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Physical Oceanographic Processes Affecting Inflow/ Outflow Through Beaufort Inlet, North Carolina

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ABSTRACT

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In this study, the relationships between Eulerian measurements of inlet and estuary currents, water level, salinity, temperature and atmospheric winds are analyzed using time series and frequency domain analysis techniques to determine the physical oceanographic conditions which result in the entrainment of shelf waters into and fresh water flow out of the Beaufort Inlet (NC) Estuary System. Analyses were done on both tidal and subtidal frequency motions.

Examination of the hydrological data showed that the transport is driven not only by astronomical tides, but also via non-tidal motions that are directly and/or indirectly forced by atmospheric winds and river discharge. In summary, the retention of shelf water in the Beaufort Inlet Estuary is dependent not only on coastal Ekman dynamics but also on northward blowing winds. Southeastward blowing winds induce outflow from Bogue Sound, Newport River, and Back Sound. Southward, southeastward and westward directed winds induce Core Creek/Neuse River southward pressure gradients and outflow as well as Back Sound outflow toward the inlet. Northeastward-directed winds favor transport into Back Sound while northwestward blowing winds favor transport into the lower Newport River.

This study shows that the Beaufort Inlet Estuary System can be classified dynamically as two different estuary types. It consists of the partially mixed estuary of the Newport River coupled to Bogue and Back Sounds that behave as lagoonal type estuaries. There is a two-way transport regime at the inlet mouth where the flood tides are strongest on the eastern side and ebbs are strongest on the western side. The primary cause is asymmetrical bathymetry coupled with separate hydraulic functions of the opposite sides of the inlet; flooding on the east and ebbing on the west side. Finally, once Core Creek Canal was opened in December of 1964, allowing free communication between Beaufort Inlet and the Neuse River these areas became subjected to wind induced salinity fluctuations.

ADDITIONAL INDEX WORDS: *Estuaries, tidal currents, wind-driven flow.*

INTRODUCTION

Beaufort Inlet (Figure 1) is located along the coast of North Carolina (NC), to the west of Cape Lookout at the northern end of Onslow Bay, the middle bay of the Carolina Capes (PIETRAFESA, 1983) region in the northern portion of the South Atlantic Bight (SAB). The inlet links the coastal ocean to a complex estuary system, consisting of the Newport River basin to the north, Back Sound to the east and Bogue Sound to the west. These small lagoons serve as tributaries to the North River and the Newport River, respectively. The entire system is separated from the continental shelf of the Atlantic Ocean, by the barrier islands of Core, Shackleford, and Bogue Banks. Shackleford Banks and Core Banks are separated by Barden's Inlet. Back Sound and Pamlico Sound are connected via Core Sound to the east. In addition, the Newport River connects with the Neuse River, via Core Creek to the north. The system serves as an important nursery for estuarine dependent finfish which spawn in offshore waters (NELSON *et al.,* 1977; MILLER *et al.,* 1984), but the physical mechanisms which may aid or cause larval transport through the inlet are not yet determined. However, as the mechanisms that induce significant random transport events through inlets are found, then logistically intensive, larval recruitment studies can be conducted more efficiently in inlets.

PIETRAFESA and JANOWITZ (1988) showed that circulation through several North Carolina inlets is forced not only via astronomical tidal currents, but also by wind induced pressure gradient forces. They postulated and presented evidence that the flow through narrow NC barrier island inlets, *e.g.* Oregon, Hatteras, and Ocracoke Inlets as being essentially bi-directional, *i.e.* either "in" or "out" throughout, while the flow at the mouth of coastal plain NC estuaries such as the lower Cape Fear is "in" on the right and "out" on the left, facing into the mouth. More recently, NICHOLS and PIETRAFESA (1999) showed a distinct correlation between southwestward winds and inshore pulses of shelf water through and into Pamlico Sound and Oregon Inlet, using moored current meters and hydrographic sensors in coastal waters, the inlet and the sound. The driving forces were as previously proposed by PIETRAFESA and JANOWITZ (1988) and were

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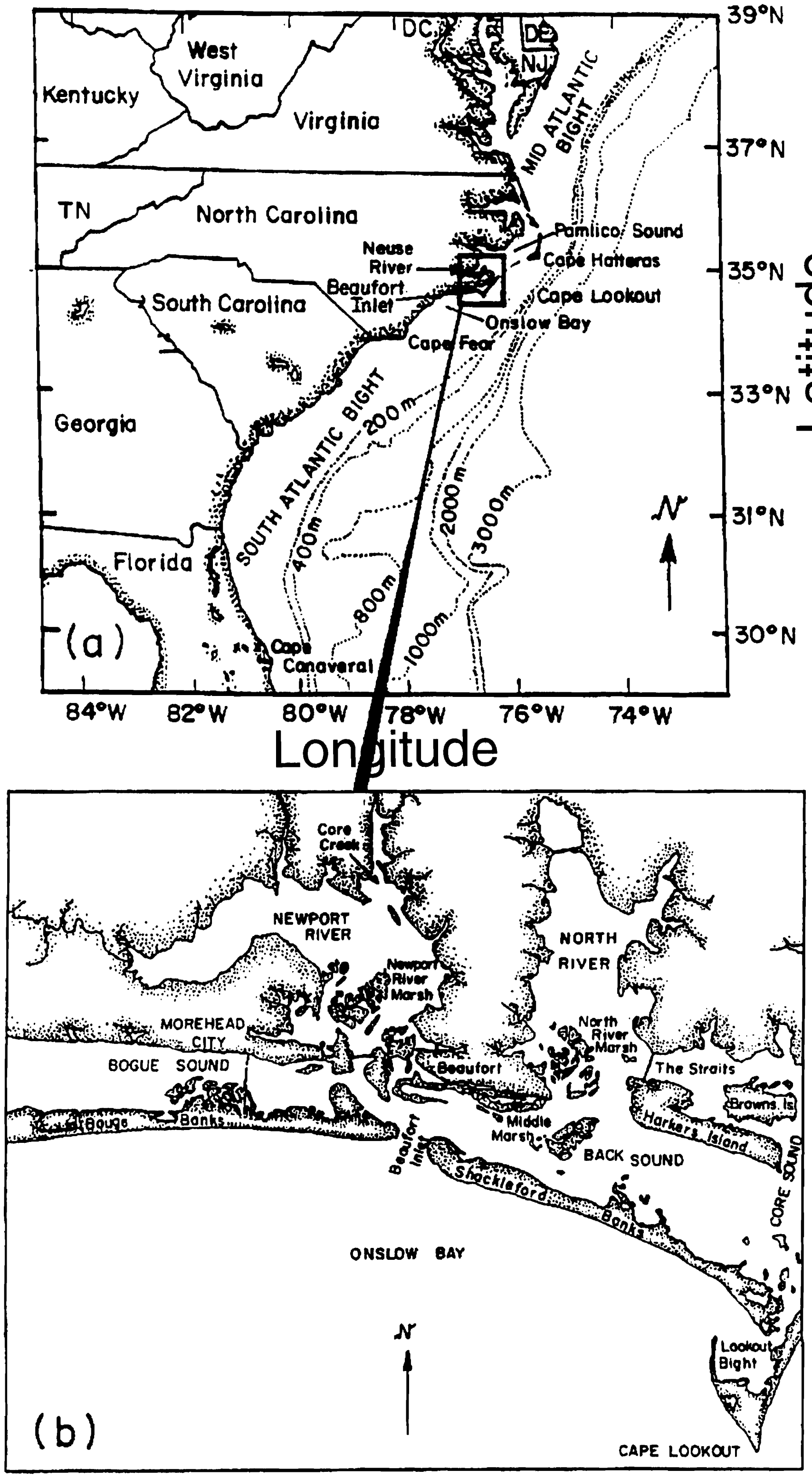

Figure 1. (a) Location of Beaufort Inlet with respect to the East Coast of the United States; (b) Geography of the Beaufort Inlet Estuary Complex.

