HYDROGRAPHY AND CIRCULATION ABOUT NANTUCKET SHOALS

by

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ABSTRACT

A series of hydrographic surveys was begun in May, 1978 to measure the spatial structure and temporal variability of the temperature and salinity fields about Nantucket Shoals over an annual cycle. Surface temperature maps obtained in May, July, and September, 1978 show localized upwelling of nutrient-rich water along the eastern edge of the shoals. The coldest surface waters are frequently found in a rectangular zone roughly 15 km by 50 km located 40 km east of Nantucket Island. The T/S characteristics of the upwelled water indicate the water in the lower seasonal thermocline (20-40 m deep) in the adjacent Gulf of Maine to be the source region. Locally, a positive net annual heat flux of 32 Watts/m^2 is calculated from the meteorological observations to maintain a steady state in the presence of upwelling. The T/S correlation shows a bimodal distribution: a Gulf of Maine mode and a

Thesis Supervisor: Dr. R. C. Beardsley, Associate Scientist shelf mode. In summer, upwelled water from the Gulf of Maine dominates the northern regions 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 infers inflow there to the Gulf of Maine. Strong tidal currents over the shoals vertically mix the entire water column for depths less than 40 m. The variability of the water properties about Nantucket Shoals is characterized by advection from the Gulf of Maine and local atmospheric forcing in which extreme events such as heating, cooling, and winds may locally and temporally dominate the circulation. Extreme cooling in February, 1979 accounted for three times the average February heat flux for the southwestern Gulf of Maine. The summer circulation can be described as a clockwise motion around the shoals and partial recirculation through Nantucket Sound. An estimated $60 \times 10^3 m^3$/sec flows to the south over Nantucket Shoals from the Gulf of Maine in early summer. In winter severe wind events advect over the shoals more saline Gulf of Maine water which has convectively overturned to depths greater than 150 m.

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I. Introduction

Nantucket Shoals is a submerged sand and gravel shallow ridge which extends 33 km eastward and 80 km southeastward from Nantucket Island, Massachusetts (Figure 1). Historically, this region is one of the most productive commercial fishing areas in North America. However, non-fishing vessels are advised to avoid the shoals because of treacherous and erratic tidal currents of up to 2.5 m/sec, shifting sand waves along the bottom, and frequent fog (U.S.C.P., 1950). This advice has been followed by the numerous hydrographic surveys to the Gulf of Maine (Bigelow, 1927), (Colton et al., 1968), (Limeburner, Vermersch, and Beardsley, 1978), and (EG&G, 1978) which used deep draft vessels that were unable to navigate over the shoals. The results of these cruises indicated that although the water properties near the edge of the shoals were usually vertically well mixed, strong horizontal gradients were observed which demonstrated our lack of knowledge in understanding this extremely energetic environment.

Nantucket Shoals, Nantucket Island, Cape Cod, and Marthas Vineyard were formed by the ice sheets of the Pleistoscene Epoch which began one million years ago and ended about ten thousand years ago. The more surficial sediments were deposited during the late Wisconsin Stage about ten to

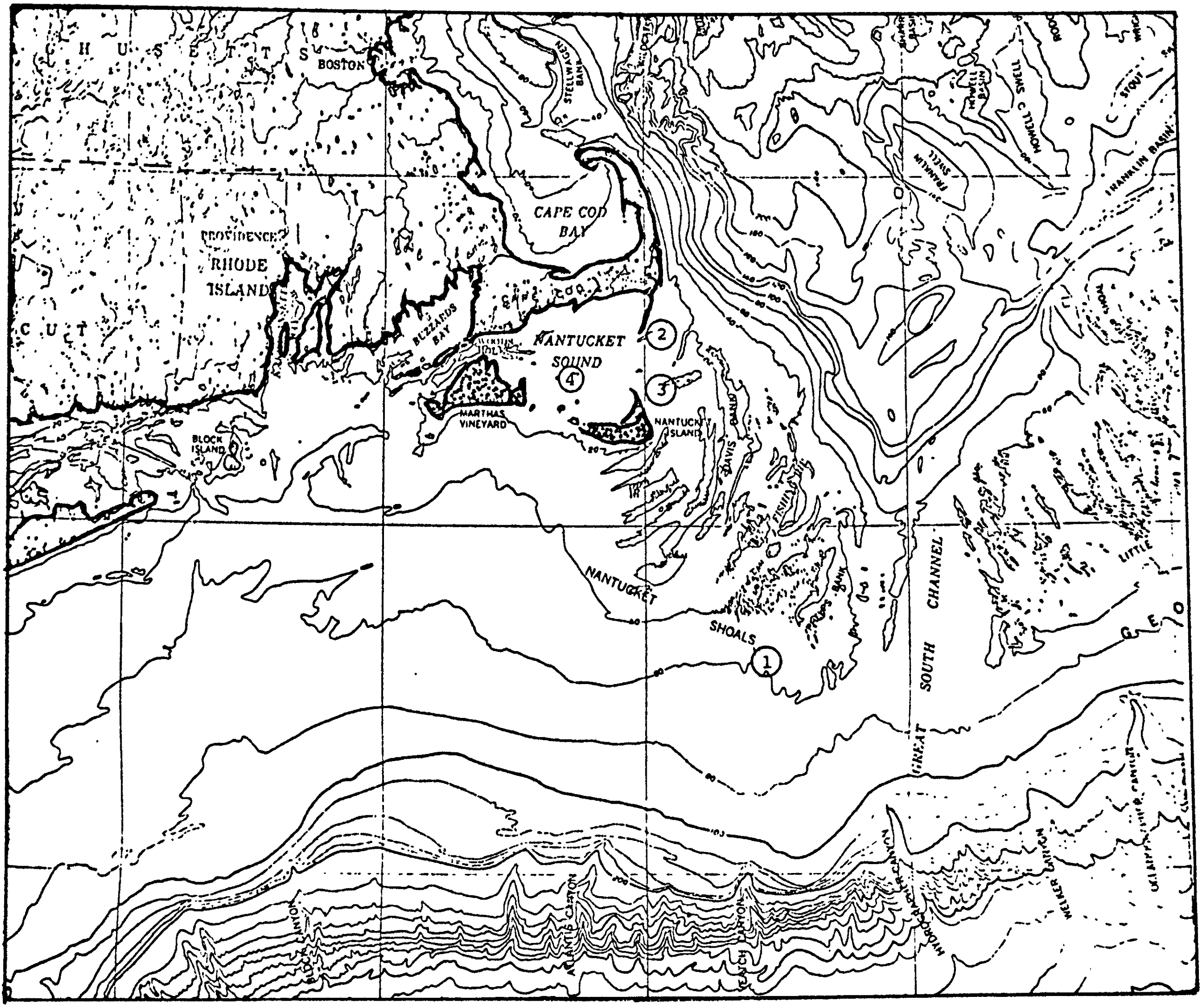


Figure 1. Topographic chart of Nantucket Shoals and surrounding area. Depth contours are shown in meters. The circled numbers denote the following lightship stations: ① Nantucket Shoals, ② Pollock Rip, ③ Great Round Shoal, ④ Cross Rip. Chatham is located on the southeastern end of Cape Cod near Pollock Rip.

fifty thousand years ago. Figure 2 shows the maximum limit of late Wisconsin glaciation and the inferred sea level. The massive sheets of ice which formed over North America, Europe, and Siberia held a great volume of water in storage as ice so that the ice formation led to a decrease in sea level of 100-150 m. Thus all of Nantucket Shoals, Georges Bank, and the continental shelf east of Cape Cod was a coastal plain above sea level during the glacial epoch. The advance of the glaciers onto the coastal plain resulted in the deposition of moraine or glacial till. During periods when the input of snow at the glacial source region equalled the loss of ice by melting and evaporation, a topographical stationarity existed as the ice flowed and deposited erosional material. This glacial stationarity is thought to have existed for several thousand years during which time glacial deposits of sand, gravel, clay, and boulders accumulated in the region of Cape Cod, Nantucket, and Nantucket Shoals (Strahler, 1966). According to Uchupi (1968), the shoals and islands are cuestas fluvially carved from shelf strata and later modified by glacial erosion and deposition.

The water depth on Nantucket Shoals varies between 1-10 m over the shoal regions while deeper slues or channels with depths of 20 m and greater are found between the shoals. Figure 3 shows the area along the southeastern New England

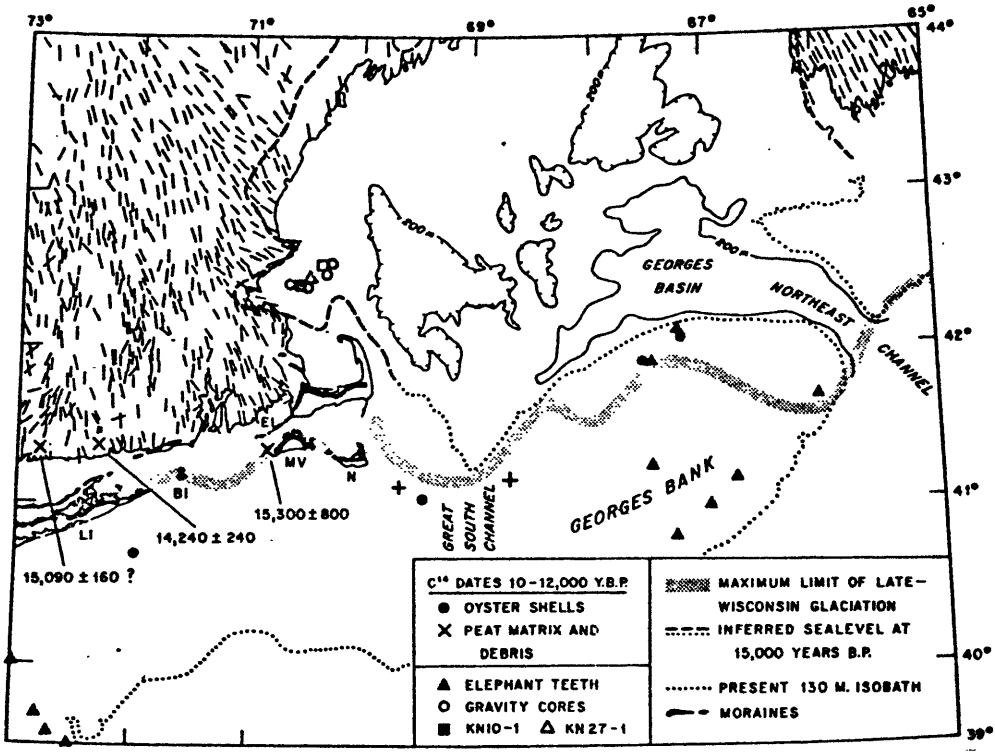


Figure 2. Map showing glacial features and locations of selected dated material in New England and the Gulf of Maine. (Tucholke and Hollister,1973)

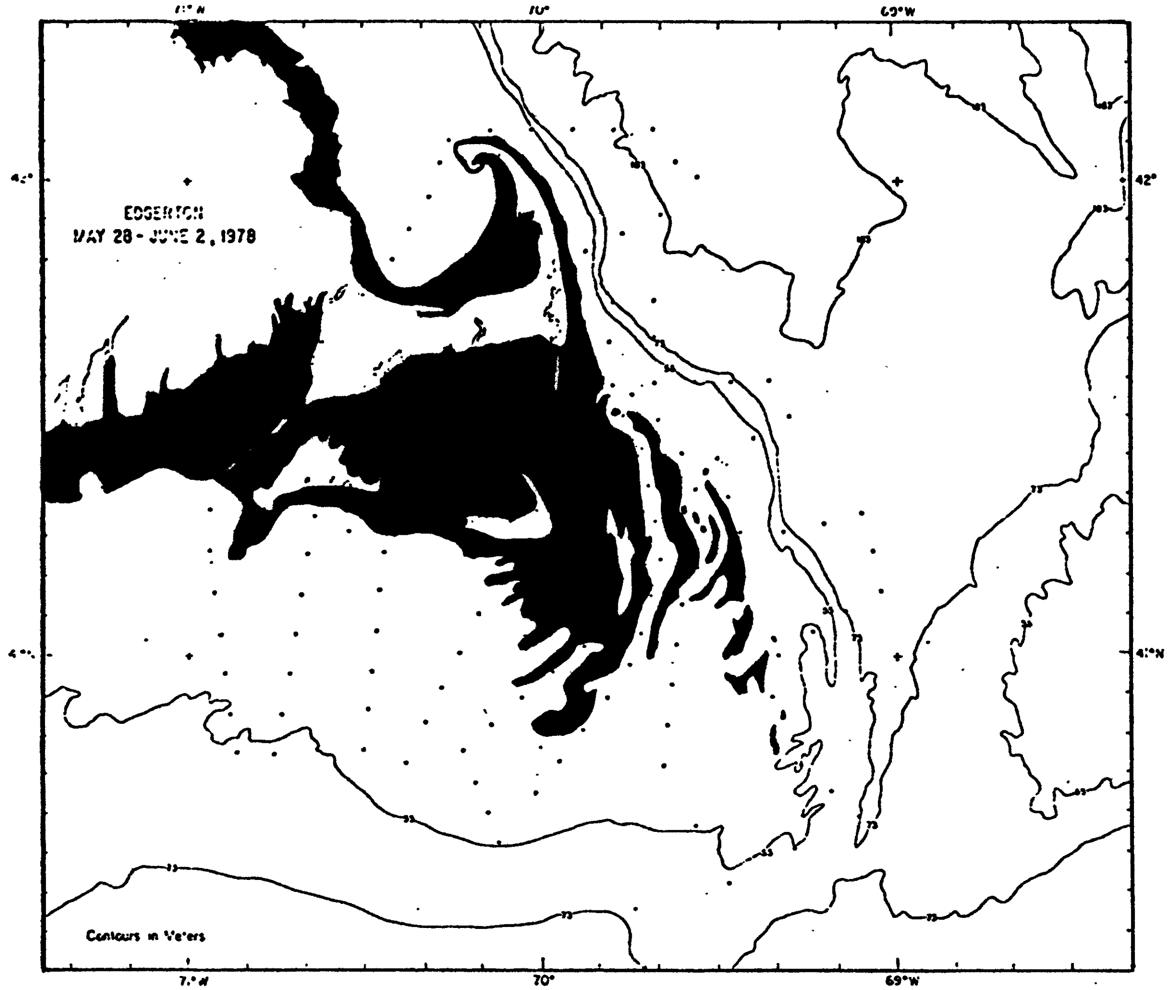


Figure 3. Nantucket Shoals bathymetry. Darker areas less than 18 m.

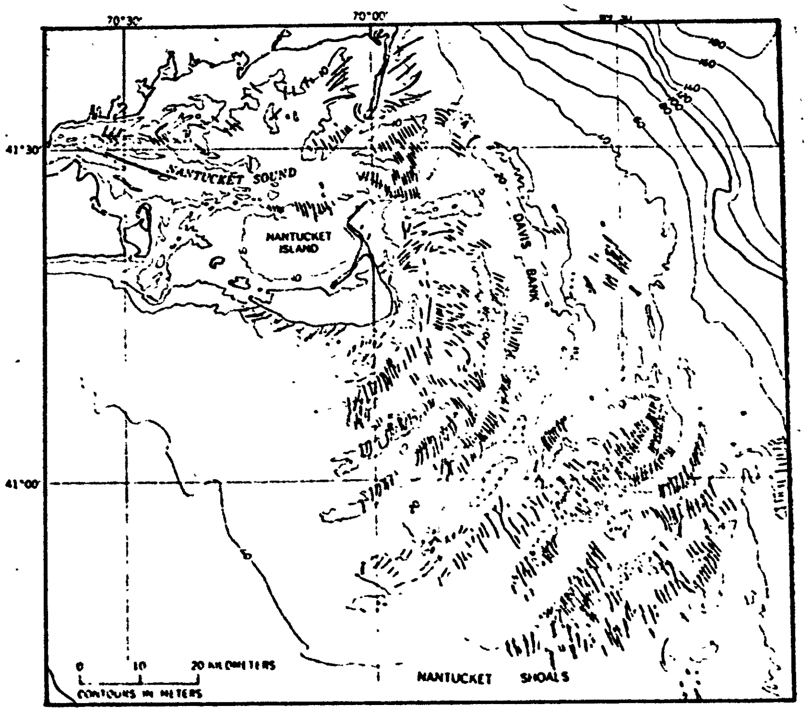


FIG. 4 —Sand shoals (contours) and sand waves (crestal lines) near Nantucket Island. From Uchupi (1968, Fig. 11).

coast with water depths less than 18 m (darker area). The deeper channels between the shoals are oriented in a north-south direction and appear to be conduits for flow between the Gulf of Maine and the shelf to the south of Cape Cod. The orientation of these channels changes to a northeast-southwest direction to the south of Nantucket Island. Thus the large shoal areas and channels are thought to be the result of glacial deposition and modification by the rising shoreline and local currents.

On a smaller length scale secondary sand waves are apparent in Figure 4 on the tops and side slopes of the shoals with a general east-west trend at right angles to the predominant north-south trend of the longer ridges and channels. These sand waves are constantly shifting (Uchupi, 1968). Long rows of usually asymmetric waves also cover large areas in Nantucket and Vineyard Sounds, Georges Bank, and on the continental shelf (Emery and Uchupi, 1972). Stewart and Jordan (1964) measured sand waves on Georges Shoal with heights of 8m and wavelengths of 560m, giving a ratio of $H/L = 1.4 \times 10^{-3}$. Erosion and deposition by tidal currents are thought to cause the sand wave formation, but surface wave action must have some modifying influence. Drilling for a Texas Tower on Nantucket Shoals showed that the sand waves consist of mediuim-to-fine-grained sand with layers of silt and gravel (Torphy and Zeigler, 1957). A more detailed study of a sand ridge in Vineyard Sound suggested that the sand shoals off the Cape Cod coast are the result of glacial deposition as well as deposition by littoral drift during periods of rising sea level (Smith, 1969). Thus on length scales of a few meters, the bottom sediments are characterized by propagating sand waves over the shallower regions of Nantucket Shoals.

Since Nantucket Shoals is essentially a topographic boundary to flow between the Gulf of Maine and the outer continental shelf, then some knowledge of the hydrographic properties in the waters adjacent to the shoals should set a framework for the new hydrographic data to be presented in Chapter 3. In 1976 two NSF- and USGS-sponsored hydrographic cruises were made in the Georges Bank region of the New England continental shelf (Limeburner, Vermersch, and Beardsley, 1978). Closely spaced (9 km) hydrographic stations were taken over Georges Bank and near Nantucket Shoals. Figure 5 shows the surface salinity for the southwestern Gulf of Maine in May, 1976. A prominent feature in the surface salinity for May is the presence of a strong offshore salt gradient on the southeastern side of Georges Bank indicating a transition from shelf water to slope water. Actually, the offshore salinity values are greater than 36 ‰ indicating the presence of Sargasso Sea water (Worthington, 1976) which has been trapped in an anticyclonic ring. A second feature in

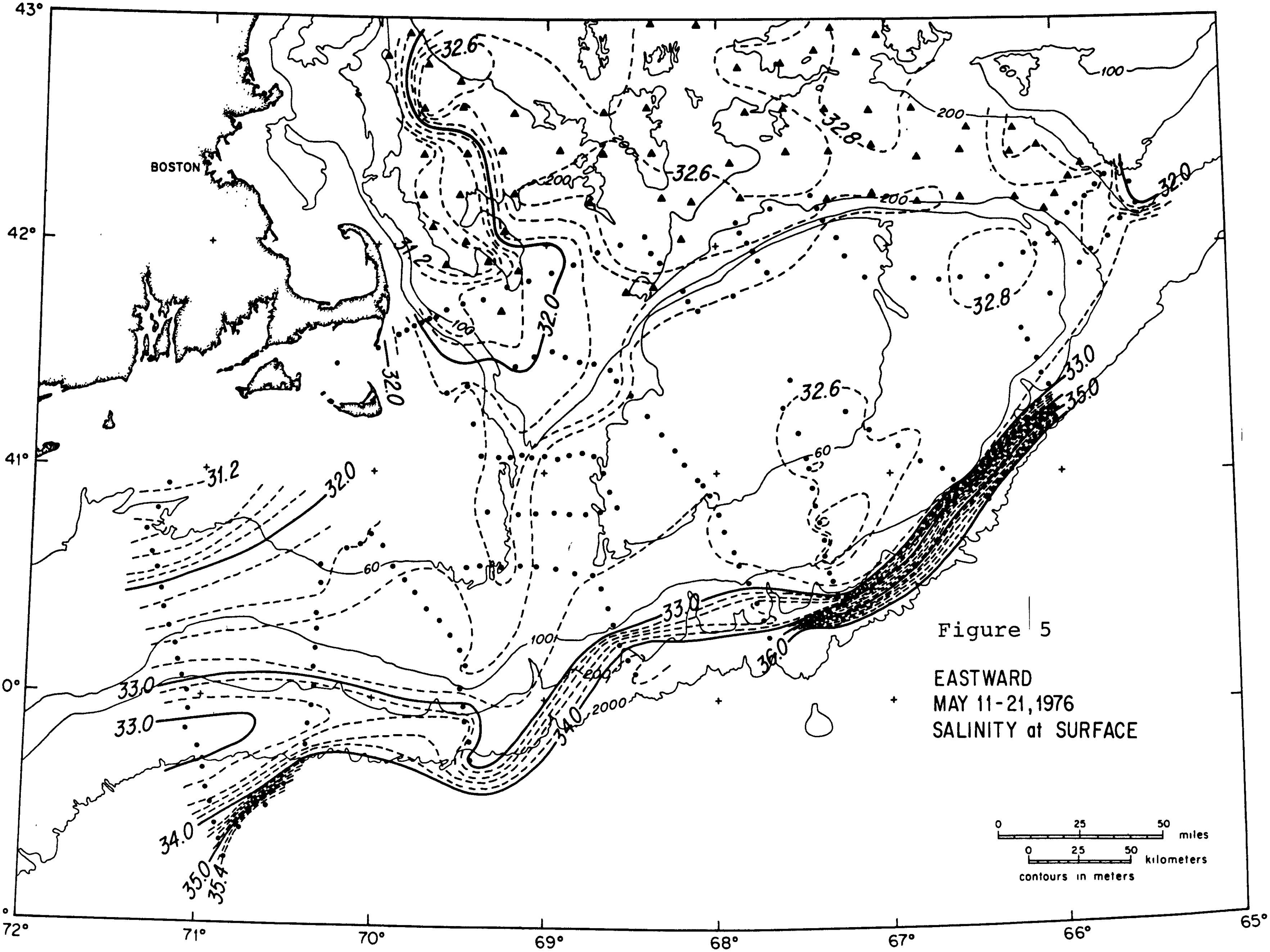


Figure 5

EASTWARD
MAY 11-21,1976
SALINITY at SURFACE

the Gulf of Maine surface salinity for May, 1976 is the plume of relatively fresh water <32 ‰, east of Cape Cod. Bue (1970) estimates the average annual streamflow into the Gulf of Maine from the St. Croix River to Cape Cod to be 1.7 x $10^3 m^3$/sec. The major contributions to this freshening of the Gulf of Maine 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). Although large intrusions of Scotian shelf water enter the Gulf of Maine off Cape Sable from winter to spring (Bigelow, 1927, p. 727), the fresh water plume in Figure 5 is a surface feature and is assumed to originate with the local river runoff from Massachusetts, New Hampshire, and Maine. The May surface salinity also shows that water fresher than 32.6 ‰ takes on a tongue-like structure to the south of the 32 ‰ isohaline as well as a similar tongue of water less than 32.6 ‰ to the east of the 32 ‰ plume off Cape Cod. Thus the surface salinity in May infers the existence of a fresh water plume off Cape Cod which divides into a southerly flow along the eastern edge of Nantucket Shoals and an easterly flow along the northern edge of Georges Bank.

The vertical extent of the freshwater plume off Cape Cod is observed in Figure 6 from May, 1976. Section m of the EASTWARD is located off Chatham in Figure 5. The 32 ‰

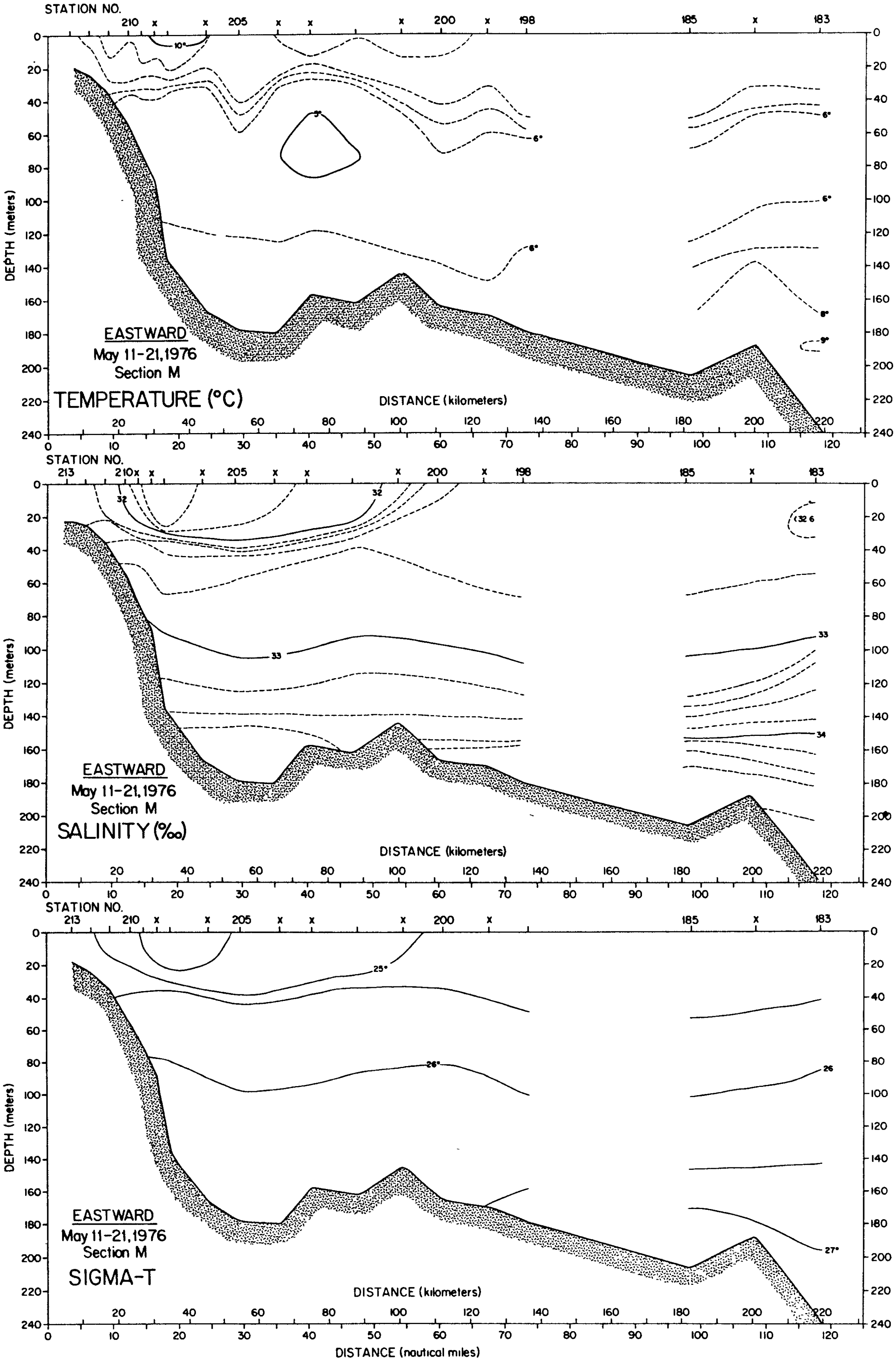

STATION NO.
210
205
200
198
185
183
213
EASTWARD
May 11-21,1976
Section M
TEMPERATURE (°C)
SALINITY (‰)
SIGMA-T
DEPTH (meters)
DISTANCE (kilometers)
DISTANCE (nautical miles)
10°
9°
6°
8°
32
33
34
<32.6
25°
26°
26
27°

Figure 6

isohaline encloses a surface approximately 30 m deep and 80 km wide. The fresh water is assumed to be flowing south until the flow divides to the south and east. Also in Figure 6 one observes water less than 8°C, and salinity between 32.2-32.4 ‰ 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 for the entire Gulf of Maine and Georges Bank survey area. 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 are assumed to be the result of the upwelling of water from the lower seasonal thermocline (depth = 20-40 m) in the Gulf of Maine. Bigelow (1927, p. 588) was the first to note the relationship between the westerly winds in the western Gulf of Maine and an offshore flux of surface water which is replaced by cooler upwelled water. Upwellings of this sort are common along the northern shore of Massachusetts Bay. However, Nantucket Shoals is not a 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 1978 a Sea Grant-supported field program began to study the physical processes which control the water structure and circulation about Nantucket Shoals. Periodic synoptic hydrographic surveys were initiated in May, 1978 to measure the spatial structure and temporal variability of the water properties in the Nantucket Shoals area over one annual cycle and a pilot moored current meter experiment was completed in January-March, 1979 to obtain the first direct subsurface current measurements made over the shoals. The research program was designed to determine how and when the temperature and salinity fields vary and what processes control the local T/S characteristics during which seasons. The influence of tidal mixing, upwelling and other modification processes like seasonal heating and cooling, wind mixing, and mean horizontal advection can be examined from the series of bi-monthly hydrographic surveys.

Chapter II will present some historical circulation concepts for the Gulf of Maine and shelf regions. Results of the new Nantucket Shoals hydrographic data and recent satellite IR imagery with respect to sea surface temperature will be given in Chapter III. Chapter IV will present the historical tidal surveys completed over the shoals. A comparison of meteorological data with the hydrographic and current meter data will be given in Chapter V. Chapter VI will present conclusions and proposed future work.

