International Commission for the Northwest Atlantic Fisheries

RESTRICTED

Serial No. 3600
(D.c. 1)

ICNAF Res.Doc/ 75/107

Corrigendum

ANNUAL MEETING - JUNE 1975

Corrigendum

to

Review of the Physical Oceanography of Georges Bank

by

Dean F. Bumpus
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

Publ. in ICNAF Res. Bull. No. 12: 119-134

This figure replaces Figure 13, page 28 of Research Document 75/107.

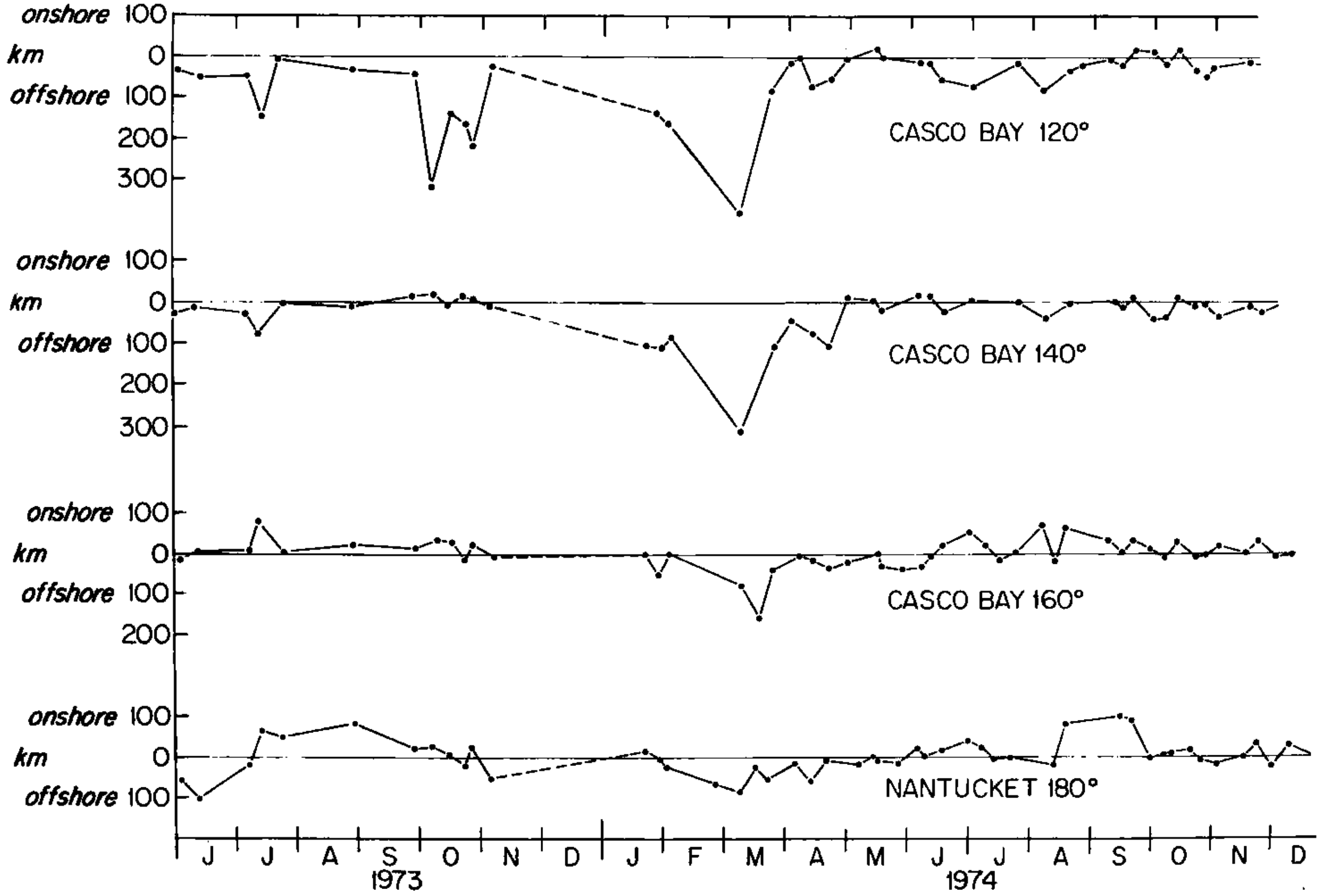

Fig. 13. Temporal variation of the position of the Shelf Water front relative to the edge of the Continental Shelf along the indicated azimuths. Positive values are shoreward from the shelf edge.

107

RESTRICTED

International Commission for the Northwest Atlantic Fisheries

Serial No. 3600
(D.c. 1)

ICNAF Res.Doc. 75/107

ANNUAL MEETING - JUNE 1975

Review of the Physical Oceanography of Georges Bank

by

Dean F. Bumpus
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

Publ. in ICNAF Res. Bull. No. 12: 119-134

Introduction

Thirty-seven and a half years ago as a young biologist I cut my oceanographic eyeteeth as we commenced a study of the distribution of certain planktonic species on Georges Bank. It became obvious over the next several years of the study that the key to the problem lay in an understanding of the circulation of the area. World War II interrupted the study, and in spite of intermittent attempts by numerous people and agencies over the intervening years, we still have only an approximate understanding of the circulation over Georges Bank, and many other continental shelf areas for that matter. We shall have to acquire a much better understanding of the dynamics if we are to evaluate the role of circulation in controlling dispersal of planktonic forms and organic production in general.

Hope springs eternal, even in the breast of one soon to retire from this field of endeavor. New techniques for making Eulerian and Lagrangian measurements are now at hand, and bright young minds are available to develop theoretical models to be compared with the real world measurements. It would appear that the chances for successfully defining the circulation scheme are now good if we are willing to make a serious attempt to elucidate it.

As background for developing a plan of attack on the problem, I shall briefly review the major known features of the physical oceanography of Georges Bank and the Gulf of Maine and then attempt to relate these features to what is known about the movement and dispersion of herring larvae. Finally I shall comment on what seem to be feasible approaches toward development of a circulation model.

Bathymetry

Uchupi's (1965) chart (Figure 1) handsomely illustrates the bathymetry of the Gulf of Maine, characterized by its rocky laybrinthine coastline and bottom topography on the north, its smoother coastline and bottom topography on the west, its deep basins interrupted by ridges and swells enclosed by the offshore banks, Browns and Georges which are intersected by the deep Northeast Channel and the shallow Great South

Channel. The south side of Georges Bank is deeply penetrated by canyons, as the continental margin slopes away to the deep ocean basin.

Rotary Tidal Currents

One of the distinctive features of Georges Bank is the strong semi-diurnal rotary tidal currents with speeds ranging from a fraction of a knot to greater than 2 knots. Progressive vector diagrams for surface current measurements (the upper 14 feet) as reported in Haight (1942) and Anonymous (1973) are shown to scale in Figure 2. Those over Georges Bank appear for the most part as elipses, with the long axes oriented NNW-SSE ranging from 4 to 8 miles in length. The short axes are 2 to 4.5 miles. Rotation is clockwise. Those over the northern edge of the bank and over the deeper parts of the south side are somewhat irregular. Those to the west of Georges, i.e., in Great South Cannel and over Nantucket Shoals, have various orientations, the westernmost over the Nantucket Shoal and another east of Chatham having a NNE-SSW orientation. One directly east of Nantucket has a counterclockwise rotation. The number alongside each tidal elipse represents the sum of the hourly speeds over a 12 hour period, an approximation of the distance traveled by a parcel of water during that time. These range from 10.7 to 19.9 miles over the shallower parts of Georges Bank, as little as 6.5 miles near the southern edge and 5.5 miles off the northern edge and 8.8 to 19.4 miles off Nantucket. One thus might think of the tidal oscillation over Georges Bank as being like a semi-solid irrotational eliptical motion with a circumference of the order of 20 nautical miles over the shallow parts of the bank, grading off to 5-6 nautical miles over the deeper parts.

Temperature and Salinity Distribution

The profiles of Colton, et al. (1968) along the 67°30' meridian from the northern shore of the Gulf of Maine, across Georges Bank to the slope water on the south provide a reasonably good characterization of the temperature/salinity depth distribution. Profiles for mid-December 1964 and 1965 are shown in Figure 3. Note that the deepest parts of the Gulf of Maine are slightly warmer and saltier than the waters above, the total range in temperature of the Gulf being 1 to 2° C, the total range in salinity from 2 to 2.5 $^{o}/oo$. The water over the bank is mixed vertically. An oceanographic front occurs well off the bank in December 1964, but lies above the 100 meter contour in December 1965.

In Figure 4 we see profiles for March 1965 and 1966. The temperature increases with depth everywhere throughout the Gulf of Maine. Over the bank the water is isothermal with a front along the southern edge, somewhat diffuse in 1965, very sharp in 1966. The salinity distribution on these occasions is markedly similar with increasing salinity with depth in the Gulf, isohaline conditions over the Bank and a salinity gradient between the southern edge of the Bank and the slope water.

Figure 5 represents the distributions in May 1965 and 1966. By this time a seasonal thermocline has begun to develop over the Gulf in the upper 50 meters below which the temperature increases with depth. Although warmer than in March the water is isothermal over the shallow (<50 m) parts of the bank with a slight thermocline beginning to develop over the deeper southern part producing an isolated cold core of "winter water" next to the bottom, which extends all the way westerly along the outer edge of the continental margin as far as about 38° N latitude, nicely illustrated in Whitcomb (1970). A bulge of this cold core extends out over the edge of the bank in the 1965 section. The temperature front between the Shelf and Slope Water lies beyond this bulge in 1965, whereas it is close in over the edge of the shelf in 1966. The salinity distribution for May is almost identical with that for March.

In Figure 6 we see the distribution for September 1965 and 1966. The strong thermocline which has developed over the central Gulf of Maine to a depth of 50 meters has begun to weaken. The coldest water appears at mid-depth with slightly warmer below. A temperature front appears at depth along the northern edge of Georges Bank occasioned by the colder vertically-mixed water over the bank. The cold core of winter water persists over the southern side of the bank and the sharp thermal front in the upper 50 meters lies just off the southern edge. The salinity distribution is little changed from that seen in May.

In discussing the general hydrographical conditions pertaining to Georges Bank, Clarke, Pierce, and Bumpus (1943) wrote in part:

"The depth of the major portion of Georges Bank lies between 40 m and 100 m, although areas of less than 25 m occur in the north central position, and shoals themselves are covered by only 5 to 15 m of water. Along the northern edge of the Bank the bottom drops rapidly from about 40 m to more than 200 m as the deep basin of the Gulf of Maine is approached. Along the southern edge the depth changes somewhat more gradually from 100 m to 200 m. Beyond 200 m it increases rapidly to about 2000 m.

"Georges Bank is therefore roughly speaking, a submerged, flat-topped plateau and it presents a sufficiently large obstacle to water movement to produce a profound effect on the ocean currents of this region. ---

"The turbulence produced by the tidal currents and by the wind in the relatively shallow water overlying Georges Bank causes a vertical mixing of the water which results in a nearly uniform distribution of temperature and salinity from top to bottom at all seasons of the year, particularly in the central part of the bank. The bank water thus contrasts sharply with the surrounding water masses, which are typically stratified during all except the winter months. Since the temperatures and salinity values on the Bank are generally intermediate between those of the surface and deeper strata on the Gulf of Maine but usually much lower than those of the water lying to the south, we know that the bank water is originally derived, in a large part at least, from the Gulf. That portion of the Bank over which vertically uniform water was found is termed the Mixed Area, and all stations at which the salinity does not vary by more than 0.2 part per mille from surface to bottom are considered to lie within it. The limits of the Mixed Area are ordinarily rather sharp... ."

A review of the profiles presented in Colton, et al. (1968) reveals that the mixed area covers all of Georges Bank shallower than 50 meters in December, deepening to 80 meters in March and returning to an area of less than 50 meters in depth during the remainder of the year.

General Circulation of the Gulf of Maine

The development of our concepts of the circulation in the Gulf of Maine, including Georges Bank, have been documented in Bumpus (1973). It is not necessary to repeat that here but we shall review the circulation as described by Bumpus and Lauzier (1965) on the basis of drift bottle data, and Bumpus (1973) on the basis of drift bottle and sea-bed drifter data. There have also been a few experiments with drifting buoys which help to confirm or amplify the inferences made from the drift bottle data.