Table 1. *Deployment Matrix and Data.*

Deployment	Site Latitude (N)/Longitude (W)	Depth (m)	Instrument Type	Sampling Period
#7	34-42.23 N/76-41.17 W	2m	TICUS	2/25/76–5/05/76
		5m		
#10	34-43.88 N/76-41.00 W	2m	TICUS	2/23/76–3/27/76
		5m		
#14	34-42.75 N/76-42.83 W	2m	TICUS	2/23/76–3/27/76
#19	34-41.53 N/76-39.13 W	2m	TICUS	2/25/76–3/30/76
Daymark #3	34-42.28 N/76-40.70 W	2m	S-4 #241	3/10/92–4/15/92
Inlet Doublet	34-41.56 N/76-40.05 W	2m	S-4 #242	1/31/93–2/07/93–3/21/93
		5m	S-4 #848	
Core Creek Bridge	34-49.70 N/76-41.50 W	n/a	Staff Gauge	10/75–4/76
				10/91–4/92
				10/92–4/93
Pivers Island	34-43.00 N/76-40.20 W	n/a	Analog/Digital Tide Gauge	10/75–4/76
				10/91–4/92
				10/92–4/93
Daymark #24	34-43.08 N/76-41.48 W	5m	Aanderaa	1/30/93–4/30/93
			RCM 5762	
			WLR 709	
Buoy “2BI”	34-38.30 N/76-39.49 W	16.8m	Aanderaa	1/30/93–5/10/93
			RCM 7366	
Cape Hatteras	35-16.00 N/75-33.00 W	3m	Anemometer (wind velocity)	10/75–4/76
				10/91–4/92
				10/92–4/93
Wilmington	34-16.00 N/77-54.00 W	10m	Anemometer (wind velocity)	10/75–4/76
				10/91–4/92
				10/92–4/93

tightly coupled to the direction, magnitude and duration of the alongshore component of the coastal synoptic scale winds.

CHAO and PIETRAFESA (1980) and PIETRAFESA and JANOWITZ (1988) found that along the South Carolina coast and the North Carolina coast south of Cape Hatteras, there is a tendency for sea level at the coast including the mouths of estuaries specifically, to fall in concert with a northeastward wind and to rise in concert with a southwestward wind, both within 8–10 hours. This is because the general alignment of the Carolina Capes coast is northeast-southwest.

However, Beaufort Inlet could be atypical of other North Carolina barrier island inlets, due to the fact that the alignment of this upper portion of Onslow Bay is east-west whereas the more general orientation of the coastline from Cape Lookout to Cape Fear is northeast-southwest. Thus, Beaufort Inlet's local orientation may allow it to be subject to local forcing from northward and southward winds in addition to southwestward and northeastward winds. Here we will use observational data to study the types of forcing that lead to inflow of waters at Beaufort Inlet and retention of these waters in the estuary system.

METHODS

When inflow occurs at Beaufort Inlet, we are interested in the following questions. How much volume is transported and retained? What is the period length over which this motion occurs? What physical forcing mechanisms are responsible?

In order to evaluate the suite of processes governing the exchange of water between the Beaufort estuary system and the adjacent continental shelf via Beaufort Inlet, data from three different collection periods were used. The collection sites are listed in Table 1 and shown in Figure 2. The first study was conducted by the NOAA National Ocean Service (NOS) from January to April, 1976 for the purpose of tidal analyses. Four of their twenty-two stations within the estuary (two of which were doublets) fit the criteria for our study interests. These criteria require simultaneous, continuous records for at least a lunar cycle (*i.e.* the order of a month). The four NOS stations are at locations #10, located just north of Newport Marsh, #7, in Morehead City Ship Channel, #14 in Bogue Sound, and #19 just north of Shackleford Point. Both sites #10 and #7 consisted of doublets where the surface (designated T) and bottom layer instruments (designated B) were located at 2m and 5m depths respectively. Stations #14 and #19 were single instrument moorings located at a depth of 2m.

North Carolina State University (NCSU) attempted to collect data on both sides of the Morehead City Ship Channel, at a depth of 2m, during March–April, 1992, using Interocean S-4 current meters. Only the data on the north side of the channel was recovered.

Data was also collected by NCSU using current meter doublets located on each side of the inlet from January–April 1993 using S-4 current meters. The western doublet was lost during the “Storm of the Century” on March 13, 1993. The eastern doublet had two S-4 current meters (S-4 #242 and S-4 #848) at depths of 2m and 5m, respectively. These meters were also equipped with pressure, conductivity and temperature sensors. In addition, an Aanderaa-Parascientific quartz crystal water level recorder was moored on the bottom along the main axis of the Morehead City Ship Channel at station “SI”.

Water level data were also collected at Core Creek Bridge by the U. S. Army Corps of Engineers and at Pivers Island

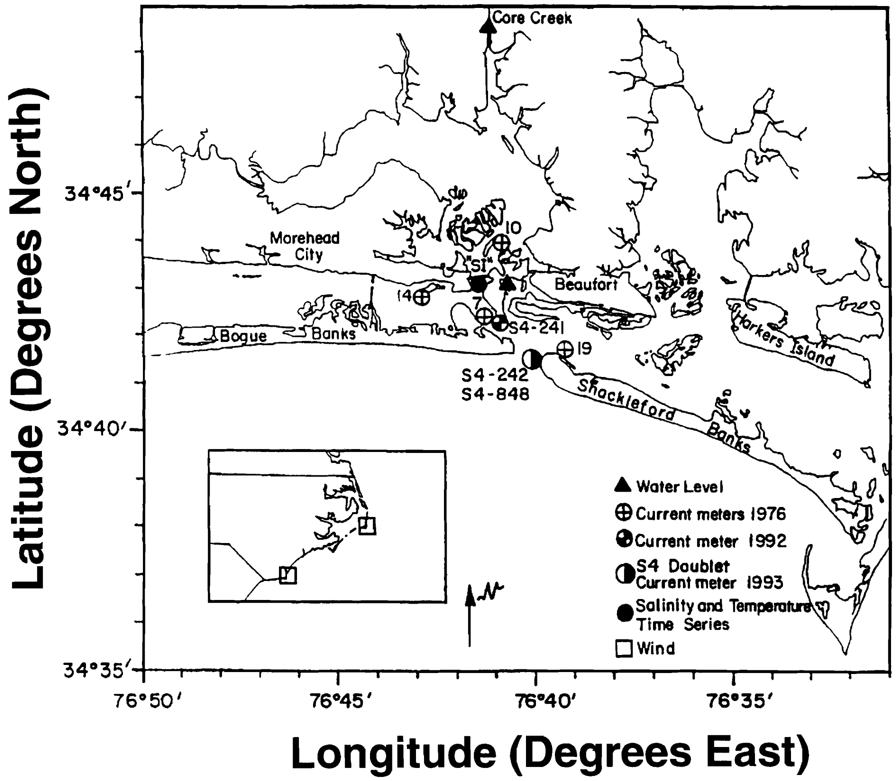

Figure 2. Locations of collection sites and instrumentation in the Beaufort Inlet system to the west of Cape Lookout. Shown in insert are relative locations of Cape Hatteras (to north) and Wilmington to (south) meteorological stations.

by the NOS, throughout the three sampling periods for which we have current meter data. Unfortunately, no data are available for river discharge for the Newport River.

Meteorological data in the form of wind velocity time series were available at Cape Hatteras, N. C., and Wilmington, N. C. (see insert, Figure 2) from the National Weather Service and archived by the National Climatic Data Center for the three sampling periods of interest. A linear average of both stations was used as an approximation of the wind fields over the Beaufort Inlet estuary system. Meteorological data were also collected "on-site" at and by the University of North Carolina at Chapel Hill's Institute for Marine Sciences (IMS) in Morehead City.

During April 1993, 1994 and 1995 GPS Lagrangian surface drifters were deployed to qualitatively describe the flow within the lower estuary and the inlet. CTD transects of the Newport River were made to quantify the temperature and salinity characteristics. In April 1995, an S-4 current meter was used to sample currents near the drifter buoys by lowering the instrument from a stationary vessel. In all years, the drifters were released within the inlet during the onset of the flood stage of the semidiurnal tide and recovered at the start of the subsequent ebb. Finally, S-4 current meter sampling was done on each side of the inlet during different stages of the tide to determine if there were any lateral flow differences across the inlet mouth.

The time series of raw data (a representative example is presented in Figure 3) were first filtered with a three-hour low pass, Lanczos cosine taper filter (PIETRAFESA *et al.*, 1978) to remove effects of high frequency noise in the data and thus to better observe tidal and subtidal frequency motion. The vector time series (wind and current meter) were analyzed in the frequency domain by means of Fourier analysis techniques, to identify periods of peak energy.

All of current meter velocity data were rotated to a coordinate system where V is along the channel axis and U is cross channel and the time series were then filtered with a 40 hour half power point, Lanczos cosine taper filter (PIETRAFESA *et al.*, 1978). This process de-emphasizes tidal, inertial, and diurnal variations, including those caused by the sea breeze. Therefore, net flooding or discharge events which remain after the "low pass" filtering process, are likely to be related to synoptic scale meteorological events. In addition to filtering, the water level data was demeaned by subtracting the average value of the record length from each measurement.

