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Flood Tide Circulation Near Beaufort Inlet, North Carolina: Implications for Larval Recruitment

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ABSTRACT: Drifter tracks and shipboard CTD observations have revealed a number of distinct features of the flood tide circulation carrying water through Beaufort Inlet, North Carolina. One of the most noteworthy of these features is a nearshore jet in the flow carrying water to the inlet on a flood tide. Characterized by a shoreward increase in longshore flow, the jet produces a narrow coastal zone over which water is carried into the inlet. The jet appears to be principally a tidal phenomenon, as it is closely reproduced by a tidally-driven barotropic numerical model. The model results also indicate the jet may be a near-inlet feature. Model simulations of spring tide conditions show the jet confined to within 4 km of the inlet mouth. Another observed phenomenon, which is reproduced by the tidal model, is a distinct splitting of the flow entering the inlet, in which water passing through a particular inlet segment tends to move up-estuary along a well-defined path. An observed flow feature not reproduced by the tidal model is an eastward skew of the region over which water is drawn into the inlet on a flood tide. This asymmetry is unrelated to the local wind. Modeling results from a previous study suggest it may be due to convergent flow at the edge of the low salinity plume issuing from the inlet. Taken together, the results of this and other recent studies in the Beaufort Inlet region reveal the importance of nearshore currents on the eastern side of the inlet in delivering oceanic-spawned larvae to the estuarine system connected to the inlet.

Introduction

The flux of water into an estuary can carry with it a number of materials that may significantly affect, or be affected by, the estuarine environment. Considerable attention has been given to the subtidal transport of material to an estuary. Subtidal estuarine inflow often occurs near the bottom, compensating for and mixing with surface buoyant discharge exiting the estuary (e.g., Pritchard 1967). Observations have revealed subtidal inflow to some estuaries may extend over the entire water column and be confined to a lateral band (e.g., Kjerfve and Proehl 1979; Wong 1994; Valle-Levinson and Lwiza 1995; Churchill et al. 1999).

Net influx of material to an estuary can also occur within purely oscillatory tidal flows. This can be the result of settling or mixing of material carried into the estuary on a flood tide (e.g., Fisher 1972; Baker et al. 1983; Lewis and Lewis 1983; Wells and Kim 1989; Geyer and Nepf 1996). For certain marine organisms, up-estuary transport in a tidal environment can be the result of behavior. Several species of larval fish appear to be able to migrate up-estuary through selective tidal stream transport—by rising into the water column during flood tide and descending to the bottom during ebb tide (e.g., Weinstein et al. 1980; Epifanio et al. 1984; Boehlert and Mundy 1988). Critical properties influencing the tidal cycle transport of material into an estuary include the flow of fresh water leaving the estuary, the geographic range over which water is drawn into an estuary on a flood tide, and the estuarine paths followed by this water.

We present results of a study of flood tide circulation of water passing through Beaufort Inlet, North Carolina (Fig. 1), in which these and other properties are examined. This study is part of the

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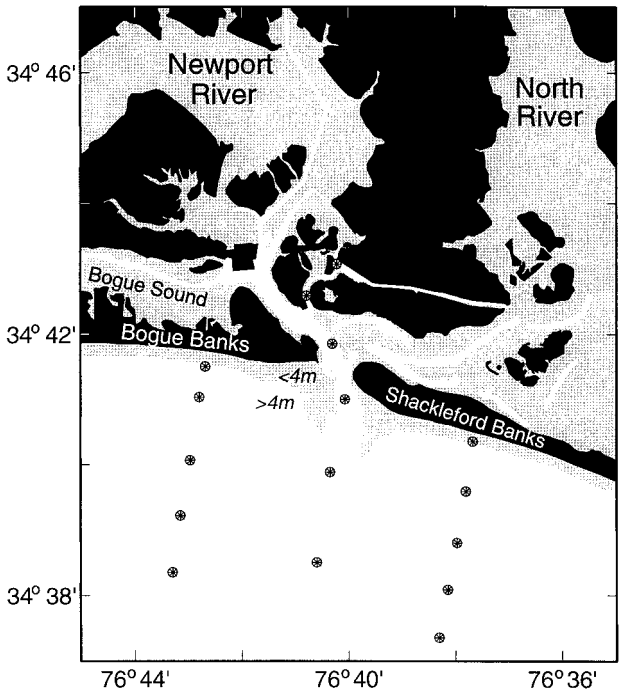

Fig. 1. Beaufort Inlet, North Carolina, and surrounding region. Shaded areas indicate water depth of < 4 m. The wagon wheel symbols mark stations of the CTD-larval collection surveys of December 1993 through March 1994.

South Atlantic Bight Recruitment Experiment (SABRE), which is directed at better understanding processes influencing the recruitment of oceanic-spawned fish to the estuaries of the southeastern U.S. The species targeted by the project appear to be capable of selective tidal stream transport (Forward et al. 1999). Movement into an estuary is a critical stage in their migration from their oceanic origins to estuarine nurseries.

This paper deals with two aspects of the flood tide circulation in the Beaufort Inlet region: flows leading to the inlet from the inner shelf, and the estuarine circulation of water which has entered the inlet. Each is examined using drifter tracks and CTD measurements. We also compare the observations with the results of a tidal circulation model to assess the extent to which the observed flow patterns are due to tidal motions. More extensive modeling of the tidal circulation of the region and its influence on larval ingress are presented by Luettich et al. (1999). Our presentation of the data analysis and modeling is preceded by brief descriptions of our experimental methods and the study region.

Data Collection and Processing

The dataset used in our study consisted of temperature and salinity measurements, drifter tracks, and wind velocities acquired over the period 1993–1996. Aquisition of the temperature and salinity data was from a research vessel using a Seabird SBE-25 CTD. The wind velocities were obtained from the Cape Lookout light station anemometer, located at 34.62°N, 76.52°W, 10 m above sea level.

The drifters used in this study (Brightwaters Instrument Corporation models 104V and 104AV) were equipped with a five-channel GPS receiver, for determining position, and with a VHF transceiver, for communication with a ship-based or shore-based tracking station. Many drifters were also outfitted with an ARGOS transmitter, which provided backup positioning and communication capability in event of GPS or VHF system failure. All drifters were rigged as Davis-style surface followers (Davis 1985) designed to track flows over roughly the uppermost 1 m. These had cross-vanes radiating from the central electronics housing cylinder which supported four submerged rectangular sails.

Typically, drifter positions were determined and relayed to a tracking station at 5-min intervals. These were not subject to differential correction and have an RMS error of roughly 30 m. Computing drifter velocities from a drifter location time series was accomplished through curve fitting. This involved carrying out linear regressions of east and north position components against time within a data window containing a specified number of drifter fixes. The slopes of the regression lines were taken as estimates of the east and north velocity components at the middle of the window. Stepping the regression window through the position component time series yielded a velocity component time series. The velocities shown here were computed with a 55-min (11 point) regression window. These were well determined by the linear regression method. All had 90% confidence intervals (of the regression slope) of $< \pm 1$ cm s^{-1}.