To quote from Bumpus and Lauzier (1965) relative to surface drift:

"Gulf of Maine -

"The indraft from off Cape Sable, from across Browns Bank and the eastern Gulf of Maine into the Bay of Fundy, is the chief characteristic during the winter season. A southerly flow develops along the western side of the Gulf of Maine and continues past Cape Cod through Great South Channel. Between the indraft in the Bay and the southerly flow along the western side of the Gulf several irregular eddies develop by February. An area of divergence north of Georges Bank is well developed by February.

"The Gulf of Maine eddy develops rapidly during the Spring months so that one large cyclonic gyre encompasses the whole of the Gulf of Maine by the end of May. There is an indraft on the eastern side of this gyre from the Scotian Shelf and Browns Bank. Abreast of Lurcher Shoals the drift may continue on northward into the Bay of Fundy or it may turn westward toward the coast of southern Maine, continue south and across Massachusetts Bay where it may divert into Cape Cod Bay or turn toward the east, north of Georges Bank.

"The Maine eddy, which reached its climax in May, begins to slow down in June. By autumn and winter the southern side breaks down into a drift across Georges Bank.

"Georges Bank -

"The few returned drift bottles from winter releases on Georges Bank suggest a southerly flow across this area during the winter months, with a westernly component across Great South Channel. During the Spring months an anti-cyclonic eddy develops over Georges Bank. The northern side of this Georges eddy is common with the southern side of the Maine eddy; an area of divergence continues along the northern edge of Georges Bank. A persistent westerly drift along the southern side of the Bank continues across Great South Channel.

"During the summer the eastern side of the Georges eddy veers southerly and off-shore. With the onset of autumn the west side of the Georges eddy breaks down into a westerly and southerly drift."

Bumpus (1973) points out that the limited drift bottle data for the 1960-1970 period in the Gulf of Maine and over Georges Bank add very little to our previous understanding of the circulations in that area.

One may note, however, that the diagrams in Bumpus and Lauzier (1965) indicate the speeds of residual drift range from 1 to 8 nautical miles per day, the greater speeds restricted to the approaches of the Bay of Fundy or the western side of the Gulf of Maine, where the circulation is significantly influenced by river runoff. The drifts over Georges Bank are frequently on the order of 2 to 3 nautical miles per day, although greater speeds have occasionally been inferred. The classic diagram of Bigelow (1927), Figure 7, illustrates as well as any the general circulation pattern.

Thus to return to our "semi-solid irrotational eliptical motion" induced by the tide over Georges Bank, we might now add a clockwise rotation of 2-3 miles per day. We might liken this surface circulation over Georges Bank to a very slowly clockwise turning record in a record player estimated at one rotation per 100 days (3.6 rotations/year) on a spindle with a large (8 mile by 4 mile) eliptical eccentricity.

As for the bottom drift, Bumpus (1973) in reporting on the seabed drifter results states: "A persistent and continuous bottom drift of 0.5 ± 0.2 nautical mile/day extends toward the southern tip of Nova Scotia and the eastern side of the Bay of Fundy from Browns and LaHave Banks east of the Northeast Channel. This is in agreement with Lauzier's (1967) findings. Along the western side of the Gulf of Maine the drifts next to the coast tend to flow directly ashore, whereas farther offshore the drift is more nearly parallel with the coast in a westerly direction. Fewer than 10% of the drifters are recovered from the deeper parts of the Gulf of Maine and from Georges Bank whereas returns are substantially greater from the periphery of the Gulf of Maine and from the Continental Shelf west of Nantucket Shoals. The drifts in the deep parts (>100 m) are less than 0.1 nautical mile/day whereas those from Georges Bank are on the order of 1 nautical mile/day. A line of divergence occurs at Northeast Channel with northerly drifts north and east of the channel and westerly drifts south of it. In general, the drifts over Georges Bank follow a clockwise rotation around the shoals with a net drift to the west and across Great South Channel."

Because there are so few returns of drift bottles and sea-bed drifters from Georges Bank, one cannot help but suspect that a great number are carried offshore, rather than drifting to the west to strand, in the case of drift bottles, or be recovered by fishermen's trawls, in the case of sea-bed drifters.

Certainly when one views the results of some drogued drifting buoy experiments conducted jointly by the U. S. Fish and Wildlife Service and the Woods Hole Oceanographic Institution in 1957, one obtains the feeling that there are ample opportunities for exchanges between Georges Bank water and Slope water. Buoys equipped with on-demand radio signals were located via ship or air-borne radio direction finders. They drifted with the top five meters of the water column.

One experiment, Figure 8, was conducted between Northeast Peak and central Georges during the period 15 April to 10 June, 1957. Buoys set out at the Northeast Peak (Mike and India) moved rapidly, more than 5 miles per day, and southerly into deep water. Buoys launched in the shallower areas exhibited a slower net movement, between 1 and 4 miles per day, in a clockwise rotation. Buoy Hotel, after a slow southwesterly movement (81 miles in 55 days), suddenly increased speed and moved 128 miles to the WSW in 12 days. Buoy November, which failed to respond after the 21st of April, was reported on 20 June just east of Hudson Canyon on the 1000 fathom contour, possibly having run parallel to the track of Hotel. This buoy, November, was subsequently sighted 500 miles to the eastward (38°42' N, 60°30' W) on 31 July, obviously drawn into the Gulf Stream.

Another experiment with four drift buoys was conducted during 9-17 October 1957 in the South Channel area, Figure 9. An easterly drift along the northern edge of the bank, between 6 and 13 miles per day was indicated, with a slower, less definite drift in the center of the channel, and a southerly set of about 5 miles per day on the western side of the channel.

Five more buoys were set out on December 6, 7, and 17, 1957, Figure 10. Hotel, launched on the south eastern part of the bank subsequently failed to function and is not shown in the figure. It was recovered about 500 miles to the SE 8 months later. Mike was picked up and replaced by a fisherman, but was apparently damaged as it ceased to respond to radio calls. It had moved 50 miles eastward in 12 days.

The remainder were repeatedly located during December. This experiment yields evidence of an easterly set on Georges Bank in December 1957 on the order of >1 to >4 miles per day as indicated by Papa and Mike. Papa eventually drifted off into deep water southeast of the bank where it was sighted. India moved at a similar rate but skirted the northern edge of Georges, then turned northerly before reaching Browns Bank, being ultimately recovered by a fisherman 21 miles SE of Matinicus Rock. This buoy was obviously in the Gulf eddy. Alpha following the inner-part of the Gulf eddy, moved more slowly, at >5 miles per day.

This experiment perhaps explains why so few drift bottles set out on Georges during the autumn and winter have been recovered. The Georges eddy has given way to an easterly drift. Bigelow (1927, p. 864-5) examined the current measurements made by the U. S. Coast and Geodetic Survey during 1911 and 1912 at Nantucket Lightship. This analysis showed "a dominant drift toward the north and west during the spring, summer, and early autumn, averaging about 3.4 miles per day; but about as strong a southeasterly set (3 miles daily) during the late autumn, winter, and early spring, averaging about S. 50° E (SE x E) in direction." Bigelow credited the presence of the strong northwest winds of the season with the reversal in drift. During our December experiment the winds were predominately from the southwest, with strong easterlies on a few occasions. Whatever the reason, the surface drift across Georges Bank during the autumn and winter is different and apparently contrary to the drift of other seasons. It is quite probable, at this stage of our information, that the net circulation on Georges Bank is not readily predictable. It is reasonable to expect that the water movements on the Bank, especially during those seasons where the water is well mixed, respond to the short-term wind effects as postulated by Chase (1955) for Georges Bank in regard to Haddock larvae and as reported by Howe (1962) in the Middle Atlantic Bight and more recently Beardsley and Butman (1974). The latter authors with measurements south of New England demonstrated that short intense wind events dominate the circulation over the shelf in winter and account for most of the observed net flow. Their observations show that large westward mass transports along the shelf were produced by strong easterly winds and the sea level rise at the coast (see Miller, 1957), while westerly winds produced little along-shore flow. However, the storm producing the westerly winds was much weaker than the one with the easterly winds. It may be that we cannot extrapolate the southern New England Shelf response to Georges Bank because the geography is quite different. However, it is quite possible that when an intense low pressure cell moves south of Georges causing easterly winds over the Bank and an increase in sea level over the shoals, there will be a strong net westerly flow over the south side of the bank. Contrarywise, an intense low passing north of Georges could similarly create strong easterly flows along the north side of the bank, with weaker flows south of the shoals.

Sea Surface Temperature Fronts

As we have seen from Colton's profiles, the interface between the colder, less saline Shelf Water and warmer, more saline Slope Water appears at the sea surface as a thermal front. This front can be observed by satellite-borne infra-red radiometers. The National Environmental Satellite Service prepares charts of the sea surface temperature fronts off the east coast of the U. S. on a weekly basis. Ingham and co-workers at the NMFS Atlantic Enfironmental Group have used these charts to monitor and analyze the position of the Shelf Water front from June 1973 through December 1974. Figure 11 is an example. Figure 12 is a composite of the frontal positions during September-December 1973 and 1974. The dashed line represents the shelf edge as defined by the 100 fathom contour.

In the course of the analysis the temporal variation of the Shelf Water front was established along certain standard lines (Figure 11). The results of the first four, Casco Bay 120°, 140°, 160°, and Nantucket 180° are shown in Figure 13. The location of the front is plotted as the distance from the shelf edge to the front.

The mean position of the front during the 18 month period is shown in Table 1. The variability of the front's position, as indicated by the standard deviation, is large on all azimuths, being largest at the eastern corner of Georges Bank and least South of Nantucket.

Table I

Bearing Line	Sample Size	Distance from shelf edge (Km) + = shoreward, - = seaward	Standard Deviation
Casco Bay 120	30	-45.5	70.9
140	31	-35.4	64.0
160	36	- 6.1	39.3
Nantucket 180	37	+ 0.6	38.5

Major offshore excursions occurred on the Casco 120° line in July and October 1973 and during the winter of 1974; on Casco 140° line in July 1973 and during the winter and early spring of 1974; in Casco 160° line during March of 1974 and on the Nantucket 180° line during June and November 1973 and winter of 1974. Intrusions of Slope Water appear greater on the Casco 160° and Nantucket 180° lines than over the eastern parts of Georges. On Casco 160° the intrusions occurred during June 1973 and during the summer of 1974 whereas they were fairly extensive on the Nantucket 180° line during the summers of 1973 and 1974. Ingham estimates 14% of Georges was invaded by Slope Water in late August 1974, increasing to 18% coverage by early September, then decreasing to about 4% by the end of the month. He states: "At no time during the year did the invasion of the Bank by Slope Water exceed 18% and the average coverage for the year was 3.5%, with a standard deviation of 4.8% based on a sample of 30 observations."

Wright (1975) has carefully examined the position of the Shelf Water/Slope Water boundary between 69° and 72° W longitude, an area which slightly overlaps our area of interest. His study shows that this interface, identified by the 10° isotherm, intersects the bottom within 16 Km of the 100 meter contour about 80% of the time, with a seasonal progression from south in the winter to north in the autumn. The sea surface boundary position is much more variable, averaging 45 Km seaward of the 100 meter contour in winter and 75 Km seaward in late summer. This boundary is much more nearly horizontal than vertical. He also finds detached parcels of shelf water in the slope water at all seasons of the year.

Estimates of Wind-Driven Ekman Transports

The Pacific Environmental Group of the N.M.F.S. provides estimates of monthly wind-driven Ekman transports computed from the monthly average atmospheric pressure charts after the method of Fofonoff (1962) as described by Bakun (1973). Figure 14 shows the estimated monthly Ekman Transport at 40° N 70° W for 1972, 1973, and 1974. It is quite obvious from this figure that the direction and intensity of the transport is extremely variable from month to month and from year to year. One is not at all assured either that the water movements are going to be in the direction of the computed Ekman transports, in the shallow waters of Georges Bank and Nantucket Shoals. They may indeed be more directly downwind, i.e., 90° to the left of these Ekman transport vectors. What these vectors mean to me is that there are periods of intense forcing which may indeed induce extreme wind-stressed flows as well as periods of minimal forcing.