Finally, we employ the relationship $g\alpha \int (\partial s/\partial x)\, dz$ to compute the vertical integral of the horizontal, axial salinity gradient, where α is the specific volume anomaly, g is the gravitational acceleration, x is the cross-channel direction and z is the channel depth using the salinity and temperature records from the S-4 current meters deployed in 1993.

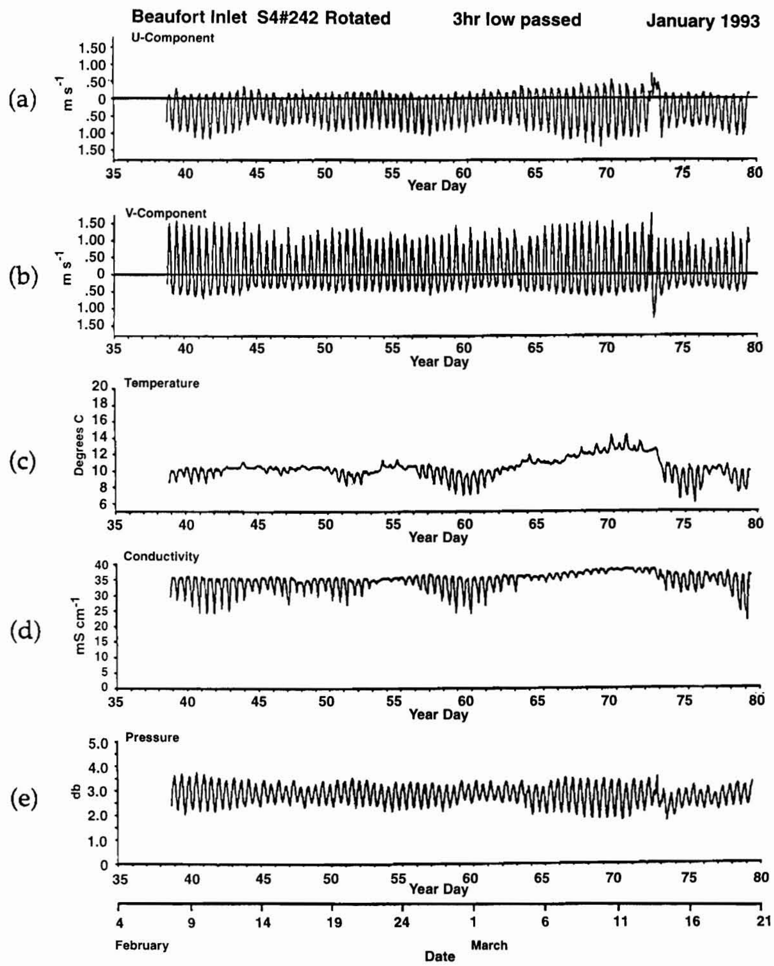

Figure 3. Raw data collected at instrument/site 242 (cf. Table 1). (a) East (+) west (−) current component time series. (b) North (+) south (−) current component time series. (c) Temperature time series. (d) Conductivity time series. (e) Water level (pressure) time series relative to mean sea level.

RESULTS

Internal Estuary Flow

An example of the energy density spectra of currents in Beaufort Inlet is presented in Figure 4. The cross-channel, U, and axial, V, velocity components exhibit peaks at the same frequencies with significant energy at periods of 100 hours or greater. There are significant peaks at 21–26 hours, associated with inertial motion (21.13 hours), with the sea-breeze (24 hours) and the K1 diurnal tide. The next and highest peak is the semi-diurnal or M2 tide (12.42 hours), followed by two peaks at the M4 (6.2 hour) and M6 (4.1 hours) tidal constituents. Although these tidal peaks have little net residual motion, they may contribute to the transport mechanisms during a single stage of the tide. Peaks at higher frequencies are not significant.

Hodograph descriptors of the measured currents were used to determine the nature of preferred water particle motion as a function of frequency. A representative example is shown in Figure 5. They indicate that the near semi-diurnal and diurnal tides are repeatable reversing currents in the inlet proper, aligned with the channel topography at about 20° north-northeast. Motions with periods between 2 days and 2 weeks follow repeatable particle paths moving clockwise about elongate ellipses aligned in a west-northwest/east-southeast direction. Motions with periods greater than several weeks are rectilinear, highly infrequent, disorganized and oriented WNW to ESE.

The plots of 40 hour, low-pass filtered current meter data shown in Figure 6 and 8, collected during the years 1976, 1992, 1993, reveal sub-diurnal frequency inflows of up to 40 cm s^{-1} in the surface layer and 30 cm s^{-1} in the lower layer of the inlet. This is especially clear in the 1993 data (Figure 6b, c). The velocities tend to decrease inland with speeds of 15 cm s^{-1} for inshore sites during the 1976 collection period (Figure 7). The most striking result from the 1992 (Figure 6f) and 1993 (Figure 6a–c) data, is that the right hand side of the channel (looking upstream) is almost completely dominated by subdiurnal frequency inflow. The only exception is

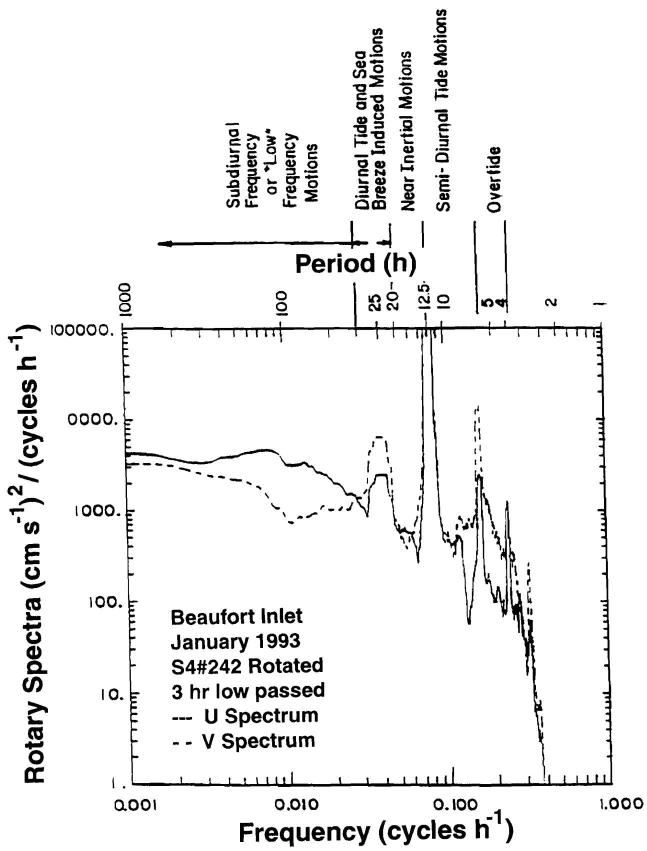

Figure 4. Energy density spectra for averaged velocity time series at Beaufort Inlet during the 1993 sampling period. The highest energy peak is at 12.42 hours as a result of the M2 tide. The peaks at 6.2 hours and 4.1 hours are a result of the M4 and M6 constituents respectively and the diurnal peak at 24–25 hours is due to the K1 diurnal tide and the inertial period.

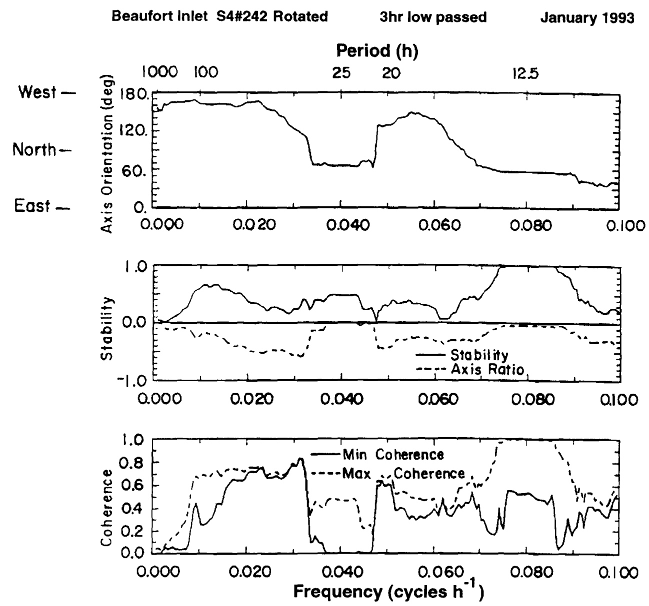

Figure 5. Axis orientation, stability and coherence of Beaufort Inlet currents at the current meter S-4 #242 site.

an outflow event in the 1993 data during the "Storm of the Century" on March 13, 1993 (Day #73).