Site Description

Beaufort Inlet is located in the northeastern portion of Onslow Bay, roughly 15 km west of Cape Lookout, North Carolina (Fig. 1). It links Onslow Bay with a complex estuarine system of interconnected sounds and rivers. The principal bathymetric features seaward of the inlet are a deep-draft navigation channel and flanking shoals (Fig. 1). Dredged to a minimum depth of 12 m, the channel is roughly 120 m wide and extends 3.5 km offshore. The abutting shoals each have a triangular form. As outlined by the 4-m depth contour (Fig. 1), each shoal extends about 1 km east-west at its base and reaches roughly 2 km offshore.

The estuarine system shoreward of the inlet may be divided into two reasonably distinct regions:

one to the east and the other to the west of the inlet. Both contain large, relatively shallow estuarine bodies: Newport River and Bogue Sound to the west of the inlet, and Back Sound and North River to the east. Linking the western estuarine region to the inlet is a deep-draft navigation channel serving the Morehead City port facility. Although deep (> 5 m) channels are found in the estuarine bodies to the east of the inlet, none of these run unbroken to the Beaufort Inlet. The western region of the estuary is also distinct in that it appears to receive the far greater share of freshwater discharge. This comes principally through the Newport River, which has a drainage area of 340 km^2 compared with the 255 km^2 drainage area of the North River and Back Sound (Kirby-Smith and Costlow 1989). The Newport also receives fresh water from the Neuse River by way of Core Creek Channel (part of the Intracoastal Waterway).

Long-term (> 1 mo) studies of circulation within the estuarine system connected to Beaufort Inlet have been presented by Klavans (1983), Logan (1995), and Blanton et al. (1999). Using data from an array of tide gauges and current meters, Klavans found that the tide advances through most of the estuary as a damped progressive wave. His analysis showed the tide is dominated everywhere by the semidiurnal, M_2, constituent, but that other constituents, principally N_2, S_2, K_1, O_1, and M_4, tend to increase in relative strength going up-estuary. Evidence of strong tidal asymmetries was reported by both Logan (1995) and Klavans (1983). Their combined analysis showed stronger flood than ebb tide currents (flood dominance) to be common on the right side (looking up-estuary) of the estuarine channels, and the reverse to be the rule on the left side of the channels. Logan also reported the occurrence of strong mean inflow on the eastern side of Beaufort Inlet. This was revealed by 40-d velocity records from current meters deployed near the eastern shore of the inlet (at 7 m mean water depth) which had means, directed up-estuary, of greater than 30 cm s^{-1}.

A complicated response to wind forcing was revealed by the studies of Logan (1995) and Blanton et al. (1999). A notable finding of both investigations was the tendency for salinity to decline in the lower estuary during periods of northerly winds. Logan attributed this to wind-driven southward flow of low salinity water from the upper estuary, including flow through Core Creek which connects to the Neuse River.

Recent short-term studies (each lasting two semidiurnal tidal cycles) of currents and larval transport in the estuary connected to Beaufort Inlet were reported by Churchill et al. (1999) and Forward et al. (1999). Their results confirmed the tidal asymmetries described above. They also found that roughly half of the total flood tide inflow through the inlet moves into the shallow regions east of the inlet.

Flood Tide Transports to Beaufort Inlet

The principal goals of our study offshore of Beaufort Inlet were to document the changing character of the inner shelf property field over the course of the flood tide, and to define, as well as possible, the range over which water is carried by flood tide currents into the inlet. These issues are considered below, beginning with a presentation of hydrographic observations and followed by a description of drifter results.

Relevant Hydrographic Conditions

Over the period December 1993 through March 1994, six hydrographic surveys were carried out to measure water properties and larval concentrations over the inner shelf to the east and west of Beaufort Inlet (see Hettler and Hare 1998 for details of the larval collections and results). The survey stations ran along three lines (Fig. 1). One followed the main navigation channel, starting 6 km offshore and extending into the Radio Island Channel (a 3–5 m deep tributary that branches north from the main navigation channel). The other two lines bracketed the navigation channel and extended 6 km offshore. The surveys were carried out over the course of a flood tide, beginning near the time of low water and ending near high water. During this time, CTD samples were acquired 2–3 times along each line. To give nearly simultaneous measurements over the eastern and western lines, two vessels were employed. One covered the easternmost line and the other traversed the westernmost line.

Data from most surveys showed a plume of low salinity water extending westward from the inlet. This was the expected behavior as a buoyant plume issuing from an estuary in the northern hemisphere tends to be deflected to the right by the action of the Coriolis Force (e.g., Bowman and Iverson 1978; Masse and Murthy 1990; Munchow and Garvine 1993). In five of the six surveys, relatively low salinity water (< 34) appeared over large portions of the west line sections, while much higher salinities (> 34) were measured over most or all of the east line sections. The March 6–7, 1994 survey shows that while < 34 water occupied roughly half of the early, mid, and late flood tide sections taken along the western line, it was observed only over a small nearshore area on all the sections taken along the eastern line (Fig. 2). In this example, and for all other east and west sections, density varied principally through salinity

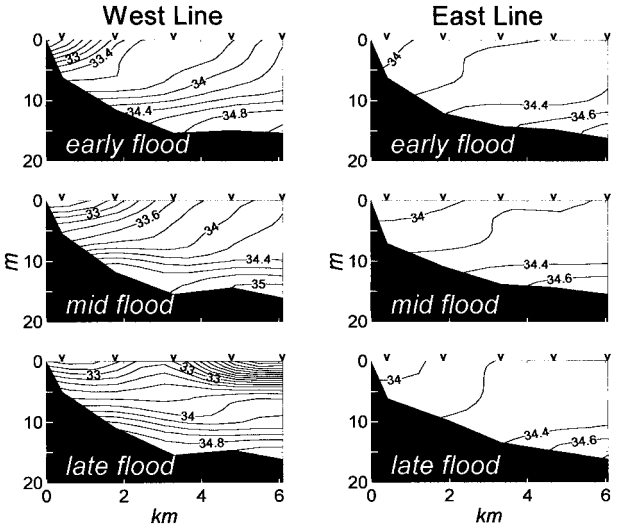

Fig. 2. Salinity measured over the inner shelf east and west of Beaufort Inlet (along the station lines shown in Fig. 1) during the flood tide of March 6–7, 1994.

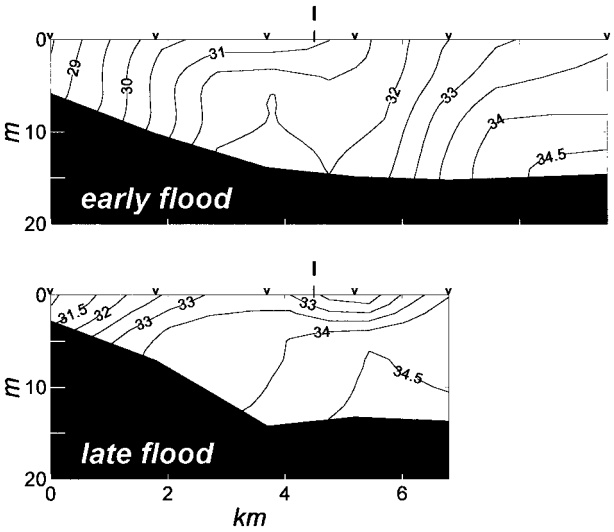

Fig. 3. Salinity measured along the navigation channel through Beaufort Inlet (see Fig. 1 for station locations) during the early and latter stages of the flood tide of February 2–3, 1994. The station marked I is at the inlet.

variations. Temperatures along the east and west line sections typically ranged over less than 2°C.

