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Systemwide Modeling of Wind and Density Driven Circulation in Croatan-Albemarle-Pamlico Estuary System Part I: Model Configuration and Testing

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ABSTRACT

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The Croatan-Roanoke-Albemarle-Pamlico-Core Sounds Estuary System (referred to as CAPES) of North Carolina, is the largest coastal lagoonal estuary in the United States. Although estuarine circulation and estuary-shelf exchange in the CAPES have been observed to be baroclinic, previous modeling studies of the CAPES and its interaction with the shelf were limited to barotropic, shallow water models and were statically coupled to the inlets to preserve continuity of water level and flux. In this study, a three-dimensional baroclinic model has been configured for the CAPES with dynamic coupling to the adjacent shelf. A test case was carried out, which predicted the flow pattern and salinity distribution in the CAPES and the exchange between the CAPES and coastal ocean during the passage of a prototype cold front which caused an abrupt wind shift from southwesterly to northwesterly. Comparison between model results and observations indicated that the three-dimensional model was able to predict realistic near-surface low-salinity plumes on the ocean side of inlets and river mouths, high-salinity plumes on the sound-side of inlets, and water mass exchange between different compartments of the CAPES.

ADDITIONAL INDEX WORDS: *Inlet, Outer Banks, estuary-shelf exchange, nonlinear model, baroclinic model, wind stress.*

INTRODUCTION

The Croatan-Roanoke-Albemarle-Pamlico-Core Sounds Estuary System (referred to as CAPES, PIETRAFESA *et al.,* 1986) is separated from the Atlantic Ocean by a chain of barrier islands known as the Outer Banks of North Carolina (Figure 1). CAPES is the largest coastal lagoonal estuary in the United States. It covers a total area of approximately 5500 km^2 (PIETRAFESA *et al.,* 1986). The CAPES is comprised primarily by two major bodies of water, Pamlico Sound ($\sim$120 km × 40 km) and Albemarle Sound ($\sim$70 km × 20 km), which are linked by the relatively small Croatan and Roanoke Sounds ($\sim$15 km × 5 km) (Figure 1). The average depth of the CAPES is about 4.5 m, but the actual water depth varies across the sound system from 2 to 3 m around the perimeter and at the shoals to over 7 m in the deepest basin. The shoaling regions within the Pamlico Sound are found near the mouths of Roanoke, Croatan and Core sounds, the Neuse and Pamlico Rivers, close to the Outer Banks inlets and at Bluff Shoal. Bluff Shoal which extends from Ocracoke Inlet across the sound to Bluff Point separates Pamlico Sound into two basins (Figure 1). The northern Pamlico basin has a maximum depth of about 7.5 m and is generally deeper than its counterpart to the south of Bluff Shoal where the maximum depth is less than 7 m (PIETRAFESA *et al.,* 1986). Albemarle Sound has a maximum depth comparable to that of Pamlico Sound but Croatan Sound is much shorter, narrower and shallower, with a maximum depth of about 4 m.

The CAPES is supplied with fresh water from several rivers including the Neuse, Pamlico, Roanoke, Alligator, Tar, Chowan, Pungo, and others. The sources of salt water for the CAPES are the barrier island inlets which include Ocracoke, Hatteras and Oregon inlets. These inlets connect Pamlico Sound to the Atlantic Ocean and allow the CAPES to interact with the water masses from the continental shelf of the Atlantic Ocean. Albemarle, Croatan and Roanoke sounds have no direct connection with the coastal ocean, but interact via the opening at the north end of Pamlico Sound, Oregon Inlet. Consequently, waters in the Albemarle Sound are generally much fresher than those in Croatan Sound which, in turn, is less salty than the waters in Pamlico Sound.

Accurate simulation of circulation in the CAPES, its tributary river estuaries and inlets, and adjacent shelf has wide applications in fishery and water quality studies. For example, while the Albemarle-Croatan-Roanoke sounds are inhabited by brackish water seeking fish, the Pamlico provides the principal nurseries for five estuarine dependent finfish which collectively constitute nearly 90% of the commercial catch in North Carolina coastal waters (MILLER *et al.,* 1984). How-

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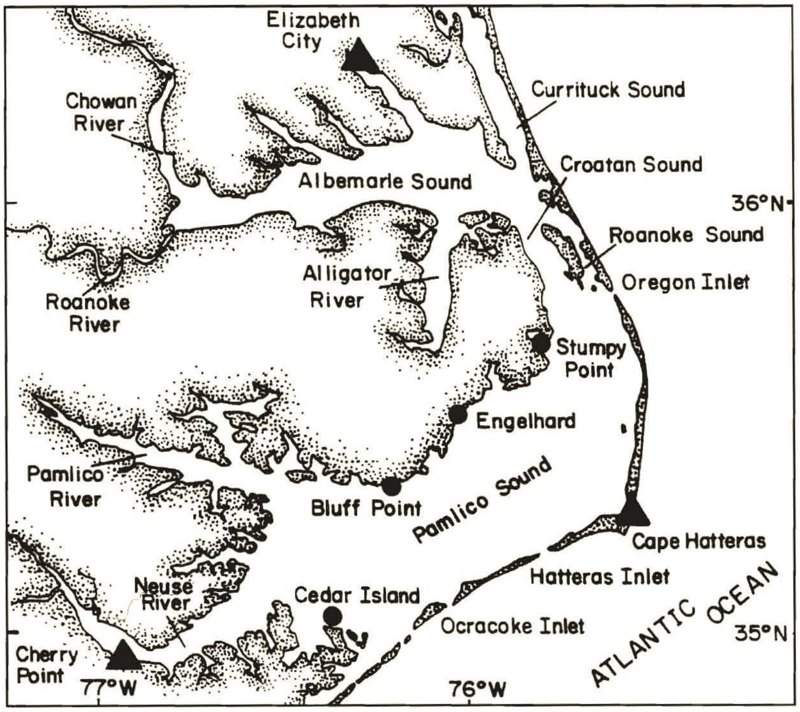

Figure 1. The Croatan-Albemarle-Pamlico Estuary System and Adjacent shelf region.

ever, numerical simulation of the CAPES circulation and estuary-shelf exchange has been hampered by its complexity. First, the CAPES is a shallow estuary system enclosed by complex and relatively low coastline, inlets and tributary rivers. Thus, during extreme weather events, the lateral boundary of the CAPES is variable due to drying and inundation. Secondly, large salinity gradient within the CAPES and near the mouths of rivers and inlets are known to produce baroclinic, density-driven circulation (PIETRAFESA *et al.,* 1986). Therefore, to accurately simulate the circulation in the CAPES and CAPES-shelf exchange, a three-dimensional, baroclinic model is needed.

The circulation in the CAPES has been numerically simulated in the past. AMEIN and AIRAN (1976) constructed a two-dimensional shallow water model to study the circulation and storm surge in Pamlico Sound. Although sea level within the Pamlico Sound was realistically reproduced by the shallow water model of AMEIN and AIRAN (1976), it did not simulate three-dimensional circulation. To simulate frictionally-induced vertical variation of current field in the CAPES and wind-induced three-dimensional exchange of water masses between Pamlico Sound and Albemarle-Croatan Sounds, a three-dimensional shallow water model (named PALPAM) was developed (PIETRAFESA *et al.,* 1986; PIETRAFESA and JANOWITZ, 1991; LIN, 1992). While PALPAM accurately predicted water level changes along the coast of CAPES (NEUHERZ *et al.,* 1993), it can not be used to simulate three-dimensional water motion in regions where significant density gradient (baroclinicity) exists, such as the vicinity of river and inlet mouths. The lack of density-driven currents in shallow water models would undoubtedly result in unrealistic estimates of horizontal transport of vertically-stratified quantities such as pollutants, nutrients, biota and general flotsam.