In the 1976 data set (Figure 7), station #7 (located on the left side of the channel looking upstream) is dominated by outflow. Station #7T (Figure 7a) has velocities slightly higher than the bottom instrument (#7B, Figure 7b) suggesting a downstream directed barotropic pressure gradient created by waters coming from Bogue Sound, the Newport River and Core Creek and an upstream directed baroclinic salt gradient. For current meter stations #10T (Figure 7c), #10B (Figure 7d), #14 (Figure 7e) and #19 (Figure 7f), there is a pattern of weak inflows and outflows that follow the prevailing wind. Located in an auxiliary channel that runs parallel to the Intracoastal Waterway, currents at station #10 generally follow the local wind with velocity peaks between 5 and 15 cm s^{-1}. Because of its' detachment from the main channel, station #10 may not represent the total flow in this vicinity. Station #14, in Bogue Sound, has relatively strong residual ebbs, about 15 cm s^{-1}, flowing towards the Morehead City Ship Channel when the wind is from eastward to northward. This causes subdiurnal flow into Back Sound (10 cm s^{-1}) through the small channel north of Shackleford Point. Subdiurnal frequency outflows at site #19 occur when the winds are from northwestward to eastward (Figure 7g).

Lagrangian drifter buoys were released just seaward of the mouth of Beaufort Inlet at the onset of a flooding M2 tide (Figure 8). The drifter data indicates flows of 120 cm s^{-1} at the inlet mouth, which reduce to 20–40 cm s^{-1} farther inland. Because some of the drifters ran aground or had to be recovered before grounding of the tracking vessel, only one drifter that entered Back Sound was tracked through the entire flood tide. At the end of the flood, this drifter had traveled more than 11 km from the inlet mouth. In general, the drifter trajectories turned toward the east upon entering the right side of the inlet channel and proceeded to Back Sound either from Beaufort Channel or Taylor's Creek. Three of the drifters released on the inlet's west side did proceed up the Morehead City Ship Channel, but traveled only a fraction of the distance the eastbound drifters covered in Back Sound.

Data within the estuary branches (Figure 2) indicate that subtidal frequency residual currents follow prevailing winds (Figure 7g). Rapid changes in subtidal frequency current direction occur with shifting wind direction. This pattern occurred at all mooring positions except at station #7 in the Morehead City Ship Channel. Currents in the Morehead City Ship Channel at station #7T (Figure 7a) exhibit outflow from the Newport River and Bogue Sound. Therefore, it appears that the ship channel is a preferred tidal ebb channel. However, inflow is favored on the northern and right side of the ship channel, as shown by the 1993 time series of S-4 #242 (Figure 6b), while the prevailing outflow on the left side of the channel reversed on occasion, as shown by current meter S-4 #241 in 1992 (Figure 6f). The west channel inflow was due to northwestward winds that blew up the axis of the

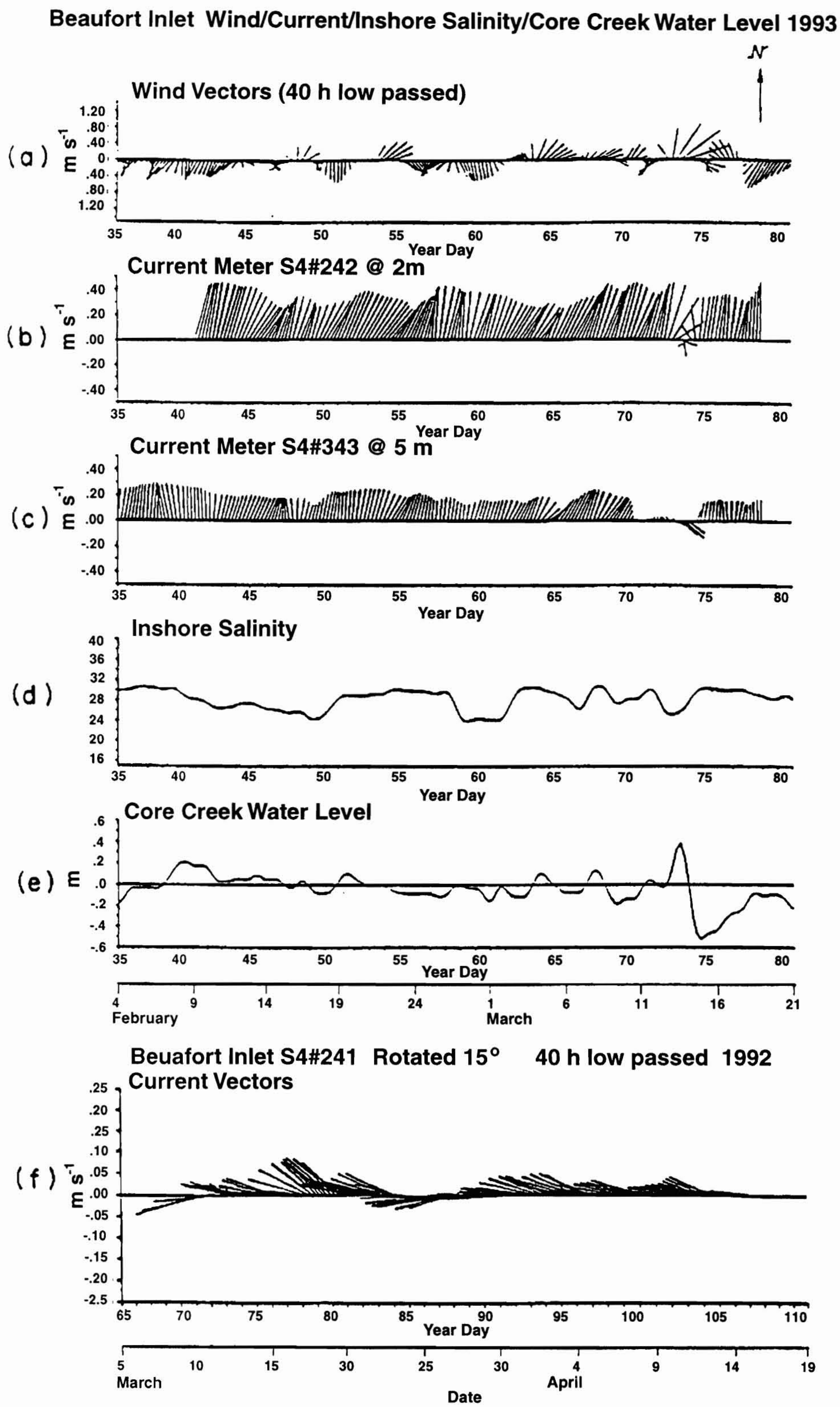

Figure 6. Forty hour low pass filtered (a) wind vectors, (b) current vectors S-4 #242, (c) current vectors S-4 #848, (d) salinity from "SI", (e) water level from Core Creek bridge during the 1993 sampling period, and (f) 40 hour low pass filtered velocities from current meter S-4 #241 on the northern side of the Morehead City Ship Channel during the 1992 sampling period. Currents and winds are plotted in the directions that the winds blow (towards) and the current flow (towards).

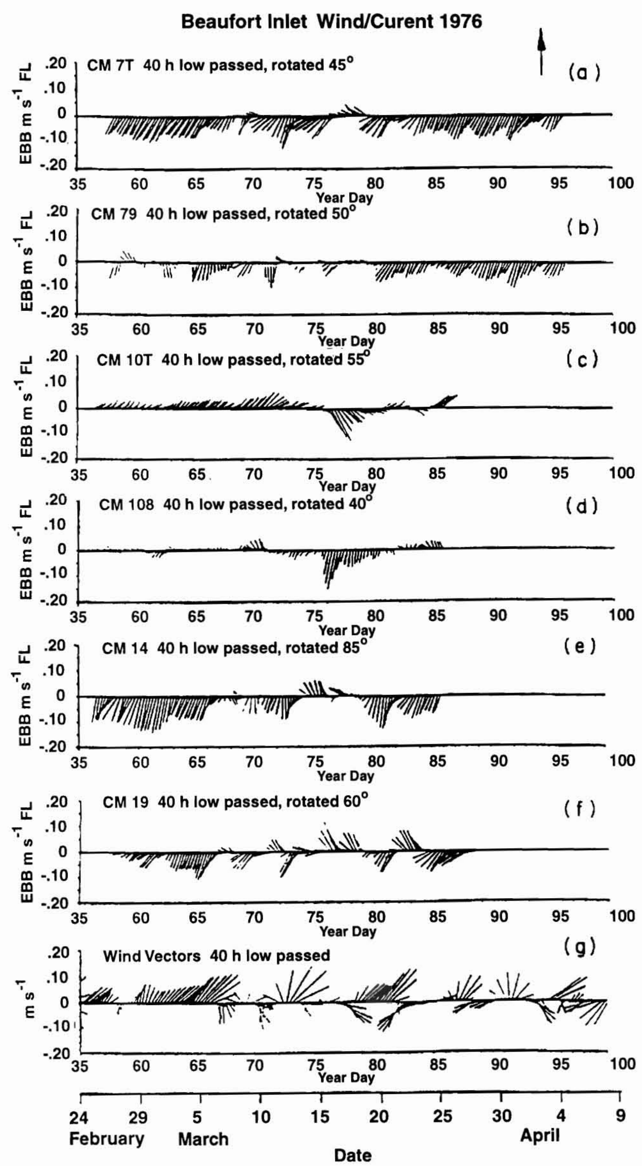

Figure 7. Forty hour low pass filtered wind and subtidal residual flow at 2 m and 5m current meter stations of #10 and #7 in the 1976 sampling period. Currents and winds are plotted with convention of Figure 7.

channel. During northeastward winds, a barotropic pressure gradient forms as the water level rises in Bogue Sound. The water is mechanically driven directly by the wind and rises in the direction that the wind blows. There is a subdiurnal frequency movement of water from Bogue Sound to both the upper and lower Newport River. Furthermore, subdiurnal frequency inflows at the entrance to Back Sound are also forced locally by northeastward winds.