Wind-induced circulation may have been responsible for the eastward skew of the plume seen during the one survey in which $S < 34$ water was observed at the east and not at the west line section. This was the only survey carried out during a time of eastward winds. The quantity of $S < 34$ water seen at the east line during this survey was small and was confined to the most nearshore station only.

It is noteworthy that the area of low salinity water seen over the western line never appreciably lessened during any survey. The area of $S < 34$ water seen at the western line during the March 6–7, 1994 survey actually increased substantially from the early to the late flood tide (Fig. 2).

CTD measurements along the central line clearly revealed shoreward progression of offshore water up the navigation channel during the flood tide. Isohalines along this line typically moved 2–5 km shoreward over the course of the flood tide (Fig. 3). Data from many surveys showed incursion of intermediate salinity (32–34) water into the estuary during the flood tide, suggesting the incoming tide carried some previously discharged water into the estuary.

Two additional surveys, carried out early during flood tides of April 21, 1994 and April 18, 1995, showed that a low salinity plume is not a persistent feature offshore of Beaufort Inlet. In the first survey, CTD data were acquired along five lines (including the central, eastern, and western lines described above). These gave no indication of $S <$ 34 water. In the second survey, measurements were acquired only over the east and west line. These also showed no $S < 34$ water (Fig. 4). The absence of plume water in these surveys was likely due to low freshwater discharge. Both surveys were conducted after lengthy dry periods. Measurements acquired at the National Weather Service station at Morehead City, North Carolina, showed no more than 1 cm total rainfall over the 20 d prior to each survey.

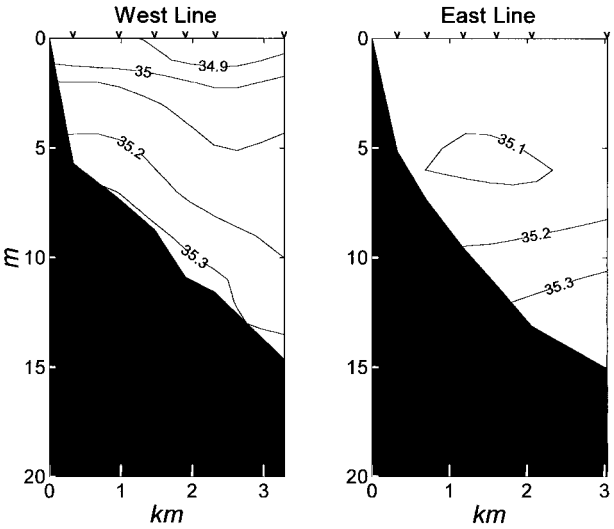

Fig. 4. Salinity measured east and west of Beaufort Inlet along the sampling lines shown in Fig. 1 (but at decreased station spacing and overall length) during April 18, 1995.

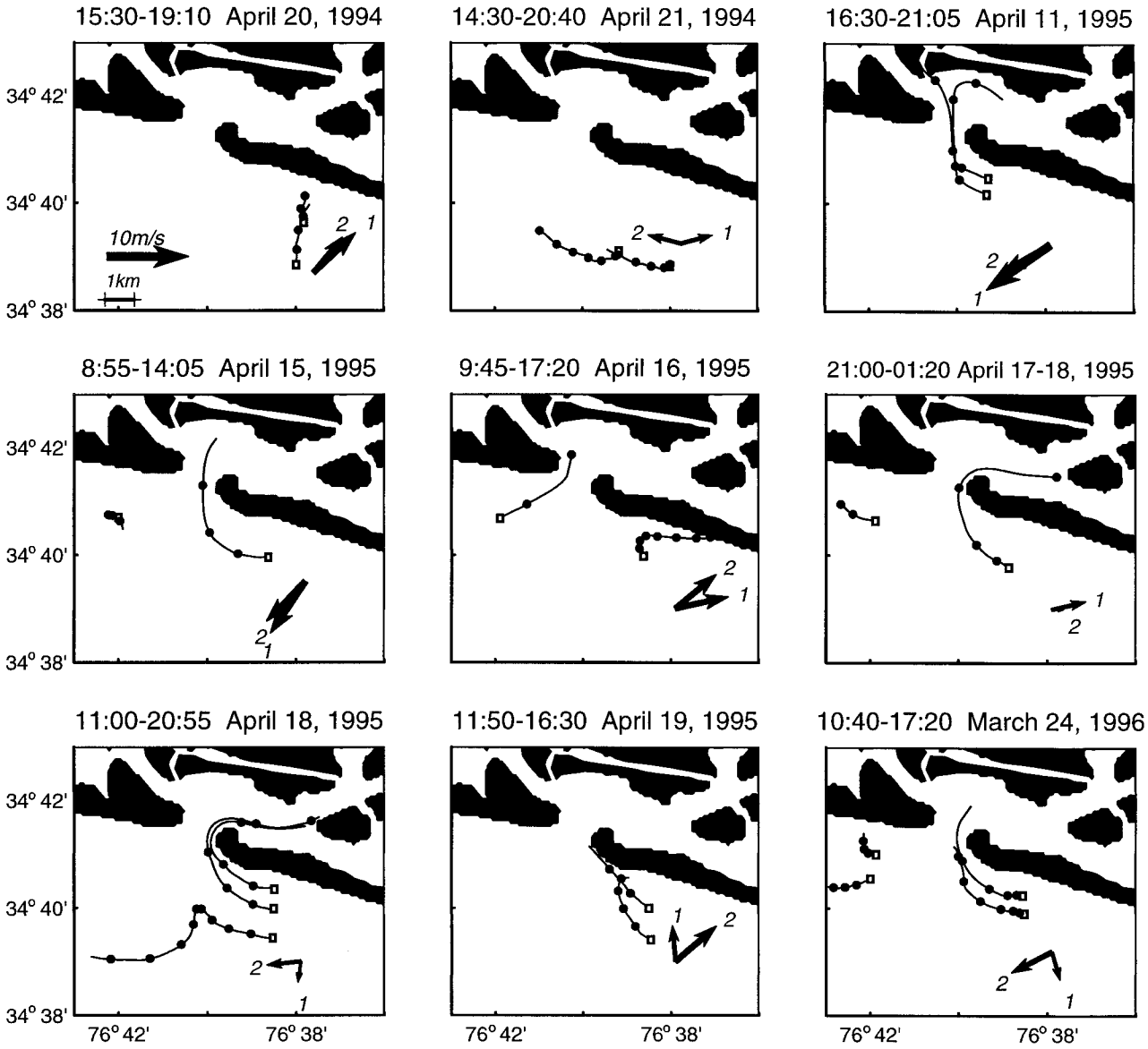

Fig. 5. Tracks of drifters released seaward of Beaufort Inlet during early flood tide. Boxes depict release locations. Dots are placed on track lines at hour intervals after release. Also shown are wind velocities measured at the beginning (labeled 1) and end (labeled 2) of the deployment period at the Cape Lookout Light Station (Fig. 1). Wind and distance scales are shown in the upper leftmost plot.