Another drawback in PALPAM was that the Albemarle-Croatan Sounds and the Pamlico Sound were simulated separately and a matching condition was used to link the two sound basins. Thus, the exchange between Pamlico Sound and Albemarle-Croatan Sounds depended on the matching technique, rather than the actual physics. Furthermore, riverine and inlet mass fluxes were prescribed in PAMPAM. Thus, estuary-shelf and estuary-river exchanges could not be studied (LIN, 1992). In this study, we take a systemwide modeling approach, *i.e.,* applying a single, three-dimensional, baroclinic model to explicitly resolve all major sound basins, river estuaries, continental shelf and inlets connecting the sounds to the shelf. Systemwide modeling of the entire coastal lagoonal estuarine complex is necessary because individual elements of the network do not function independently. Rather, the lagoonal elements are inextricably coupled in cause and effect relationships (PIETRAFESA *et al.,* 1986).

This is the first of a multi-part report on the CAPES modeling study at the Coastal Fluid Dynamics Laboratory (CFDL) of North Carolina State University. Here, we focus on model description and testing. More detailed discussions on inlet plume dynamics and its sensitivity to varying winds, applications of this model to transport and recruitment patterns of fish larvae and juveniles within the CAPES and the adjacent shelf using trajectory simulation and blue crab postlarvae distribution data from a companion field program will be presented in the future.

METHODS

A numerical model based on the Princeton Ocean Model (POM) (MELLOR, 1993) was used. POM solves the three-dimensional primitive equations cast in horizontally and vertically staggered grids with a terrain-following (σ) coordinate in the vertical, where $\sigma = (z - \eta)/(H + \eta)$ and z, H, η are, respectively, height relative to mean sea surface ($z = 0$), water depth, sea surface elevation relative to $z = 0$. Prognostic equations governing momentum, temperature, salinity and free surface elevation are solved with a finite difference scheme that utilizes an implicit numerical scheme in the vertical and a mode splitting technique in time. A unique feature of POM is its imbedded second order turbulence closure submodel. It is based on the governing equations that contain parameterized Reynolds stress and flux terms which account for the turbulent diffusion of momentum, heat, and salt (MELLOR and YAMADA, 1974). The incorporation of this turbulence submodel into the coastal ocean model should yield realistic Ekman surface and bottom layers. Boundary conditions used in POM include a free surface condition determined by surface momentum and heat fluxes, a lower boundary determined by the bottom topography and a bottom frictional stress that is governed by the quadratic stress law with a drag coefficient $c_d = 0.0025$. A radiation condition, which allows surface gravity waves to radiate out across open boundaries, is prescribed along the open boundaries. For more details of the model numerics, the reader should consult MELLOR (1993).

The use of POM to simulate circulations in estuaries and bays has been generally successful. These applications include the Hudson-Raritan estuary in New York (OEY *et al.*, 1985), the Delaware Bay and river system (GALPERIN and MELLOR, 1990a,b) and Prince William Sound (WANG and MOOERS, 1995). The model has realistically simulated current and salinity distributions, tidal cycle variability, events of strong mixing induced by winds and rapid salinity changes caused by river runoff.

Model Domain

In this study, the model domain extends, in the north-south direction, from the southern boundary of the Pamlico Sound including the Neuse River Estuary and Core Sound, to the northern coastline of the Albemarle Sound including the Chowan River Estuary, and in the east-west direction, from the western coastlines of Pamlico and Albemarle Sounds including the lower Tar-Pamlico Rivers to the shelfbreak off Cape Hatteras (Figure 2). The horizontal grid size is uniformly set to 1 km in both x and y directions which are rotated 45° counter-clockwise from the zonal and meridional directions, respectively. Spatially-varying vertical resolution which is determined by six vertically-stretched (σ) levels are used. The spacing of vertical levels varies according to local water depth, *i.e.*, higher vertical resolutions are achieved in the shallow water regions including the CAPES and the inner shelf while relatively lower vertical resolutions are used over the deeper parts of coastal ocean near the shelfbreak. Realistic bottom topography and coastline are used in the model as shown in Figure 2. Major topographic features such as Bluff Shoal which separates Pamlico Sound into southern and northern basins and Roanoke Island are realistically resolved. Figure 2 also shows the major river estuaries including the Neuse, Pamlico, and Chowan rivers and the three passageways from the sounds to the ocean including the Ocracoke, Hatteras, and Oregon inlets of the CAPES. The cut-off minimum depth depicted in Figure 2 is 1.5 m. Water depths between 1.5 and 1 m are approximated as 1.5 m while waters shallower than 1 m are assumed to be the peripheral land boundary.

Model Initialization

Temperature

Water temperature in the CAPES varies seasonally from as low as 7°C in February to about 30°C in July, but it is fairly uniform and well-mixed within the system with a systemwide temperature contrast of less than 3°C horizontally and 1°C vertically (SCHWARTZ and CHESTNUT, 1973). The average winter season temperature in the CAPES is just over 10°C near major inlets and decreases to about 7°C near the coast on the mainland side. The average summer season water temperature in the CAPES is about 28°C with a horizontal difference generally less than 2°C. The average water temperature in the CAPES during spring and fall is typically in the mid-to-lower 20s. Based on this climatology of water temperature in the CAPES, a uniform temperature of 25°C representing typical late spring, early summer and early fall conditions is prescribed for the entire model domain.

Salinity

The salinity field in the CAPES also experiences considerable seasonal variability with lower values occurring during the winter and higher values in the summer. Unlike the temperature field, salinity in the CAPES varies significantly spatially with larger values generally found near the major inlets of Pamlico Sound, lower values near major river mouths, and nearly fresh water in Albemarle Sound (SCHWARTZ and CHESTNUT, 1973). In February, the highest surface salinity (19 ppt) is found near Ocracoke Inlet with lower values (less than 10 ppt) found on the western side of Pamlico Sound and in Croatan and Roanoke sounds and nearly fresh waters (less than 5 ppt salinity) in Albemarle Sound. In July, the mean surface salinity near Ocracoke and Hatteras inlets reaches more than 21 ppt. Salt plumes with salinity values greater than 26 ppt often intrude into the CAPES through Oregon Inlet in August, further intensify during the Fall with peak values reaching 32 ppt in September and October. Salinity also varies between surface and bottom waters. The largest reported salinity difference between surface and bottom waters is 3 ppt though much larger, event related difference are assumed to occur particularly near river mouth and inlets (PIETRAFESA *et al.*, 1986). On average, bottom waters are approximately 0.66 ppt saltier