II. A Review of Past Work on the Physical Oceanography of the Nantucket Shoals Region

Most of our present notions about circulation over Nantucket Shoals originate 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 hydrogdraphic 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. A schematic of this circulation model is shown in Figure 7. 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 depending on actual runoff and wind conditions and perhaps other causes. While more recent data presented by Bumpus (1976), Butman et al. (1977), Brown and Beardsley (1978), and Vermersch et al. (1979) generally support Bigelow's two-gyre circulation scheme, the physical processes which govern the circulation remain unclear.

Bigelow indicates in Figure 7 that some near-surface water does leak from the Gulf of Maine gyre over Nantucket

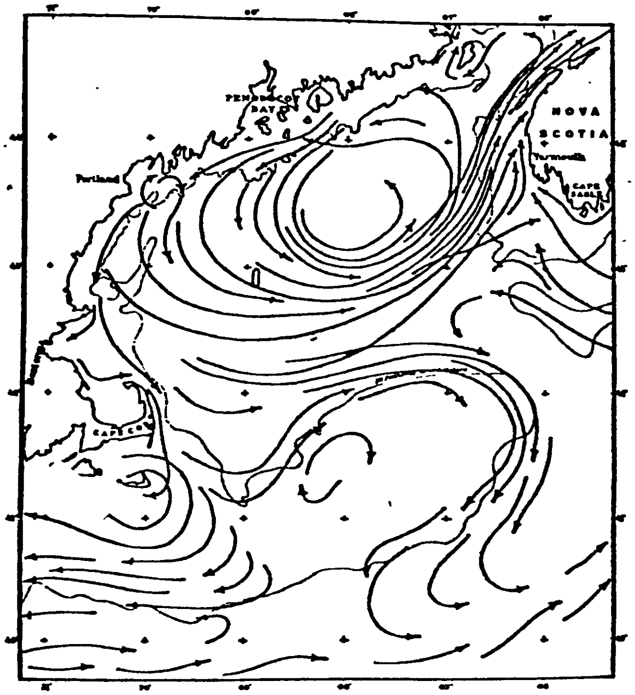


Figure 7 Bigelow's (1927) schematic representation of the dominant summer non-tidal circulation in the Gulf of Maine.

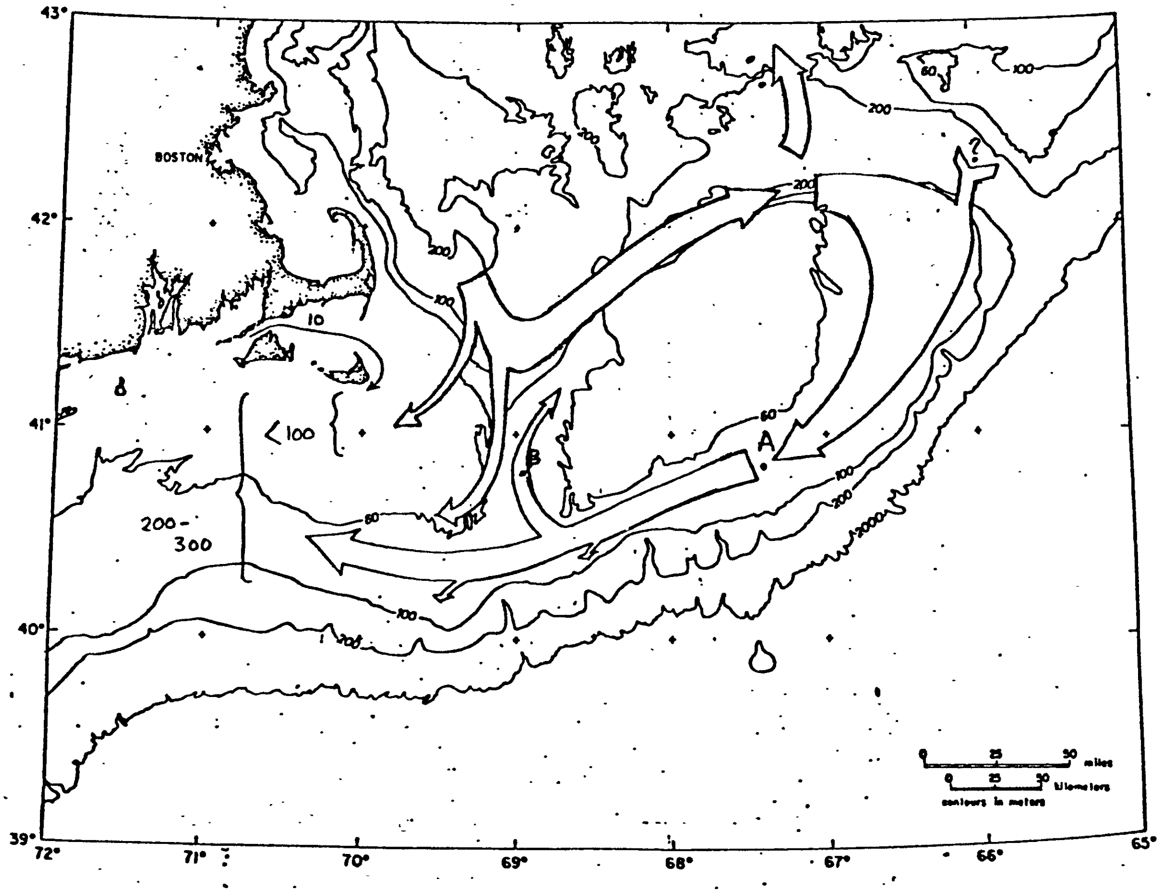


Figure 8 A modern transport schematic for this region. Units of transport are 10^3 m^3/sec. (Beardsley,Vermersch,Limeburner,1978)

Shoals toward the southwest. Bigelow released 600 drift bottles along a 130 nm line running SE from Chatham in July, 1922 and found that most of the bottles released over Nantucket Shoals were recovered along the New England coast to the west and south. Additional summer drift bottle releases and the occurrence of a distinct faunal division near Chatham indicate an eastward current through Nantucket Sound. The net effect implied by Bigelow is thus a summer clockwise circulation around Nantucket Island and Marthas 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 by Walford (1938), Day (1958), Bumpus (1958), Bumpus and Lauzier (1965), and Bumpus et al. (1971) also tend to support Bigelow's scheme for the late spring/summer clockwise near-surface circulation around Nantucket Shoals.

Bumpus and Lauzier (1965) and Bumpus (1973) have analyzed surface drifter data for other seasons and while the recovery rate from the Nantucket Shoals region was extremely low during winter, they report a southward near-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 Figure 1) a mean summer near-surface current of about 10 cm/sec towards W to NW which reversed during winter to a southeastward current of less than 4 cm/sec, presumably in response to stronger eastward winds during winter (Saunders, 1977). The mean summer near-surface currents found by Haight at Great Round Shoal and Pollock Rip are also consistent with Bigelow's scheme. Haight 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 Marthas 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 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.

Our present picture of circulation over and around Nantucket Shoals is thus based primarily on inferred trajectories of surface and bottom drifters. The drifter information for Nantucket Shoals does appear reasonably consistent with current data from surrounding areas and may be combined to form a schematic mean transport diagram as shown in Figure 8. The USGS current measurements at Site A described by Butman et al. (1977) indicate continuous westward flow of shelf water along the southern side of

Georges Bank (except perhaps during brief periods of extremely high westerly winds). The simple box model calculations of Brown and Beardsley (1978) suggest a net westward flux of roughly 200 to 300 x $10^3 m^3$/sec of shelf water south of Nantucket. How much of this transport comes directly from the Gulf of Maine via Nantucket Shoals and the Great South Channel is not known, but the flux over the Shoals is probably less than 100 x $10^3 m^3$/sec. Most of this water must come from the Gulf of Maine since the eastward transport through Nantucket Sound is relatively small. Walford (1938), Bumpus (1976), and Butman et al. (1977) show evidence that shelf water from the southern side of Georges Bank may flow northward around Little Georges through the eastern side of the Great South Channel. These observations imply some recirculation of shelf water within the Georges Bank gyre, a phenomenon of key importance to the biological productivity of this area, but no estimates of the amount or variability of this recirculation have been made. A single current meter record at a depth of 47 m from a location along the axis of the Great South Channel in the summer of 1976 (Folger, Butman, Knebel, Sylvester, 1978) indicated a mean flow of 5 cm/sec toward 349°.

Current and sea level observations made on the New England continental shelf (Beardsley and Butman, 1974) during winter storms show that intense wind events dominate the circulation over the shelf. Large westward mass transports were produced by east winds, but west winds produced little long-shore flow. Mean speeds of 6.2 cm/sec to the west were observed on the shelf 70 km SE of Block Island at a depth of 42 m. Two northeasterly wind events increased the mean westward speed to 30 and 45 cm/sec. The Ekman mass transport associated with the easterly winds created an onshore pressure gradient and the longshore currents were in geostrophic balace to within 15%.

In December, 1976 the grounding of the oil tanker ARGO MERCHANT on Fishing Rip, 27 miles southeast of Nantucket provided an unwanted but nevertheless interestisng tracer of motion in the top 50 cm of the water column. Essentially, strong westerly and northwesterly winds dragged seven million gallons of crude oil in a downwind direction at a rate of about 3% the windspeed. This result is similar to Bigelow's (1927, p. 864) measurements of a mean southeastward flow in winter at the Nantucket Lightship due to strong northwest winds. Two separate current meter moorings were deployed (Butman, personal communication) by the USGS during the ARGO MERCHANT oil spill (Figure 10 and Table 1). One short record (12.98 tidal cycles) was obtained 25 miles east of Nantucket Island at a depth of 15 m. The mean flow of 5.6 cm/sec was toward 202°. A second mooring 32 miles south of Nantucket Island provided a 45-day record at a depth of 18 m. The mean flow of 5.1 cm/sec was toward 258°.

The region near the Nantucket Shoals Lightship, located $40^{o}30.8'N$, $69^{o}29.3W$ (Station 58 in Figure 12) is particularly interestisng because of the merging of the longshore shelf orientation and cross shore shoals orientation. Bigelow measured a southeasterly flow here in winter and a northeasterly flow in summer. Haight's (1942) analysis of tide pole measurements from the lightship gives an estimate of the wind-driven currents. A 15 cm/sec velocity is implied in the top 4 m during a 30Kt northwesterly wind. During the ARGO MERCHANT oil spill two current meters were deployed at the lightship at depths of 18 m and 28 m in 60 m of water. The 18 m record has a strong mean to the south (16 cm/sec) and the 28 m level showed a small westerly drift. The amplitude of the tidal signal was approximately 18 cm/sec at 18 m and 30 cm/sec at 28 m. The east component of the tidal ellipse was 15% greater than the north component at both levels. The kinetic energy density spectra (EG&G, 1977) are shown in Figure 9. The energy density at the semidiurnal frequency is higher at mid-depth (28 m) than at 18 m. In the low frequency band, 1-5 days, the 18 m and 28 m energy levels are comparable in the east component. The 18 m energy is greater at the lowest frequency due to a higher east-west mean velocity at this level. The north component energy level is higher at 28 m than at 18 m except for the

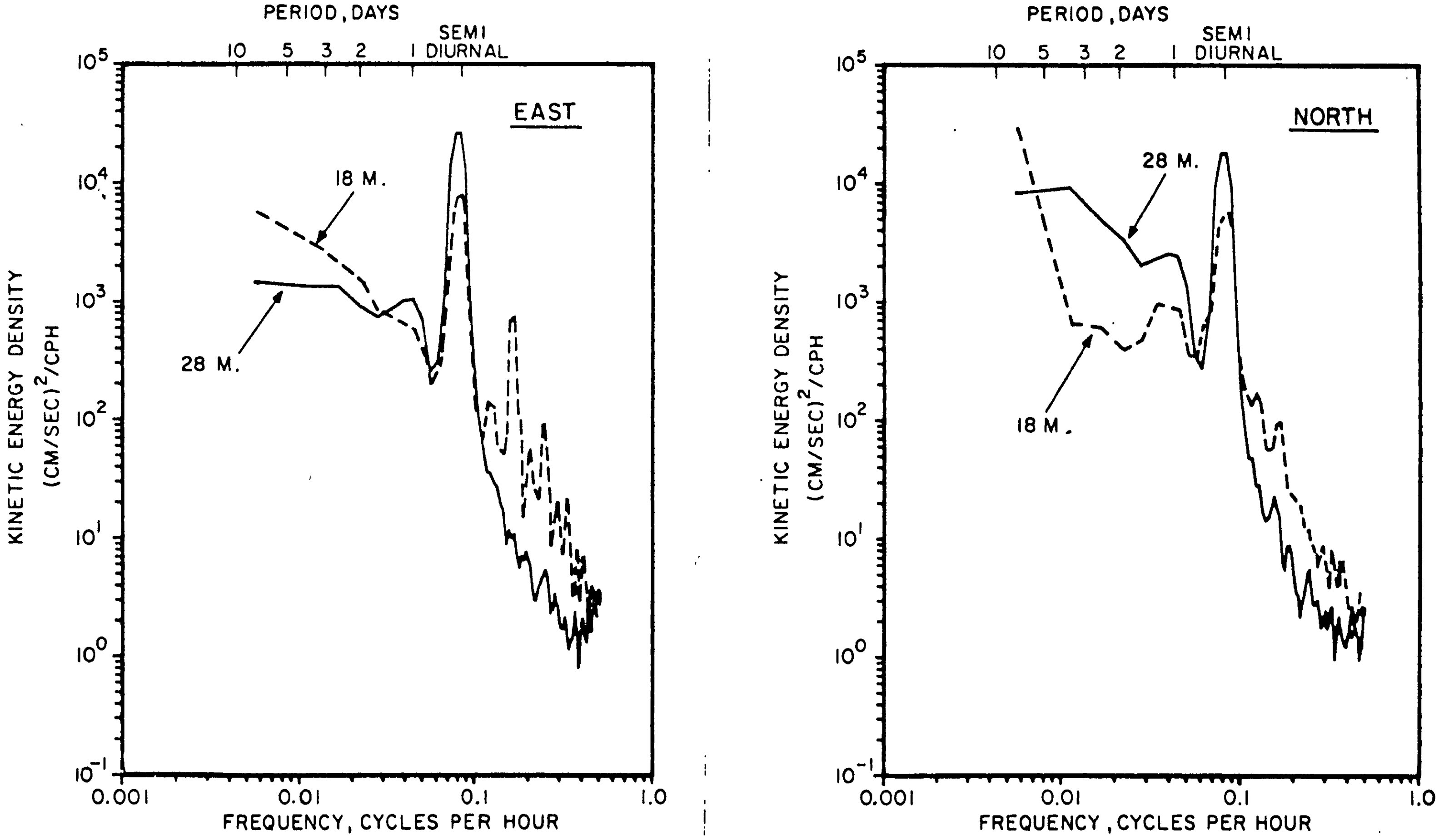


Figure 9. Kinetic energy density spectra, east and north components, over the period Dec 28 - Jan 26,1977 (EG&G,1977).

lowest frequency (a large southerly mean of 16 cm/sec at 18 m). The higher energy at mid-depth in the north component is difficult to relate to the wind since one would expect the wind-induced motions to be stronger near the surface. The proximity of the Great South Channel may complicate the interpretation of the low frequency motions.

The north component energy level was greater by a factor of 3 than the east component at both depths. A comparison of the low frequency currents to winds at Logan airport showed inconsistent results and more recent data proves the winds at the Nantucket lightship to be very different in winter than the winds at coastal stations. A summary of the measured mean flow near Nantucket Shoals is presented in Figure 10 and Table 1.

More recently an effort to document the motion of the surface water in the Gulf of Maine was undertaken by EG&G (1978) using surface current tracers and relocation with airplanes. Difficulties related to the short deployment, position errors, changes in tidal phase between observations, and the slippage due to the wind of the tracers relative to the water lead to a complicated interpretation of the motions observed in Figure 11. However, the inferred surface motion is generally in a downwind direction.

Thus many of the recent short-term current meter measurements from near Nantucket Shoals agree in a

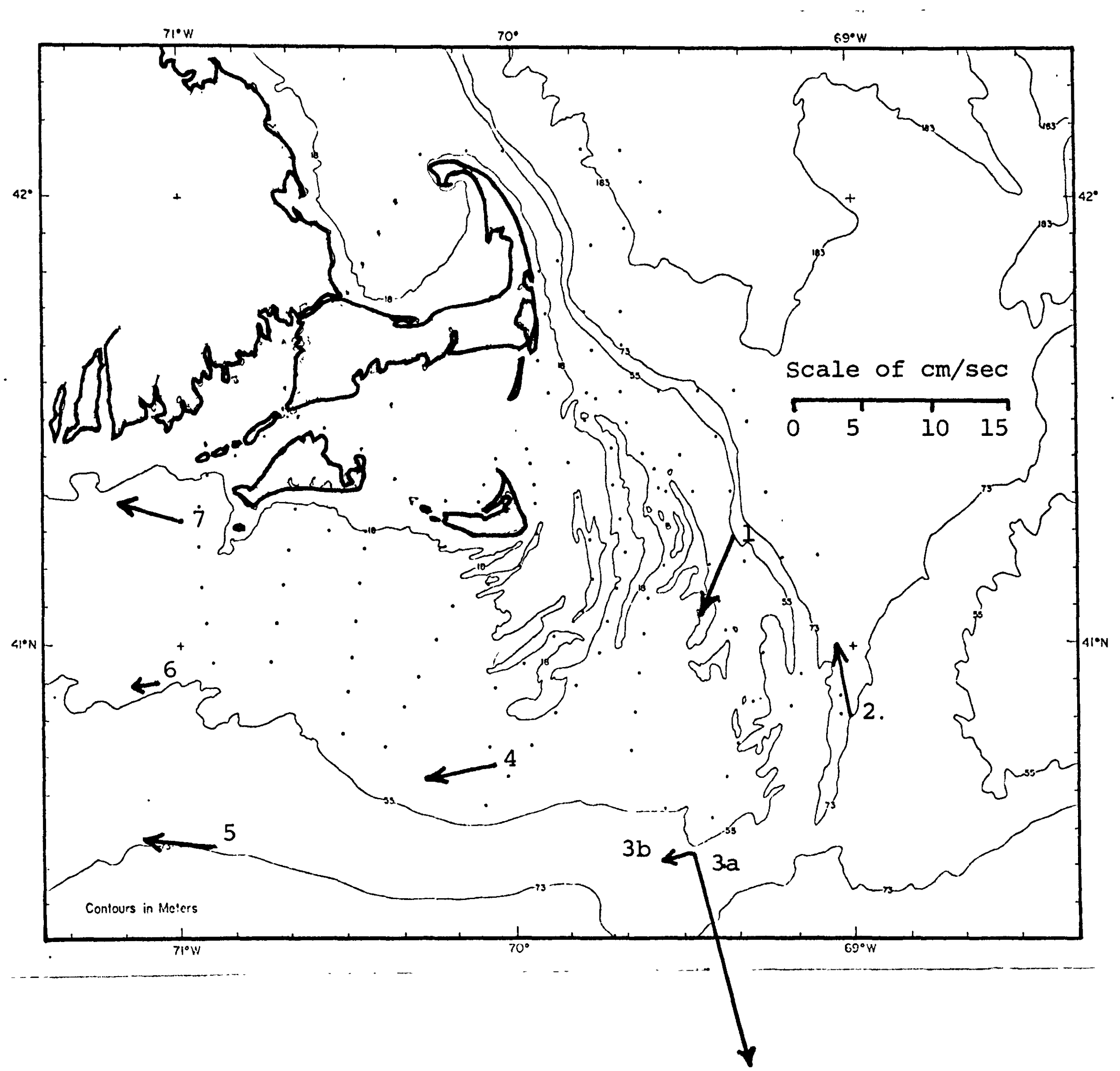


Figure 10. Mean flow from current meter measurements. See Table 1 for more information.

Table 1. Current Meter Measurements near Nantucket Shoals

Station	Location	Origin	Inst. Depth	Instrument	Record Length [Day(s)]	Date
1	41 14.0N, 69 22.5W	Butman, USGS	15m	VACM	9.5	28 Dec 76 - 6 Jan 77
2	40 50.0N, 69 00.0W	Butman, USGS	58m	VACM	102	Summer, 1976
3a	40 30.8N, 69 29.3W	EG&G	18m	CT3	30	28 Dec 76 - 26 Jan 77
3b	40 30.8N, 69 29.3W	EG&G	28m	CT3	30	28 Dec 76 - 26 Jan 77
4	40 42.5N, 70 00.5W	Butman, USGS	18m	850	47	Winter, 1977
5	40 32.6N, 70 55.6W	Flagg, WHOI-MIT	24m	VACM	37	27 Feb - 4 Apr, 74
6	40 54.0N, 70 04.3W	Flagg, WHOI-MIT	28m	VACM	37	27 Feb - 4 Apr, 74
7	41 17.5N, 71 01.2W	McCullough, WHOI	10-13m	VACM, ENDECO, ACOUSTIC	10	3-13 Jun, 78

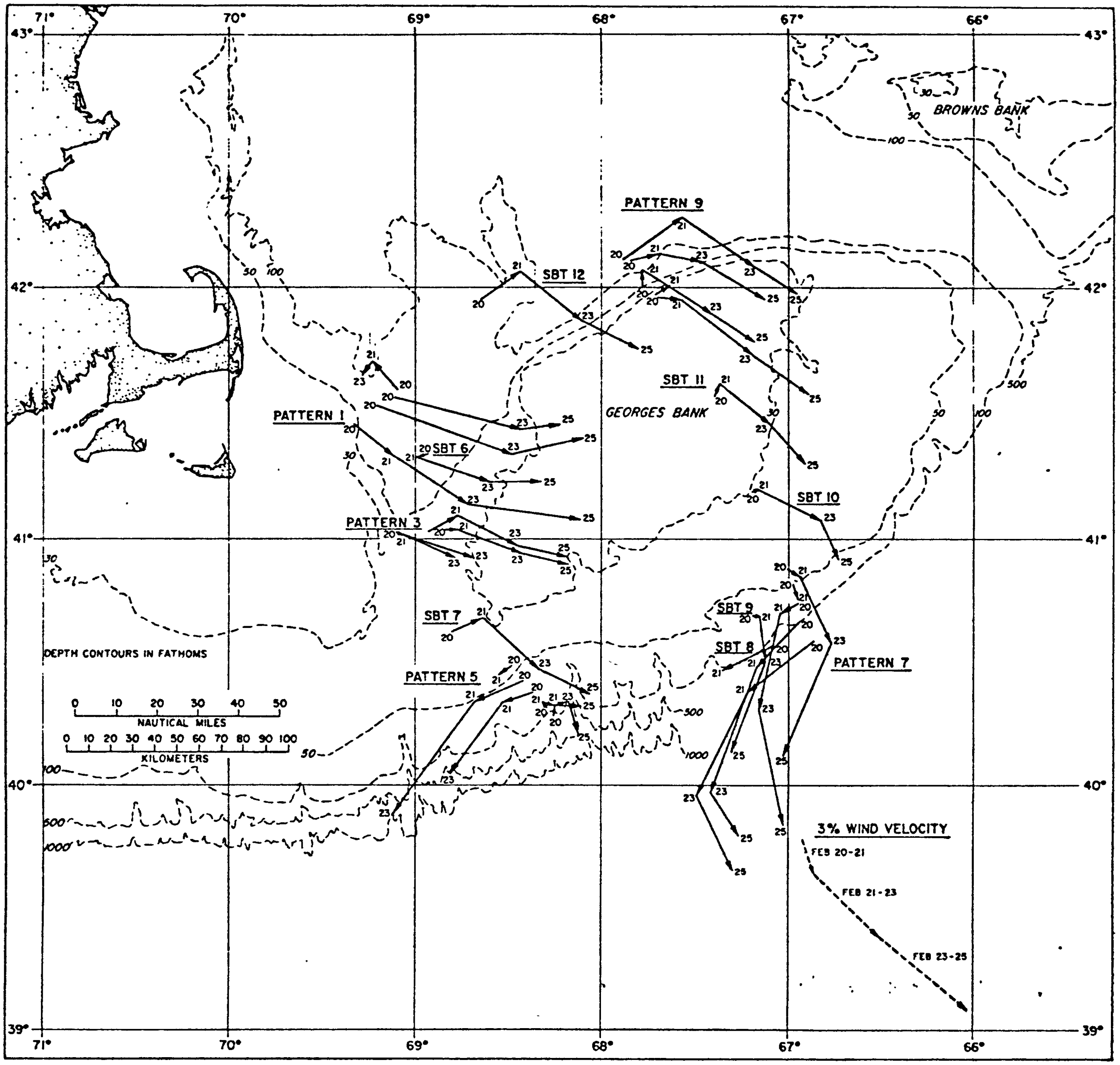


Figure 11 Surface drift February, 1978 (EG&G,1978).

qualitative sense to the historical circulation patterns inferred from drifters, fish larvae, and tide poles. A clockwise circulation around Nantucket Shoals partially recirculates through Nantucket Sound via Vineyard Sound and Muskeget Channel. However, the surface water in the top few meters appears to flow primarily downwind and the local variability is directly related to the wind forcing.

III. Results of the 1978-1979 Hydrographic Cruises

In May, 1978 periodic (every two months) synoptic hydrographic surveys were initiated to document the spatial and temporal variability of the water properties in the Nantucket Shoals area over one annual cycle. Figure 12 shows the general topography and cruise track which was followed during the May, July, September, and March surveys. The January cruise was shortened due to winter storms. A summary of the hydrographic observations for the May (NS1), July (NS2), and September (NS3) cruises is given by Limeburner and Beardsley (1979) and a summary of the January (NS4), March (NS5), and planned final May cruise is forthcoming. All the hydrographic cruises were completed on the MIT 65-foot converted T-boat, the R/V EDGERTON. CTD stations were taken approximately every five nautical miles along a cruise track which covered the coastal zone between one and fifty nautical miles offshore, and in the general area to the east and south

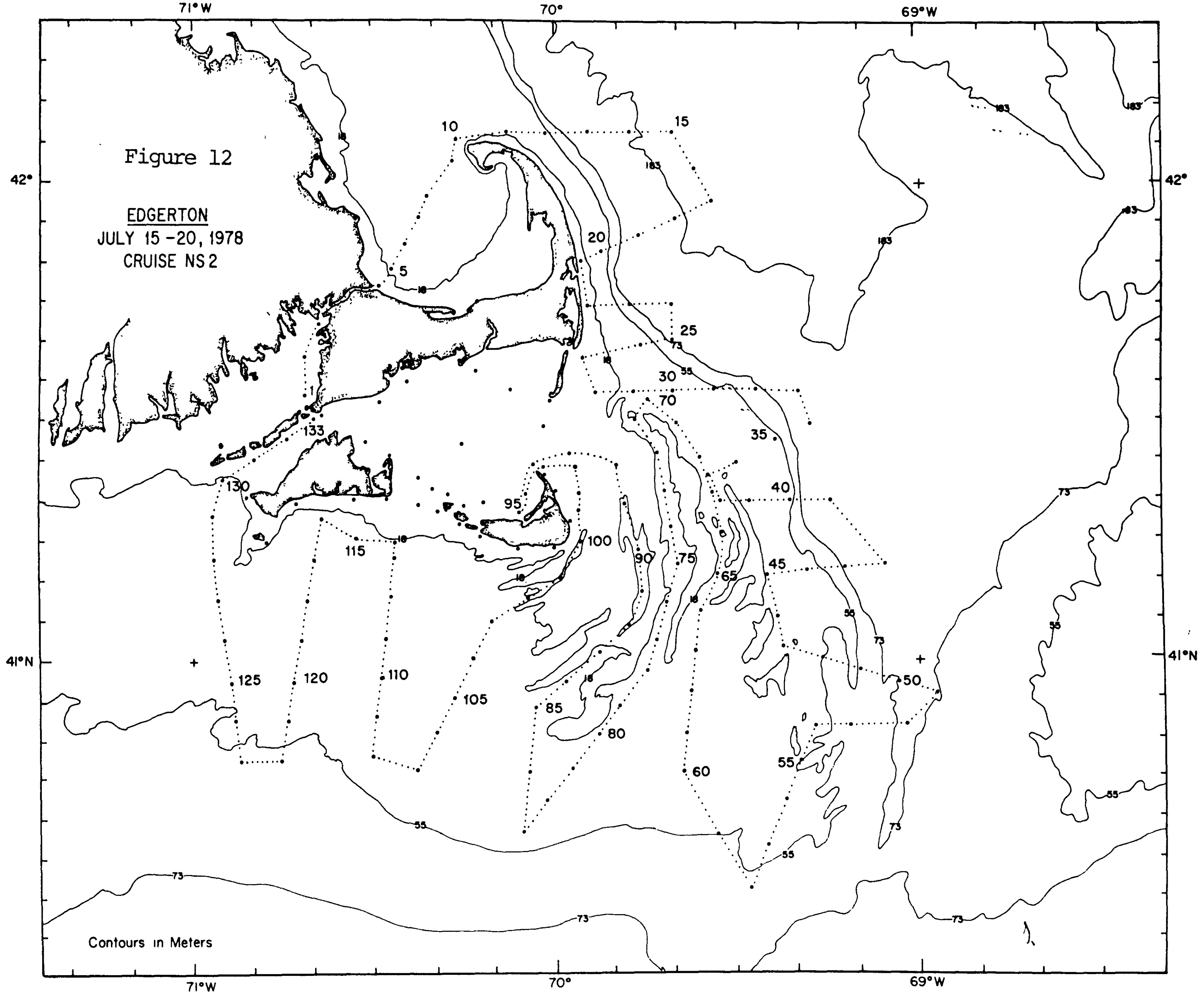


Figure 12

EDGERTON
JULY 15 -20, 1978
CRUISE NS 2

Contours in Meters

of Cape Cod, Nantucket, and Marthas Vineyard. During the January and March, 1979 cruises, surface samples replaced CTD casts since the water column was well mixed in the top 100 m over the entire survey region. Also, in summer at station locations where strong tidal currents produced a vertically mixed water column, only a surface water sample was taken.

A Plessy model 9040 CTD fish with a Plessy model 8400 digital data logger was used as the profiling instrument on all the hydrogdraphic cruises. A complete description of the instrumentation, error analysis, and data processing is given by Limeburner and Beardsley (1979). Table 2 gives a summary of the number of CTD stations for each cruise and the average offset and standard deviation between the instrument data and temperature and salinity values obtained independently using Nansen bottles.