Drifter Observations

To sample the flood tide transport to Beaufort Inlet, we deployed drifters over the inner shelf outside the inlet on nine occasions. All releases occurred within ± 1.5 h of slack low water as deduced by visual observations of flow at the inlet channel. Figure 5 shows the drifter tracks of each deployment together with the wind velocities, determined from the Cape Lookout wind record, at the initial drifter deployment and at the final drifter recovery.

The overall collection of drifter tracks suggests that flood tide transport approaching the inlet from along the adjacent banks may be confined to a relatively narrow nearshore region. No drifter released more than 2 km from the coast entered the inlet during the flood tide. A nearshore zone of flood tide flow to the inlet is particularly well illustrated by the drifter tracks of April 18 and 19, 1995 (Fig. 5). On April 18, drifters were released along a line 2.7 km east of the navigation channel at 0.6 km, 1.2 km, and 2.2 km from shore. The two most

nearshore drifters entered the inlet within 3 h after deployment, while the other drifter moved steadily westward and bypassed the inlet. On April 19, drifters were deployed 2.7 km east of the channel at 1.2 km and 2.3 km from shore. The more nearshore drifter ran aground as it entered the inlet, due to the influence of a strong northwestward wind. The more seaward drifter was traveling eastward, away from the inlet, when it was recovered to avoid its anticipated grounding.

On four occasions, drifters were deployed to the east and west of the inlet at points roughly 2.7 km from the navigation channel. The tracks of these drifters suggest that the region over which water is carried into the inlet may not be symmetrical about the inlet mouth. During three of the deployments, all drifters released to the east of the navigation channel entered the inlet. Those released west of the channel initially traveled westward (away from the inlet) and were a considerable distance from the inlet by the turn of the tide. This behavior cannot be solely attributed to wind forcing. On two deployments (April 17–18, 1995 and March 24, 1996), all drifters initially moved westward while the wind was light (< 4.5 m s^{-1}) with an eastward component. Wind forcing can be held accountable for the single episode in which a drifter deployed west of the channel entered the inlet (on April 16, 1995). Winds during this deployment were strong and directed eastward. Even so, the track of the drifter released east of the inlet suggests there may be a strong resistance to flood tide flow away from the inlet in this region. Over the first 2 h after its release, this drifter moved slowly, at < 10 cm s^{-1}, to the north even though the average wind velocity was 6.5 m s^{-1} to the east. Based on this limited collection of drifter tracks, we tentatively conclude that, except for times of strong westward winds, the region over which water is transported to the inlet on a flood tide is heavily skewed to the east of the inlet.

The general westward trend of drifters released west of the inlet may have been, in part, due to buoyancy related flow of low salinity water exiting the inlet (more on this in the section on Modeling of Flood Tide Transports). Unfortunately, we are not able to rigorously test this because CTD data were acquired on only one deployment in which drifters were set out west of the inlet. These data show that surface water at the western release locations was slightly less saline and less dense (by 0.3 and 0.25 σ_T) than surface water at the eastern deployment sites (Fig. 6).

A noteworthy feature of the nearshore flow is revealed by the velocities of drifters approaching the inlet from the east. These show that the flood tide flow to the east of the inlet often has the form

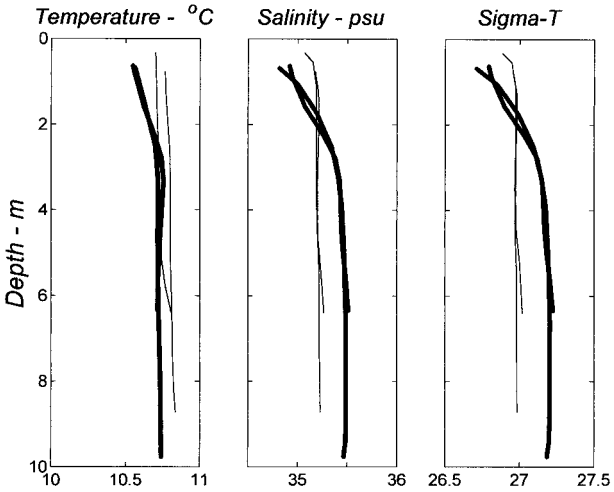

Fig. 6. Profiles of temperature, salinity, and σ_T measured at drifter release locations east (thin curves) and west (bold curves) of the inlet on March 24, 1996.

of a narrow coastal jet with current strength increasing toward shore. Characteristics of the jet are illustrated by plots of the locations and velocities of drifters deployed on April 18 and 19, 1995 and on March 24, 1996 (Fig. 7). Consider, for example, the velocities of the three drifters released on April 18, 1995. At 12:30 GMT (roughly 1 h into the deployment) the drifters were 0.5 km, 1.2 km, and 2.7 km from shore and were moving westward at velocities of 36 cm s^{-1}, 29 cm s^{-1}, and 24 cm s^{-1}, respectively. CTD data acquired during the April 18, 1995 and March 24, 1996 deployments reveal that the coastal jet seen on these dates was not related to any hydrographic feature. On both days, water measured along the deployment line was nearly homogeneous, with salinities and temperatures varying by less than 0.2 and 1.0°C, respectively (Figs. 4 and 6).

The potential impact of the flood tide coastal jet on larval ingress to the estuary is realized by considering the tracks of the two drifters released east of the inlet on March 24, 1996 (Fig. 5). The drifter deployed closer to shore (at 0.75 km) entered the inlet traveling north at 65 cm s^{-1} and was recovered shortly thereafter. The other drifter, released only 0.6 km further seaward, entered the inlet 1.5 h after its companion, just as the tide turned to ebb (as determined from visual observations), and was recovered to avoid possible collision with a dredge. Taken together these tracks suggest that larvae very close to shore at the beginning of flood tide have a greater likelihood of being carried into the estuary than do those larvae that are slightly further offshore.