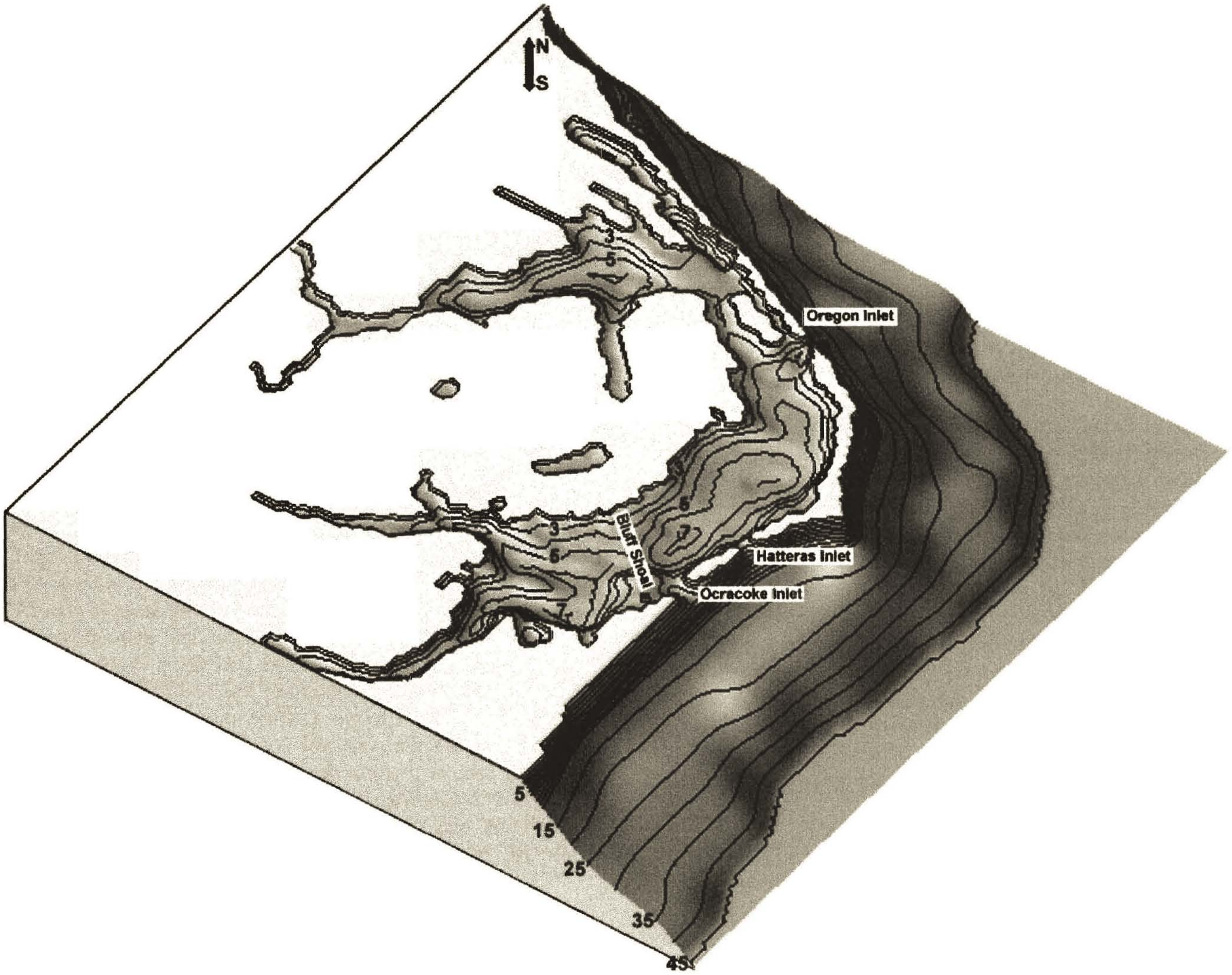

Figure 2. Model domain and bathymetry. The numbers indicate depths in meters.

than surface waters (ROELOFS and BUMPUS, 1953). Salinity values on the continental shelf off the Outer Banks south of Cape Hatteras are on the order of 35 ppt and below 32.5 ppt north of Cape Hatteras throughout the year except near major inlets where low salinity plumes rushing out from the CAPES can lower the salinity in the vicinity of the plumes (PIETRAFESA *et al.,* 1994).

To represent the mean characteristics of surface salinity distribution in the CAPES, values of 18–20 ppt are specified for Pamlico Sound, 5–10 ppt for Croatan and Roanoke sounds and the Neuse and Pamlico River estuaries, and 2–4 ppt for Albemarle Sound and the Chowan River estuary. For continental shelf waters, a uniform salinity of 35 ppt is assumed initially, though it is known that inner shelf waters north of Cape Hatteras are generally less than 32.5 and can occasionally be less than 32.5 ppt to the south of Cape Hatteras (PIETRAFESA *et al.,* 1994).

Current Field

The CAPES is assumed to be initially at rest, and well-mixed vertically. Then, a 5 m/s northeasterly wind is applied to the water surface for 5 days to mix riverine, estuarine, and shelf waters horizontally and vertically and generate a dynamically adjusted three-dimensional flow field in the CAPES system. Surface salinity was held constant during the initialization simulation. The resultant three-dimensional salinity and velocity fields were then saved as the adjusted initial conditions for subsequent simulations.

RESULTS

The response of the CAPES to a sudden shift of wind direction from southwesterly (SW) to northwesterly (NW) winds was conducted to test the model. SW-NW wind shifts often occur during cold front passages. For simplicity, a moderate wind speed of 5 m/s was used for the entire process. Furthermore, in order to isolate wind effects, no heat flux was considered.

Response to Southwesterly Winds

Surface Responses

Figure 3 shows the temporal evolution of surface salinity and velocity fields in the CAPES forced by a 5 m/s southwesterly wind during a 5-day period. The surface salinity field and streamline patterns in the CAPES from Day 1 to Day 4 are depicted in Figures 3a through 3d, respectively. The main characteristics of the responses of CAPES circulation and CAPES-shelf exchange are summarized below.

Oregon Inlet: At the start of the simulation, a uniform southwesterly wind was ramped up from 0 to 5 m/s over a 24 hour period. The onset of southwesterly winds produced wind-driven transports which advect salinity across major salinity fronts (or boundaries separating the water masses) in the inlets and river mouths of the CAPES. We note (Figures 3a–d) the fresh water plume on the ocean or outwelling side of Oregon Inlet as waters flowed out of northern Pamlico Sound. A well-defined anticyclonic circulation was associated with the outwelled plume.

From Days 2–4, the fresh water plume on the offshore side of Oregon Inlet continued to grow spatially. The surface flow associated with the plume was characterized by two vortices, an anticyclonic one on the right and a cyclonic one on the left. The anticyclonic cell was better organized than its cyclonic counterpart. It is also worth noting that this anticyclonic plume expanded offshore approximately in the direction of the wind, which indicates that in the absence of southward inflow from the Virginia Coast, a southwesterly wind would produce a northward coastal flow which might, in turn, support offshore-flowing fresh-water plumes during southwesterly winds. This result is in keeping with the analytical results of ZHANG *et al.* (1986). ZHANG *et al.* (1986) presented observations and a theoretical basis for outwelling estuarine plumes having several degrees of freedom; *i.e.*, they could turn right, turn left or somewhere in between. In fact, the ZHANG *et al.* case of a plume which jetted straight offshore can look remarkably like the flow of Figure 3. Straight offshore plume can also be seen in high-resolution satellite SST imagery taken over the CAPES (Figure 4). Note that the outwelling plume at the mouth of Oregon Inlet observed on March 16, 1996 has an offshore scale of approximately 15 km (Figure 4) or about 12–13 times the width ($\sim$1.2 km) of Oregon Inlet. The width of Oregon Inlet in the model was set to three grid points or 3 km for computational purposes. The offshore scale of the simulated, fully-developed, outwelling Oregon Inlet plume was about 40 km (Figure 3d) or approximately 13 times the width of the modeled inlet. This 1/13 ratio between the width of the Oregon Inlet and the offshore scale of the outwelling plume predicted by the model was coincidentally close to that of the observed plume shown in Figure 4. The effect of the width of the estuary on the plume was discussed by TAKANO (1954a,b, 1955). He showed that in the absence of ambient flow, the plume deviates to the right in the Northern Hemisphere, with the extent of deviation being dependent on the parameter R_0, which is related to the width of the mouth of the estuary (W), the Coriolis parameter (f), and the horizontal eddy viscosity (A_h), through $R_0 = fW^2/A_h$. As we noted earlier, outwelling plumes may also deviate to the left or straight offshore when bottom slope (BEARDSLEY and HART, 1978) and ambient flow (ZHANG *et al.*, 1987) were considered. Thus, the offshore structure of the plume may be affected by ambient flow, inlet depth and width, bottom slope, and winds. Therefore, the meteorological and oceanographic processes that determined the offshore scale of the plume observed in Figure 4 must be diagnosed, and the sensitivity of the modeled plume in Figure 3 to variations in inlet width and depth, ambient coastal currents, and winds must be analyzed further before conclusions about the dynamics of inlet plume can be made.

