strongly suggest the southward advection of Savannah River water. The other clear pattern is the band of the higher tritium offshore in the middle shelf waters. This band must be caused by episodic movement of coastal water offshore or advection of tritium northward from the Cape Canaveral area.
3.6 Comparison of model results with observation

This section describes the comparison between currents derived from the wind driven model currents and current meter observation. This is necessary because the model derived currents are used for the transport calculations in the next chapter. The comparisons show that model results agreed well with the observed longshore currents.

Brunswick section

Comparisons between the observed currents and model results at the B2 current meter station are given in Figures 29 and 30. Longshore velocity from the model showed good agreement with observations during the experiment period (Figures 29c and 30c). The correlation coefficient $r^2$ indicated that about 80% of the variance in the longshore velocity was explained by a linear function of the model results. The regression formula between observed ($Y$) and modeled ($X$) longshore velocity was $Y = 0.73X - 0.40$ (Figure 31b). The intercept (0.40) was not significantly different from zero. The slope in this linear regression formula showed that the model overestimates the observed velocity magnitudes by 27%. The cross-shelf velocity regression revealed poor correlation between observed and modeled values (Figure 31a). This discrepancy may be explained by the limitations of linearized shallow water equations and wind generated cross-shelf pressure gradient.

Cape Canaveral section

The Cape Canaveral section had the shortest cross-shelf length and steepest slope among the four hydrographic sections and no doubt was strongly influenced by the Gulf Stream. Current measurements in this section revealed strong southeastward
Figure 29. Comparison of the current observation and model results at B201 current meter station. (a) Wind stress is the averaged value of SNLT and SAUF wind station, (b) cross-shelf and (c) longshore velocity components.
Figure 30. Same as in Figure 29, except for B202.
(a) Wind Stress

(b) B202U

(c) B202V

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Figure 31. Linear regressions between the observed and the model results. (a) cross-shelf velocity: $r^2$ is 0.11 and regression line formula is $Y = -0.51X + 1.70$, (b) longshore velocity: $r^2$ is 0.79 and regression line formula is $Y = 0.73X - 0.40$. 

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(a) Cross-shelf current

![Graph showing cross-shelf current comparison between observation and model result. The equation is $Y = -0.52X + 1.70$ with $r^2 = 0.11$.]

(b) Longshore current

![Graph showing longshore current comparison between observation and model result. The equation is $Y = 0.73X - 0.40$ with $r^2 = 0.79$.]

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currents (Figures 10 and 11). The calculated currents did not agree well with observed currents because, most likely, of the strong influence of the Gulf Stream, which was not accounted for in the model. As discussed in section 3.2, current fluctuations at this section were caused by Gulf Stream forcing and other pressure field forcing rather than local wind forcing. The observed current velocity components at C102 and C202 current meter stations are marked in Figures 41 and 42 (in later section 4.2.2), respectively.
Chapter 4
Discussion

In this chapter analytical model results and transport processes are discussed and quantified. First simple flushing rates are calculated, and then a wind driven model is used to calculate freshwater transport. Cross-shelf mixing and exchange processes are also discussed by using the advection-diffusion equation for salt transport. Finally, an explanation for the observed transport pathways is offered.

4.1 Flushing time

Averaged river discharge between Savannah and Brunswick was $7 \text{ m}^3\text{s}^{-1}\text{km}^{-1}$ during the experiment (J. Blanton, personal communication). Mean river discharge during the past 34 years was $15 \text{ m}^3\text{s}^{-1}\text{km}^{-1}$ (Atkinson et al., 1983). Thus FLEX was during a period of low river flow.

The initial mixing of river and coastal water produces a zone of low salinity water which moves with the coastal currents, gradually mixes with oceanic water further offshore and is eventually absorbed in it. At any given time, there will be an accumulated volume of freshwater within the zone; its magnitude depending on the efficiency of the removal processes. The extent to which freshwater is retained in a coastal zone is of interest not only in itself but because the freshwater acts as a tracer for other substances, such as nutrients or pollutants, which are brought in with the

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river water. The estimation of retention times derived in this way may also be applied to the dispersion of substances discharged or dumped into the coastal zone in other ways.

The simplest estimate of flushing time is to assume that freshwater is removed at the same rate as it is being added by river discharge. The flushing time is then given by

\[ t = \frac{F}{R} \]  

(4.1.1)

where \( R \) was the rate of influx of freshwater and \( F \) was the total volume of freshwater accumulated in the study area (Ketchum and Keen, 1955). If \( S \) denotes the salinity of a sample taken at any point within the region and \( S_o \) is the salinity of the offshore water available for mixing, the freshwater fraction at that point is given by

\[ f_f = \frac{S_o - S}{S_o} \]  

(4.1.2)

In this study, 36.2 \text{ psu} was used for the value of oceanic mixing salinity. To determine the total volume of freshwater \( F \), the region was divided horizontally into a number of elements of volume \( \delta V \), and the value of \( f_f \) assigned to each element. The total freshwater content was then given by

\[ F = \sum f_f \delta V \]  

(4.1.3)

where the summation was carried out over the total water volume \( V \) out to the 40 m isobath. Flushing time was then calculated using \( F = 5.7 \text{ km}^3 \) and \( R = 7.8 \times 10^2 \text{ m}^3 \text{ s}^{-1} \). The result was \( t = 2.8 \text{ months (85 days)} \). 70\% of the total freshwater volume was within the 20 m isobath, and all of the freshwater was present within 80 km of the coastline.
This method of estimating the flushing time was quite general and did not involve any assumptions about the freshwater removal process, but it did agree with previous calculations. Atkinson et al. (1978) calculated a shelf flushing rate of 2.7 months for the area off South Carolina, Georgia and northeast Florida. In another calculation Lee et al. (1985) found a flushing time of 3 months in the SAB during winter. The agreement, although reassuring, does not explain the process well.
4.2 Model results

In this section density and wind driven current models are used to investigate both the current producing forces and to calculate currents required in transport and diffusion coefficient calculations.

4.2.1 Density driven currents

A density driven model was used to investigate the effects of freshwater runoff and subsequent horizontal density gradients on currents. This current model was applied only to the Savannah section using a spatial interval of 5 km ($\Delta x$) and 1 m ($\Delta z$). Calculated streamlines and longshore currents at the Savannah section are given in Figure 32 and 33. Details of the calculations are equations (A.1) and (A.2) in Appendix A. The density gradient effects (not including freshwater flow) are shown in Figures 32a and 33a. There was a clockwise circulation within the frontal zone (about 35 km off coast at the 20 m isobath). Counterclockwise circulation appeared offshore of the frontal zone creating a convergent flow at the frontal zone. The region of closed streamlines may be regarded as a frictional coastal boundary layer (Csanady, 1982). Longshore velocity profiles showed southward flow within the frontal zone and northward flow offshore. Cross-shelf streamlines and longshore velocity profiles of density driven currents with freshwater inflow rate ($7 \text{ m}^3\text{ km}^{-1}\text{ s}^{-1}$) included are shown in Figures 32b and 33b, respectively. The circulation patterns were similar to the case without freshwater inflow.

The boundary condition for the preceding cross-shelf transport was that the vertical integration of cross-shelf flow equaled river runoff:
Figure 32. Cross-shelf streamfunction (in nondimensional units) contours of density driven currents in Savannah section. (a) not including freshwater influx, (b) including freshwater influx.
Density driven currents w/o freshwater

Density driven currents with freshwater
Figure 33. Longshore velocity (in cm s$^{-1}$) profiles of density driven currents in the Savannah section. (a) not including freshwater influx and (b) including freshwater influx.

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Density driven currents w/o freshwater

Density driven currents with freshwater
\[
\int_{h}^{0} u \, dz = R \tag{4.2.1}
\]

\( R \) is the rate of coastal discharge for the Savannah and Brunswick sections, assuming \( h = 20 \, m \), gives \( u = 0.04 \, cm \, s^{-1} \).