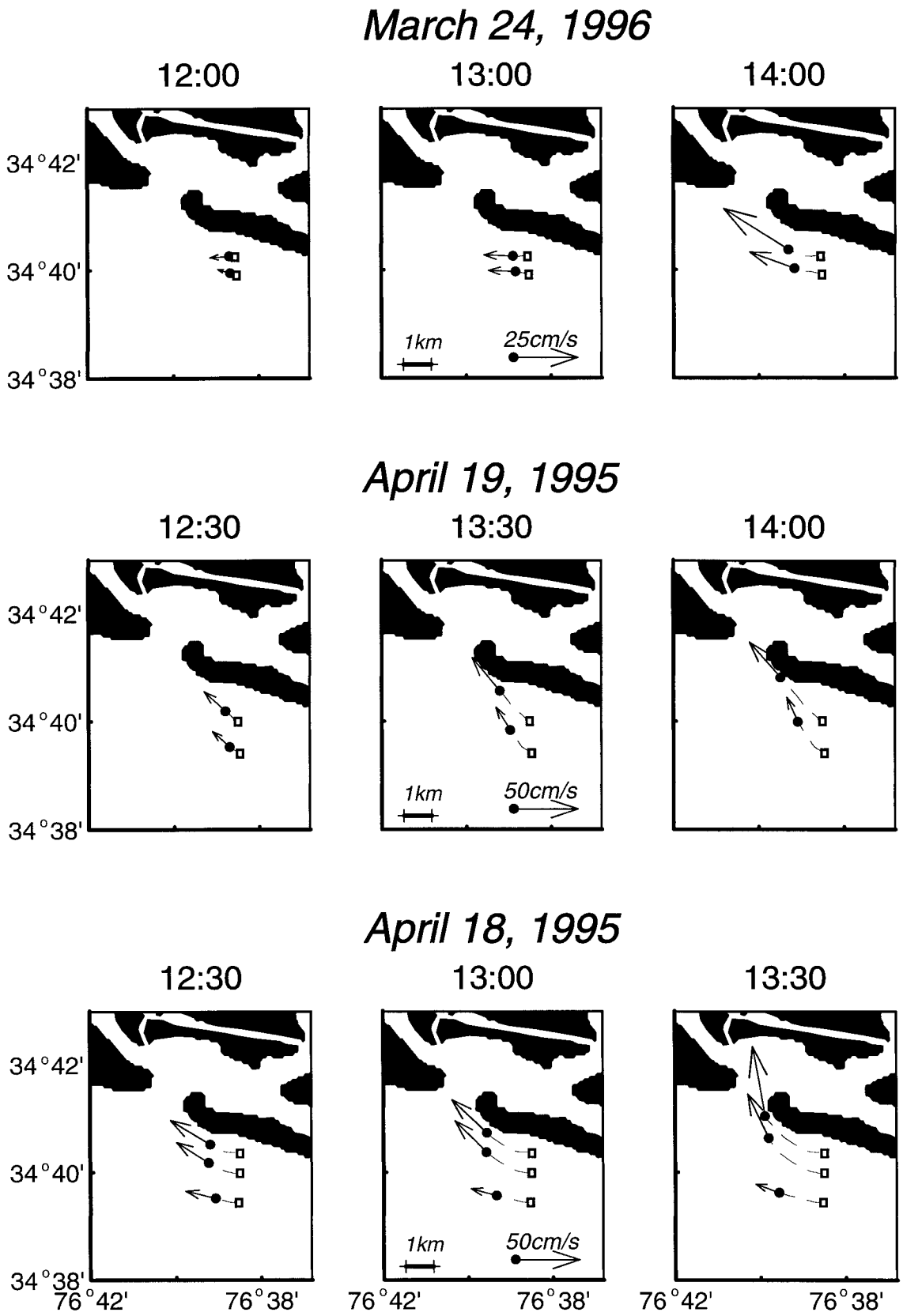

Fig. 7. Positions and velocities of drifters at different times (GMT) on the designated dates. Boxes depict release locations. Note that the velocity scale of the upper series of plots differs from that of the lower two series.

Estuarine Flood Tide Transports

We now examine the paths taken by water passing through Beaufort Inlet during the flood tide. As above, hydrographic observations and drifter tracks are presented.

Hydrographic Observations

The evolving flood tide property field shoreward of Beaufort Inlet was documented by three shipboard surveys during which CTD measurements were acquired 3–5 times at various estuarine sites over the course of an incoming tide. The character of and changes in the salinity fields measured by these surveys were remarkably similar. Here we describe results from the survey of April 19, 1999 in which data were acquired at 12 estuarine sites. Seven sites were located along a line extending northwestward 8 km from the inlet along the main navigation channel and into Newport River. Three other stations were located east of the inlet and the remaining two extend into Radio Island Channel (the channel to the east of Radio Island, at 34°43′N, 76°41′W).

The salinity fields of this survey (and the other surveys) showed that the Newport River is the region's primary source of low salinity water. The early flood tide measurements of this survey showed a continual decline in salinity, from 34.5 to 30, going from the inlet into the lower Newport River. Near-oceanic salinities ($S > 34$) were measured at all times at the stations in the Radio Island Channel and to the east of the inlet. As the tide progressed, the CTD measurements showed high salinity water advancing northwestward through the navigation channel. At the time of the last set of measurements, near the end of the flood tide, oceanic water ($S > 34$) reached to the entrance of the Newport River, ~ 5 km from the inlet. The average rate at which this water advanced along the navigation channel, as determined by the movement of the $S = 34$ contour, was relatively slow: roughly 0.3 m s^{-1}. A similar rate of advance into the Newport River was seen in the other surveys.

Drifter Observations

To sample estuarine flood tide transport, we released drifters at Beaufort Inlet during the first half of an incoming tide on 10 occasions. Release points for nine of the deployments were within the navigation channel (Fig. 8), which encompasses about 30% of the inlet width and is to the east of the inlet center. The other deployment had release points near the edges of the inlet. During most of the inlet channel deployments, the first drifter was released 1–1.5 h after slack low water and a second drifter was released about 1 h later, near the time of maximum flood tide inflow. All deployments occurred during the weaker of the two daily flood tides because these happened to occur during the daylight hours on the dates of our studies.

Drifter velocities revealed a mid-flood tide current of 1–1.2 m s^{-1} through the inlet channel. Strong currents, in the 50–100 cm s^{-1} range, were seen inside the estuary, principally within the main navigation channel and in the smaller channels to the east of the inlet. In spite of frequent problems with grounding of drifters, a number of tracks extended through the turn of the tide. These revealed 4–7 km estuarine excursions over the later half of the flood tide. Only one track (April 19, 1994) spanned the full range of the incoming tide, from slack low to slack high water. This track extended 10 km northeastward to the entrance of the North River (Fig. 8).

An unanticipated result was that of the 17 drifters released at the inlet channel, only one (set out on April 18, 1994) followed the navigation channel westward into Bogue Sound (Fig. 8). Most of the drifters turned eastward, veering from the navigation channel into shallower water, after entering the inlet. Other drifters initially followed the main navigation channel northwestward before turning northward into the much narrower and shallower Radio Island Channel (e.g., the tracks of April 11, 12, and 15, 1994). All of the drifters that entered the estuary from offshore release points also followed one of these paths (Fig. 5).

This tendency for surface water entering the inlet channel to move eastward cannot be attributed solely to wind forcing. The drifter tracks of April 18, 1994 suggest that the exclusion of near-surface channel inflow from Bogue Sound may, under some circumstances, be an early flood tide phenomenon. The first drifter released on this date moved eastward in the face of a 5 m s^{-1} southwestward wind. The second drifter, set out 1 h later under nearly identical wind conditions, advanced northwestward along the navigation channel, where it eventually became entangled in the Morehead City dockage facility.

