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The seasonal hydrography and circulation over Nantucket Shoals

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ABSTRACT

Bimonthly hydrographic surveys were begun in May, 1978 to measure the spatial structure and temporal variability of the temperature and salinity fields about Nantucket Shoals over one annual cycle. Moored current meters were also deployed in January, 1979 and in July, 1979 to directly measure the current field and examine low-frequency current variability over the shoals. Surface temperature maps obtained during the spring and summer show cores of relatively cold, nutrient rich water along the northeastern edge of the shoals which result from the advection of stratified Gulf of Maine water into the tidally well-mixed region over the shoals. The regional *T/S* distribution during the spring and summer shows a bimodal distribution: a Gulf of Maine mode and a shelf mode. The Gulf of Maine mode dominates the local water structure over the northern part of Nantucket Shoals, and a mixture of the two modes dominates the southern shoals. The presence of the shelf mode in the Great South Channel region implies inflow here through the Channel. Advection and tidal mixing and to a lesser extent local air/sea heat exchange and wind forcing directly influence water properties over the shoals. Direct current measurements over the eastern shoals near 41°30′ suggest a southward flow of order 10 cm/sec, indicating a minimum transit time of order 10 days through this eastern region. While local wind forcing can influence the low-frequency current variability over the shoals (and indeed reduce the minimum transit time to a few days during periods of strong northeast winds), the mean south and southwestward flow over the shoals appears to be driven on monthly and longer time scales by the larger scale regional circulation regime in the western Gulf of Maine, Georges Bank, and New England shelf region.

1. Introduction

Nantucket Shoals is a submerged sand and gravel shallow ridge which extends 52 km eastward and 93 km southeastward from Nantucket Island, Massachusetts (Fig. 1). The bathymetry of the shoals is characterized by deep (20-30 m) north-south channels separating shoal areas which are only a few meters deep. On length scales of meters, migrating sand waves are found in the shallow regions. In general, the shoals are the southwestern boundary of the Gulf of Maine and form a topographic barrier to deep flow between the Gulf of Maine and the New England continental shelf. To the east of Nantucket Shoals is a 60 m deep channel, the

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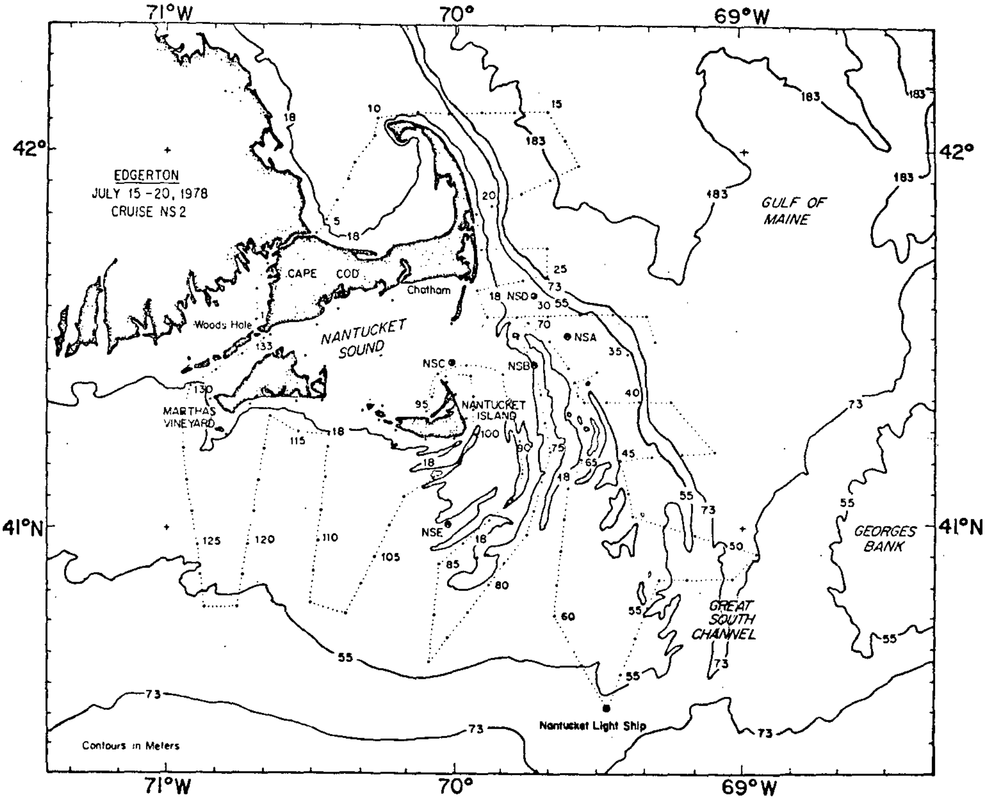

Figure 1. Nantucket Shoals moored current meter and hydrographic station locations, regional bathymetry, and coastal locations.

Great South Channel, and then Georges Bank extends toward Nova Scotia. The Gulf of Maine with depths greater than 200 m is located a few kilometers to the northeast of Nantucket Shoals but water depths are generally less than 100 m on the shelf to the south and southwest of the shoals.

Increased interest in protecting regional fishery resources and development of offshore oil resources have motivated a new effort to understand the ecology of the northeast U.S. shelf and coastal environment. We will present here an overview of previous physical oceanographic measurements made near Nantucket Shoals, then describe our hydrographic and moored current measurements made over the shoals during 1978-1979, and finally give an improved circulation scheme for the shoals. Previous hydrographic surveys to the Gulf of Maine (Bigelow, 1927; Colton *et al.*, 1968; Limeburner *et al.*, 1978; EG&G, 1978) used deep draft vessels that were unable to navigate over the shoals. The results of these cruises showed that although the water properties near the edge of the shoals were vertically well mixed,

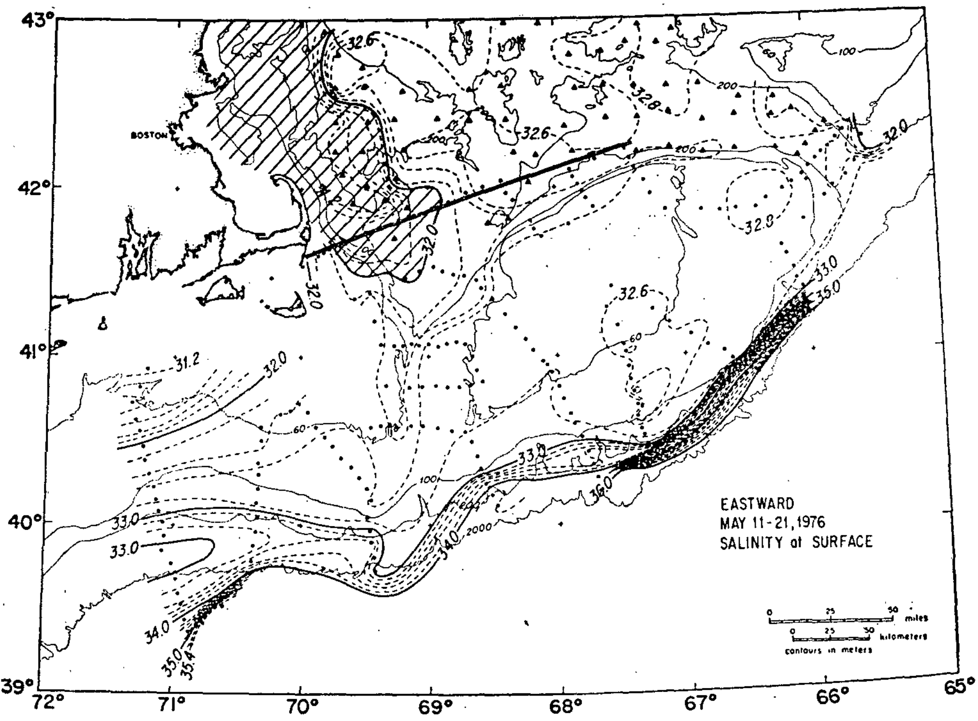

Figure 2. May, 1976 surface salinity for the Gulf of Maine and Georges Bank.

strong horizontal gradients in temperature and salinity were observed indicating that advection and tidal mixing may be important in controlling regional hydrographic properties. Extensive short-term current measurements were made by Haight (1942) using a "tide pole" to observe the speed, direction, and phase of the tide over Nantucket Shoals, but no long-term current measurements were made over the shoals prior to 1979.

In 1976, two extensive hydrographic surveys were made with closely-spaced stations in the Georges Bank and adjacent continental shelf region (Limeburner *et al.*, 1978). A prominent feature in the surface salinity pattern for May, 1976 shown in Figure 2 is the presence of a strong offshore salt gradient on the southeastern side of Georges Bank indicating the transition from shelf water to slope water. A second prominent feature is the plume of relatively fresh water ($\leq 32‰$ located east of Cape Cod. Bue (1970) estimates the average annual streamflow into the Gulf of Maine from the St. Croix River near New Brunswick to Cape Cod to be $1.7 \times 10^3 m^3/sec$. The major contributions to this annual runoff are from the Penobscot River (26%), the Kennebec and Androscoggin Rivers (30%), and the Merrimac River (16%). Approximately 50% of the annual river discharge occurs in the months of April, May, and June (Bigelow, 1927, p. 839). An additional average annual streamflow of 1.3 × 10^3m^3/sec enters the Gulf of Maine from the St. John's River and other Canadian tributaries (Meade, 1971). Although large intrusions of Scotian shelf water enter the Gulf of Maine off Cape Sable from winter to spring (Bigelow, 1927, p. 727; and Smith, 1981), the fresh water plume shown in Figure 2 is a surface feature and is assumed to originate with the local river runoff within the Gulf of Maine. The May surface salinity map also shows that water fresher than 32.6‰ takes on a tonguelike structure to the southeast of Cape Cod as well as a similar tongue of water less than 32.6‰ to the east of Cape Cod. Thus the surface salinity pattern in May infers the existence of a south flowing fresh water plume off Cape Cod which divides into a southward flow along the eastern edge of Nantucket Shoals and an eastward flow along the northern edge of Georges Bank.

The vertical extent of the May, 1976 freshwater plume off Cape Cod is shown in the EASTWARD Section M (Fig. 3) located offshore of Chatham (see solid line in Fig. 2). The 32‰ isohaline encloses a surface approximately 30 m deep and 80 km wide. The freshest water within the 32‰ surface was found on the western side of the plume. Also note in Figure 3 that water less than 8°C, and salinity between 32.2-32.4‰ occurred on the edge of Nantucket Shoals adjacent to the fresh water plume. In fact, surface temperatures less than 7°C were observed over the eastern edge of Nantucket Shoals and these cold surface temperatures were the coldest observed during the Gulf of Maine and Georges Bank survey. Similarly cold surface temperatures were observed on the eastern edge of Nantucket Shoals in August, 1976 with a horizontal temperature gradient of 1°C/km to the east of a surface cold patch (Limeburner *et al.*, 1978). These temperature anomalies to the east of Nantucket were assumed to be the result of the upwelling of water from the lower seasonal thermocline (at depths of = 20-40 m) in the southwestern Gulf of Maine. Bigelow (1927, p. 588) was the first to note a relationship between westerly winds in the western Gulf of Maine and an offshore flux of surface water which is replaced by cooler upwelled water. Upwelling of this type is common along the northern shore of Massachusetts Bay. However, Nantucket Shoals is not an obvious barrier to an offshore wind-driven surface flux, and the cause of the cold surface waters east of Nantucket was not understood after the 1976 hydrographic surveys.