The effect of river runoff to cross-shelf velocity was larger in the nearshore region than in the middle shelf because of depth. River discharge increased southward flow (about \(-0.1 \, cm \, s^{-1}\)) with uniform effect across the shelf. The contribution of freshwater discharge to the magnitude of the currents was small: \( 0.04 \, cm \, s^{-1} \) for the cross-shelf velocity and \(-0.1 \, cm \, s^{-1} \) for longshore velocity. This is similar to Csanady's (1984) finding that in a well mixed continental shelf runoff-induced circulation is relatively small.

### 4.2.2 Wind driven currents

A wind driven model was used for the transport calculation and analysis of driving forces in shelf circulation. Velocity components at each section were calculated using values listed in Table 2. This table shows cross-shelf density gradients, frontal zone distance and wind stress values at each hydrographic section. Wind stresses were rotated for each section and averaged over the preceding 24 hours. As discussed in section 3.3, the value \(-2.0 \times 10^{-7}\) was used for the longshore pressure gradient at all sections, and \(7 \, m^3 km^{-1} s^{-1}\) for freshwater inflow rate only between the Savannah and Brunswick sections. In the calculation, the resolution was \(5 \, km (\Delta x) \) by \(1 \, m (\Delta z)\).

**Savannah section**

Calculations were made for two hydrographic sections (S01 and S02). The cal-
culated cross-shelf streamlines and longshore velocity profiles are shown in Figures 34 and 35. S01 (October 25) section was during a moderate southward wind event ($\tau^y = -0.92 \text{ dyne cm}^{-2}$). The whole upper layer showed onshore flow, and the lower layer of this section showed adjusting offshore flow (Figure 34a). The maximum onshore flow appeared in the middle shelf surface layer. The Ekman depth almost matched the zero cross-shelf velocity contour line. The mean longshore velocity was $-11.4 \text{ cm s}^{-1}$. The variability was mainly affected by the local wind forcing. The maximum longshore velocity ($25 \text{ cm s}^{-1}$) appeared in the surface layer 40 km offshore (Figure 34b).

The S02 (October 31) section was during a weak wind event ($\tau^y = -0.24 \text{ dyne cm}^{-2}$). The frontal zone was 25 km offshore, 10 km closer than during S01. The surface layer offshore of the frontal zone exhibited Ekman drift structure, while inshore of the front flow was offshore. The Ekman depth in the upper layer of the S02 was shallower than that of S01 section because of the weak wind. There was a clockwise circulation within the frontal zone, counterclockwise circulation on the upper layer of middle shelf and again clockwise flow in the lower layer of middle shelf (Figure 35a). Therefore, there were two onshore flows (surface and bottom layers of middle shelf), while offshore flow occurred in the middle layer. Ekman convergence appeared at frontal zone. Freshwater spread offshore into the convergence. The inner shelf density gradient was relatively higher in S02. Longshore velocities were southward and confined between the coast and the frontal zone. Maximum longshore velocities in the inner shelf surface layer were $-10 \text{ cm s}^{-1}$. Coastal freshwater discharge ($7 \text{ m}^3 \text{ km}^{-1} \text{s}^{-1}$) was included at these sections, but the effect of that was very small (less than 0.1 cm s$^{-1}$). Vertical profiles of velocity at the 10, 20 and 30 m isobaths
Figure 34. Cross-shelf streamfunction (in nondimensional units) and longshore velocity (in $cm \, s^{-1}$) profile at the Savannah section S01, on October 25, 1987 (moderate wind event).
Figure 35. Same as in Figure 34, except for S02, on October 31, 1987 (weak wind event).
Figure 36. Vertical profiles of calculated current velocity at 10, 20 and 30 m isobaths at Savannah section.
SO1, Strong Wind Event (Oct. 25, 1987)

SO2, Weak Wind Event (Oct. 31, 1987)
during the two wind events, S01 and S02, are illustrated in Figure 36.

Brunswick section

The calculated velocity profiles for sections B01, B02 and B03 are given in Figures 37, 38 and 39, respectively. B01 section was the moderate wind event, B02 the strong wind event and B03 the weak wind event. The maximum southward longshore velocity ($-25 \text{ cm s}^{-1}$) at B01 was found 10 km offshore (Figure 37b). This is the coastal jet. In the outer shelf region, flow reversal is expected (Figure 37b). During the strong wind event (B02) the maximum southward velocity ($-30 \text{ cm s}^{-1}$) appeared in the whole surface layer and flow reversal may appear farther offshore than B01 section extended (Figure 38b). During the weak wind event (B03) maximum southward flow ($-10 \text{ cm s}^{-1}$) appeared in the surface layer of inner shelf region. Longshore velocity reversed direction about 65 km offshore (Figure 39b). This implies there was no southward transport in the middle shelf during the weak wind regime or wind relaxation periods. Three cross-shelf velocity profiles (Figures 37a, 38a and 39a) during typical wind events exhibited similar flow pattern and velocity magnitudes. The upper layer had onshore Ekman transport and lower layer compensating offshore flow. Near the outer shelf region, cross-shelf velocity magnitude of B02 was a little larger than that of B01. During the weak wind event, cross-shelf velocity profiles had weak upper layer Ekman transport and weak lower layer offshore flow over the whole shelf (Figure 39a). Velocity profiles at the 10, 20 and 30 m isobaths for various wind events are illustrated in Figure 40.
Figure 37. Current velocity (in \( cm\, s^{-1} \)) profiles at Brunswick section B01, on October 24, 1987 (moderate wind event). Marked by X show the positions of current meter and values denote the current measurements.
Figure 38. Same as in Figure 37, except for B02, on October 26, 1987 (strong wind event).
Cross-shore Velocity Profile

FLEX
Brunswick Section
B02 Oct.26, 1987
Strong Wind

Longshore Velocity Profile

FLEX
Brunswick Section
B02 Oct. 26, 1987
Strong Wind

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Figure 39. Same as in Figure 37, except for B03, on October 29, 1987 (weak wind event).
Figure 40. Vertical profiles of calculated current velocity at 10, 20 and 30 m isobaths at Brunswick section.
BO1, Moderate Wind Event (Oct. 24, 1987)

BO2, Strong Wind Event (Oct. 26, 1987)

BO3, Weak Wind Event (Oct. 29, 1987)
St. Augustine section

The St. Augustine section calculations were made with SAUF winds and no freshwater influx. All St. Augustine sections occurred during relatively weak wind events (weaker than B01 moderate wind event, see Table 2). The longshore wind stress during A01 was $-0.71 \, \text{dyne cm}^{-2}$. The upper layer at the A01 section had onshore flow over the shelf region, while lower layer had adjusting offshore flow (Figure 41a). Longshore velocity profile of A01 had strong southward flow over the inner shelf and reverse of flow at 75 km offshore (Figure 41b). The maximum longshore velocity in the inner shelf surface layer was 15 cm s$^{-1}$. During a very weak wind event (A02, $\tau^y = -0.23 \, \text{dyne cm}^{-2}$) there was weak offshore flow over the shelf, but onshore flow appeared at the near bottom and surface layers of middle shelf. Weak convergent flow occurred at the inner shelf frontal zone (Figure 42a). Longshore velocity during A02 exhibited southward flow only in the inner shelf upper layer, while flow was northward in the rest of region (Figure 42b). During a very weak wind event, there was northward transport over the shelf region except in the nearshore. The calculated velocity profiles (Figures 41 and 42) showed weak southward velocities compared to the Savannah and Brunswick sections. This is attributed mainly to decreased wind stress.

Cape Canaveral section

As with the St. Augustine section, SAUF winds and no freshwater influx were used in this calculation. During the moderate wind event (C01, $\tau^x = -0.83$ and $\tau^y = -0.81 \, \text{dyne cm}^{-2}$), the cross-shelf velocity profile had strong onshore Ekman drift in
Figure 41. Cross-shelf streamfunction (in nondimensional units) contour and longshore velocity (in cm s\(^{-1}\)) profile at St. Augustine section A01, on October 24, 1987.
Figure 42. Same as in Figure 41, except for A02, on October 28, 1987.
the surface layer and offshore flow in the lower layer (Figure 43a). Cross-shelf current observations at C102 and C202 stations exhibited strong offshore flow (Figure 11). The calculated longshore velocities were southward flow in the inner shelf and northward flow over the middle shelf (Figure 43b). During the weak wind event (C02, $\tau^x = 0.03$ and $\tau^y = -0.23$ dyne cm$^{-2}$), the calculated cross-shelf velocities revealed weak onshore flow in the surface layer and offshore flow in the middle layer and again onshore flow in the bottom layer of the middle shelf. Inner shelf currents were weakly offshore in the upper layer and weakly onshore in the lower layer (Figure 44a). Longshore velocity during the weak wind event was southward only in the nearshore region and northward over the middle shelf (Figure 44b).