We have compared the data for 40° N 70° W with data for 39° N 69° W, 39° N 66° W, 42° N 60° W, and 42° N 66° W for 1974 and found the 40° N 70° W representative of the area. However, the position of the fronts relative to the edge of the bank in the last half of 1973 and all of 1974 do not appear to correlate well with the monthly Ekman transport vectors. It is very possible that the development of eddies north of the Gulf Stream have a significant impact on the location of the Shelf Water-Slope Water front.

Evidence from the Distribution of Herring Larvae

We have inspected the information presented by Schnack and Stobo (1973) and Schnack (1974) summarizing the results of the 1972 and 1973 joint herring larval surveys and the several separate reports on the 1974 cruises. These cruises took place as follows:

1972	1973	1974
22-30 Sep	16-28 Sep	6-24 Sep
2-28 Oct	29 Sep-20 Oct	27 Sep-18 Oct
12-28 Oct	15 Oct-1 Nov	18-30 Oct
31 Oct-12 Nov	28 Oct-8 Nov	16-23 Nov
28 Nov-15 Dec	4-20 Dec	4-19 Dec

We have delineated the areas where 10 or more herring larvae per 10 m^2 were caught, Figures 15, 16, and 17, and made some inferences from the distributions of the various size categories. We have inferred that the area occupied by herring larvae <10 mm in length to be the spawning area and have outlined it and the spawning area for the preceding cruise. We have then outlined the area occupied by the 10-15 mm larvae and the >15 mm larvae and drawn arrows representing the inferred spread of the larval distribution of the larger size categories from the spawning areas. It is quite apparent that advection and dispersion have occurred.

The spread from the "spawning area" between the first and second cruises in 1972 appears to be on the order of one mile per day and due to dispersion by the tidal oscillation. Between the second and third cruises an advective spread of >10 miles per day southwestward occurred with a lesser northerly drift north of Georges Shoal and northeasterly drift from Nantucket Shoals. Between the third and fourth cruises mixed movements of 1-2 miles per day occurred over Georges Bank, but a four mile per day spread occurred westward from Nantucket Shoals spawning area. By the fifth cruise herring larvae are well spread over the whole area, the major drift having been westward from Nantucket Shoals at about two miles per day. It would appear that there had been no drifts away from the shallow waters except for a small tongue of 10-15 mm larvae over the edge of SE Georges on the second cruise. An anticyclonic eddy was drifting westward just south of Georges Bank during this period (U. S. Naval Oceanographic Office, 1972).

During the interval between the first and second cruises of 1973 there was a southwestward advection from the Georges spawning area of about five miles per day and a weak Southeasterly drift. Between the second and third cruise the southwestward drift continued coupled with a general expansion from the Nantucket Shoals spawning area and possibly a northeastward drift along the NW side of Georges. The westward drift continued between the third and fourth cruises and a weak southerly drift was apparent between the fourth and fifth cruises. The larval population was larger in 1973 than in 1972 and tended to move closer to the southern edge of Georges Bank or even beyond the 100 meter contour during 1973. There were no anticyclonic Gulf Stream eddies in the vicinity during this period (U. S. Naval Oceanographic Office, 1973).

Spawning was late in 1974 so that no herring larvae were caught during the first cruise. Between the second and third cruises there appear to be westward advections from the spawning areas at speeds of 3 to 8 miles per day. Between the third and fourth cruises there appeared a general dispersion from the spawning areas. Between the fourth and fifth cruises the overall tendency was for the area occupied by larval herring to compress slightly latitudinally with a slight westward drift of the whole at between 1 and 2 miles per day. As in 1973, the larval herring population tended to extend beyond the limits of the 100 meter contour. The computed monthly Ekman transports during this period were moderate toward the SW, being somewhat stronger in October than for the 10-year mean for October, which is usually weak. It is interesting to note that an anticyclonic eddy drifted during November from the vicinity of the Gulf Stream to the Southern edge of Georges Bank and continued westward along the edge during December (U. S. Naval Oceanographic Office, 1974).

Table II provides us with an idea of how the total population of herring larvae changes from cruise to cruise in relation to the change in area occupied.

Table 2. Change in total number of herring larvae and area occupied from cruise to cruise.

	Δ Total Number of Herring Larvae					
	1972	1973	1974	1972	1973	1974
From 1st to 2nd cruise	3.8*	24	-	4.7	5.0	-
From 2nd to 3rd cruise	1.5	2.5	1.3	1.2	1.6	1.3
From 3rd to 4th cruise	.42	.64	1.4	1.1	1.3	3.0
From 4th to 5th cruise	.34	.16	.47	.73	.80	.82

*Georges Bank only.

It is apparent from this information that the herring population tends to increase at a greater rate than the area it occupies through the end of October (the third cruise) but somewhat later in 1974, and then begins to decrease due to the various exigencies which cause a decrease in the population while the area occupied by the population continues to increase through the fourth cruise (prior to the first of December) following which the area decreases slightly.

The evidence from the Joint Herring Larvae Surveys appears to suggest that the larvae are retained within the shelf water. The area they occupy expands with time due to the vigorous tidal stirring and advection. The advection appears to be principally toward the west. There are some indications of a northeasterly drift north of Georges Shoal, i.e., a continuation of a clockwise gyre around the shoal part of the bank. We do not have adequate data to evaluate the effect of the passage of storms through the area.

It is possible that some larvae may drift off the southeast edge of Georges Bank. This is the location where the thermal fronts, as observed by satellite, appear to have their maximum excursion. It is also possible that the anticyclonic eddies drifting away from the Gulf Stream along the southern edge of the bank may entrain shelf water along their perimeter. The sampling pattern for larval herring may not extend far enough off the bank in this vicinity. It is also fairly obvious that we do not know how far the larvae drift west of Nantucket Shoals in November and December, inasmuch as the sampling is not adequate west of 71° W longitude.

Summary

In summary, we are dealing with an area which has the temperature and salinity characteristics of the Continental Shelf bordering on Slope Water to the south. The front between the Shelf and Slope Water ranges from diffuse to very sharp and it frequently wanders large distances (several hundred kilometers) at the surface, probably much shorter distances (tens of kilometers) at the bottom. Anticyclonic eddies from the Gulf Stream drift close to the southern edge of the bank, impinging directly against it as they move westward. The energetic tidal oscillations over the bank are predictable whereas the net drifts are much less well understood. There appears to be a clockwise rotation around the bank during the seasons when the thermocline is developing. At other seasons it would appear that the winds may be the mechanism for providing advective forces on the sea surface.

It is high time that a concerted effort be made to understand the advective processes above and around Georges Bank and the physical forces which regulate them!

In order to determine how the circulation is conditioned by the wind systems it would seem that a drogued buoy program should be conducted with initial buoy plantings in the spawning areas. The movements of these buoys should be related to the daily, or better still, 6 hourly, components of the wind stress. Equipping the drogues with recording thermistors or conductivity meters would provide some clues as to how well the buoys stay within the shelf water. The presence of the winter water, as seen in Figure 6, is enigmatic. Does this water move at all? Is there a shear zone above it? Drogues should be placed in it and above it to determine this.

The forcing by the wind and an evaluation of the Ekman transport needs also to be determined by judicious employment of current meter arrays at the northern and southern edges of the bank, with at least one array over a shallower part of the bank. Equipping these current meter arrays with conductivity cells would permit an estimate of the flux of salt across the bank and its boundaries.

Both Lagrangian and Eulerian current measurement studies should be accompanied by concurrent synoptic temperature and salinity profiles in order to gain a clear understanding of the characteristics of the water being advected. Sampling for nutrients along these profiles would also make it possible to estimate nutrient fluxes across isobaths so necessary in the evaluation of primary production.

As learning proceeds the locations of fixed and drifting elements of the experiments should be modified to develop time and space scales of the transport processes. Assistance from oceanographers skilled in the technical and theoretical aspects of this research should be enlisted.

Acknowledgements

The preparation of this report has been funded through National Marine Fisheries Service Contract No. 03-5-043-327. The author gratefully acknowledges the generous assistance of Marvin D. Grosslein, Merton C. Ingham, and R. Gregory Lough, all of the National Marine Fisheries Service, in providing data and wise counsel.

References

Anonymous. 1973. Tidal current tables 1974 Atlantic Coast of North America, U. S. Department of Commerce, N.O.A.A., National Ocean Survey, 200 p.

Bakun, A. 1973. Coastal upwelling indices, West Coast of North America 1946-1971. N.O.A.A. Tech. Report NMFS SSRF-671, 103 p.

Beardsley, R. C. and B. Butman. 1974. Circulation on the New England Continental Shelf: Response to strong winter storms. Geophys. Res. Letters 1(4):181-184.

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

Bumpus, D. F. and Lauzier, L. M. 1965. Surface circulation on the Continental Shelf of eastern North America between Newfoundland and Florida. Am. Geograph. Soc., Serial Atlas of the Marine Environment, Folio 7, 4 p., 8 pl., Appendix.

Bumpus, D. F. 1973. A description of the circulation on the Continental Shelf of the east coast of the United States. Progress in Oceanography 6, Ch. 4: 111-157. Appendix.

Chase, J. 1955. Winds and temperatures in relation to the brood-strength of Georges Bank haddock. Jour. du Conseil Int. p. l'explor. de la Mer 21(1):17-24.

Clarke, G. L., Pierce, E. L., and Bumpus, D. F. 1943. The distribution and reproduction of Sagitta elegans on Georges Bank in relation to hydrographic conditions. Biol. Bull. 85, 201-226.

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 p.

Fofonoff, N. P. 1962. Machine computations of mass transport in the North Pacific Ocean. J. Fish. Res. Bd. Can. 19(6):1121-1141.

Haight, F. J. 1942. Coastal currents along the Atlantic Coast of the United States. U. S. Coast and Geodetic Surv. Spec. Pub. No. 230, 73 pp, 35 figs.

Howe, M. R. 1962. Some direct measurement of the non-tidal drift on the Continental Shelf between Cape Cod and Cape Hatteras. Deep-Sea Res. 9:445-455.

Ingham, M. C. 1974. Variations in the Shelf Water Front off the Atlantic Coast between Cape Hatteras and Georges Bank. Prepared for the NMFS 1974 Status of the Environment Report. Draft copy of unpublished manuscript.

Lauzier, L. M. 1967. Bottom residual drift on the Continental Shelf area of the Canadian Atlantic Coast. J. Fish. Res. Bd. Can. 24, 1845-1859.

Miller, A. R. 1957. The effect of steady winds on sea level at Atlantic City. Meteorological Monographs 2(10):24-31.

Schnack, D. and W. T. Stabo. 1973. ICNAF joint larval herring survey in Georges Bank - Gulf of Main areas in 1972 - preliminary summary. ICNAF Res. Doc. 73/115:55 p. Manuscript restricted.

Schnack, D. 1974. Summary report of the 1973 ICNAF joint larval herring survey in Georges Bank-Gulf of Maine areas. ICNAF Res. Doc. 74/105: 23 p. Manuscript restricted.

Whitcomb, V. L. 1970. Oceanography of the mid-Atlantic bight in support of ICNAF, September-December 1967. U. S. Coast Guard Oceanographic Report No. 35, 157 p.

Uchupi, E. 1965. Map showing relation of land and submarine topography, Nova Scotia to Florida. U. S. Geol. Surv. Misc. Geol. Invest., Map 1-451.

U. S. Naval Oceanographic Office. 1972. Monthly summary, the Gulf Stream (116782-6S), Vol. 7, nos. 9, 10, 11, and 12.

U. S. Naval Oceanographic Office. 1973. Monthly summary, the Gulf Stream (116782-6S), Vol. 8, nos. 8, 9, 10, 11.

U. S. Naval Oceanographic Office. 1974. Monthly summary, the Gulf Stream (116782-6S), Vol. 9, nos. 10, 11, and 12.

Wright, W. R. 1975. The limits of shelf water south of Cape Cod, 1941 to 1972. J. Mar. Res. (submitted for publication).

Fig. 1. Bathymetry of the Gulf of Maine (Uchupi, 1965).