In May, 1978 we began a series of bimonthly hydrographic surveys in the Nantucket Shoals region as part of a program designed to measure the spatial and temporal structure and variability of the water properties in the Nantucket Shoals-Great South Channel region and investigate the general circulation of the shoals. Figure 1 shows the regional topography and cruise track which was followed during the May, July, September, 1978 and March, 1979 surveys. The November, 1978 cruise was cancelled and the January and May, 1979 cruises shortened due

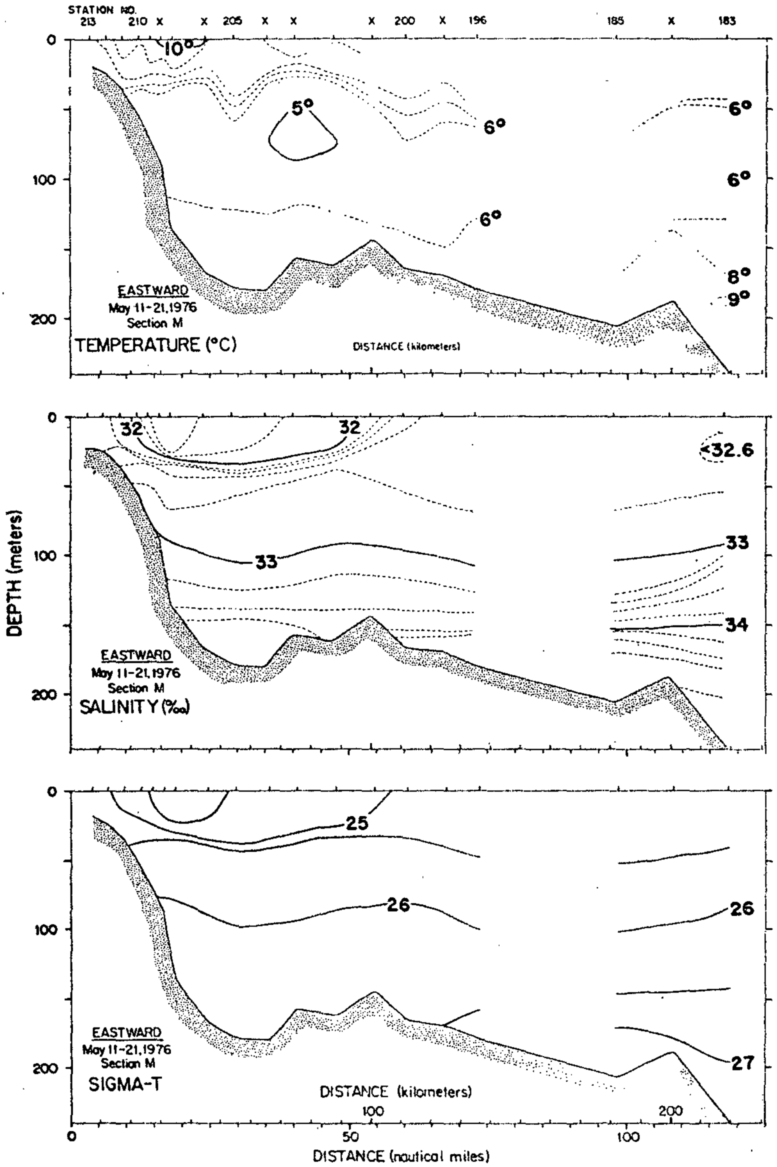

Figure 3. May, 1976 vertical distribution of water properties to the east of Chatham, Massachusetts. Location of section shown as heavy line in Figure 2.

to weather conditions. The dates and number of stations occupied on each cruise are given in Table 1. A Plessy model 9040 CTD fish and model 8400 digital data logger were used to make CTD stations approximately every 9 km along a cruise

Table 1

Nantucket Shoals Hydrographic Cruises

Cruise	Date	No. CTD Stations	No. Surface Stations
NS1	May 28-June 2, 1978	108	25
NS2	July 15-20, 1978	120	13
NS3	September 14-19, 1978	100	27
NS4	January 23-29, 1979	10	52
NS5	March 22-26, 1979	24	80
NS6	May 19-23, 1979	29	56

track which covered the coastal zone between one and fifty nautical miles offshore and in the general area to the east and south of Cape Cod, Martha's Vineyard, and Nantucket Island. Surface temperature and salinity samples were also taken along the cruise track, especially during the winter cruises and in well-mixed regions. In addition, chlorophyll and nutrient data were obtained during several hydrographic cruises to help understand the formation and dynamics of phytoplankton patches in relation to upwelling and advection. All cruises were made aboard the MIT 20 meter converted T-boat, the R/V *Edgerton.* A summary of the hydrographic observations for surveys NS1-NS3 is given by Limeburner and Beardsley (1979) and a summary of the hydrographic and biological data obtained on all six cruises as well as a complete description of the instrumentation and data processing is given by Limeburner *et al.* (1980).

We will present next in Section 2 a description of the hydrographic features and variability observed during our six cruises to Nantucket Shoals. Description of our pilot moored current observations made in January-February, 1979, and in July-August, 1979 will be presented in Section 3. Section 4 will discuss the factors (e.g., heating, cooling, precipitation, advection, tidal mixing, etc.) which influence the annual T/S cycle over Nantucket Shoals and our principal results will be summarized in the final section.

2. Water structure over and adjacent to Nantucket Shoals

We will now describe the distribution of hydrographic properties observed on the almost-bimonthly hydrographic surveys to Nantucket Shoals. The dates of the individual surveys are given in Table 1 for reference. In May, July, September, 1978 and in May, 1979, the water adjacent to the Shoals was stratified at depths less than 40 m, while the adjacent waters were well mixed during the January and

March, 1979 cruises. We will describe the water structure during the spring and summer stratified and winter unstratified periods next.

a. Spring and summer water property distributions

NS1: May 1978. Water adjacent to Nantucket Shoals was stratified to depths greater than 40 m in the May (NS1), July (NS2), and September (NS3), 1978 and in May (NS6), 1979 surveys. The water property distributions for this spring and summer stratified period can be characterized by the surface temperature and salinity distributions and the *T/S* diagram for the May (NS1), 1978 survey shown in Figures 4a and 6, respectively. The surface temperature map shows lower temperatures over the shoal area to the east of Nantucket than to the east in the Gulf of Maine or to the south and west over the New England shelf. A core of water colder than 7°C was found over a large area on the southeastern flank of the shoals. A similar structure is also shown in the sea-surface temperature map (Fig. 5) obtained by Legeckis *et al.* (1979) from NOAA-5 polar orbiting satellite infrared measurements made on June 6, 1978 four days after the NS1 survey. [Legeckis *et al.* (1979) demonstrate that sea-surface temperature fronts can be quantitatively detected with an uncertainty of ± 0.5°C by remote sensing when coastal radiosonde profiles are used to estimate the correction for atmospheric attenuation of the infrared radiation.] The structure of this cold core of surface water was localized along the eastern edge of the shoals, and had *T/S* characteristics similar to water in the lower seasonal thermocline in the Gulf of Maine. Similar *T/S* characteristics could also result from mixing a shallow column of stratified Gulf of Maine water. The surface water to the southwest of Nantucket Shoals over the shelf was warmer than over the shoals due to less vertical mixing. The warmest surface temperatures were found in Nantucket Sound where the shallow depths of less than 10 m tend to concentrate the vernal heat input. The surface salinity map for May, 1978 shows a freshwater plume east of Cape Cod which implies a southward flow of surface water just east of Cape Cod. This freshwater minimum was relatively shallow (10-15 m) and assumed to be similar in origin and structure to the low salinity water observed in this area in May, 1976 (Fig. 2). The salinity of the water in the low-temperature core along the eastern edge of the shoals was higher than to the north, east, or west. Also, all of Nantucket Shoals and most of the shelf to the south of Cape Cod was covered by surface water with salinities less than 32‰, indicating that this region was influenced more directly by river runoff than the mid- and outer shelf water.

The *T/S* diagram for May, 1978 (Fig. 6) shows that the *T/S* curves from local areas form into distinct groups indicative of different water masses. The Gulf of Maine water was characterized by a temperature minimum at mid-depth called Maine Intermediate Water by Hopkins and Garfield (1980), and was quite distinct from the shelf water group found on the New England shelf south of Nan-

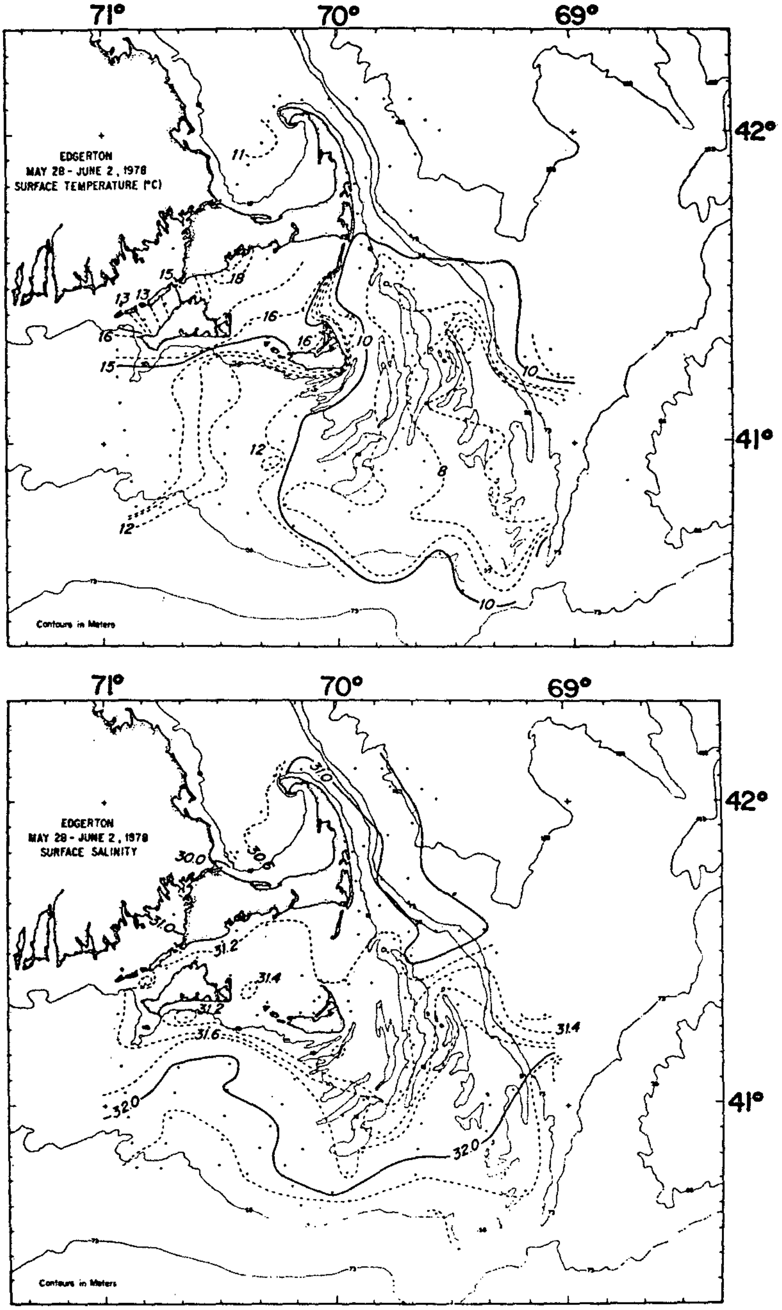

Figure 4a. Nantucket Shoals surface temperature and salinity distributions for Cruise NS1, May, 1978.

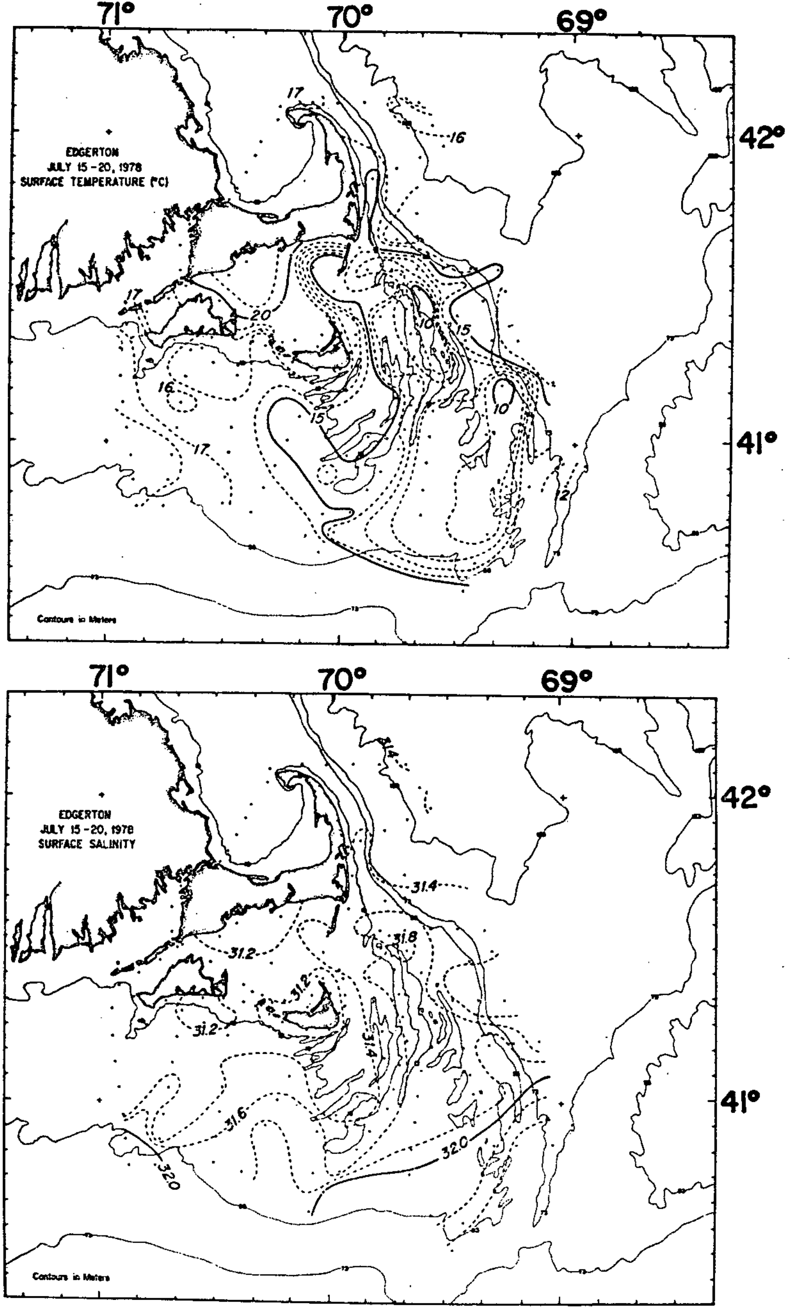

Figure 4b. Nantucket Shoals surface temperature and salinity distributions for Cruise NS2, July, 1978.

