Journal of Coastal Research	2	3	311-336	Fort Lauderdale	Summer 1986

Summer and Winter Hydrography of the U.S. South Atlantic Bight (1973-1979)[1]

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ABSTRACT

MATHEWS, T.D. and PASHUK, O., 1986. Summer and winter hydrography of the U.S. South Atlantic Bight (1973-1979). *Journal of Coastal Research*, 2(3), 311-336. Fort Lauderdale, ISSN 0749-0208.

Hydrographic data from winter and summer cruises during the period 1973 to 1979 were used to illustrate oceanographic conditions in the South Atlantic Bight (SAB). During this period meteorological conditions resulted in unusually low water temperatures in nearshore regimes (<6°C in South Carolina coastal waters in January 1977). During other winter cruises surface waters were cooler off Georgia than off South Carolina. Zones of upwelling were observed regularly near Cape Canaveral and off Charleston, while Gulf Stream intrusions were detected at many outer shelf locations. Low salinities indicative of runoff (<35 ‰) occurred near the coast from South Carolina to Florida during both winter and summer cruises with a surface salinity of 27 ‰ off the Georgia coast during the winter 1973 cruise. High salinity water (36 ‰) was also present during the winter cruises in some coastal areas, indicating Gulf Stream intrusions. Surface salinities 35 ‰ near river mouths during summer cruises corresponded to drought conditions in the coastal states. Surface circulation, as derived from density distributions, indicated both typical and atypical patterns during this study. The cyclonic eddy normally in Long Bay (south of Cape Fear) was not well-defined during most of our cruises or was simply outside of our sampling area. During all cruises the coastal countercurrent was present, but was continuous from Long Bay to Cape Canaveral only during the summer except for winter 1977.

ADDITIONAL INDEX WORDS: *Circulation, eddy, Gulf Stream, South Atlantic Bight, salinity profile, upwelling, water temperature.*

INTRODUCTION

Until the past two decades, relatively little emphasis had been placed on understanding the chemistry and physics of continental shelf waters off the southeastern coast of the United States. Much of what was done was either large scale, covering the east coast (BUMPUS, 1973, SHROEDER, 1966), or small scale, covering an area off one state (BUMPUS, 1955, WELLS and GRAY, 1960, GRAY and CERAME-VIVAS, 1963, BLANTON, 1971, STEFANSSON, *et al.* 1971, and SCHYMACHER and KORGEN, 1976). Data were frequently so sketchy in the larger studies that only the most general circulation features could be detected. The small scale studies were often exceptionally detailed, but too narrow in areal extent to delineate large scale features.

Despite this apparent lack of information on the oceanography of the South Atlantic Bight (SAB) shelf waters, most of the major circulation features have been identified and described in some detail, *e.g.*, the Charleston bump (BROOKS and BANE, 1978; LEGECKIS, 1979; PIETRAFESA *et al.*, 1978, and ROONEY *et al.*, 1978), topographically-induced upwelling (ATKINSON and TARGETT, 1982; BLANTON *et al.*, 1981; JANOWITZ and PIETRAFESA, 1982, and SMITH, 1983), and Gulf Stream frontal eddies (LEE and ATKINSON, 1983; LEE *et al.*, 1981, and PIETRAFESA, 1983). These studies utilized satellite pictures, current meters, research vessels, drift bottles, or some combination thereof for data collection. Numerous models and theories have been proposed to explain or elucidate further the various circulation features present in the SAB, such as, KOURAFALOU, *et al.* (1984), LEE *et al.* (1984), WANG *et al.* (1984), and some of the above works.

[1] *Contribution No. 190 from the S.C. Marine Resources Division. Funding for this study was provided by the National Marine Fisheries Service, Marine Resources Monitoring, Assessment and Prediction Program (Southeast Fisheries Center contract number 6-35147). 85002 received 17 January 1985; accepted in revision 16 April 1985.*

In general, however, the above studies have been of limited scope, based on a single cruise, satellite data only, or hydrographic data from one season. Our studies in the SAB cover the 1973-79 period seasonally from Cape Fear and/or Lookout to Cape Canaveral. With few exceptions, all seasons are fully represented, those exceptions being cruises reduced in areal extent for a particular research effort, gear failure, or extended periods of bad weather.

During this study oceanographic parameters reflected normal to extreme meteorologic conditions. Large amounts of precipitation (both rain and snow) and concommitant runoff occurred in 1973, as well as record low temperatures throughout the region in 1977. The effects on nearshore oceanography were quite distinct in both years, with nearshore surface salinities depressed 7-8 ‰ in 1973 and surface temperatures lowered 5-7° C during 1977. Even though the physical causes and effects of the abnormal weather conditions are well known, the long-term biological effects are less well understood. Shrimp landings, for instance, were drastically lowered for at least two years (1977-78) as a result of two consecutive cold winters. Data from this and other oceanographic studies are being utilized in concert with estuarine data to aid in correlating fluctuations in shrimp landings with river discharge and water temperature.

This paper presents data and descriptions of both normal and abnormal oceanographic conditions in the SAB during the 1973-79 period. Included are temperature and salinity distributions and surface circulation patterns as derived from density distributions. Some supporting biological data are also included to illustrate effects of abnormal weather conditions.

METHODS

All hydrographic data, except temperature, were derived from water samples collected aboard the R/V DOLPHIN or the R/V OREGON. Temperature was determined using reversing thermometers (placed on Niskin bottles) and bathythermographs, both mechanical and expendable. Unprotected thermometers were used at deep stations to determine the depths of reversal. Salinity samples were stored in polyethylene bottles and analyzed ashore. Salinities were determined conductometrically with a Beckman RS-7B induction salinometer.

RESULTS

Our data are displayed in Table 1 and a series of horizontal plates (Figs. 1-21). No plots are included for summer 1973 or winter 1979 due to either a very restricted cruise or a complete lack of data. No salinities are available for winter 1975 due to questionable results. (Our salinities were outside NODC range and considered suspect.) Also only surface salinities were collected during the late summer 1974 cruise.

Table 1 contains ranges and averages of bottom temperature and salinity by depth strata for the 1973-79 period. The table is included to provide for easy comparison of seasonal data in the horizontal plots.

Broken lines in some figures represent implied isopleths in areas where data are lacking or incomplete. An exception is that dash-dot broken lines are used for surface temperatures during summer 1974 for half degree isotherms to provide additional detail.

DISCUSSION

In general, the shallow, nearshore waters of the SAB respond rapidly to climatic influences, runoff, and Gulf Stream meanders and eddies. Surface water temperatures may vary 15-20° C from winter to summer, whereas corresponding Gulf Stream surface water may only fluctuate 5-8° C. Usually a band of comparatively stable bottom water is present at or beyond the shelf break with a temperature range of perhaps 5° C and a winter temperature of 18°-22° C. Topographically-induced zones of upwelling (shelf-edge intrusions) are present downstream of Cape Canaveral at several locations during all seasons, as described by BLANTON *et al.* (1981) and JANOWITZ and PIETRAFESA (1982). These zones have high nutrient concentrations, thus serving as significant pathways for the on-shelf transport of nutrient-rich water. Salinity tends to be constant from the shelf break to beyond the shelf edge, with surface values being $\geq$ 35 ‰. Salinities up to 37 ‰ are found at times at the surface in the Gulf Stream, usually near the shelf edge. The effects of runoff are clearly evident much of the year in a nearshore band extending from about 33° N latitude down to northern Florida. Salinities in this zone are usually <34 ‰, occasionally dropping below 30 ‰ near river mouths, *e.g.*, at Charleston and Savannah. Bottom salinities can be <35 ‰ at the shelf edge, but generally are higher except in the very shallow nearshore zone.

Temperature 1973

Winter 1973 was somewhat colder than usual in the Southeast, *e.g.*, air temperatures in January and February were 1.2° C and 3.1° C below the forty-year mean for Charleston (NOAA 1977a). Large

Table 1. Winter and summer ranges and averages of bottom temperature and salinity (1973-1979).

Depth Zone (m)	Temperature °C		Salinity ‰	
	Range	Average	Range	Average
9-18 m	W 5.40-20.82	12.84	28.55-36.42	34.66
	S 22.46-29.18	27.18	33.80-36.39	35.59
19-27 m	W 6.29-20.52	15.29	33.72-36.54	35.76
	S 21.83-28.62	26.06	34.66-36.47	36.06
28-55 m	W 10.33-23.09	17.66	35.34-36.46	36.15
	S 14.15-28.99	24.44	35.77-36.62	36.24
56-110 m	W 11.14-22.72	17.38	35.39-36-43	36.20
	S 12.35-26.80	19.25	35.64-36.64	36.24
111-183 m	W 7.02-17.68	13.82	34.94-36.34	35.84
	S 8.50-20.77	13.72	35.10-36.78	35.74
>183 m	W 6.20-16.44	9.76	34.85-36.20	35.25
	S 7.16-15.46	9.16	34.83-36.00	35.24

amounts of snow fell at or near the coast in both South Carolina and Georgia, with traces being recorded in northern Florida. This cold period was bracketed, however, by relatively warm weather in December and March. As a consequence, the effects on the biota, *e.g.*, white shrimp, were not severe, since white shrimp landings were up during 1973 in North and South Carolina and Georgia (MCKENZIE, 1981). Surface temperatures varied from <10° C near Charleston, reflecting runoff from the snow, to >25° C at the shelf edge (Figure 1). Near 32°30′ N latitude a zone of 20° C water was located, indicating Charleston-bump upwelling.

Topographically-induced upwelling or shelf-edge intrusions were observed downstream of Cape Canaveral at 29°-30° N and 32° N latitudes, where cold tongues of bottom water and compressed isotherms were evident (Figure 1). In addition, the usual band of warm, shelfbreak water (20°-23° C) was present from Cape Canaveral to Cape Fear, with distinctly colder water located on both sides.

Temperature 1974

The winter 1974 cruise covered Onslow Bay near Cape Fear (Figure 2). Though small in areal extent the data were representative of normal SAB temperatures and Onslow Bay in particular (see Table 1 for comparisons). We measured a low of <12° C for nearshore waters (surface and bottom) and a high >23° C at the shelf edge. These values correspond well with the results of STEFANSSON and ATKINSON (1967), who reported a surface range of 10° C to 23° C and bottom temperatures <8° C beyond the shelf edge for February-March 1966. The southward advance of Virginia coastal water close to the North Carolina coast contributed to the lower nearshore minimum as did the colder air temperatures in 1966. January 1966 air temperatures were 3-4° C below the mean, whereas January 1974 air temperatures were 6-7° C above the mean (NOAA 1977a). Both the 1966 and 1974 data indicated the presence of warm (20° C), shelfbreak water.

Surface and bottom isotherms during summer 1974 varied considerably in orientation (Figure 3). Surface temperatures were distributed in patches, but the bottom isotherm followed the orientation of the coast. The lowest surface temperatures were either at the coast, *e.g.*, in Long Bay (33° N latitude), or in zones of upwelling, *e.g.*, near Cape Canaveral and southeast of Charleston. The Charleston-bump upwelling was indicated by a zone of <27.5° C surface water at the outer shelf southeast of Charleston, but south of the summer 1973 location (as seen in a short cruise not shown in this paper). The coldest bottom water was found at the shelf edge in areas of topographically-induced upwelling, where temperatures were <8° C northeast of Cape Canaveral and southeast of Charleston (Figure 3).