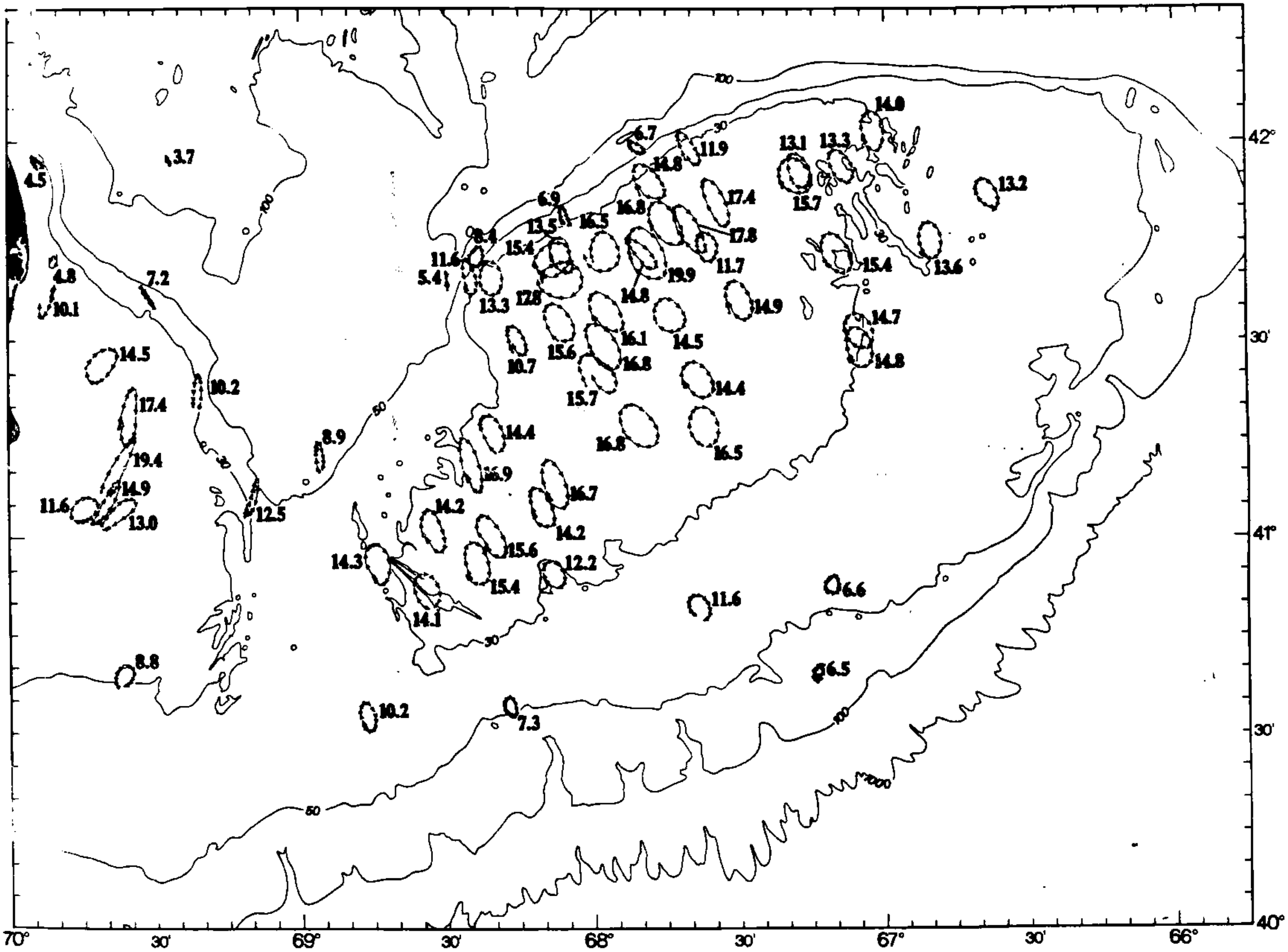

Fig. 2. Progressive vector diagrams of tidal oscillations on Georges Bank drawn to chart scale.

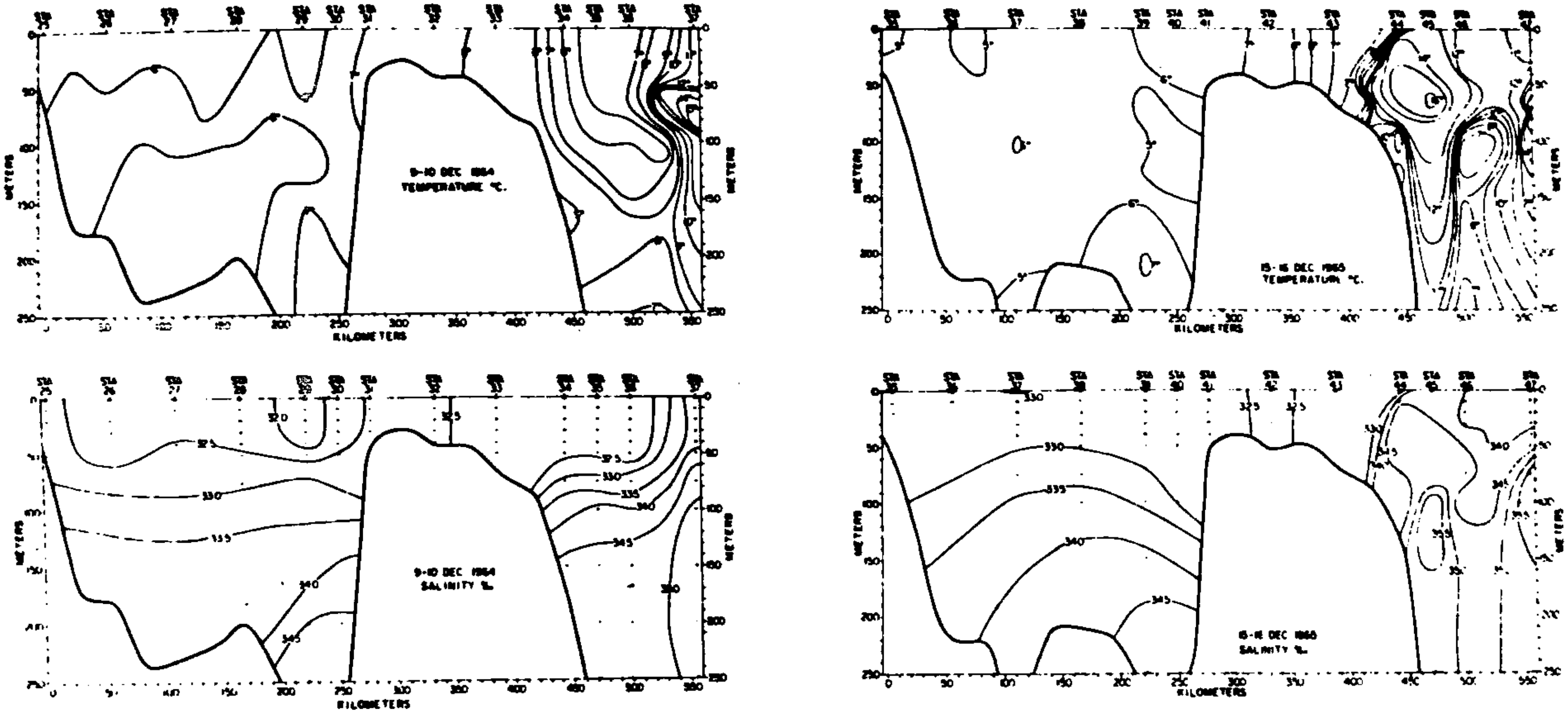

Fig. 3. Temperature, salinity profiles along 67° 30'W across Gulf of Maine for December 1964 and 1965 (Colton, et al. 1968).

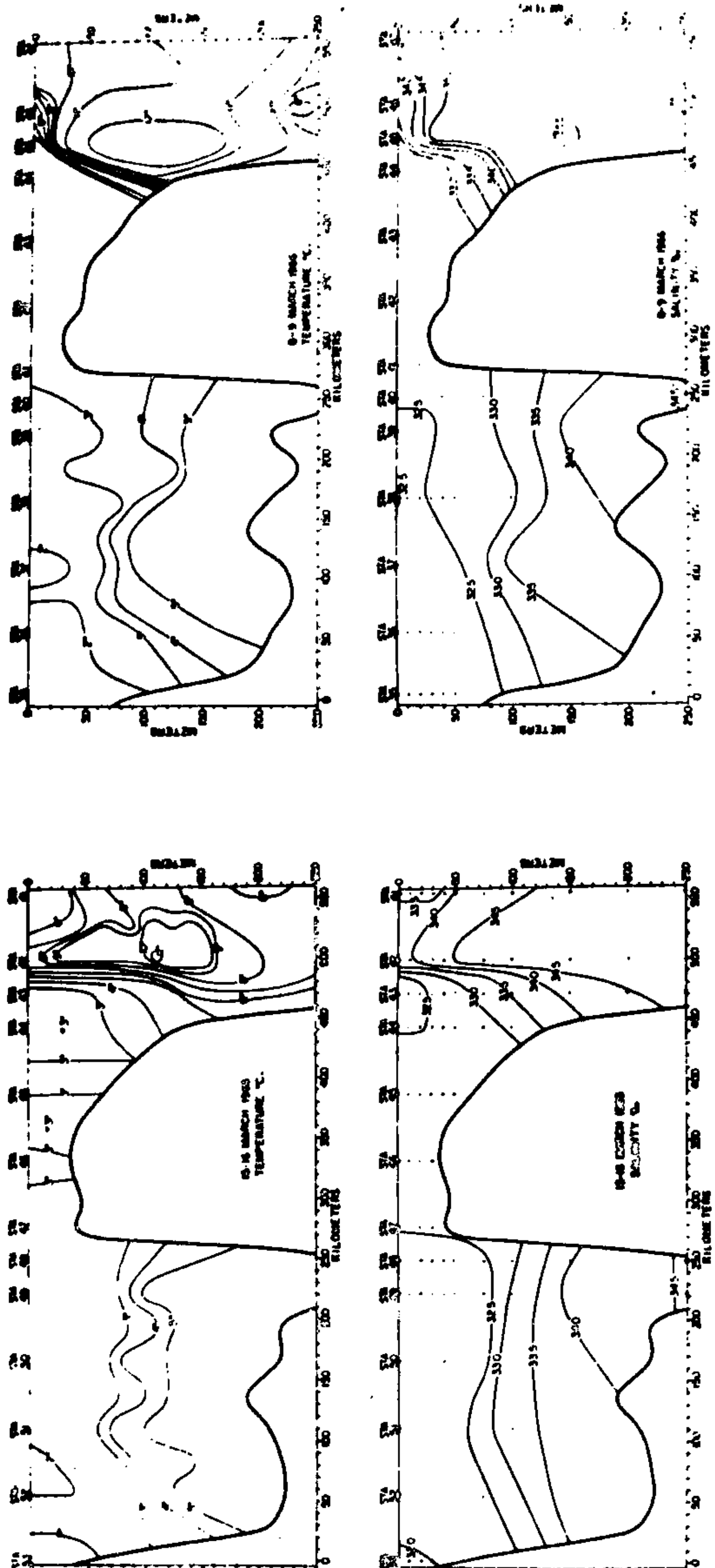

Fig. 4. Temperature, salinity profiles along 67° 30'W across Gulf of Maine for March 1965 and 1966 (Colton, et al. 1968).