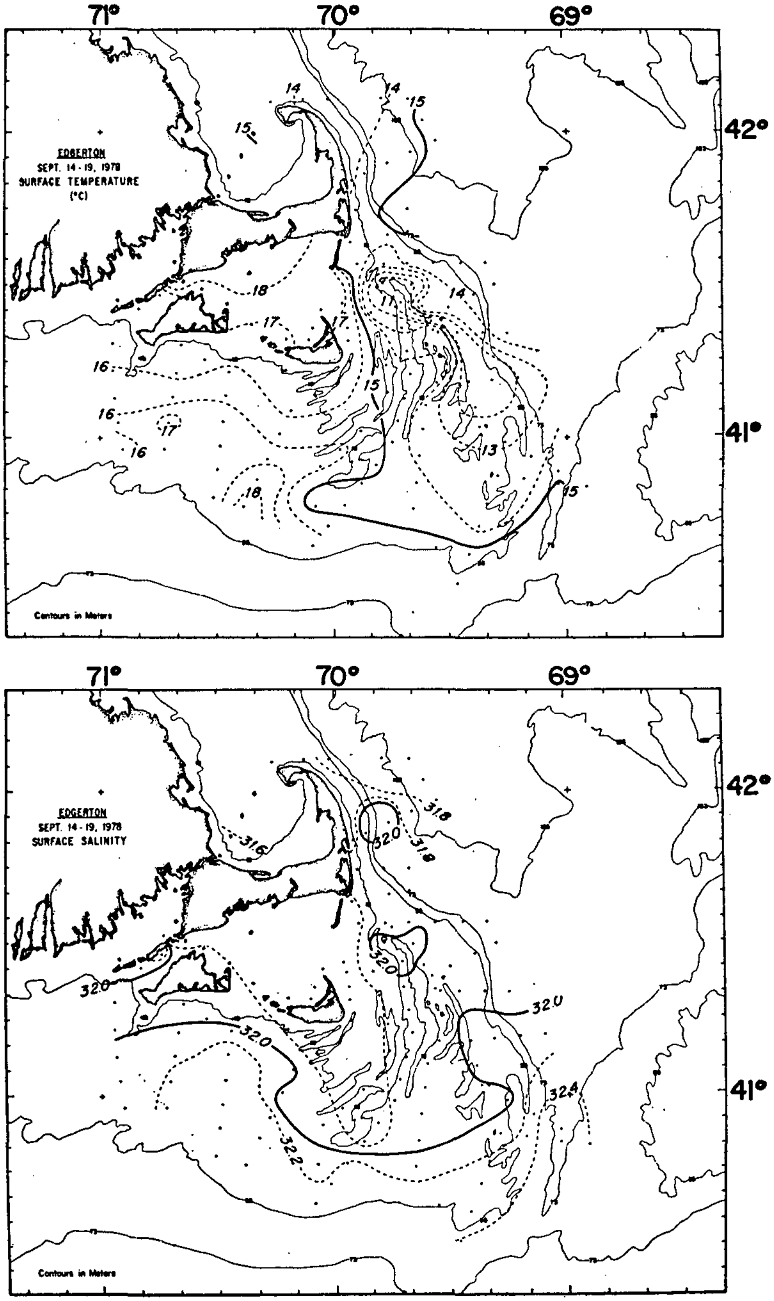

Figure 4c. Nantucket Shoals surface temperature and salinity distributions for Cruise NS3, September, 1978.

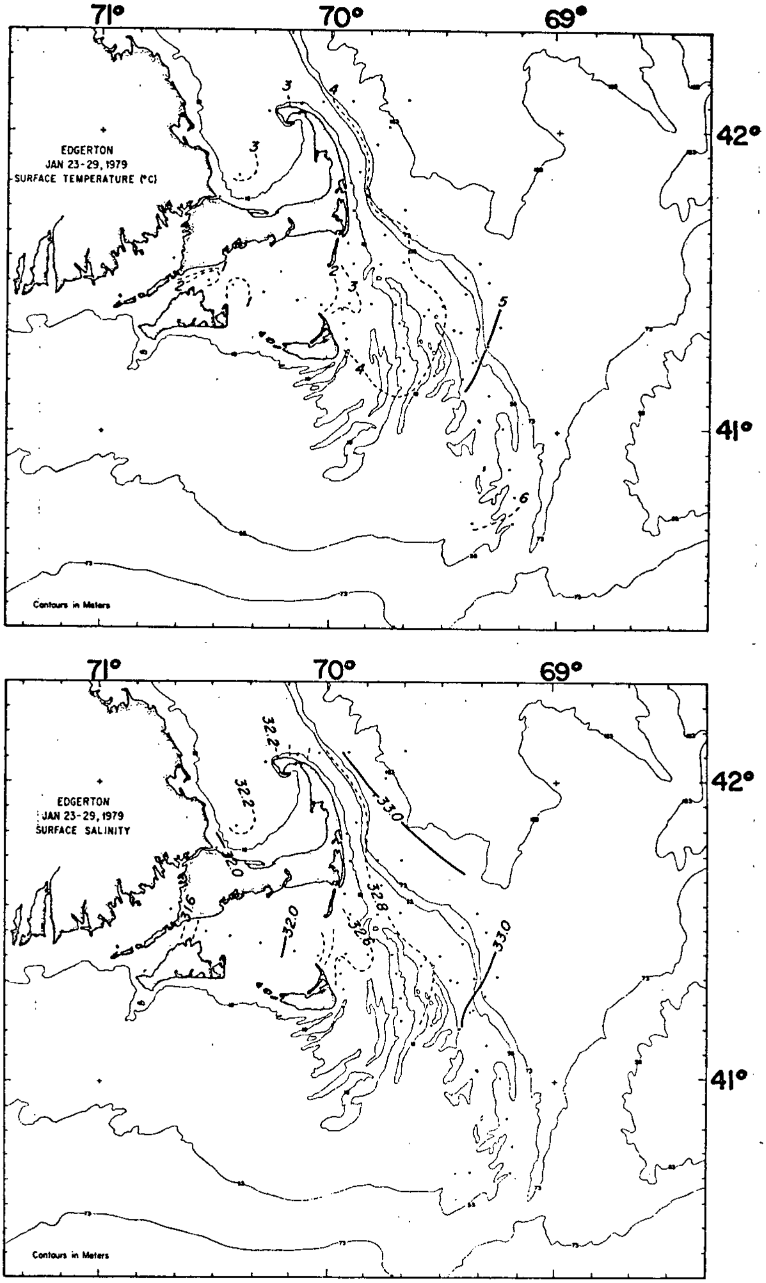

Figure 4d. Nantucket Shoals surface temperature and salinity distributions for Cruise NS4, January, 1979.

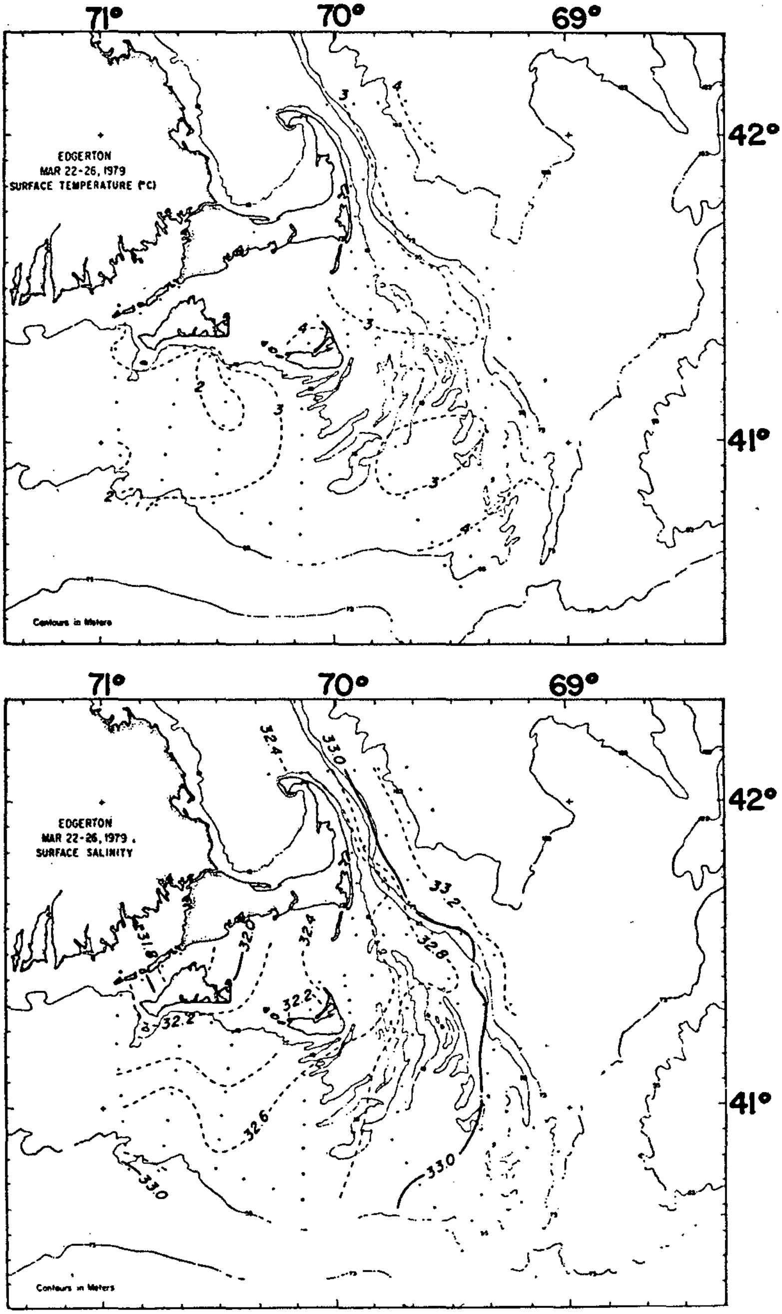

Figure 4e. Nantucket Shoals surface temperature and salinity distributions for Cruise NS5, March, 1979.