A. Nantucket Shoals Upwelling

Past hydrographic work near Nantucket Shoals and remote sensing of sea surface temperatures have revealed two important processes, tidal mixing and upwelling, which directly influence water properties over and near the shoals. Tidal currents are sufficiently strong over shallower sections of Nantucket Shoals and Georges Bank that the local water column in those areas is kept well mixed by

Table 2

Calibration Results

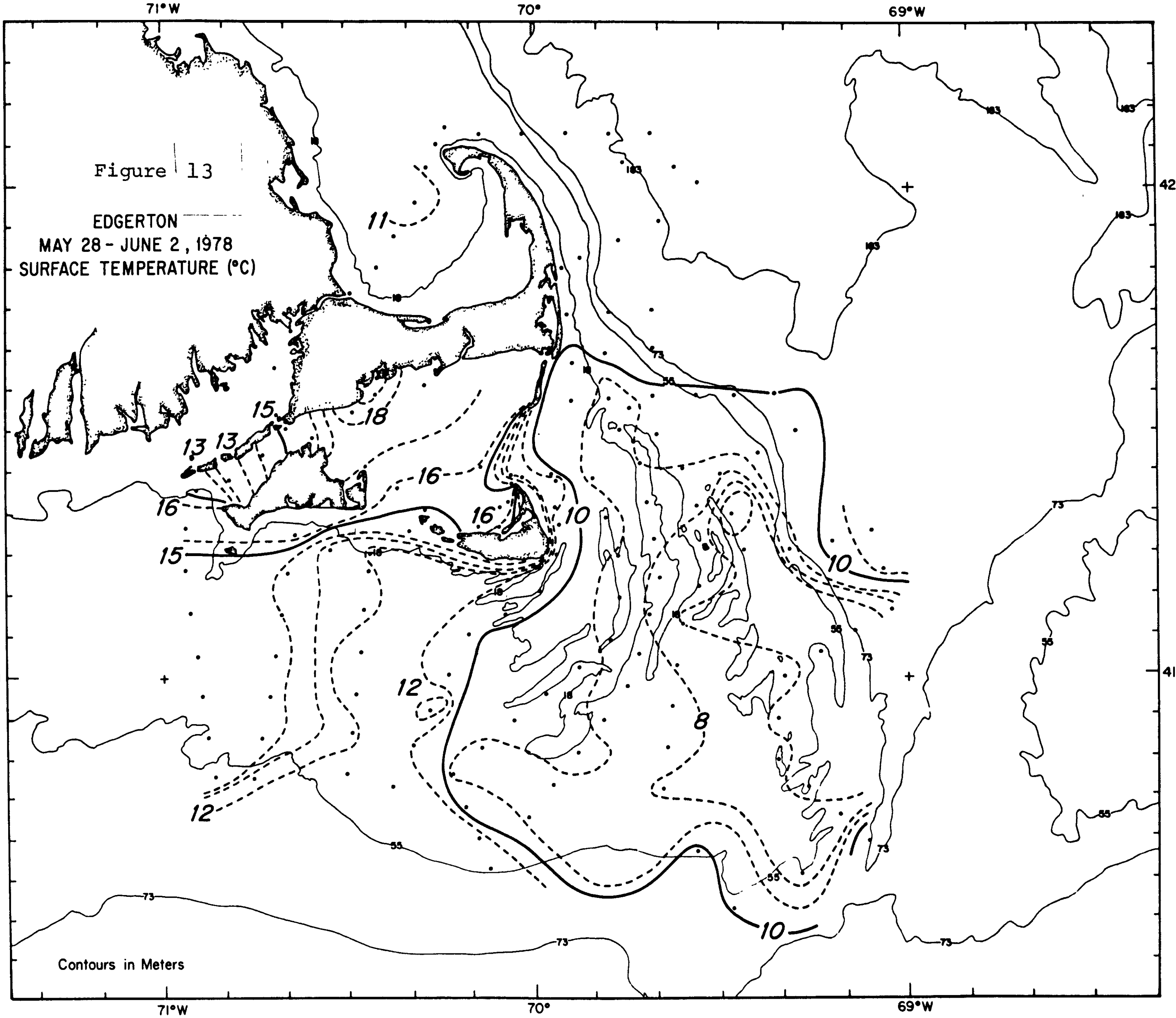
Cruise	Number of CTD Stations	Variable	Average Offset	Standard Deviation
NS1	108	Temperature	+.006°C	.016°C
		Salinity	-.001‰	.015‰
NS2	120	Temperature	.010°C	.021°C
		Salinity	-.015‰	.014‰
NS3	100	Temperature	.001°C	.011°C
		Salinity	-.004‰	.014‰
NS4	10		-	-
NS5	24	Temperature	-.004°C	.014°C
		Salinity	-.007‰	.006‰

mechanical mixing. Satellite infrared photographs frequently show a region of intense upwelling in summer along the eastern edge of Nantucket Shoals from Chatham to the Great South Channel.

A.1 May, 1978

The surface temperature map for the May cruise (Figure 13) shows lower temperatures over the shoal areas than to the east in the Gulf of Maine or to the south and west over the New England shelf. The minimum surface temperature of $<6^{\circ}C$ was observed 40 km east of Nantucket Island in 25 m of water. A core of water cooler than $7^{\circ}C$ was found over a large area on the southeastern flank of the shoals. An independent measure of the structure of the surface temperature variations east of Nantucket is given by the polar orbiting (NOAA) satellite infrared observations (Legeckis, Legg, and Limeburner, 1979) in Figure 14. False color enhancement is used to demonstrate that satellites are capable of detecting sea surface temperature fronts when coastal radiosonde profiles are used to estimate the correction for atmospheric attenuation of the infrared radiation. The structure of the cold patch of surface water in Figures 13 and 14 is very localized along the eastern edge of the shoals. The May surface salinity map (Figure 15) shows the upwelled water to be more saline than the adjacent surface water to the north, east, or west. Although similar

Figure 13



EDGERTON
MAY 28 - JUNE 2, 1978
SURFACE TEMPERATURE (°C)

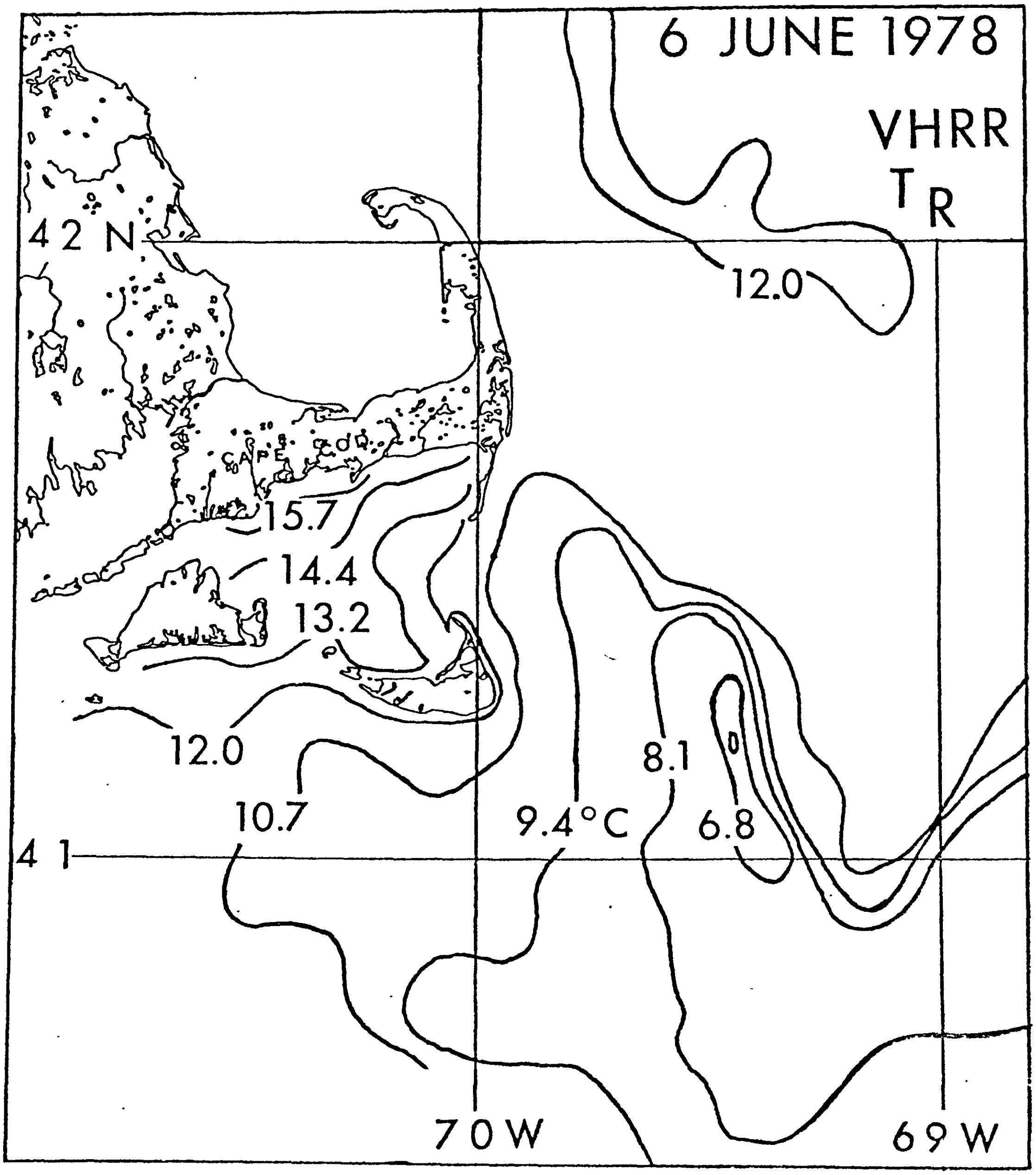


Figure 14. Polar orbiting (NOAA) satellite infrared observations of sea surface temperature.

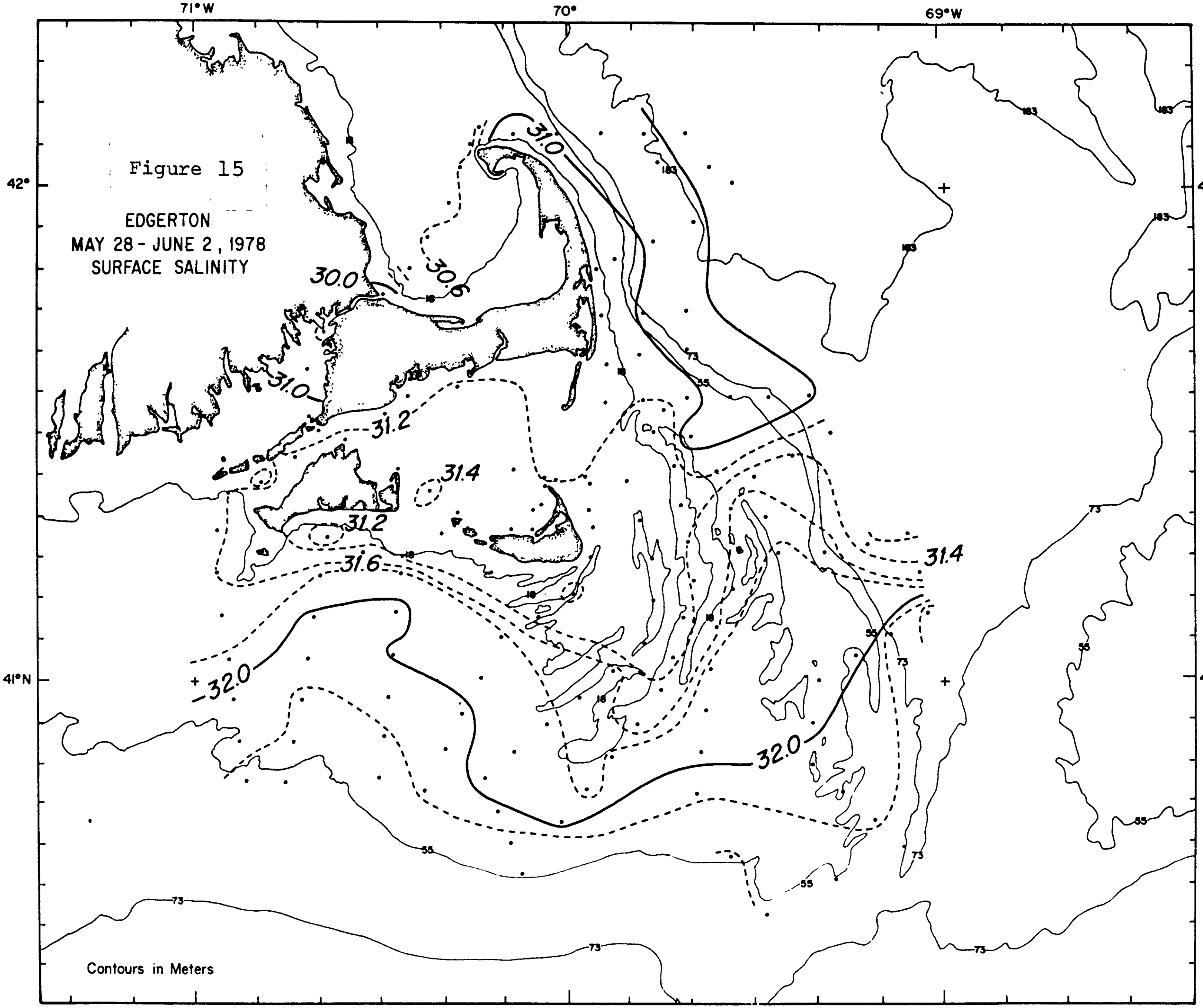


Figure 15

EDGERTON
MAY 28 - JUNE 2, 1978
SURFACE SALINITY

in temperature characteristics, surface water south of the upwelled core was more saline at a given temperature. These relationships are more clearly illustrated in the T/S diagram in Figure 16 in which the T/S bounds (or envelopes) of the upwelling and Gulf of Maine waters are plotted for the first three cruises. The upwelling water is usually vertically well-mixed and thus forms a single point on the T/S diagram for each station in the upwelling zone. The Gulf of Maine T/S curves indicate a monotonically increasing salinity with depth while temperature attains a definite minimum at mid-depth due to the formation of a seasonal thermocline in the warmer months and a deep influx of relatively warm, saline slope water into the gulf through the Northeast Channel. Thus the upwelled water observed in May appears similar in T/S characteristics to water found at depths of 20 to 30 meters in the adjacent Gulf of Maine, but the water 20 km southeast of the upwelled core is .6 ‰ more saline than the Gulf of Maine water at $6^{o}C$. This wide range of salinity values in the May upwelling area will be discussed later.

The temperature minimum in the Gulf of Maine water (Figure 16) has been referred to as the Maine Intermediate Water (Hopkins and Garfield, 1976). This seasonal water mass is produced during winter by atmospheric buoyancy extraction processes. The warmer, saltier waters below the MIW is

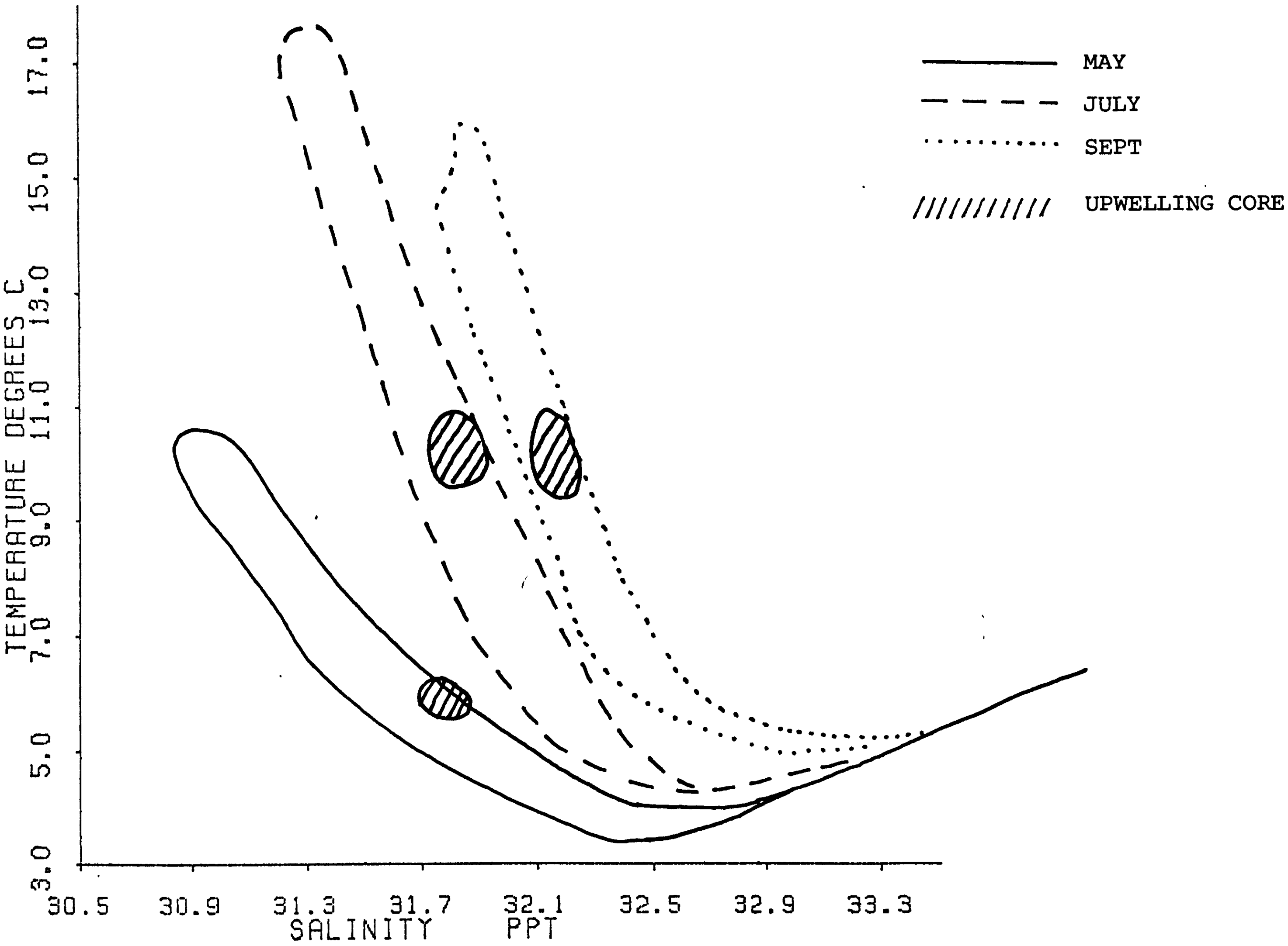


Figure 16. Simplified T/S diagram of the first three cruises.

really modified slope water which has entered the Gulf of Maine through the Northeast Channel. In summer the MIW is generally found in the 50-120 m depth range and is 1-6°C and 32-33 ‰ . During the May, 1978 cruise, the MIW (Limeburner and Beardsley, 1979) was observed shallower than 30 m north of the upwelling core and offshore of Chatham. The MIW is found at a depth of 40 m along the entire eastern edge of the survey area. Figures 17 and 18 are given to demonstrate the vertical stucture of the upwelling east of Nantucket. Each profile begins at Nantucket Island to the west and intersects the upwelling core on the east. The cold surface temperature is shown to be similar in temperature and salinity to water at 20-30 m deep to the east in the Gulf of Maine. The low salinity water (<31.4 ‰) at Station 34 in Figure 17 and Station 41 in Figure 15 is related to the freshwater plume which flows southward off Cape Cod. The cooler and more saline water at Stations 35, 36, 38, and 39 (Figures 17 and 18) is assumed to be a vertical intrusion or upwelling of deeper water into the region which is otherwise dominated by freshwater runoff. The 32 ‰ isohaline probably surfaces eastward of the survey region and can be considered a convenient offshore boundary to the less saline nearshore region. The strong horizontal gradients in temperature and salinity are a consequence of the upwelling.

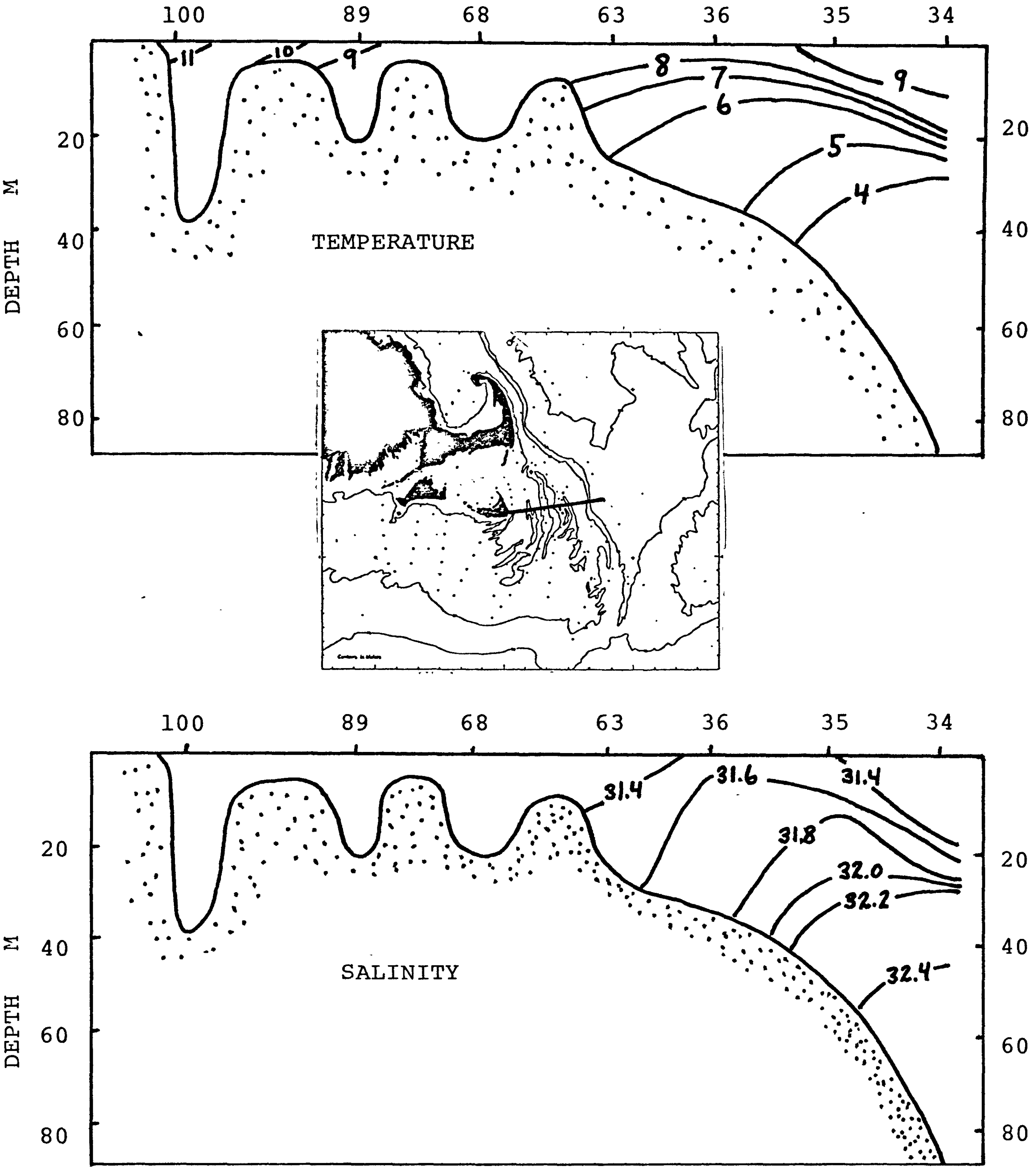


Figure 17 . Vertical profile of temperature and salinity across Nantucket Shoals May, 1978.

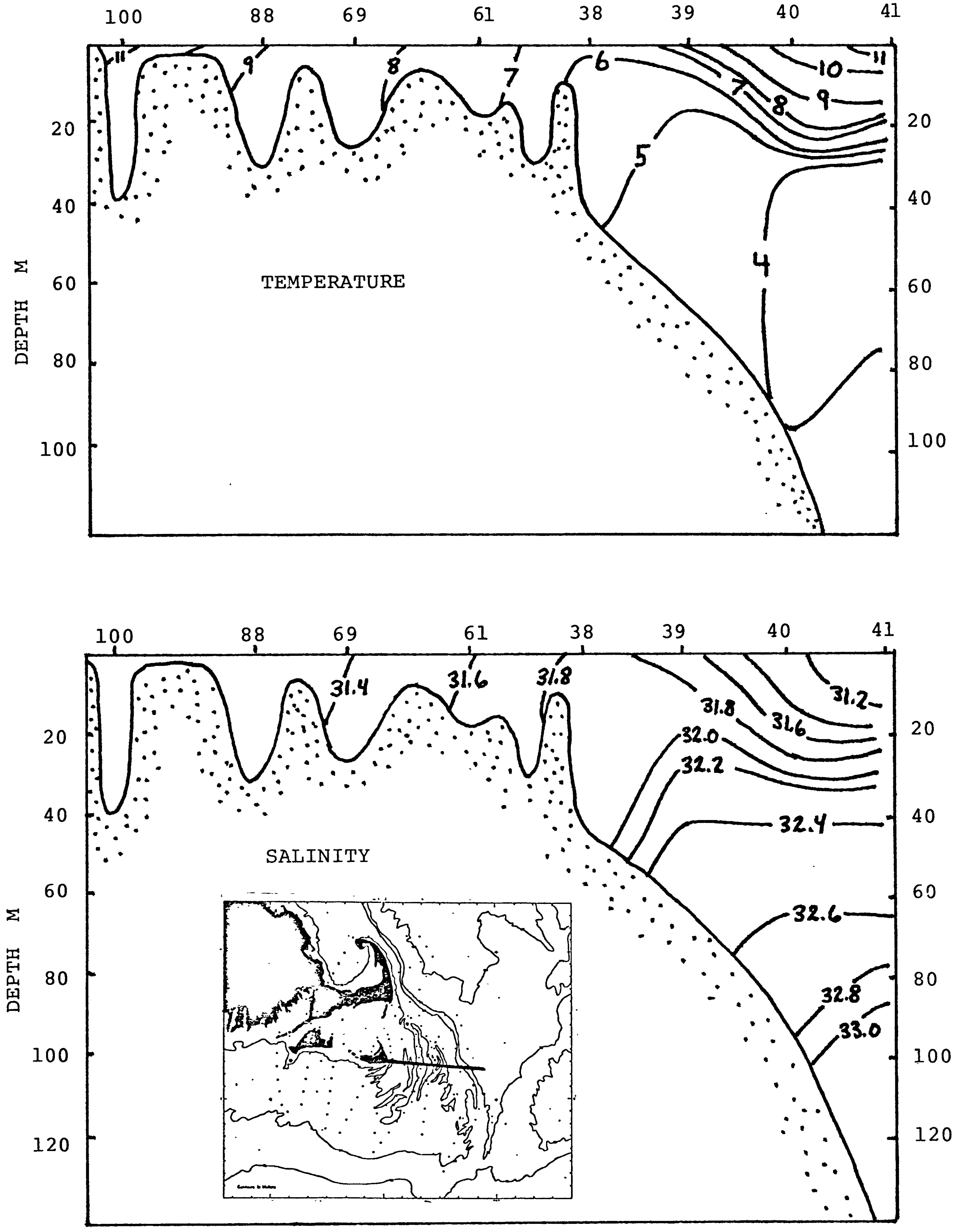


Figure 18. Vertical profile of temperature and salinity across Nantucket Shoals May, 1978.