Further details of the early flood tide flow were revealed by the tracks of the drifters set out over the inlet shallows (at 5.5 m water depth) on either side of the navigation channel (Fig. 9). These were released over a 3-min interval at about 1 h into the flood tide. The drifter released east of the channel moved directly eastward at a speed of nearly 70 cm s^{-1}. By contrast, the drifter released over the shallows west of the channel remained within the inlet for 1.5 h, while executing a counterclockwise loop, and then proceeded northwestward along the navigation channel to the entrance of the Newport River. CTD measurements acquired immediately after the drifters' deployment showed a large salin-

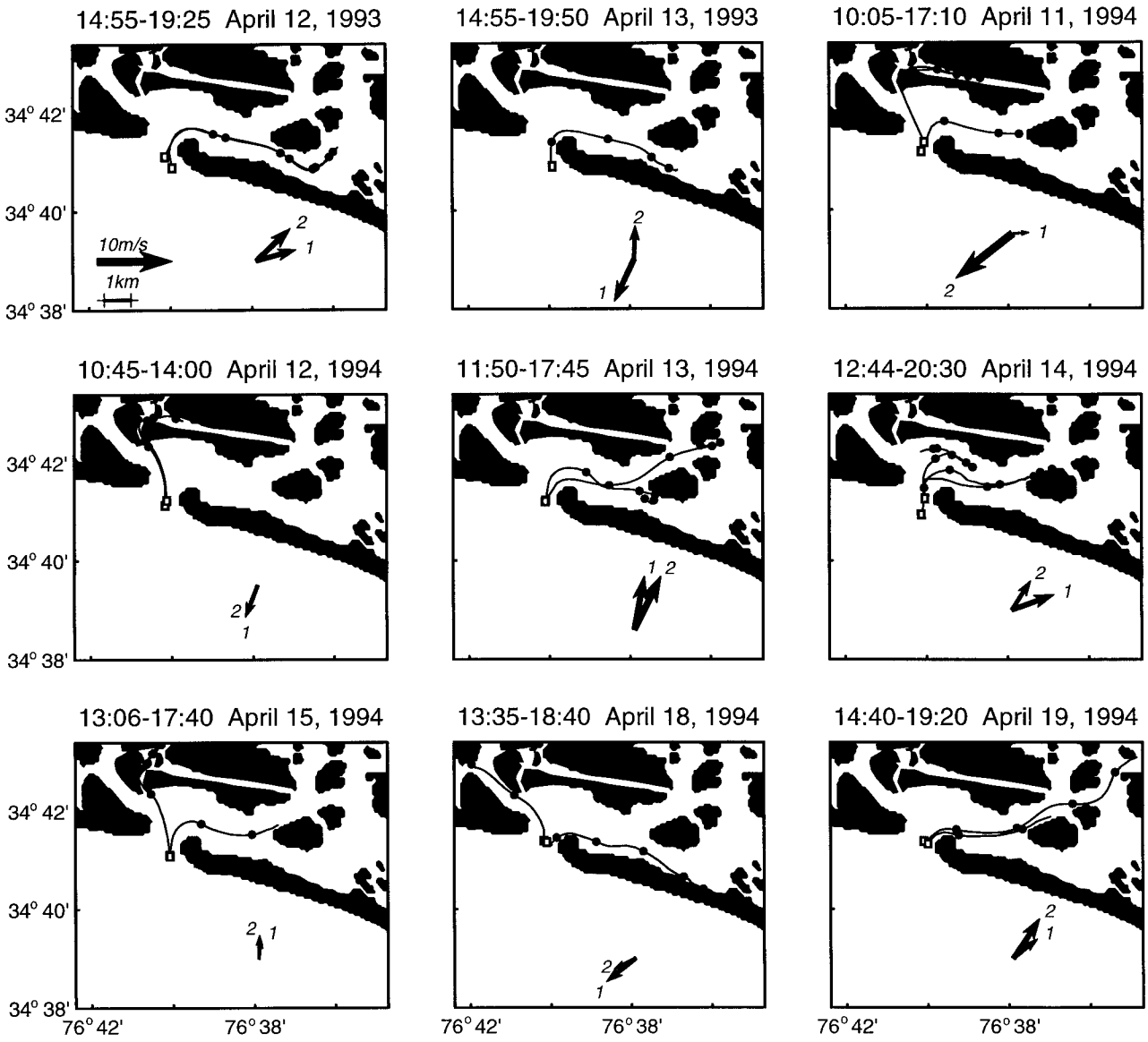

Fig. 8. Same as Fig. 5, except showing the tracks of drifters released during early flood tide within the main navigation channel at Beaufort Inlet. Dots are placed on track lines at hour intervals after release.

ity gradient across the channel, water at the western release site was roughly 1.2 less saline than water at the eastern release site. This pattern of fresher water on the western side of the inlet appears to be a common feature of the early flood tide. It was observed in four of the five early flood tide CTD surveys conducted across the inlet. A conclusion is that water entering the western side of the inlet during the early flood tide is relatively fresh, presumably containing some of the low salinity discharge of the previous ebb tide, and comprises a large fraction of the early flood tide transport through the main navigation channel.

Modeling of Flood Tide Transport

To examine further the character of flood tide currents near Beaufort Inlet, we simulated the circulation of the region using a nonlinear, finite element hydrodynamic model (Luettich et al. 1992; Westerink et al. 1994; Grenier et al. 1995). The model solved the vertically-integrated, barotropic momentum balance and continuity equations over a domain that extended roughly from the North Carolina-Virginia border to the South Carolina-Georgia border and from the deep ocean ($\sim$ 5,000 m depth) to the coastline and estuaries. The lateral extent of the domain elements varied from $>$ 10

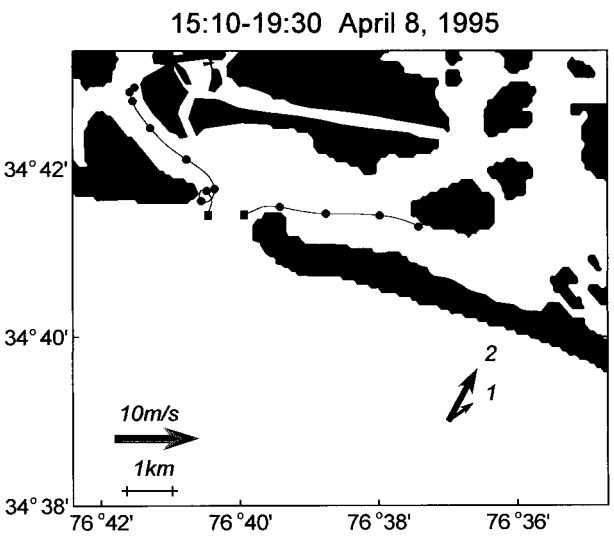

Fig. 9. Tracks of drifters released near the eastern and western shores of Beaufort Inlet during April 8, 1995. Drifters were set out over a 3-min interval roughly 1 h into the flood tide.