Ocracoke and Hatteras Inlets: No fresh water plumes developed off Hatteras and Ocracoke inlets throughout the southwesterly wind events (Figures 3a–d). Instead, saltier coastal waters flowed into Pamlico Sound. However, such salt-water plumes appeared to be confined to the vicinity of the inlets except near Bluff Shoal where a clockwise circulation could be found in the northern Pamlico Sound and a cyclonic cell could be found in the Southern Pamlico Sound, apparently due to topographic steering by the shoal. These two recirculation patterns produced a northwestward flow over the shoal which caused a northwestward advection of saltier water from the inlet region along the eastside of the Pamlico Sound (Figure 3b). This advection was more evident on Days 3 and 4 (Figures 3c and d). Saltier water inwelled into the CAPES through Hatteras and Ocracoke inlets and was advected to the center of the sound along Bluff Shoal by the northwestward surface current along the shoal. Excepting for this cross sound transport of surface water along Bluff Shoal, higher salinity near surface coastal waters were mostly confined to the inshore and soundsides of Ocracoke and Hatteras inlets and along the sound-side boundaries of the Outer Banks to the north of these two inlets within 3 km of the coastline. This is consistent with the 2–3 km jetting-distance of salty inwelling inlet plumes found by PIETRAFESA and JANOWITZ (1991). Meanwhile, within Pamlico Sound, the circulation pattern to the north and south of Bluff Shoal was gradually replaced by a more northward flow.

Pamlico and Neuse River Estuaries: The salinity and current fields in the Pamlico and Neuse rivers were forced by both wind stress applied at water surface throughout and fresh water fluxes applied at the heads of the model rivers. A 0.1 m/s barotropic inflow was prescribed on a 1 km wide and 2 m deep cross-river section for the Neuse River and on a 1 km wide and 1.5 m deep section for the Pamlico River. These values are equivalent to fresh water fluxes of 200 m^3/sec for the Neuse and 150 m^3/sec for the Pamlico River which are in keeping with the observed annual-mean runoffs from these two rivers (173 and 153 m^3/sec, respectively) as estimated by GIESE *et al.* (1985).

As shown in Figures 3a–d, fresh water flowed downstream in the upper sections of the rivers in response to the pressure gradient force effected by the input of freshwater at the head.

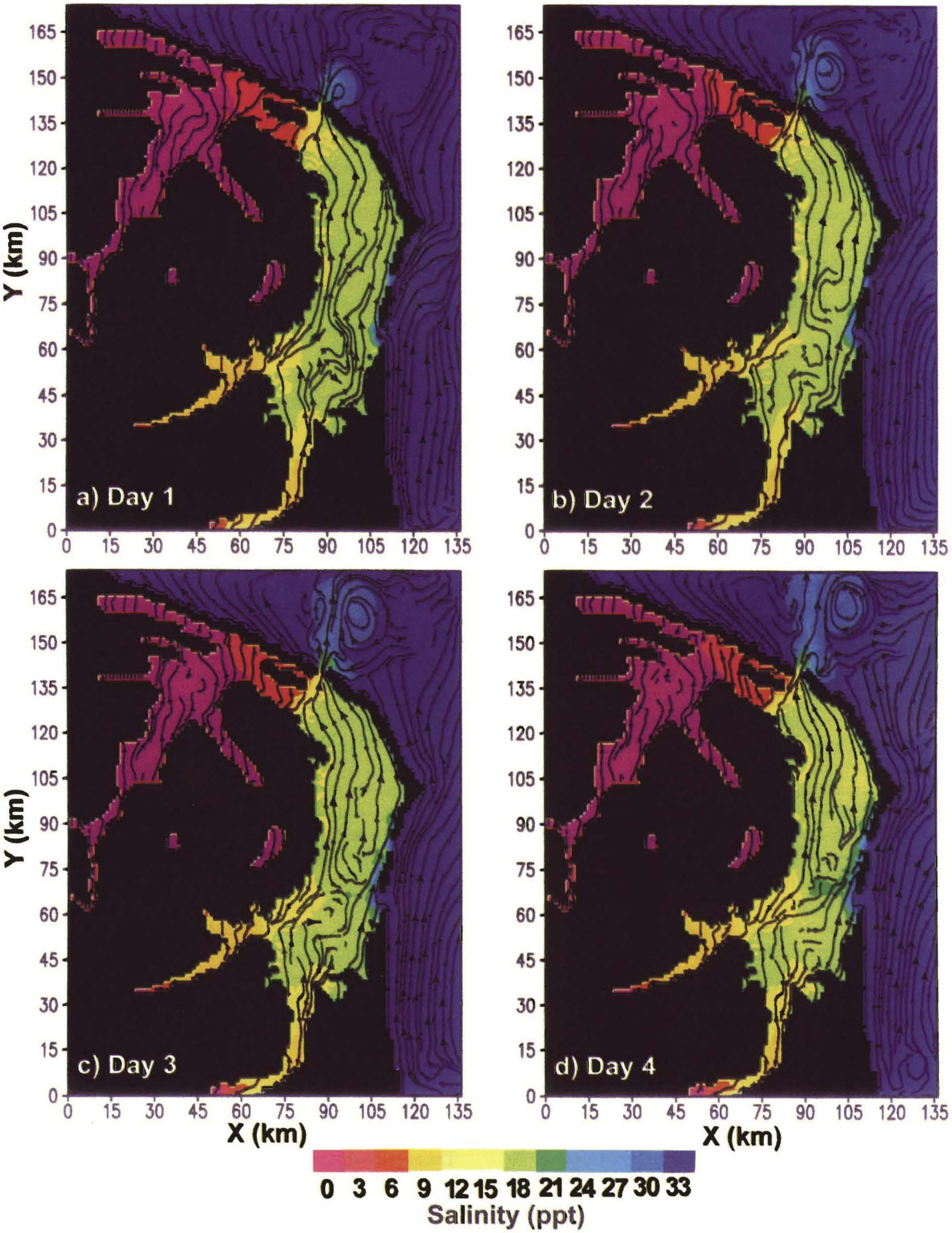

Figure 3. Simulated near-surface velocity and salinity fields associated with southwesterly winds. (a–d) are for Days 1–4, respectively.

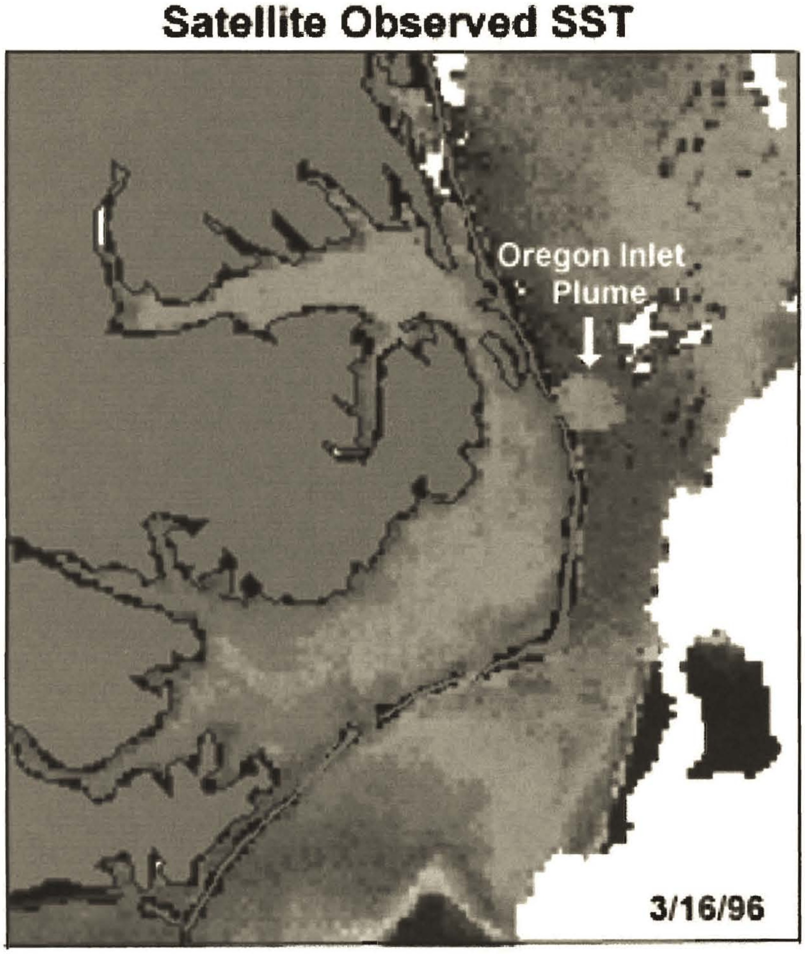

Figure 4. AVHRR image of sea surface temperature observed by NOAA satellite on March 16, 1996. This image shows an outwelling Oregon Inlet plume which extends approximately 16 km offshore (Courtésy of E. Bohm).