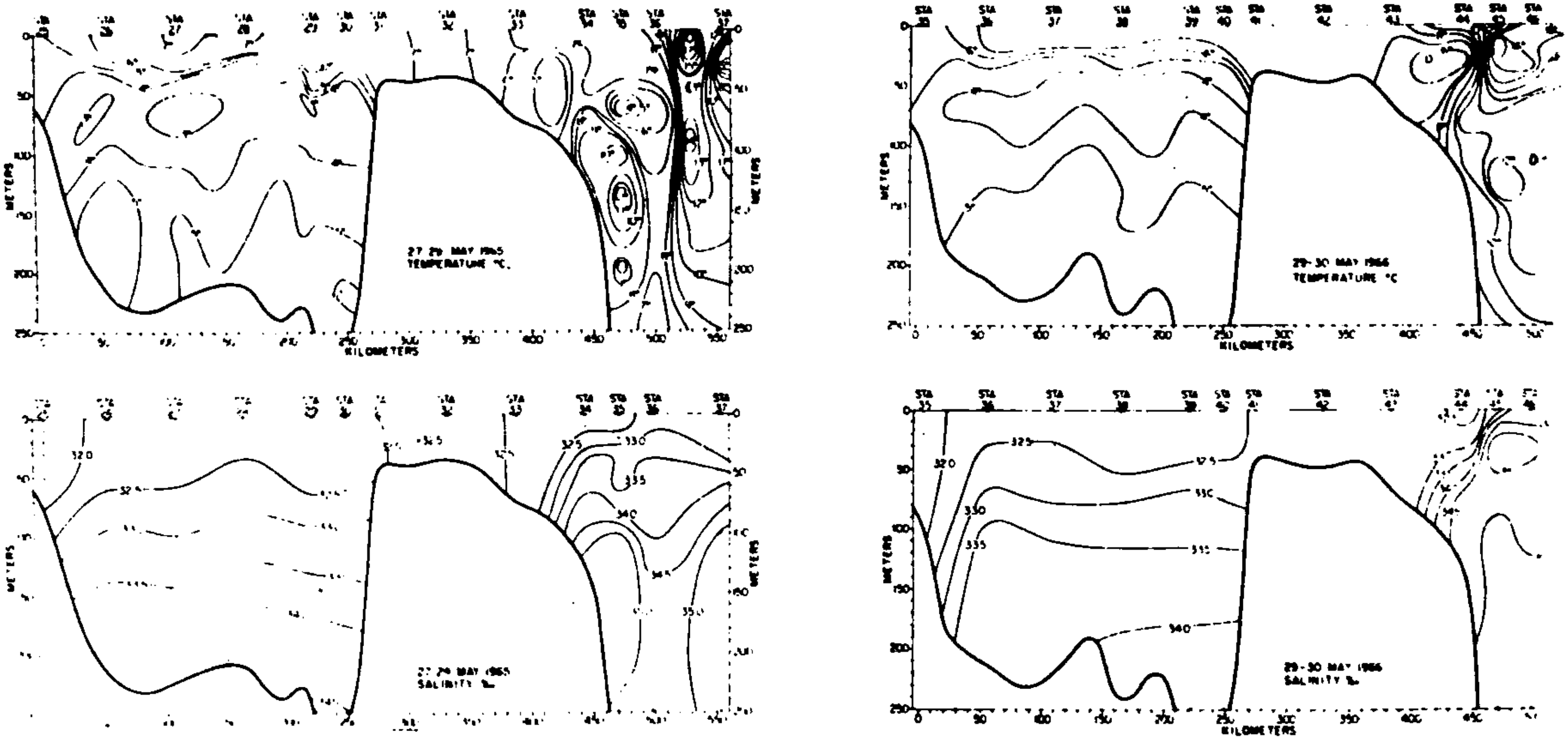

Fig. 5. Temperature, salinity profiles along 67° 30'W across Gulf of Maine for May 1965 and 1966 (Colton, et al. 1968).

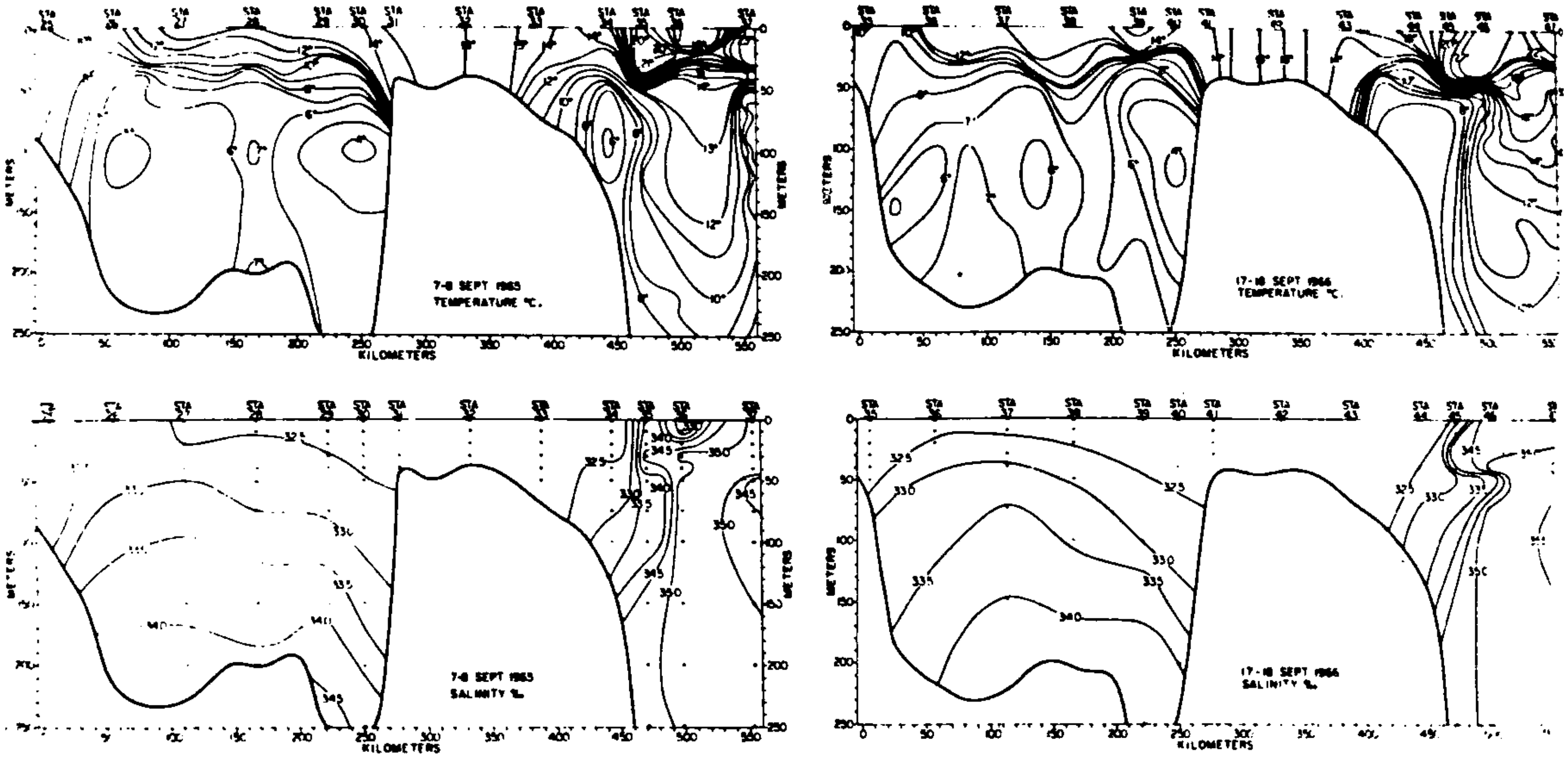

Fig. 6. Temperature, salinity profiles along 67° 30'W across Gulf of Maine for September 1965 and 1966 (Colton, et al. 1968).

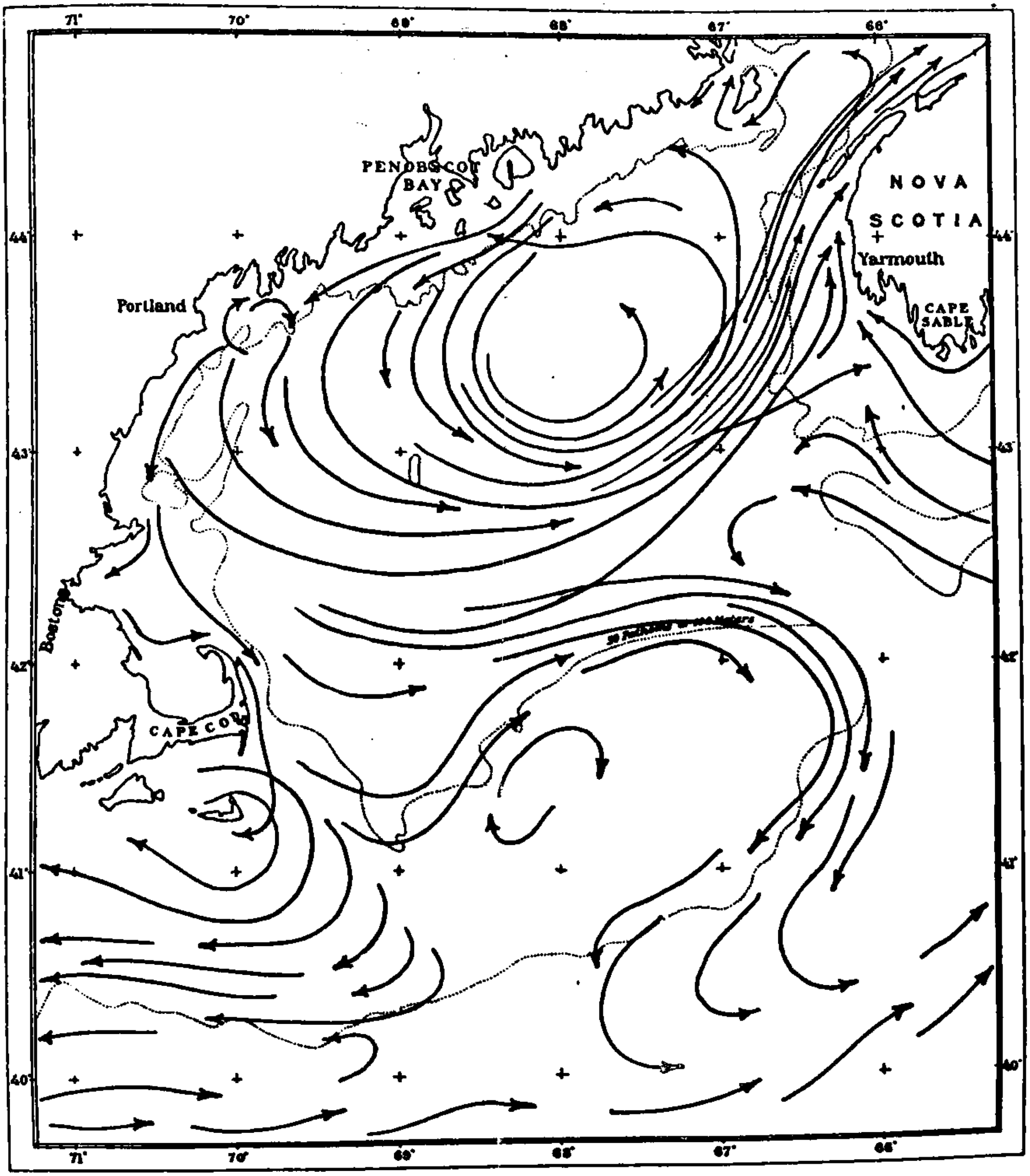

Fig. 7. Schematic representation of the dominant non-tidal circulation of the Gulf of Maine, July to August (Bigelow, 1927).