A.2 July, 1978

The surface temperature map for the July cruise (Figure 19) shows the cooler upwelling water to have two temperature-minimum cores with surface temperatures less than 10°C. As shown in Figure 20, the upwelled water has higher salinities than the adjacent warmer waters indicating a mid-depth origin in the Gulf of Maine. The July T/S diagram shown in Figure 16 demonstrates that the upwelling water has very similar T/S characteristics to water found in the lower thermocline in the adjacent Gulf of Maine. The July temperature at a depth of 10 m (Figure 21) demonstrates that the localized surface expression of the upwelling events have a broader horizontal distribution along the eastern edge of Nantucket Shoals. The water less than 10°C at 10 m in July occupies a region approximately 90 km by 15 km. Also a temperature minimum exists at 10 m in a nearshore band along the entire coastline east of Cape Cod. The July surface sigma-t map (Figure 22) illustrates how the upwelled water appears as a region of higher density along the eastern edge of the shoals. Note also the tidal advection of the colder upwelled water into Nantucket Sound south of Monomoy Island. These stations near Monomoy were taken at the end of the ebb tide and the cooler (denser) water would be advected out of Nantucket Sound to the east at the end of flood tide. This demonstrates the inherent noise in the hydrographic data due

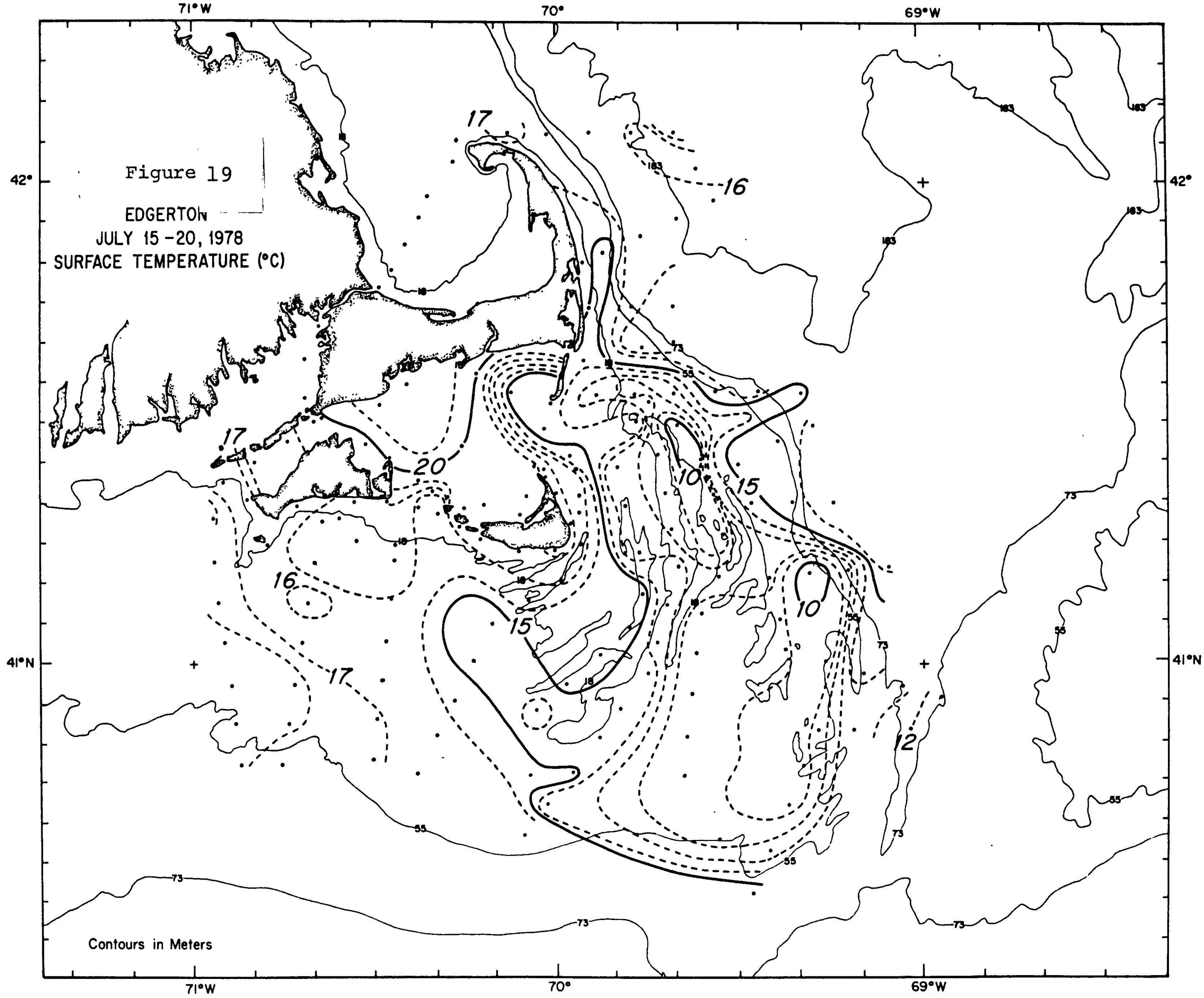


Figure 19

EDGERTON
JULY 15-20, 1978
SURFACE TEMPERATURE (°C)

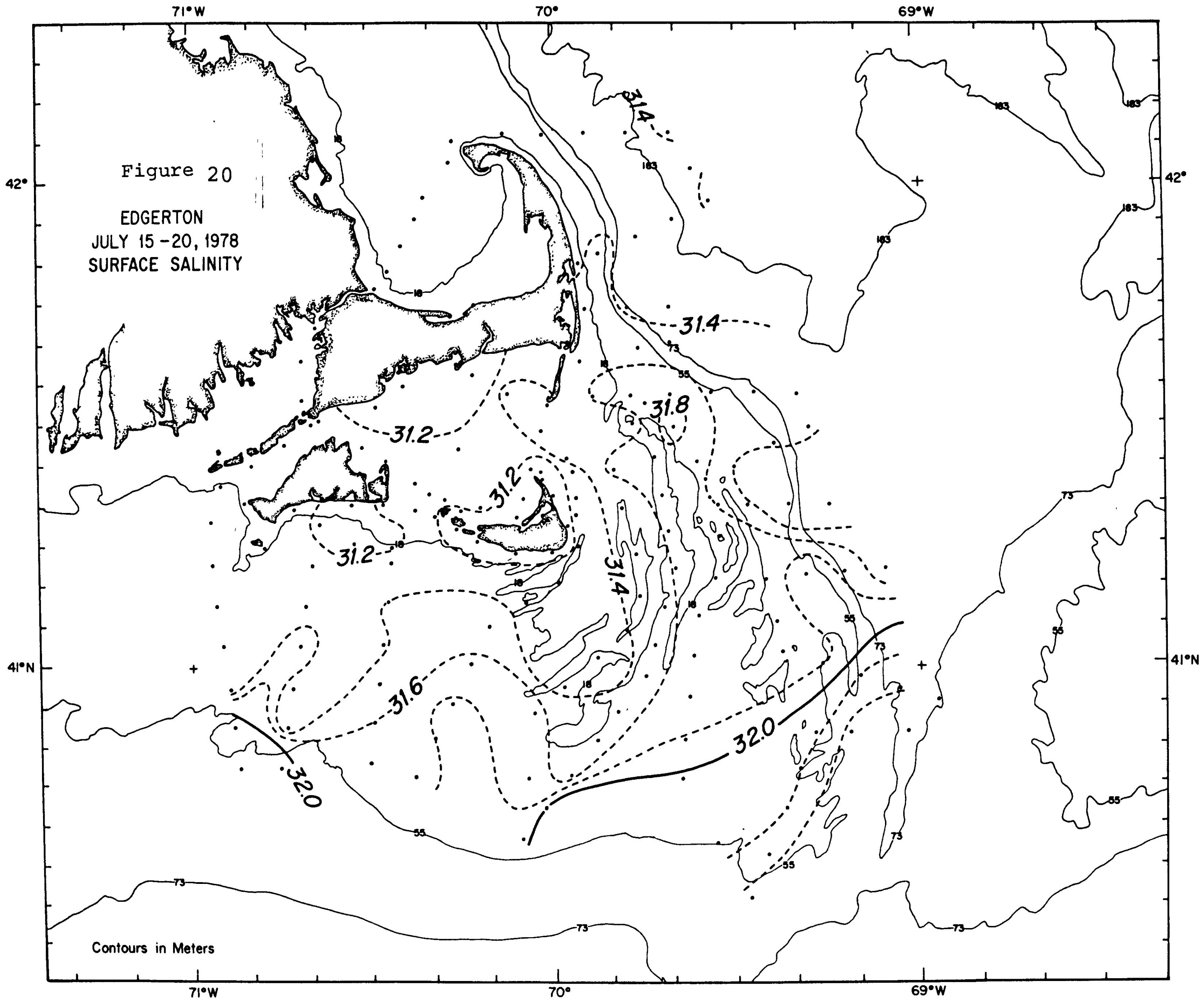


Figure 20

EDGERTON
JULY 15-20, 1978
SURFACE SALINITY

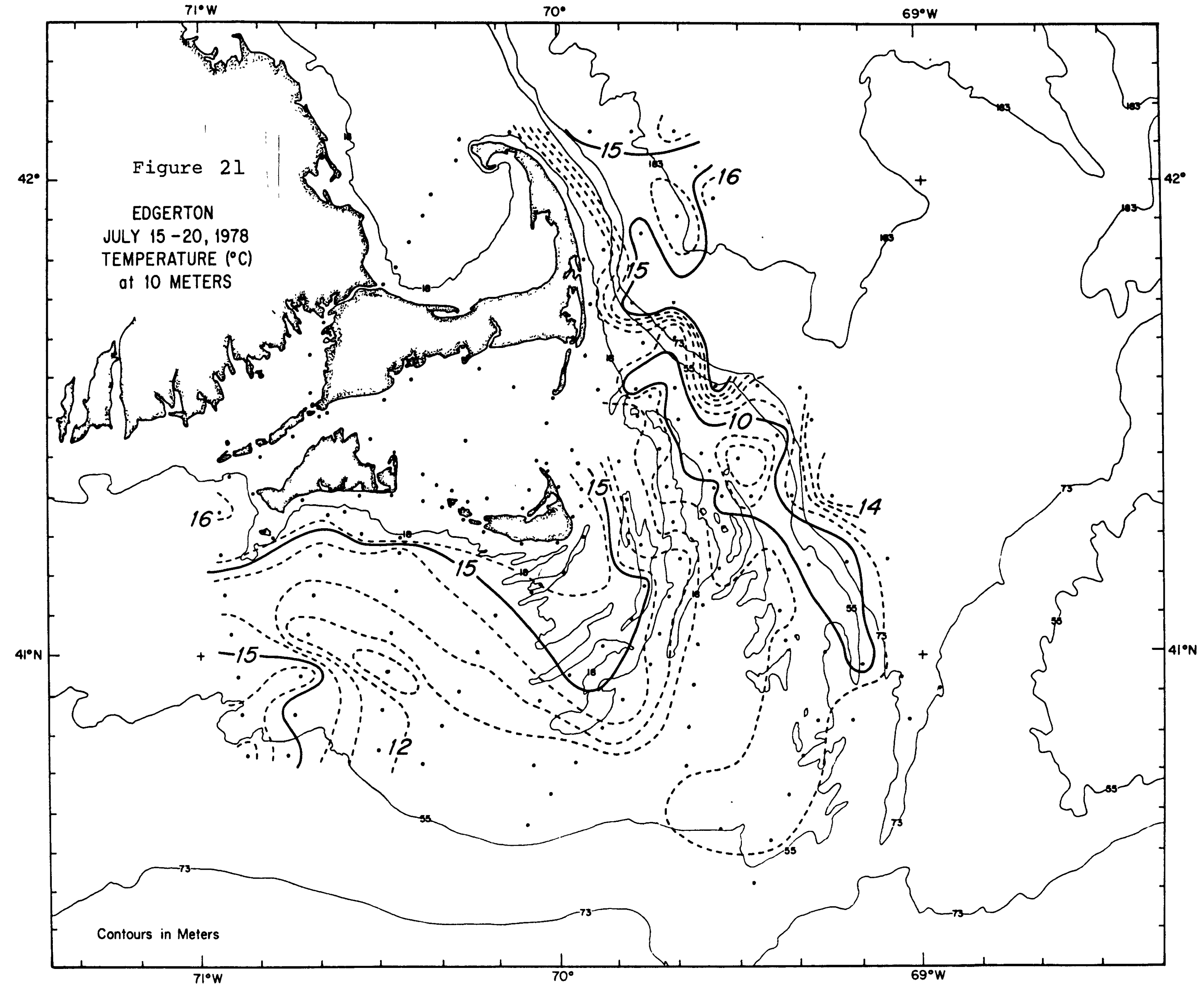


Figure 21

EDGERTON
JULY 15-20, 1978
TEMPERATURE (°C)
at 10 METERS

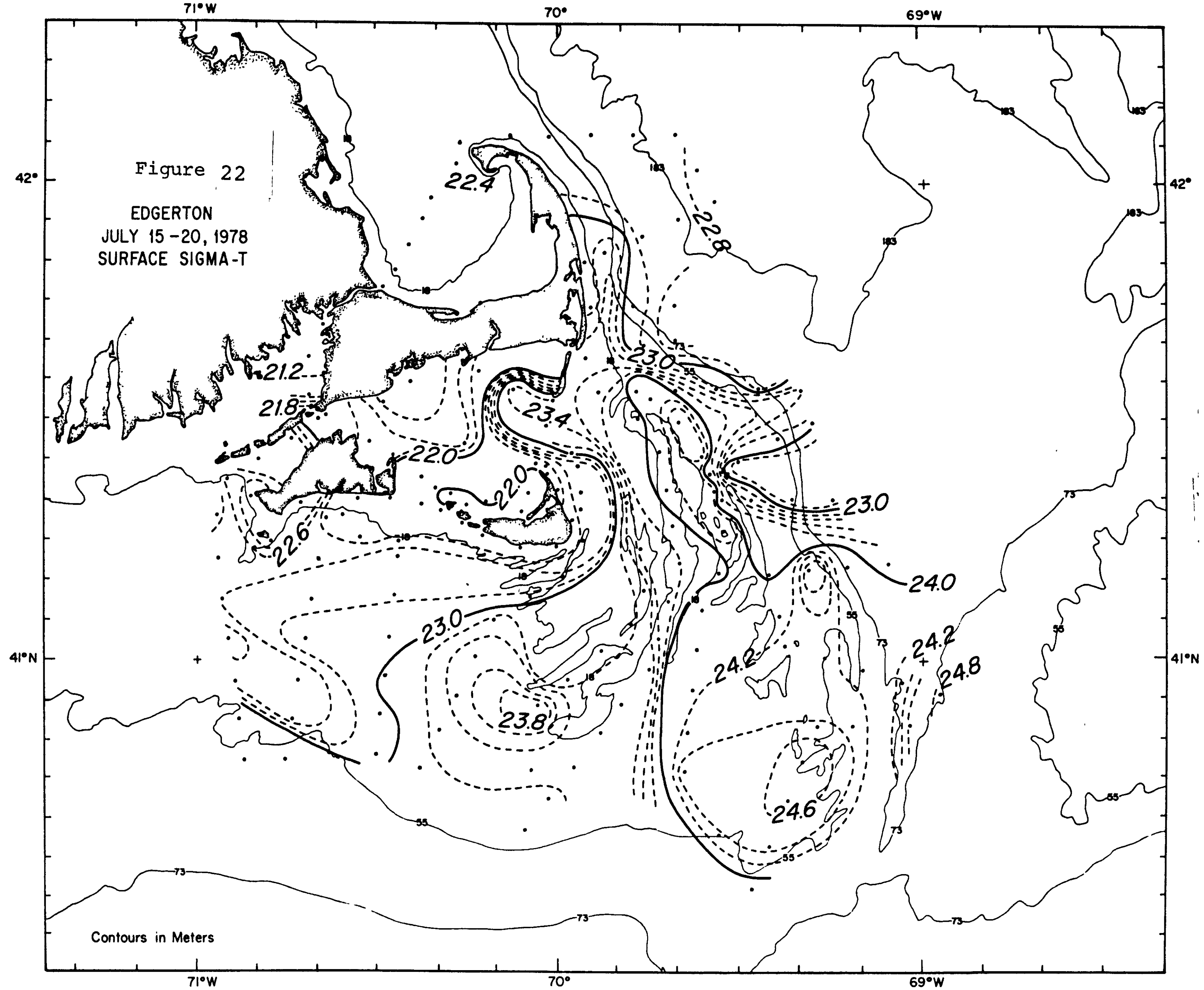


Figure 22

EDGERTON
JULY 15-20, 1978
SURFACE SIGMA-T

to sampling at different phases of the tide. The surface density in July shows denser water presumably of upwelling origin adjacent to the costline off Cape Cod. Thus, although the upwelling events appear stronger on the eastern edge of Nantucket Shoals, there is also evidence of upwelling off Cape Cod.

A.3 September, 1978

The surface temperature map for the September cruise (Figure 23) also shows a two-core upwelling zone along the eastern edge of Nantucket Shoals, which is similar in structure and location to the July upwelling pattern. The September surface salinity map (Figure 24) shows that the upwelled water was more saline than the adjacent warmer waters. The upwelled water also has similar T/S characteristics as the adjacent Gulf of Maine water (see Figure 16).

A.4 Winter, 1978-79

The November cruise was cancelled due to problems with ship scheduling and the January and March cruises were characterized by vertically mixed conditions in the upper 100 m due to convective overturning. Thus upwelling may still exist in winter, but no evidence is available in the winter hydrographic data.

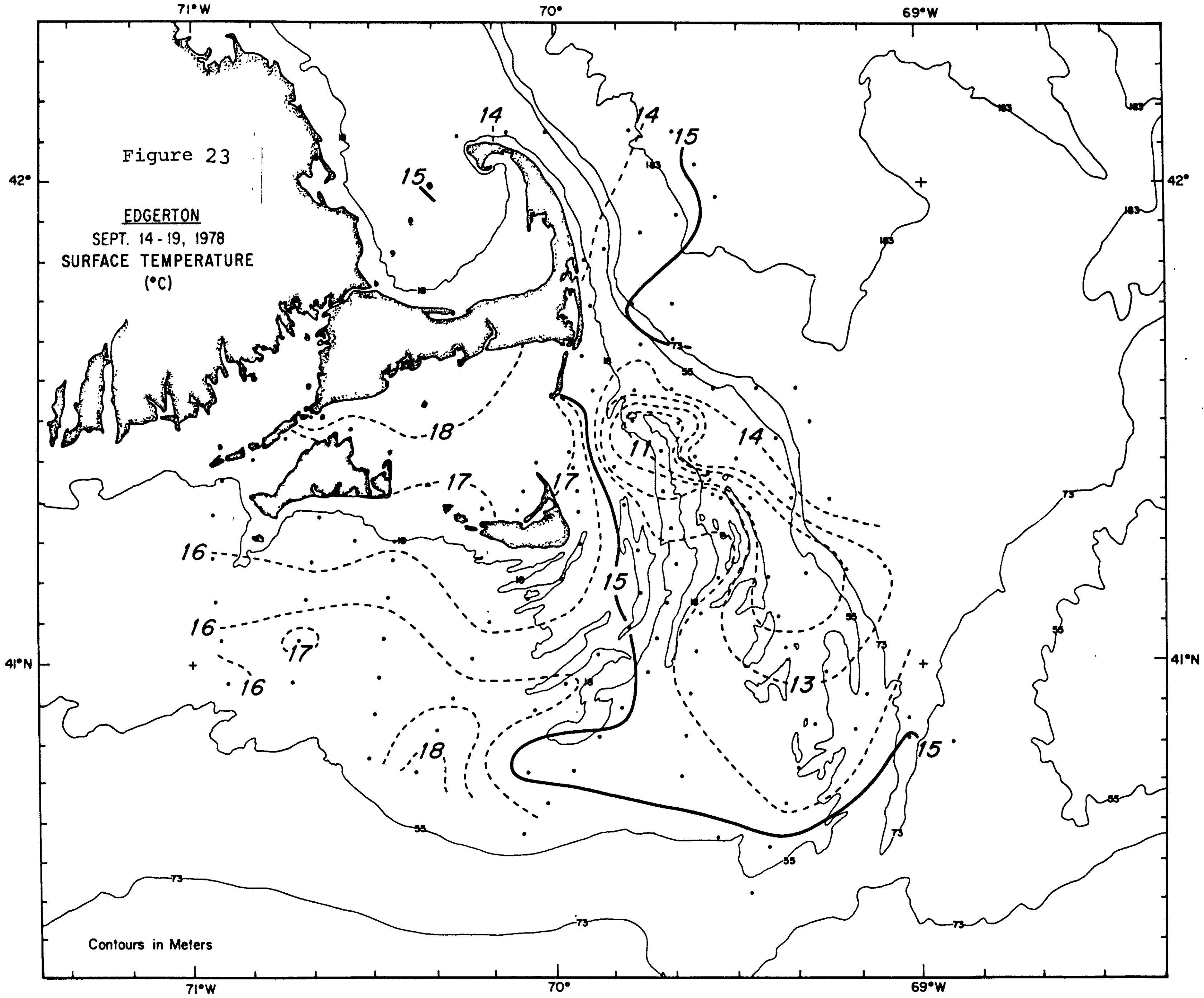
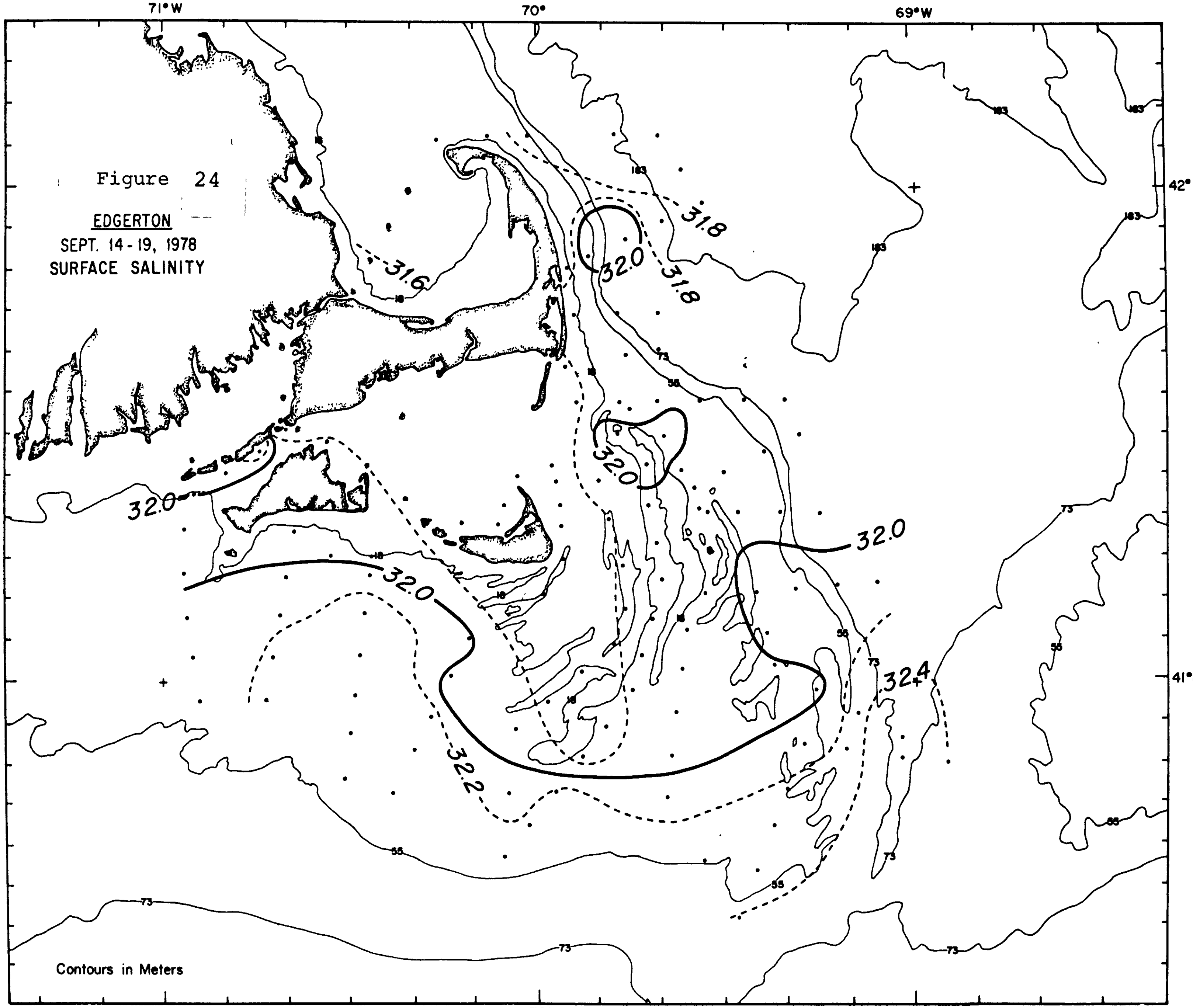


Figure 23

EDGERTON
SEPT. 14-19, 1978
SURFACE TEMPERATURE
(°C)

Figure 24



EDGERTON
SEPT. 14-19, 1978
SURFACE SALINITY
71°W
70°
69°W
42°
41°N
31.6
31.8
32.0
32.2
32.4
18
55
73
183
Contours in Meters

B. Tidal Mixing

Tidal currents are sufficiently strong over the shallower sections of Nantucket Shoals to vertically mix the local water column. Fifield (1977) has attempted with some success to predict the location of the front or boundary between the well-mixed and adjacent stratified water using the Qh/u_o^3 criterion developed by Simpson and Hunter (1974), where Q is the net surface buoyancy flux, h the local water depth, and u_o the local surface tidal current. The quantity QH/u_o^3 represents the ratio of the input of potential energy by surface heating to the dissipation of tidal kinetic energy through bottom friction; when Qh/u_o^3 is less than some approximately constant value, the water is well mixed. The spatial extent of the well-mixed water over the shoals and the seasonal fluctuation of the position of the front separating this water from the surrounding stratified water was not known in any detail prior to our hydrographic surveys.

Contour maps of the vertical sigma-t differences observed in each survey are presented in Figures 25 to 27. Here the difference between surface and bottom σ_t values is used to indicate the degree of local stratification. The $\Delta\sigma_t = .1$ contour is emphasized in these figures as the transition boundary between well-mixed ($\Delta\sigma_t < .1$) and more stratified waters. These maps show that water over much of the shoals was generally well-mixed. Superposition of these maps onto

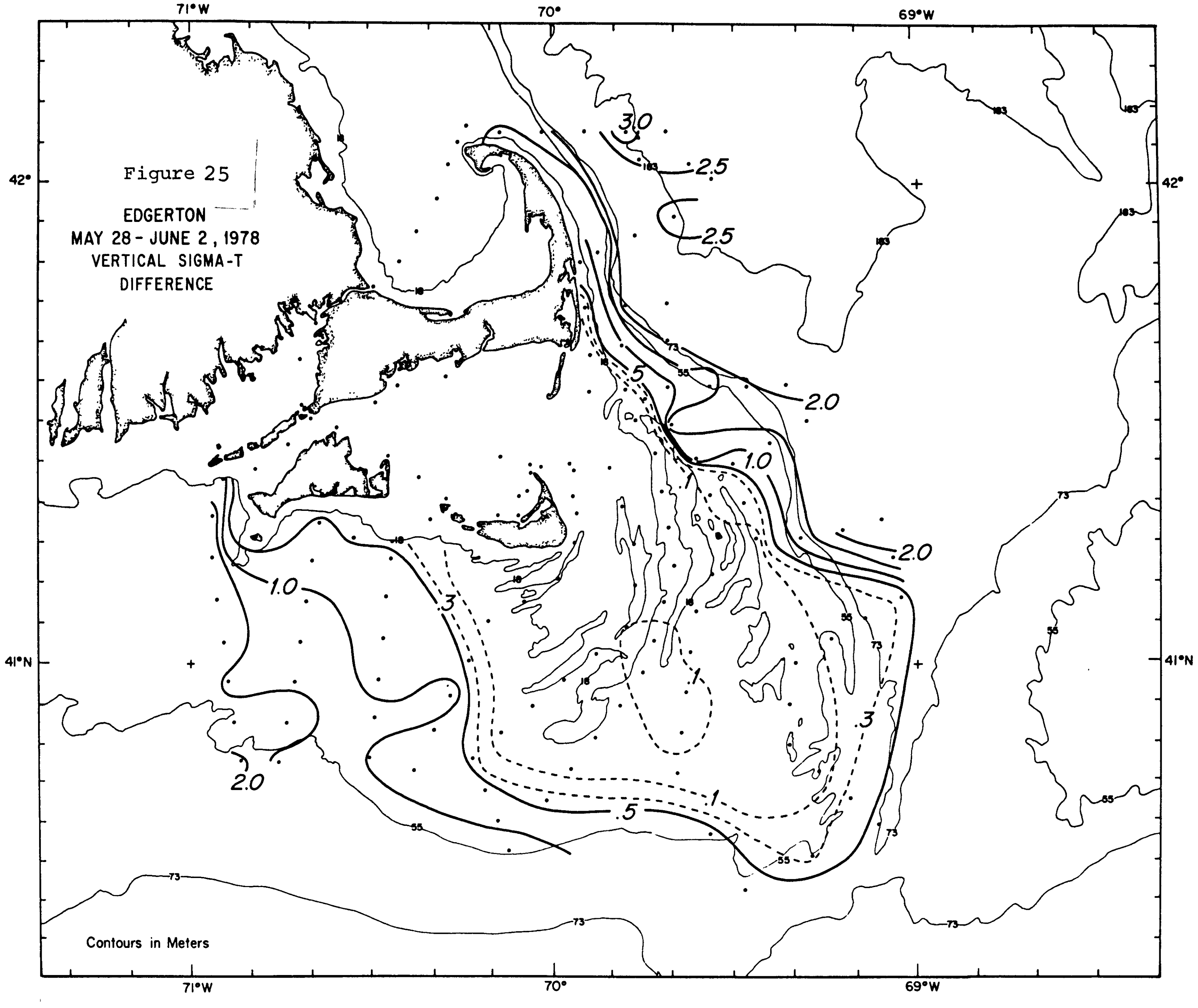
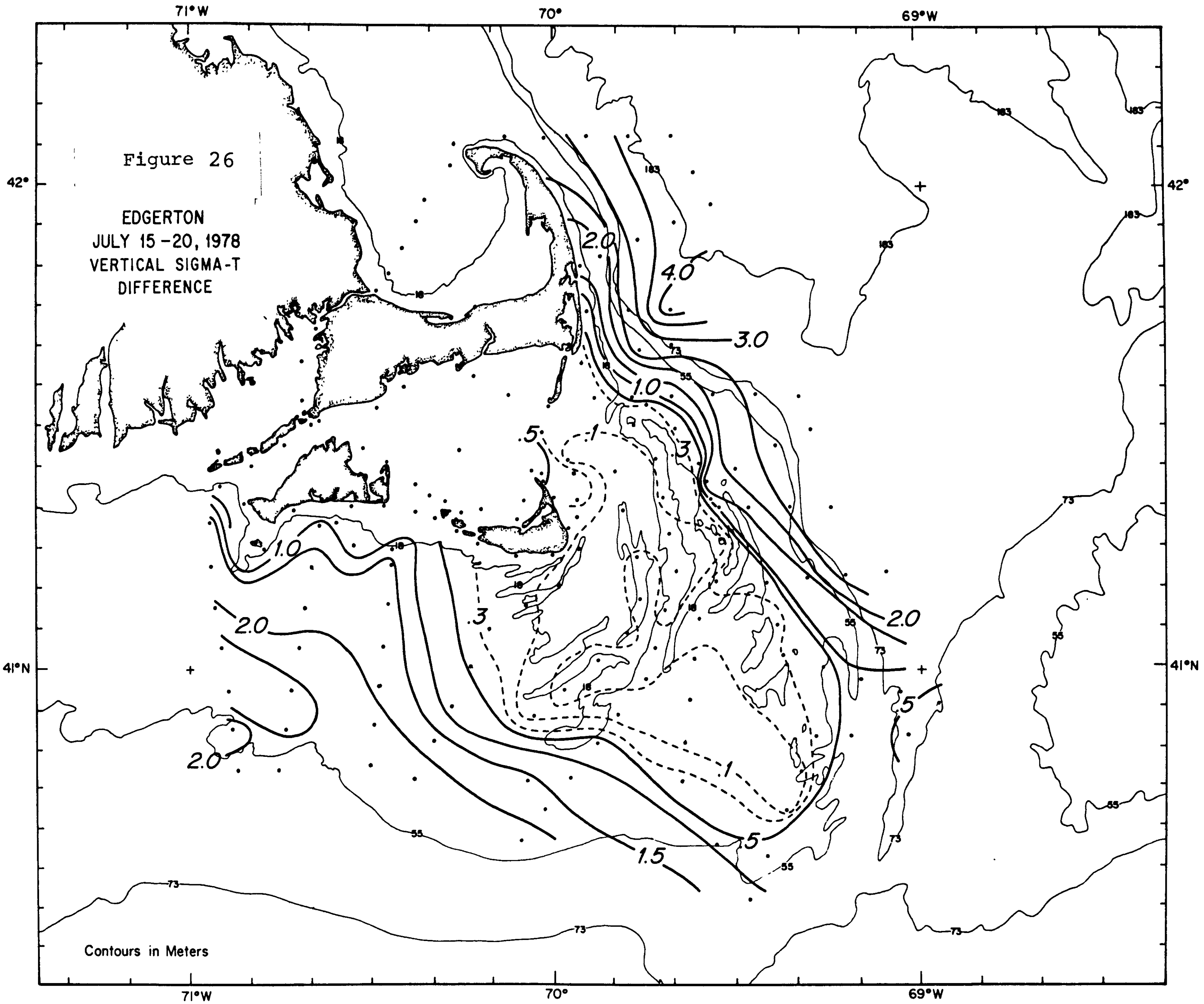