Temperature 1975

Winter 1975 was also warmer than usual, with air temperatures 2-3° C above the mean (NOAA 1977a). Because the winter cruise was incomplete, however, the effects (if any) on the Charleston-bump upwelling were not detected for 1975 (Figure 4). Although both surface and bottom temperature ranges for winter 1975 were similar to those for the 1973 and 1974 winters, all three years had noticeable differences. Shelf-edge intrusions were evident each winter, but the intrusions were more pronounced, *i.e.*, lower temperatures, were recorded (*cf.* Figures

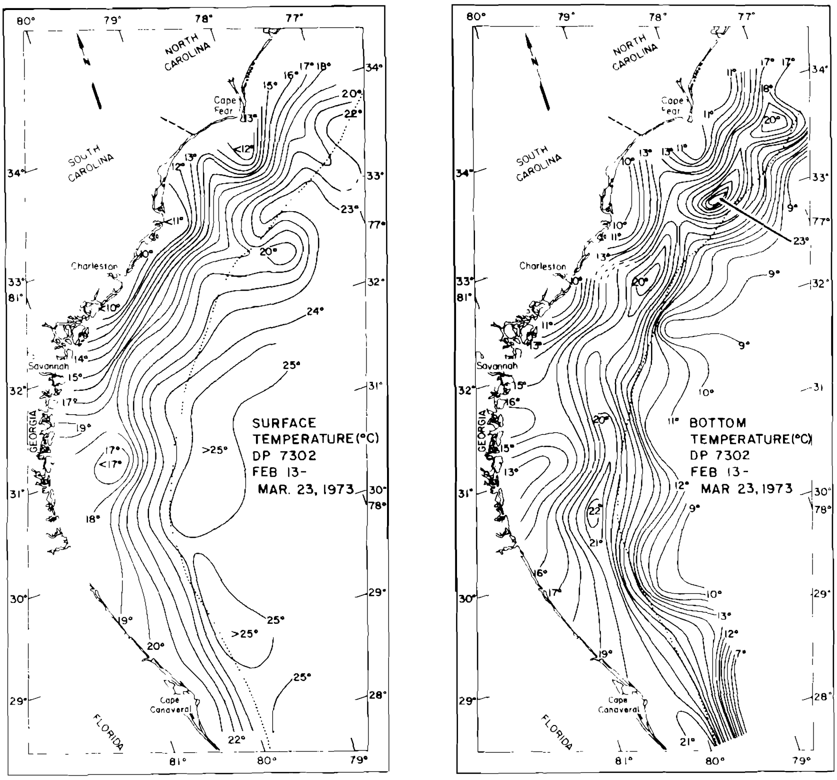

Figure 1. Surface and bottom temperature for winter 1973.

1, 2, and 4). The warmest water (25° C) was again off Florida, while a secondary maximum (24° C) was recorded at the shelf edge off Cape Fear (Figure 4). Warm, midshelf bottom water was present as before, but during 1975 temperatures were lower than during 1973 and 1974, probably as a consequence of the intensified shelf-edge intrusions (*cf.* Figures 2, 4, and 8).

Summer 1975 temperature distributions were similar to those of 1974. Again surface and bottom isotherms were oriented differently (Figure 4). Also, two areas of cool surface water were located northeast of Cape Canaveral (<27.5° C) and southeast of Charleston (<26.5° C), indicating upwelling. Nearshore surface water off Georgia indicated runoff as in 1974, but in 1975 the temperature was higher (>29° C vs <27.5° C) The usual areas of bottom intrusions were detected at roughly equidistant locations along the shelf edge, where temperatures were <8° C to <10° C at four different latitudes.

Temperature 1976

The winter of 1975-76 was relatively mild, especially with respect to the succeeding winters December 1975 air temperatures averaged <1.0° C below the thirty year mean, January and February 1976 were about 3.0° C below and 2.3° C above the mean respectively (NOAA 1977).

Despite the mildness of the winter, the nearshore isotherms were unusual in distribution Surface and bottom waters below Savannah were cooler (<11° C) than water near Charleston (<12° C) and about the same as waters in Long Bay below Cape Fear, probably due to increased runoff from the Georgia rivers (Figure 5). The Altamaha River discharge, for example, was about 70% above normal during January 1976 (USGS 1977). We found surface water temperatures of 14° to 18° C near Savannah during winter 1973 (Figure 1), while SCHROEDER (1966) reported long-term surface water averages of about 14° to 16° C for January in the Savannah area.

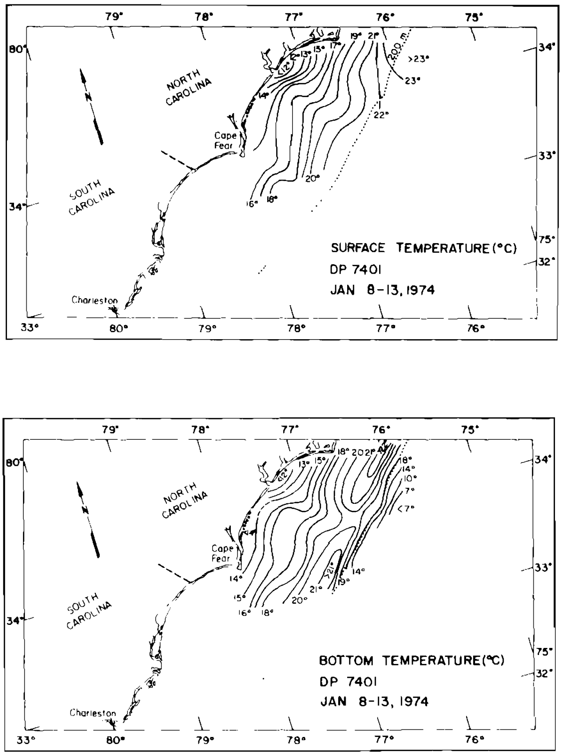

Figure 2. Surface and bottom temperature for winter 1974.

ANDERSON *et al.* (1961) found nearshore surface temperatures of 12.76° to 16.50° C along the Georgia coast during the 1953-54 R/V THEODORE N. GILL cruises. Offshore surface water temperatures were basically normal, especially near the Gulf Stream where temperatures were 22° to 24° C or higher (Figure 5).

Although surface and bottom nearshore waters in winter 1976 were isothermal, considerable differences existed at outer shelf stations. Bottom water at the shelf edge was <8° C in several areas due to intrusions of cold, deep water as in previous years (Figure 5).

Summer water temperatures were moderately cool, reflecting air temperatures which were lower than normal. Negative air temperature anomalies up to 1.8° C were recorded during summer 1976 (NOAA 1977). Surface waters were similarly cool, *e.g.*, <26° C in Long Bay (Figure 12). Off Charleston the temperature was about 26° to 28° C, as compared with 27° to 29.5° C in 1973 (MATHEWS and PASHUK, 1977) and about 28.5° C in 1974 (Figure 3).

Charleston Harbor was also cooler during this period compared to other years, *e.g.*, only a few days in late July and early August 1976 had water temperatures up to 29° C, but the same summer period in 1972 and 1975 went up to 30° C and often over 29° C (Mathews unpublished data).

Surface and bottom water temperatures were similar out to midshelf locations (Figure 5). Near the shelf edge, however, bottom temperatures declined sharply to <8° C near latitude 32° N, probably the result of Charleston-bump upwelling. Other areas along the shelf edge were <9° C with rather compressed isotherms, especially near 31° N latitude, where bottom temperatures ranged from about 10° to 27° C (Figure12).

Temperature 1977

The winter of 1976-77 was unusually cold, with both air and surface water temperatures being among

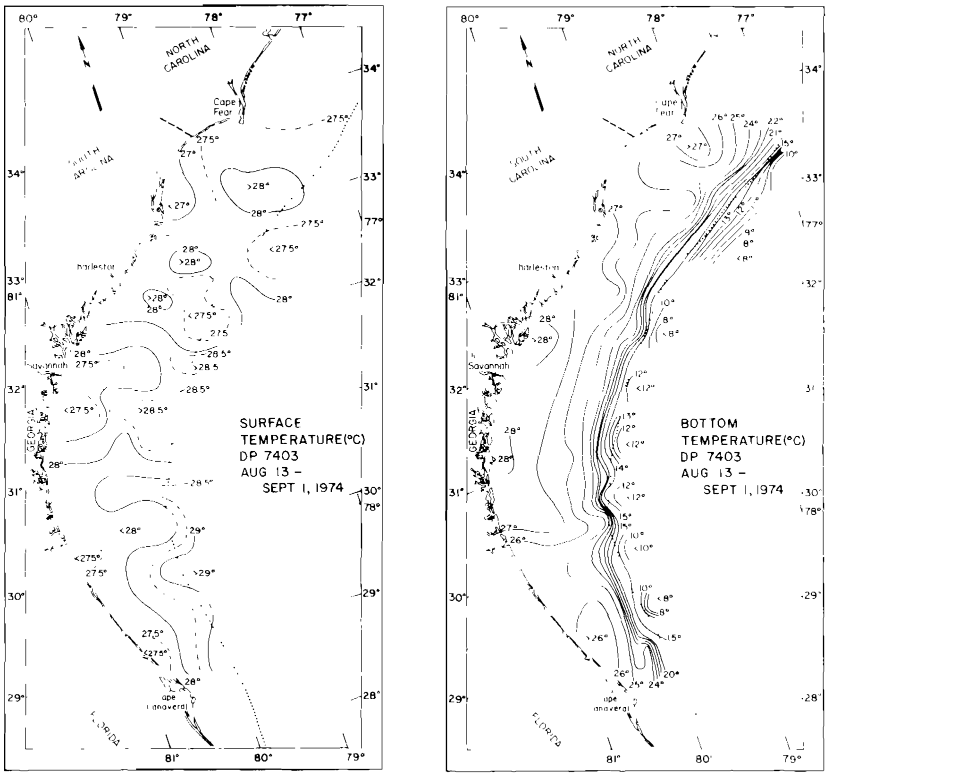

Figure 3. Surface and bottom temperature for summer 1974.

the lowest recorded in the Southeast since 1940 (NOAA 1977a). A surface water minimum of 5.39° C was recorded in January in Long Bay near the North Carolina border (Figure 6), which was the lowest surface temperature we recorded anywhere in the SAB for the 1973-79 period. Historic surface temperatures for January in the SAB have been as low as 9° and 10°, but are generally higher (SCHROEDER 1966, ANDERSON *et al.*, 1961). During January 1977 surface temperatures off Charleston and northern Florida were <8° C and <10° C respectively (Figure 13). In most areas temperatures were 3° and 4° C lower than in 1976 at the same location. Surface Gulf Stream temperatures were about 2° C lower than in 1976 in the zone from Cape Canaveral to Savannah, but more than 4° C lower east of Long Bay. Even in March, waters off Savannah were still <12° C (SINGER *et al.*, 1980) as compared with February and March 1973, when temperatures were 14° or 15° C in the same area (Figure 1). While 1973 was not as cold as 1977, cold runoff from snow lowered nearshore water temperatures from Charleston to southern Georgia, but not to the extent of 1977.

The estuarine water temperatures were <8.5° C (an empirical temperature associated with white shrimp mortality) for 48 days, resulting in high mortality in overwintering white shrimp (FARMER *et al.*, 1978). After these mild winters with landings of 4.0-4.7 x 10^6 kg of white shrimp (heads off) in the South Atlantic states, white shrimp landings dropped to about 1.5 x 10^6 kg after the abnormally cold winter of 1977 (MCKENZIE, 1981). The most severe decreases were related to latitude or northern limit of the white shrimp, for the reductions in landings from 1976 were as follows: 98% for North Carolina, 89% for South Carolina, 50% for Georgia, and 42% for Florida (East Coast).