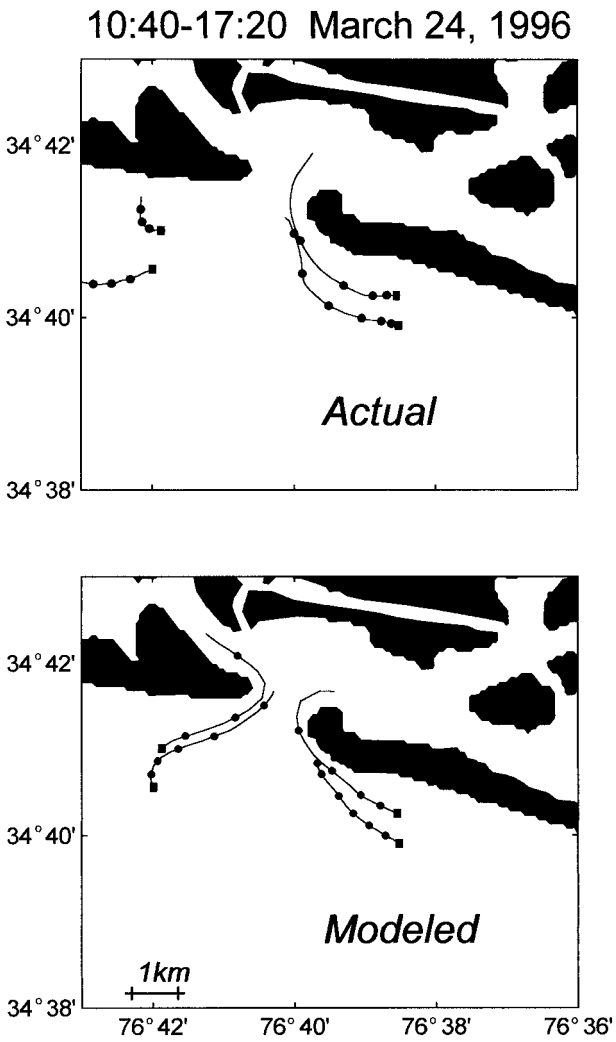

Fig. 10. Comparison of modeled drifter trajectories (bottom panel) with tracks of drifters deployed on March 24, 1996 (top panel). Dots are at hour intervals. Modeled tracks have time of origin and duration identical to the actual tracks.

km in the deep ocean to < 25 m near the shore. Specified as part of the simulations were a constant bottom friction coefficient of 0.0025 and a constant lateral viscosity of 2 m^2 s^{-1}. In executing the model, flows were forced by imposing elevations of the M_2, S_2, N_2, O_1, and K_1 astronomical tides at the model's open boundary. These elevations were extracted from a tidal database generated from a larger model simulation of the western North Atlantic, Gulf of Mexico, and the Caribbean Sea. For later generation of simulated current fields at a given time and tidal phase, the model currents were analyzed harmonically to extract the Eulerian residual mean and specified tidal constituents.

Performance of the model within the estuary connected to Beaufort Inlet has been assessed using water elevation and velocity measurements collected by the National Ocean Survey in the late 1970s (Luettich et al. 1999). In general, tidal ellipses of the modeled and observed currents were in close agreement in direction and phase although the modeled tidal ellipses were about 15% smaller than the tidal ellipses of the measured currents near the inlet mouth.

Tracing the movement of drifters in the simulated flow field was done with a particle-tracking model (Baptista et al. 1984; Foreman et al. 1992). The simulated flow used by the model was formulated by combining the residual mean, M_2, and S_2 current constituents extracted from the hydrodynamic model output. The aim of this effort was not to seek an optimal match between modeled results and the observations, which were influenced by factors not included in the simulations (e.g., winds and freshwater discharge). Rather, our principal goals were to assess the extent to which observed features of the flood tide flow may be attributed to tidal forcing, and to examine more closely the details of the tidally forced inflow in the study region.

A sample comparison of actual and modeled tracks of drifters deployed over the inner shelf on either side of the inlet is given in Fig. 10. To generate the modeled tracks, the drifters were released into the simulated flow field at a tidal phase matching that of the corresponding, actual releases. The comparison of the actual and modeled tracks is distinctly different on either side of the inlet. The tracks of drifters released into the simulated flow east of the inlet nearly match the actual

drifter tracks. In particular, both sets of tracks show evidence of a coastal jet in the westward flow leading toward the inlet. In both sets of tracks, the jet is characterized by an increase in westward current speed approaching shore. By contrast, modeled and actual tracks of drifters released west of the inlet show little similarity. While the actual tracks reveal weak flow tending away from the inlet, the modeled tracks show a strong northeastward influx to the estuary.

This difference between the modeled and actual drifter tracks west of the inlet presents a dilemma. It cannot be attributed to local winds, which were light and eastward during the time of drifter tracking (Fig. 5). Upon first consideration, the influence of a low salinity plume also seems an unlikely candidate for explaining the difference. Surface densities at the western deployment sites were only 0.25 σ_T less than surface densities at the eastern release sites (Fig. 6). Recent modeling results reported by Kapolnai et al. (1996) indicate that a density contrast of this magnitude can alter significantly the tidal inflow to an inlet. In their idealized model, buoyant inflow is introduced to a sound connected to the open ocean by a broad inlet (roughly similar in scale to Beaufort Inlet). This inflow creates a weak, low density plume over the inner shelf, with a minimum density roughly 0.3 σ_T less than the surrounding oceanic water. During flood tide, modeled flow at the edge of the plume veers cyclonically, almost at right angles, to the flooding tide inside the plume (see Fig. 7 in Kapolnai et al. 1996).

To illustrate further the details of the modeled influx to the estuary, tracks of drifters released at various points on the inner shelf into a simulated spring-tide circulation field at the onset of flood tide are shown in Fig. 11. These reveal a split of the trajectory of water entering the inlet that is consistent with that inferred from the actual drifter tracks (Figs. 5, 8, and 9). Both modeled and actual tracks indicate that inflow through the western portion of the inlet continues northwestward through the estuary, whereas water entering the central and eastern portions of the inlet immediately or eventually moves eastward through the estuary during the course of the flood tide. The modeled drifter tracks also conform closely with the flow pattern deduced by Forward et al. (1999) on the basis of larval concentration measurements. They found that inflow through the center of the inlet tends to branch northward through Radio Island Channel, matching the paths of the simulated drifters that pass through the inlet center (Fig. 11). A conclusion is that the observed branching of the flow entering the estuary may be principally a tidal phenomenon. While this branching will likely be

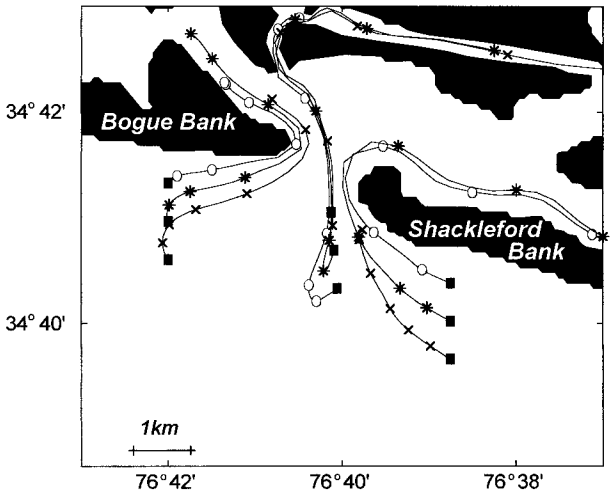

Fig. 11. Tracks of drifters released into a simulated flow field near the beginning of flood tide, as deduced by the modeled flow at the inlet mouth. Symbols appear on the track lines at hourly intervals. The currents are characteristic of spring tide conditions (0° phase difference between M_2 and S_2 constituents).

affected by freshwater discharge, the model results indicate that it may be present during times of minimal discharge.