Figure 25

EDGERTON
MAY 28 - JUNE 2, 1978
VERTICAL SIGMA-T
DIFFERENCE

Figure 26



EDGERTON
JULY 15-20, 1978
VERTICAL SIGMA-T
DIFFERENCE

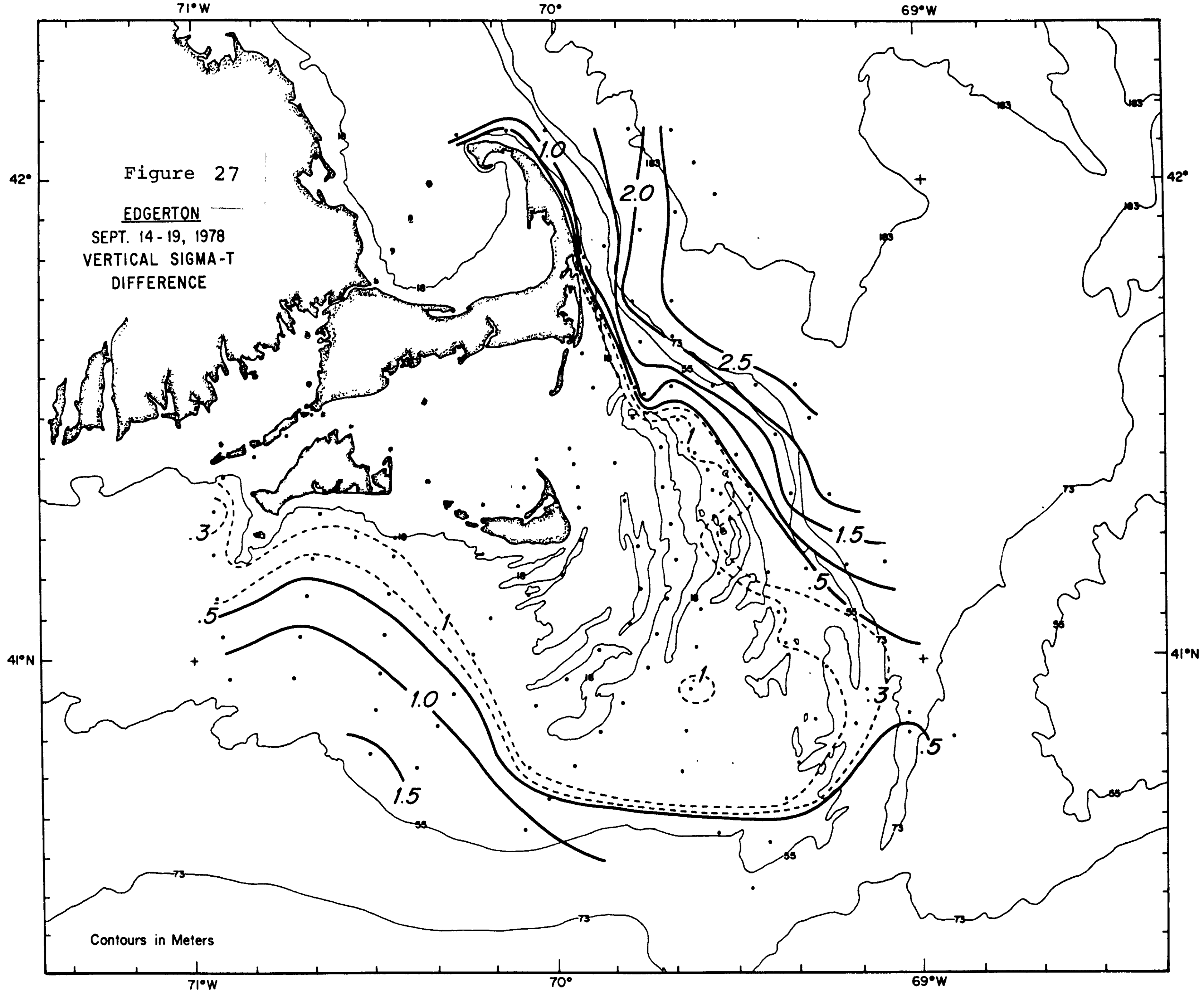


Figure 27

EDGERTON
SEPT. 14-19, 1978
VERTICAL SIGMA-T
DIFFERENCE

Contours in Meters

the surface T and S maps presented earlier shows that significant horizontal gradients in T and S occurred within the well-mixed zones. The core(s) of the upwelling usually occurred along or just outside the eastern boundary of the well-mixed zone. 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 σ_t difference found there.

While certain sub-areas of the shoals are always well-mixed, other areas (very near Nantucket and Chatham and along the eastern side of the shoals) become more stratified during July. Whether this is a consequence of an increase in Q in July is not yet clear. While tidal stirring is sufficient to keep some areas on the shoals locally well-mixed throughout the heating season, a conclusive quantitative test of the Qh/u_o^3 criterion will require a much more detailed map of tidal dissipation (or currents) in the Nantucket Shoals region than is presently available.

C. Water Mass Analysis

C.1. May, 1978

A T/S diagram is constructed by plotting the T and S values observed at a station on an x-y plot with S and T the x and y variables and measurement depth a parameter along the T/S curve. The T/S curve condenses into a single T/S point if the water column is locally well-mixed. The T/S diagram shown in Figure 28 is compiled from data taken during the May

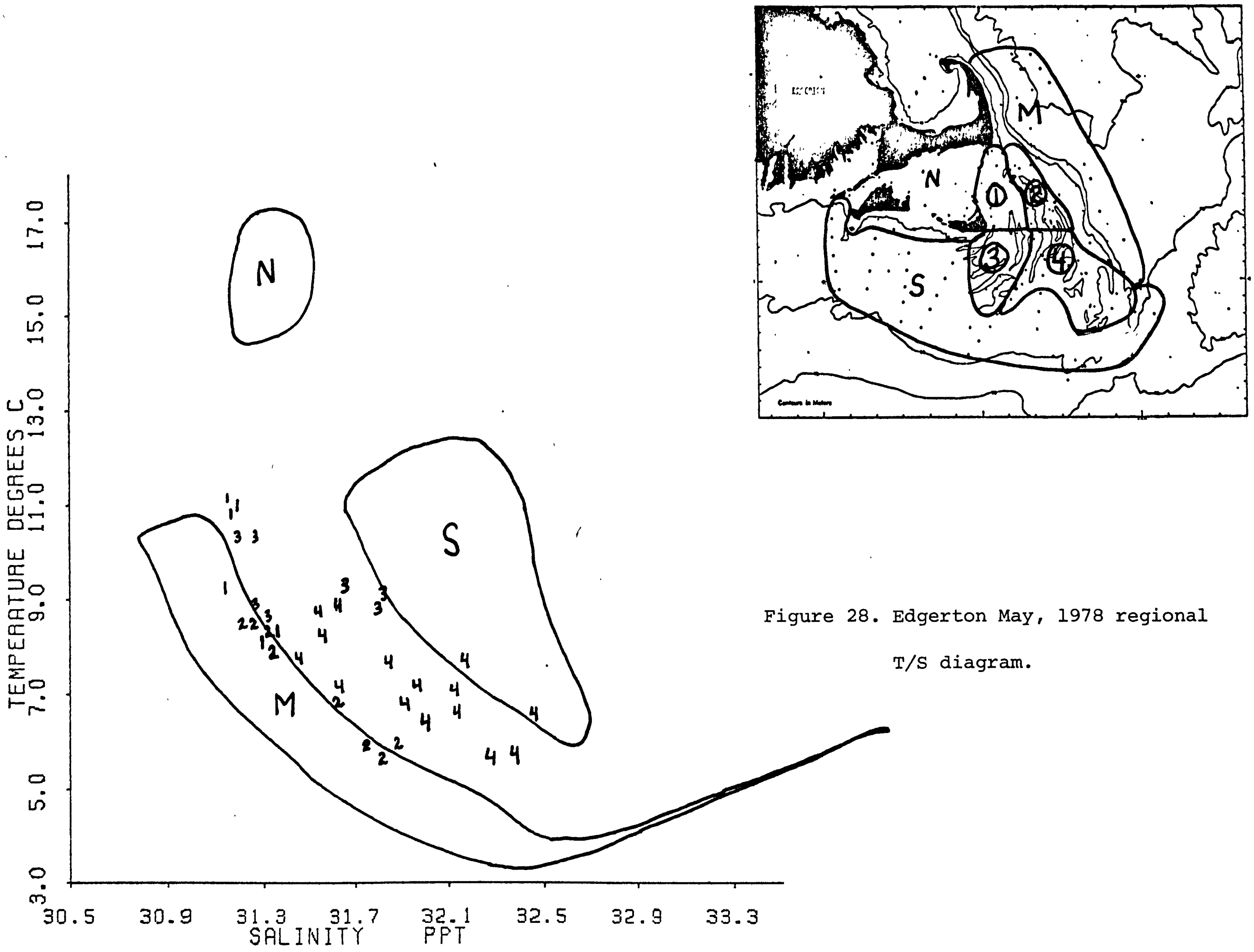


Figure 28. Edgerton May, 1978 regional T/S diagram.

cruise and illustrates how the T/S curves from local areas form into distinct groups indicative of different water masses. The Gulf of Maine water (M) is characterized by a temperature minimum at mid-depth and is quite distinct from the shelf water (S) found on the New England shelf south of Nantucket which is more saline at a given temperature than the Gulf of Maine water (M). However, shelf water is also found in the western side of the Great South Channel, suggestive of northward flow of shelf water through this channel or at least partial penetration.

Since the Gulf of Maine stations (M) are really located along the western boundary of the Gulf of Maine in a region which is dominated by river runoff and freshening of the water in the upper 40 m, one might just as easily say that the water in the region (S) on the T/S diagram (Figure 28) is simply Gulf of Maine water which has been warmed but not freshened. This could occur by asserting that the water in region (S) came from the Gulf of Maine in early spring before the freshwater runoff. As water flows southward offshore of Cape Cod some flow diverts to the east and flows along the northern edge of Georges Bank (Figure 7). In March this northeastward flow is simply MIW which has not been freshened by local runoff. This shelf water (S) exits the Gulf of Maine through the Northeast Channel in early spring as MIW, $T = 4^{\circ}C$ and $S = 32.4$. As the water (S) drifts to the southwest along the southern side of Georges Bank some warming and freshening occurs, but less freshening than the western Gulf of Maine stations. The shelf water flows to the southwest past Nantucket Shoals and also to the northeast through the Great South Channel, thus recirculating around Georges Bank. A T/S diagram from May, 1976 (Figure 29) across Little Georges Bank is shown with water to the north slightly fresher than the water to the south of Georges Bank. This demarcation is clear by the location of the vertically mixed stations on Georges Bank. An extensive survey of Georges Bank (EG&G, 1978) in May, 1978 shows water on the north and south sides of Georges Bank to be very similar in T/S properties with the shelf water (S) in Figure 28.

The water over Nantucket Shoals in May is divided into four geographical regions in Figure 27. Essentially the water in regions (1) and (2) is from the Gulf of Maine. The shoal water in regions (3) and (4) appears to be mostly a mixture of Gulf of Maine water (M) and shelf water (S). The water over the eastern edge of the shoals is dominated by cooler upwelled Gulf of Maine water modified by mixing towards the south with more saline shelf water (S) which has flowed north into the Gulf of Maine through the Great South Channel. The water found over the northwestern shoals (denoted by (1) in Figure 27) is more shallow Gulf of Maine water modified by mixing with Nantucket Sound water (denoted

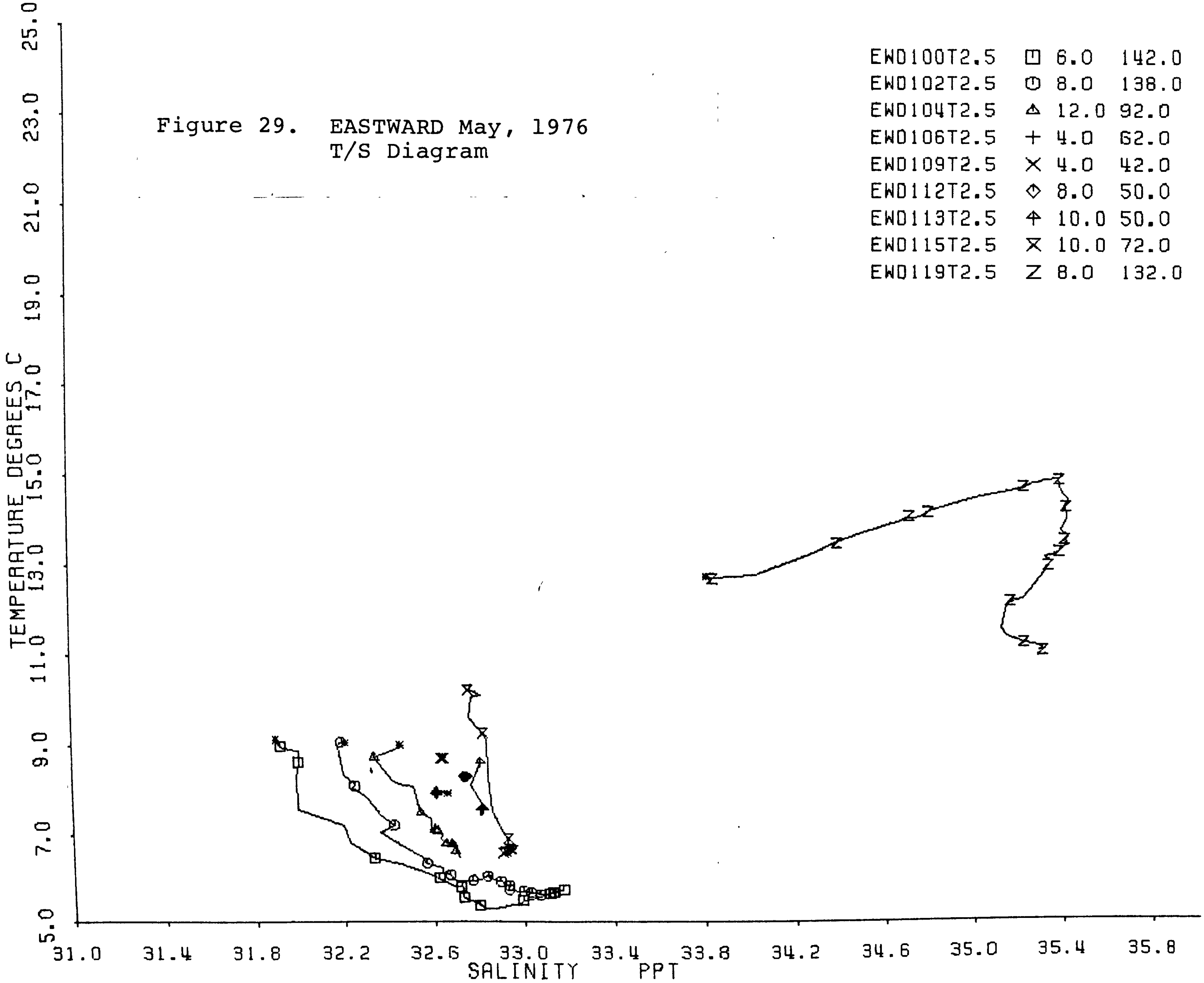


Figure 29. EASTWARD May, 1976
T/S Diagram

by (N) in Figure 28) flowing eastward and with shelf water along the southwestern edge of the shoals. Thus, the water found over Nantucket Shoals in May was primarily upwelled Gulf of Maine water dominating the northern and eastern shoals, and a mixture of upwelled Gulf of Maine water and shelf water dominating the southern and western shoals.

C.2 July, 1978

The T/S diagram for the July survey (shown in Figure 30) again indicates two distinct water masses, Gulf of Maine water (M) and shelf water (S) surrounding the shoals to the north and south respectively. Water over both eastern and western shoals was dominated by upwelled Gulf of Maine water and little mixing was evidenced with the more saline shelf water along the southern edge of the shoals. The water found over most of the inner shelf west of the shoals (denoted by (M')) is similar in the upper part of the water column to Gulf of Maine and shoal water and to a mixture of shelf and Gulf of Maine water in the lower part of the water column. This T/S diagram suggests either a stronger flow of Gulf of Maine water across the shoals or significantly less mixing of shelf water over the shoals and shelf to the west of the shoals in July.

C.3 September, 1978

The T/S diagram for the September survey is shown in Figure 31. The Gulf of Maine water and shelf water were the

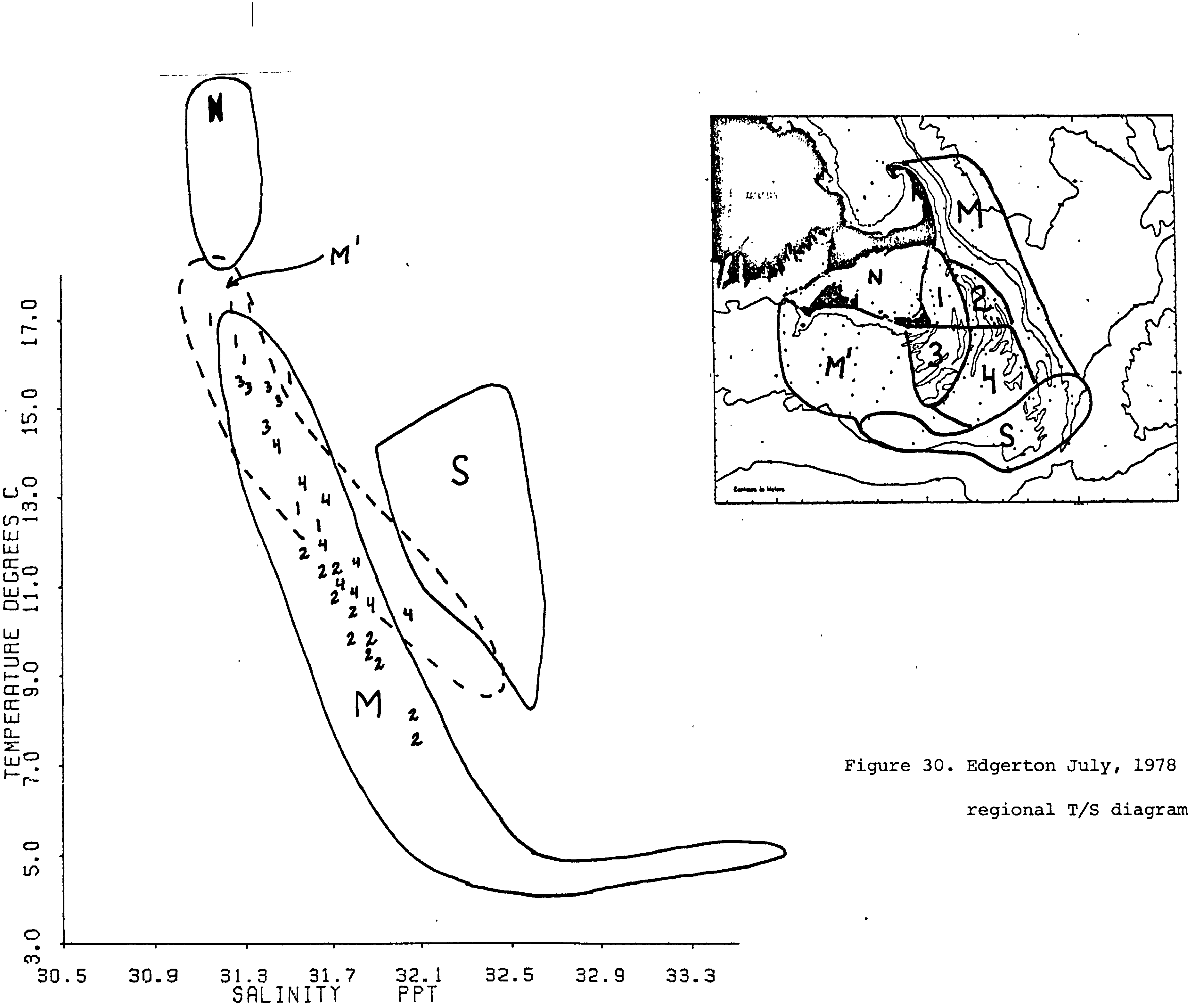
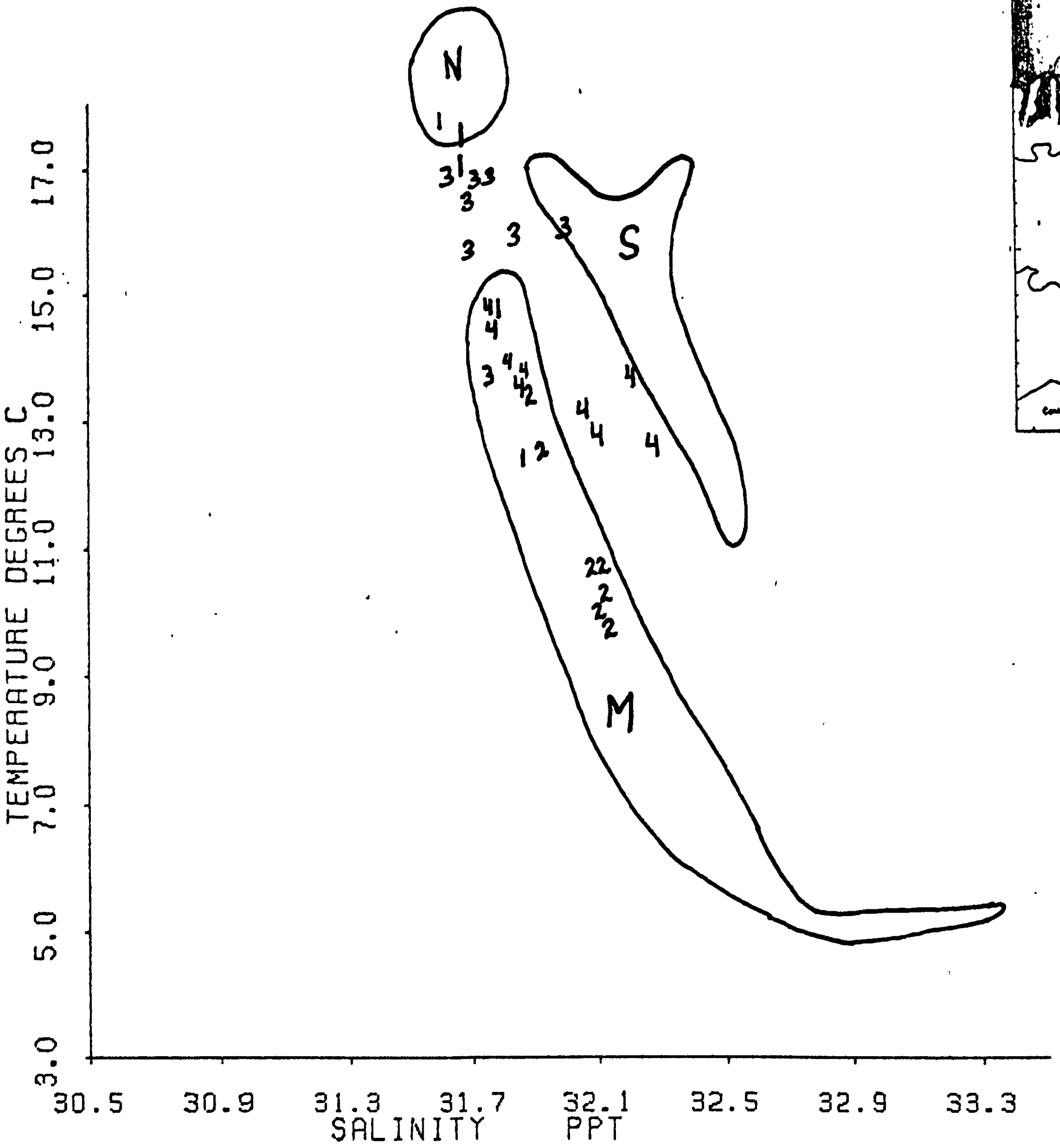


Figure 30. Edgerton July, 1978 regional T/S diagram.



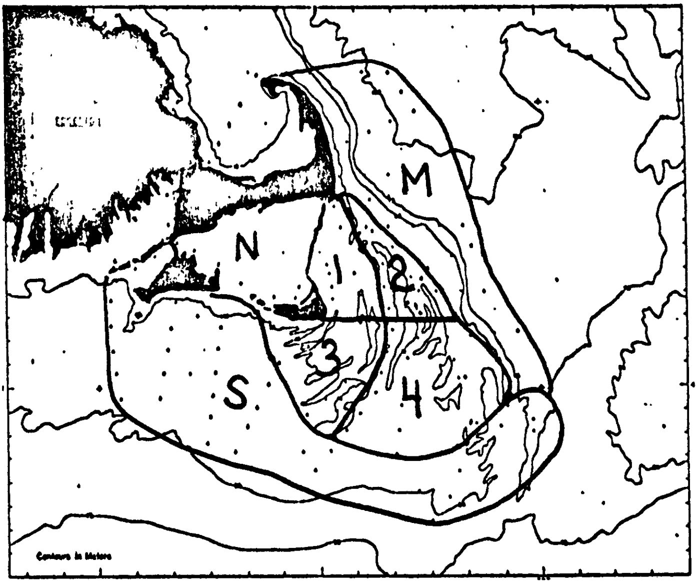


Figure 31. Edgerton September, 1978 regional T/S diagram.

two main surrounding water masses, with the latter filling the shelf south and west of the shoals. While some mixing of shelf and upwelled Gulf of Maine water was observed along the southeast edge of the shoals, the water found over the shoals originated in the Gulf of Maine, both at depth in the upwelling cores and near surface elsewhere. A mixture of Gulf of Maine and Nantucket Sound waters are found very near Nantucket Island. The mixing of Nantucket Shoals water and shelf water (S) occurs only on the southern and southeastern edge of the shoals.

Thus in the first three surveys, we find that water over Nantucket Shoals is dominated by the flow of both near surface and upwelled water from the Gulf of Maine. This water is then usually mixed with shelf water along the southern and western edge of the shoals. These T/S diagrams demonstrate that the surrounding water masses are distinctive and that we can infer some of the flow properties over and around the shoals by the T/S characteristics of the water found over the shoals.

D. Winter Hydrography, 1979

Two winter hydrographic cruises were completed January 23-29 (NS4) and March 22-26 (NS5). Initial CTD stations in the Gulf of Maine indicated constant temperature and salinity values in the upper 100 m due to a surface buoyancy flux and convective overturning. The water column from 100-200 m increased 1°C in temperature and approximately 0.3 ‰ in salinity for stations in the Gulf of Maine. All of the stations over the shoals (depths <40 m) were well mixed during the two winters cruises and surface samples were taken in place of CTD casts.

The surface temperature, salinity, density, and T/S diagrams are given in Appendix A for both winter cruises. These maps are considered to vertically characterize the entire survey area except for the water below 100 m at stations in the Gulf of Maine. The water temperatures were less than 1°C in the vicinity of Nantucket Sound and Buzzards Bay in January. By mid-February large areas in Nantucket Sound, Buzzards Bay, and over Nantucket Shoals were covered with ice. The shoals and Nantucket Sound in January were 1 ‰ more saline than the previous May. The Gulf of Maine stations 40 km east of Race Point were > 2 ‰ more saline than the previous surface May values. These higher salinities in winter are due to the surface cooling and deep convective overturning with more saline deep water in the Gulf of Maine. The T/S diagram for January is characterized by a relatively tight correlation for the region. The coldest and freshest stations were found in the shallow areas of Nantucket Sound.

In March the mean temperature over the shoals was colder than in January, but the salinity distribution appears quite similar. The T/S diagram shows a general shift of 1.3°C lower in March than January for a given salinity, except in Nantucket Sound which has begun to reflect early spring warming. The warming and freshening of the surface water in the Gulf of Maine was not apparent in our March survey.