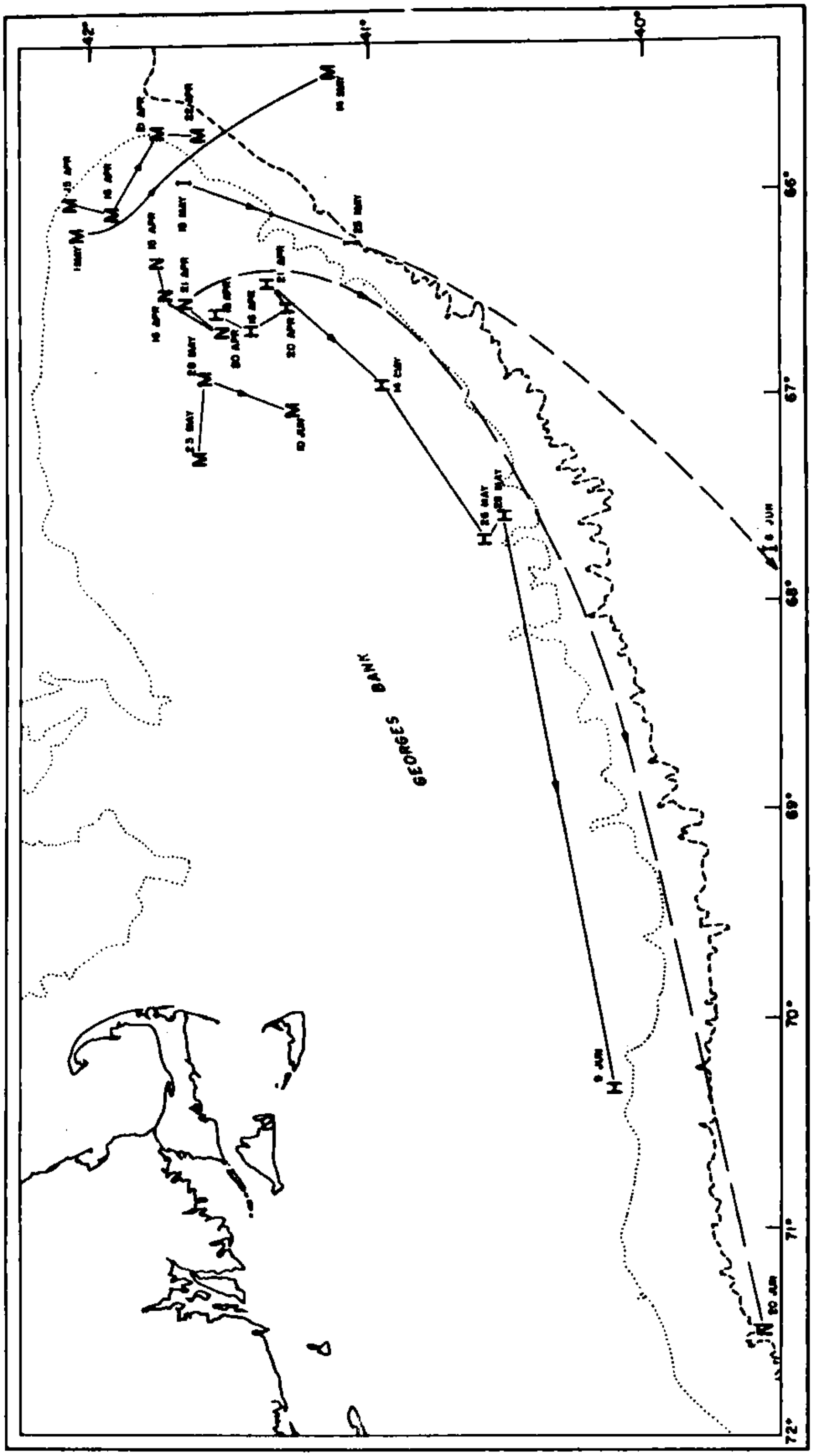

Fig. 8. Drift buoy trajectories 15 April to 10 June, 1957.

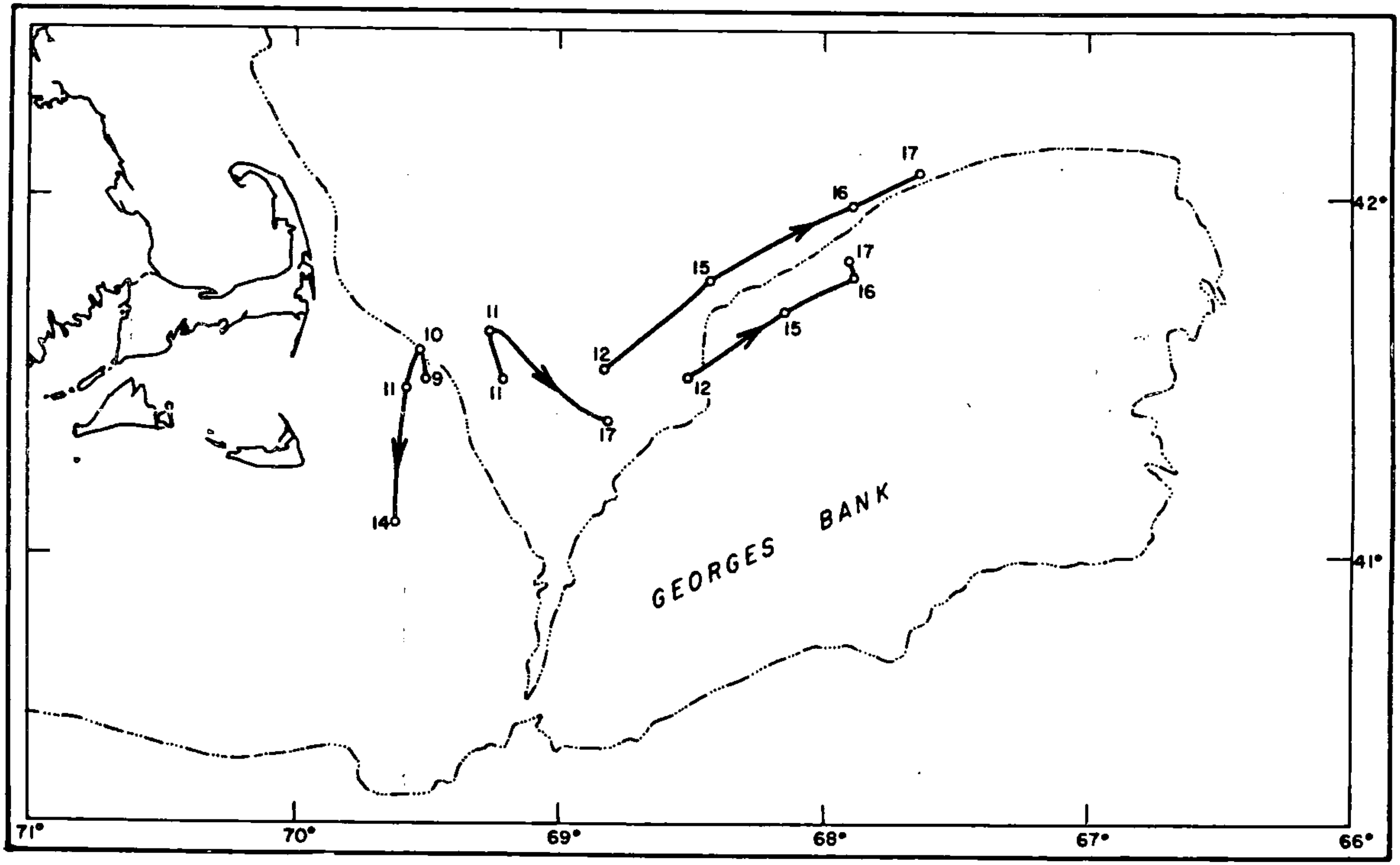

Fig. 9. Drift buoy trajectories 9-17 October, 1957.

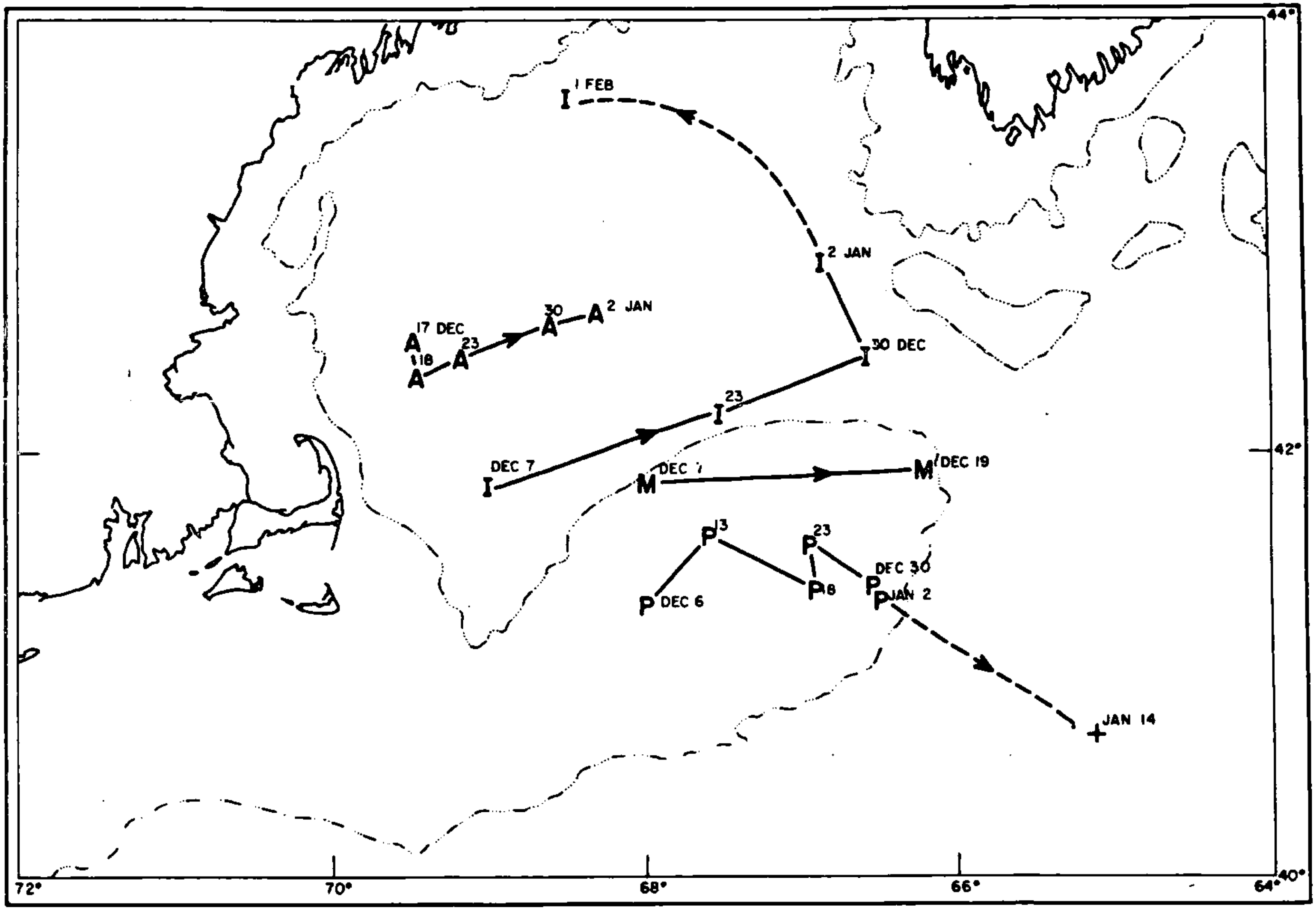

Fig. 10. Drift buoy trajectories December 1957.

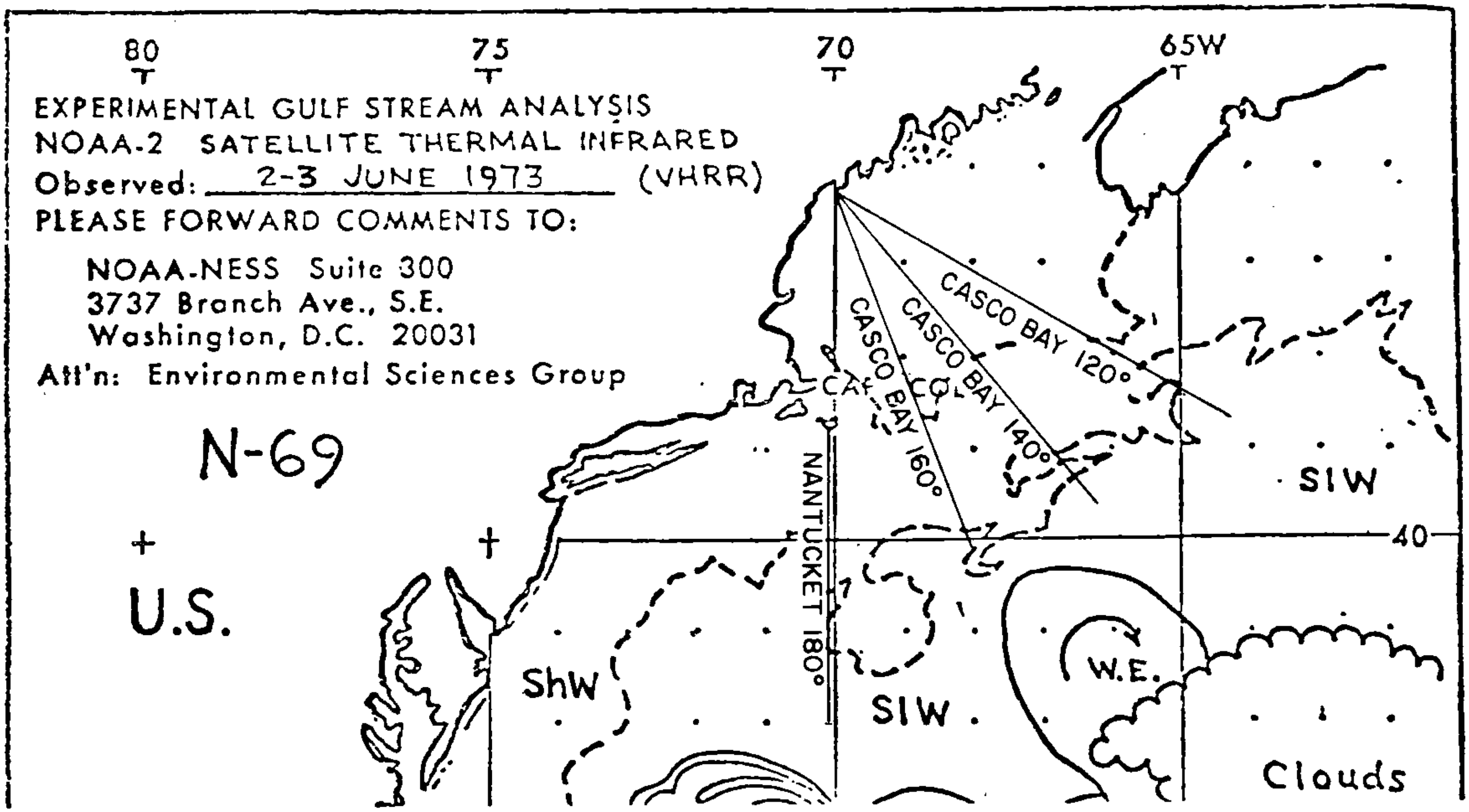

Fig. 11. Example of weekly frontal chart produced by National Environmental Satellite Service, NOAA.