The modeled drifter tracks also reveal that the simulated inflow through individual estuarine channels originates from distinct regions offshore. Drifters released at the onset of flood tide over the inner shelf west of the inlet tend to be carried by the simulated flow through the inlet and northwestward through the main navigation channel leading to the port of Morehead City (Fig. 11). Drifters set out over the inner shelf east of the inlet tend to be carried by the simulated flood tide eastward through the estuarine channel north of Shackleford Bank (Shackleford Channel). This flow pattern is consistent with the hydrographic observations presented previously, which show that salinities within the Shackleford Channel tend to be persistently high throughout the flood tide. The high salinities match those typically found on the inner shelf east of the inlet, but are unlike the plume-influenced water typically seen west of the inlet. But we must caution against an oversimplified view of water mass transport in this region. Blanton et al.'s (1999) moored time-series measurements revealed that salinities within the Shackleford Channel can vary significantly throughout a tidal cycle (by more than 10) and are sometimes less than those within the estuary to the west of the inlet.

One of the most noteworthy features of the observed inner shelf currents is the coastal jet of along-shore flow seen over the inner shelf east of

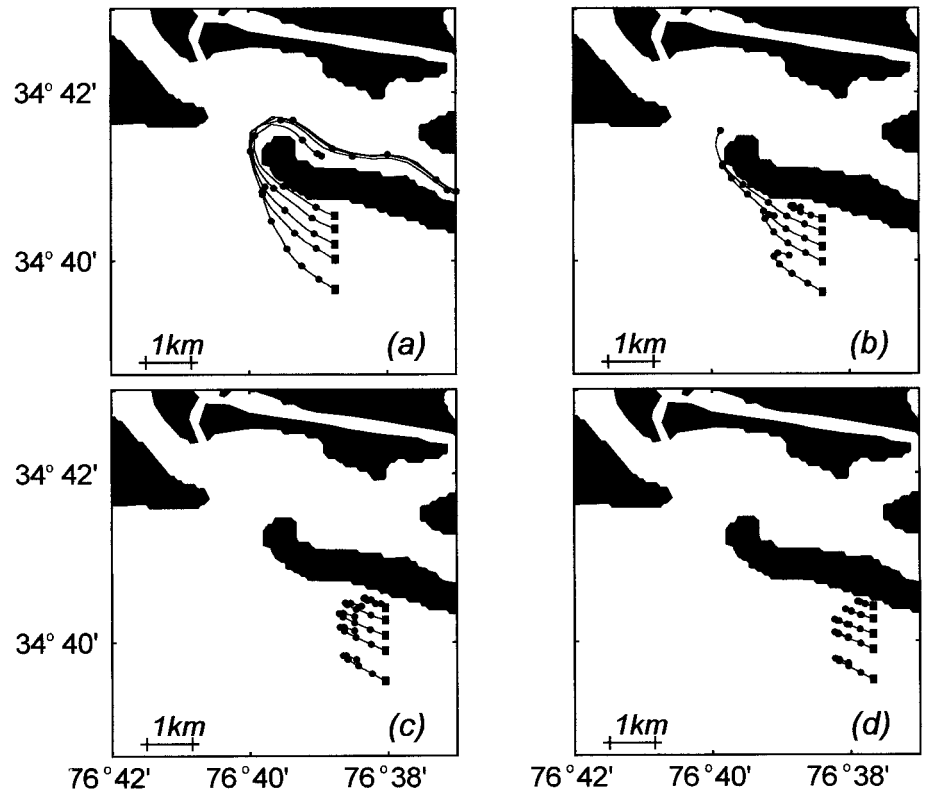

Fig. 12. Same as Fig. 11, except showing tracks of drifters released into a simulated flow field along four lines extending off the shore east at various distances from Beaufort Inlet. The tracks reveal the extent of the coastal flood tide jet in the modeled flow field.

the inlet. This appears both to the east and west of the inlet in the simulated flood tide circulation field (Fig. 11). In the simulated field, it has relatively well-defined limits (Fig. 12a–d). Tracks of drifters released into simulated flow at points 2 km east of the inlet show clear evidence of the flood tide jet (Fig. 12b). At this location the jet reaches a maximum in along-shore velocity about 0.6 km from shore. Evidence of the jet is absent from the tracks of drifters released less than 1 km farther east (Fig. 12c). These reveal relatively small alongshore velocities that decline in strength from 0.7 km offshore to the coast.

Summary and Discussion

Our limited collection of drifter tracks, combined with CTD observations and modeling results, have given a reasonably clear view of the flood tide circulation carrying water through Beaufort Inlet during conditions in which currents are dominated by tidal flows. The water properties seaward of the inlet usually have the expected form, with a plume of low salinity water veering westward from the inlet (to the right looking seaward). The plume is not a constant feature outside the inlet, however. It is not evident in CTD observations acquired after long periods of drought. There is evidence that flood tide flows through the inlet tend to follow relatively well-defined paths from the inner shelf through the estuary. As part of this flow pattern, nearshore water from the east (west) of the inlet appears to move through the eastern (western) side of the inlet and then move eastward (northwestward) through the estuary. Much of the inflow approaching the inlet from the east appears to be concentrated within a nearshore flood tide jet. This jet and the splitting of inflow entering the inlet are closely reproduced by a barotropic tidal model and so may be due principally to the barotropic tide. The model results do not compare favorably with observations of flood tide flows over the inner shelf to the west of the inlet, possibly due to the effect of the low salinity plume.

The potential importance of the nearshore flood-tide jet in carrying larvae to the estuary is realized by considering the results of larval transport surveys mentioned in the section Site Description. During these surveys, most of the larvae entering the estuary passed through the eastern side of the inlet and continued eastward along Shackleford Banks. In the first survey, for example, roughly 80% of the influx of spot, croaker, pinfish, and

flounder larvae passed through the eastern inlet sector (Churchill et al. 1999). In view of our results, it is likely that these larvae were transported from the nearshore region east of the inlet.

The importance of nearshore transport is also indicated by the recent examination of larval distributions offshore of Beaufort Inlet by Hettler and Hare (1998). Using survey data from the eastern and western lines shown in Fig. 1, they presented densities of six ocean-spawned, estuarine-dependent larval species for eight separate cruises. The patterns changed considerably from cruise to cruise and from species to species. In general, however, larval concentrations for all but one species (Atlantic menhaden) tended to increase moving toward shore. These results, combined with our findings, indicate that nearshore flows can be critical in carrying larvae to Beaufort Inlet. Changes in the nearshore region that impact these flows could alter significantly the delivery of larvae to the estuary connected to the inlet.

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