In the upper section of the Neuse River estuary just downstream of New Bern, the relatively fresh (less than 9 ppt) water tended to flow along the northern river bank, apparently in response to mechanical forcing of southwesterly winds. This is most evident in Figures 3c and d. However, in the lower section of Neuse River, 12–18 ppt estuary water flowed into Pamlico Sound along the right-side bank, despite the southwesterly wind forcing. In contrast to this rightward deflection, the water from the Pamlico River tended to flow into Pamlico Sound along its northern Bank under southwesterly winds. Such a difference can be understood via the interaction between the river estuary flow and the flow within Pamlico Sound. At the mouth of the Neuse River estuary, the water from the river flowed approximately in the same direction as the Pamlico Sound water because the axis of the lower Neuse was approximately parallel to the southwesterly wind which was aligned with the major axis of the sound also. Therefore, the fresh water plume from Neuse River deflected to the right without encountering significant opposing currents from Pamlico Sound. On the other hand, due to the east-west orientation of the lower Pamlico River, as the river water flowed from the Pamlico River estuary into the sound, it encountered north to northeastward flowing sound water. As a result, the Pamlico River fresh water plume was pushed against the northern and western banks (Figures 3a–d). Therefore, under the southwesterly winds, waters from the Neuse and Pamlico Rivers were forced to flow along the boundaries of southern and western Pamlico Sound and thus were prevented from intruding into the center of the Sound.

Bottom Responses

Figures 5a–d shows the evolution of near-bottom currents and salinity distribution in response to the southwesterly wind from Day 1 to Day 4. The near-bottom current pattern in the CAPES was almost opposite to that near the surface, which was evident throughout the 4 day period. The near-bottom salinity field also showed considerable difference from that near the surface. Major characteristics of the bottom responses can be summarized below.

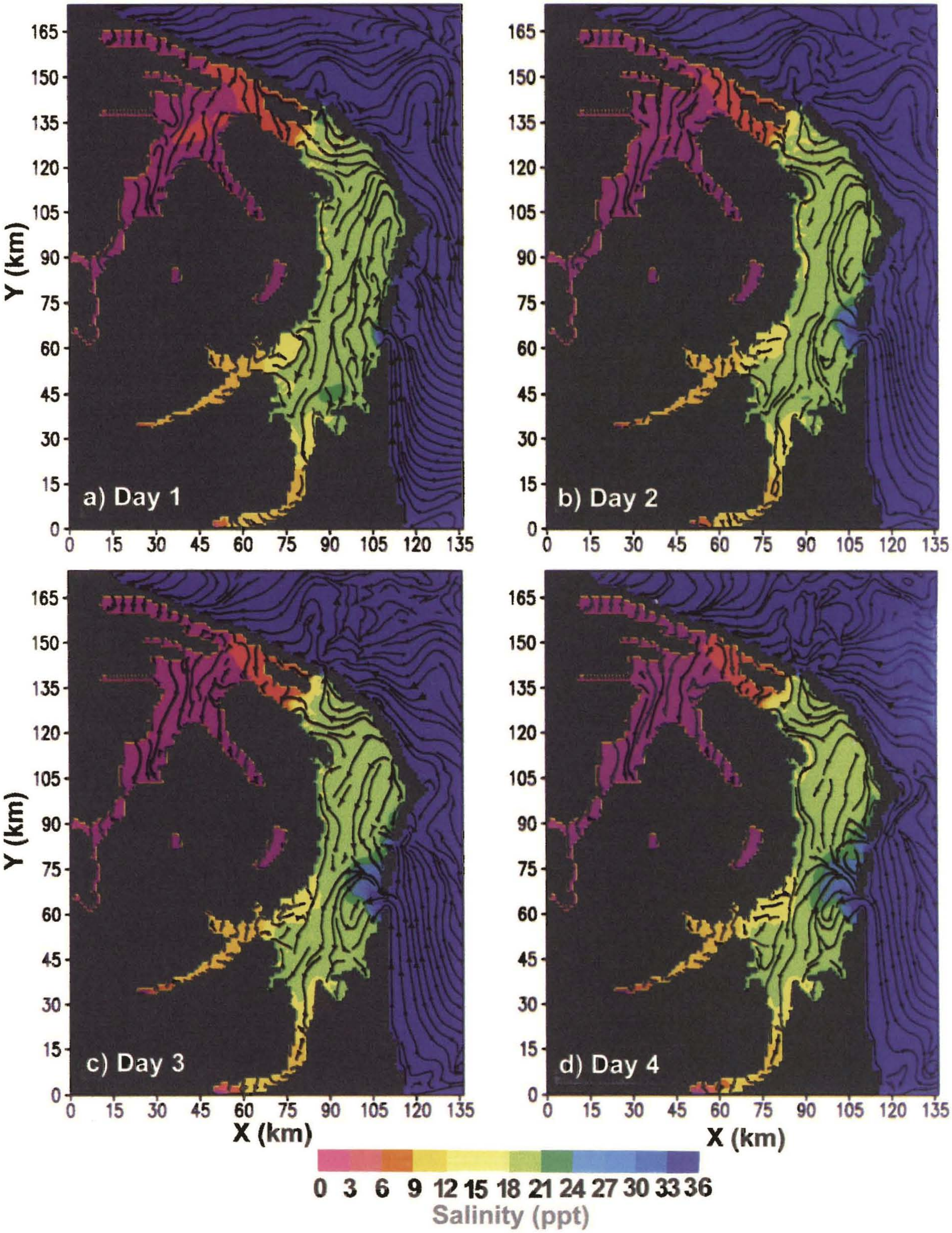

Figure 5. Simulated near-bottom velocity and salinity fields associated with southwesterly winds. (a–f) are for Day 1–4, respectively.

Oregon Inlet: A convergent flow pattern could be seen near Oregon Inlet starting from Day 1 (Figure 5a). Waters from Pamlico Sound flowed offshore while waters from the shelf flowed onshore. Such a convergent flow pattern was also evident from Day 2–4, and did not result in a plume formation (Figures 5b–d). Therefore, the fresh water plume seaward of Oregon Inlet was confined to the upper layers.

Ocracoke and Hatteras Inlets: A soundward expanding high-salinity plume is easily seen near Ocracoke Inlet (Figures 5a–d). Similar to the surface current pattern, a westward flowing current was observed along Bluff Shoal starting from Day 2. This current was associated with a cyclonic circulation to the south of the shoal. However, no well defined anti-cyclonic pattern can be identified north of the shoal. Rather, a convergence line can be found between the westward flowing saltier water and the southward flowing water from the northern basin of Pamlico Sound. This southward current was apparently caused by the pressure gradient resulting from the sea-level setup due to the northward flowing surface current driven by wind. It can be seen from Figures 5a–d. As the high-salinity water, inwelling plume expanded westward from Ocracoke Inlet, the southward-flowing bottom current was obstructed on Bluff Shoal by the plume. From Days 2–4, the southward current in Pamlico Sound can only be found near the western boundary. Bottom currents were northward along the soundside of the Outer Banks to the south of Ocracoke Inlet.

Although a high-salinity inwelled plume can be seen on the sound side of Hatteras Inlet on Days 3 and 4, this plume was much smaller in size than that of Ocracoke Inlet, suggesting that southwesterly winds are more favorable for the entrainment of shelf waters into the CAPES from Ocracoke Inlet than Hatteras Inlet and Oregon Inlet. This issue will be discussed in more detail in another paper.