Bottom water temperatures were approximately the same as those at the surface out to midshelf locations (Figure 6). Temperatures <6° C were found in Long Bay, <8° C off Charleston, <9° C near Savannah, and <10° C off northern Florida. Several cells of warm water were detected along the

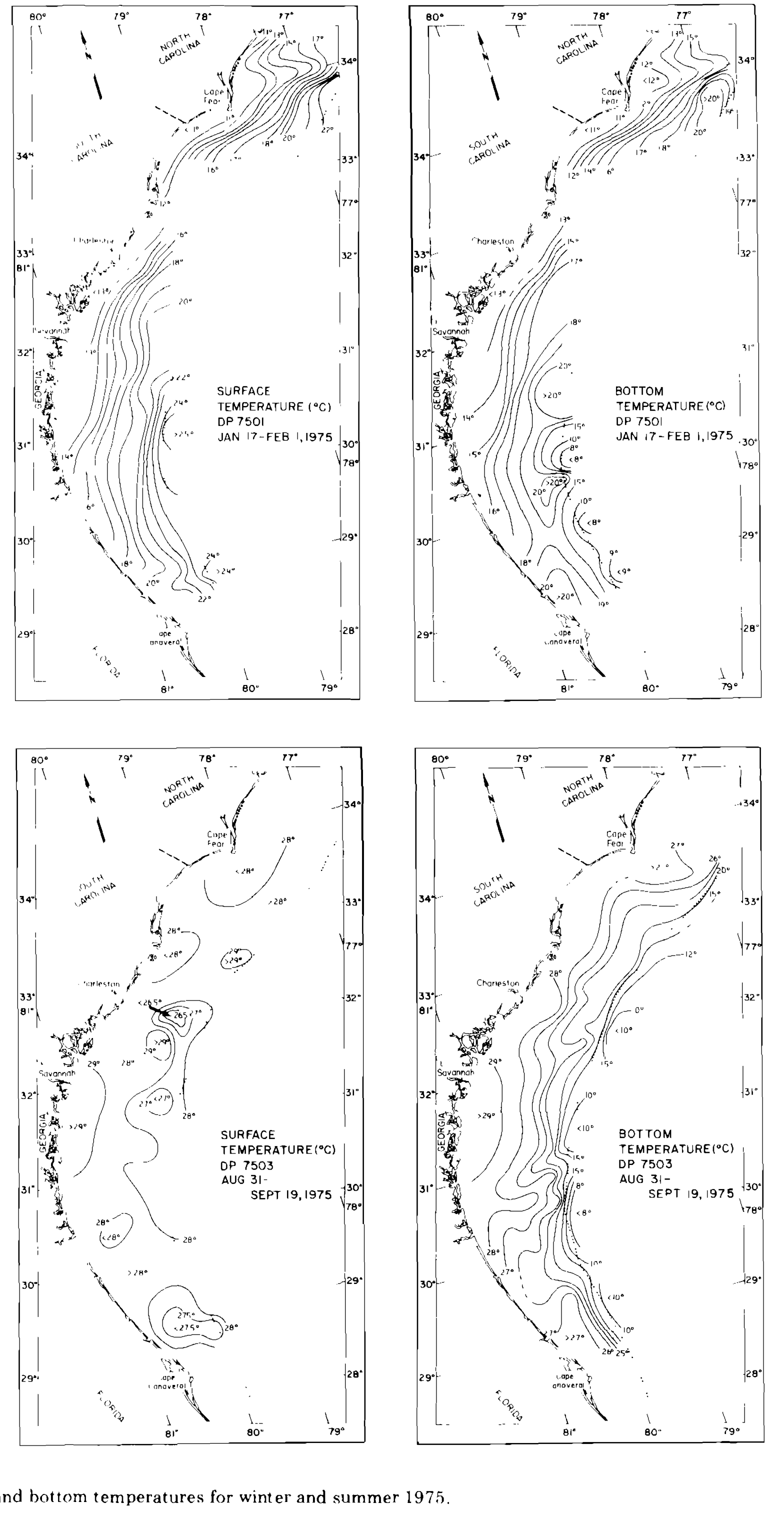

Figure 4. Surface and bottom temperatures for winter and summer 1975.

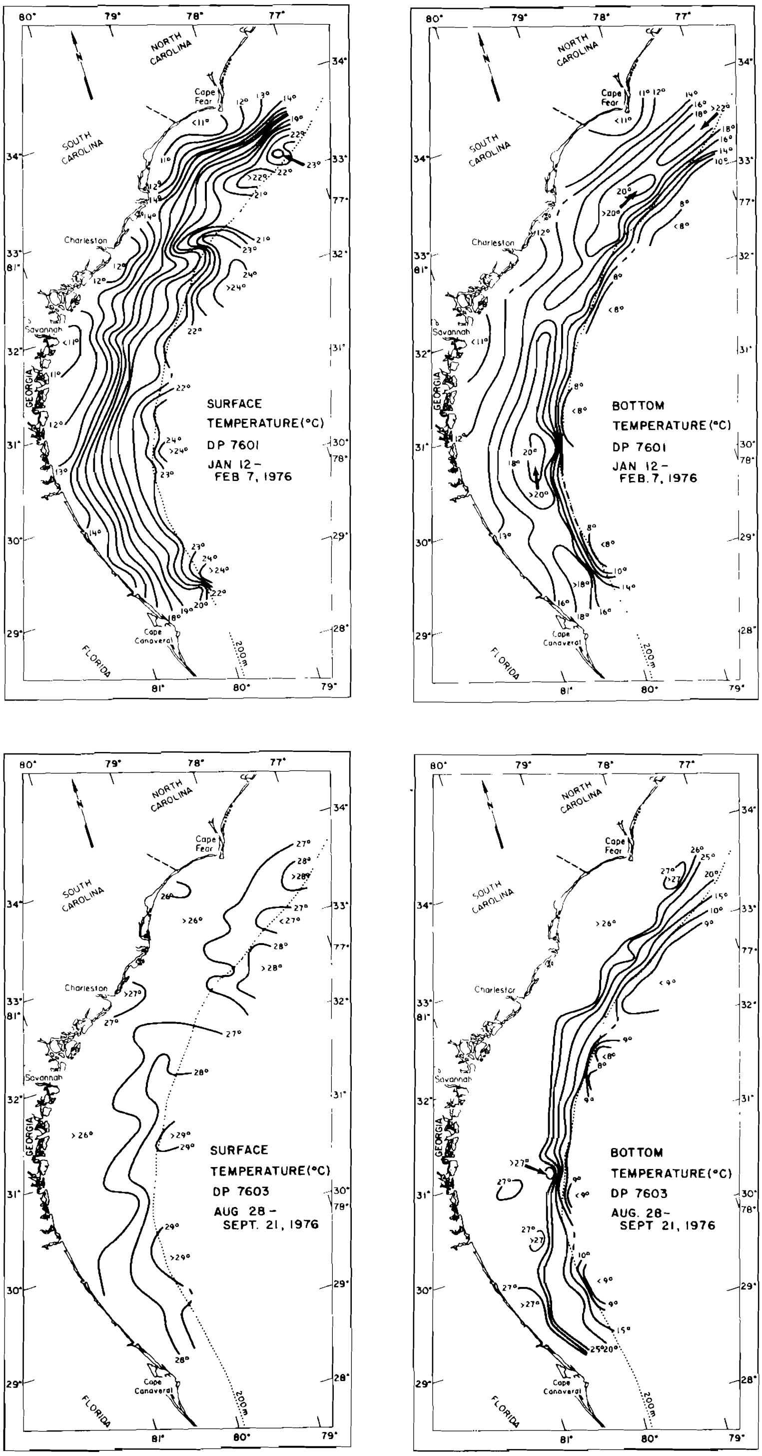

Figure 5. Surface and bottom temperature for winter and summer 1976.

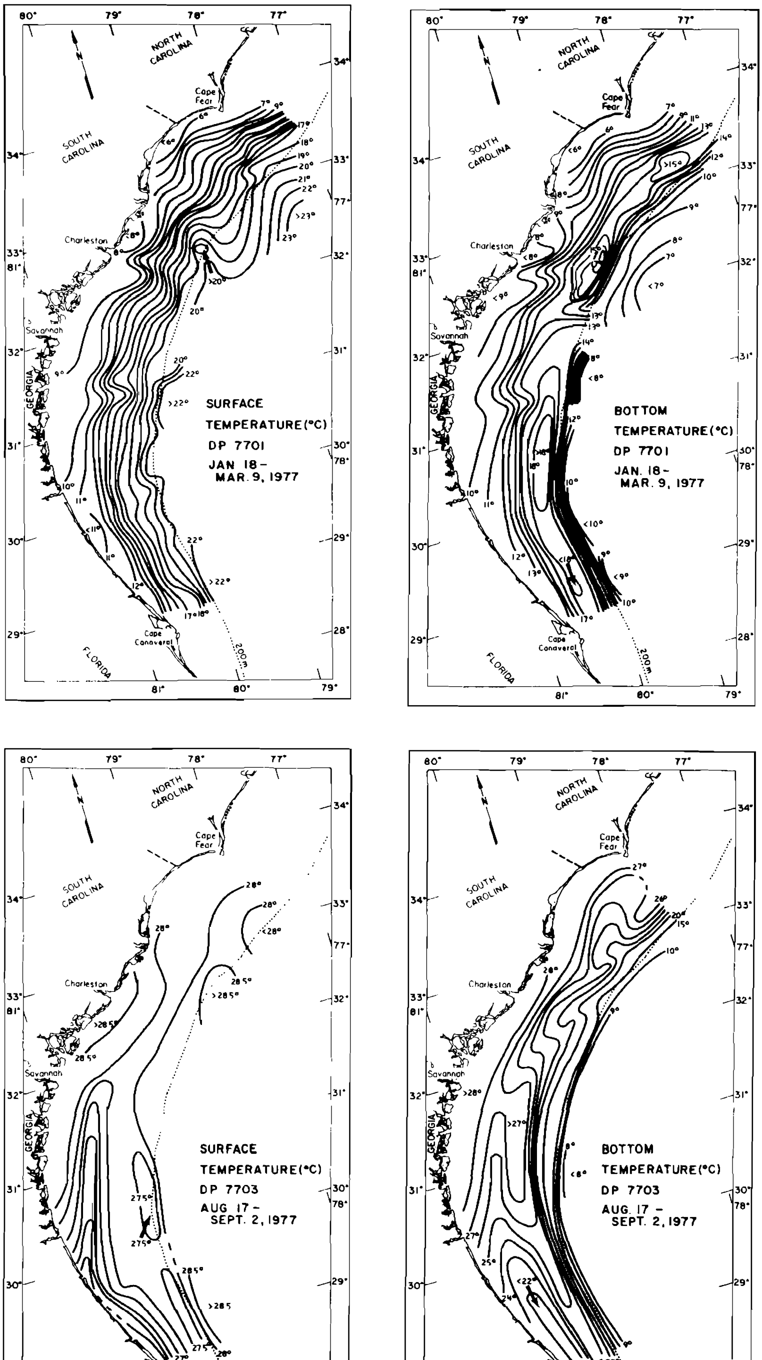

Figure 6. Surface and bottom temperature for winter and summer 1977.