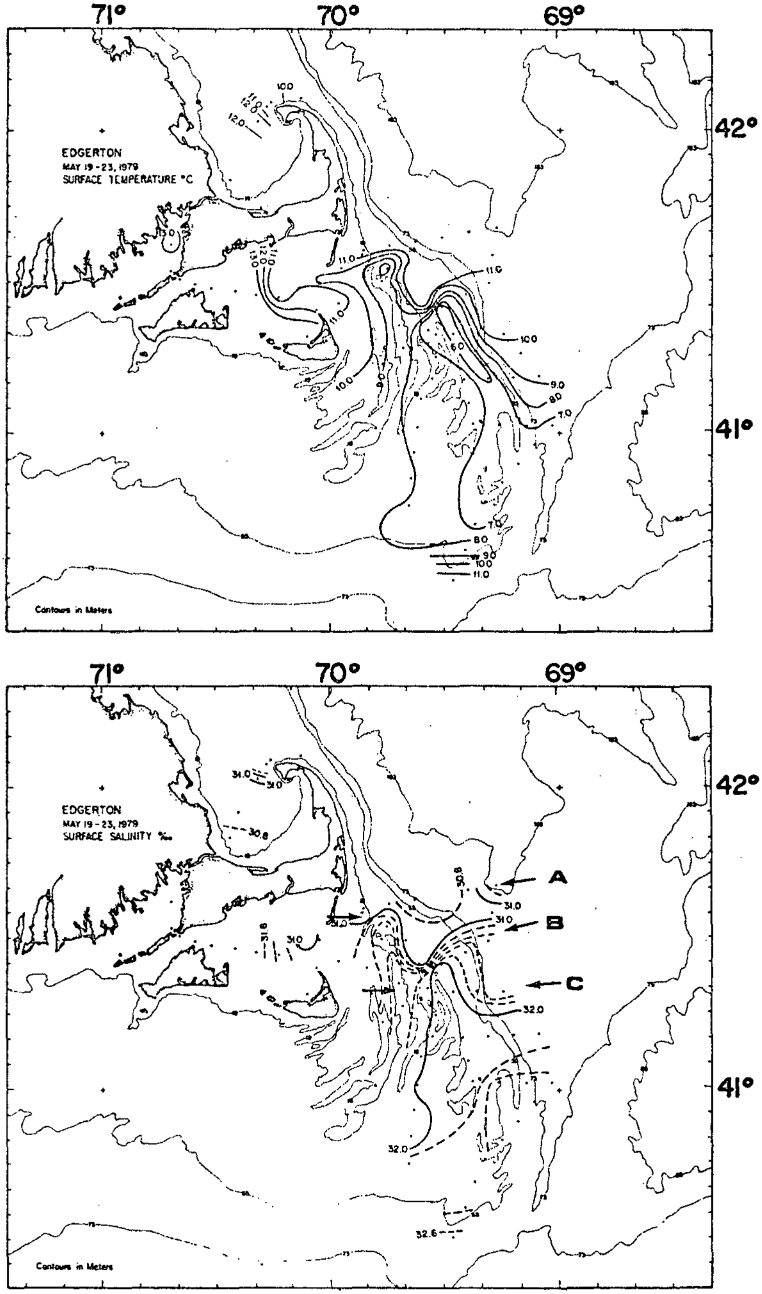

Figure 4f. Nantucket Shoals surface temperature and salinity distributions for Cruise NS6, May, 1979.

tucket. The shelf water was more saline at a given temperature than the Gulf of Maine water and temperature monotonically decreased with increasing salinity. However, the shelf water mode was also found in the Great South Channel, suggestive of northward flow of shelf water through this channel or at least partial penetration. Thus the *T/S* diagram for May, 1978 shows a bimodal distribution for the survey area; a Gulf of Maine mode (M) and a shelf mode (S). Many of the well-mixed stations from over Nantucket Shoals which plot as single points in Figure 6 appear to be mixtures of each or both of the two larger modes. Actually most of the stations over the northern regions of Nantucket Shoals and including the temperature minimum core had similar *T/S* properties to the Gulf of Maine mode. The coldest surface water had *T/S* characteristics similar to water found at 20-30 m in the Gulf of Maine. The stations over the southern region of the shoals appear more as a mixture of the two larger modes.

Thus we infer a spring time southward drift of Gulf of Maine water over the shoals which mixes with shelf water both flowing northward through the Great South Channel and flowing southwestward along the southern extent of the shoals. The core of cold water found along the eastern edge of the shoals has similar *T/S* properties to water in the lower seasonal thermocline in the western Gulf of Maine, and the water over the western part of the shoals was fresher than water over the eastern shoals, implying a southeastward flow of Nantucket Sound water to Nantucket Shoals.

NS2: July, 1978. The surface temperature map for July, 1978 (Fig. 4b) shows the shoals were dominated by cold, mid-depth water from the Gulf of Maine. Minimum surface temperatures less than 10°C were found along the eastern edge of Nantucket Shoals, but two temperature minimum cores are observed instead of one as in the May cruise, suggesting that upwelling may have occurred north of the shoals to the east of Cape Cod. The temperature distribution at 10 m depth along the eastern edge of Nantucket Shoals (Limeburner and Beardsley, 1979) shows a single core of water less than 10°C in July that occupied a region approximately 90 km by 15 km. Thus the subsurface expression of the temperature minimum zone has a much broader horizontal distribution than is evident from the surface temperature map. Again, the *T/S* characteristics of the cooler water along the eastern edge of the shoals were similar to those found in the lower seasonal thermocline in the Gulf of Maine. The warmest surface temperatures were found in the shallow Nantucket Sound. However, an intrusion of cold, relatively saline Gulf of Maine water did appear in the northeast region of the Sound near Monomoy Island. The surface salinity for July (Fig. 4b) shows low salinity water to the east of Cape Cod, but no plumelike structure is apparent. The two cores of cold water along the eastern edge of the shoals were more saline than the adjacent water to the east.

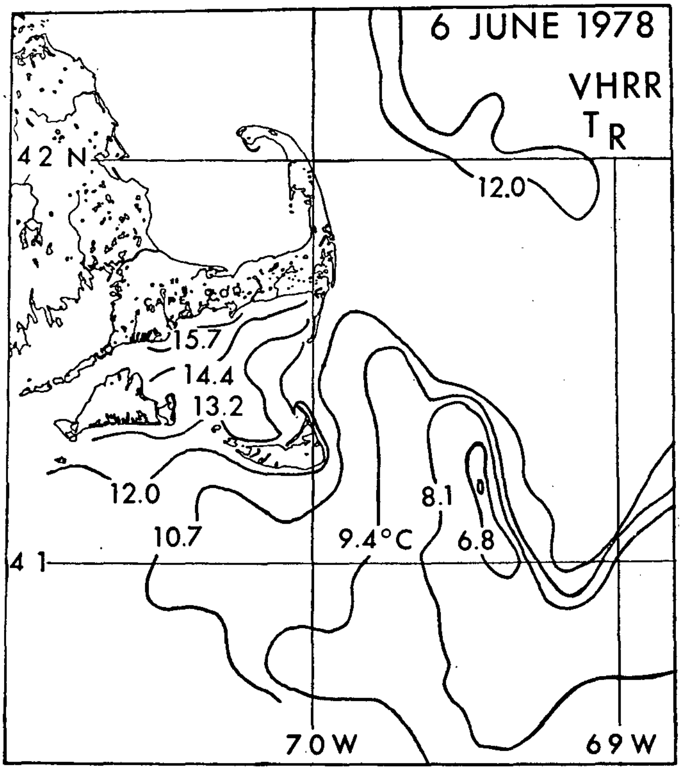

Figure 5. Sea-surface temperature distribution for June 6, 1978, obtained with the very high resolution radiometer aboard the NOAA polar orbiting satellite (Legeckis *et al.*, 1980).

The *T/S* diagram for July, 1978 (Fig. 6) did not form into two distinct modes as was found in the previous May. Gulf of Maine stations formed into a distinct group with a characteristic temperature minimum at mid-depth, but the minimum temperature was approximately 1°C warmer in July than in May. Great South Channel stations were similar to the shelf mode found in May, but the stations to the south of Cape Cod on the shelf were similar in surface *T/S* properties to the Gulf of Maine mode (M), and appear to be distinctly different from the Gulf of Maine mode at depth as indicated in the branching in the July *T/S* diagram.

Thus, water in the Great South Channel was different in hydrographic properties from the Gulf of Maine water, and the water on the shelf to the southwest of the shoals was mostly Gulf of Maine water. We feel that a strong southwestward wind event 10 days prior to our July survey was responsible for flooding the shelf to the southwest of Nantucket Shoals with Gulf of Maine water. The *T/S* properties of the mixed water over the shoals were similar to those of the Gulf of Maine water in July.

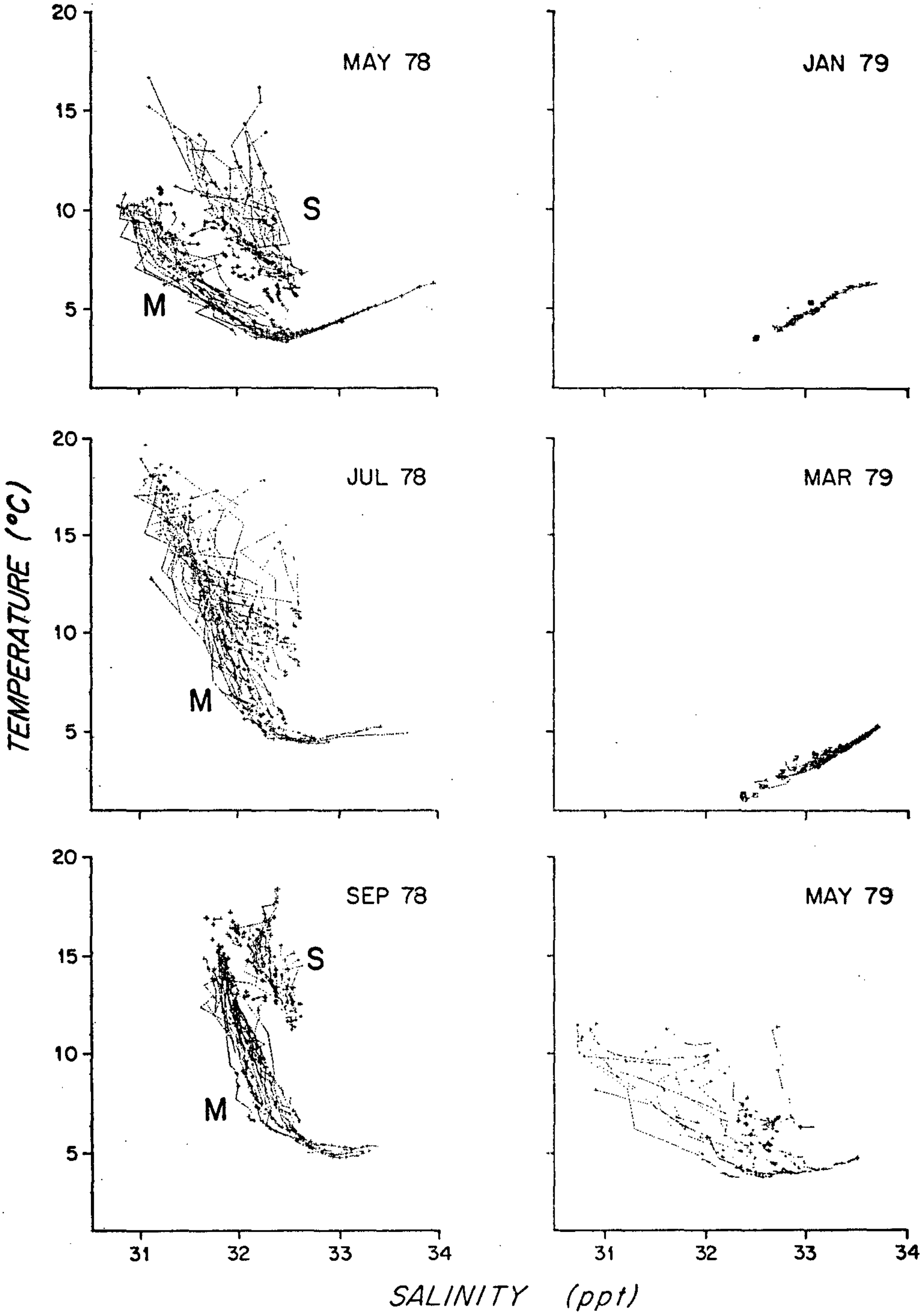

Figure 6. Temperature/salinity diagrams for Cruises NS1, May, 1978; NS2, July, 1978; NS3, September, 1978; NS4, January, 1979; NS5, March, 1979; and NS6, May, 1979.

NS3: September, 1978. The surface temperatures in September (see Fig. 4c) were highest over Nantucket Shoals compared to previous surveys, however, a well-defined temperature minimum was still observed along the eastern edge of the shoals and also along the nearshore area of outer Cape Cod. Lowest temperatures over the shoals were approximately 10°C along the eastern edge and the low-temperature regions appear in two cores separated by 50 km. Subsurface temperatures also show a double core distribution of low-temperature water along the eastern edge of the shoals. The water in Nantucket Sound has cooled and become more saline since the July survey. The surface salinity map for September shows local salinity maxima in the two temperature minimum cores which again infer the source region to be at depth in the Gulf of Maine. Much of Nantucket Sound and Nantucket Shoals had a salinity of about 31.8‰. The highest surface salinities of about 32.4‰ for the survey area were found along the axis of the Great South Channel in what appears to be an intrusion of water flowing into the Gulf of Maine (Butman *et al.*, 1982).

The *T/S* diagram for September, 1978 (Fig. 6) shows that the water properties again form two distinct groups. Salinity in the Gulf of Maine mode water increased monotonically with depth but the temperature has a well-defined minimum of 4.5°C at mid-depth. The minimum temperature and salinity for the Gulf of Maine mode increased 0.5°C and 0.2‰ from the July temperature minimum. The water properties over Nantucket Shoals indicate the Gulf of Maine as the source region with a transition to the shelf water mode occurring in the Great South Channel and along the southern boundary of the shoals. The distinct character of the September *T/S* modes means that horizontal mixing must be occurring within a narrow zone of order 10 km or less in the survey region.