During southwestward blowing wind events, the motions described above reverse, and Back Sound ebbs while Bogue Sound floods, where the wind event is of sufficiently strong magnitude to overwhelm the tidal component of the total flow. Velocities at stations #7B (Figure 7b) and station #10B (Figure

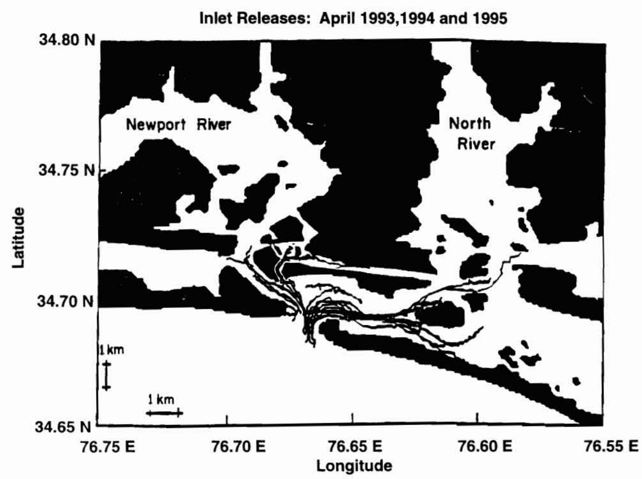

Figure 8. Summary of Inshore GPS surface drifter trajectories during the months of spill 1993–1995.

7d), both located at 5m depth, show small-scale flooding events while station #19 (Figure 7f) experiences outflows during southward wind events. This shows that water coming from Back Sound meets less dense Newport River surface water, sinks below it and progresses towards the Newport River and Bogue Sound, driven by a baroclinic pressure gradient force set up by horizontal salinity gradients. The vertical integral of the horizontal, axial salinity gradient, which is responsible for this mass field force, can be assessed via the relation $g\alpha \int (\partial s/\partial x)\, dz$, using the data shown in Figure 9.

The Influence of the Neuse River

The Neuse River, via Core Creek, influences the flow field of the upper Beaufort estuarine system. Fluctuations in the wind, water-level gradient between Core Creek and Pivers Island, and salinity at the Morehead City Ship Channel (Figure 9), show distinct correlations suggesting a coupling between the Neuse River and Beaufort Inlet. Southward to westward (*i.e.* southwest quadrant) winds cause water level in Core Creek to rise faster than at Pivers Island and a pressure gradient force directed from north to south is established (PIETRAFESA *et al.*, 1986). The pressure gradient force causes an augmentation of riverine discharge from the Neuse River to the Newport River through Core Creek (Figure 10a), resulting in a drop in salinity at the Morehead City Ship Channel. These inshore salinity fluctuations are independent of salinity fluctuations offshore. Winds blowing towards the north or northeast have opposite results where the water level at Pivers Island is higher than that at Core Creek, indicating saline intrusions driven by a surface pressure gradient force (Figure 10b).

In the lower parts of the Neuse River, winds blowing west-southwestward are followed by the largest increases in water level and salinity while northeastward directed winds have opposite effects. This process occurs fairly quickly. PIETRAFESA *et al.* (1986) reported on a field study of water level fluctuations due to wind forcing in the Pamlico Sound and

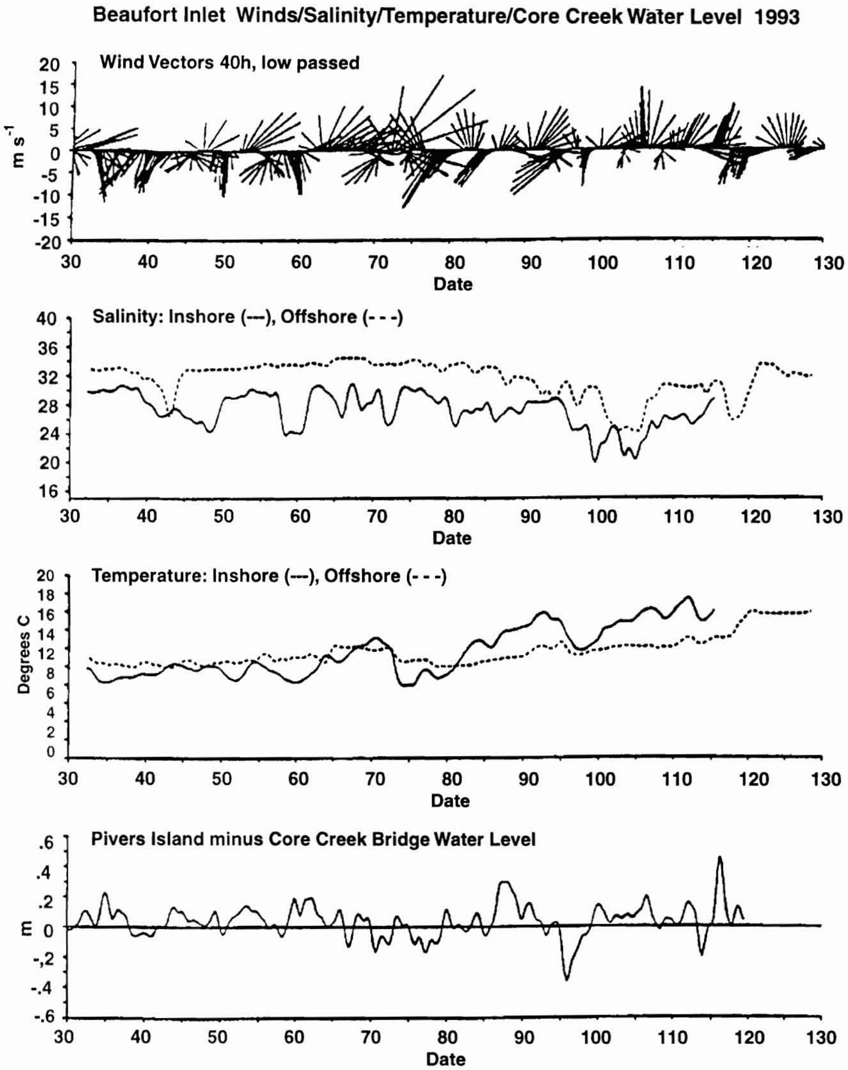

Figure 9. Forty hour low pass filtered wind, estuary salinity vs. offshore salinity, estuary temperature inshore vs. temperature offshore, and water level gradient between Pivers Island and Core Creek (when gradient is a negative value Core Creek water level is higher than Pivers Island).

determined that the entire sound sets up or down within three hours of the onset of persistent winds blowing either southwestward or northeastward. Increases in salinity and water level in the lower Neuse River are the result of intrusions of relatively saline Pamlico Sound water driven by southwestward winds (Figure 10a). Northeastward winds caused the opposite effect (Figure 10b). The intrusions of Pamlico Sound water into the lower Neuse River are also subject to the effect of the Earth's rotation, the Coriolis force, and therefore favor the northern bank of the river, while the outflowing relatively fresh water (minimum salinity values of approximately 6 in April) are trapped along the southern bank (Figure 10a).