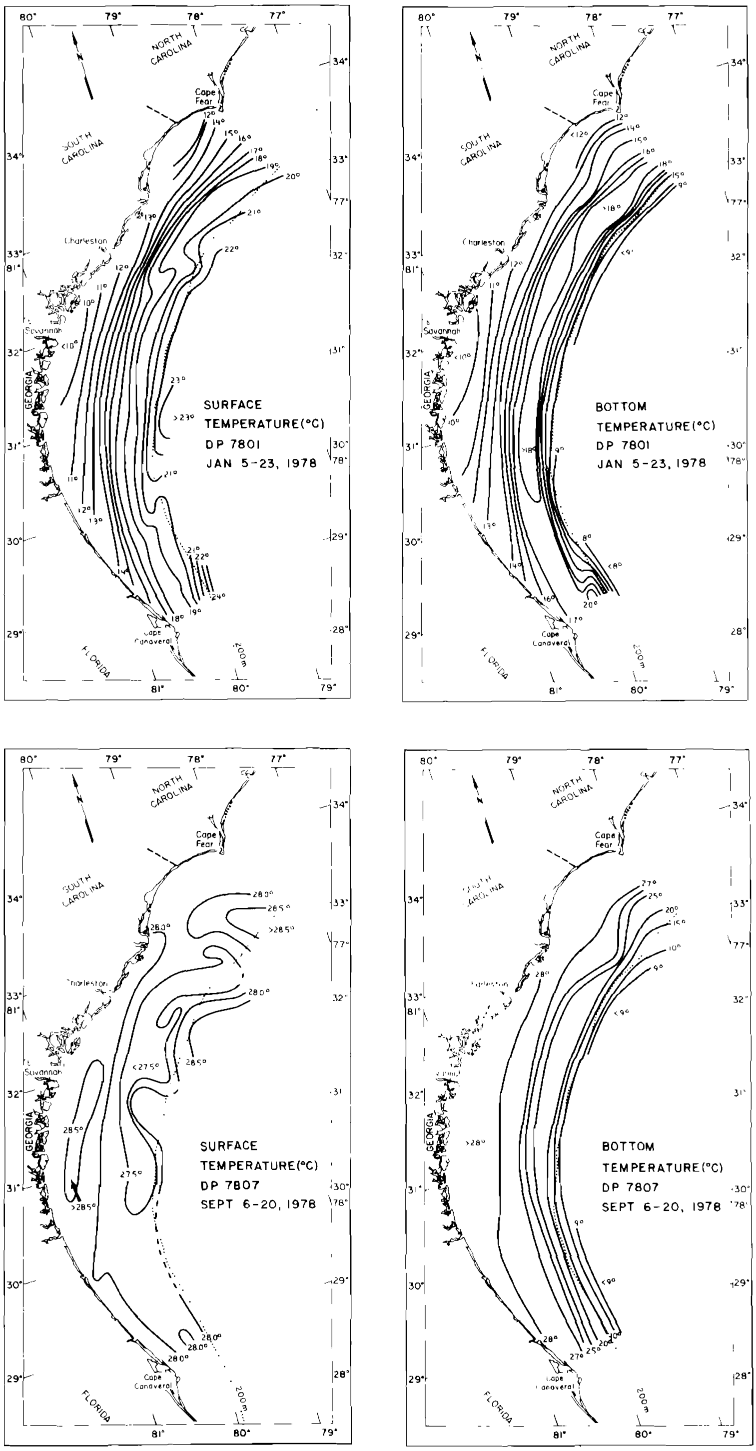

Figure 7 Surface and bottom temperature for winter and summer 1978.

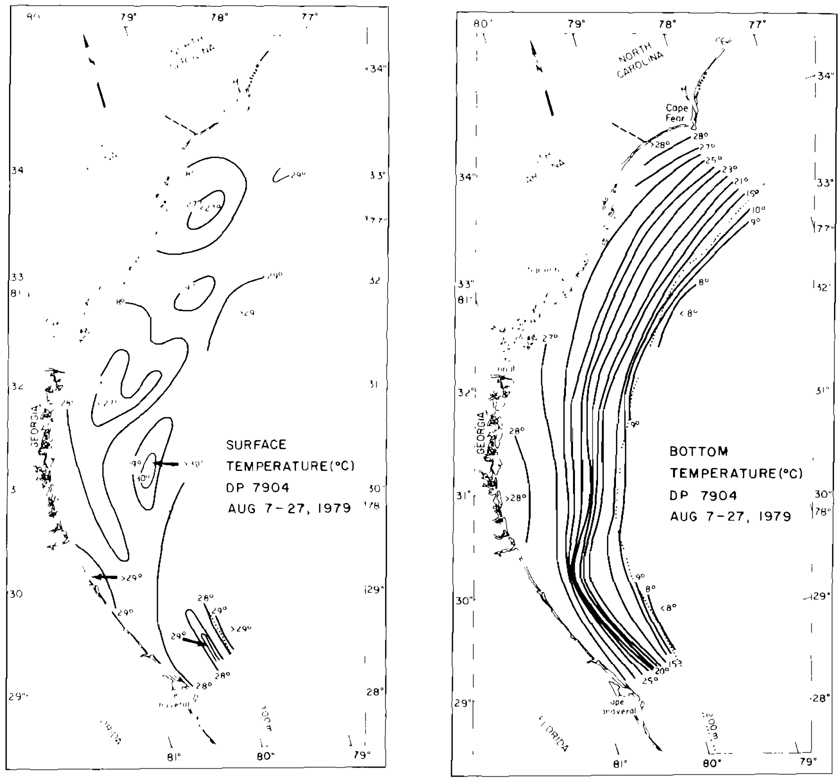

Figure 8. Surface and bottom temperature for summer 1979.

outer shelf as in 1976, but temperatures were lower, *i.e.*, 15° to 18° C vs. 18° to 22° C. Bottom water near the shelf edge was actually warmer than surface or bottom water in Long Bay and near Charleston.

The summer of 1977 was one of the hottest and driest for coastal South Carolina since 1954, with air temperatures near 40° C (NOAA, 1978). As a consequence, surface waters were warm, *e.g.*, >28.5° C off Charleston and at the shelf edge (Figure 6). A relatively cool (25° to 27° C) tongue of water extended from Cape Canaveral to about 32° N latitude, due perhaps to upwelling of deep Gulf Stream water near Cape Canaveral.

Bottom waters were similar to surface waters in temperature primarily in nearshore locations. Cold water (<10° C) was present at the shelf edge from Florida to North Carolina (Figure 6), similar to July 1977 conditions in the Georgia Bight reported by ATKINSON *et al.* (1979). The cool surface water north of Cape Canaveral extended to the bottom, supporting the premise of upwelling. Temperatures <22° C were recorded in this zone spread along the inner shelf.

Temperature 1978

The winter of 1978 was very cold, but not as severe as 1977. As in 1976, surface and bottom waters were colder off the Georgia coast than in the zone from Long Bay down to Charleston, *i.e.*, about 10° near Savannah vs. 12° C in Long Bay (Figure 8). As in 1976, runoff from Georgia rivers was high, *e.g.*, about 60% above normal for the Altamaha River (USGS, 1979).

First appearances suggest that the winter of 1978 was quite similar to 1976 in terms of water temperatures and the distribution of isotherms. While many similarities existed with respect to offshore waters, the estuaries experienced 45 days with <8.5° C water temperatures (BIERNBAUM, 1981). Hence, the adverse effects of two cold winters were compounded, resulting in greatly reduced white shrimp landings in the South Atlantic states for the second consecutive year.

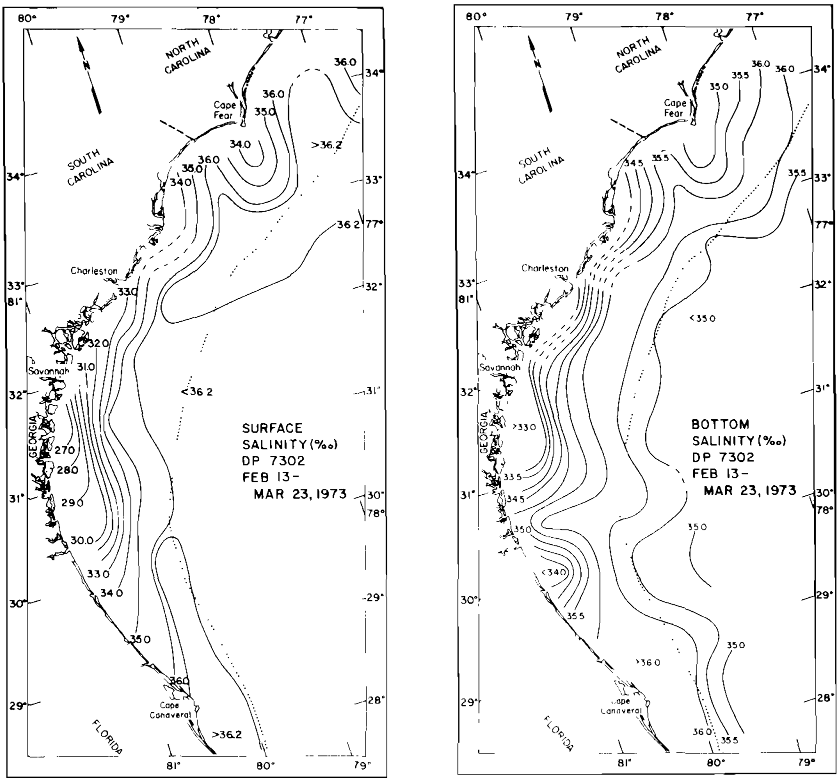

Figure 9. Surface and bottom salinity for winter 1973.

The coolest water (<10° C) was found along the Georgia coast, with 11° and 12° isotherms extending down to northern Florida (Figure 7). The highest temperatures (up to 24° C) were at the surface in the vicinity of the Gulf Stream. SINGER *et al.* (1980) reported essentially the same results for a transect off Savannah in January 1978. The warmest bottom water was located at middle and outer shelf stations, where a long band of >18° C water and a small area of >20° C water (off Cape Canaveral) were present (Figure 7). The warm water indicated Gulf Stream water on the outer shelf. Located beyond the warm zone were areas of cold, upwelled water from <8° to <9° C.

During the summer of 1978 surface water temperatures of about 28.5° C were observed over much of the SAB (Figure 7). A band of cooler water (<27.5° C) was located along the outer shelf from Charleston to upper Florida. A Gulf Stream deflection was also evident off Charleston, where the isotherms turned sharply eastward.

Surface and bottom temperatures agreed reasonably well in shallow, nearshore zones, but the orientation of the isotherms was quite different. Bottom isotherms, unlike surface isotherms, followed the shelf orientation closely (Figure 7). The bottom temperature gradient was rather even out to the shelf edge, where temperatures dropped from 15° C to <9° C.