Pamlico and Neuse River Estuaries: Near the bottom, Pamlico Sound waters flowed past and into the lower reaches of the Neuse and Pamlico River estuaries and met the discharging river flow within the estuaries under southwesterly winds (Figures 5a–d). However, the surface currents within the sound as well as in the lower rivers were directed northeastward as the sound waters were mechanically driven to the northeast and the rivers then went into an accelerated drainage mode. Saltier bottom sound waters did move into the lower river mouths in response to the axial horizontal salinity gradients.

Response to Northwesterly Winds

Surface Responses

Oregon Inlet: Figure 6a shows the surface salinity and streamline patterns just before the onset of northwesterly winds (Day 5). A noticeable feature in the Oregon Inlet outwelled plume was the development of a secondary anticyclonic circulation seaward of the mouth of the inlet. At this time, major features such as the northward intrusion of saltier water from Hatteras Inlet along the Outer Banks and the westward intrusion of saltier water from Ocracoke Inlet along Bluff Shoal continued to persist and were similar to those on Day 4 (Figure 3d). On Day 6, northwesterly winds had blown over the CAPES for 24 complete hours. In response to this new wind field and within an inertial period of ~18 hours, the coastal current on the continental shelf had switched to a southward direction. As a result of the adjustment of shelf currents to the wind change, the nearshore portion of the outwelled fresh water plume outside of Oregon Inlet was sheared to the right along the Outer Banks. This eventually led to a cut-off of the anticyclonic vortex on the front portion of the plume from the source of the fresher water near the inlet (Figure 6b). From Days 7 and 8, a high-salinity plume had inwelled into northern Pamlico Sound via Oregon Inlet (Figures 6c and d). The previously existing fresh water plume had now separated into two patches of low salinity water and had been completely cut-off from the sound water; with one patch associated with the anticyclonic vortex offshore and the second patch sheared southward along the Outer Banks and near the coast.

Albemarle-Roanoke-Croatan Sounds: While no significant water mass adjustments occurred in Roanoke, Croatan and Albemarle sounds under southwesterly winds, the shift of winds into northwesterly produced a well-defined southward discharge of these relatively fresh waters into northern Pamlico Sound (Figure 6b). This water moved into Pamlico Sound faster than did the saltier water from Oregon Inlet (Figures 3c and d). A strong salinity front resulted and can be identified between these two water masses in northern Pamlico Sound just to the south of Roanoke Island. This front was maintained by the confluent zone between the southward flowing high-salinity coastal water inwelled through Oregon Inlet and the southward flowing low salinity water discharged through Croatan and Roanoke sounds; principally by the former since it was wider and deeper than the latter.

Ocracoke and Hatteras Inlets: Surface flow and salinity pattern underwent complete reversals in Ocracoke and Hatteras inlets as the wind shifted from southwesterly to northwesterly. From Day 5 (Figure 6a) to Day 6 (Figure 6b), high-salinity waters on the sound side of Ocracoke and Hatteras inlets were replaced by seaward flowing lower-salinity sound waters. On Day 6, one low-salinity plume formed off Hatteras Inlet and another formed off Ocracoke Inlet. Both turned to the right as they flowed offshore.

On Day 7, the plume off Hatteras Inlet extended into the region of the Ocracoke Inlet plume (Figure 6c) and the two plumes merged. However due to the blocking effect of the Ocracoke Inlet plume, the Hatteras Inlet plume was constrained to grow in an offshore direction while the Ocracoke plume continued to flow southward in the direction of the coastal current (Figure 6d).

Pamlico and Neuse River Estuaries: The southwesterly to northwesterly wind shift altered the salinity distribution within the Pamlico and Neuse river estuaries. Compared with Day 5 (Figure 6a), and following the wind shift on Day 6, a stream of Pamlico River water flowed into Pamlico Sound along the southern boundary (Figure 6b). This low-salinity Pamlico River water continued to flow southward on Days 7 and 8 (Figures 6c and d). However, the northwesterly wind prevented the low-salinity water in the lower Neuse River from flowing into Pamlico Sound. Only a small patch of

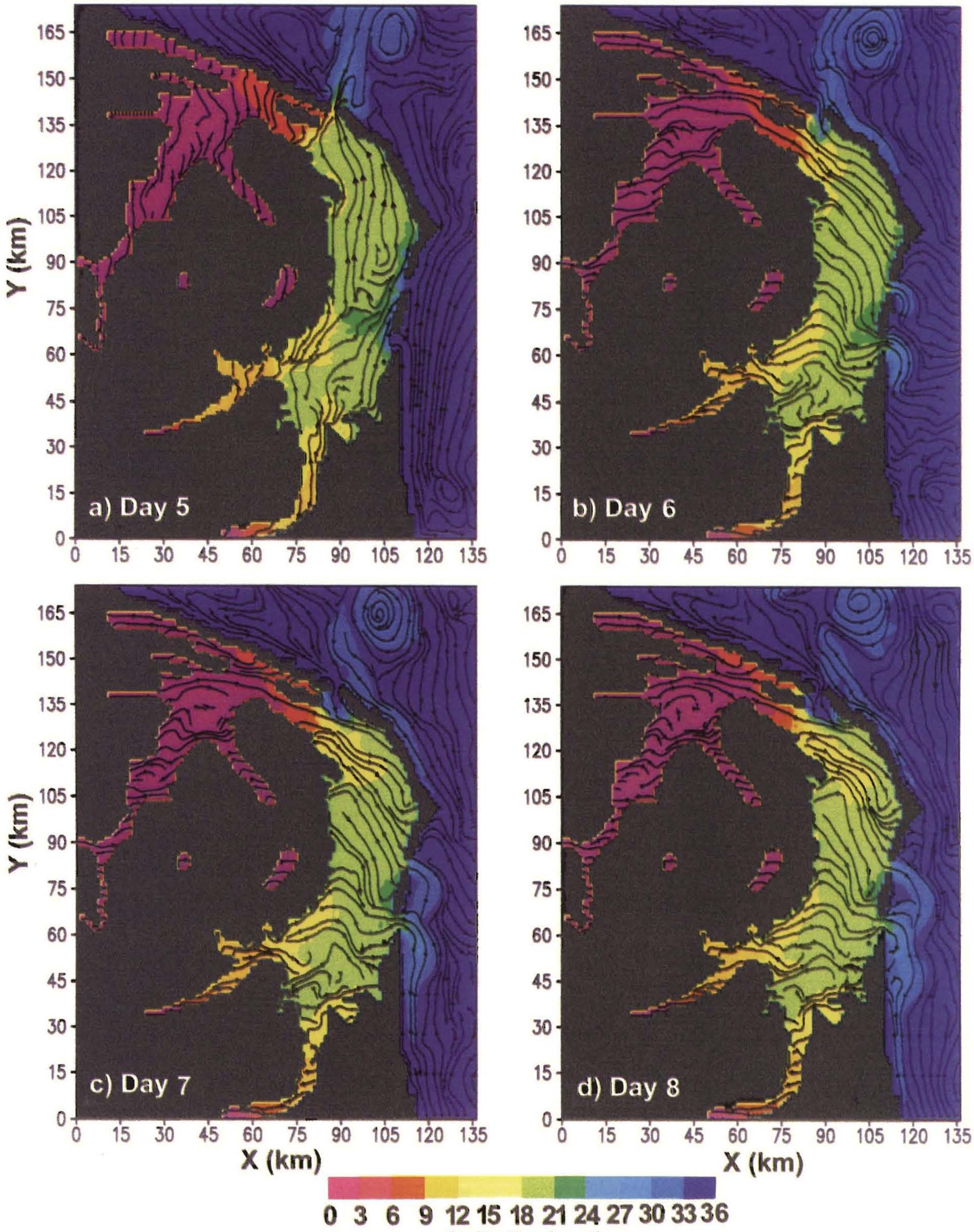

Figure 6. Simulated near-surface velocity and salinity fields associated with southwesterly-to-northwesterly wind shift. a) is under southwesterly winds on Day 5. (b–d) are for northwesterly wind conditions from Day 6–8, respectively.

Neuse River water can be found along the southern boundary of Pamlico Sound.