Revisiting Figure 9 we see from the time series of salinity and water level differences, that occasional, rapid decreases in salinity occurring in the lower Newport River can be attributed to the surface pressure gradient, $-g\partial\eta/\partial x$, where η is the free surface. This gradient can act in opposition to the internal pressure gradient force $-g\alpha\int(\partial x/\partial x)\,dz$ and prevent salinity intrusions from the inlet. This results in lower salinities over the span of a tidal cycle. These salinity decreases occur as Neuse River water (though well mixed with Bogue Sound and Newport River water) is transported to the Morehead City Ship Channel via Core Creek. This happens when the winds force the lower Neuse River into a storage mode resulting in significant discharge via Core Creek as conceptualized in Figure 10a. The largest amplitude fluctuations in Morehead City Ship Channel occurred when a strong northeastward wind was immediately followed by a southwestward wind of similar magnitude. For example, between days 93 and 108 (in Figure 9), there were eight reversals of winds that resulted in salinities falling in Morehead City Ship Channel to lows of near 20. The wind reversals may produce a pumping mechanism. Following the onset of northeastward

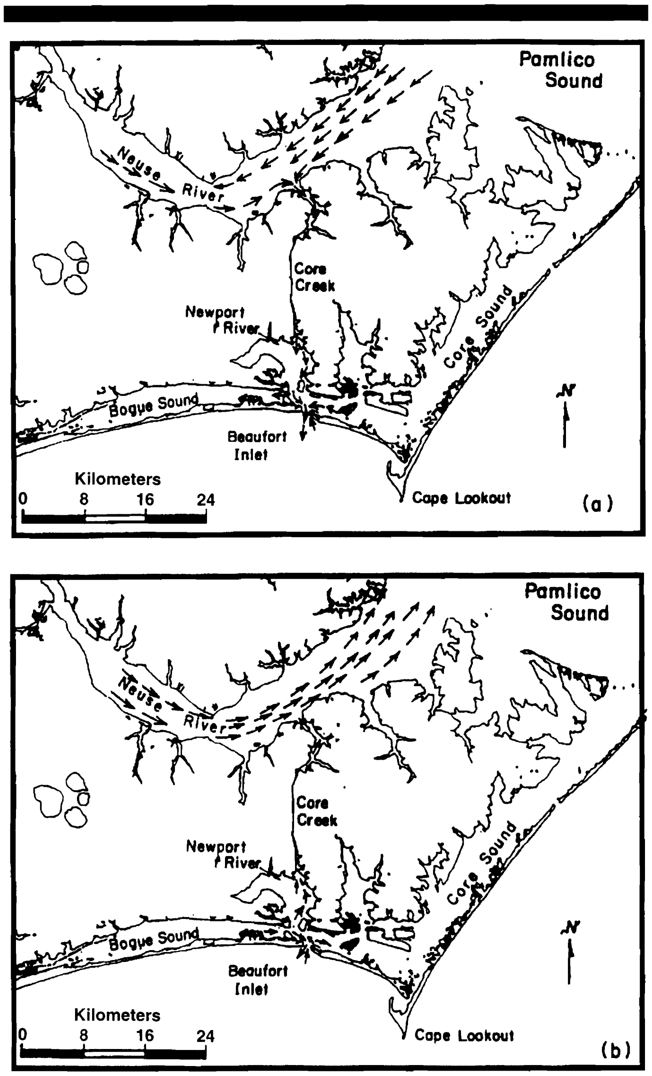

Figure 10. Wind and subtidal estuary flow throughout the Beaufort Inlet/Estuarine System. (a) Southwest quadrant winds cause water level in Core Creek to rise faster than at Pivers Island and a pressure gradient force from north to south is established. (b) Northeast quadrant winds cause water level at Pivers Island to rise faster than at Core Creek and a pressure gradient force from south to north is established.

winds, water flushes out of the Neuse River (Figure 10b). Then, if the wind shifts and is directed southwestward, two effects occur. First, the drainage of Neuse River into the Pamlico Sound is retarded and repressed. Next, the water level in the lower Neuse builds up which results in the forcing of fresh water down Core Creek, where it mixes with Newport River water. The distance from the Neuse River to station SI (Figure 2) is 28 km. The average lag time between the onset of a northeastward wind event and minimum salinity values was six days. This equates to a transport speed of approximately 5 cm s^{-1}, which is akin to the observations of subinertial frequency, residual ebb velocities in the lower Newport River (Figure 7c).

This yields new insight into the findings of JANOWITZ and PIETRAFESA (1980), HOFFMAN *et al.* (1981) and ASKARI *et al.* (1989). They collectively found that following the onset of northeastward winds, the water level at Beaufort drops initially, within 8 hours, but then rises about two and a half days later. The explanation given was that initially there is a direct frictional response to the wind, but this is followed by an offshore geostrophic flow that pushes against Cape Lookout (Figure 1a); an example of "frictional equilibrium" (CSANADY, 1982). Figure 9 provides confirming evidence of this change in pressure gradient slope associated with the process where we see that Pivers Island water level is lower than Core Creek water level during southward winds, but two and a half days after the onset of northeastward winds, water level rise is accompanied by a saline intrusion and a downhill slope of water from Pivers Island to Core Creek.

The Two Way, Lateral Inlet Flow Field

KLAVANS (1983) proposed that the eastern side of Beaufort Inlet is flood dominated and the western side is ebb dominated. This concept is confirmed by our findings, as shown in the time series of current vectors in Figures 6a and 7a for the flood and ebb dominations, respectively. In general, the primary influences for cross-inlet asymmetries in the axial flow across the mouth of an inlet are asymmetric bathymetry of the inlet and the preference for outwelling plumes to persist on the right sides of inlet mouths, looking downstream. The western side of Beaufort Inlet is shoal dominated and the eastern portion is maintained as a dredged channel (Figure 11). Thus, it appears that a majority of the flood tidal prism could enter through the eastern half of the inlet squeezed into an inlet jet, though unfortunately, no good hydrodynamic model of the inlet exists to test this hypothesis. As the tide approaches the coast from offshore, in the form of a Poincare wave (PIETRAFESA *et al.,* 1985), the western side of the advancing wave is hindered by bottom friction. These frictional influences create the M4 and M6 overtides seen in the doublet spectra (refer to Figure 4). The doublet's high flood velocities of 140 cm s^{-1} (Figure 3b, c) are evidence of this jetting, which are 30% higher than the maximum flood current measured by KLAVANS (1983) in the Morehead City Ship Channel (there were no stations located in the mouth of the inlet in that study). These dominant floods and relatively weak ebbs (40 cm s^{-1}) produce a subtidal residual inflow of 20 to 30 cm s^{-1}. A portion of this inflow proceeds up the Newport River, favoring depth and the right side (facing upstream) as indicated by the S-4 #241 data set in 1992 (Figure 6f).

Once through the inlet, the flow encounters a hindering pressure gradient in the Morehead City Ship Channel when winds are blowing towards the southwest quadrant, *i.e.* winds directed southward to westward and the Morehead City Ship Channel is flooded with Neuse River water via Core Creek. In addition, northeastward to southeastward winds force flow from Bogue Sound to the Morehead City Ship Channel, which deflects a significant part of the flood tidal prism into Back Sound (estimated as 41% from calculations performed over a tidal cycle). Examples of this can be seen in the drifter trajectories (Figure 8).