Temperature 1979

The winter of 1979, though less severe than the preceding two, was nonetheless colder than usual. Negative temperature anomalies were recorded for the air and surface waters in the southeast during the winter and spring of 1979, succeeding strong positive air temperature anomalies in the fall of 1978. INGHAM and HAYNES (1980) reported surface water temperature anomalies up to 2.4° C for December 1978, −3.5° C for January 1979, −4.2° C for February 1979, and −3.0° C for March 1979 in the SAB. Somewhat cooler conditions continued into June, with May and June having air tempera-

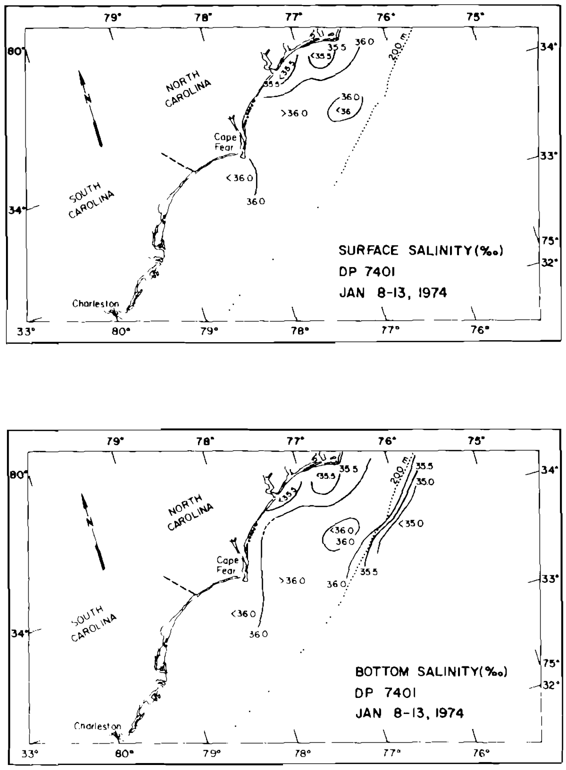

Figure 10. Surface and bottom salinity for winter 1974.

ture anomalies of about −1.7° and −2.1° C for the Charleston area (NOAA, 1980).

Surface water temperatures in the summer of 1979 were indicative of the preceding cool winter and spring, with a return to normal summer conditions being incomplete. The 1979 summer surface temperature range (<27° to >30° C) was not abnormal overall (*cf.* ATKINSON 1976), but the distribution was somewhat unusual, *e.g.*, off Savannah (Figure 18). Temperatures in this zone were <27° C, probably due to runoff. Another cool area with temperatures <27° C was located in Long Bay, due to the offshore spreading of runoff from Winyah Bay (located on the South Carolina coast at about 33° N latitude).

Bottom water isotherms were zonal with regular contours following the coast. Agreement with surface temperatures was only minimal, even in nearshore areas (Figure 8). Topographically-induced upwelling was evident at the shelf edge downstream from Cape Canaveral, where temperatures <8° C were recorded.

Salinity 1973

Nearshore surface salinities during winter 1973 were some of the lowest recorded during the 1973-1979 period with values down to 27 ‰ off the Georgia coast (Figure 9). Unusually high amounts of precipitation fell during the November 1972 to March 1973 period, resulting in very high amounts of runoff Rainfall in the Charleston and Savannah areas was up to three times the forty-year mean, *e.g.*, during November 1972 in Charleston rainfall was 18.67 cm vs the mean of 5.74 cm (NOAA, 1977a).

Surface and bottom salinities during winter 1973 were similar over the whole SAB (Figures 18-19). The highest salinities (>36 ‰) were found at the surface beyond the midshelf region, except in Long Bay, where water ≥36 ‰ was present nearshore Bottom salinities were <35 ‰ in shelf-edge and deeper water, while nearshore bottom waters very closely reflected surface salinities (see Table 1 for salinity ranges by depth strata).

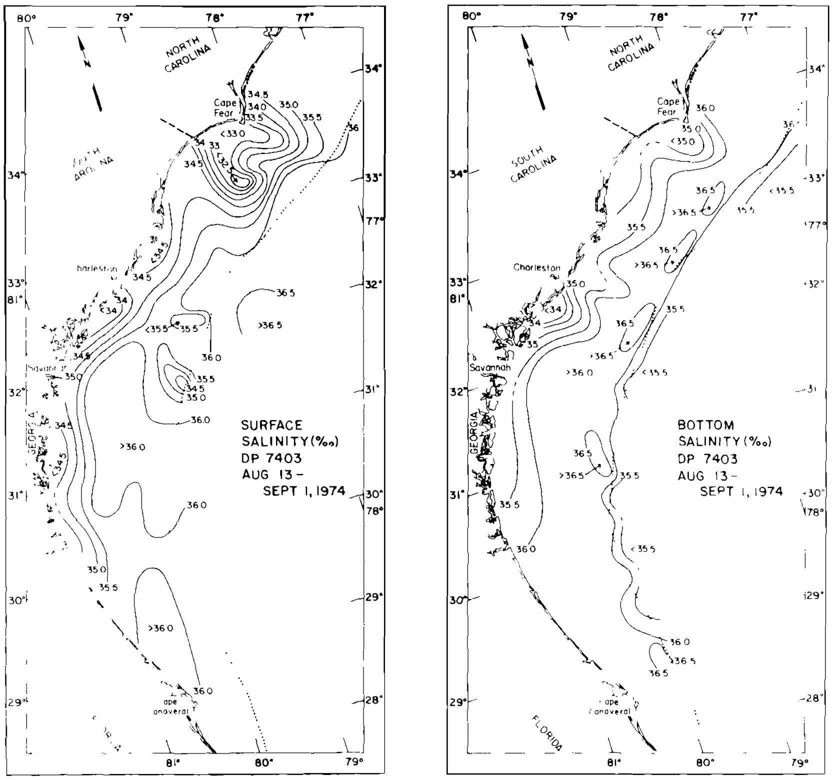

Figure 11. Surface and bottom salinity for summer 1974.

Only surface salinities were collected during summer 1973 off Charleston. Salinities varied from a low of 27 ‰ (about 20-30 km from Charleston) to a high >36 ‰ in the midshelf region. The low salinity water resulted fom runoff following record amounts of rainfall, *e.g.*, 69.2 cm in Charleston in June 1973 (NOAA, 1977a).

Salinity 1974

Winter salinities observed in curtailed sampling were in very close agreement (surface and bottom) with a relatively small range of <35 ‰ to >36 ‰ (Figure 10). The lowest salinities were found beyond the shelf edge on the bottom. High salinity surface water (>36 ‰) was located from the coast near Cape Fear out to the continental slope.

Summer isohalines (surface and bottom) were relatively similar in orientation (Figure 11). Runoff was evident along the coast from Cape Fear to Florida, where salinities were <34.5 ‰. The lowest salinity water (<32.5 ‰) spread out from Cape Fear to the shelf break in shallow layers. Another shallow layer of low salinity water (34.5 ‰) was present at the outer shelf southeast of Savannah, which we feel was coastal water entrained by a Gulf Stream eddy (Figure 11). (Supplemental data indicate the water to be nutrient poor and low in density, *i.e.*, orthophosphate <0.2 g-at/ and t <22.5) Bottom salinities increased smoothly from a nearshore minimum of <34.5 ‰ through a shelfbreak maximum of >36.5 ‰ to slope water of <35 ‰ (Figure 11).

Salinity 1975

Surface and bottom salinities from summer 1975 were very similar in value, but different in orientation (Figure 12). Surface-to-bottom variations were relatively slight even in waters beyond the shelf break, *e.g.*, at 30° N latitude water at the shelf edge was <36 ‰ at the surface and <35.5 ‰ at the bottom. Other areas with comparable ranges were evident at many locations. The lowest salinity water

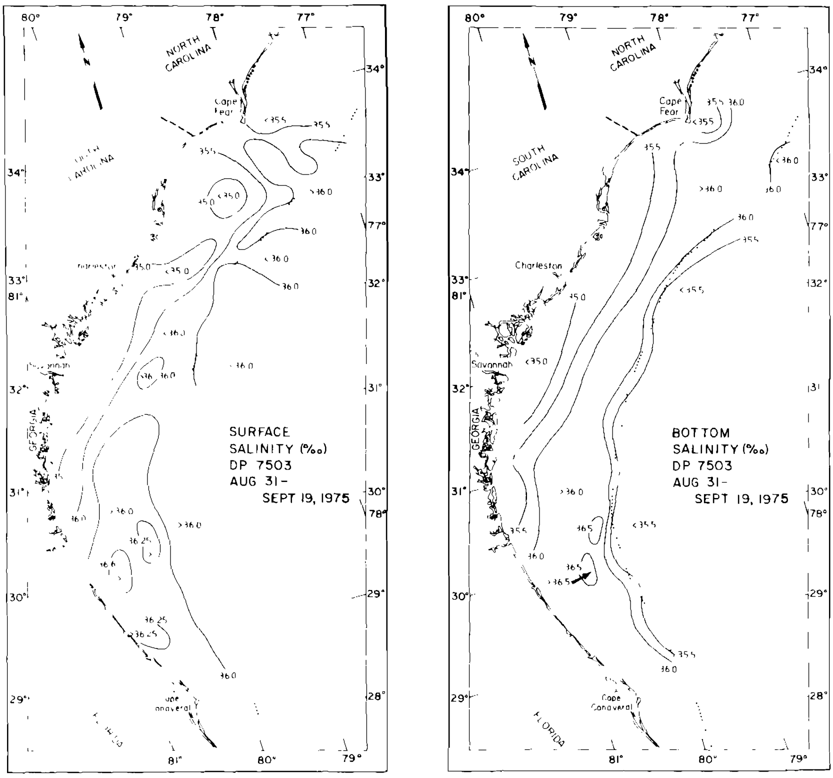

Figure 12. Surface and bottom salinity for summer 1975.

(<35 ‰) was present along the coast and in Long Bay as a cell extending to the shelf break. No unusually low salinity water was detected at any stations during this cruise. However, a large area of high salinity surface water (>36 ‰) extended from Cape Canaveral to 31°30′ N latitude, due to a Gulf Stream intrusion along the Florida shelf.

Salinity 1976

Surface salinities were relatively low in nearshore zones during the winter due to runoff Salinities <33.5 ‰ were evident near Cape Fear and along the Georgia coast down to northern Florida (Figure 13). Runoff extended from Charleston almost to Cape Canaveral. High salinity water (>35 ‰) was located from the middle shelf out to the shelf edge. One exception to this occurred north of Charleston, where water >36.25 ‰ came within a few kilometers of the coast due to a shoreward deflection of the Gulf Stream.

Winter bottom isohalines closely followed surface isohalines in terms of orientation and concentration, with low salinities (<35 ‰) near the coast and high salinities (>35 ‰) at midshelf and outershelf zones (Figure 13). Near the shelf edge were several areas with salinities <35 ‰ , indicating upwelling. Very similar results were obtained during winter 1973 and 1974 (Figures 9, 10).

Summer surface salinities ranged from <35 ‰ near the coast to >36 ‰ at midshelf locations (Figure 13). Salinities in 1974 were found to be distributed comparably from Savannah southward to Cape Canaveral. The high salinity (>36 ‰) tongue of water north of Cape Canaveral was evidently a Gulf Stream intrusion, resembling a zone of high salinity in the same area during summer 1974 (Figure 10).