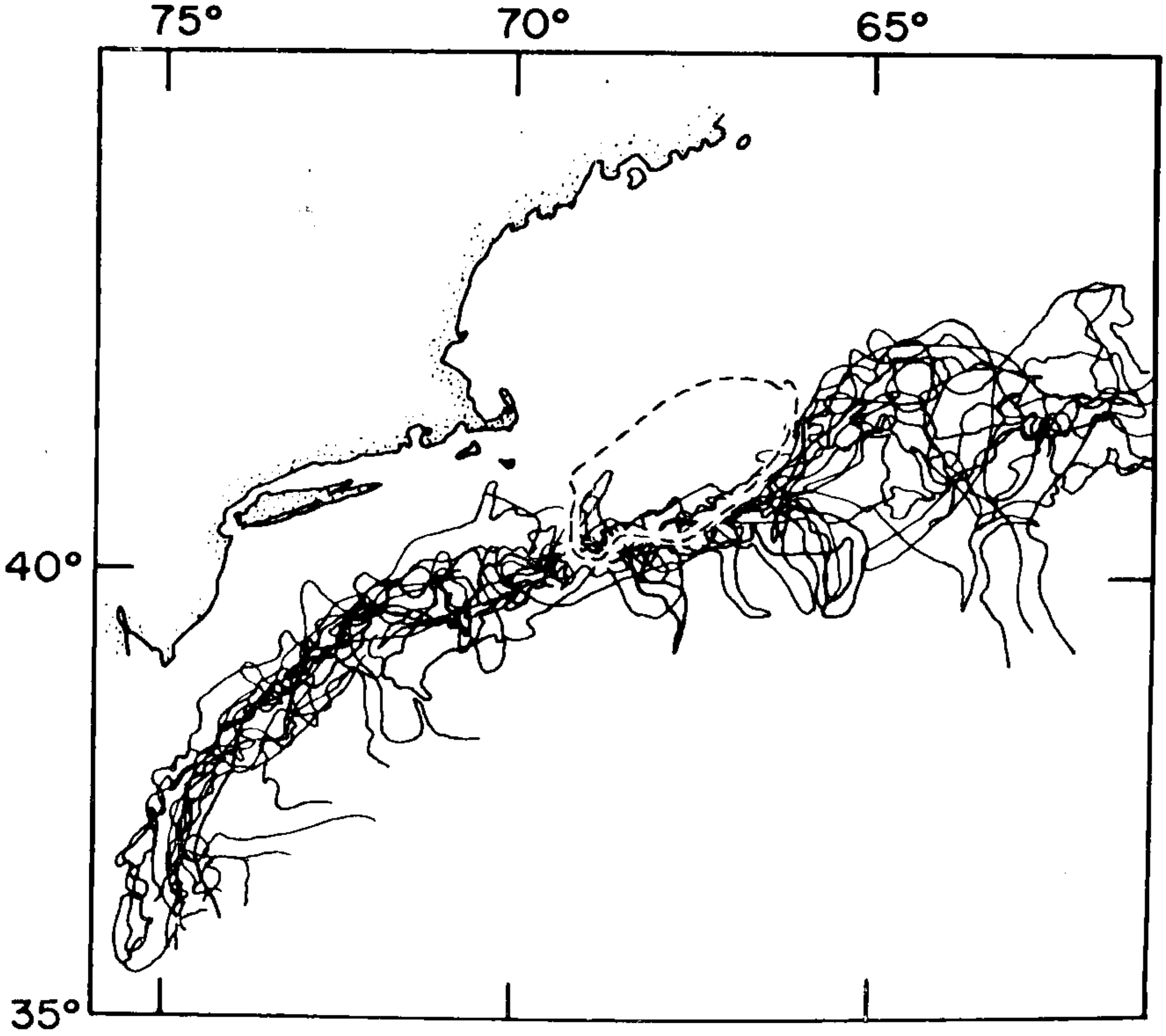

Fig. 12. Frontal positions as reported during September to December 1973 and 1974.

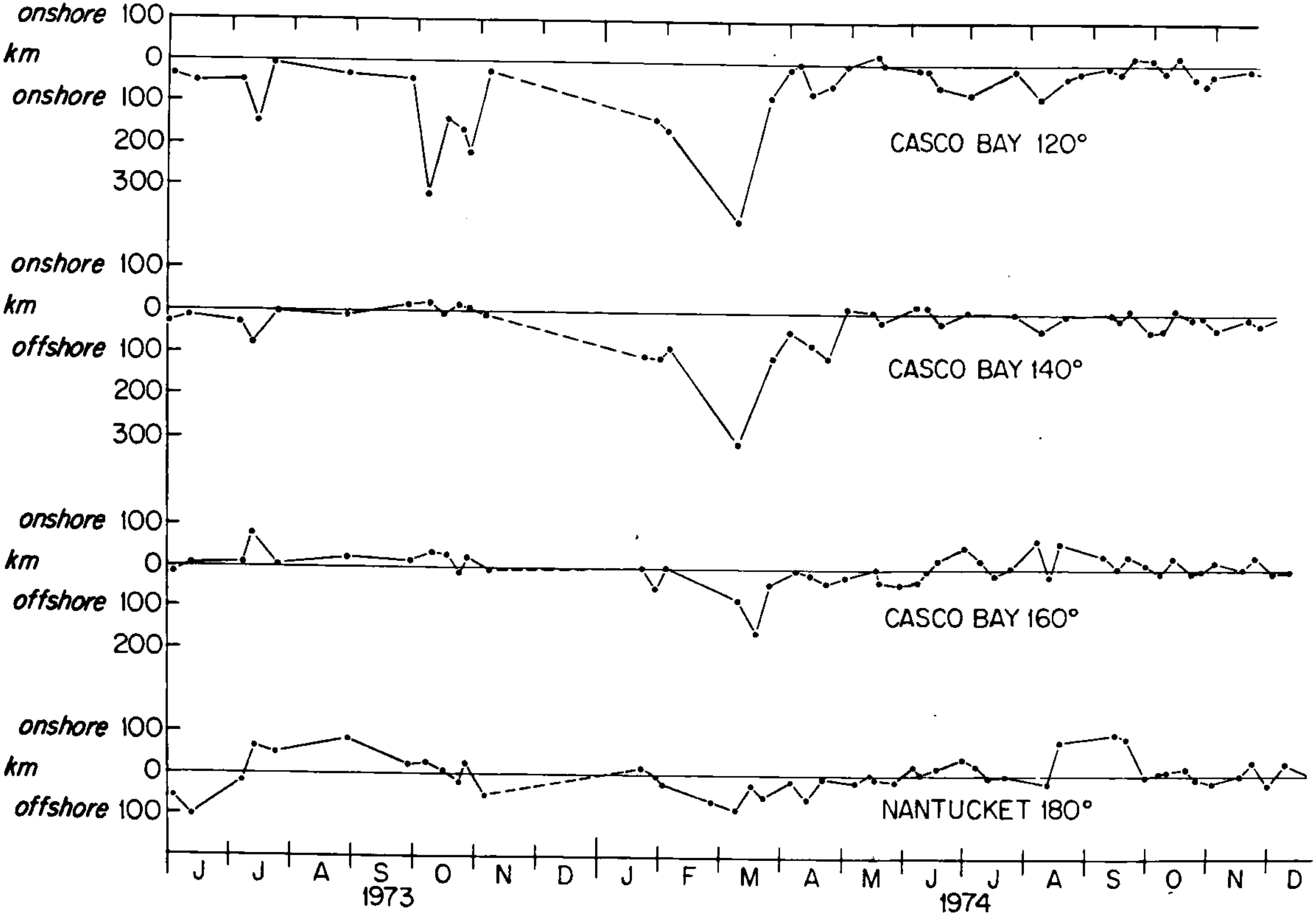

Fig. 13. Temporal variation of the position of the Shelf Water front relative to the edge of the Continental Shelf along the indicated azimuths. Positive values are shoreward from the shelf edge.

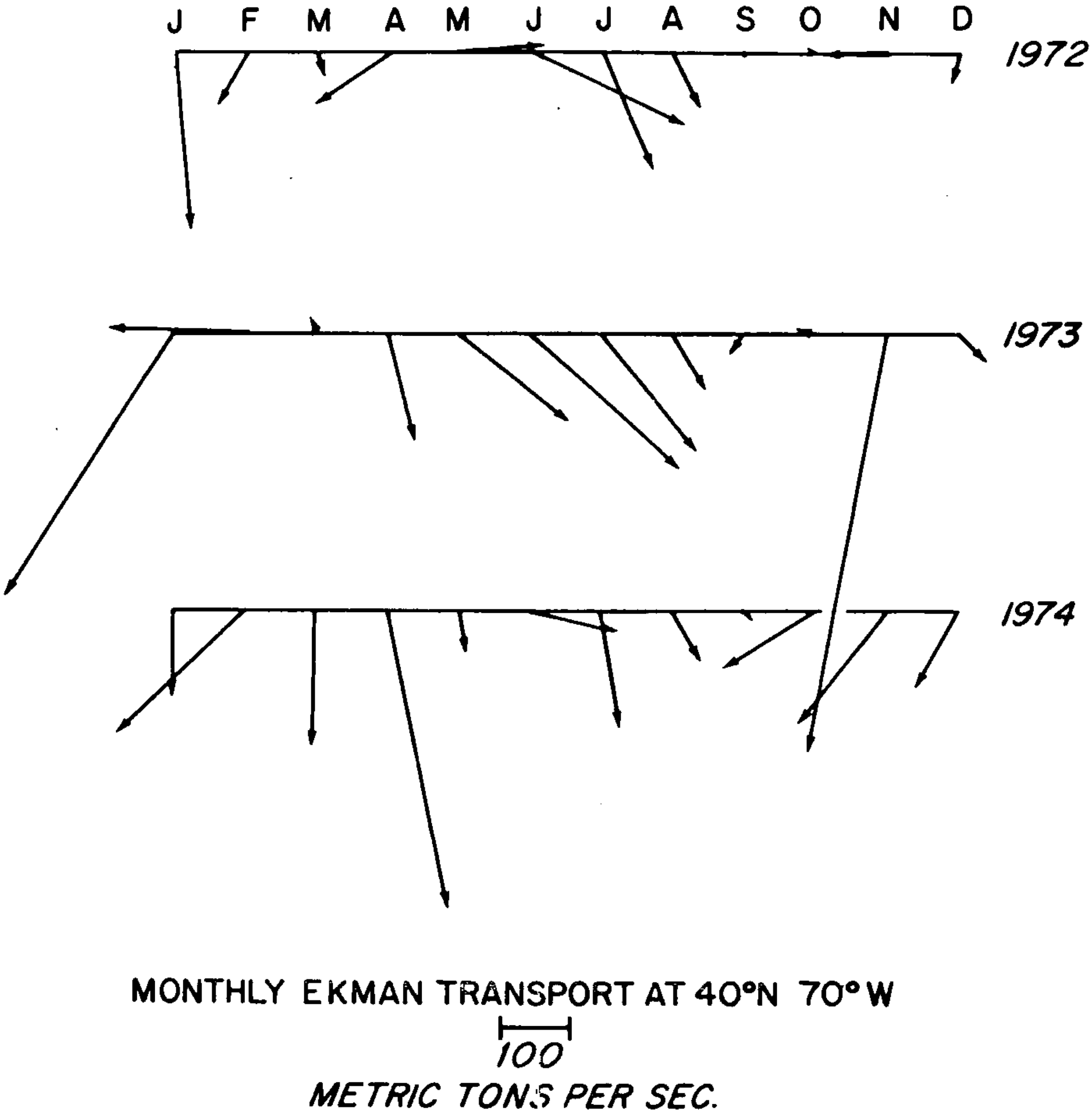

Fig. 14. Monthly Ekman Transport at 40° N 70° W for 1972-1974.