Longshore velocity profiles at all sections showed the maximum velocities at about 10 - 30 km offshore. The coastal jet was reduced during weak winds. Most of the cross-shelf velocity profiles showed that the upper layer had onshore flow and the lower layer had offshore flow. But during the weak wind events, flow was more complicated with onshore flow in the surface and near bottom layers and offshore flow in the middle layer.
Figure 43. Current velocity (in $cm \, s^{-1}$) profiles at Cape Canaveral section C01, on October 23, 1987 (moderate wind event).
Figure 44. Same as in Figure 43, except for CO2, on October 28, 1987 (weak wind event).
4.3 Quantitative analysis of driving forces in circulation

Quantitative analysis of the forces driving currents were performed for the three wind strength events. The purpose of this analysis was to illustrate the importance of various factors in driving the coastal circulation. For the calculation, each driving force was separately determined assuming other forces were zero.

Moderate wind event (B01, October 24)

The analysis of factors affecting shelf circulation at the Brunswick section B01, during the moderate wind event \( \tau^x = -0.73, \tau^y = -1.22 \text{ dyne cm}^{-2} \), is shown in Table 5. Wind stress was the primary driving force for both longshore and cross-shelf velocity components, and longshore wind stress was most important. This is not unexpected since the cross-shelf component of wind stress is typically found to be relatively ineffective for driving longshore currents (Mitchum and Clarke, 1986; Brink et al., 1987). However, the cross-shelf wind stress was the major driving force for cross-shelf velocity (56%). The longshore pressure gradient was the most resisting force for southward longshore flow. Freshwater inflow, \( q \), had a very small influence (0.2%) on longshore velocity, but it is one of the major driving forces (25%) for cross-shelf velocity. Cross-shelf density gradient contributed least to both of the velocity components. Longshore wind stress and freshwater inflow were the two important driving forces for southward flow, and cross-shelf wind stress was the only driving force for onshore flow. Of course, the depth-averaged magnitude of cross-shelf velocity was quite small compare to longshore velocity.
Table 5. Quantitative analysis for factors affecting the shelf circulation (B01, moderate wind event).

<table>
<thead>
<tr>
<th>Factor</th>
<th>$u$ $cm\ s^{-1}$</th>
<th>%</th>
<th>$v$ $cm\ s^{-1}$</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^x$</td>
<td>-0.076</td>
<td>55.6</td>
<td>$\tau^y$</td>
<td>-25.43</td>
</tr>
<tr>
<td>$q$</td>
<td>0.033</td>
<td>24.6</td>
<td>$\partial \zeta / \partial y$</td>
<td>7.19</td>
</tr>
<tr>
<td>$\tau^y$</td>
<td>0.019</td>
<td>14.1</td>
<td>$\tau^x$</td>
<td>2.20</td>
</tr>
<tr>
<td>$\partial \zeta / \partial y$</td>
<td>0.007</td>
<td>5.4</td>
<td>$q$</td>
<td>-0.08</td>
</tr>
<tr>
<td>$\partial \rho / \partial x$</td>
<td>0.0</td>
<td>0.3</td>
<td>$\partial \rho / \partial x$</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Notes:
- Wind stress $\tau^x = -0.73$, $\tau^y = -1.22$ dyne cm$^{-2}$,
- Longshore pressure gradient $\partial \zeta / \partial y = -2.0 \times 10^{-7}$,
- Freshwater inflow rate $q = 7 \ m^3 km^{-1} s^{-1}$,
- Cross-shelf density gradient
  \[ \partial \rho / \partial x = 6.7 \times 10^{-10} \ (\text{onshore}), \ -1.7 \times 10^{-11} \ (\text{offshore}) , \]
- Bottom friction coefficient $r = 0.16 \ cm\ s^{-1}$.
Strong wind event (B02, October 26)

The quantitative analysis of affecting factors at B02 section during the strong wind event ($\tau^x = -1.01$, $\tau^y = -1.80$ dyne cm$^{-2}$) is given in Table 6. This table shows a similar pattern of moderate wind event; except that longshore wind stress contributed more to the cross-shelf velocity (from 14% to 26%). The roles of the wind stresses increased with increasing wind stress, and the other driving forces decreased in influence as would be expected. For example, the effect of longshore pressure gradient on cross-shelf velocity was 15% versus 1% for weak winds.

Weak wind event (B03, October 29)

The analysis of factors affecting shelf circulation at Brunswick section B03 during weak winds ($\tau^x = -0.12$, $\tau^y = -0.43$ dyne cm$^{-2}$) is given in Table 7. Though wind effects were reduced on this event, they were still the primary driving forces for the shelf circulation (58% for cross-shelf and 67% for longshore velocity). The longshore pressure gradient became an important driving force for both northward (33%) and offshore flow (15%). The freshwater inflow was the major driving force to the onshore flow (27%) although the absolute magnitude of effect (0.03 cm s$^{-1}$) was quite small. The freshwater inflow had a very small influence (0.4%) on the southward flow. Cross-shelf density gradient again showed the smallest contribution to both of the velocity components as two previous wind events.

A summary of this analysis of driving forces is shown in Figure 45. Wind stress was the primary forcing term, and the longshore pressure gradient was the secondary forcing term for longshore current. For cross-shelf current, wind stress components
Table 6. Quantitative analysis for factors affecting the shelf circulation (B02, strong wind event).

<table>
<thead>
<tr>
<th>Factor</th>
<th>$cm \ s^{-1}$</th>
<th>%</th>
<th>Factor</th>
<th>$cm \ s^{-1}$</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_x$</td>
<td>-0.079</td>
<td>50.8</td>
<td>$\tau_y$</td>
<td>-30.72</td>
<td>78.4</td>
</tr>
<tr>
<td>$\tau_y$</td>
<td>0.041</td>
<td>26.3</td>
<td>$\partial \zeta / \partial y$</td>
<td>6.12</td>
<td>15.6</td>
</tr>
<tr>
<td>$q$</td>
<td>0.034</td>
<td>21.5</td>
<td>$\tau_x$</td>
<td>2.29</td>
<td>5.8</td>
</tr>
<tr>
<td>$\partial \zeta / \partial y$</td>
<td>0.002</td>
<td>1.4</td>
<td>$q$</td>
<td>-0.03</td>
<td>0.1</td>
</tr>
<tr>
<td>$\partial \rho / \partial x$</td>
<td>0.00</td>
<td>0.0</td>
<td>$\partial \rho / \partial x$</td>
<td>0.03</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Notes:
- Wind stress $\tau_x = -1.01, \tau_y = -1.80 \ dyne \ cm^{-2},$
- Longshore pressure gradient $\partial \zeta / \partial y = -2.0 \times 10^{-7},$
- Freshwater inflow rate $q = 7 \ m^3 km^{-1} s^{-1},$
- Cross-shelf density gradient
  
  *no data* (onshore), $2.0 \times 10^{-11}$ (offshore),
- Bottom friction coefficient $r = 0.16 \ cm \ s^{-1}.$
Table 7. Quantitative analysis for factors affecting the shelf circulation (B03, weak wind event).