Bottom Responses

As in the southwesterly wind case, the response of the bottom salinity and flow under northwesterly winds differed considerably from those at the surface. A number of features can be noted.

Oregon Inlet: After the onset of northwesterly winds, a high-salinity inwelling plume formed not only near the surface as discussed above, but also near the bottom (Figure 7b). Again, fresh waters flowed into the northern Pamlico Sound via Croatan (and Roanoke) Sound. The salinity front south of Croatan Sound was tilted toward the sound as the water depth increases. This was indicated by the greater soundward extension of the salinity plume near the bottom than that near the surface (Figures 7c and d). This salt wedge extended from the surface to the bottom, unlike the fresh water plume seen during the southwesterly winds (Figure 3), which was primarily confined to the near-surface.

Ocracoke and Hatteras Inlets: Since the near-bottom waters flowed northwestward within the Pamlico Sound, high-salinity waters entrained into Pamlico Sound remained within the northern basin of the Pamlico Sound (Figures 7b–d). No high-salinity water remained in the southern basin of the Pamlico Sound by Day 8 (Figure 7d). The fresh water plumes seen on the ocean side of the Hatteras and Ocracoke Inlets did not extend to the bottom except for a very thin stream of fresh water that flowed southward along the Outer Banks south of the Ocracoke Inlet (Figures 7c and d). Therefore, due to the control of buoyancy, fresh water plumes stayed mainly near the surface even if the coastal current was equivalent-barotropic.

Pamlico and Neuse River Estuaries: The near-bottom salinity pattern within and near the Pamlico and Neuse River estuaries (Figures 7b–d) is similar to that near the surface (Figures 6b–d) despite the difference in the flow patterns between the surface and bottom. For example, low-salinity waters can be found along the west coast of Pamlico Sound both near the surface and the bottom, although surface waters flowed toward the sound and bottom waters flowed toward the estuaries. Thus, the relatively fresh waters found on the western side of the southern Pamlico Sound to the south of the Pamlico River mouth (Figures 7c and d) must be caused by vertical mixing.

DISCUSSION AND CONCLUSIONS

A three-dimensional, 1 km horizontal resolution primitive equation hydrostatic model (POM) has been successfully configured for the CAPES. A test experiment under southwesterly and northwesterly winds revealed realistic flow pattern and salinity distribution near major inlets and river estuaries. Main results are:

(1) The formation of a low-salinity plume off the Oregon Inlet during southwesterly winds. This plume was confined near the surface and grew in the offshore direction. After the onset of the northwesterly winds, the Oregon Inlet outwelling fresh water plume on the shelf was sheared off and split into two pieces by the coastal current. One plume piece remained offshore and appeared as an anticyclonic vortex. The other piece was confined near the coast and flowed southward. This result suggests that synoptic wind events strongly affect the structure of near-surface outwelling plumes.

(2) Under northwesterly winds, a high-salinity plume formed on the sound side of Oregon Inlet. It was wedge-shaped and extended from the surface to the bottom with a greater sound-side extension near the bottom. Meanwhile, fresher water rushed out from Croatan Sound into northern Pamlico Sound. This fresh water current met the Oregon Inlet salt-water plume and formed a salinity front in between. Thus, inwelling high salinity plumes from Oregon Inlet strongly affect the density gradient between northern Pamlico and Croatan Sounds, and hence the exchange between the Pamlico and the Croatan-Albemarle Sounds.

(3) High-salinity coastal ocean plumes intruded into Pamlico Sound from Hatteras and Ocracoke Inlets during southwesterly winds. Again, such plumes were wedge-shaped and had wider bases. Saltier water from the Ocracoke Inlet may intrude into the center of Pamlico Sound along Bluff Shoal. High-salinity bottom waters entrained into the northern basin of Pamlico Sound can remain there even after the onset of northwesterly winds. However, after the onset of northwesterly winds, sound surface waters flowed seaward through Hatteras and Ocracoke inlets. This caused the formation of low-salinity plumes off Hatteras and Ocracoke inlets which tend to flow to their right (southward). Due to the proximity of these two inlets and the southward coastal current in the presence of northwesterly winds, the two plumes from Hatteras and Ocracoke Inlets can converge as the Hatteras Inlet plume flowed into the Ocracoke Inlet plume. The result of this merging of plumes caused the Hatteras Inlet plume to grow more seaward after encountering the offshore flow associated with the Ocracoke Inlet Plume. Hence, the existence and proximity of multiple inlets along the barrier islands created a more complex estuary-shelf exchange scenario due to plume interactions.

(4) Although fresh water plumes from the Pamlico and Neuse River Estuaries tended to move along their southern or right-side banks, the interactions between the river discharge and the wind driven Pamlico Sound flow significantly affected the salinity distribution near the mouth of the estuaries. Thus, the exchange between the river and the estuary is quite similar to that between the estuary and the shelf in that both are affected by winds as well as mean currents along the coast near the mouth of the river or inlet.

The implications of the model results are several under the considered subinertial frequency conditions of southwesterly and northwesterly winds:

(1) The barrier island inlets play multiple roles in the continual interaction of the coastal ocean with the coastal lagoonal sound system. When all three are flooding, the sound system goes into a storage mode and becomes saltier. When all three are ebbing, the sound is discharging and freshening. However, individual components of the CAPES system respond to inlet forcing differently. For example, under northwesterly winds the saltier coastal water flooded the northern Pamlico Sound through Oregon Inlet, but the same winds