NS6: May, 1979. The May, 1979 hydrographic survey was limited in the coverage of the Gulf of Maine and shelf region due to weather conditions, but the general temperature minimum region along the eastern edge of the shoals was well resolved (see Figure 4f). Surface temperatures were again lowest (< 6.0°C) along the eastern edge of Nantucket Shoals in a two-core structure similar to the distributions observed the previous July and September cruises. Surface temperatures in Nantucket Sound were lower than in May, 1978, but the 1979 cruise was conducted nine days earlier in May. Daily sea-surface temperature data obtained from the Woods Hole Oceanographic Institution pier show local surface temperatures in relatively shallow water frequently increasing 0.5°C per day during the latter part of May. The structure of the freshwater plume east of Cape Cod was not observed in May, 1979 due to the limited coverage of the survey area. However, a salinity minimum along the northern edge of Nantucket Shoals is believed to be the southern extent of the freshwater plume. Adjacent to the low salinity water along the northern shoals were the more saline cores of the temperature minimum water.

The May, 1979 T/S diagram (Fig. 6) shows a very tight T/S relation for the deeper water in the Gulf of Maine, but water in the top 50 m was more variable in salinity for a given temperature than the Gulf of Maine stations obtained during the first three cruises the previous summer. The shelf mode was noticeably absent in the May, 1979 T/S diagram although one CTD station located at the Nantucket Shoals Lightship had a shelf mode T/S correlation. Other stations in the Great South Channel were more saline at a given temperature than the few Gulf of Maine stations, but were not grouped into a well defined more saline T/S mode as was observed the previous May.

The vertical structure of the cold surface cores observed in May, 1979 is shown in Figure 7 for three sections along the eastern edge of Nantucket Shoals. Section A made near 41°40′N is considered to be upstream of the cold surface cores located farther to the south along the edge of the shoals. Note the shallowness of the temperature minimum water at station 29. The minimum temperature core ($<$ 4.0°C) was actually an isolated subsurface structure along the edge of the shoals from 20-80 m deep. The low salinity surface lens in Section A of fresh water runoff origin was less than 10 m deep and approximately 40 km wide. As a consequence, a relatively strong pycnocline of $\Delta\ \sigma_t = 1.8$ in the upper 25 m occurred in Section A. Section B made near 41°30′N, 20 km downstream of Section A shows a minimum surface temperature of less than 6°C at station 36 adjacent to the less saline surface lens at station 34. The transition from the stratified Gulf of Maine to the well-mixed shoal water is clear. Section C made near 41°20′N, 20 km south of Section B again shows the relatively local, shallow nature of the minimum temperature core along the eastern edge of the shoals. The mean temperature and salinity values resulting from mixing the surface water at station 34 in Section B to 40 m and 50 m are 6.1°C, 32.04‰ and 5.7°C, 32.13‰, respectively. These temperature and salinity values are nearly equal to the T/S values of the minimum temperature core (5.8°C, 32.11‰ at station 39) to within experimental uncertainty; thus uniform vertical mixing of the near-surface Gulf of Maine water is one possible mechanism for the formation of the temperature minimum core water.

b. Winter water property distributions

NS4: January, 1979. The January, 1979 hydrographic survey was much less extensive than the three previous cruises due to frequent storms accompanied by strong northwest winds. However, the survey did manage to sample a few deep stations in the Gulf of Maine and nine stations taken concurrently by J. Vermersch on the R/V *Oceanus* in the vicinity of the Great South Channel have been included in our analysis. One prominent feature in the January distribution of water properties in the survey area was the relative vertical homogeneity of temperature and salinity in the upper layer. Temperature variations were less than 0.4°C in the

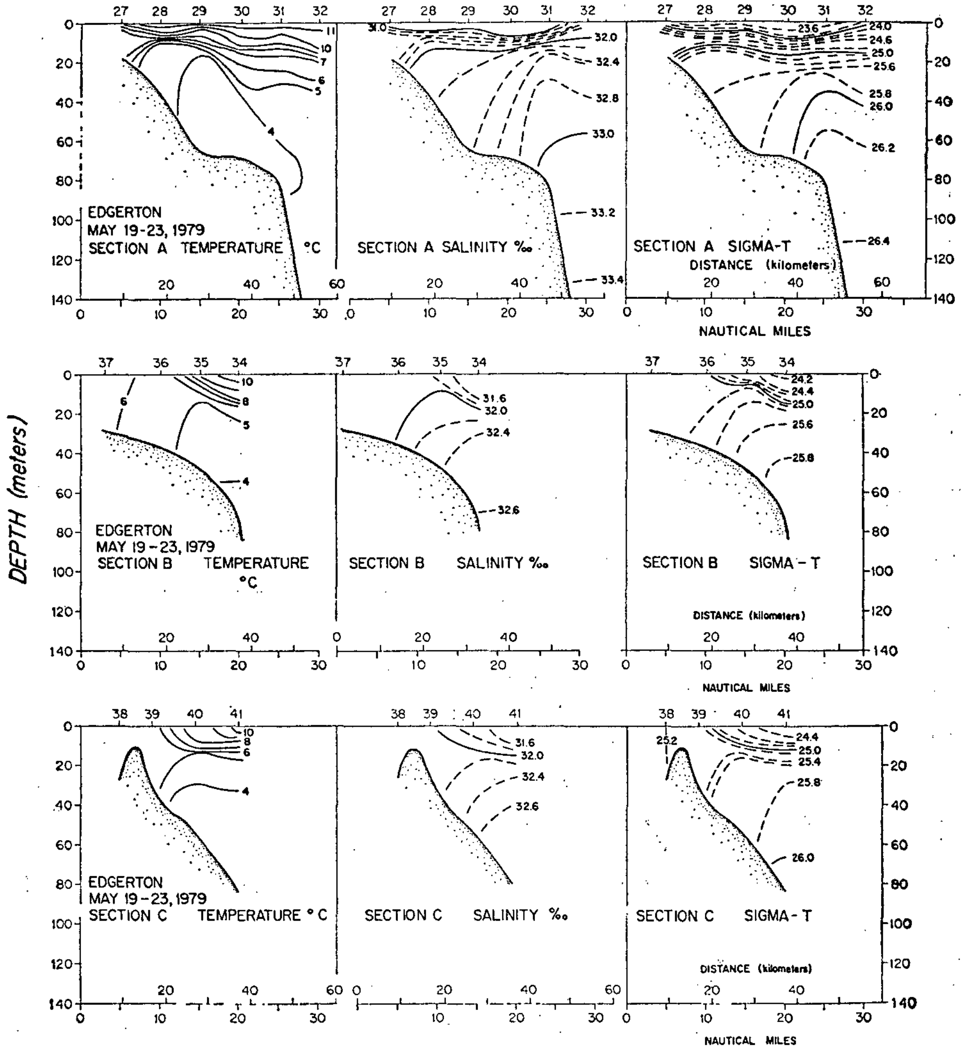

Figure 7. Vertical sections of temperature, salinity and sigma-*t* along transects A, B, and C over the eastern edge of Nantucket Shoals, May 19-23, 1979. Locations of transects indicated by labelled arrows in Figure 4f.

upper 100 m and salinity variations were typically less than 0.1‰. Many of the shallow stations over Nantucket Shoals (depths < 50 m) consisted only of a surface sample and we have assumed the water column was locally vertically well mixed. The surface temperature distribution for January, 1979 (see Fig. 4d) shows minimum temperatures (< 2°C) in the shallow Nantucket Sound, and warmer surface temperatures (> 4°C) were observed at the deeper stations in the Gulf of

Maine where a relatively large amount of heat is stored below 100 m in water of slope origin. Surface salinity in the Gulf of Maine was approximately 2.0‰ more saline than in the previous May during the period of large runoff. These high surface salinities are presumably a result of reduced runoff in the winter and fall and winter convective overturning of the near-surface water with deeper, more saline Gulf of Maine water (Brown and Beardsley, 1978). Over Nantucket Shoals salinity values have increased 1 to 1.4‰ from the previous May values.

The *T/S* diagram for January (Fig. 6) has lost the seasonal thermocline characteristics and the shelf mode is no longer present. Although the survey did not cover the shelf region to the southwest of the shoals, the linear *T/S* correlation for the Gulf of Maine and Nantucket Shoals stations at various depths leads us to believe that the shelf mode on the *T/S* diagram was not present over the shoals in January, especially in view of the strong offshore winds that exist in winter. The surface samples obtained over the shallower regions of Nantucket Shoals and Nantucket Sound have not been plotted in the January *T/S* diagram in Figure 6, but they do exhibit the same linear *T/S* correlation at lower temperatures and salinities. Thus the January hydrographic properties in the vicinity of Nantucket Shoals appear dominated by large heat losses to the atmosphere and mechanical mixing by strong winter winds.

NS5: March, 1979. The temperature distribution for March, 1979 (Fig. 4e) exhibited the lowest temperature found on any of our surveys. Minimum temperatures in the Gulf of Maine occurred in the near-shore region of the outer Cape. The water column at all stations was characterized by vertical homogeneity in the upper layer, with temperature variations in the upper 100 m typically less than 0.5°C and salinity variations less than 0.2‰. The temperature minimum core over the eastern edge of Nantucket Shoals was not present in the hydrographic data due to the vertical homogeneity of the adjacent water column in the Gulf of Maine. The salinity distribution over the shoals was roughly similar to that in January with minimum salinities of < 31.8‰ observed in Vineyard Sound near Woods Hole.

The *T/S* diagram for March, 1979 (see Fig. 6) shows a distinct linear relationship for most stations including the well-mixed shallow stations over the shoals as well as the deeper Gulf of Maine stations which were well-mixed above and stratified below 100 m. However, the linear *T/S* relationship was shifted down 1.5°C for any given salinity from the previous January survey. Surface *T/S* values were shifted off the linear correlation for stations in Nantucket Sound to a warmer distribution due to solar radiation and the reduced heat capacity of the shallow Nantucket Sound.

3. Circulation over Nantucket Shoals

Most of our present notions about circulation over Nantucket Shoals originate

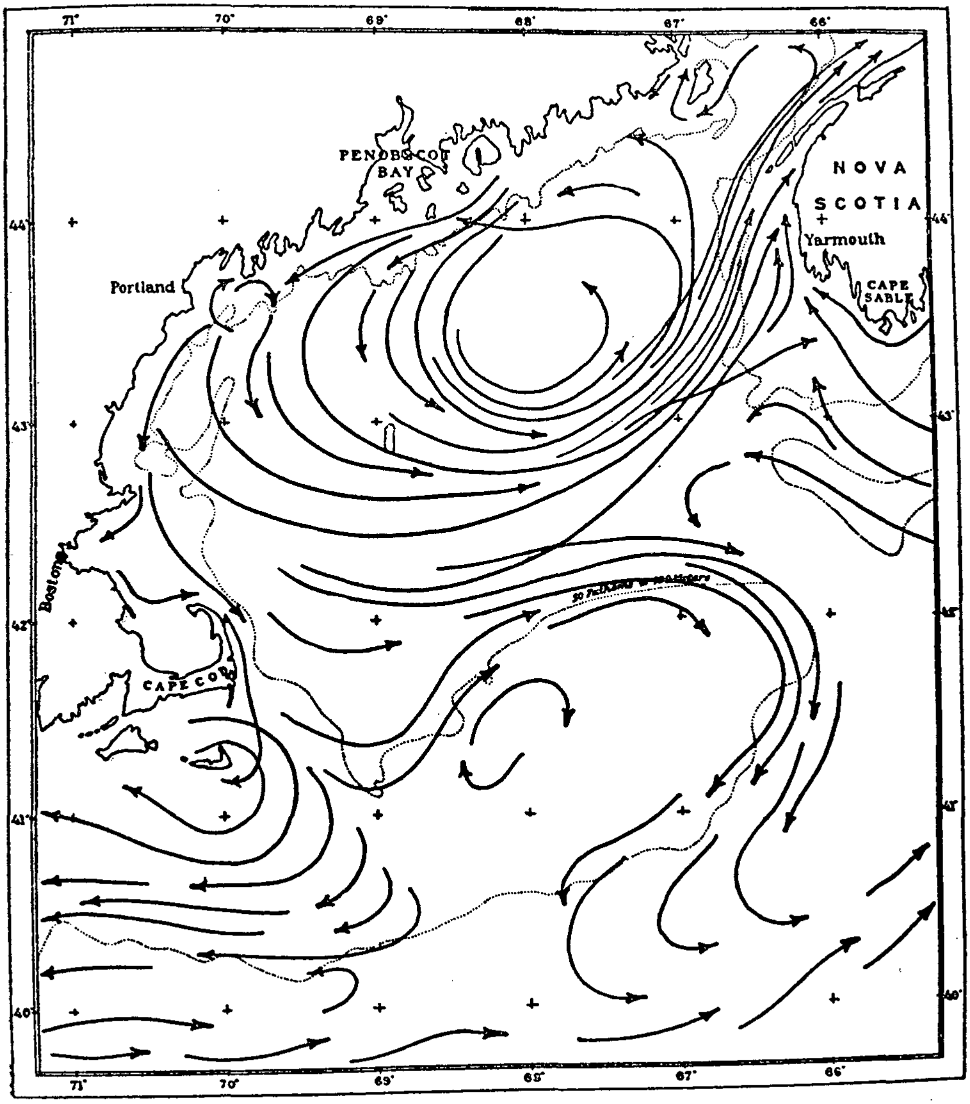

Figure 8. Nontidal circulation pattern for the Gulf of Maine from Bigelow (1927).

from Bigelow's (1927) classic study of water properties and circulation in the Gulf of Maine, Georges Bank, and New England shelf region. Using mostly surface drift bottle data, sparsely-spaced hydrographic data, and the observed movement of fish eggs and larvae, Bigelow described the development in spring of two large counter-rotating eddies of near-surface water, a clockwise eddy forming over Georges Bank called the Georges Bank gyre, and a counterclockwise eddy forming to the north called the Gulf of Maine gyre (see schematic shown in Fig. 8). Bigelow believed that this two-gyre system intensified during the late spring in response to increased river runoff but the relative strength of the circulation varied from year to year depending on actual runoff and wind conditions and perhaps other causes.