<table>
<thead>
<tr>
<th>Factor</th>
<th>$cm; s^{-1}$</th>
<th>%</th>
<th>Factor</th>
<th>$cm; s^{-1}$</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^x$</td>
<td>-0.038</td>
<td>31.3</td>
<td>$\tau^y$</td>
<td>-25.13</td>
<td>65.4</td>
</tr>
<tr>
<td>$q$</td>
<td>0.033</td>
<td>26.7</td>
<td>$\partial \zeta / \partial y$</td>
<td>12.53</td>
<td>32.6</td>
</tr>
<tr>
<td>$\tau^y$</td>
<td>-0.033</td>
<td>26.6</td>
<td>$\tau^x$</td>
<td>0.50</td>
<td>1.3</td>
</tr>
<tr>
<td>$\partial \zeta / \partial y$</td>
<td>0.020</td>
<td>15.3</td>
<td>$q$</td>
<td>-0.14</td>
<td>0.4</td>
</tr>
<tr>
<td>$\partial \rho / \partial x$</td>
<td>0.00</td>
<td>0.1</td>
<td>$\partial \rho / \partial x$</td>
<td>0.11</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Notes:

- Wind stress $\tau^x = -0.12$, $\tau^y = -0.43$ dyne cm$^{-2}$,
- Longshore pressure gradient $\partial \zeta / \partial y = -2.0 \times 10^{-7}$,
- Freshwater inflow rate $q = 7\; m^3\; km^{-1}\; s^{-1}$,
- Cross-shelf density gradient
  \[
  \partial \rho / \partial x = 8.0 \times 10^{-10} \; (onshore), \; -1.7 \times 10^{-11} \; (offshore),
  \]
- Bottom friction coefficient $r = 0.16\; cm\; s^{-1}$.
Figure 45. Driving forces for (a) cross-shelf and (b) longshore velocity components.
(a) Cross-shelf velocity

(b) Longshore velocity
also played important roles. Horizontal density gradients had the least effect on longshore and cross-shelf circulation.
4.4 Freshwater transport

Understanding the route of removal of freshwater from this study area is vital to our understanding of circulation in the SAB. Knowing the route of removal will also increase our ability to predict the distribution and fate of river-borne pollutants in the coastal ocean.

Longshore and subsequent cross-shelf freshwater transport was determined using a box model assuming mass conservation. Longshore freshwater volume transport was calculated using the equation:

\[ V_{lf} = \int (A \times f_f \times \bar{v}) \, dx \]  \hspace{1cm} (4.4.1)

where \( A \) is area, \( f_f \) freshwater fraction, and \( \bar{v} \) is average longshore velocity of the corresponding water column (\( \Delta z = 5 \, m \)). The oceanic mixing salinity value of 36.2 psu (see section 3.4) was used to calculate the freshwater fraction, and average longshore velocity came from the results of wind driven current model. In this calculation the diffusive term was neglected because the longshore gradient of freshwater fraction was negligible. Cross-shelf freshwater transport \( (V_{cf}) \) in each box was calculated using the difference of input and output longshore transports and the coastal discharge.

\[ V_{cf} = (V_{lf})_{input} - (V_{lf})_{output} + \text{Coastal Discharge} - \text{Storage} \]  \hspace{1cm} (4.4.2)

Coastal discharge was zero except for the shoreline between the Savannah and Brunswick. Freshwater storage amount can be determined from the freshwater content change with time. The freshwater influx into the Savannah - Brunswick inshore box consists of that flowing in from the north through the section and the combined gaged
rivers between Savannah and Brunswick, including the Savannah River. Because the Savannah section starts about 10 km offshore, it is assumed that the Savannah River does not contribute freshwater to the flow through the section. This assumption is confirmed in a paper by Blanton and Atkinson (1983).

The storage of freshwater can be tested by determining the change of freshwater or salinity contents in any section with time. The results of such an analysis are shown in Tables 8 and 9. Note that in all cases the time change in the average salinity between one occupation of a section and the next is less than $-0.4\%$ (Table 8). Subsequent examination of the changes in freshwater content were less than 3\% per day in Brunswick and less than 1.5\% per day in St. Augustine (Table 9). The amount of stored freshwater was determined using the increase rate of freshwater content at each section during various winds.

The calculated longshore freshwater transport on October 24, moderate wind event, is given in Table 10 and schematically in Figure 46. The total longshore freshwater transport at Brunswick was $-3.82 \times 10^3 \text{ m}^3\text{s}^{-1}$ compared to $-3.68 \times 10^3 \text{ m}^3\text{s}^{-1}$ at Savannah, an increase of 4\% due to the freshwater inflow from the coast. The longshore freshwater transport at St. Augustine decreased to $-1.69 \times 10^3 \text{ m}^3\text{s}^{-1}$, 56\% less than Brunswick and 54\% less than Savannah. At the Cape Canaveral section, freshwater transport was reduced to $-0.5 \times 10^3 \text{ m}^3\text{s}^{-1}$, 88\% less than Savannah or Brunswick. Note that freshwater transport over the middle shelf of each section from Savannah to Cape Canaveral was $-0.5$, $-1.0$, $-0.4$, $0.0 \times 10^3 \text{ m}^3\text{s}^{-1}$, respectively. A key finding is that the Brunswick middle shelf had twice the transport of the Savannah middle shelf transport. Apparently, freshwater was transported offshore between Savannah and Brunswick. Also, more than half of the freshwater transport flowing
Table 8. Salinity contents (unit: $10^2 psu m^2$) in sections.

<table>
<thead>
<tr>
<th>Section</th>
<th>Salinity contents of water column</th>
<th>Total salinity content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-10</td>
<td>10-20</td>
</tr>
<tr>
<td>B01</td>
<td>38.2</td>
<td>139.2</td>
</tr>
<tr>
<td>B02</td>
<td>38.5</td>
<td>138.9</td>
</tr>
<tr>
<td>B03</td>
<td>37.7</td>
<td>139.4</td>
</tr>
<tr>
<td>B04</td>
<td>37.9</td>
<td>138.5</td>
</tr>
<tr>
<td>B05</td>
<td>37.4</td>
<td>137.9</td>
</tr>
<tr>
<td>A01</td>
<td>13.5</td>
<td>160.7</td>
</tr>
<tr>
<td>A02</td>
<td>13.36</td>
<td>160.8</td>
</tr>
<tr>
<td>A03</td>
<td>13.6</td>
<td>160.5</td>
</tr>
</tbody>
</table>

Notes:

- Salinity contents were calculated area of the water column multiply by vertical averaged salinity of each water column.
Table 9. Freshwater contents (unit: $10^2 m^2$) in sections.

<table>
<thead>
<tr>
<th>Section</th>
<th>Freshwater contents of water column</th>
<th>Total freshwater content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-10</td>
<td>10-20</td>
</tr>
<tr>
<td>B01</td>
<td>84.4</td>
<td>105.3</td>
</tr>
<tr>
<td>B02</td>
<td>77.7</td>
<td>112.2</td>
</tr>
<tr>
<td>B03</td>
<td>98.8</td>
<td>99.8</td>
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<tr>
<td>B04</td>
<td>94.2</td>
<td>123.9</td>
</tr>
<tr>
<td>B05</td>
<td>107.6</td>
<td>139.8</td>
</tr>
<tr>
<td>A01</td>
<td>26.5</td>
<td>42.0</td>
</tr>
<tr>
<td>A02</td>
<td>30.9</td>
<td>38.6</td>
</tr>
<tr>
<td>A03</td>
<td>24.3</td>
<td>45.6</td>
</tr>
</tbody>
</table>

Notes:

- Freshwater contents were calculated area of the water column multiply by vertical averaged freshwater fraction of each water column.
Table 10. Longshore freshwater volume transport on October 24.

