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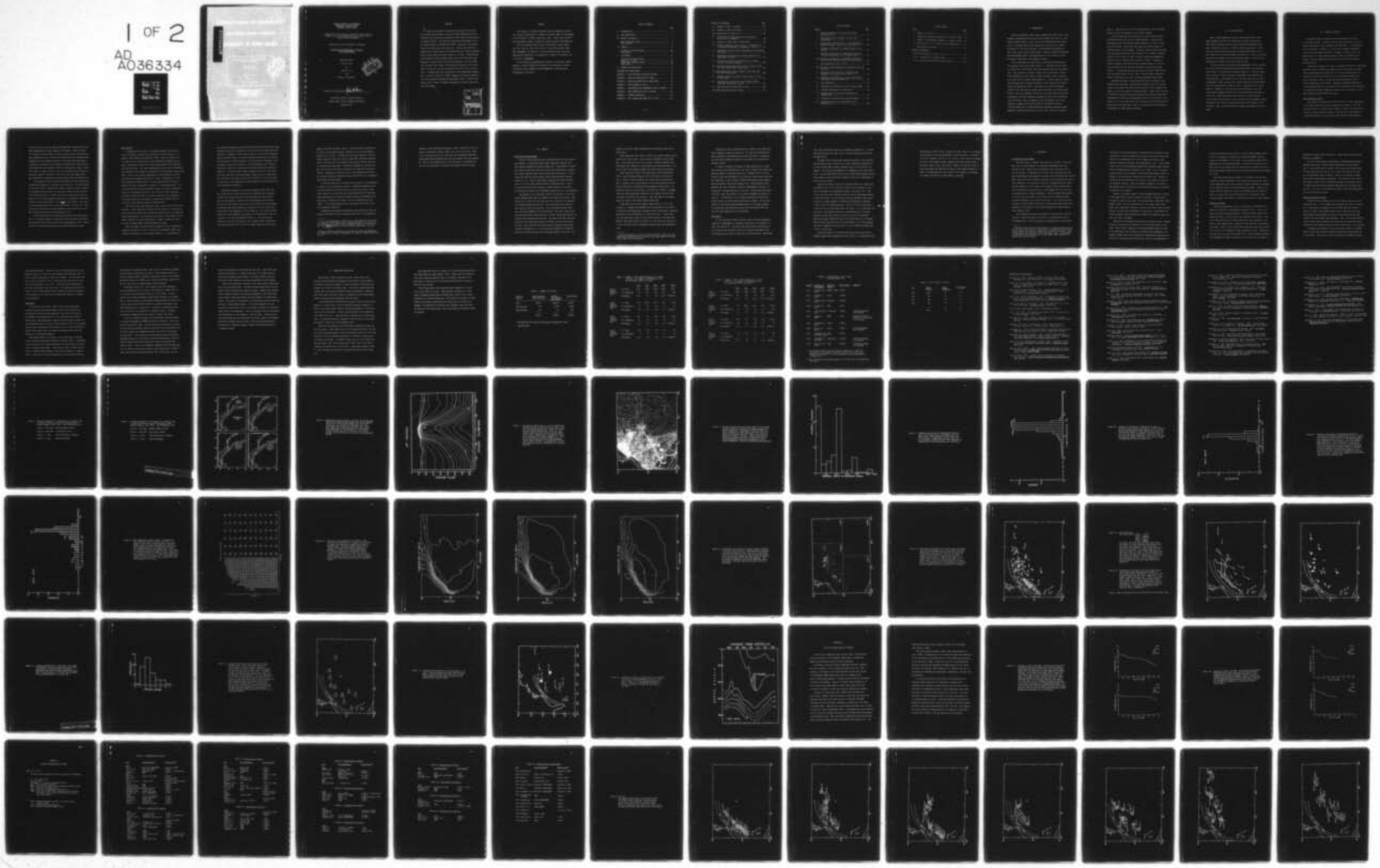

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Distribution and Movement of Cyclonic Gulf Stream Rings