Bigelow suggests in Figure 8 that some near-surface water does leak from the Gulf of Maine gyre over Nantucket Shoals toward the southwest. Bigelow released 600 drift bottles along a 130 nautical mile line running southeast from Chatham in July, 1922 and found that most of the recovered bottles released over Nantucket Shoals were found along the New England coast to the west and south. Additional summer drift bottle releases in Nantucket Sound and the occurrence of a distinct faunal division near Chatham indicated an eastward current through Nantucket Sound. The net effect implied by Bigelow was thus a summer clockwise circulation around Nantucket Island and Martha's Vineyard with water from both southern New England via Nantucket Sound and the Gulf of Maine flowing south and west over Nantucket Shoals. More recent surface drifter studies summarized by Walford (1938), Day (1958), Bumpus and Lauzier (1965), and Bumpus *et al.* (1971) also tend to support Bigelow's scheme for the late spring/summer clockwise surface circulation around Nantucket.

Bumpus and Lauzier (1965) and Bumpus (1973) have analyzed surface drifter data from other seasons and while the recovery rate from the Nantucket Shoals region was extremely low during winter, they report a southward surface drift in the Great South Channel during winter. Haight (1942) analyzed tide pole data taken at several lightships near the shoals and found at the Nantucket Lightship (see Fig. 1) a mean summer surface current of about 10 cm/sec toward west to northwest which reversed during winter to a southeastward current of less than 4 cm/sec, presumably in response to stronger northwest winds during winter (Saunders, 1977). The mean summer surface currents found by Haight (1942) at Great Round Shoal and Pollock Rip are also consistent with Bigelow's scheme. Haight also found a mean eastward current of about 12 cm/sec throughout the year at Cross Rip inside Nantucket Sound. Sanford and Flick (1975) estimated the net volume transport through Vineyard Sound using a submarine cable stretched between Falmouth and Martha's Vineyard to measure the electric field induced by the water movement through the earth's magnetic field; they found a net eastward transport of about $10 \times 10^3 m^3/sec$ over a non-windy two-day period in August, 1969. The bottom drifter data summarized by Bumpus (1965 and 1973) and Bumpus and Lauzier (1965) indicate a persistent southward to westward near-bottom drift across Nantucket Shoals in all seasons.

This historical picture of circulation over and around Nantucket Shoals is thus based primarily on inferred trajectories of surface and bottom drifters. In January, 1979, we conducted a pilot moored current meter experiment to collect the first long-term direct subsurface current measurements in the shoals. Two Endeco model 174 ducted-impeller current meters were successfully deployed at location

Table 2

Station Location, Time and Current Statistics from the Moored Array

Station	Location	Date	Water Depth (m)	Instrument Depth (m)	East Mean cm/sec	Standard Deviation	Low Freq. Standard Deviation	North Mean cm/sec	Standard Deviation	Low Freq. Standard Deviation
NSA	41 30.4N 69 35.9W	Jan 17-Mar 18 1979	33	5	3.2	12.9	8.6	-7.2	52.6	11.3
NSA	41 30.4N 69 35.9W	Jan 17-Mar 18 1979	33	25	-3.7	9.6	5.6	-7.0	46.3	7.7
NSB	42 26.0N 69 44.1W	Jul 18-Aug 28 1979	22	10	-3.3	28.9	1.5	-10.5	48.3	2.5
NSC	41 26.6N 69 59.2W	Jul 18-Aug 28 1979	16	8	5.8	36.9	2.9	0.5	12.6	1.5
NSD	41 36.4N 69 43.8W	Jul 18-Aug 28 1979	33	16	-4.4	19.6	4.4	-2.3	32.6	4.1
NSE	40 59.0N 70 04.0W	Jul 18-Aug 28 1979	22	10	1.6	37.4	2.4	1.3	31.2	2.7

NSA (Fig. 1) at depths of 5 m and 25 m in 33 m of water on a slack surface-following mooring. In July, 1979, we deployed surface-following moorings supporting a single Endeco 105 current meter each at locations NSA, NSB, NSC, NSD, and NSE shown in Figure 1. All instruments were retrieved and functioned correctly except at NSA where only direction data was obtained during the July deployment. Location, mooring information and current statistics for these deployments are given in Table 2.

The mean currents measured over Nantucket Shoals are shown here in Figure 9. The winter measurements at NSA showed a mean near-surface (5 m) flow of 7.9 cm/sec toward 156°, the general downwind direction of the prevailing winter northwest winds. The mean flow at 25 m depth (5 m above the bottom) at NSA was 7.9 cm/sec toward 208°, or 52° to the right of the near-surface current and more southwestward near the bottom.[2] The winter low-frequency current variance at 5 m at NSA was slightly polarized with the larger (north) component roughly aligned with the local topography While the ratio of the east to north components of the low-frequency variance was similar at both depths, the variance decreased by a factor of two from 5 m to 25 m depth.

The mean currents measured during the summer moored array deployment over Nantucket Shoals are also shown in Figure 9. Mooring NSB was located in the main north-south channel which runs through the shoals. Water depths in this 6 km

[2] In December, 1976, the oil tanker *Argo Merchant* went aground and broke apart on Fishing Rip, 27 miles southeast of Nantucket Island (roughly near station 46 in Fig. 1). This accident provided an unwanted tracer of near-surface motion. Strong northeast winds forced 7 million gallons of crude oil in a general downwind direction. The speed of the oil slick was 70-80 cm/sec under the influence of mean eastward winds of 15 m/sec on December 20-22, 1976 (Grose and Mattson, 1977) or a mean drift rate of 5% of the windspeed.

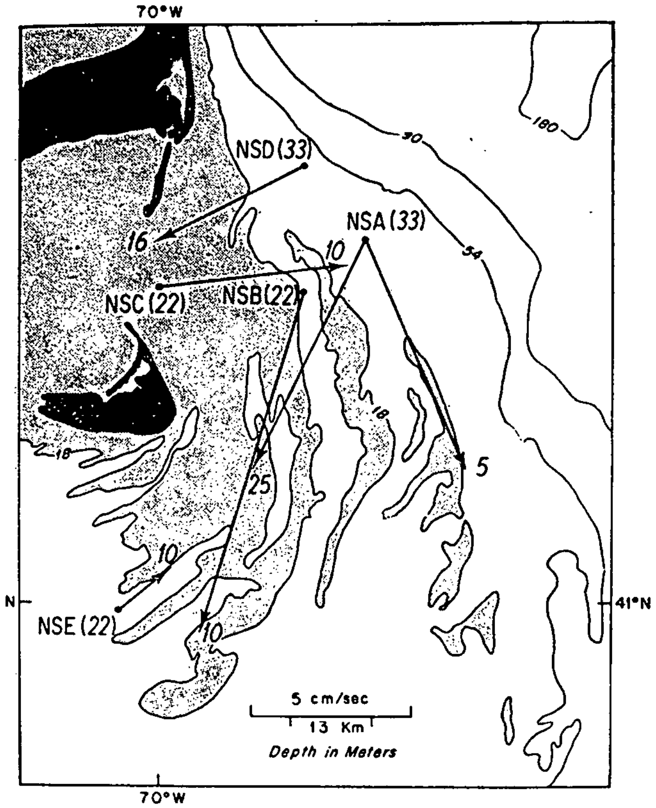

Figure 9. Observed mean flow on Nantucket Shoals from winter (NSA) and summer (NSB-E) moored current meter arrays.

wide channel approach 30 m with 5 m deep shoal areas on either side. The current data from mooring NSB showed a mean southward current of 11 cm/sec aligned with the local channel axis. The 5 cm/sec mean flow at mooring NSD, located on the northern edge of the summer upwelling core, was not as strong as at NSB and was directed more across the local topography toward the southwest.

Mooring NSC was located between Nantucket Sound and Nantucket Shoals in an east-west channel below a large round shoal area. The hydrographic data showed intrusions of cold Gulf of Maine water into Nantucket Sound to the north of this round shoal area but no Gulf of Maine water in the vicinity of mooring NSC. The mean flow at NSC was 5.8 cm/sec toward 085°, indicating a net drift of Nantucket Sound water flowing eastward which is consistent with the hydrographic results. Some Gulf of Maine water may leak into Nantucket Sound with the ebb tide near the southern tip of Monomoy Island (see Fig. 4b) but the net flow is apparently eastward between Nantucket and Monomoy Islands. Mooring

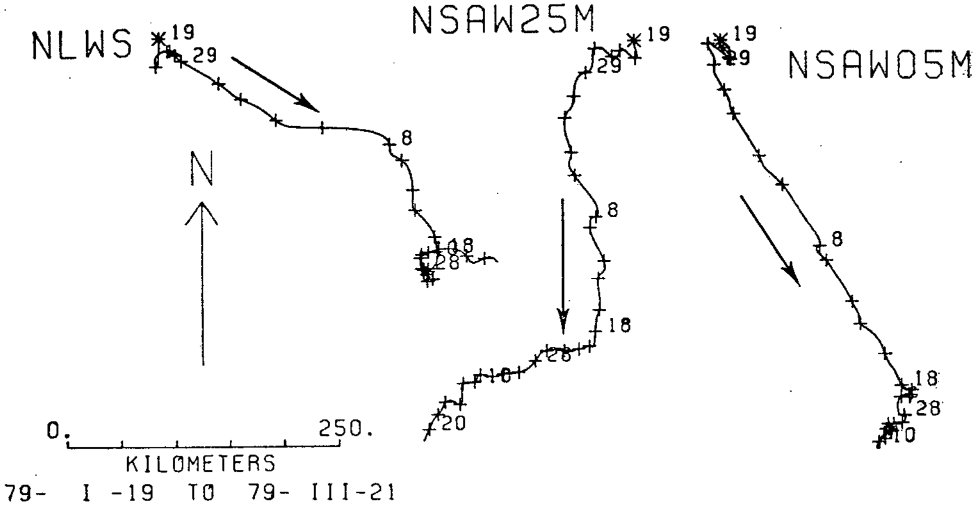

Figure 10. Low-frequency progressive vector diagrams of currents and windstress (Nantucket Lightship) for January 19-March 21, 1979. A mean windstress of 1 dyne/cm^2 acting for 40 days corresponds to a scale length (using the current displacement scale) of 250 km.

NSE was located on the southwestern edge of Nantucket Shoals and in a presumably downstream location to the mean flow observed over most of the shoals. A mean flow at NSE of 2 cm/sec toward 051° suggests some weak back flow in summer onto Nantucket Shoals south of Nantucket Island. We emphasize that all of the Nantucket Shoals moorings except NSA and NSD were located within the region which is vertically well mixed due to tidal mixing. Repeated CTD stations and moored temperature data showed that moorings NSA and NSD were located in the transition region between the stratified Gulf of Maine water and the tidally mixed shoal water. Thus at NSA and NSD the water column was periodically stratified and homogeneous due to the tidal advection of the front between stratified and mixed water through the mooring sites.