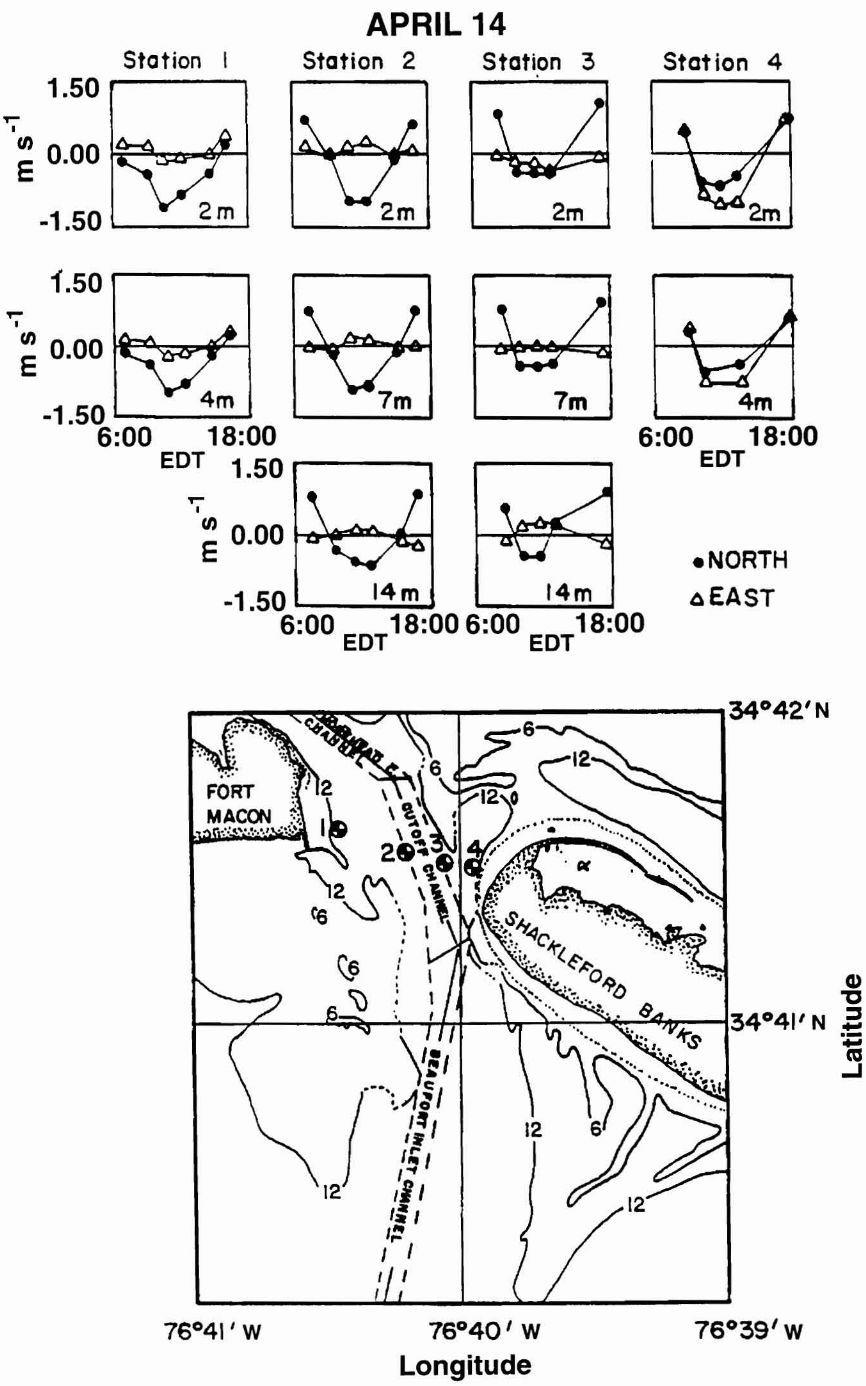

Figure 11. Cross section of velocities in Beaufort Inlet over a tidal cycle.

As the ebb flow progresses, waters coming out of Back Sound are no longer restricted to flow to the narrow channel along Shackleford Banks. The shallow flats, now inundated, carry some of the ebb flow out of Back Sound which results in reduced ebb velocities at station #19 (Figure 7f), establishing a flood dominance in the channel. Some of these waters flow the inlet across and join the Morehead City Ship Channel ebb, resulting in larger ebb velocities and transport on the western side. This can be seen in the overall ebb dominance of station #7T (Figure 7a).

The two-way inlet flow was also observed in the inlet mouth over a tidal cycle in April 1995 (Figure 11) during a ship survey. Strong flood (140 cm s^{-1}) and weak ebb velocities (40 cm s^{-1}) were observed on the eastern side of the inlet

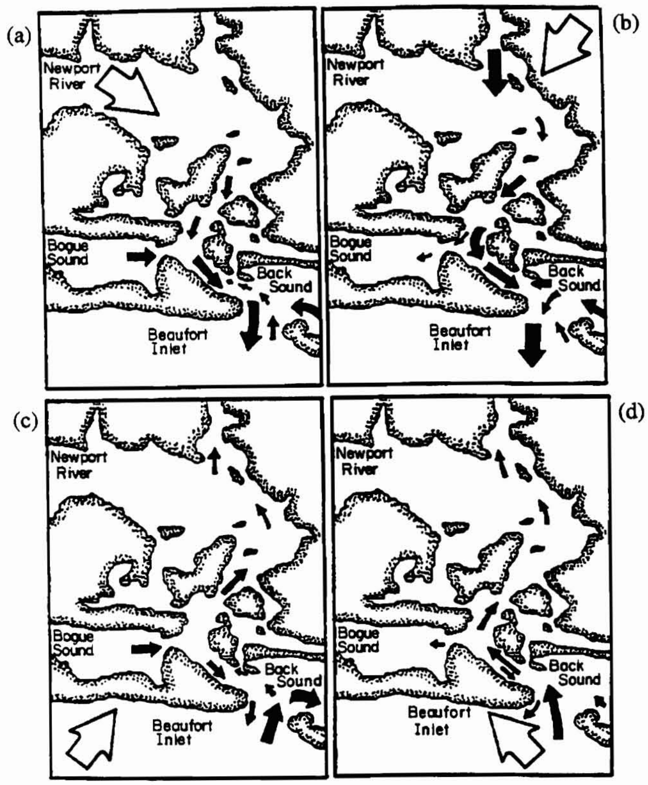

Figure 12. Schematic of wind versus flow fields throughout the estuarine complex. Flow (⧫ magnitude and direction) in Beaufort Inlet system in relationship to flow in the lower Neuse River and through Core Creek relative to winds (⇒) blowing (a) Southeastward, (b) Southwestward, (c)Northeastward, (d) Northwestward.

channel as well as a strong ebb and virtually no flood current on the western side. In addition, ebb velocities on the western side were equal in magnitude but opposite in direction to the maximum flood velocities on the eastern side of the channel.

This type of flow pattern contrasts with that in NC barrier island inlets, but is similar to that at the mouth of the Cape Fear. In Beaufort Inlet (as in the Cape Fear), inward flows are greater near the top than near the bottom. However, lateral position in the inlet is important. The east side of Beaufort Inlet will virtually always encounter inflow conditions, with retention of waters in the system, while the western side of the inlet is dominated by outflow.

Wind Forcing

Transport into and out of the estuary system is controlled by winds from three broad directional sectors. These three sectors are: the 135° T sector of southeastward to westward; the 45° sector of northwestward to northward; and the 60° T sector or north-northeastward to east-northeastward. Southeastward, southward, southwestward and westward winds hinder inflow. Southeastward winds usually result in nontidal outflows from each branch of the estuary system. Southward to westward wind cause outflows to Back Sound and result in a transport hindering pressure gradient in the Newport River from Core Creek. Northwestward and northward winds mechanically drive waters into the Newport River, Bogue Sound, and Back Sound. Finally, northeastward to eastward wind cause outflow from Bogue Sound while resulting in inflow into and retention in Back Sound. These scenarios are depicted in Figure 12 that is a schematic of wind versus flow fields throughout the estuarine complex. Table 2 provides a summary of the above.

Table 2. *Wind Direction (towards)/subtidal flow matrix.*

	Southeast-ward	Southwest-ward	Northwest-ward	Northeast-ward
Bogue Sound	Outflow	*	*	Outflow
Back Sound	Outflow	Outflow	Outflow	Inflow
Newport River	Outflow	Outflow	Inflow	Outflow
Core Creek	−	−	+	+
Salinity in	Decrease	Decrease	Increase	Increase

*Flow weak and variable.
−Core Creek water level higher than Pivers Island water so surface and interior flow are directed out
+Pivers Island water level higher than Core Creek water level so surface and interior flow are directed in

Salinity fluctuations can be not only an indicator of the presence and passage of differing water types with different origins, oceanic versus riverine, but can also be used to indicate the importance of wind direction and duration. In Figure 13, salinity fluctuations in the Morehead City Ship Channel are correlated with the direction of the wind vector and the duration of the period that the wind blows from that direction. This novel representation of three variables indicates that salinity fluctuations are marginally affected by winds blowing from/to the ENE for 1.2 days, and from/to the NE at 1.8 days. However, when the wind is blowing from a direction of 8° T to 68° T, *i.e.,* to or from the north all the way to, to or from the east-northeast, the maximum coherency contour of 0.3 can be found over a frequency band centered at 0.136 cycles per day, *i.e.,* a period of 7-⅓ days. This suggests that, if this fluctuation were due to the actual transport of Neuse River water to the Morehead City Ship Channel via Core Creek, due to a southeastward wind, the transport speed would be 4.4 cm s^{-1}. Alternatively, if the wind was northwestward then waters could have come from some 30 km offshore at the nominal onshore speed of 5 cm/sec.

Even though continental shelf waters brought in on the flooding tide regularly penetrate Bogue Sound (HYLE, 1976), retention of these shelf waters in this area is not considerable because of the local forcing of the predominant winds.