Technical Report

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by

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and

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ABSTRACT

A study of the general distribution and movement of cyclonic Gulf Stream rings was made by analysing 50,000 temperature records obtained from the National Oceanographic Data Center and Fleet Numerical Weather Central. The data were taken from 1970 through 1973 in the region bounded by 20-40°N and 50-80°W. Additional ring observations from other sources were also used. Twelve ring time-series, together with fifteen single ring observations were obtained; approximately eleven rings were found to exist at one time. They typically moved westward, turned southwest when close to the Gulf Stream and appeared to coalesce with the Stream near Florida. On the average, about one and a half rings a year moved down this path, with a mean speed of three km a day and an estimated life span of two to three years. Although rings were concentrated in the northwestern Sargasso Sea, a few were found east of 60°W. However, the low data density in the eastern region prevented detailed analysis there. Several warm eddies, with at least a 150-meter deepening of the main thermocline, were also found.

PREFACE

This report in a slightly different form was submitted by David Lai as partial fulfillment of a Master of Science degree in Oceanography at the University of Rhode Island (Lai, 1976). Recent data (1974-76) has been added in order to extend the initial results (see Appendix H).

Data was obtained from a series of R/V Trident cruises (TR-98, 104, 125, 128, 161, 168, 175), as well as from other sources, NODC, FNWC, NAVOCEANO. We thank all those who generously made their ring observations available to us, especially R. Cheney, G. Gotthardt, and R. Pershal of NAVOCEANO.

We are pleased to acknowledge the support of the Office of Naval Research, contract N00014-68-A-215-0003 to the University of Rhode Island and contract N00014-74-C-0262 NR083-004 to the Woods Hole Oceanographic Institution.

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I. INTRODUCTION

Despite considerable effort spent studying Gulf Stream rings, their movement, geographical distribution and the number that exist at a time remains largely unknown. This is due to the difficulty and the large cost in following rings by ship and aircraft and the lack of remote techniques to track them over time. The problem being addressed in this study was to use all data sources: satellite infrared photographs, bathythermographs (XBT's) and hydrostations, in an attempt to reveal the general distribution and movement of rings.

Gulf Stream rings are formed east of Cape Hatteras from pinched off meanders of the Gulf Stream (Figure 1). Although they are formed on either side of the Stream, this study concerns those on the southern side. They consist of a cooler, fresher core of Slope Water (Iselin, 1936) embedded in a swift ring of counterclockwise current, and hence, are called cold or cyclonic rings (Figure 2). Cyclonic rings are large scale features with an overall diameter of 200 to 300 km and a depth of several km (Fuglister, 1972). They appear to be the most energetic eddies in the ocean and are integral and vital parts of the Gulf Stream System. They are responsible for part of the recirculation of the Gulf Stream water via their formation, movement and their final coalescence with the Stream. They are thought to play an important role in the transfer of energy from the Gulf Stream to the midocean areas as transient eddies and in redistributing low frequency mesoscale energy, momentum, chemicals and even biota in the ocean. Hence, the study of rings is important not only to the understanding of the Gulf Stream System, but also the dynamics of the midocean regions.

Cyclonic rings were first discovered by Iselin (1940) studying long-term variations of the Gulf Stream transport. Fuglister and Worthington (1951) observed the actual formation of a ring in a Multiple Ship Survey. Since then, there have been several reports on different types of ring movement. Fuglister (1972) observed two rings for five months during which time they moved in a looping, clockwise trajectory with a speed of about 10 cm/sec; their mean movement was slightly south of westward with a speed of 7 cm/sec. Richardson, Strong and Knauss (1973) reported the southwest motion of a ring for fourteen months and its apparent coalescence with the Stream near Florida. A westward moving ring was remotely tracked by SOFAR floats for four months (Cheney, et al., 1976). Further remote tracking of rings is being done by the use of satellite-tracked surface buoys.

Although the number of rings formed each year is unknown, a few estimates have been made. Newton (1961) estimated that five to seven cyclonic rings might form each year and Fuglister (1972) suggested the number to be five to eight by a different model. Parker (1971) was able to identify 62 rings in the western Sargasso Sea, using the Woods Hole Oceanographic Institution bathythermograph data file from 1932 to 1970. However, it is very likely that some of these 62 rings are different observations of the same rings. Hence, the question of the distribution and movement of rings remains unresolved.