Progressive vector diagrams of the low passed current records and local windstress are shown in Figure 10 for the winter deployment and in Figure 11 for the summer deployment. The winter windstress was computed from 3 hr observations at the Nantucket Lightship using a quadratic drag law ($C_d = 1.2 \times 10^{-3}$). Winds were low passed with a Gaussian filter (half power frequency of .03 cph). The winter deployment was characterized by strong winds from the northwest as well as frequent storms. The winter current displacements at 5 m were directed in a generally downwind direction. For January 19-29, 1979 a moderate north and east windstress appears to have a small effect on the low-frequency currents. Between February 1-20, strong, steady northwest winds dominated the region. The low-

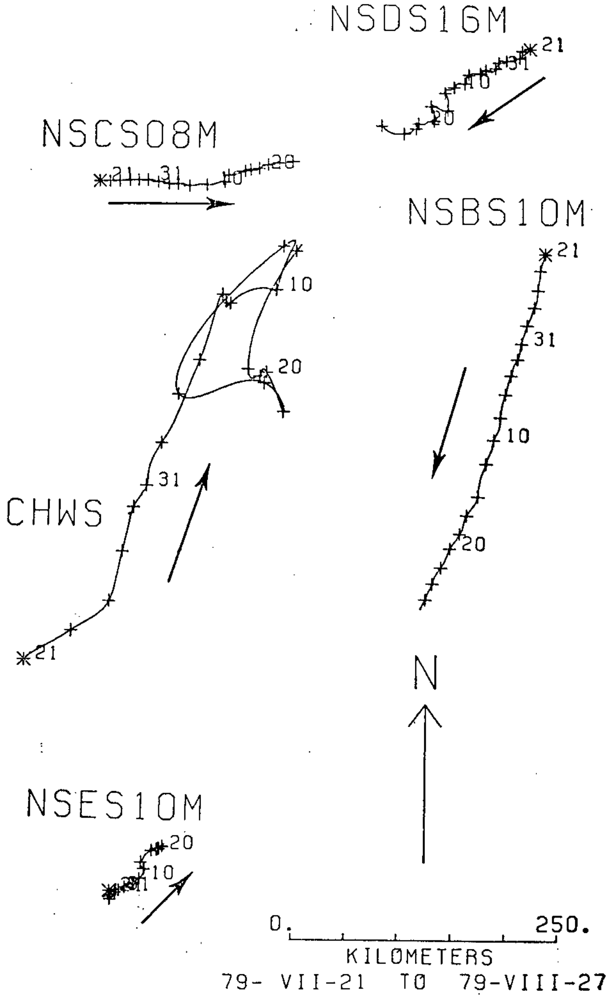

Figure 11. Low-frequency progressive vector diagram of currents and windstress (Chatham Weather Station) for July 21-August 27, 1979. A mean windstress of 0.1 dynes/cm^2 acting for 20 days corresponds to a scale length (using the current displacement scale) of 250 km.

frequency current response at 5 m was a steady southeastward flow during this entire period with speeds ranging from 20 to 40 cm/sec. Note that the 5 m current does not show any obvious change in direction even though the wind direction changed during February 4-14. The 5 m vector displacements show relatively small flow after February 20 when the persistent northwest winds moderated and were replaced by frequent south winds and a moderate northeaster on February 26. The 25 m flow in Figure 10 was generally directed to the right of the 5 m flow (about 30° for the February 1-20 period). Of interest here is the strong relatively along-isobath flow associated with the persistent northwest wind and the apparent cross-isobath mean flow when the wind was more moderate and from a different quarter.

The summer low-frequency currents are shown in the progressive vector diagram in Figure 11. We emphasize that the winds were light and variable during the summer deployment except for a strong northeast wind on August 12. The windstress for the summer deployment was computed using the quadratic drag law on 3 hr wind observations made by the United States Weather Service in Chatham (see Fig. 1). The Chatham wind measurements were used during the summer deployment rather than the Nantucket Lightship wind measurements since local variability is more likely in summer than in winter. Chatham is located less than 15 miles from moorings NSB, NSC, and NSD and is considered to be representative of the local offshore windfield. Mooring NSB was located in the main north/south channel through the shoals and the low-frequency vector displacements at 10 m were in a steady southward direction in opposition to the prevailing northeastward windstress. On August 12, a small acceleration in the southward current displacement was observed and believed to be associated with the August 12 southwestward windstress event. The steadiness of the 10 m southward flow at NSB with the relatively small opposing windstress was surprising in view of the winter measurements made at mooring NSA. The progressive vector displacements at NSC, located at the eastern entrance to Nantucket Sound, show a net eastward displacement and an arresting of this eastward flow on August 12 associated with the southwestward windstress event.

The vector displacements at 16 m at mooring NSD, located on the northeast edge of the shoals in the temperature minimum region, show a southwestward flow opposite to the prevailing summer windstress. On August 12 the flow became more southward in response to the southwestward wind event. Thus we find water from the Gulf of Maine flowing southwestward onto Nantucket Shoals in summer throughout the deployment period. The low-frequency currents at 10 m at NSE, located south of Nantucket Island on the edge of the shoals, were the weakest observed at any of the other winter or summer moorings.

Rotary spectra, coherence, and phase information are presented in Figure 12 for the winter subtidal current fluctuations at depths of 5 m and 25 m from mooring NSA and the windstress from the Nantucket Lightship (NLS). The windstress spectrum shows significantly more energy in the clockwise component. The 5 m and 25 m currents at NSA have a similar spectral shape, however, with energy split roughly equally into clock- and counterclockwise components consistent with quasi-rectilinear flow. Although the energy in the .005 to 0.15 cph band did decrease with depth, the 5 m and 25 m current fluctuations at NSA were significantly coherent and roughly in phase for periods greater than 50 hrs. Current fluctuations at both levels were coherent with windstress for clockwise frequencies between .0075 and .015 cph,and were coherent over a narrower band of counterclockwise

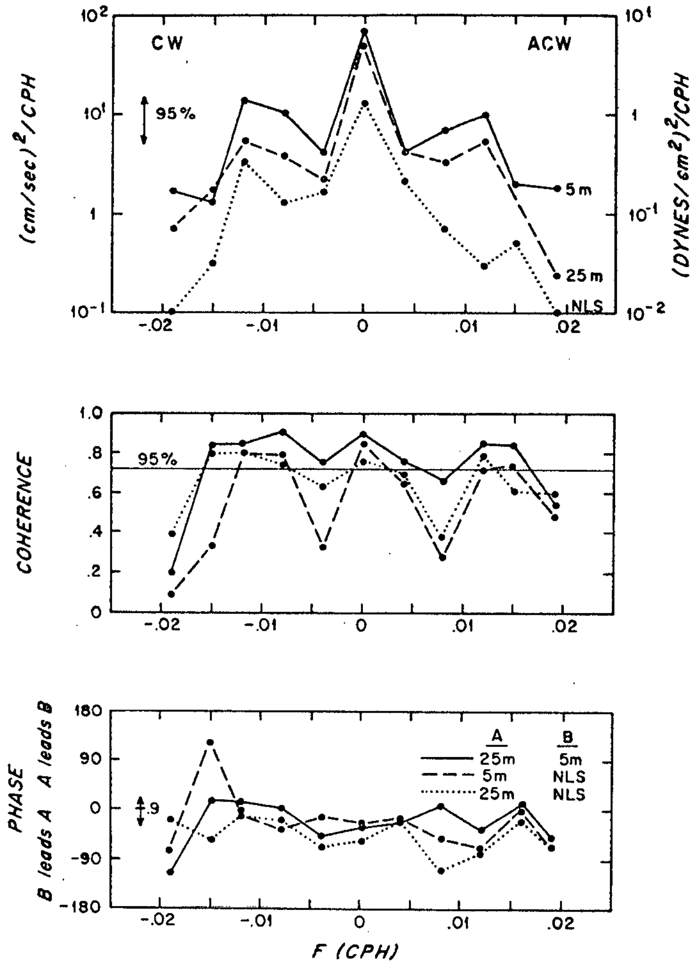

Figure 12. Rotary spectra and coherence between the Nantucket Shoals Lightship (NLS) windstress and moored current observations at NSA at depths of 5 m and 25 m.

frequencies where the wind energy was lower. The current fluctuations appear to slightly lag the windstress fluctuations when coherent. The mean windstress in winter was approximately 1.0 dynes/cm^2 (Nantucket Lightship) as opposed to a mean windstress of 0.1 dynes/cm^2 (Chatham Weather Station) during the summer deployment. The large windstress fluctuations were coherent with the low-frequency current fluctuations over Nantucket Shoals in winter but the summer windstress was so weak and uneventful that no coherence with currents was observed. However, in the latter part of February, 1979 when the local wind became light and variable, a significant cross-isobath mean flow persisted for the remainder of the current

Table 3

Amplitude and Phase of the Nantucket Shoals Tidal Constituents

		K1		O1		95% limits		M2		S2		N2		95% limits	
		H cm/s	G deg	H cm/s	G deg	H %	G deg	H cm/s	G deg	H cm/s	G deg	H cm/s	G deg	H %	G deg
NSA05 41.51N 69.60W	E	.7	60	1.9	63	-51,+245	±61	7.7	40	2.7	169	2.3	23	-26,+47	±19
5m 1440hrs	N	4.4	-3	6.4	3	-45,+170	±34	58.8	-16	16.3	102	16.3	304	-19,+30	±14
NSA25 41.51N 69.60W	E	1.4	63	1.2	35	-42,+144	±42	6.4	16	.3	172	1.5	-14	-22,+35	±16
25m 1523hrs	N	4.5	-3	1.8	-21	-36,+92	±32	59.3	319	9.4	44	11.9	288	-7,+9	±5
NSB10 41.43N 69.73W	E	3.4	40	2.4	24	-24,+41	±18	37.0	20	1.8	130	6.8	355	-10,+12	±6
10m 1002hrs	N	2.9	-31	1.1	-27	-22,+35	±16	62.9	345	4.7	66	11.0	319	-7,+8	±4
NSC08 41.61N 69.99W	E	4.5	44	3.9	9	-30,+61	±23	45.9	32	1.9	117	8.4	9	-10,+12	±6
8m 1002hrs	N	1.3	251	.9	218	-42,+150	±44	14.9	247	1.0	280	1.5	245	-17,+27	±12
NSD16 41.61N 69.73W	E	2.3	25	.6	274	-53,+257	±75	21.5	327	4.1	144	5.4	292	-22,+41	±17
16m 1002hrs	N	3.2	306	.5	187	-46,+186	±53	41.5	345	2.6	82	9.3	320	-13,+16	±8
NSE10 40.98N 70.07W	E	5.4	67	2.7	64	-45,+178	±51	39.5	10	5.8	216	14.9	333	-37,+104	±34
10m 993hrs	N	7.2	-47	4.6	-54	-52,+257	±72	35.0	267	5.6	164	13.2	245	-32,+69	±26

record. In summer, 1979 the winds were generally quite light and variable, and the mean flow over the shoals was directed against the windstress. These results indicate that strong winds can contribute significantly to the low-frequency current variability over Nantucket Shoals, but a southward and southwestward mean flow is apparent when the local wind forcing is weak.

The tidal components for the different Nantucket Shoals current records have been computed and are presented in Table 3 and Figures 13 and 14. The M2 constituent (T = 12.42 hrs) shown in Figure 13 is the most energetic component on Nantucket Shoals with the greatest amplitude occurring at mooring NSB. The phase angle is indicated by the tick mark as the number of degrees after the constituent center moon passes Greenwich, England. In general, the M2 ellipses are aligned with the local bathymetry of the shoals except at mooring NSE where the major and minor axes are of the same magnitude. The K1 tidal ellipses ($T = 23.93$ hrs) shown in Figure 14 have a similar orientation to the local bathymetry as the M2 constituent, but the magnitudes of the K1 ellipses are much smaller than those of the M2 constituent. Also, the K1 amplitude at mooring NSE to the south of Nantucket Shoals is larger than the K1 amplitude on the shoals. The reader is referred to Daifuku (1981) and Moody and Butman (1981) for a description of

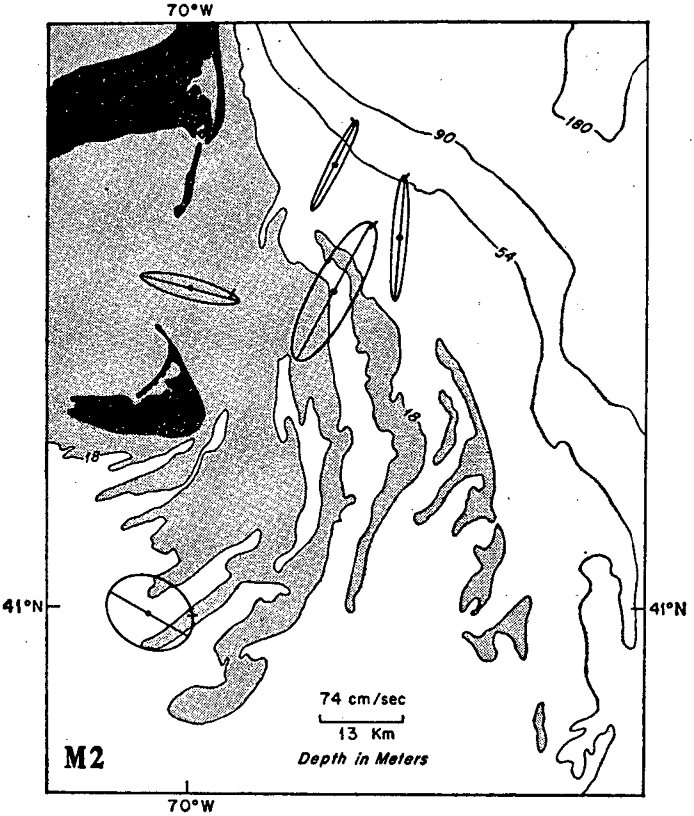

Figure 13. Nantucket Shoals current ellipses showing amplitude and orientation of the M2 tidal constituent.

the diurnal and semidiurnal tides on the northeast U.S. continental shelf, respectively.