<table>
<thead>
<tr>
<th>Section</th>
<th>Depth (m)</th>
<th>Area (m²)</th>
<th>( f_f ) (%)</th>
<th>( \bar{v} ) (cm s(^{-1}))</th>
<th>Freshwater (m³ s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savannah</td>
<td>0-10</td>
<td>0.55 \times 10^5</td>
<td>(8.6)</td>
<td>(-12.0)</td>
<td>-0.57 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>1.75 \times 10^5</td>
<td>5.0</td>
<td>-18.3</td>
<td>-1.60 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>2.36 \times 10^5</td>
<td>2.4</td>
<td>-18.1</td>
<td>-1.03 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>20-25</td>
<td>3.04 \times 10^5</td>
<td>0.6</td>
<td>-18.9</td>
<td>-0.34 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>25-30</td>
<td>3.71 \times 10^5</td>
<td>0.2</td>
<td>-18.8</td>
<td>-0.14 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>30-35</td>
<td>4.39 \times 10^5</td>
<td>0.0</td>
<td>-17.4</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>1.58 \times 10^6</td>
<td></td>
<td></td>
<td>-3.68 \times 10^3</td>
</tr>
<tr>
<td>Brunswick</td>
<td>0-5</td>
<td>0.13 \times 10^5</td>
<td>(8.5)</td>
<td>(-10.0)</td>
<td>-0.11 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>5-10</td>
<td>1.01 \times 10^5</td>
<td>7.2</td>
<td>-16.6</td>
<td>-1.21 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>1.50 \times 10^5</td>
<td>4.0</td>
<td>-14.9</td>
<td>-0.89 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>2.45 \times 10^5</td>
<td>1.7</td>
<td>-14.3</td>
<td>-0.58 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>20-25</td>
<td>3.15 \times 10^5</td>
<td>1.3</td>
<td>-14.4</td>
<td>-0.57 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>25-30</td>
<td>3.85 \times 10^5</td>
<td>0.7</td>
<td>-14.0</td>
<td>-0.38 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>30-35</td>
<td>4.55 \times 10^5</td>
<td>0.2</td>
<td>-12.3</td>
<td>-0.08 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>1.66 \times 10^6</td>
<td></td>
<td></td>
<td>-3.82 \times 10^3</td>
</tr>
<tr>
<td>Augustine</td>
<td>0-10</td>
<td>0.40 \times 10^5</td>
<td>(5.5)</td>
<td>(-4.0)</td>
<td>-0.09 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>0.63 \times 10^5</td>
<td>5.0</td>
<td>(-6.0)</td>
<td>-0.19 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>3.85 \times 10^5</td>
<td>4.3</td>
<td>-6.1</td>
<td>-1.01 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>20-25</td>
<td>3.38 \times 10^5</td>
<td>2.1</td>
<td>-5.2</td>
<td>-0.37 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>25-30</td>
<td>4.00 \times 10^5</td>
<td>0.2</td>
<td>-3.7</td>
<td>-0.03 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>30-35</td>
<td>4.71 \times 10^5</td>
<td>0.0</td>
<td>-1.1</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>1.70 \times 10^6</td>
<td></td>
<td></td>
<td>-1.69 \times 10^3</td>
</tr>
<tr>
<td>Canaveral</td>
<td>0-10</td>
<td>0.50 \times 10^5</td>
<td>(3.7)</td>
<td>(-5.0)</td>
<td>-0.09 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>1.63 \times 10^5</td>
<td>2.7</td>
<td>-7.5</td>
<td>-0.33 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>0.53 \times 10^5</td>
<td>1.1</td>
<td>-6.4</td>
<td>-0.04 \times 10^3</td>
</tr>
<tr>
<td></td>
<td>20-25</td>
<td>0.68 \times 10^5</td>
<td>0.0</td>
<td>-5.1</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>25-30</td>
<td>0.91 \times 10^5</td>
<td>0.0</td>
<td>-4.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>30-35</td>
<td>1.04 \times 10^5</td>
<td>0.0</td>
<td>-1.5</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>0.53 \times 10^6</td>
<td></td>
<td></td>
<td>-0.46 \times 10^3</td>
</tr>
</tbody>
</table>

Notes: \( f_f \) is freshwater fraction (in %), and the values in parentheses show estimation.
Figure 46. Schematic freshwater volume transport on October 24, 1987 (moderate wind event). Transport expressed as % total freshwater input. Values in parentheses represent the stored freshwater in each box. 100% is equal to 4840 $m^3 s^{-1}$.
through the Brunswick section disappeared at St. Augustine section. This implies that a major portion of freshwater (41%) moved offshore across the 40 m isobath between Brunswick and St. Augustine (Figure 46). And about 30% of freshwater was stored in the shelf region. By Cape Canaveral section, only 10% of the original freshwater was present. Thus, another 20% of the initial freshwater is lost between St. Augustine and Cape Canaveral.

Longshore freshwater transport, during the October 26 strong wind event, is given in Table 11 and a schematic diagram (Figure 47). The longshore freshwater transport at Brunswick was $-5.77 \times 10^3 \text{ m}^3\text{s}^{-1}$ compared to $-4.98 \times 10^3 \text{ m}^3\text{s}^{-1}$ at Savannah, an increase of 16% more than Savannah because of stronger southward current. St. Augustine section showed freshwater transport was $-1.71 \times 10^3 \text{ m}^3\text{s}^{-1}$, 70% less than Brunswick and 66% less than Savannah. The freshwater transport at Cape Canaveral was reduced to $-0.93 \times 10^3 \text{ m}^3\text{s}^{-1}$, 81% less than Savannah. This transport pattern was similar to that of the moderate wind event. Freshwater volume transport at Cape Canaveral, during the strong wind event, was almost twice that of the moderate wind event (about 14% of freshwater input). About 53% of the freshwater input moved offshore between Brunswick and St. Augustine, and 8% was stored there (Figure 47).

The calculated freshwater transport on October 29, weak wind event, is presented in Table 12. Figure 48 shows the freshwater transport for this wind event. The freshwater transport at Savannah was $-1.64 \times 10^3 \text{ m}^3\text{s}^{-1}$. At Brunswick section, freshwater transport reduced to $-1.43 \times 10^3 \text{ m}^3\text{s}^{-1}$, 13% reduction from Savannah. St. Augustine freshwater transport decreased to $-0.21 \times 10^3 \text{ m}^3\text{s}^{-1}$, 87% less than Savannah. Cape Canaveral showed the same amount of freshwater transport ($-0.22 \times 10^3 \text{ m}^3\text{s}^{-1}$, 87% less than Savannah) as St. Augustine. During this weak wind event,
Table 11. Longshore freshwater volume transport on October 26.

<table>
<thead>
<tr>
<th>Section</th>
<th>Depth (m)</th>
<th>Area ($m^2$)</th>
<th>$f_f$ (%)</th>
<th>$\bar{v}$ (cm s$^{-1}$)</th>
<th>Freshwater ($m^3 s^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savannah</td>
<td>0-10</td>
<td>$0.55 \times 10^5$</td>
<td>(8.6)</td>
<td>(-17.0)</td>
<td>$-0.80 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>$1.75 \times 10^5$</td>
<td>5.0</td>
<td>-25.0</td>
<td>$-2.19 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>$2.36 \times 10^5$</td>
<td>2.4</td>
<td>-23.9</td>
<td>$-1.35 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>20-25</td>
<td>$3.04 \times 10^5$</td>
<td>0.6</td>
<td>-24.4</td>
<td>$-0.45 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>25-30</td>
<td>$3.71 \times 10^5$</td>
<td>0.2</td>
<td>-25.5</td>
<td>$-0.19 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>30-35</td>
<td>$4.39 \times 10^5$</td>
<td>0.0</td>
<td>-25.6</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>$1.58 \times 10^6$</td>
<td></td>
<td></td>
<td>$-4.98 \times 10^3$</td>
</tr>
<tr>
<td>Brunswick</td>
<td>0-5</td>
<td>$0.13 \times 10^5$</td>
<td>(8.0)</td>
<td>(-15.0)</td>
<td>$-0.16 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>5-10</td>
<td>$1.01 \times 10^5$</td>
<td>(6.5)</td>
<td>-22.4</td>
<td>$-1.47 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>$1.50 \times 10^5$</td>
<td>(3.0)</td>
<td>-21.1</td>
<td>$-0.95 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>$2.45 \times 10^5$</td>
<td>2.5</td>
<td>-19.9</td>
<td>$-1.22 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>20-25</td>
<td>$3.15 \times 10^5$</td>
<td>1.7</td>
<td>-20.0</td>
<td>$-1.07 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>25-30</td>
<td>$3.85 \times 10^5$</td>
<td>0.8</td>
<td>-20.4</td>
<td>$-0.63 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>30-35</td>
<td>$4.55 \times 10^5$</td>
<td>0.3</td>
<td>-19.9</td>
<td>$-0.27 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>$1.66 \times 10^6$</td>
<td></td>
<td></td>
<td>$-5.77 \times 10^3$</td>
</tr>
<tr>
<td>Augustine</td>
<td>0-10</td>
<td>$0.40 \times 10^5$</td>
<td>(8.0)</td>
<td>(-7.0)</td>
<td>$-0.22 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>$0.63 \times 10^5$</td>
<td>6.7</td>
<td>(-10.0)</td>
<td>$-0.42 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>$3.85 \times 10^5$</td>
<td>2.6</td>
<td>-10.1</td>
<td>$-1.01 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>20-25</td>
<td>$3.38 \times 10^5$</td>
<td>0.2</td>
<td>-9.5</td>
<td>$-0.06 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>25-30</td>
<td>$4.00 \times 10^5$</td>
<td>0.0</td>
<td>-8.7</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>30-35</td>
<td>$4.71 \times 10^5$</td>
<td>0.0</td>
<td>-7.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>$1.70 \times 10^6$</td>
<td></td>
<td></td>
<td>$-1.71 \times 10^3$</td>
</tr>
<tr>
<td>Canaveral</td>
<td>0-10</td>
<td>$0.50 \times 10^5$</td>
<td>(4.0)</td>
<td>(-8.0)</td>
<td>$-0.16 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>$1.63 \times 10^5$</td>
<td>(3.5)</td>
<td>-12.2</td>
<td>$-0.70 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>$0.53 \times 10^5$</td>
<td>1.3</td>
<td>-10.6</td>
<td>$-0.07 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>20-25</td>
<td>$0.68 \times 10^5$</td>
<td>0.0</td>
<td>-9.3</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>25-30</td>
<td>$0.91 \times 10^5$</td>
<td>0.0</td>
<td>-8.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>30-35</td>
<td>$1.04 \times 10^5$</td>
<td>0.0</td>
<td>-6.3</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>$0.53 \times 10^6$</td>
<td></td>
<td></td>
<td>$-0.93 \times 10^3$</td>
</tr>
</tbody>
</table>
Figure 47. Same as in Figure 46, except on October 26, 1987 (strong wind event). Transport expressed as % total freshwater input. Values in parenthesis represent the stored freshwater in each box. 100% is equal to $6630 \, m^3 \, s^{-1}$. 