IV. Tidal Currents

The tidal currents at locations greater than 10 km offshore the New England coast change direction continuously. Such currents are called rotary currents. The typical rotary tidal currents in the Nantucket Shoals region (Haight, 1942) are shown in Figure 32. The current changes direction in a clockwise sense. This Eulerian measurement is in the opposite sense as a Lagrangian tracer which would measure a counterclockwise drift of a passive tracer. In Figure 32 the tips of the arrows represent velocity and direction at the beginning of each hour and thus define an ellipse. Bumpus (1975) has summarized Haight's (1942) tidal data by showing the tidal ellipses over Georges Bank and Nantucket Shoals in Figure 33. The numbers next to each tidal ellipse represent the sum of hourly speeds (Kt) over a 12-hour period, an approximation of the distance traveled by a parcel of water during that time. These distances range from 4.8 to 19.4 miles over the shoals with the greater

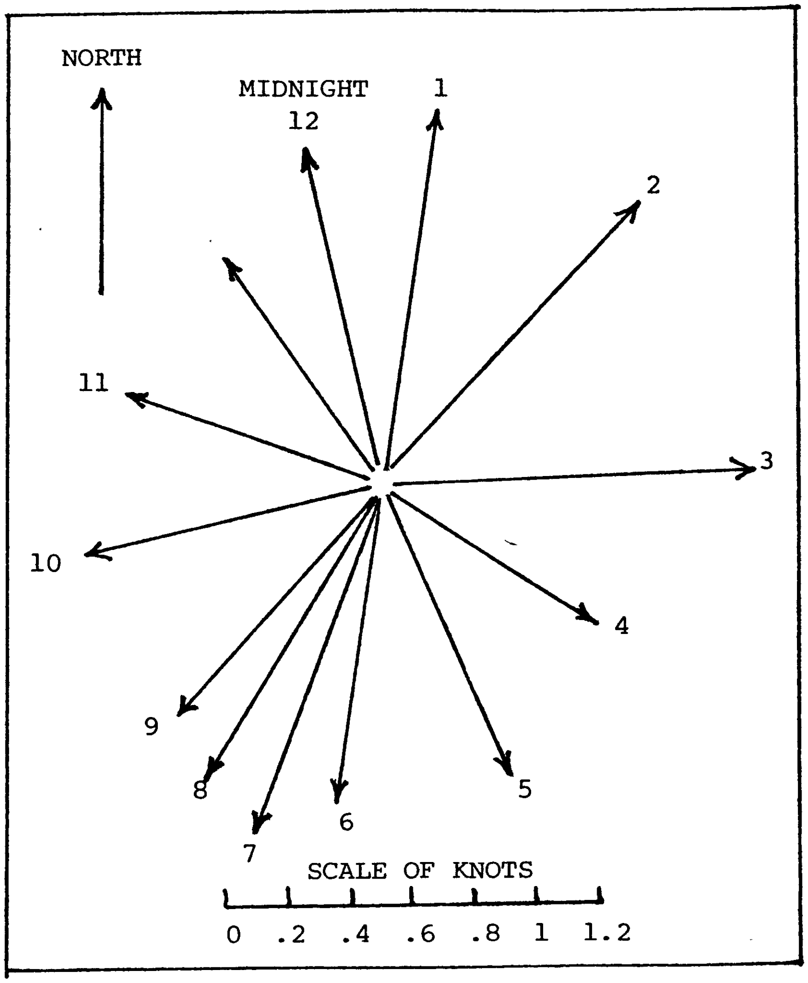


Figure 32. Rotary currents, Nantucket Lightship, forenoon of July 30,1922 (Haight,1942).

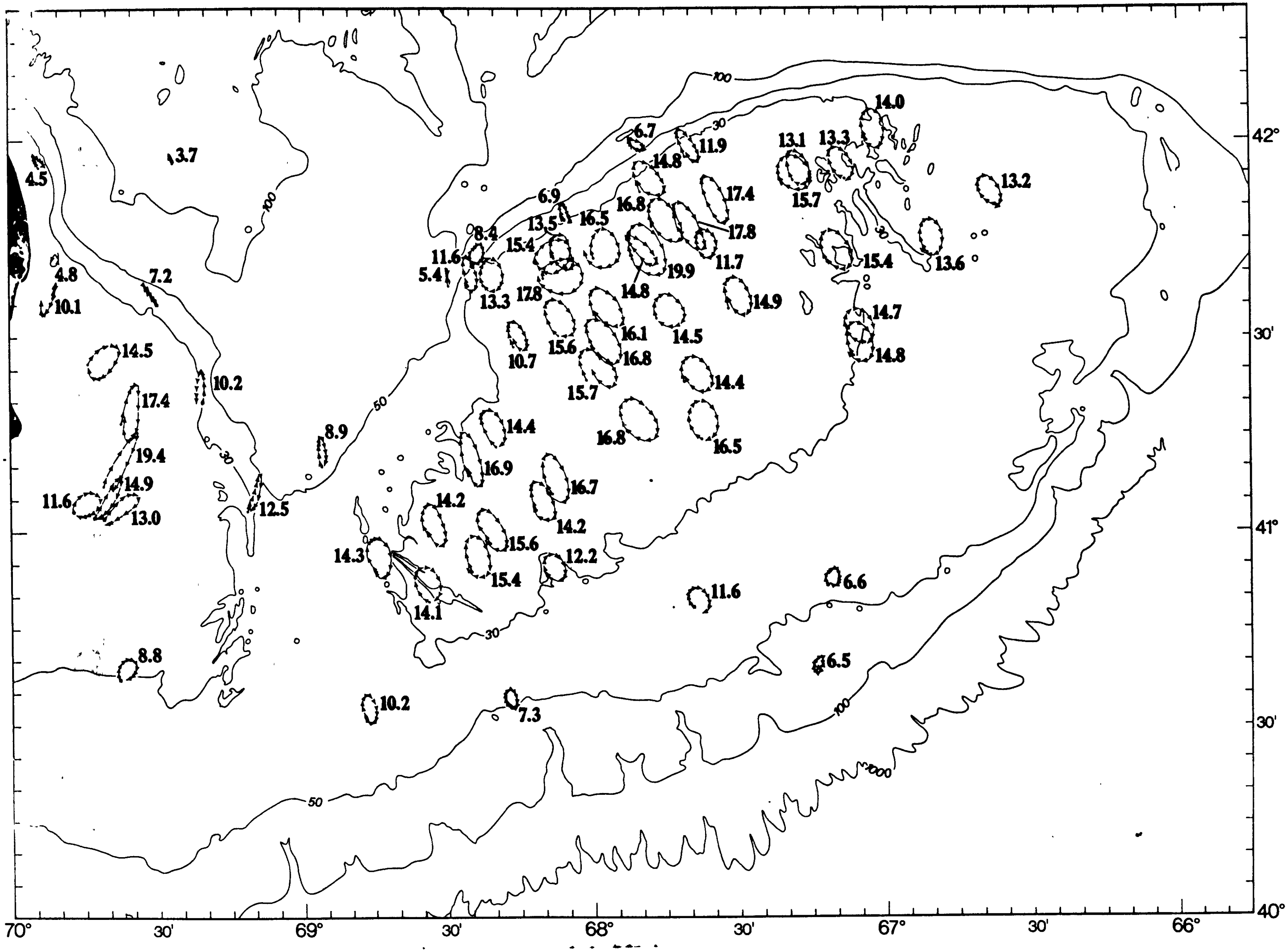


Figure 33. Progressive vector diagrams of tidal oscillations on Georges Bank drawn to chart scale (Bumpus, 1975).

distances over the more shoal water. One measurement made 25 miles east of Nantucket indicated a tidal ellipse which changed direction in a counterclockwise sense. Butman's (personal communication) post ARGO MERCHANT current meter record from this general location indicates a clockwise change in the tidal current ellipse.

Redfield (1953) discussed the idea that a tidal wave approaches Nantucket Sound from the west through Vineyard Sound and also from the east between Great Point and Monomoy Island. As the two waves propagate in opposing directions, regions of interference are observed when the two waves are out of phase off Nobska Point, Muskegat Channel, and over Nantucket Shoals to the immediate southeast of Nantucket Island as in Figure 34. The offshore extent of this interference pattern is presently not known.

V. Discussion

A. Winds

An understanding of the circulation about Nantucket Shoals is assumed to be dependent upon meteorological forcing as well as the mean flow characteristics of the Gulf of Maine and continental shelf. The local winds can be characterized by their variability which can be averaged to give a mean windstress, but this average value is usually different from the observed windstress.

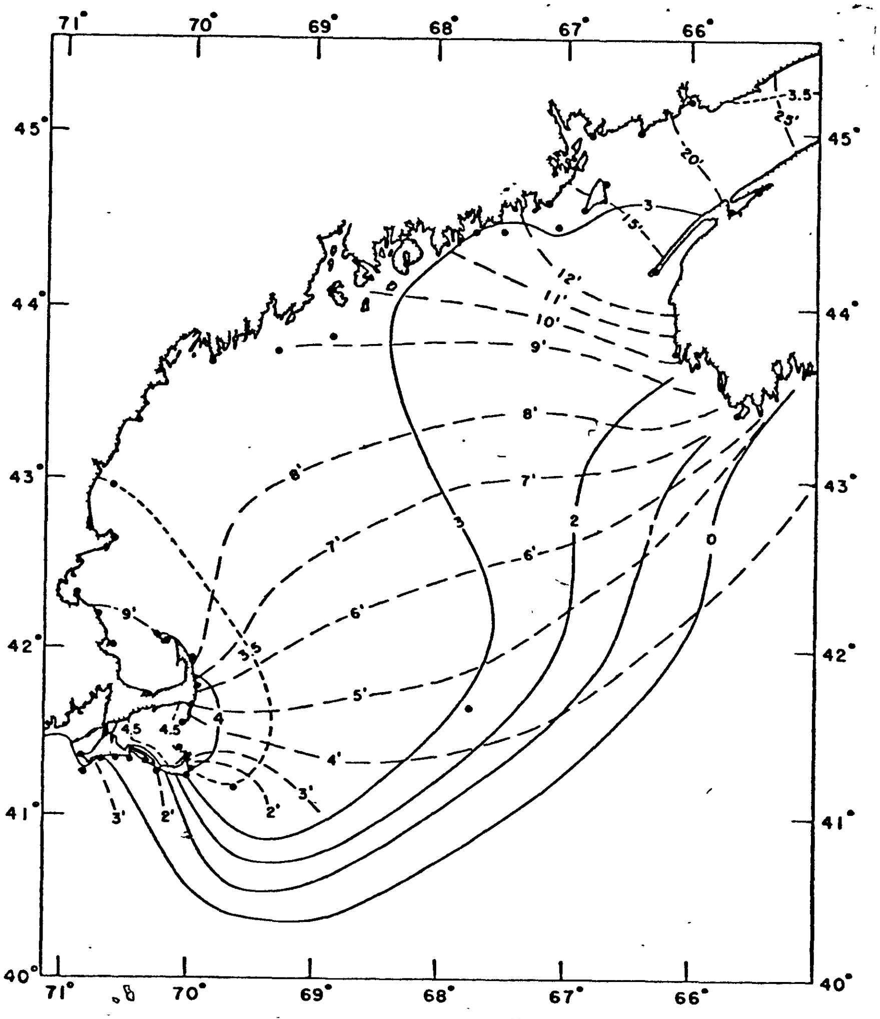


Figure 34. Cotidal and corange lines for the Gulf of Maine. Mean times of high water shown by continuous and broken lines in lunar hours relative to moon transit at Greenwich. Mean range of tide shown by dashed lines in feet (Redfield,1953).

The windstress prior to the first hydrographic survey, May 27-June 2, 1978 is shown in Figure 35 for Chatham, Massachusetts and for the Nantucket Shoals light vessel (located at Station 56 in Figure 12). The windstress was derived using

$$\tau = \rho C_D U|U|$$

where ρ = density, $\overline{U}$ the measured wind velocity, and C_D a drag coefficient with $C_D = 1.2 \times 10^{-3}$. Winds are recorded every three hours by the National Weather Service in Chatham. The two windstress measurements agree reasonably well and there appears to be a slight increase in the magnitude of the surface stress offshore at the lightship. May was characterized by northeasterly winds on May 5 and May 14, and strong southerly winds (5 dynes/cm^2) on May 9. The winds at other times during the month of May were light and variable. Just prior to the May cruise the winds were from the northeast, a condition which would not be advantageous to inducing upwelling in the classical sense of an offshore Ekman transport.

The monthly mean windstress in the Nantucket Shoals region is given in Table 3 from 19 years of ship data in the NODC files. Westerly winds throughout the year tend more northwest in winter and southwest in summer. Figure 36 shows

Figure 35. Windstress at Chatham and Nantucket Lightship

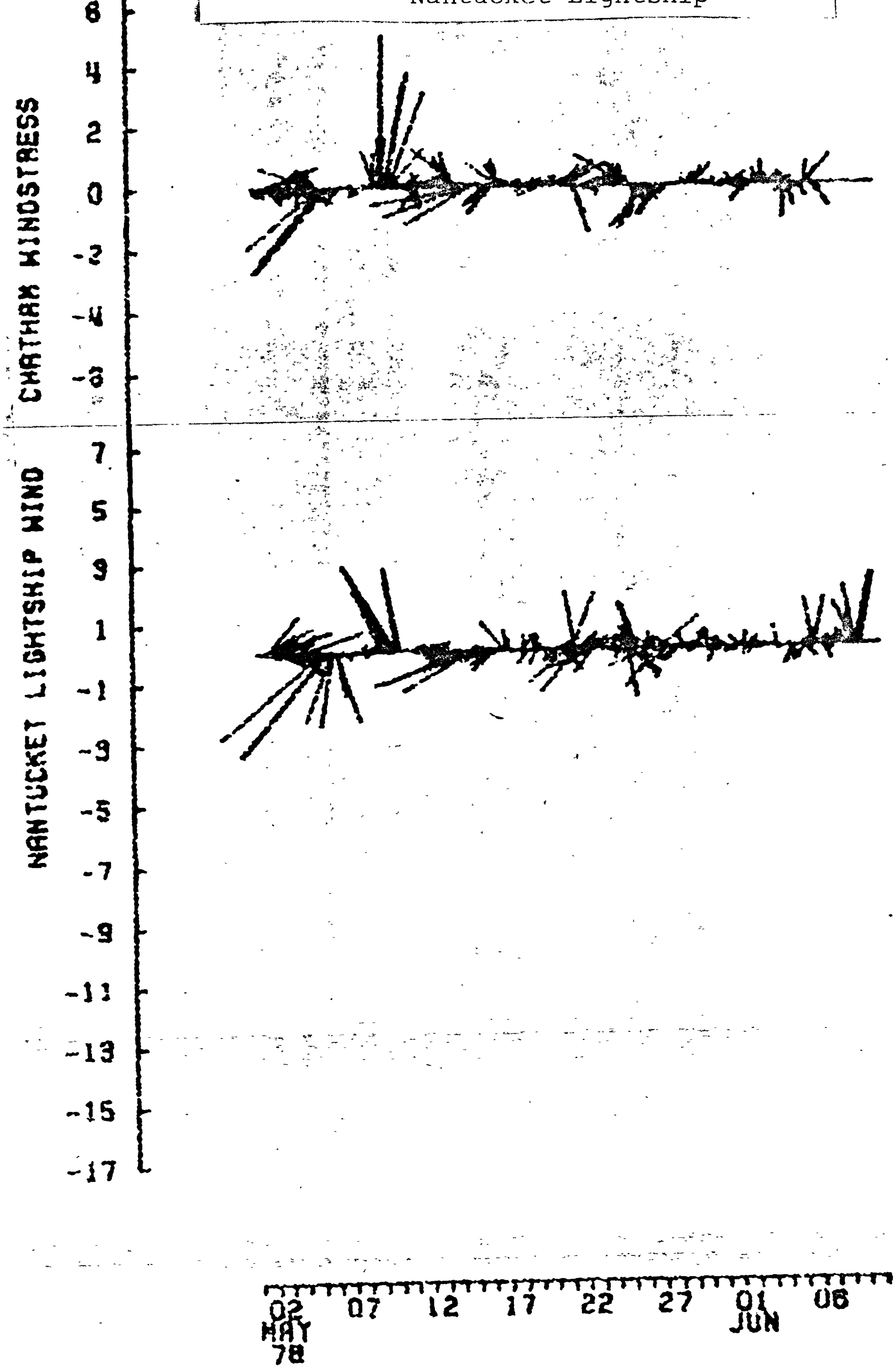


Table 3

Monthly Mean Windstress for the Nantucket Shoals Region

MEAN WINDSTRESS (PASCALS)

	J	F	M	A	M	J	J	A	S	O	N	D
EAST COMPONENT	.15	.14	.03	.05	.01	.02	.01	.02	.01	.04	.06	.08
NORTH COMPONENT	-.09	-.05	-.14	.00	.01	.02	.01	.05	-.02	-.12	-.02	-.10

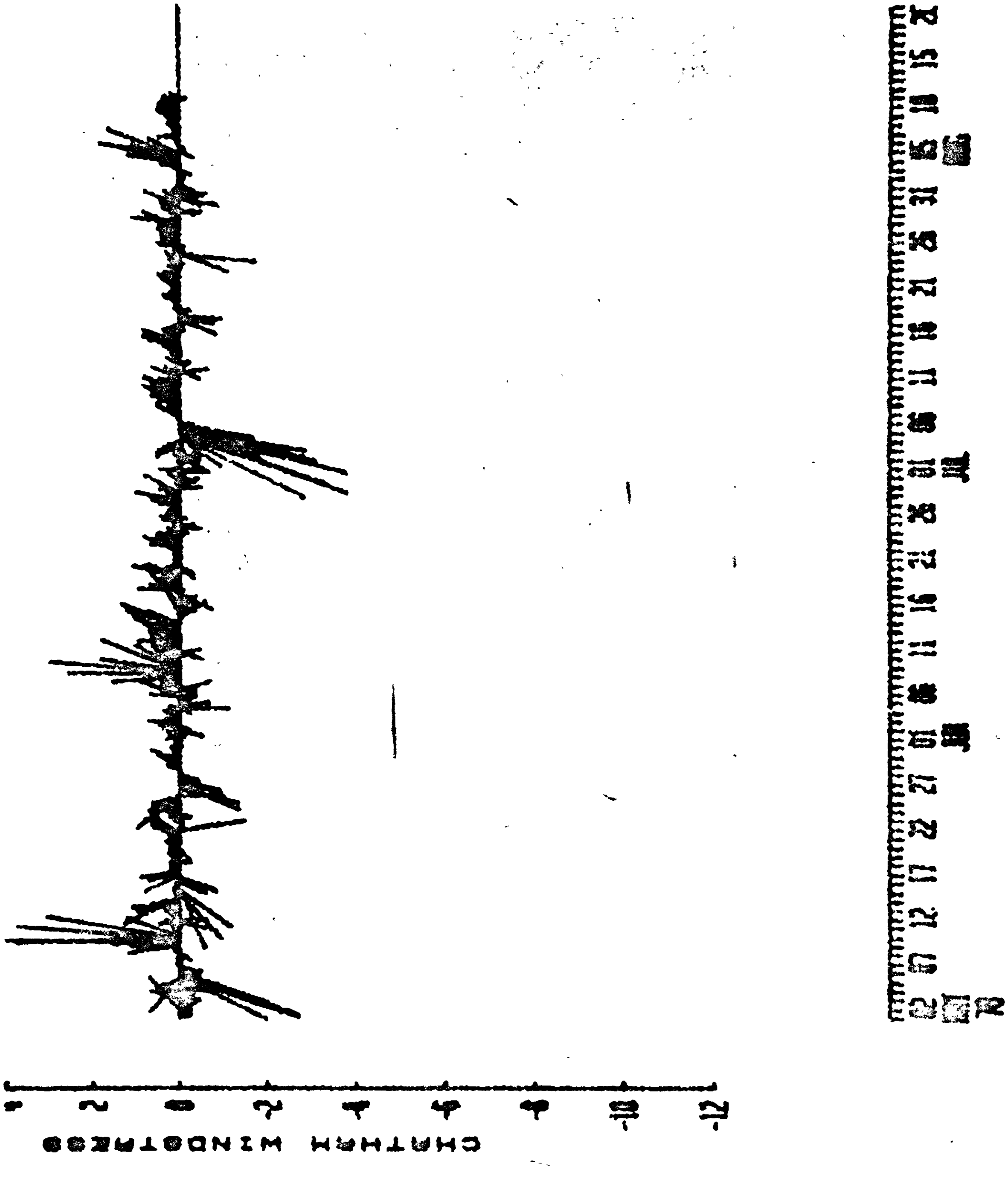


Figure 36. Windstress at Chatham, May-August, 1978

the windstress calculated from the Chatham observations for the period May to mid-August, 1978. The record appears to be dominated by moderate southwesterly winds, but northerly winds are evident every week and four major windstress events characterize the summer observations. The second hydrographic survey, July 15-20, took place after a period of moderate southwesterly winds which would presumably favor upwelling. The third hydrogdraphic survey experienced 25 knot southerly winds during the time the upwelling was observed over the eastern edge of the shoals.

The winter windstress at the Nantucket Lightship shows a marked increase in magnitude over the summer windstress as well as an increase over the values observed at shore stations. The dynamical significance of the winter offshore increase in the windstress is not understood at present. Figure 37 is shown to demonstrate that although winters are characterized by strong northwest winds, January was characterized by strong northward stresses. In contrast, February was dominated for a period of three weeks by a steady, cold northwest wind. These February winds were less variable than any other period during the preceding 10 months.

B. Regional Heat Fluxes

The annual heat exchange cycles for the North Atlantic have been calculated (Bunker, 1976) using bulk aerodynamic equations and exchange coefficients which vary with wind

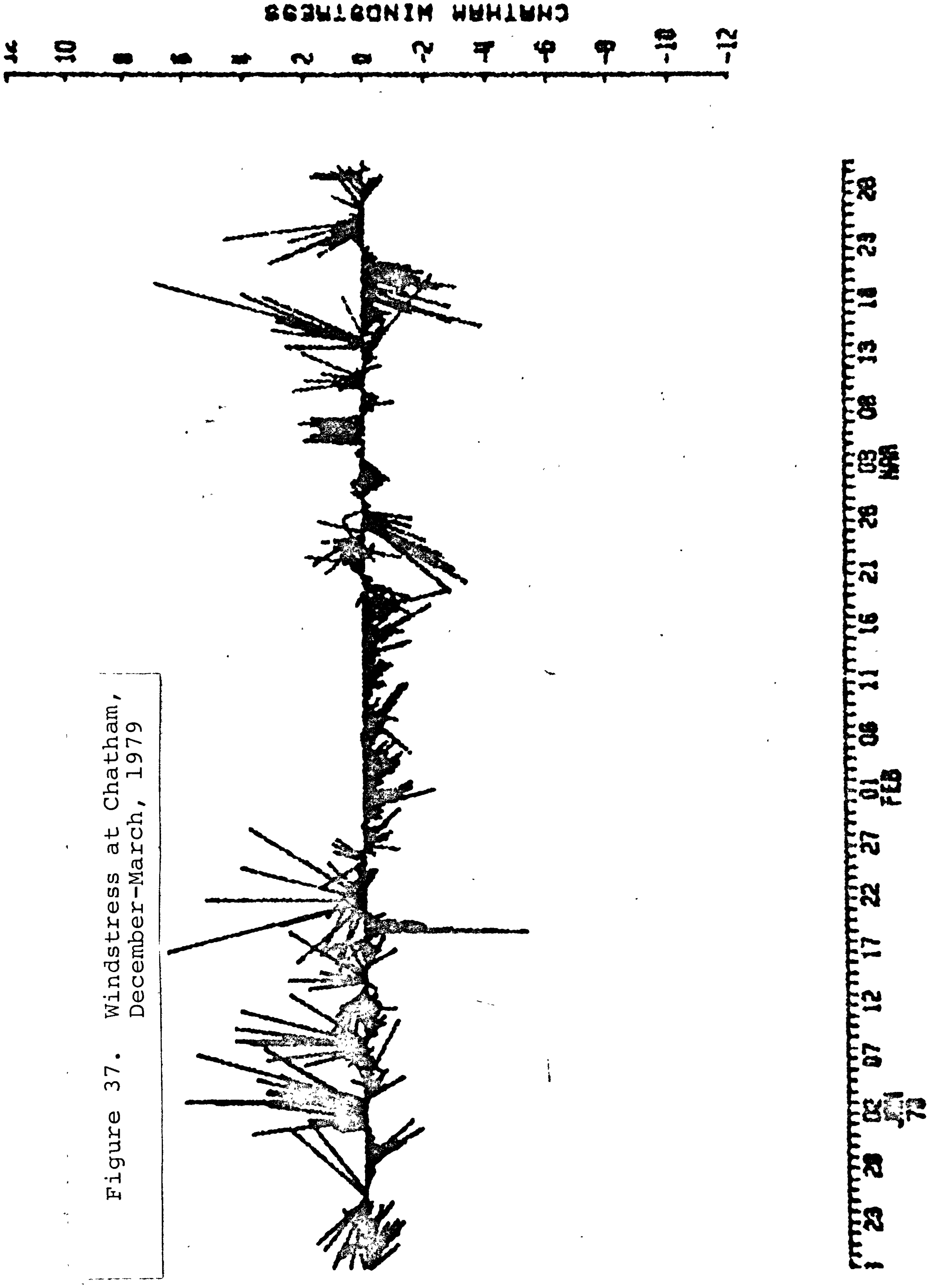


Figure 37. Windstress at Chatham, December-March, 1979

speed and stability. Figure 38 summarizes the monthly averages of the various energy fluxes for the one degree square 41-42N, 69-70W which generally covers Nantucket Shoals and the Gulf of Maine. The net radiational exchange R has been defined as

$$R \equiv Q(1-\alpha) - IR$$

where the amount of radiation absorbed is given by $A(1-\alpha)$, α is the albedo of the ocean which varies with solar altitude and cloudiness. IR is the infrared radiation. The net heat gain by the ocean, A, was computed from

$$A = R - LE - S \text{ (Watts/m}^2\text{)}$$

L represents the latent heat of evaporation, E the average exchange of water vapor, and S represents sensible heat. In Figure 38, 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 of about 60% LE. In summer the winds decrease and become warmer and more moist decreasing the latent heat flux and the sensible heat flux becomes positive. The largest heat flux to the Gulf of Maine in summer is due to a radiant energy flux. The winter hydrography gives an opportunity to compare the winter 1978-1979 heat flux in the Gulf of Maine to the mean winter

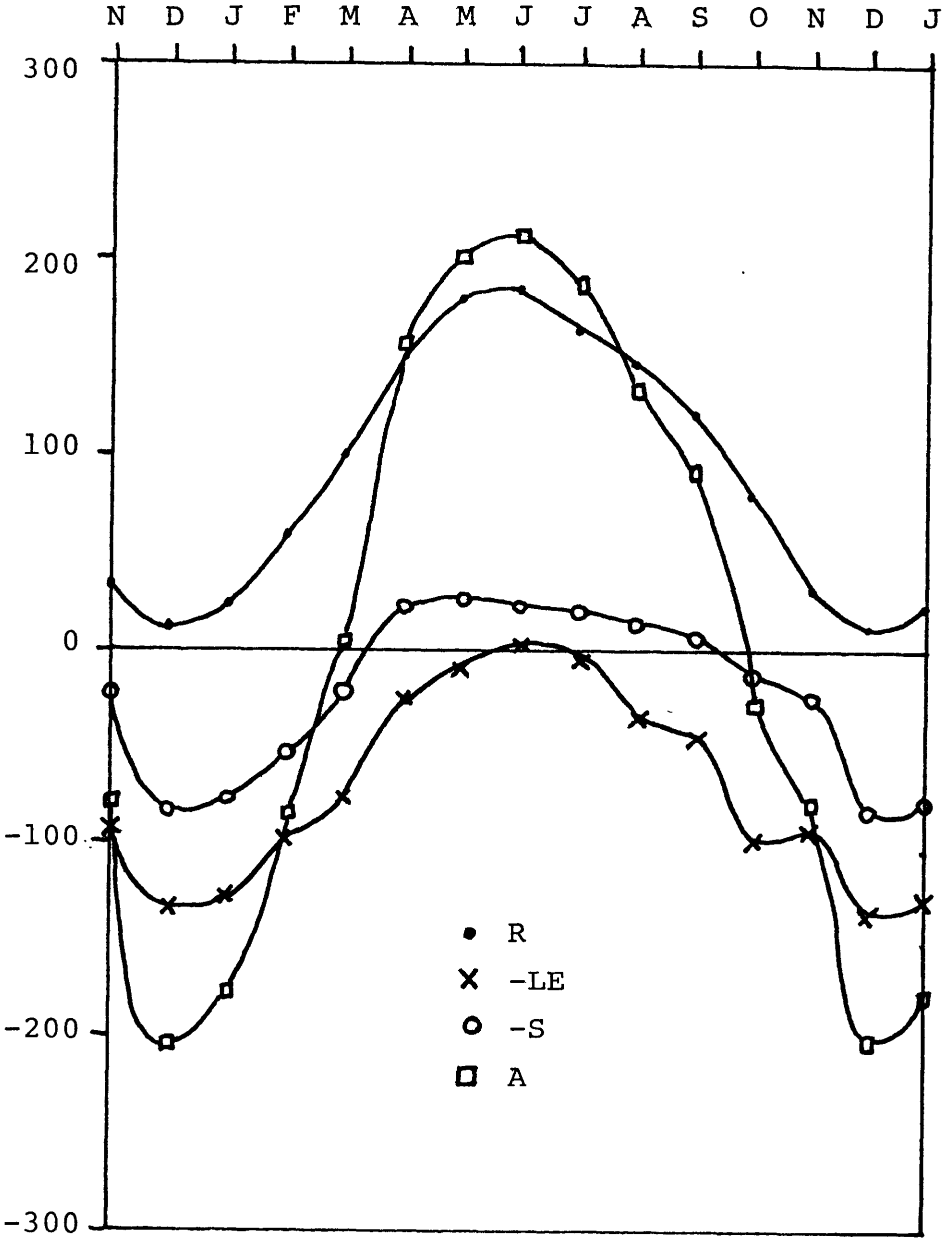


Figure 38. Annual heat exchange cycles (watts/m^2) for the one degree square 41-42N, 69-70W.

values calculated from historical data. The January and March T/S correlations (Appendix A) show a decrease in temperature of about 1.3°C for stations in the Gulf of Maine in 200 m of water. A heat flux can be calculated by integrating

$$\rho C_p \frac{DT}{Dt} = -\nabla \cdot Q$$

over the water column and ignoring the advective terms. Q is the heat flux across the sea surface. One may assume a ΔT = 1.3°C over a depth of 200 m to occur mostly during the three week period in February when strong northwest winds, cold air temperatures, and clear nights characterized the weather. This gives a -573 Watt/m^2 heat flux to the southwestern Gulf of Maine over a three week period. Thus a variation of 2 to 3 times the mean heat flux values can be expected in winter. A different interpretation which seems less plausible is that the heat flux is normal, but colder water has been advected into the region. The intense February heat loss should have a decided effect of depressing the temperature minimum of the Gulf of Maine water in the summer of 1979.