4. Discussion

In this section we will attempt to identify the important processes which control the *T/S* structure over Nantucket Shoals. Local processes like tidal mixing and air/sea interaction can readily be identified, but the influence of nonlocal processes like increased river runoff in spring in the western Gulf of Maine are more subtle and difficult to quantify.

We have observed that over most of Nantucket Shoals, the water column is locally well mixed in the vertical over the entire year. A contour map of the vertical sigma-*t* difference between surface and bottom values observed in the May, 1978 hydrographic survey is shown in Figure 15. Taking the $\Delta\ \sigma_t = .1$ contour as the

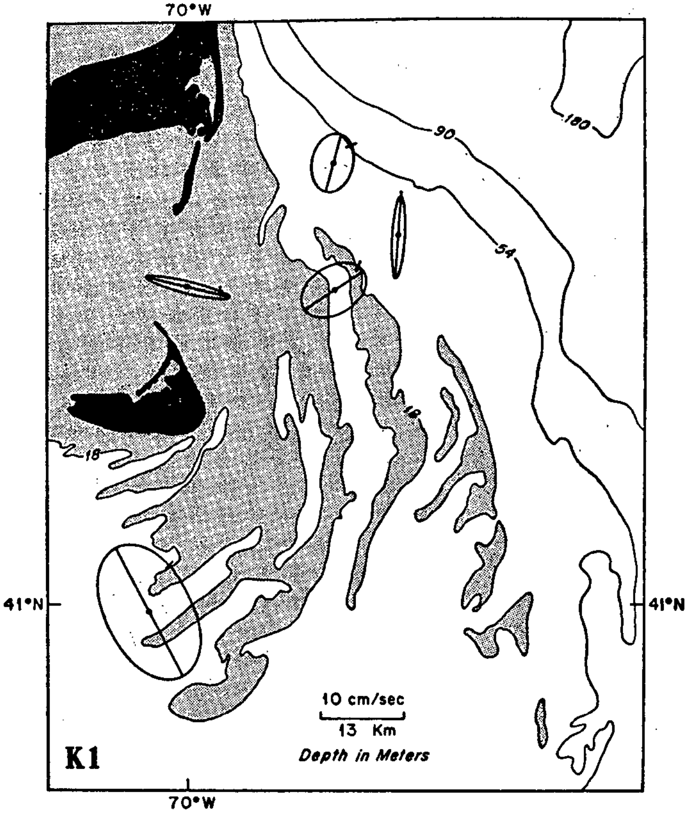

Figure 14. Nantucket Shoals current ellipses showing amplitude and orientation of the K1 tidal constituent.

transition between well mixed ($\Delta\ \sigma_t < 0.1$) and stratified water, this and similar maps for July and September demonstrate that the water over most of the shoals is well mixed even through the spring and summer period. This local vertical homogeneity is a direct consequence of the mechanical stirring associated with the dissipation of strong tidal currents over the shallower variable topography. Fifield (1977) and Garrett *et al.* (1978) have shown that the h/U_0^3 criterion suggested by Simpson and Hunter (1974) is applicable to the Nantucket Shoals and Georges Bank region and that this simple parameter can be used to crudely predict the location of the front between the tidally-mixed vertically homogeneous water over Nantucket Shoals and the shallow top of Georges Bank and the adjacent stratified water. Superposition of the $\Delta\ \sigma_t$ map (Fig. 15) onto the May, 1978 surface temperature and salinity maps (Fig. 4a) shows that significant horizontal gradients in T and S occur within the well-mixed zones. The temperature minimum core(s) are usually located along or just inside the eastern boundary of the well-mixed zone.

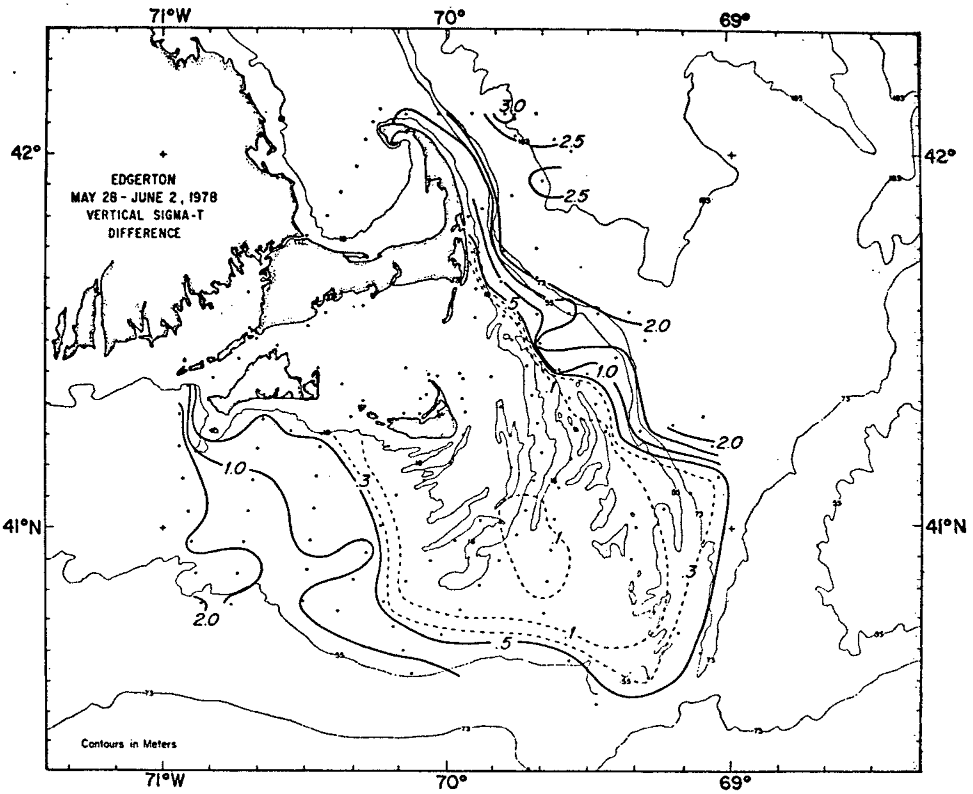

Figure 15. Vertical sigma-*t* difference distribution over Nantucket Shoals for Cruise NS1, May, 1978.

Along the eastern edge of the shoals, the rapid increase in depth into the adjacent Gulf of Maine causes in part the front or zone of large horizontal gradients in the vertical sigma-*t* difference found there. However, the boundary between the stratified and well-mixed water over the shoals was not observed in the January and March surveys when the upper 100 m of water in the Gulf of Maine was well mixed due to winter convective overturning and mechanical mixing due to the strong winter windstress.

The *T/S* characteristics of water over Nantucket Shoals are dominated by local tidal mixing and advection from upstream sources. Thus, many of the hydrographic stations over the northeastern shoals that are well mixed plot as individual points superimposed on the Gulf of Maine water *T/S* curve above the temperature minimum, a direct consequence of the mixing of the top 40 to 50 m of stratified Gulf of Maine water which has been advected into the high tidal energy environment of the shoals. A relatively strong southward mean flow of order 10 cm/sec was observed at the head of the main channel (NSB) in winter and over the eastern flank of the shoals (NSA) in summer. If the seasonal mean flow in this eastern zone is about 10 cm/sec to the south, we estimate a minimum transit time of order 10 days through this outer eastern region. Due to the large horizontal tidal excursions and the likelihood of weaker flows over the shallower sections of the shoals, individual fluid particles may take considerably longer to move across the shoals. Thus, the hydrographic properties upstream in the Gulf of Maine and to a lesser extent in Nantucket Sound directly influence the *T/S* properties over the shoals on time scales of order 10 days and longer. As stratified Gulf of Maine water is advected into the tidally mixed region over the northeastern shoals, the water is mechanically mixed throughout the water column. The resulting *T/S* structure is a core of cooler surface temperatures along the northeastern edge of the shoals. As the relatively cold water advects more to the south, incoming solar radiation and mixing with warmer Nantucket Sound water produce an increase in temperature, thus accounting for the stationary corelike structure of the surface temperature minimum regions. The observations in May, 1978 and 1979, of the temperature minimum water along the northeastern edge of the shoals during periods when prior winds were quite light and variable strongly argues against any local wind-induced upwelling mechanism. [Subsequent observations of near-shore cold surface temperatures along the eastern edge of Cape Cod during periods of moderate southwest winds have been attributed to local wind-induced upwelling by Limeburner and Beardsley (1979), however.]

Water properties over Nantucket Shoals are also influenced by local heat and to a lesser extent water exchange with the atmosphere. Bunker (1976) has calculated the annual heat exchange cycles for the North Atlantic using bulk aerodynamic equations and exchange coefficients which vary with windspeed and stability. Monthly averages of the various energy fluxes taken from Bunker's data for the one degree square including Nantucket Shoals (41-42N, 69-70W) show a net heat gain for the months March to October caused primarily by solar radiation. Warm, moist winds in summer also decrease the latent heat loss and the sensible heat flux to the shoals is positive. (We note that Nantucket Shoals is characterized in spring and summer as being locally very foggy. This fog is a result of the cold surface temperatures over the shoals and subsequent cooling of the warm moist summer air below the dew point.) In winter, the largest heat losses occur in December and January due to a latent heat flux exceeding 130 watts/m^2 and a sensible heat flux equal to about 60% latent heat flux (Limeburner, 1979). Thus we observe water warming as it moves across the shoals in spring and summer and significant cooling in winter. Convective overturning also occurs in the adjacent shelf and Gulf of Maine waters at least to depths of 100 m or deeper (Brown and Beardsley, 1978). This deep mixing and subsequent advection of the primary source water into the shoals causes the general increase in mean salinity over the shoals between September and March. During the period from September, 1978 to March, 1979, the mean salinity over the shoals increased by 1.5‰. While it is difficult to estimate the net precipitation minus evaporation rate for this region, we have used precipitation data from the Chatham National Weather Service station and evaporation values computed from Bunker's latent heat flux data to estimate that the mean salinity over the shoals should decrease by roughly 0.5‰ over the same September to March period. This freshening tendency due to a local excess of precipitation over evaporation is thus obscured by the stronger influence of winter convective overturning in the Gulf of Maine. The mean salinity decrease observed over the shoals from March to September is due primarily to the freshening of the upstream near-surface Gulf of Maine water east of Cape Cod.

5. Conclusions

Nantucket Shoals forms a leaky boundary between the western Gulf of Maine and the eastern New England shelf. Most of the water flowing south and southwestward over the shoals originates in the western Gulf of Maine and subsequently mixes with Nantucket Sound water and shelfwater near the Great South Channel before joining the general westward flow over the mid- and outer New England shelf. While the scarcity of direct current measurements prevents construction of accurate seasonal circulation models for any region of the shoals, the current data obtained at NSA and NSB suggest a mean current of order 10 cm/sec southward through the main channel and over the adjacent outer flank within the 30 m isobath near 41°30′. This current magnitude times the cross-sectional areas of $1.5 \times 10^5 m^2$ and $2.0 \times 10^5 m^2$ respectively suggests a southward flow of Gulf Maine water of order $15 \times 10^3 m^3/sec$ through the main channel in summer and $20 \times 10^3 m^3/sec$ over the outer shoals within the 30 m isobath near 41°30′ in winter. Over most of Nantucket Shoals, the semi-diurnal tidal currents are sufficiently energetic to keep the local water column well mixed throughout the year. This mechanical stirring plus advection from upstream sources (primarily the western Gulf of Maine) strongly influences the water property distributions over the shoals. The surface temperature-minimum cores observed in spring and summer along the eastern edge of Nantucket Shoals are primarily a consequence of the advection of stratified Gulf of Maine water into the tidally well-mixed region. Subsequent advection to the south leads to warming from incoming solar radiation and mixing with warmer Nantucket Sound water, thus producing a local structure to the cold surface temperatures. While strong local wind forcing can contribute to the low-frequency current variability, the mean flow over the shoals appears to be driven by the larger-scale seasonal circulation system in the Gulf of Maine, Georges Bank, and New England shelf region.

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