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Table 12. Longshore freshwater volume transport on October 29.

<table>
<thead>
<tr>
<th>Section</th>
<th>Depth (m)</th>
<th>Area ($m^2$)</th>
<th>$f_f$ (%)</th>
<th>$\bar{v}$ (cm s$^{-1}$)</th>
<th>Freshwater ($m^3 s^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savannah</td>
<td>0-10</td>
<td>$0.55 \times 10^5$</td>
<td>(11.5)</td>
<td>(-5.0)</td>
<td>$-0.32 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>$1.75 \times 10^5$</td>
<td>7.4</td>
<td>-7.5</td>
<td>$-0.97 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>$2.36 \times 10^5$</td>
<td>2.4</td>
<td>-6.1</td>
<td>$-0.35 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>20-25</td>
<td>$3.04 \times 10^5$</td>
<td>0.0</td>
<td>-3.1</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>25-30</td>
<td>$3.71 \times 10^5$</td>
<td>0.0</td>
<td>0.7</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>30-35</td>
<td>$4.39 \times 10^5$</td>
<td>0.0</td>
<td>4.7</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>$1.58 \times 10^6$</td>
<td></td>
<td></td>
<td>$-1.64 \times 10^3$</td>
</tr>
<tr>
<td>Brunswick</td>
<td>0-5</td>
<td>$0.13 \times 10^5$</td>
<td>(11.0)</td>
<td>(-5.0)</td>
<td>$-0.07 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>5-10</td>
<td>$1.01 \times 10^5$</td>
<td>8.7</td>
<td>-7.1</td>
<td>$-0.62 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>$1.50 \times 10^5$</td>
<td>5.0</td>
<td>-6.6</td>
<td>$-0.50 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>$2.45 \times 10^5$</td>
<td>2.2</td>
<td>-4.9</td>
<td>$-0.26 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>20-25</td>
<td>$3.15 \times 10^5$</td>
<td>1.6</td>
<td>-2.2</td>
<td>$-0.11 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>25-30</td>
<td>$3.85 \times 10^5$</td>
<td>1.3</td>
<td>0.6</td>
<td>$0.03 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>30-35</td>
<td>$4.55 \times 10^5$</td>
<td>0.5</td>
<td>4.4</td>
<td>$0.10 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>$1.66 \times 10^6$</td>
<td></td>
<td></td>
<td>$-1.43 \times 10^3$</td>
</tr>
<tr>
<td>Augustine</td>
<td>0-10</td>
<td>$0.40 \times 10^5$</td>
<td>(8.0)</td>
<td>(-1.0)</td>
<td>$-0.03 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>$0.63 \times 10^5$</td>
<td>6.7</td>
<td>(-1.5)</td>
<td>$-0.06 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>$3.85 \times 10^5$</td>
<td>2.6</td>
<td>-1.4</td>
<td>$-0.14 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>20-25</td>
<td>$3.38 \times 10^5$</td>
<td>0.2</td>
<td>2.6</td>
<td>$0.02 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>25-30</td>
<td>$4.00 \times 10^5$</td>
<td>0.0</td>
<td>6.1</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>30-35</td>
<td>$4.71 \times 10^5$</td>
<td>0.0</td>
<td>10.2</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>$1.70 \times 10^6$</td>
<td></td>
<td></td>
<td>$-0.21 \times 10^3$</td>
</tr>
<tr>
<td>Canaveral</td>
<td>0-10</td>
<td>$0.50 \times 10^5$</td>
<td>(4.0)</td>
<td>(-2.0)</td>
<td>$-0.04 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>$1.63 \times 10^5$</td>
<td>(3.5)</td>
<td>-3.2</td>
<td>$-0.18 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>$0.53 \times 10^5$</td>
<td>1.3</td>
<td>-0.2</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>20-25</td>
<td>$0.68 \times 10^5$</td>
<td>0.0</td>
<td>4.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>25-30</td>
<td>$0.91 \times 10^5$</td>
<td>0.0</td>
<td>10.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>30-35</td>
<td>$1.04 \times 10^5$</td>
<td>0.0</td>
<td>12.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>total</td>
<td>$0.53 \times 10^6$</td>
<td></td>
<td></td>
<td>$-0.22 \times 10^3$</td>
</tr>
</tbody>
</table>
Figure 48. Same as in Figure 46, except on October 29, 1987 (weak wind event).

Transport expressed as % total freshwater input. 100% is equal to 2300 m$^3$s$^{-1}$. 

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southward freshwater transport occurred only in the inner shelf. The middle shelf region between Savannah and St. Augustine showed only offshore transport (Figure 48). About 56% of freshwater input moved offshore along the 20 $m$ and 40 $m$ isobaths of between Brunswick and St. Augustine sections, and freshwater was not stored in there because of the freshwater content decrease. About 9% of freshwater input arrived at Cape Canaveral. This freshwater percentage was similar to percentages during the moderate wind event, but the amount of freshwater transport was half of that found during moderate winds. This is because the currents were reduced.

The freshwater transport pathway as the water moved towards the Cape Canaveral was determined during various winds. Calculations showed that transport across the shelf was significant. Typical results, during the moderate wind event, showed that although freshwater appeared to be moving towards the Cape, a major portion of freshwater input (41%) was moving offshore north of 30°N, over 200 km north of Cape Canaveral. Analysis of several different time periods during the experiment yielded percentages (50-90%) of movement offshore north of 30°N. The higher percentage occurred during weaker winds.

The cross-shelf transports and routes of removal can be explained by considering the characteristics of the SAB. The key parameters are longshore wind stress, shelf width and freshwater fractions. All decrease to the south (Table 13). Wind stress decreases to the south because of the weather patterns. In addition to the wind stress decrease, the orientation of the coast changes causing additional variability in longshore winds because of rotation changes. Table 13 shows the variability in longshore wind stress for a constant southwestward wind stress off Brunswick and St. Augustine. For example, consider the case of a typical moderate wind event
Table 13. Factors that affect the longshore freshwater transport on moderate wind event.