Figure 39 shows the net annual results of one degree square energy flux calculations for the entire Gulf of Maine. The offshore region to the southeast is dominated by a net negative heat flux to the ocean due to the advection of

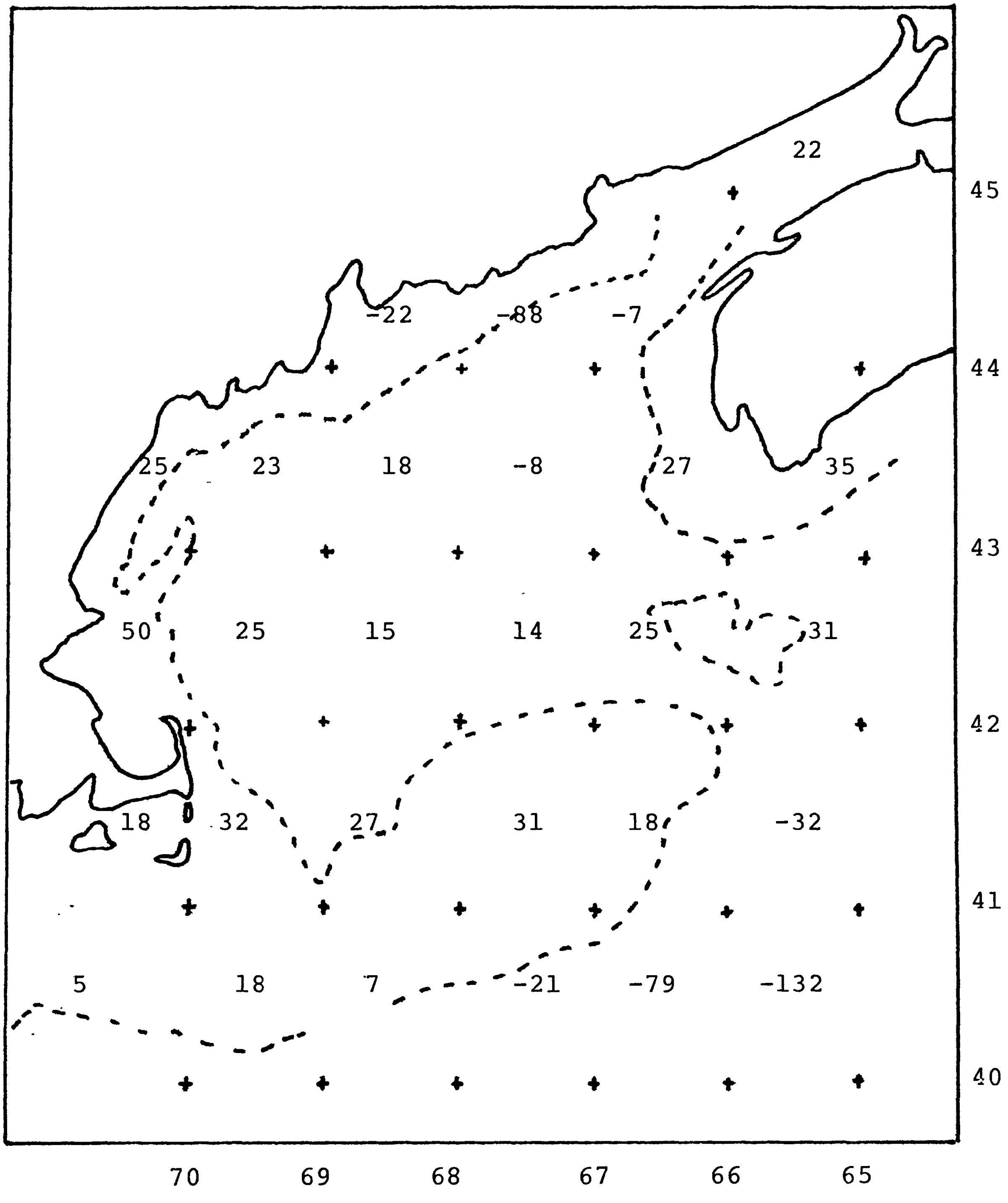


Figure 39. Annual net heat flux to the ocean (Watts/m^2) from NODC data base (Bunker, 1978. Unpublished Manuscript).

water from a source region where the water is approaching thermal equilibrium to a region off Georges Bank where the warm water is far from thermal equilibirum with its environment, especially in winter during periods of cold northwesterly winds (Bunker, 1976). For a steady state to exist in regions with a negative heat flux, the water entering the region must have a higher mean temperature than the water exiting in the region. Over the shoal areas of Browns Bank, Georges Bank, and Nantucket Shoals a slight maximum (>30 Watts/m^2) is observed. This is clearly related to the upwelling events on Nantucket Shoals and the relationship may be more obscure for the offshore banks. Thus the heat flux calculations imply cold water flooding Nantucket Shoals must gain heat before advecting off the shoals. Also of interest in Figure 39 is the negative annual flux between Yarmouth, N.S. and Portland, Maine. Warm surface temperatures in this region in winter create large latent heat fluxes. The relatively warmer surface temperatures may be related to upwelling off Nova Scotia (Garrett and Loucks, 1975) and advection in the Gulf of Maine gyre. The high positive heat flux south of Cape Ann can be related to wind-driven upwelling in this region.

C. Temperature and Salinity Variability

To understand the non-advective variability in temperature and salinity in the water over Nantucket Shoals requires a knowledge of the net precipitation-evaporation and net surface heat flux. Then the observed T/S variability can be related to surface precipitation and warming. Bunker (1978, unpublished manuscript) estimates a net heat gain for the one degree square 41°-42°N. 69°-70°W of 32 Watts/m^2. Precipitation was measured at the National Weather Station in Chatham and evaporation was calculated from the monthly mean latent heat fluxes. A depth of 40 m over the shoals was assumed and Table 4 summarizes the calculated changes in temperature and salinity and the observed changes. During the 11 month period from May 1978 - March 1979 a net precipitation-evaporation of 36 cm was measured. The variability between the calculated dT/dS and that observed is assumed to be consistent with a net annual heat flux to the shoals and the advection of cooler upwelling Gulf of Maine water over the shoals in summer. The cooler observed temperature over the shoals in winter can be related to the advection of cold (winter) Nantucket Sound water over the shoals, an overestimation of the depth in certain regions over the shoals, and the fact that instantaneous heat fluxes on the shoals can be very different from the 19-year mean values used in the calculations. The observed increase in salinity was very different from the predicted salinity decrease due to excess precipitation. The interpretation is that the colder upwelled water is more saline, and advection

Table 4

ΔT and ΔS Calculated from Meteorological Data and Measured from Ships on Nantucket Shoals

	Calculated		Observed	
	ΔT°C	ΔS‰	ΔT°C	ΔS‰
May-Jul 1978	5.4	-.08	5	+0.2
Jul-Sep 1978	3.5	-.04	1.5	+0.3
Sep-Jan 1979	-6.8	-.08	-11	+0.8
Jan-Mar 1979	-1.3	-.04	- 1	+0.2

and mixing more than compensates for the precipitation. In winter deep convective overturning in the Gulf of Maine brings more saline deep water to the surface. Surface salinity values offshore of Race Point in May were <31 ‰, and >33 ‰ in January and March. The advection of this saline winter water over the shoals is necessary to explain the salinity increase in winter.

D. Water Mass Variability

The T/S diagrams in Figures 27, 29, and 30 show the regional distribution of two different water masses in the vicinity of Nantucket Shoals; a Gulf of Maine mode and a shelf mode. The boundary between these two water masses is shown in Figure 40 for each of the first three cruises. Horizontal gradients between water masses are the result of mixing between the two modes and occurs within 10 km of the indicated boundary. The area to the southwest of the shoals is dominated by the shelf type water in May and September, but in July an outflow from the Gulf of Maine characterized the water properties. The boundary region over the southeastern edge of the shoals was similar for the period May-September with more saline shelf water dominating the Great South Channel and inferring inflow to the Gulf of Maine in summer. Outflow of Gulf of Maine water over Nantucket Shoals is consistent with the hydrographic observations.

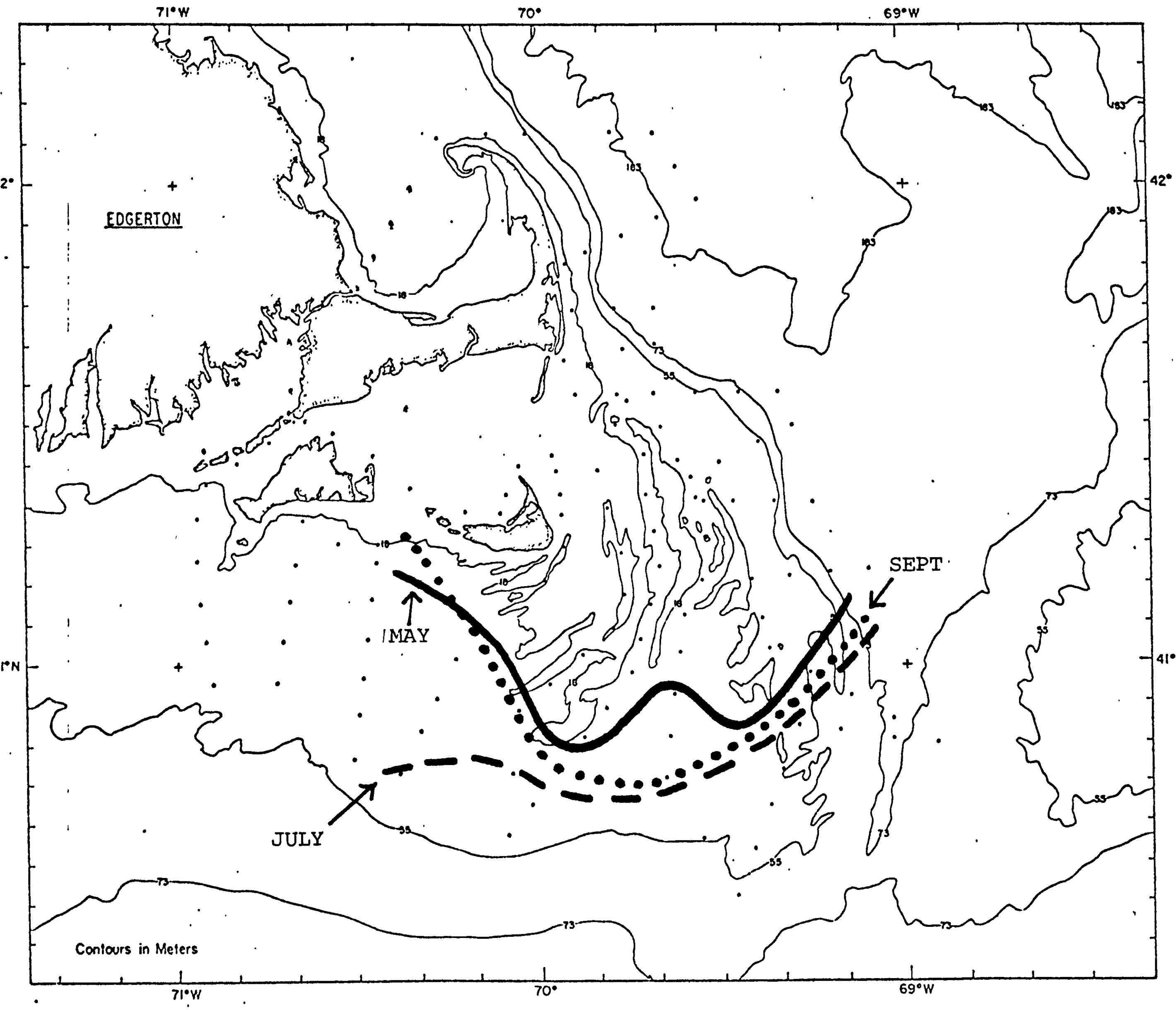


Figure 40. Gulf of Maine and shelf water mass boundary in 1978.

The winter hydrographic data shows an increase in salinity over the entire survey area. The bimodal water mass distribution over the survey region no longer exists and a tight T/S relation is evident between the cold nearshore stations and the warmer more saline offshore stations.

E. Variability of the Upwelling

The structure of the upwelling core is observed to change from a single surface core located 28 nm east of Nantucket Island in May to a two-core structure in July and September. The temperature distribution at depth suggests that water is upwelling along the entire nearshore region above depths 20-100 m, from Race Point to the Great South Channel. The strength of the upwelling appears greater along the edge of the shoals from Chatham to the Great South Channel (see Figure 20). Minimum surface temperatures in May of $6^{\circ}C$ at the surface and $10^{\circ}C$ in July and September infer the shallowness (depth = 20-30 m) of the source region in the Gulf of Maine. However, profiles from Nantucket Shoals to Georges Bank (Limeburner, Vermersch, and Beardsley, 1978) show the isotherms at depth to rise up towards Nantucket Shoals and depress towards Little Georges Bank.

One central question raised by the initial results is why does upwelling occur along the eastern boundary of Nantucket Shoals. The most pronounced upwelling areas are found along the western continental boundaries and are generally attributed to Ekman forcing by longshore winds. If we imagine the eastern edge of the shoals to be replaced by a straight wall oriented towards $330^{o}T$, then winds from the west and northwest should drive downwelling while winds from the southwest should drive weak upwelling. According to Saunder's (1977) seasonal mean wind stress charts for this region, only the mean summer winds are upwelling-favorable. The winds were from the east for several days prior to our May cruise and only light and variable winds occurred during the cruise, yet the hydrographic data shows a strong upwelling signal. This observation plus similar results from the other cruises strongly suggest that the upwelling cores are not associated with local or regional wind forcing and that upwelling is a permanent feature of the general circulation along the eastern boundary of the shoals.

F. Nantucket Shoals Circulation

The windstress is a major driving force for coastal circulation, especially in regions where shallow depths essentially concentrate the momentum transfer. One might expect low frequency energy levels over the shoals to be highly coherent with the windstress. Neumann (1939) has derived relations between wind and drift currents for shallow depths in enclosed seas to be

$$\alpha = 22^{\circ} - 6.3\sqrt{(w-4)\ \mathrm{m/sec}}$$

where α is the angle of deflection of the surface drift and the wind (w in m/sec). Since Nantucket shoals is characterized by strong winds in winter one would expect a strong surface flow in the downwind direction with high windspeeds. Haight (1942) estimates the response of the upper four meters of the water column at the Nantucket lightship due to winds to be downwind. For example, a 30k northwest wind is shown to produce a 15 cm/sec flow to the south. The 1977 measurements (EG&G, 1977) made at the lightship at a depth of 18 m indicate a mean southerly flow of 16 cm/sec. Unfortunately the low-passed current records were compared to the winds at Logan airport and little coherence was found. The offshore windstress is decidedly different from the winds at shore locations. The period in January when the EG&G (1977) measurements were made was characterized by very strong winds. Thus the idea begins to form that strong winter winds create high levels of turbulence in the upper (20 m) of the ocean. Consider the mixing which would accompany 4 m high waves that are breaking. Similar conditions occur over the Gulf of Maine and Nantucket Shoals during 30 k northwest winds. Because the region to the southwest of Nantucket Shoals is fetch limited to northerly winds, one may expect a different response here to wind forcing than at the lightship. A January, 1977 mooring to the northwest (48 km) of the lightship indicated a 5.1 cm/sec mean toward 258° at a depth of 18 m. If a 30 k northwest wind drives a 15 cm/sec offshore flow in the top 20 m from Nantucket to Cape Sable, then $10^{6}m^{3}$/sec would flow out of the Gulf of Maine. Shallow regions such as Nantucket Shoals and parts of Georges Bank would be regions of large offshore mass fluxes and an onshore pressure gradient would be established. The onshore flow would be found in the Great South Channel and the Northeast Channel with large vertical shears resulting from the offshore wind drift and the onshore pressure gradient. This idealized accounting of the spacial variability in current meter records near Nantucket Shoals is oversimplified and no account of the earth's rotation has been mentioned. Two observations were made on separate hydrographic cruises which show strong winds and rapid turbulent mixing in the near surface. In September the surface mixed layer deepened from 1 m to 20 m after a 35 k wind had been blowing for 6 hours. In January 30 k winds may occur 10 km offshore of Nantucket in winter when mild winds are observed at shore stations. These localized winds are not related to the temporal passage of a weather front.

Understanding the regional circulation is also complicated by the presence of barotropic and baroclinic pressure gradients. The alongshore pressure gradient on the New England shelf is necessary to account for the mean southwest flow on the shelf. The winter current meter measurements at the Nantucket lightship show that the eastward component of the winter windstress may be balanced by the alongshore pressure gradient. Thus a strong vertical shear should exist since the pressure gradient is a body force and the windstress a surface force. However, the region between the lightship and the Great South Channel is where the cross isobath Gulf of Maine direction and the alongshore shelf direction merge. One might expect large cross shelf flows near the lightship due to the closeness of the Great South Channel and mass fluxes between the shelf and the Gulf of Maine. The summer hydrography infers flow into the Gulf of Maine in the Great South Channel and deep inflow was measured to be 5 km/day (Folger et al., 1978).

The shoals north of 41^{o}N is dominated in spring and summer by water coming from the lower seasonal thermocline (depths of 20-30 m) in the Gulf of Maine. Shelf water flowing west mixes with the cooler Gulf of Maine waters over the southern shoals. In winter the hydrography infers a southerly flow of water over the entire region due to the strong winter winds.

The eastern shoals is the general area which separates the southerly flow over the shoals from the inflow of water to the Gulf of Maine in the Great South Channel. Thus a region of large shear in the horizontal flow exists betweem the eastern edge of Nantucket Shoals and the Great South Channel axis. A crude estimate of the mean velocity over the shoals can be made from the observed horizontal temperature gradient and the net daily heat flux in the summer. If one assumes that upwelled water over the northern shoals is passively advected to the south and heated by the sun, then a velocity of 5 km/day can be calculated from the horizontal temperature gradient in Figure 19. A net flow of 60 x $10^3 m^3$/sec to the south would exist over the shoals in July.

Locally over Nantucket Shoals one may expect residual currents due to nonlinear interactions between the strong tidal currents and the irregular bottom topography. Zimmerman (1978) has shown that shallow topographic features may act as a catalyst for transferring vorticity from the oscillating tidal field to the mean field. Thus a bottom friction torque due to local depth variations produces an oscillatory vorticity field which can be advected by the tides. The complicated tidal current field in Figure 33 shows some variability in the ellipses at different locations. Residual eddies generated by the tides may be related to the local upwelling.

Vl. Conclusion and Future Work

The first three hydrographic cruises indicate that centers of upwelling occur frequently along the eastern edge of Nantucket Shoals. The upwelling cores, however, are found in different areas along the edge of the shoals. These cores may be effectively stationary and locked to some topographic feature or they may propagate along the edge of the shoals in the manner of a baroclinic Kelvin wave. The strength of the onshore subtidal currents associated with the upwelling is not presently known.

In January, 1979, two current meters were deployed along the eastern edge of the shoals to measure the near surface and near bottom flow in water 30 m deep. The mooring was recovered in March, 1979 and the data is presently being processed. A planned deployment of three current meters in the summer of 1979 should help determine the current structure and temporal variability of temperature in the upwelling region. The planned array should also determine the stationarity or propagating nature of the upwelling phenomena.

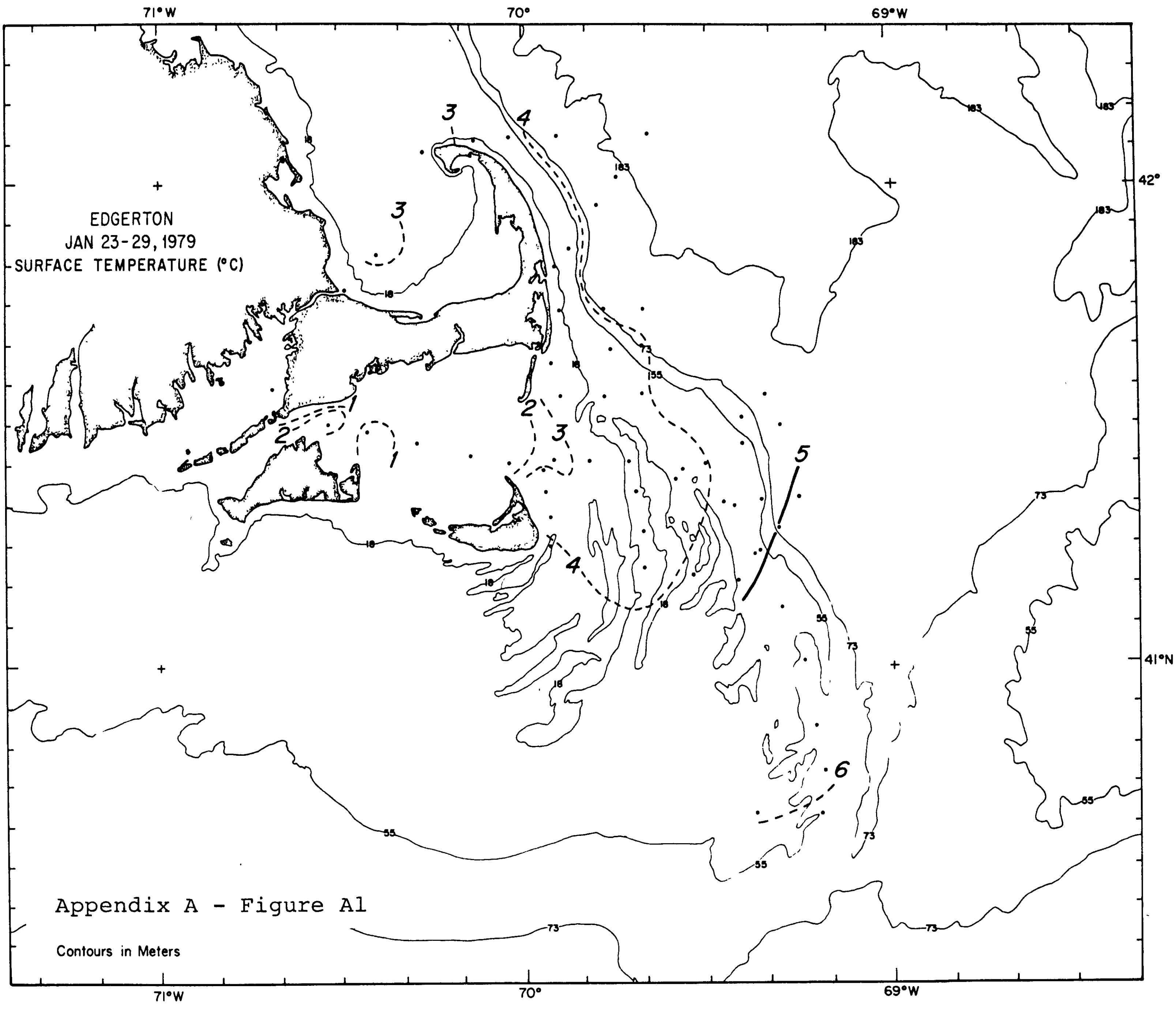
The water mass analysis has shown the presence of Gulf of Maine water over most of Nantucket Shoals, and a mixture of Maine water and recirculating shelf water over the southern region of the shoals. The region of horizontal mixing between the two water masses occurs over a length of 15-20 km and this boundary moves offshore in July to the southwest of the shoals.

The persistence of shelf water in the Great South Channel infers inflow here to the Gulf of Maine. Thus a strong horizontal shear must exist between the southerly flow over the shoals and the inflow to the Gulf of Maine through the Great South Channel.

The meteorlogical data gives evidence for an annual net heat gain over Nantucket Shoals which accounts for the advection of cool upwelled water which warms as it moves horizontally to the south and southwest in summer. Deep convective overturning in the Gulf of Maine in winter transports salt to the surface water which later drifts over the shoals. Freshwater river flow along the New England coast freshens the shoals in spring and summer.

Surface nutrient measurements made during the hydrographic surveys indicate higher values of SiO_4, PO_4, NO_2, and NO_3 in the general upwelling zones. High chlorophyll values are noted to the southwest of the upwelling cores and to the east of Nantucket Sound. The upwelling is a nutrient source for the high productivity over Nantucket Shoals.

Many of the observations in this report have been used to infer a regional circulation in the vicinity of Nantucket Shoals. Different interpretations are possible and the interpretation of the data presented here is subjective, but consistent with the hydrography. Bigelow's (1927) analysis of the circulation of the Gulf of Maine was also inferred from various sources. Yet most of our modern current meter measurements confirm Bigelow's scheme. Hopefully, this report will provide a knowledge of the temporal and spacial variability of the important physical events near Nantucket Shoals so that future theoretical modeling and understanding the dynamics will be more realistic.