Bottom salinities, in general, paralleled surface salinities during summer 1976, especially in nearshore environs. The 35.5 ‰ isohaline extended from Cape Fear to northern Florida, generally following the coastline (Figure 13). A rather large zone of water >36 ‰ extended from Cape Canaveral

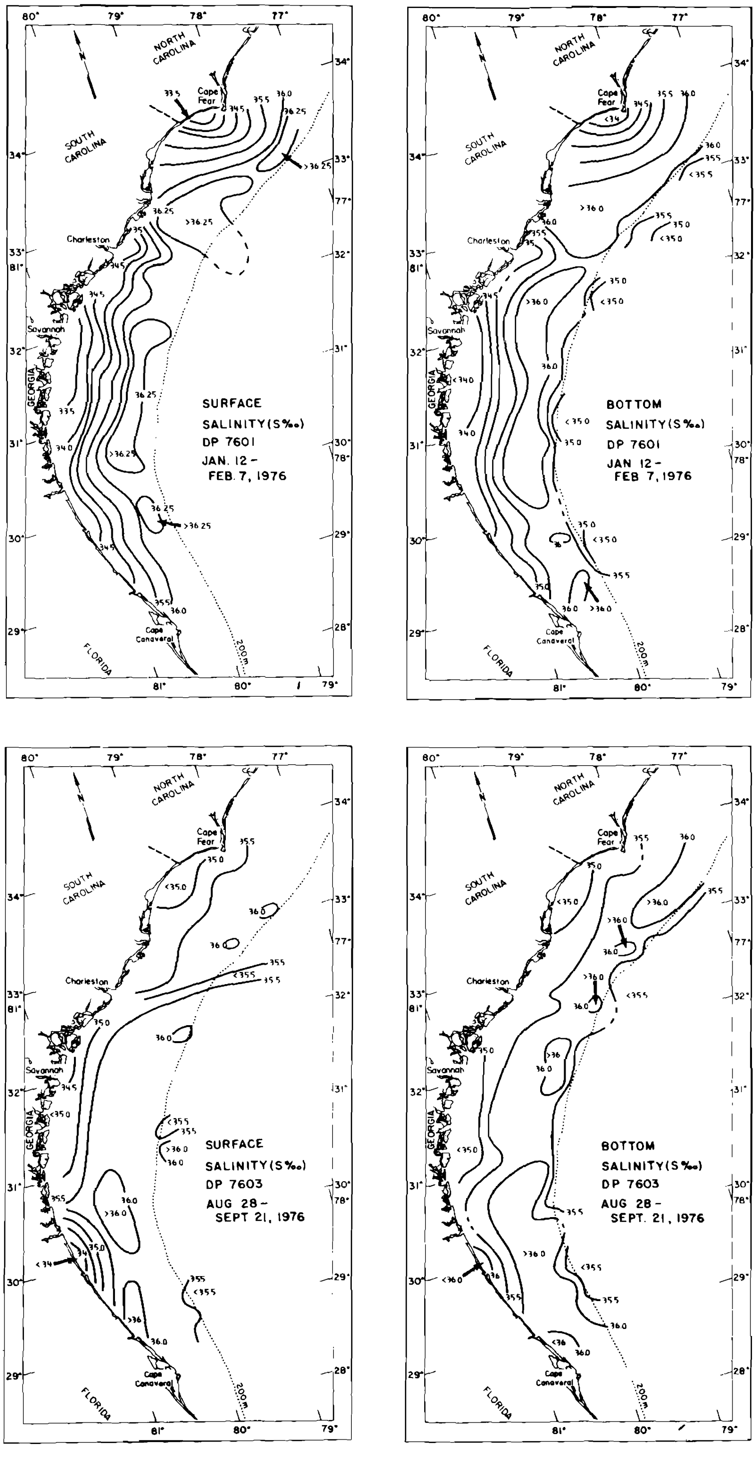

Figure 13. Surface and bottom salinity for winter and summer 1976.

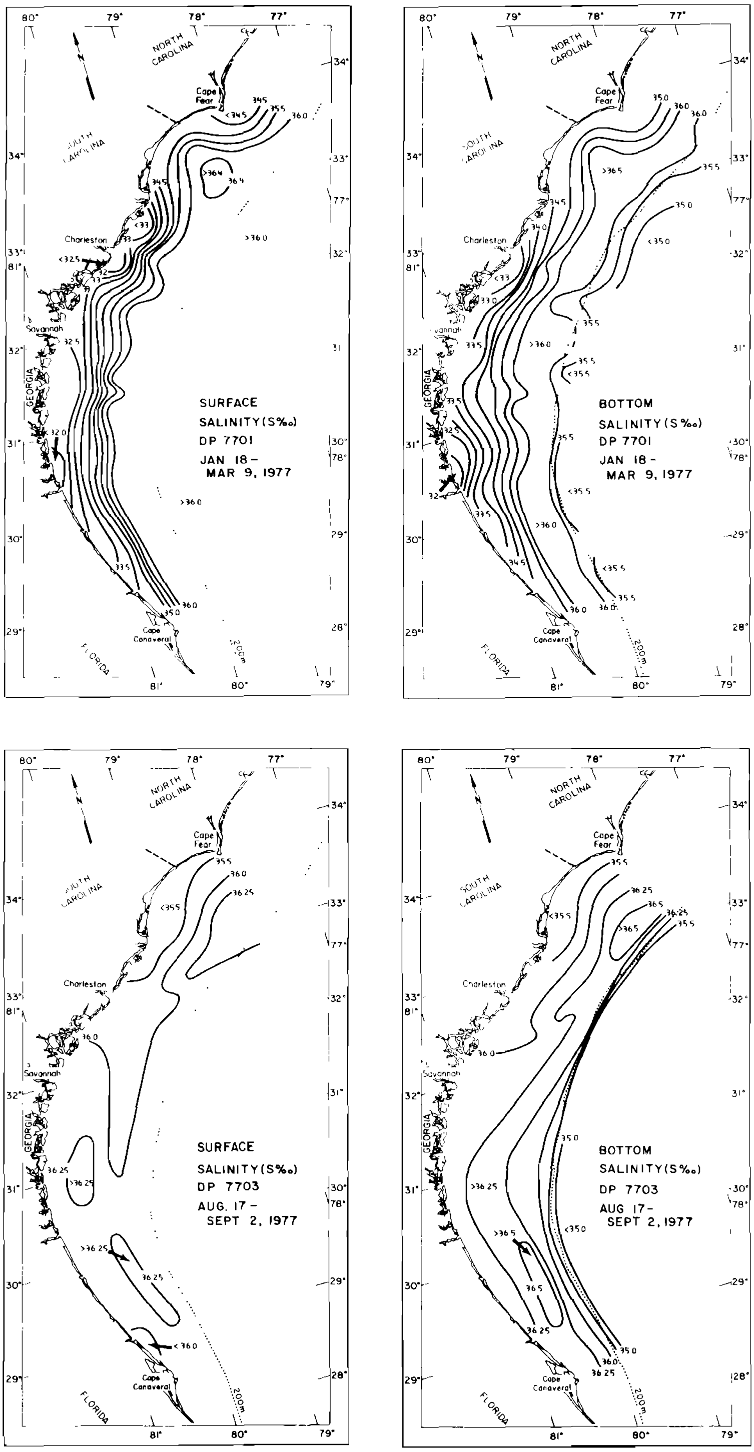

Figure 14. Surface and bottom salinity for winter and summer 1977.

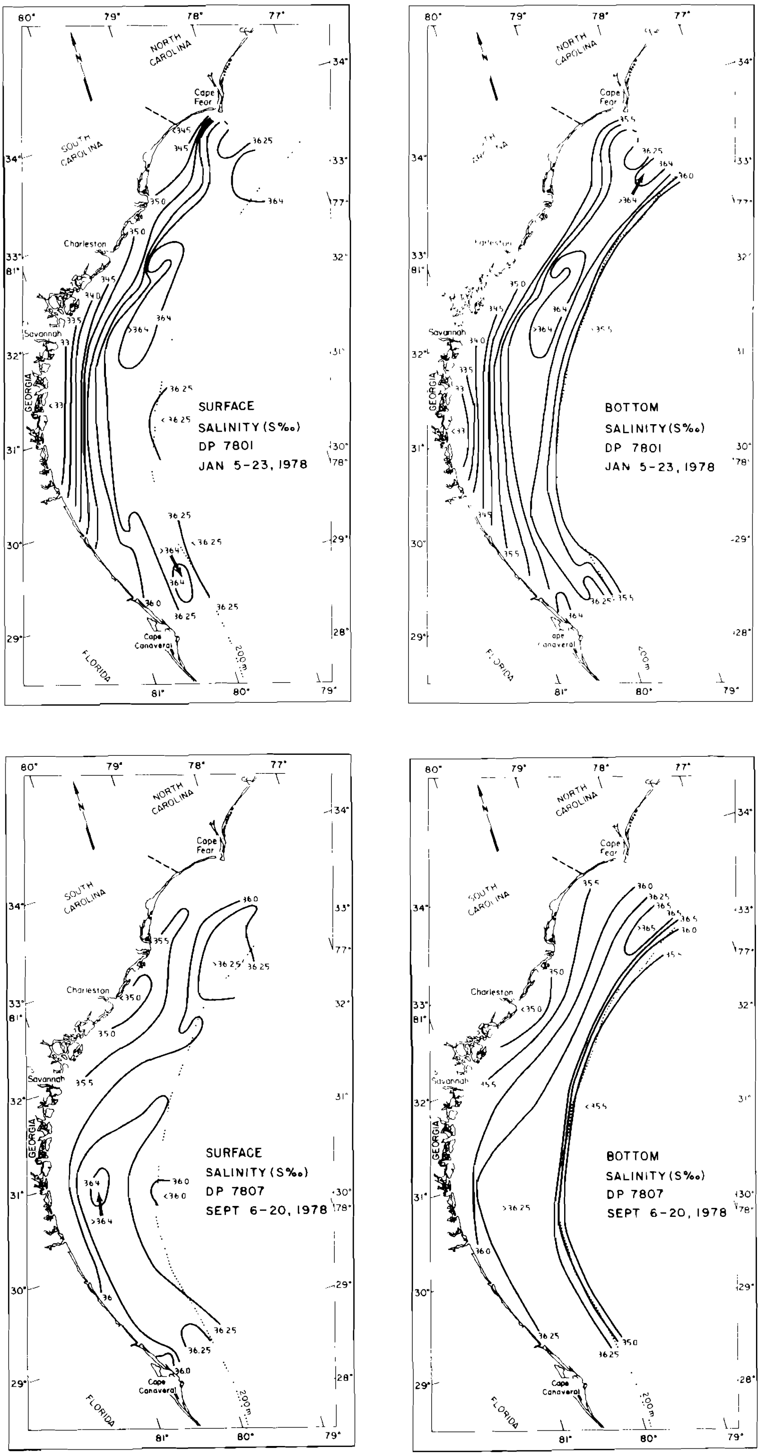

Figure 15. Surface and bottom salinity for winter and summer 1978.