<table>
<thead>
<tr>
<th>Section</th>
<th>$\tau^y$</th>
<th>Area ($m^2$)</th>
<th>$\bar{v}$ (cm s$^{-1}$)</th>
<th>$\partial \tau^y / \partial y$</th>
<th>$M_{fy}$ ($m^3 s^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savannah</td>
<td>-1.42</td>
<td>$1.58 \times 10^6$</td>
<td>-17.53</td>
<td>$2.15 \times 10^{-3}$</td>
<td>$-3.68 \times 10^3$</td>
</tr>
<tr>
<td>Brunswick</td>
<td>-1.22</td>
<td>$1.66 \times 10^6$</td>
<td>-13.34</td>
<td>$4.38 \times 10^{-3}$</td>
<td>$-3.82 \times 10^3$</td>
</tr>
<tr>
<td>Augustine</td>
<td>-0.73</td>
<td>$1.70 \times 10^6$</td>
<td>-2.56</td>
<td>$-1.83 \times 10^{-4}$</td>
<td>$-1.69 \times 10^3$</td>
</tr>
<tr>
<td>Canaveral</td>
<td>-0.76</td>
<td>$0.53 \times 10^6$</td>
<td>1.52</td>
<td></td>
<td>$-0.46 \times 10^3$</td>
</tr>
</tbody>
</table>

Notes:
- $\tau^y$ is rotated longshore wind stress along each section (original longshore wind stress is $-1.0 \ dyne \ cm^{-2}$),
- $\bar{v}$ is the mean longshore current velocity over the section,
- $\partial \tau^y / \partial y$ is the longshore wind stress gradient ($dyne \ cm^{-2} \ km^{-1}$),
- $M_{fy}$ is the longshore freshwater volume transport.
(\(\tau_x = -1.0, \tau_y = -1.0 \text{ dyne cm}^{-2}\)). After rotation of axes to follow the coastline, the longshore wind stress decreases from \(-1.42\) to \(-0.73 \text{ dyne cm}^{-2}\). Thus, decreasing wind stress would cause weaker southward currents and weaker southward freshwater transport. The next factor is decreasing shelf width towards the south. Shelf cross sectional area shows 1.58, 1.66, 1.70 and \(0.53 \times 10^6 \text{ m}^2\) from Savannah, Brunswick, St. Augustine and Cape Canaveral. Therefore, for the same current off St. Augustine, less water is transported to Cape Canaveral. The final factor is the reduced freshwater fraction because of mixing, transport and lack of runoff input. These all contribute to significantly decrease southward freshwater transport.
4.5 Cross-shelf mixing and exchange processes

Quantitative estimates of cross-shelf flux of properties are important for understanding continental shelf dynamics. For example, on the Nova Scotian shelf the estimated cross-shelf flux of nitrogen appears to quantitatively match the biological uptake over the shelf and the observed longshore gradients (Houghton et al., 1978). Studies concerned with pollutant dispersal also require quantitative estimates of cross-shelf flux.

The following advection-diffusion equation commonly has been used to estimate the cross-shelf diffusion processes. Salt flux per unit time across unit area perpendicular to the cross-shelf was given by

\[ F_s = \bar{u} \bar{S} - K_x \frac{\partial \bar{S}}{\partial x} \]  \hspace{1cm} (4.5.1)

where \( \bar{u} \) is the average advective cross-shelf velocity, \( \bar{S} \) depth average salinity over the water column and \( K_x \) diffusion coefficient in the \( x \)-direction that will be determined. \( \frac{\partial \bar{S}}{\partial x} \) is the salinity gradient. The schematic salt transport and exchange processes between the hydrographic sections including the freshwater inflow during the moderate wind event are illustrated in Figure 49. \( F_s \) was determined from the salt conservation relation in each small box. Also, \( \bar{u} \) was determined from the mass conservation equation. \( \bar{S} \) represented the average salinity value of two sections at discrete isobaths. Evaporation minus precipitation is assumed to be zero (Atkinson et al., 1983). The values for all sections are shown in Table 14.
Figure 49. Schematic salt transport (in ton s$^{-1}$) and exchange process between the hydrographic sections on October 24, 1987.
Salt Transport and Exchange Process on Oct. 24

unit: ton/sec
Table 14. Cross-shelf advective and diffusive salt flux (unit: \( g \, s^{-1} \, cm^{-2} \)).

<table>
<thead>
<tr>
<th>Event</th>
<th>( D^* ) (m)</th>
<th>Savannah - Brunswick</th>
<th>Brunswick - Augustine</th>
<th>Augustine - Canaveral</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Advection</td>
<td>Diffusion</td>
<td>Advection</td>
<td>Diffusion</td>
</tr>
<tr>
<td>Oct. 24</td>
<td>10</td>
<td>-3.17</td>
<td>-0.24</td>
<td>4.54</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>-0.10</td>
<td>-0.18</td>
<td>6.79</td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wind</td>
<td>20</td>
<td>1.46</td>
<td>-0.21</td>
<td>7.39</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3.34</td>
<td>-0.15</td>
<td>10.49</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>5.58</td>
<td>-0.15</td>
<td>13.43</td>
</tr>
<tr>
<td>Oct. 26</td>
<td>10</td>
<td>-4.45</td>
<td>-0.25</td>
<td>6.12</td>
</tr>
<tr>
<td>Strong</td>
<td>15</td>
<td>-0.45</td>
<td>-0.20</td>
<td>9.24</td>
</tr>
<tr>
<td>wind</td>
<td>20</td>
<td>1.18</td>
<td>-0.24</td>
<td>9.08</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3.04</td>
<td>-0.17</td>
<td>12.40</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>5.38</td>
<td>-0.11</td>
<td>15.55</td>
</tr>
<tr>
<td>Oct. 29</td>
<td>10</td>
<td>-1.47</td>
<td>-0.04</td>
<td>-</td>
</tr>
<tr>
<td>Weak</td>
<td>15</td>
<td>-0.39</td>
<td>-0.10</td>
<td>-</td>
</tr>
<tr>
<td>wind</td>
<td>20</td>
<td>0.11</td>
<td>-0.04</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.74</td>
<td>-0.02</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0.64</td>
<td>-0.02</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes: \( D^* \) is isobath of the water column.

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Savannah - Brunswick

Both sections volume transport and salt transport were calculated using the same wind stress value. The coefficients of diffusion \( K_x \) for the Savannah - Brunswick volume during moderate wind stress were as follows: \( 2.3 \times 10^6 \) at 10 m isobath, \( 3.5 \times 10^6 \) at 15 m isobath, \( 7.8 \times 10^6 \) at 20 m isobath, \( 1.3 \times 10^7 \) at 25 m isobath and \( 1.1 \times 10^7 \) cm\(^2\) s\(^{-1}\) at 30 m isobath. Inside the 15 m isobath water column there was onshore salt flux to supply the salt deficiency due to the entering freshwater. For example, at the 10 m isobath the advection accounted for 93% of total salt flux while at 15 m isobath it was 37%. This calculation indicated that diffusive salt flux was greatest at 15 m isobath (Table 14, moderate wind event).

Brunswick - St. Augustine

For the Brunswick - St. Augustine, the diffusion coefficients were as follows: \( 3.2 \times 10^5 \) at 10 m isobath, \( 3.6 \times 10^6 \) at 15 m isobath, \( 2.9 \times 10^7 \) at 20 m isobath, \( 4.4 \times 10^7 \) at 25 m isobath and \( 5.6 \times 10^7 \) cm\(^2\) s\(^{-1}\) at 30 m isobath. There was net offshore salt flux in the entire longshore section (Table 14) and the outer shelf of St. Augustine section exhibited northward salt flux (Figure 49). Also, the largest salt transport appeared at outer shelf of these longshore sections. Diffusive flux were less than 5% of advective flux.