CONCLUSIONS

The retention of shelf water in the Beaufort Inlet Estuary is dependent not only on coastal Ekman dynamics but also on northward blowing winds. Southeastward blowing winds induce outflow from Bogue Sound, Newport River, and Back Sound. Southward, southeastward and westward directed winds induce Core Creek/Neuse River southward pressure gradients and outflow as well as Back Sound outflow toward the inlet. Northeastward directed winds favor transport into Back Sound while northwestward blowing winds favor trans-

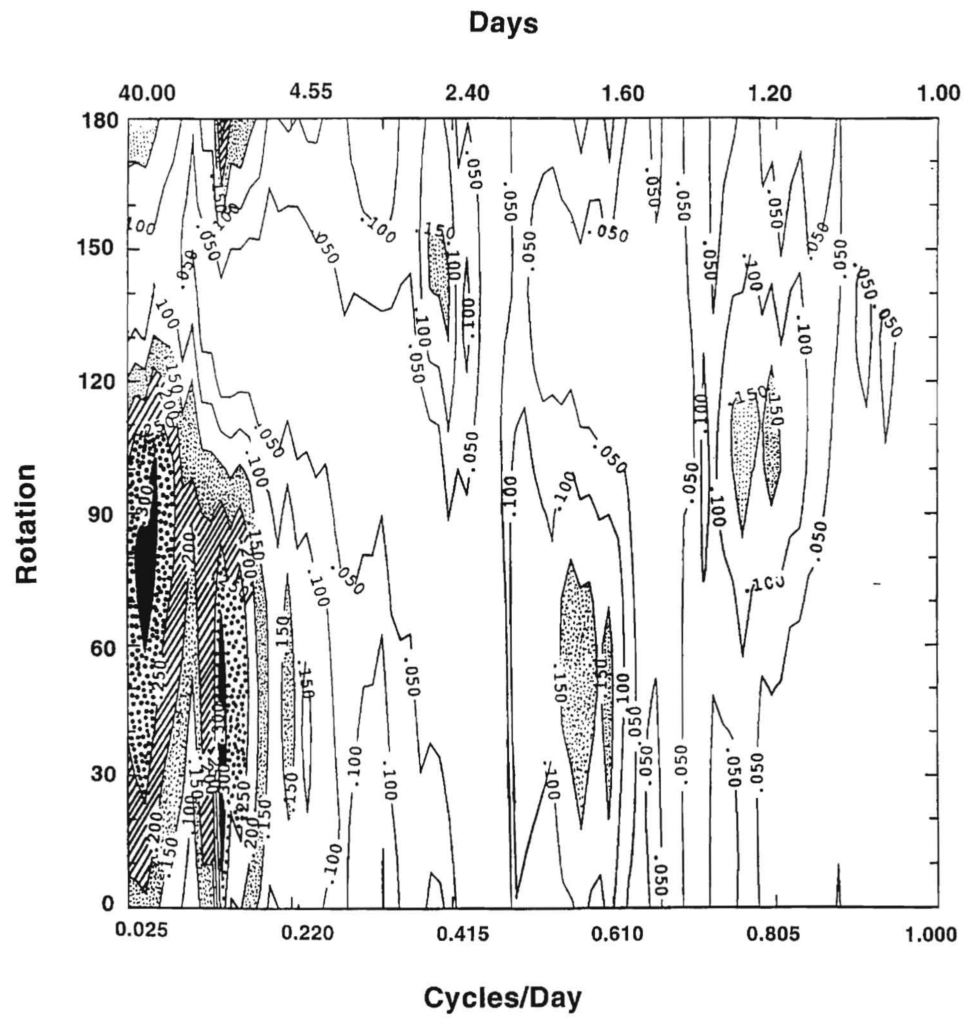

Figure 13. Coherency between direction of the wind vector and salinity fluctuations as a function of period of persistence the wind events. Direction of the wind vector is given on the vertical axis with 0° indicating "from the" north, 90° is "from the" east and 180° is "from the" south. Values of $C^2 > 0.1$ are above the 90% confidence level.

port into the lower Newport River. KLAVANS (1983) had speculated this from his tidal analysis survey. He based his idea on weather logs from the NOAA Ship FERREL. These logs indicated that northeastward directed winds might retard tidal ebb flow.

In summary, the Beaufort Inlet Estuary System can be classified dynamically as two different estuary types. It consists of the partially mixed estuary of the Newport River coupled to Bogue and Back Sounds that behave as lagoonal type estuaries. There is a two-way transport regime at the inlet mouth where the flood tides are strongest on the eastern side and ebbs are strongest on the western side. The primary cause is asymmetrical bathymetry coupled with separate hydraulic functions of the opposite sides of the inlet; flooding on the east and ebbing on the west side. The asymmetric ebb flow can easily be seen from an aerial photograph taken by the U. S. Army Corps of Engineers in 1992 (Figure 14), where turbid flow from the lower Newport River on the left side appears to be moving faster than the lagoonal ebb on the right side. This photo is very representative of the frontal conditions observed in Beaufort Inlet.

Another important finding was the effects of Core Creek Canal on the transport of surface water from the inlet to the upper Newport River. Prior to its opening in December of 1964, one can speculate that salinities were less variable in areas of the Newport River near the entrance to the canal. Once free communication with the Neuse River via the canal was allowed, these areas became subjected to wind induced salinity fluctuations.

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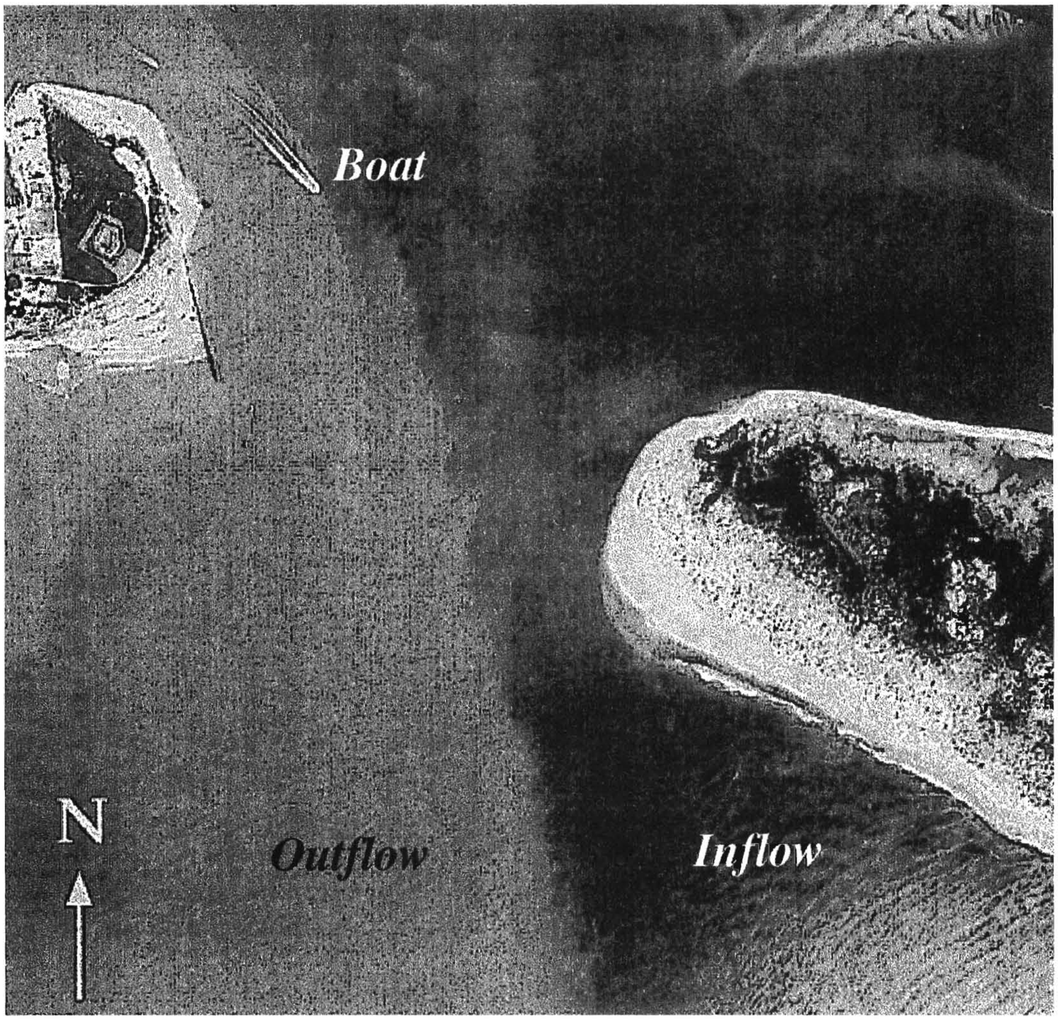

Figure 14. Aerial Photograph of Beaufort Inlet showing an assymetric flow pattern (from the Army Corps of Engineers Photogrammetry Unit, Wilmington, N.C.) where turbid flow from the lower Newport River on the left side appears to be moving faster than the lagoonal ebb on the right side.

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