II. DATA ACQUISITION

Nearly 50,000 temperature records taken during 1970-73 in the region bounded by 20-40°N and 50-80°W were obtained from the Navy Fleet Numerical Weather Central and the National Oceanographic Data Center (hereafter refered to as FNWC and NODC respectively). The records are unevenly distributed and are concentrated heavily in the Gulf Stream and the western Sargasso Sea (Figure 3). There is an abrupt decrease in the number of data in the eastern region. There are also some apparent erroneous data which appear on land.

The data are mostly expendable bathythermographs (XBT's), together with a few salinity-temperature-depth stations (STD's) and hydrostations (Table 1), reaching various depths (Figure 4). They were taken from a variety of ships including oceanographic, Navy, merchant and fishing vessels. Unfortunately most of the XBT's from the U.S. Naval Oceanographic Office cruises, which contain numerous ring observations, have not been submitted to NODC and were not analysed in this study. However, a summary of their results has been published in the Gulf Stream Monthly Summary (1970-73) and these observations were added to this study. Other ring observations reported by other available sources which did not appear in the above data file (Richardson, Strong and Knauss, 1973; Stumpf, Strong and Pritchard, 1973; Raschig, 1973; Gotthardt, 1973), including satellite infrared photographs, were also added.

III. METHOD OF ANALYSIS

Analysis consisted of computing the mean temperature field at five different depths. Anomalies from the mean, equivalent to a 150 m upward displacement of the isotherms, were identified. A "ring observation" was defined to consist of at least three anomalies identified within a five day period and within a diameter of 100 km. Since the identification of rings depends strongly on what is considered as an anomaly, the mean temperature field and ring criteria are carefully described below.

Although the change in the depth of isotherms was used for identifying anomalies, maps of isotherm topography were not used because the XBT's with minimum temperatures higher than that of the isotherm under consideration would have been left out in the computation, making such maps cold-biased. Hence, the mean horizontal temperature field at various depths were used instead. Temperature anomalies equivalent to a certain displacement of an isotherm from its mean depth were identified by considering the mean temperature gradient and the difference in the mean temperature field between two depths.

Mean Temperature Field

The region was divided into small bins (1°X1° or 2°X3°, depending on the data density) and the mean temperature at depths of 300, 450, 500, 600 and 700 m in each bin were computed. However, the data distribution is neither random nor normal, often due to the large number of measurements taken in a ring within a short period of time (Figure 5).

This bias is more acute in some bins (Figure 6a,b), resulting in lower mean temperatures and large temperature variances. These cold data were removed from the dataset in order to obtain a more representative mean temperature field. Those which deviated from the preliminary mean temperature by one standard deviation in bins whose root mean square temperature is greater than one degree Centigrade were removed and the mean temperature was recomputed from the remaining data; figure 7 shows the values at a depth of 450 m. Due to the extreme low data density or high percentage of ring data in a few bins, their mean temperatures were obtained by interpolating between adjacent values (see Appendix F).

The temperature contour maps were obtained by linear interpolation between mean temperature of adjacent bins (Figure 8). The mean position of the Gulf Stream is marked by the region of large horizontal temperature gradient and the axis of the mean Gulf Stream coincides with the 13°C isotherm at 300 m. At 300 m, the field is dominated by water between 17.5 to 18°C (the Eighteen Degree Water, Worthington, 1959) which extends south to nearly 20°N. In the deeper layer (700 m), the center of the subtropical gyre can be seen centered near 34°N and 72°W. South and east of this point, the main thermocline rises, indicative of the Gulf Stream recirculation gyre (Worthington, 1977).

A search was made for the seasonal variations in the main thermocline. No seasonal change in temperature at depths greater than 400 m was detectable from noise level which was approximately ± 50 m. Identification of rings was made using time averaged temperature fields.

Ring Criteria

In general practice and as a convenient standard, the size of a ring is frequently estimated from the extent of the 15°C water at a depth of 500 m (Cheney and Richardson, 1976). Since the depth of the 15° surface lies at about 650 m in the northwestern Sargasso Sea, the edge is equivalent to about 150 m upward displacement of the isotherms from the mean field. The 150 m displacement is about twice the displacement amplitude of the eddies in the MODE area (Draft Synoptic Atlas, 1974). Thus, a 150 m or more upward displacement of the thermocline at 450 m was chosen as an anomaly indicative of a ring. Furthermore, at least three anomalies observed within a five day period within a 100 km of diameter were then considered to consist of a "ring observation". The five day period and 100 km of diameter criteria are based on realistic values of ring movement and size. The criterion of three anomalies was used to reduce the effect of erroneous data (see also Appendix A). The criteria used here are similar to those used by Parker (1971) in his study, using older and shallower mechanical BTs.