St. Augustine - Cape Canaveral

Between St. Augustine - Cape Canaveral sections, the diffusion coefficients were \( 8.9 \times 10^4 \) at 10 m isobath, \( 3.2 \times 10^5 \) at 15 m isobath, \( 3.3 \times 10^6 \) at 20 m isobath, \( 3.6 \times 10^6 \) at 25 m isobath and \( 2.3 \times 10^6 \) cm\(^2\) s\(^{-1}\) at 30 m isobath. At 15 m isobath
water column, there was onshore salt transport. The outer shelf at the Cape Canaveral section showed northward salt transport due to the influence of the Gulf Stream. In most cases, diffusive flux was less than 3% of total salt flux except for the 10 m isobath water column (6%).

The summary of advection and diffusion terms of above calculations is presented in Table 14. The maximum diffusive salt flux (63% of total flux) occurred at the 15 m isobath between the Savannah and Brunswick sections due to the salt deficiency caused by entering freshwater. The other isobaths showed diffusive flux ranged from 1% to 13% of total salt flux during a moderate wind event. Thus, advective salt flux was dominant everywhere except for the 15 m isobath between the Brunswick and St. Augustine sections.

Ketchum and Keen (1955) computed values of cross-shelf mixing coefficients ranging from 0.6 to $5 \times 10^6 \text{ cm}^2 \text{s}^{-1}$, and Stommel and Leetmaa (1972) obtain a value of $2.3 \times 10^6 \text{ cm}^2 \text{s}^{-1}$ in the Middle Atlantic Bight. Both sets of investigators assume that everywhere the flux of freshwater across the shelf is equal to the flux onto the shelf from tributary rivers. Fischer (1980) has estimated the cross-shelf mixing coefficient to be the order of $3 \times 10^5$ at middle shelf in MAB using yearly average freshwater inflow. Coachman (1982) calculated horizontal diffusion coefficients in the range $1 \times 10^5$ to $6 \times 10^6 \text{ cm}^2 \text{s}^{-1}$ for the southeastern Bering Sea continental shelf using perturbation analysis.

In this study, diffusion coefficients ranged from $1.0 \times 10^5$ to $5.0 \times 10^7 \text{ cm}^2 \text{s}^{-1}$. The minimum value appeared for the inner shelf between St. Augustine and Cape Canaveral, and the maximum value was for the outer shelf between Brunswick and St.
Augustine. The values of diffusion coefficients increased offshore. While diffusion coefficients may parameterize the exchange process, the actual process often occurs during wind events. In general, higher diffusion coefficients occurred during stronger wind events due to the increase of the total salt flux. As noted by Atkinson and Blanton (1986), a sequence of northward and southward winds moves coastal water offshore.
Chapter 5

Conclusion

This study investigated the circulation pattern, fluctuation of freshwater transport, mechanism for the cross-shelf-transport and exchange processes on southeastern part of the South Atlantic Bight during the Fall Removal Experiment from late October to early November 1987. Major conclusions from the study are summarized as follows.

In the study area, the onset of the downwelling season was clearly defined by the presence of low salinity water along the coast. So, the typical autumnal distribution of surface salinity at this study area was dominated by the episodic southward wind and other forces resulting in a band of low salinity water extending southward to Cape Canaveral even though river runoff ceases at Jacksonville. Such a pattern is also seen in monthly data averaged over 34 years (Atkinson et al., 1983).

Freshwater, as a tracer, was used for estimating the flushing time. The flushing time in this study area was 2.8 months (85 days). The inner shelf retained about 70% of the total freshwater volume.

Sea level departure indicated a longshore pressure gradient of $-2 \times 10^{-7}$ ($-2.2 \text{ cm deg}^{-1}$). This agrees with other studies (Sturges, 1974; Bishop, 1980; Lee et al., 1989). This negative slope is dominant especially during fall season and is generally attributed to the meteorological phenomena and the larger scale oceanic effect.
A steady-state two dimensional analytical model was used for the circulation pattern in this study area during FLEX period. This model was constructed by taking into accounting forcing by wind stress, both longshore and cross-shelf, freshwater influx and a longshore pressure gradient. The circulation of the study area was characterized by a southward drift at velocities of order 10 cm s\(^{-1}\). Comparison of wind and density driven analytical model results and observations indicated that current variability was primarily frictional response to local wind forcing.

Quantitative analysis of driving forces was performed to show the importance of their effects in driving the coastal circulation. Wind stress was the primary driving force for shelf circulation, i.e. about 70\% for longshore and 45\% for cross-shelf current velocity. Longshore pressure gradient showed an important role in shelf circulation during weak winds. Over the South Atlantic Bight continental shelf, the density driven and runoff-induced residual circulation made generally weak contributions to the mean flow field.

Freshwater transport was highly correlated with the local longshore wind stress. During moderate winds, about 10\% of freshwater input in the Savannah region arrived at Cape Canaveral section which is the southern boundary of study area, and about 60\% of the freshwater left the shelf north of the Cape Canaveral by offshore transport and eventual entrainment into the Gulf Stream. About 30\% of freshwater was stored in the shelf area. During strong and weak winds, 14 and 9\% of freshwater input arrived at Cape Canaveral section, respectively. The observed freshwater pathways were related to the wind stress rotation along each section, subsequent wind driven longshore current velocity and the narrowing shelf area.
The horizontal diffusion coefficient was estimated using the salt flux for cross-shelf direction. On the inner shelf the diffusion coefficient showed $1.0 \times 10^5 \text{cm}^2\text{s}^{-1}$ and in the middle shelf region the diffusion coefficient showed order of $5.0 \times 10^7 \text{cm}^2\text{s}^{-1}$.

In this study the following points may be extended as future work.

- To predict the cross-shelf current field more realistically a three dimensional numerical wind driven model is desirable.

- Time variations of freshwater content are not zero. Therefore further detail investigation about the temporal variation and the effect of 'storage' problem over the shelf is needed.

- More wind observations are required since offshore wind is different from nearshore wind.

- Salt flux calculations using the full advection-diffusion equation are needed to understand the mixing and exchange processes.
Bibliography


Ketchum, B. H., and D. J. Keen, 1955. The accumulation of river water over the continental shelf between Cape Cod and Chesapeake Bay, *Deep-Sea Res.*, 3(suppl.), 346-357.


485-496.


Appendix A. Solution for the density driven current.

A solution for the density driven currents allowing friction in a form suitable for application to a practical case was given by Heaps (1972) as following:

\[ u = \frac{(gH/f)(XQ - YP)(\partial p/\partial x)/\rho - (fR/r)(MP - LQ)}{S} \]  
\[ v = \frac{(gH/f)(XP + YQ + \Lambda + \eta)(\partial p/\partial x)/\rho - (fR/r)(1 - LP - MQ)}{S} \]

In the above expressions for \( u \) and \( v \), the first term represents the effect of density and the second the influence of coastal discharge. The various parameters involved here may be specified by passing sequentially through the following definitions:

\[ Z = -z - \zeta, \quad H = h + \zeta, \quad \eta = Z/H, \]
\[ a_1 = H/D_E, \quad a_2 = a_1(1 - \eta), \quad a_3 = a_1 \eta, \quad b_1 = rH/A_2, \]
\[ C = a_1(\sinh a_1 \cos a_3 - \cosh a_1 \sin a_3) + b_1 \cosh a_1 \cos a_1, \]
\[ E = a_1(\sinh a_1 \cos a_3 + \cosh a_1 \sin a_3) + b_1 \sinh a_1 \sin a_1, \]
\[ L = b_1 \cosh a_3 \cos a_3, \quad M = b_1 \sinh a_3 \sin a_3, \]
\[ P = C/(C^2 + E^2), \quad Q = E/(C^2 + E^2), \]
\[ T = P \cosh a_1 \cos a_1 + Q \sinh a_1 \sin a_1, \quad S = 1 - Tb_1, \]
\[ \Lambda = (T - P - S)/S, \quad \lambda = 1 + b_1 + b_1 \Lambda, \]
\[ X = \cosh a_2 \cos a_2 + (b_1/2a_1)(\sinh a_2 \cos a_2 + \cosh a_2 \sin a_2) - \lambda \cosh a_3 \cos a_3, \]
\[ Y = \sinh a_2 \sin a_2 + (b_1/2a_1)(\cosh a_2 \sin a_2 - \sin a_2 \cos a_2) - \lambda \sinh a_3 \sin a_3. \]
AUTOBIOGRAPHICAL STATEMENT

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