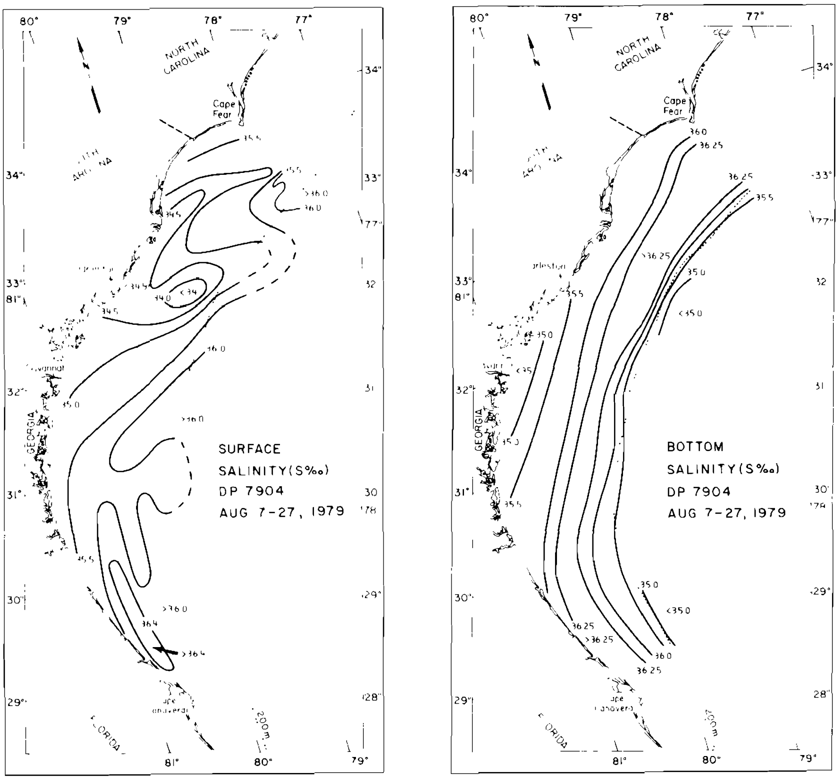

Figure 16. Surface and bottom salinity for summer 1979.

northward to southern Georgia, corresponding closely to the 36 ‰ surface water noted above. Other isolated pockets of >36 ‰ bottom water were present along the shelf edge up to Cape Fear.

Salinity 1977

The surface and bottom salinities during winter 1977 were very similar and appeared to be a continuation of summer 1976 conditions, *i. e.*, low nearshore salinities (<35 ‰) and high midshelf salinities (>36 ‰) (Figure 14). The winter 1977 isohalines were more continuous than those of the previous summer with even lower salinities near the coast. In fact, the surface salinity of 31.59 ‰ during the winter 1977 cruises was the lowest of the 1976-79 period. At the same time, however, a high salinity Gulf Stream intrusion was evident in the region near Long Bay, where salinities ≥36.5 ‰ were measured.

Summer 1977 was characterized by unusually high salinities throughout the SAB. While surface and bottom isohalines did not correspond as well as those of winter 1977, they were nonetheless close enough for general comparison (Figure 14). Salinities >35.5 ‰ and >36 ‰ were observed off Charleston and Savannah, with the 36.25 ‰ bottom isohaline extending southward to Cape Canaveral. Such high salinities near river mouths are uncommon, especially when encountered throughout the area. SINGER *et al.* (1980) also found comparably high salinities (35.5 ‰) near Savannah during September 1977 (about two weeks after our transect). As in winter 1977, another high salinity Gulf Stream intrusion was present in Long Bay, where surface and bottom salinities were >36.25 ‰ and >36.5 ‰ respectively. The only salinities <35.5 ‰ were near the coast in Long Bay and on the bottom near the shelf edge.

Salinity 1978

Surface and bottom salinities during winter 1978 agreed well, except at the shelf edge. Nearshore

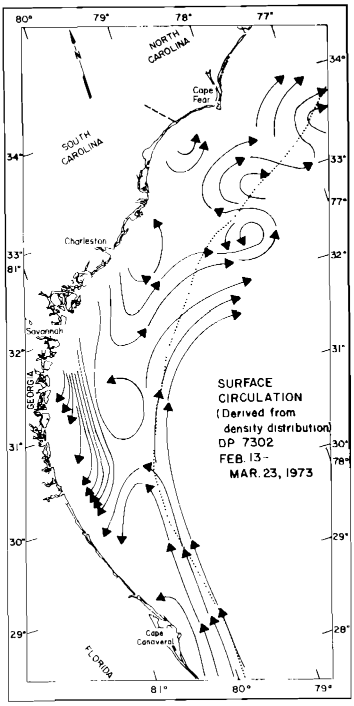

Figure 17. Surface circulation for winter 1973.

salinities were low (<34.5 ‰) from Charleston to upper Florida and even lower (<33 ‰) along the southern Georgia coast (Figure 15). Surface salinities were high (>36.25 ‰) from Cape Fear to Cape Canaveral at midshelf to outer-shelf locations (Figure 15). The bottom counterpart to the surface was a band of >36.25 ‰ water along the middle shelf more or less following the coastline. Both surface and bottom salinities indicated a Gulf Stream intrusion in Long Bay extending close to Cape Fear.

Summer 1978 salinities were generally high throughout the SAB, although not as high as during summer 1977. Surface and bottom salinities (summer 1978) were in good agreement near the coast as usual. The only low salinity water (<35 ‰) recorded was off Charleston in a small nearshore area (Figure 15). Bottom salinities were >36.25 ‰, occupying most of the shelf from Cape Canaveral northward to about 31° 30′ N latitude. A Gulf Stream intrusion was indicated by high salinity surface (>36.25 ‰) and bottom water (>36.5 ‰) in the Long Bay area much like summer 1977.

Salinity 1979

Summer salinities during 1979 were like those recorded during the two preceding summers in several ways. Surface salinities were high (>36 ‰) near Long Bay and Cape Canaveral, indicating Gulf Stream intrusions (Figure 16). Bottom salinities were highest (>36.25 ‰) in a midshelf band. Also, the only low bottom salinities (<35 ‰) were found near Savannah and at the shelf edge. Unlike 1977 and 1978 however, the 1979 surface salinities were low (<34.5 ‰) in a rather large area near Charleston, indicating a spreading of runoff from South Carolina rivers.

Surface Circulation

The general characteristics of circulation in the SAB have been summarized and discussed by BUMPUS (1973), who observed that the southerly flowing coastal current is very transient, restricted to a narrow band along the coast, and secondary to a broad, slow, northerly drift along most of the continental shelf. The amount of river runoff, wind direction and force, and location of the Gulf Stream all have an effect on the circulation, especially on the coastal current. Specific circulation features, such as upwelling and intrusions, have been examined by BROOKS and BANE (1978), PIETRAFESA *et al.* (1978), LEGACKIS (1979), BLANTON *et al.* (1981), JANOWITZ and PIETRAFESA (1982), and SMITH (1983). Much of the preceding work was performed utilizing satellite imagery to detect large-scale features, while using hydrographic data from oceanographic cruises (as available) for confirmation. As a consequence, upwelling near Cape Canaveral and the Charleston bump has been identified and described in some detail. Shelf-edge intrusions were also detected at many locations by utilizing similar techniques.

Our studies in conjunction with many other similar programs have indicated that circulation below Cape Fear is roughly bimodal with discernible winter and summer patterns. Several features are usually found: a countercurrent of varying intensity (longer in the summer), a cyclonic eddy in Long Bay (generally larger in the summer), a large offshore deflection of the Gulf Stream in the area of the Charleston bump and consequent upwelling of deeper water downstream of the deflection, and upwelling to the north of Cape Canaveral. A relatively stable midshelf band of bottom water also exists, most evident during winter in terms of temperature

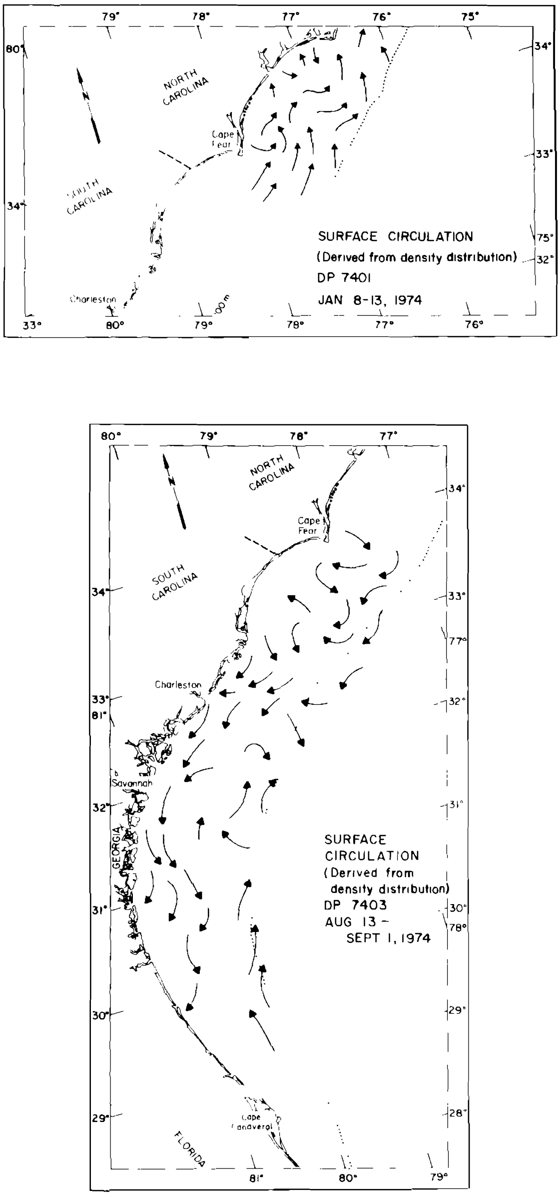

Figure 18. Surface circulation for winter and summer 1974.

and salinity and, to a lesser degree, during summer with respect to salinity. Due to shoals at Capes Lookout and Fear, circulation is divided roughly into three unequal zones, *i. e.*, Raleigh Bay, Onslow Bay, and south of Cape Fear to Cape Canaveral.

Surface circulation (based on density distribution) is shown in Figures 17-21. The countercurrent can be seen in every season except during winter 1974. Each year the summer countercurrent is continuous from Long Bay southward, while the winter countercurrent usually begins near Savannah or the lower portion of South Carolina. The extent of the countercurrent is related to the amount of runoff and often to the size of the cyclonic eddy in Long