Appendix A - Figure A1

Contours in Meters

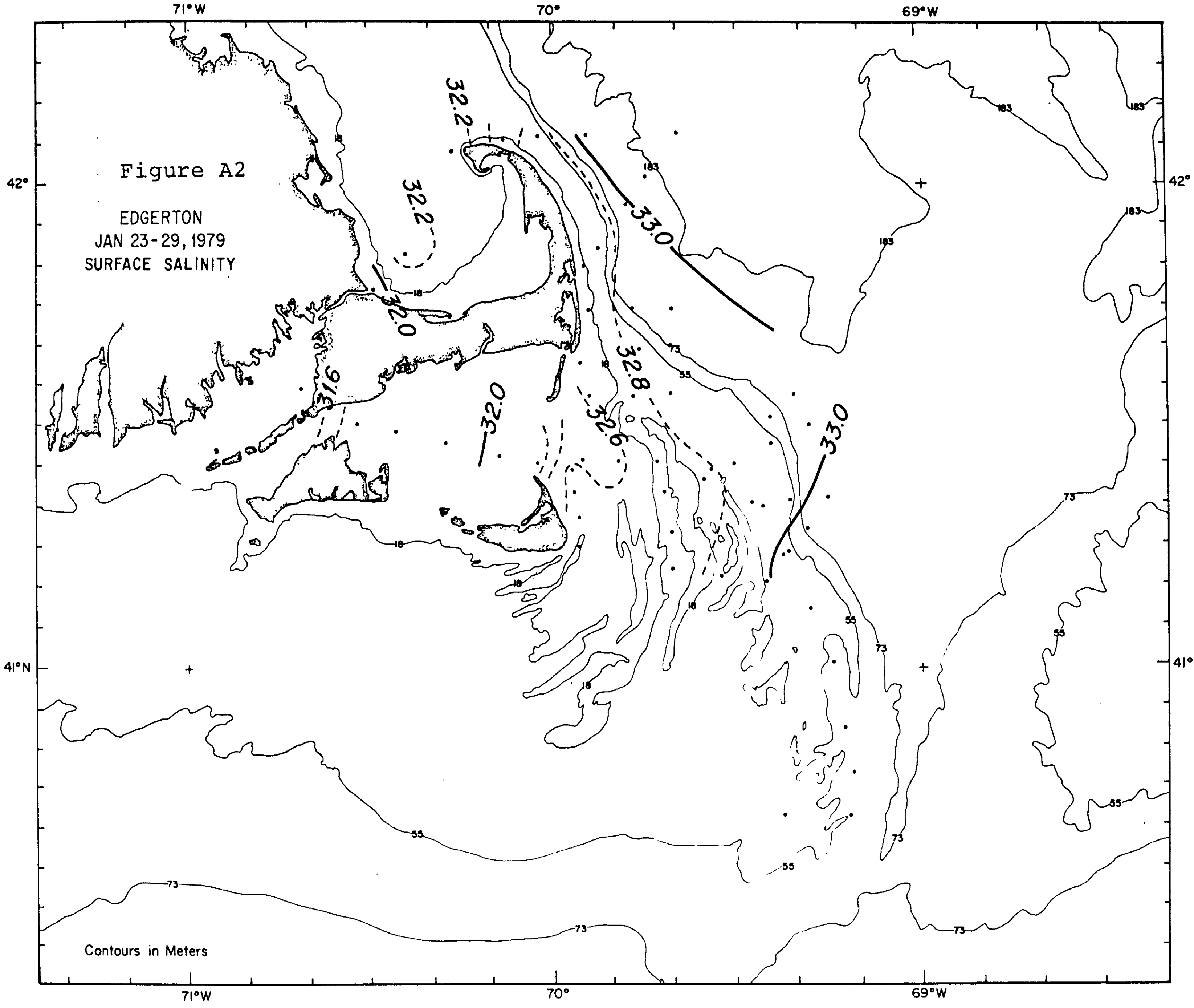


Figure A2

EDGERTON
JAN 23-29, 1979
SURFACE SALINITY

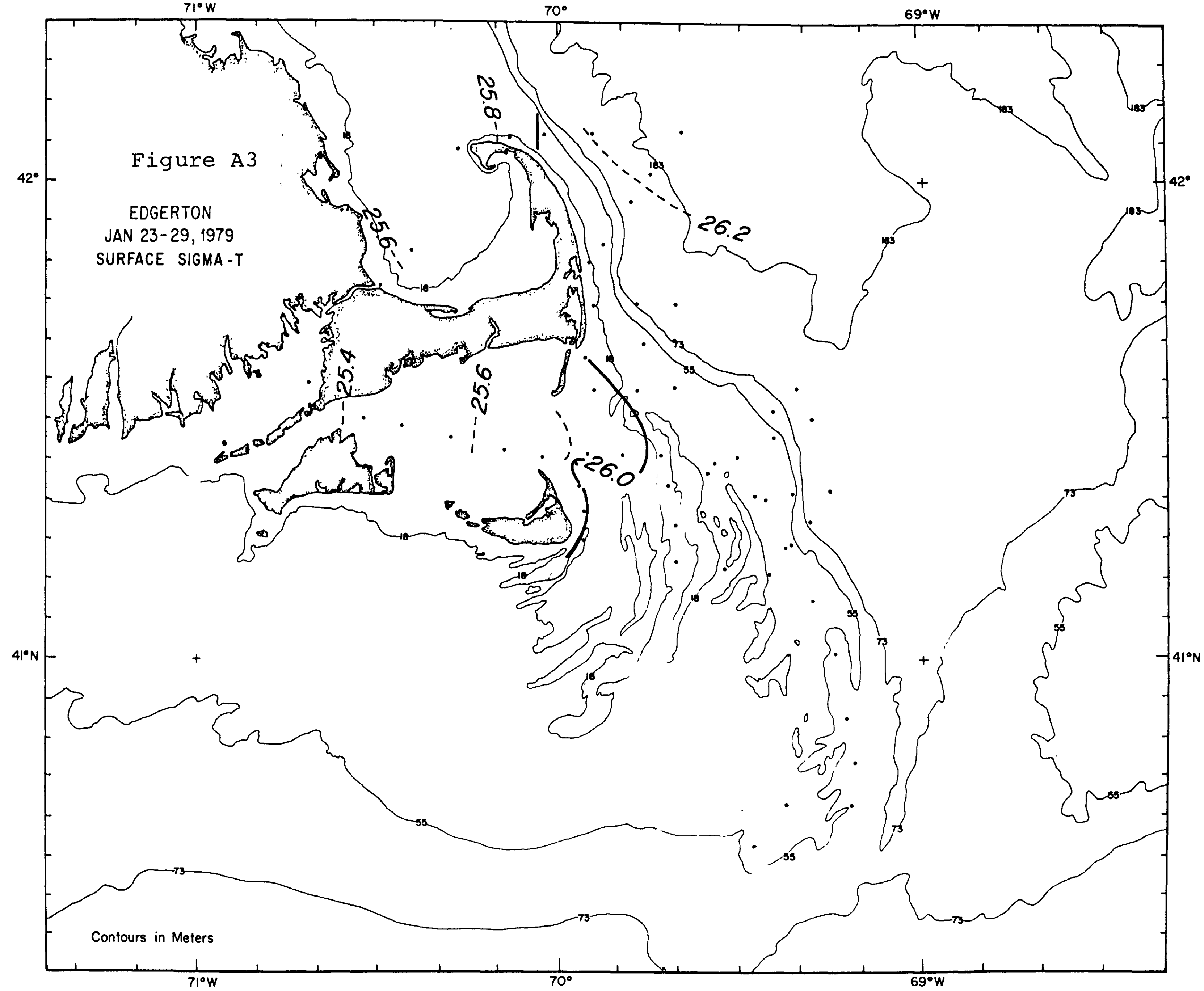


Figure A3

EDGERTON
JAN 23-29, 1979
SURFACE SIGMA-T

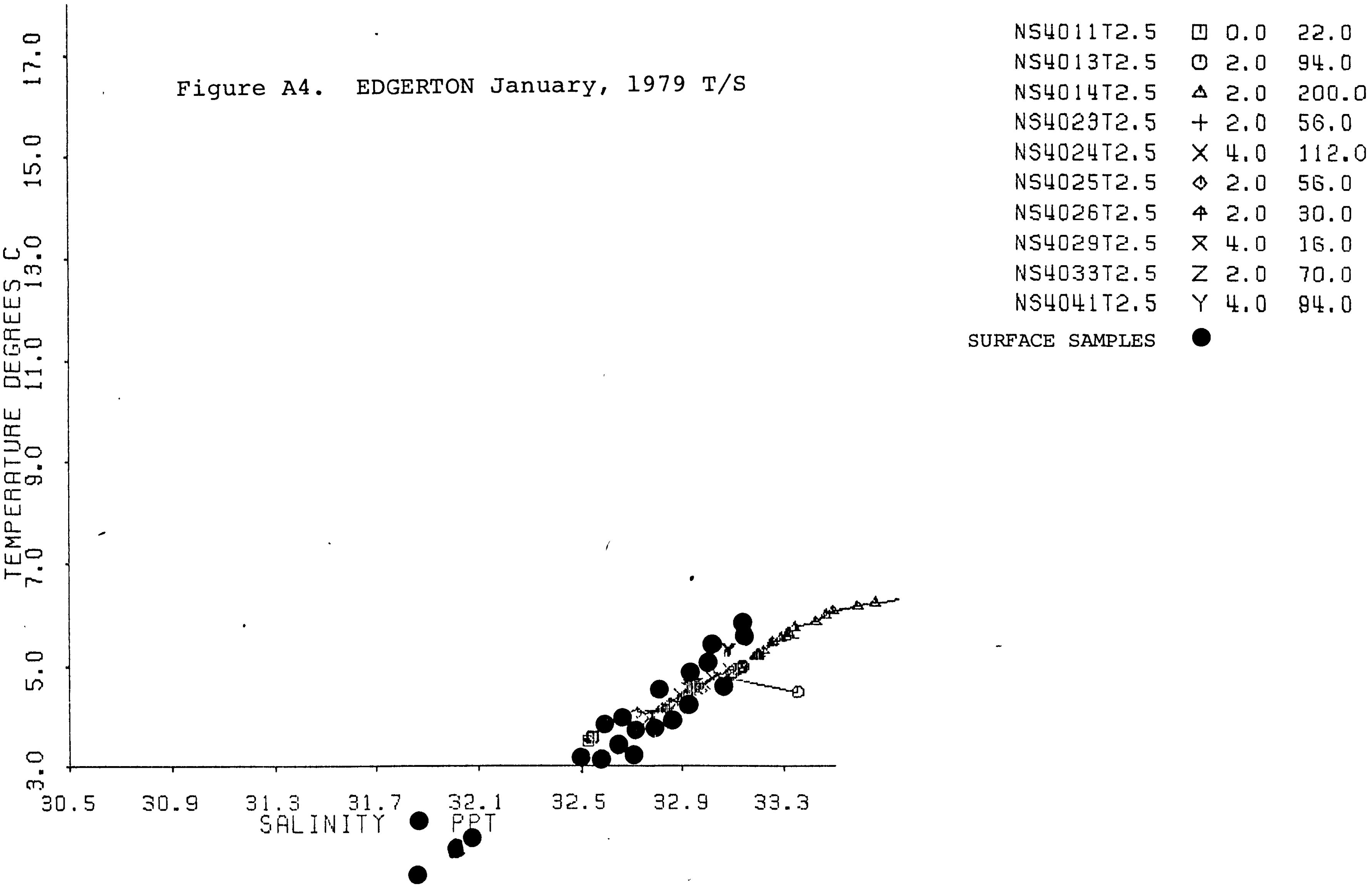


Figure A4. EDGERTON January, 1979 T/S

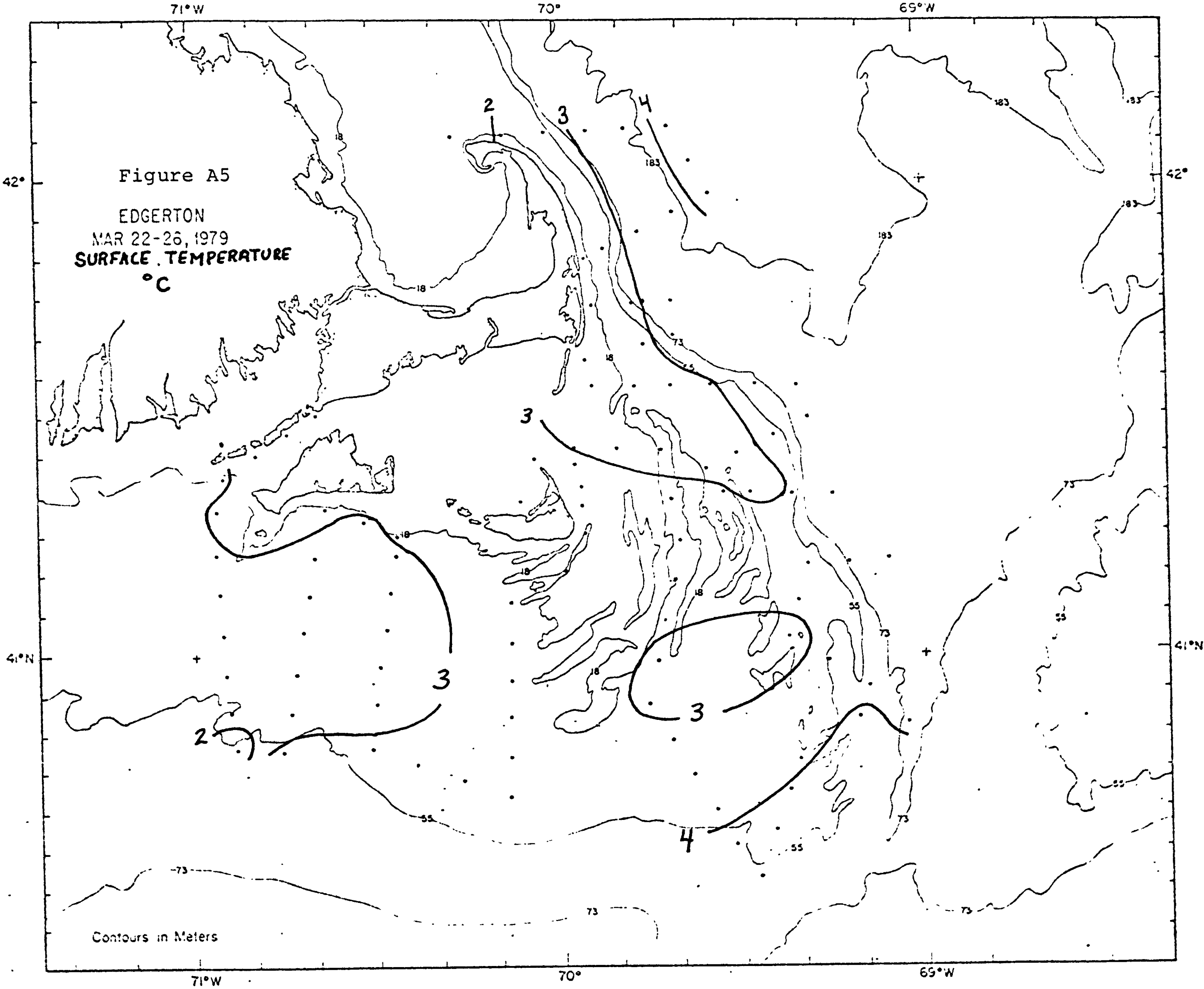


Figure A5

EDGERTON
MAR 22-26, 1979
SURFACE TEMPERATURE
°C

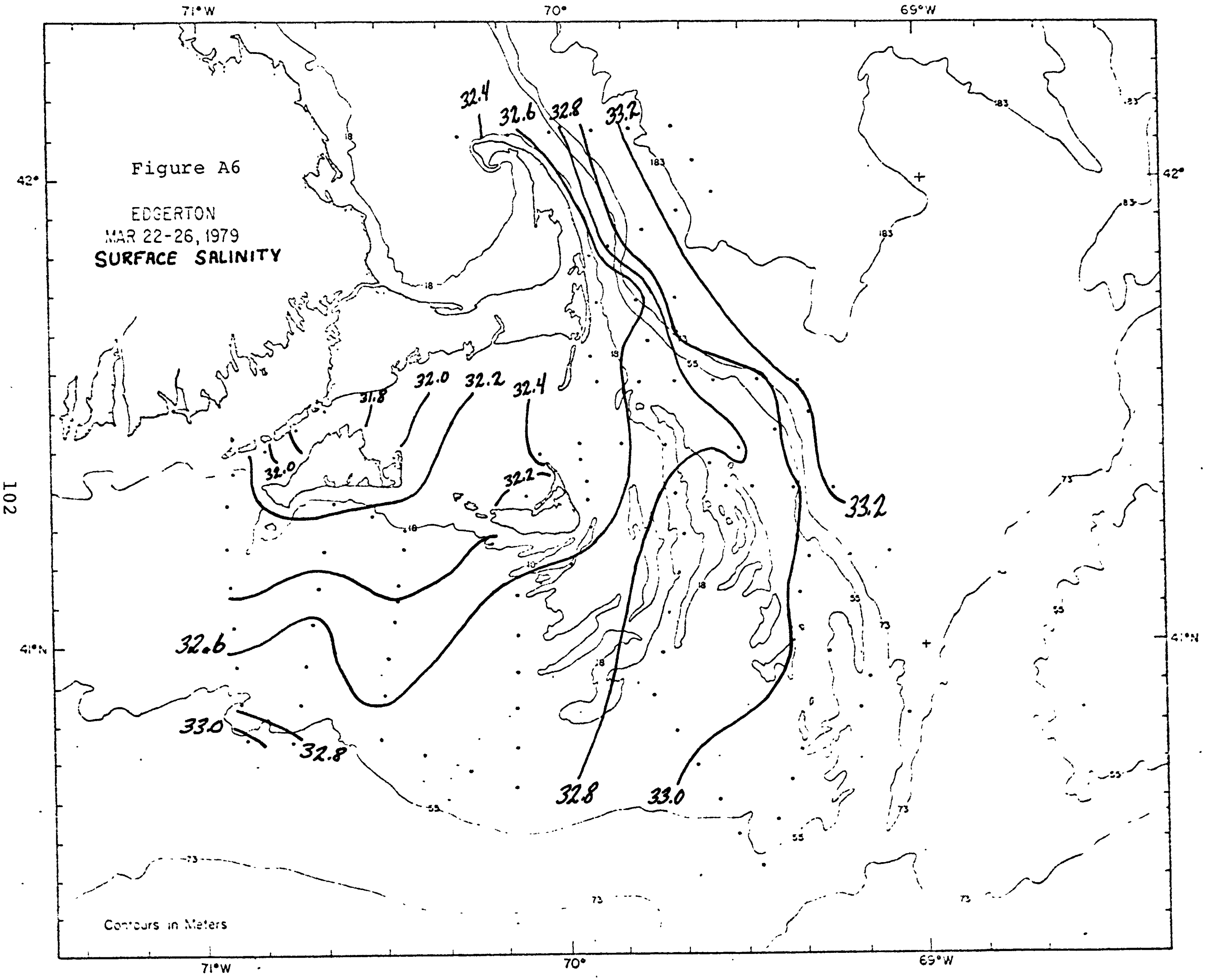


Figure A6

EDGERTON
MAR 22-26, 1979
SURFACE SALINITY

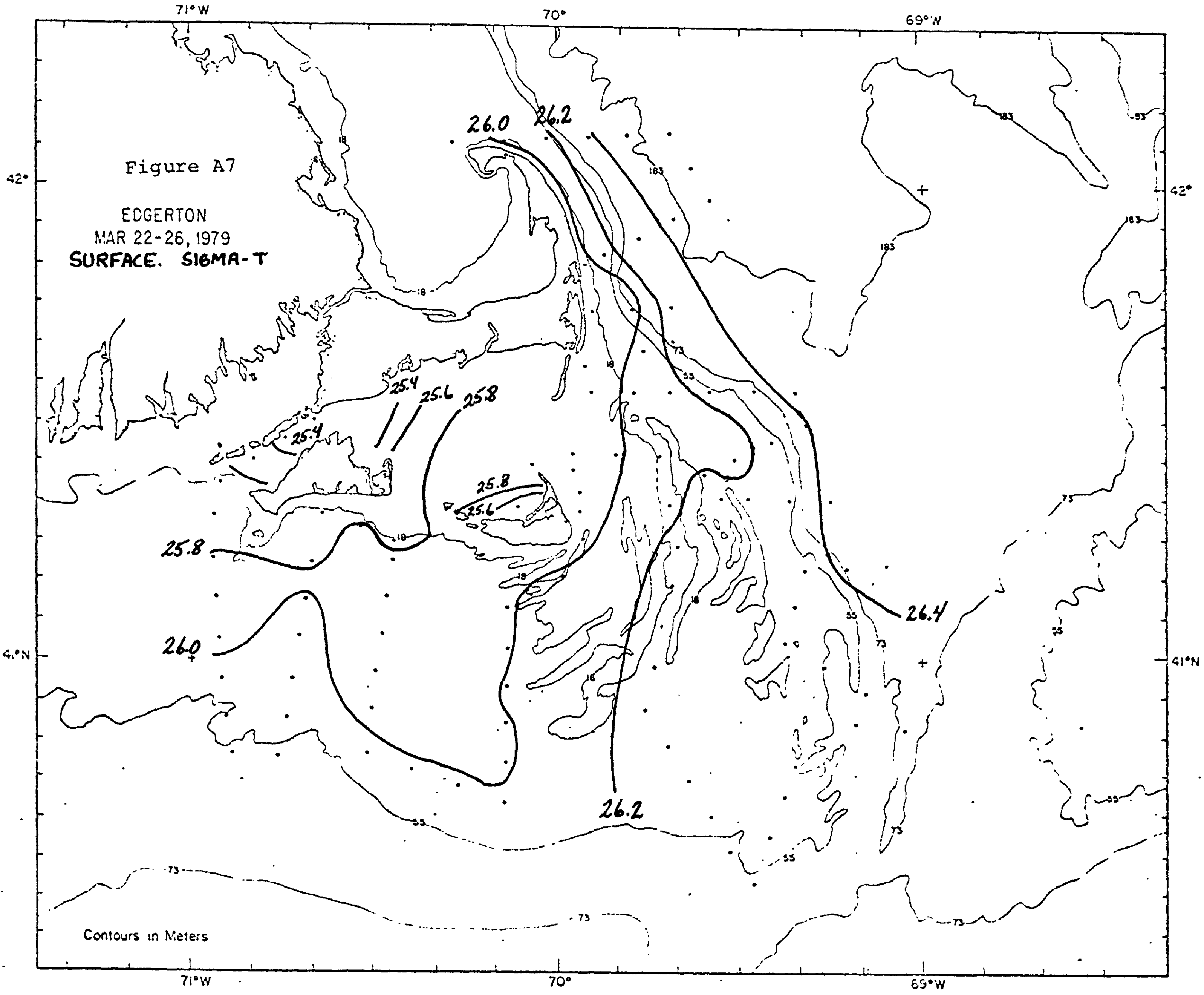
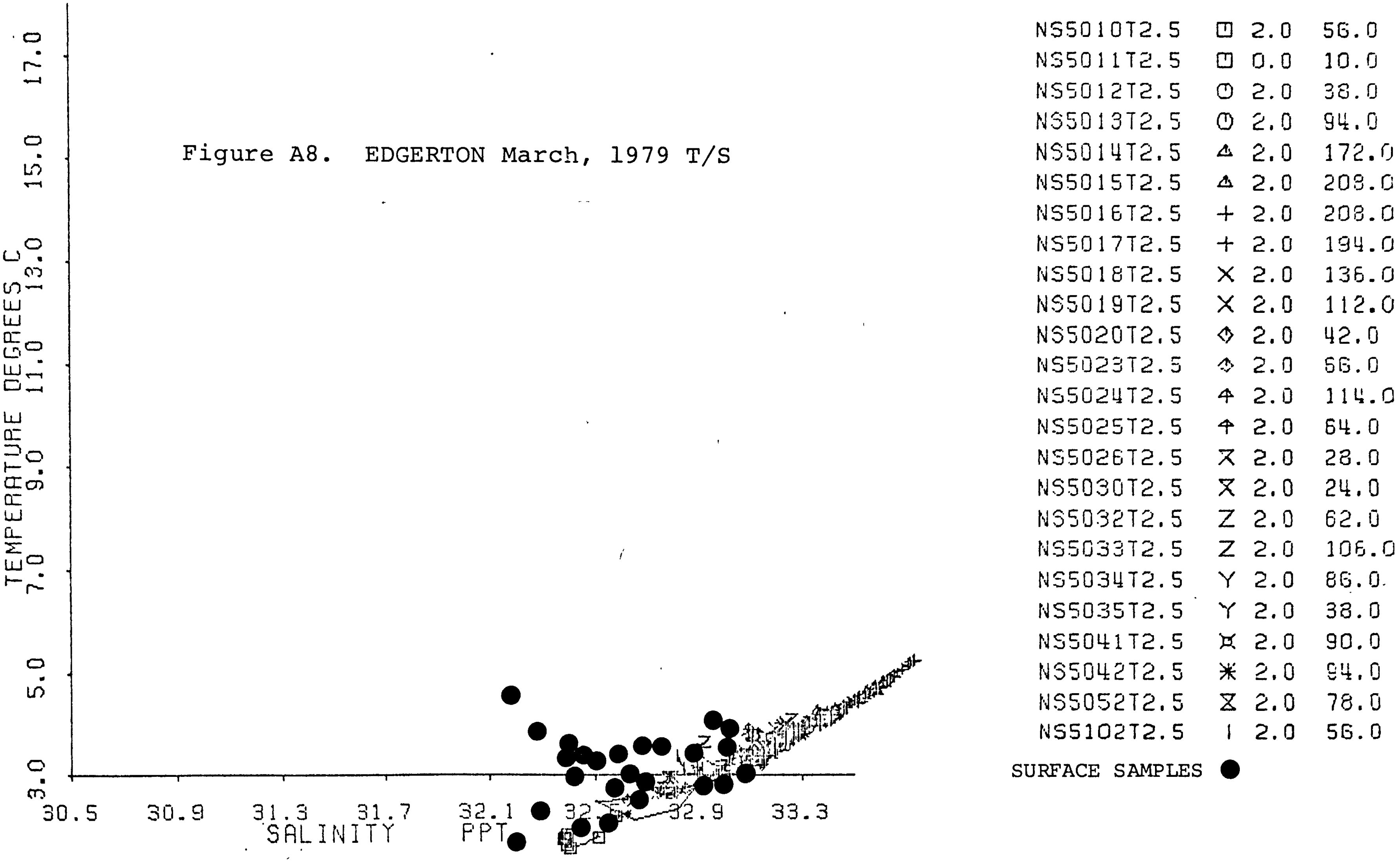


Figure A7

EDGERTON
MAR 22-26, 1979
SURFACE. SIGMA-T

Figure A8. EDGERTON March, 1979 T/S



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Finally, I would like to thank Doris Haight for typing the manuscript.

VI. References

Bigelow, H. B., 1927. Physical oceanography of the Gulf of Maine. Bull. U. S. Bureau of Fisheries, 40,(2), 511-1027.

Beardsley, R. C. and B. Butman, 1974. Circulation on the New England continental shelf: Response to strong winter storms. Geophysical Research Letters 1, 181-184.

Brown, W. S. and R. C. Beardsley, 1978. Winter circulation in the western Gulf of Maine. Part 1: Cooling and water mass formation. J. Phys. Oceanogr. 8(2), 265-277.

Bue, C. D., 1970. Streamflow from the United States into the Atlantic Ocean during 1931-60. Geological Survey Water-Supply Paper 1899-I, 36 pp.

Bunker, A. F., 1976. Computations of surface energy flux and annual air-sea interaction cycles in the North Atlantic Ocean. Monthly Weather Review 104, 122-1140.

Bumpus, D. F., 1958. Investigations of climate and oceanographic factors influencing the environment of fish. Final Report of Initial Contract covering period 1 July 1955 - 30 June 1958 under Contract No. 14-19-008-2377 with the U.S.F.W.S. Woods Hole Oceanographic Institution Technical Report WHOI 58-45.

Bumpus, D. F. and L. M. Lauzier, 1965. Surface circulation on the continental shelf off eastern North America between Newfoundland and Florida. American Geographical Society, Serial Atlas of the Marine Environment Folio 7, 4 pp.

Bumpus, D. F., W. R. Wright, and R. F. Vaccaro, 1971. Sewage disposal in Falmouth, Massachusetts, II. Predicted effect of the proposed outfall. J. Boston Soc. Civil Eng. 58(4), 255-277.

Bumpus, D. F., 1973. A description of the circulation on the continental shelf of the east coast of the United States. Progr. Oceanogr. 6, 111-157.

Bumpus, D. F., 1976. Review of the physical oceanography of Georges Bank. I.C.N.A.F. Res. Bull. 12, 119-134.

Butman, B., R. C. Beardsley, and J. A. Vermersch, 1977. Observation of currents on Georges Bank: Mean flow. Trans., Am. Geophys. Un. 58, 860.

Colton, J. B., Jr., R. R. Marak, S. R. Nickerson, and R. R. Stoddard, 1968. Physical, chemical, and biological observations on the continental shelf, Nova Scotia to Long Island, 1964-1966. U.S.F.W.S. Data Report 23, 190 pp.

Colton, J. B., Jr. and R. R. Stoddard, 1972. Average monthly sea-water temperatures, Nova Scotia to Long Island 1940-1959. Am. Geograph. Soc., Serial Atlas of the Marine Environment Folio 21, 2 pp.

Day, C. G., 1958. Surface circulation in the Gulf of Maine as deduced from drift bottles. U.S.F.W.S. Fish. Bull. 58, 443-472.

EG&G, 1977. Third Quarterly Progress Report, July 1977 New England Continental Shelf Physical Oceanography Program. EG&G Environmental Consultants, Waltham, MA.

_____, 1978. Data Report Surface Currents Deployment January-February 1978. EG&G Environmental Consultants, Waltham, MA.

_____, 1978. Data Report Support Hydrography Cruise May 1978. EG&G Environmental Consultants, Waltham, MA.

Emery, K. O. and E. Uchupi, 1972. Western North Atlantic Ocean: Topography, rocks, structure, water, life, and sediments. Tulsa, Oklahoma, American Association of Petroleum Geologists, 532 pp.

Fifield, J., 1977. Consequences of a simple model of vertical mixing for Georges Bank. Unpublished WHOI Summer Fellowship report.

Flagg, C. N., Vermersch, J. A., and R. C. Beardsley, 1976. 1974 M.I.T. New England shelf dynamics experiment (March 1974) data report - Part II: The moored array. Meteorology Department, M.I.T., GFD Lab Report No. 75-1.

Folger, D. W., B. Butman, H. J. Knebel, and R. J. Sylvester, 1978. Environmental hazards on the Atlantic outer continental shelf of the United States. 10th Annual OTC, Houston, TX, OTC 3313.

Garrett, C. J. R. and R. H. Loucks, 1976. Upwelling along the Yarmouth shore of Nova Scotia. Bulletin Fisheries Research Board of Canada 33, 116-117.

Haight, F. J., 1942. Coastal currents along the Atlantic coast of the United States. U. S. Coast and Geodetic Survey Special Publication No. 230, 73 pp.

Hopkins, T. and N. Garfield, 1977. The existence of Maine Intermediate Water. A summary of an informal workshop of the Gulf of Maine and adjacent seas. WHOI Special Report, 52 pp.

Legeckis, R., E. Legg, and R. Limeburner, 1979. Comparison of polar and geostationary satellite infrared observations of the sea surface temperatures in the Gulf of Maine. Submitted to Remote Sensing of the Environment.

Limeburner, R., J. A. Vermersch, and R. C. Beardsley, 1978. Hydrographic station data obtained in the vicinity of Georges Bank, May and August, 1976. Woods Hole Oceanographic Institution Technical Report WHOI 78-83, 116 pp.

Limeburner, R. and R. C. Beardsley, 1979. Hydrographic station data obtained in the vicinity of Nantucket Shoals, May, July, September, 1978. Woods Hole Oceanographic Institution Technical Report WHOI 79-30, 88 pp.

Neumann, G., 1939. Triftstromungen an der Oberflache bei "Adlergrund Feuerschiff." Ann. d. Hydr. v. Marit. Meterol. 67, 82 (in German).

Redfield, A. C., 1953. Interference phenomena in the tides of the Woods Hole region. Journal of Marine Research 12(1), 121-140.

Sanford, T. and R. Flick, 1975. On the relationship between transport and motional electric potentials in broad, shallow currents. Journal of Marine Research 33(1), 123-139.

Saunders, P. B., 1977. Wind stress on the ocean over the eastern continental shelf of North America. J. Phys. Oceanogr. 7, 555-566.

Simpson, J. and J. Hunter, 1974. Fronts in the Irish Sea. Nature 250, 404-406.

Smith, J. D., 1969. Geomorphology of a sand ridge. Journal Geology 77, 39-55.

Stewart, H. B. and G. F. Jordan, 1964. Underwater sand ridges on Georges Shoal. Papers in Marine Geology, Shepard Commemorative Volume, edited by Robert L. Miller. MacMillan and Co., New York, 102-114.

Strahler, A. N. 1966. A geologist's view of Cape Cod. Natural History Press, New York, 115.

Torphy, S. R. and J. M. Zeigler, 1957. Submarine topography of Eastern Channel, Gulf of Maine. Journal of Geology 65, 433-441.

Tucholke, B. and C. D. Hollister, 1973. Late Wisconsin glaciation of the southwestern Gulf of Maine: New evidence from the marine environment. Geological Soc. of Am. Bulletin 84.

Uchupi, E., 1968. Atlantic continental shelf and slope: Physiography. U. S. Geol. Survey Prof. Paper 529-C, 30 pp.

United States Coast Pilot, Atlantic Coast Section B, Cape Cod to Sandy Hook, 1950. U. S. Dept. of Commerce, Coast and Geodetic Survey. Ser. No. 736.

Vermersch, J., R. C. Beardsley, and W. S. Brown. Winter circulation in the western Gulf of Maine. Part 2, Current and pressure variability. Submitted to Journal of Physical Oceanography.

Walford, L. A., 1938. Effect of currents on distribution and survival of the eggs and larvae of the haddock (Melanogrammus aeglefinis) on Georges Bank. Bull. U. S. Bur. Fish. 49(29), 1-73.

Worthington, L. V., 1976. On the North Atlantic Circulation. The Johns Hopkins Oceanographic Studies, 6, 110 p.

Zimmerman, J. T. F., 1978. Dispersion by tide-induced residual current vortices. In: Hydrodynamics of Estuaries and Fjords. Edited by J. C. J. Nihoul, Elsevier Scientific Publishing Co., New York, 207-216.