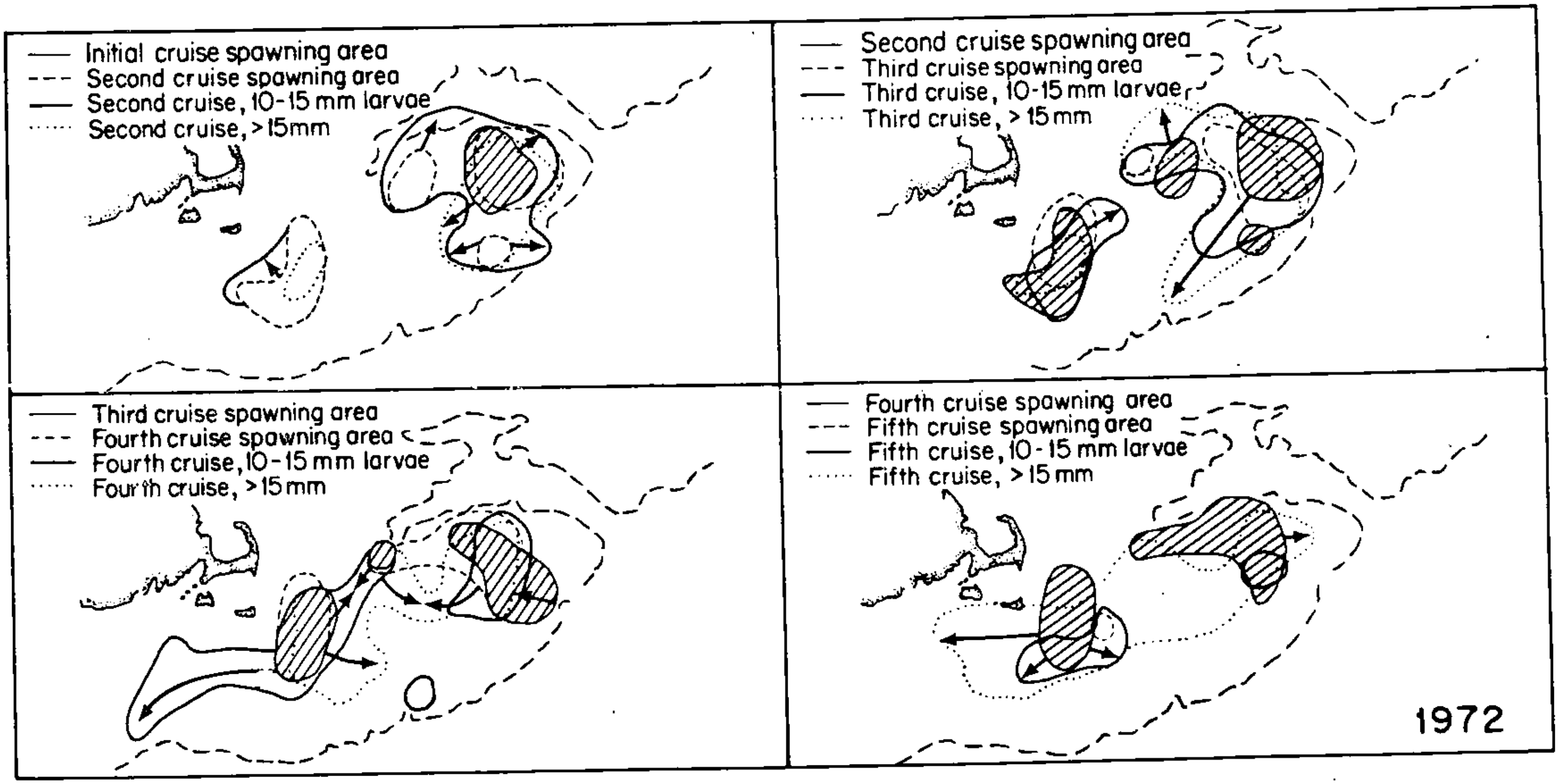

Fig. 15. Locations of various length herring larvae relative to previous cruises in 1972.

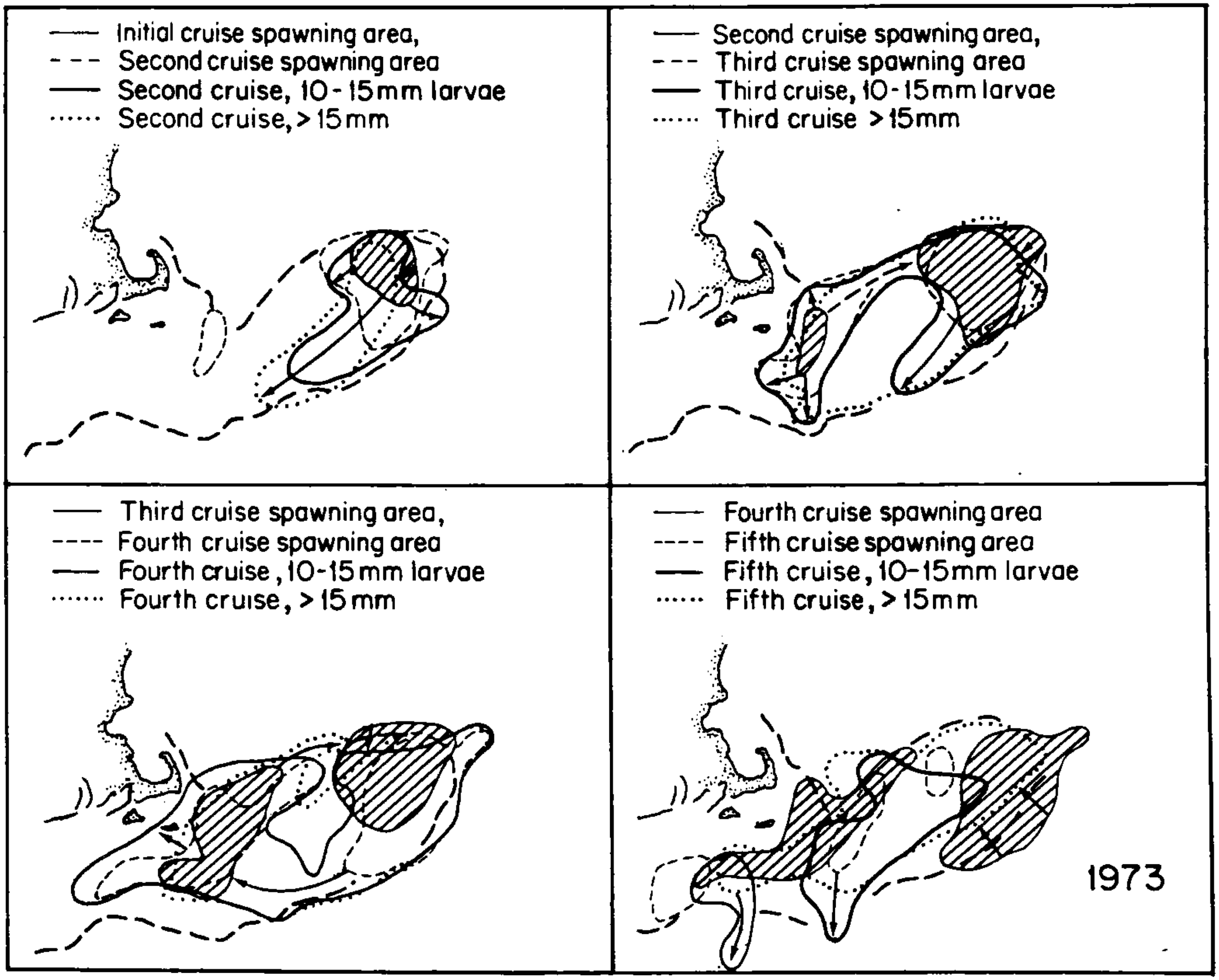

Fig. 16. Locations of various length herring larvae relative to previous cruises in 1973.

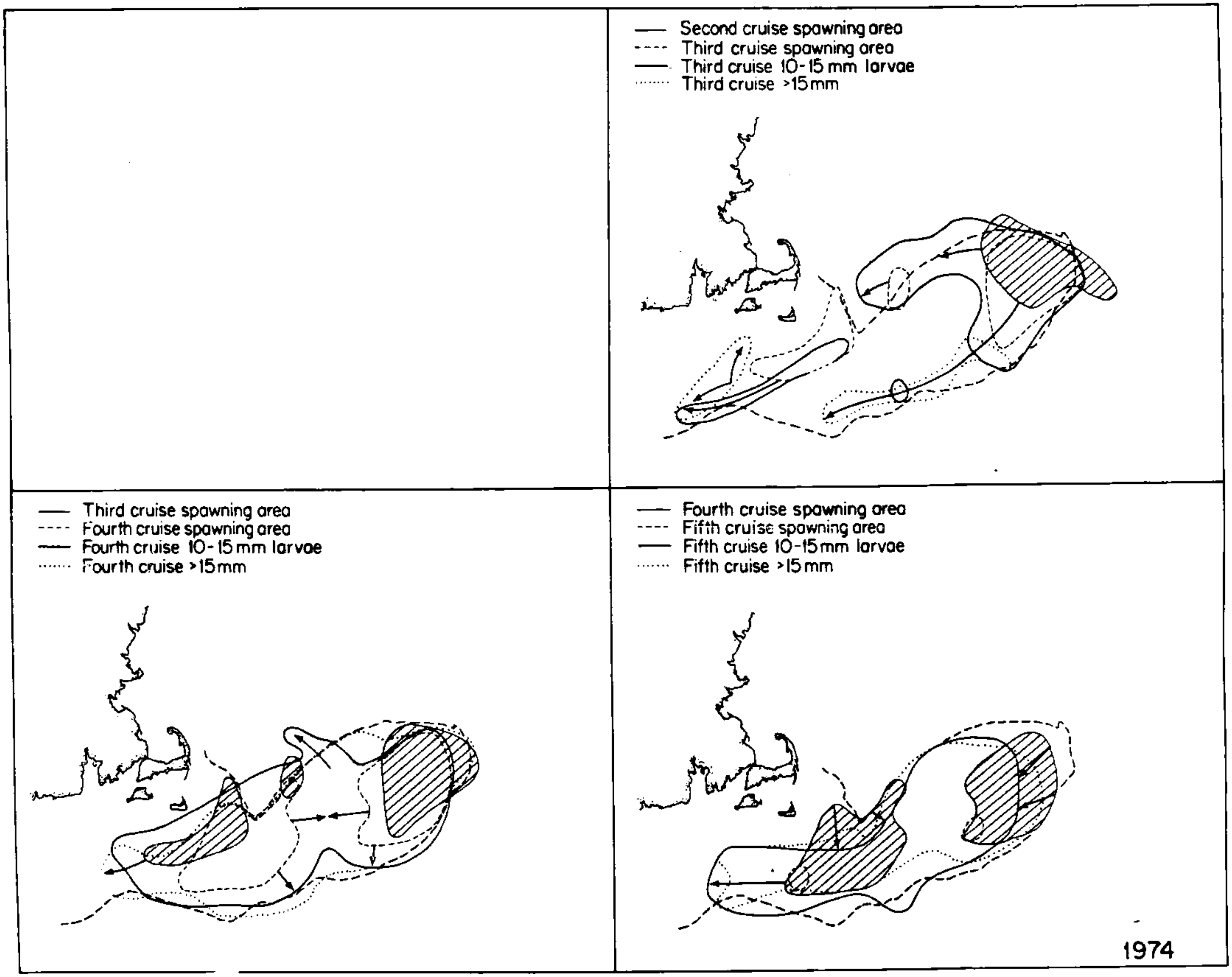

Fig. 17. Locations of various length herring larvae relative to previous cruises in 1974.