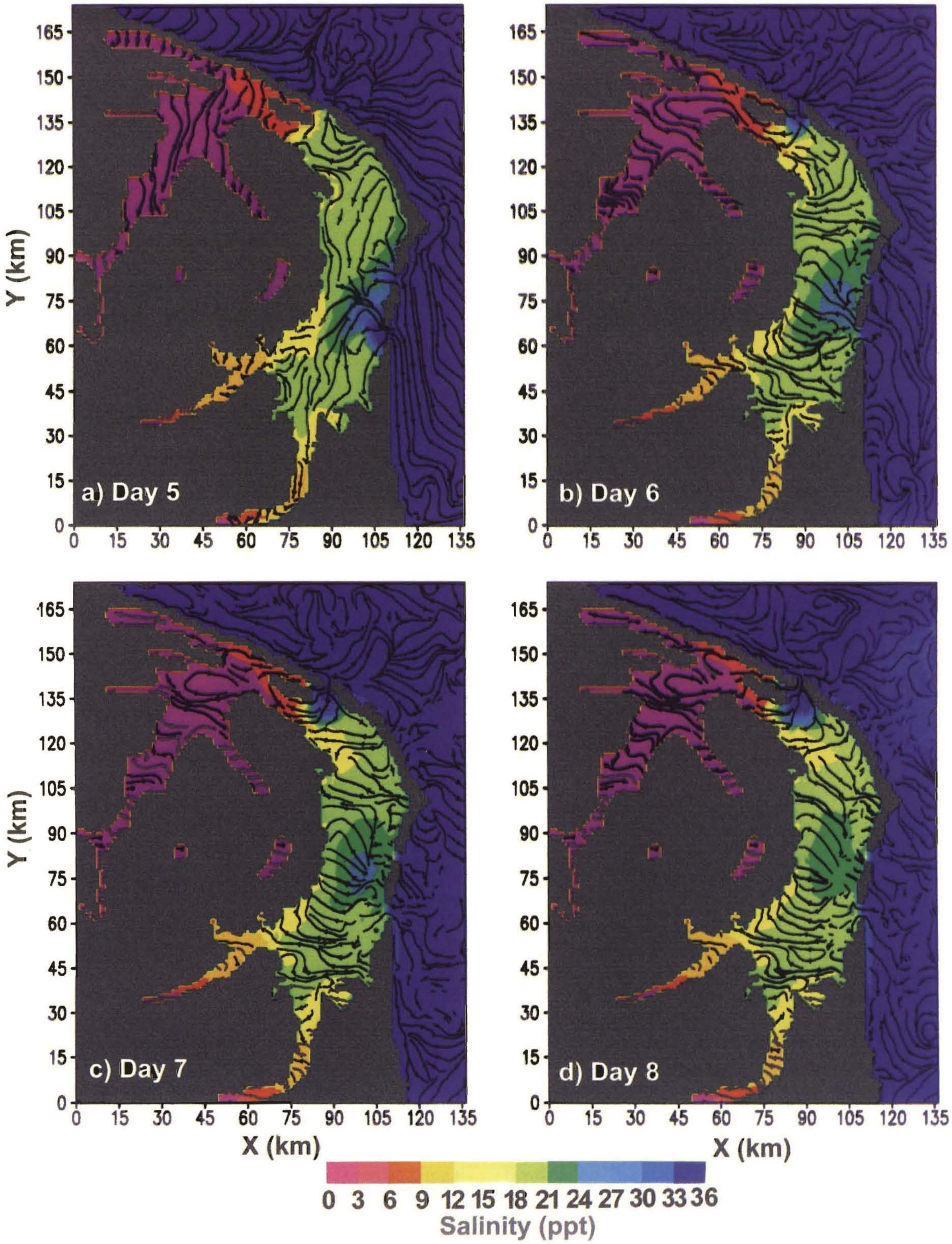

Figure 7. Simulated near-bottom velocity and salinity fields associated with southwesterly-to-northwesterly wind shift. (a) is for southwesterly winds on Day 5. (b–d) are for northwesterly winds from Day 6–8, respectively.

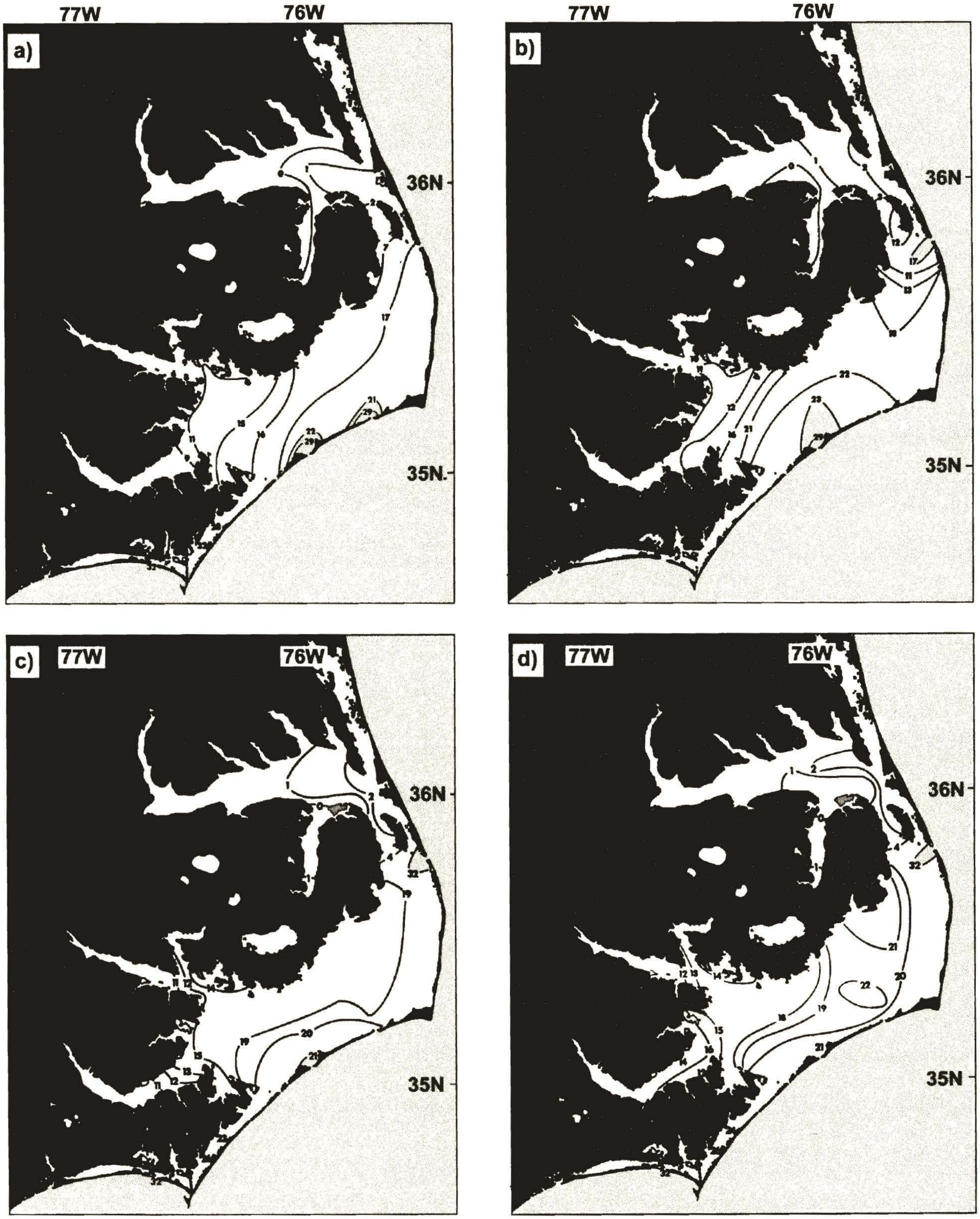

Figure 8. Observed surface and bottom salinity within the CAPES (From SCHWARZ and CHESTNUT, 1973). (a) surface salinity in May; (b) bottom salinity in May; (c) surface salinity in September; (d) bottom salinity in September.

also drove fresher Albemarle-Croatan Sound water into Pamlico Sound. As a result, the Albemarle-Croatan Sounds remained relatively fresh while a salinity front formed between the soundward flowing Albemarle-Croatan Sound water and the coastal water inwelled through Oregon Inlet. This supports the hypothesis that Albemarle Sound is recruitment limited (PIETRAFESA *et al.,* 1986).

(2) Generally Oregon Inlet accommodates the discharge requirements of Albemarle Sound and the Pamlico Sound's northern basin while Hatteras and Ocracoke inlets service the sound system south of Bluff Shoal. Under southwesterly winds, fresher sound water discharges into the ocean through Oregon Inlet as outwelling plumes;

(3) Oregon Inlet and the Hatteras-Ocracoke Inlet doublet often play supportive roles with the former discharging (ebbing) while the latter pair is ebbing (discharging);

(4) The inlet outwelling plumes can maintain their identities throughout the course of a wind event and can become vortices of fresh water in the more saline coastal environment;

(5) The inlet inwelling plumes stay in the sound system providing new sources of saltwater to the system to maintain the CAPES system's salt balance; thus the salt balance is maintained via a balance of freshwater discharge which entrains salt as it leaves the system, and wind induced inwelling of coastal waters. Generally, inwelling salt water plumes are wedge-shaped and extend toward the interior sound basin near the bottom. Vertical mixing within the CAPES plays an important role in the eventually redistribution of salinity in the CAPES system. On the other hand, outwelling plumes are confined near the surface and are strongly affected by near-shore coastal currents.

Comparisons of the main salinity features within the CAPES simulated by the model with available observations show remarkable similarity. Three dimensional flow and salinity fields display complex spatial and temporal variations within the CAPES throughout the year. In late spring and early summer, such as the month of May, southwesterly surface winds prevail over the CAPES. Observations of salinity distributions reveal well defined high-salinity plumes on the sound side of Hatteras and Ocracoke Inlets with salinity values ranging from 20 to 24 ppt (Figures 8a and b). The location and strength of these plumes resemble those simulated by the model under southwesterly winds (Figures 3 and 5). In late summer and early fall, the prevailing surface wind in the CAPES region shifts to northwesterly winds blowing southeastward. Observed salinity plumes within the CAPES during the northwesterly winds-dominated fall months indicate a well defined salinity plume near Oregon Inlet (Figures 8c and d). This plume extends from the surface to the bottom. Such a pattern resembles the simulated salinity distribution under northwesterly winds (Figures 6b–d and Figures 7b–d).

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