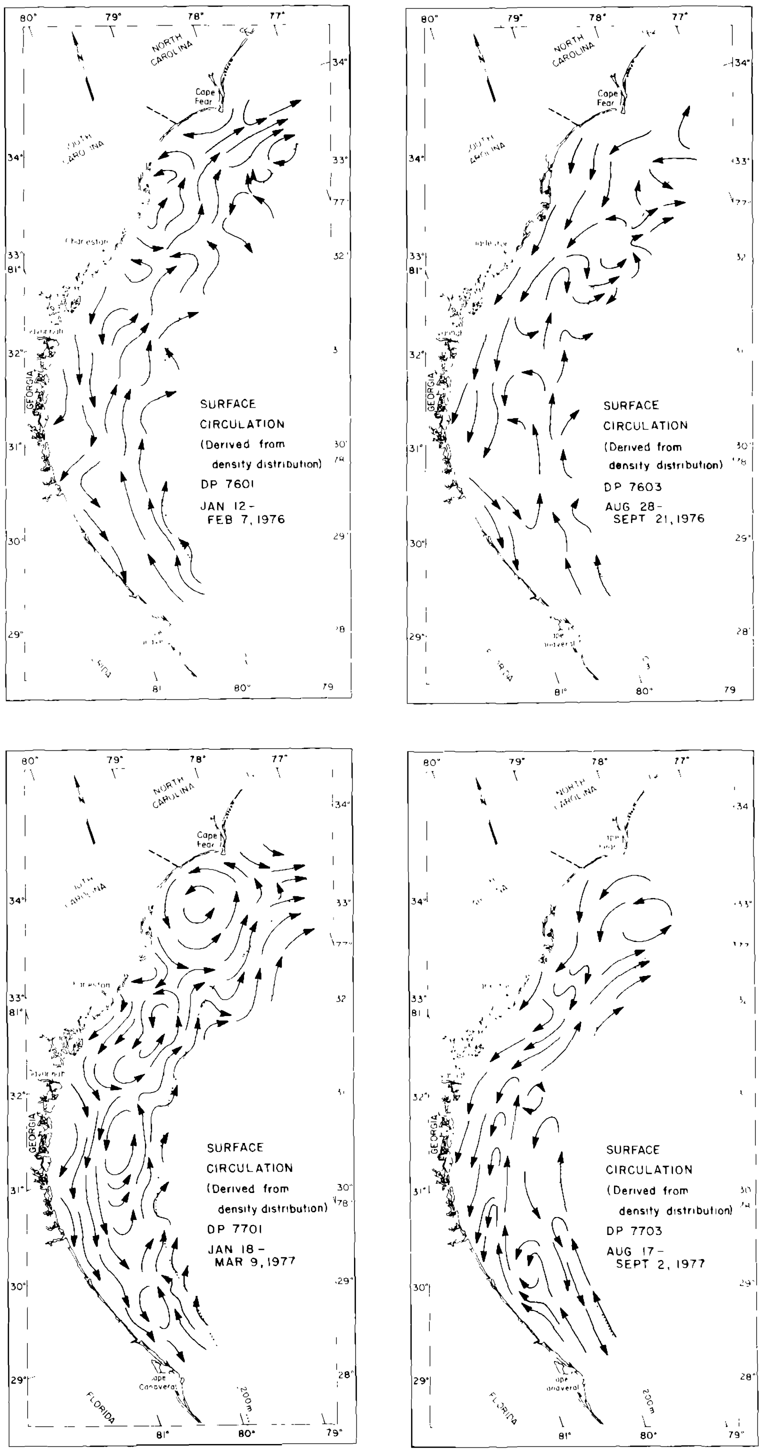

Figure 19. Surface circulation for winter and summer 1976 and 1977.

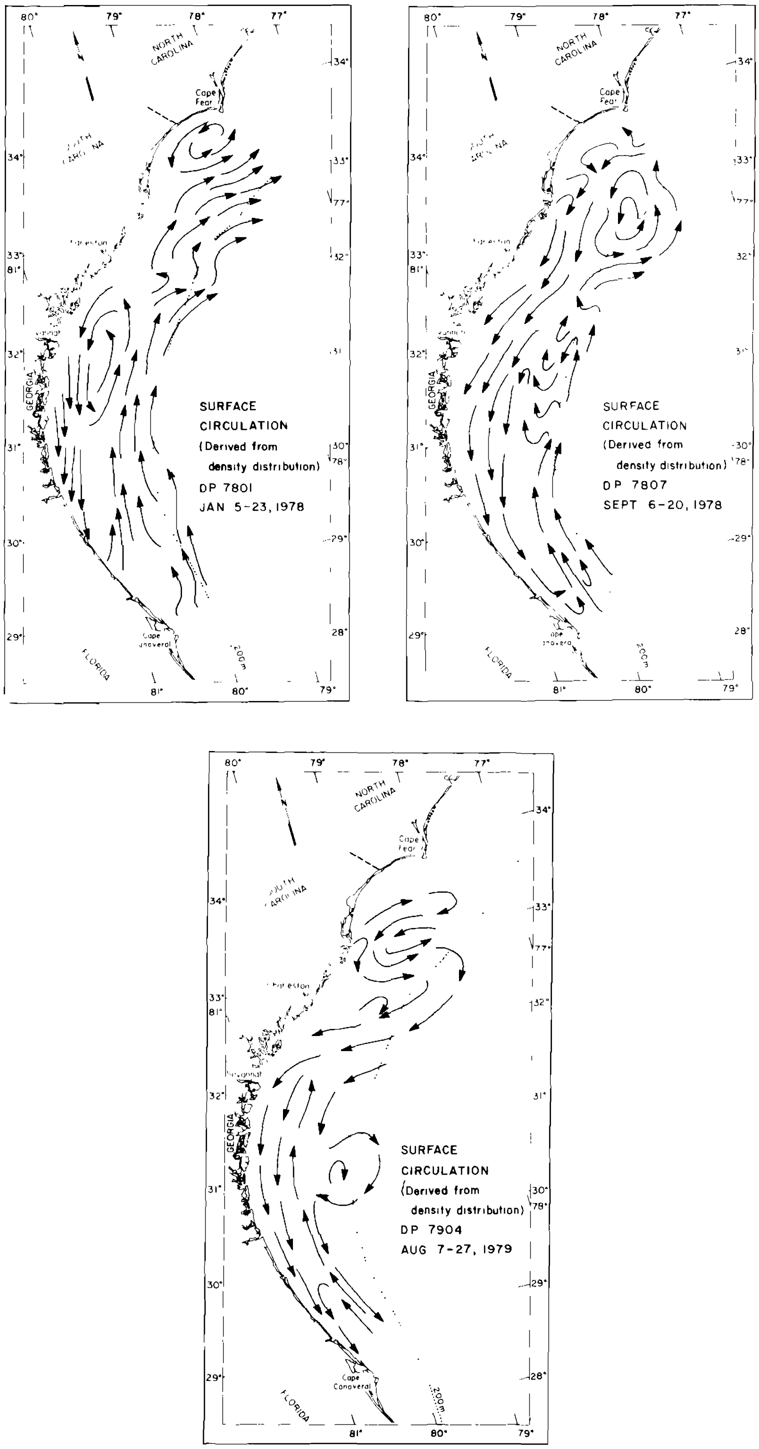

Figure 20. Surface circulation for winter and summer 1978 and summer 1979.

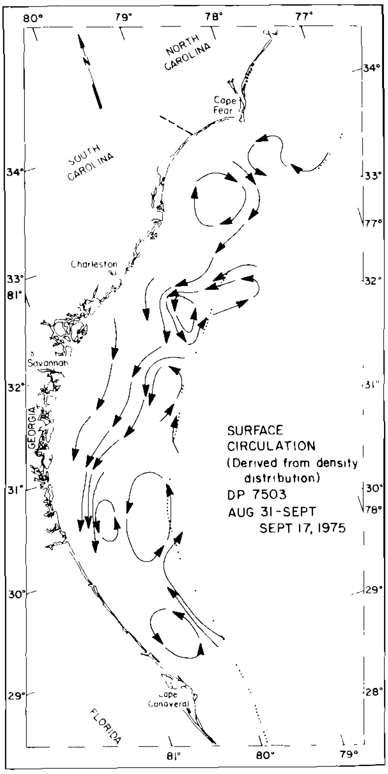

Figure 21. Surface circulation for summer 1975.

Bay. When the eddy is large, it tends to reinforce the general southwesterly flow of nearshore waters, typically during summer. On the other hand, when the eddy is small or displaced to the north or east (usually during winter), the countercurrent is much shorter, beginning as far south as Savannah.

Upwelling, occurring on a quasi-permanent basis downstream of the Charleston bump (32° 30′ N and 78° W) and near Cape Canaveral, may be the result of bottom topography, downstream or lee eddies, or divergent isobaths (JANOWITZ and PIETRAFESA 1982). Meanders of the Gulf Stream presumably increase the probability of upwelling or intrusions onto the shelf as discussed by ROONEY *et al.* (1978) and BLANTON *et al.* (1981).

While most of the features described above are to some extent evident in our results, considerable differences were observed overall. Some of the surface circulation details may be obscured in density-derived plots due to the formation of a shallow, low density layer over much of the inner shelf during summer. Winter circulation patterns should not be affected.

During winter 1973 circulation patterns were typical, with a shortened countercurrent extending from Savannah to northern Florida and a Gulf Stream deflection at the Charleston bump near 32° 30′ N latitude (Figure 17). Winter 1974 data were confined to the North Carolina shelf, where the flow in Onslow Bay was generally north to northeast with some evidence for a cyclonic eddy below Cape Lookout (Figure 18). Circulation during winter 1976 was normal without a Long Bay eddy and with a shortened countercurrent (Figure 19). Winter 1977 had a well-established cyclonic eddy in Long Bay with three other cyclonic eddies at midshelf locations and a countercurrent from Long Bay to Cape Canaveral (Figure 19). A small, but distinct, cyclonic eddy was also present in Long Bay during winter 1978, but the countercurrent was normal, beginning near Savannah in the vicinity of an elongated cyclonic eddy (Figure 20).

Summer circulation was characterized by the usual countercurrent extending from Long Bay to Florida. Both 1974 and 1975 summers had rather well-defined countercurrents, but either no cyclonic eddy in Long Bay (1974) or a suggestion of both cyclonic and anticyclonic eddies (1979) (Figures 18, 20-21). Summer 1976 had a continuous countercurrent from Cape Fear to northern Florida, where a cyclonic eddy formed the southern end of the current (Figure 19). Long Bay had no well-defined cyclonic eddy, however, unlike the summers of 1977 and 1978, which were normal (Figures 19-20). The currents during summer 1979 were considerably modified in that the Gulf Stream deflection at Charleston was far greater than usual, resulting in an offshore movement of the countercurrent and the spreading of warm, low salinity water off Charleston (Figure 20). The countercurrent was, however, continuous from Long Bay down to Cape Canaveral.

SUMMARY AND CONCLUSIONS

Major characteristics of SAB hydrography were described for the 1973-79 period, utilizing temperature and salinity plots from winter and summer cruises. Semi-permanent circulation features, as derived from density distribtions, were identified. The effects of climatic influences such as large amounts of precipitation (runoff) and abnormally low air temperatures were also elucidated throughout the study.

Perhaps the most important observation of this study was that meteorological conditions can be a major influence on continental shelf oceanography. The effects of weather on nearshore waters, *e.g.*, rainfall via river runoff, have been recorded many times, but generally they have been assumed to be relatively minor in the SAB. During winter 1973, however, salinities were reduced out to midshelf locations and from South Carolina to Florida, driving nutrient-rich water and white shrimp shrimp from the estuaries onto the shelf. Because the heavy river discharge and low water temperatures occurred late in winter 1973, the white shrimp population was apparently unaffected. If the heavy snowfall and subsequent runoff had occurred during December or January, the impact might have been severe.

As widespread as the winter 1973 effects were, the winter 1977 impacts were felt over an even larger area. Low salinities and unusually low temperatures were recorded in shelf waters from North Carolina to Florida out to midshelf locations The influence of the Gulf Stream on shelf-water oceanography was diminished as shown by the distribution of temperature and salinity and the surface circulation patterns The predominant flow over the shelf was not northeasterly, rather it was southwesterly with a large cyclonic eddy in Long Bay in series with three other cyclonic eddies to the southwest. The countercurrent was continuous from Long Bay to Cape Canaveral, which was unusual for winter circulation. The abnormal conditions were further illustrated by the disruption of the band of warm bottom water, normally found at mid- to outer-shelf locations. In addition, the inshore or estuarine impacts of the cold winter of 1977 in conjunction with the second cold winter in 1978 were devastating to white shrimp populations.

In conclusion, although the Gulf Stream is responsible for most of the major SAB circulation features and is a stabilizer for temperature and salinity, atmospheric influences can significantly alter shelf-water oceanography. The abnormally cold weather of winter 1977 may, in fact, have been the dominant factor in SAB oceanography during that season.

ACKNOWLEGEMENTS

The authors wish to thank W.D. Anderson, J.D. Whitaker and V.G. Burrell, Jr. for their review of the manuscript and helpful comments. In addition thanks are extended to K.R. Swanson and D.B. Stone, III, for illustrations, to N.M. Peacock for typing the manuscript, and to K.H. Austin for proofing and analyses.

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