The ring criteria were changed in order to see how the results were affected. It was found that although the total number of ring observations varied with changes in time and size criteria (up to two weeks and 200 km respectively), the ring trajectories and the total number of different rings did not vary significantly. However, variations in the criteria of height anomaly did show different results.

When the height criteria was 100 m instead of 150 m, the number of anomalies increased by a factor of three in the southwest region; the increases were smaller in other regions (Table 2). A large number of the additional anomalies were associated with previously identified rings obtained from the 150 m anomalies, but five new "ring observations" were identified. Attempts to infer ring time-series from the 100 m anomalies proved fruitless because the results depended critically on the subjective decisions as to which anomalies to use and which to disregard. When the height criteria was lowered to a 50 m displacement, even "ring observations" could not be identified without much subjective choosing of anomalies. On the other hand, when an anomaly criterion of more than 150 m was used, most of the measurements taken on ships of opportunity were eliminated since usually they were not taken at or near the center of the rings; it was impossible to infer movement of rings from the few ring observations identified.

Temperature anomalies in the region bounded by 20°N, 50°W, the Gulf Stream and the Antilles Islands were identified and "ring observations" were formed from those which satisfied the ring criteria. The ring observations, together with those anomalies which did not satisfy the ring criteria, were used to trace individual ring movement. One thousand and eight temperature records, 6% of all the data, were identified as cold anomalies at 450 m (Figure 9). The region has been divided into four subregions, according to the differences in the distribution of the data and anomalies (Table 2). The percentage of anomalies of the data is highest in the northwest region, indicating the higher probabiliy (8.7 ± 0.5%) of finding rings there; the second number is the 90% confidence limits.[1] Very few rings are expected to be found in the southwest region, indicated by the low percentage of anomalies (1.1 ± 0.2%). Although the percentage anomalies in the two eastern regions is about 5%, the much larger 90% confidence intervals (about 1 and 2%), due to much smaller data density, make it difficult to conclude that rings exist. Temperature anomalies at 400 and 700 m were also used but they did not contribute any additional ring observations. Temperature at 300 m were only used supplementally because of the small temperature gradient between 300 and 450 m in the Eighteen Degree Water at these depths.

It appeared that some of the data from the same set of instruments or vessels were of questionable quality. Individual temperature profiles were checked for possible errors (incorrect positions, inversions, spikes, etc.) and those that looked suspicious were discarded. Ring observations were checked by comparing them to non-anomalous observations; if there was a conflict, the ring observation was discarded. In the ring observations and time-series, 697 (69%) of the total anomalies, were used.

Temperature and salinity measurements taken inside cold rings revealed a difference in the T-S relation from that of the Sargasso Sea

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[1] If P is the proportion of success (i.e. the probability of success) in a sample of size N drawn from a binomial population in which p is the proportion of success, then the confidence limits for p are given by $P \pm Z_c \sqrt{\frac{p(1-p)}{N}}$ where Z_c is the confidence coefficient. All the

confidence intervals computed in this study were done by assuming all the temperature records are independent and using the sample proportion P as p.

(Molinari, 1970; Cheney and Richardson, 1976), indicative of the presence of Slope Water (Iselin, 1936) in the core of the rings. Some of the rings observed in this study have this additional supporting measurement which documented that they were indeed rings (see Appendix B). Not all ring observations in this study were so documented but the six that were give us confidence that others really are rings.

IV. RESULTS

Cyclonic Gulf Stream Rings

Forty-two ring observations were identified when the ring criteria were applied. An additional twenty-eight rings were obtained from other sources mentioned previously (Figure 10). The movement of individual rings was inferred from these seventy ring observations, together with single anomalies which did not satisfy the ring criteria. Twelve ring time-series and fifteen single ring observations were obtained (Figure 11, 12). Some of these single rings may be repeated observations of the same rings separated widely in time and space. Five of the time-series were long, covering a period from one to two years. An additional six series were established using only one or two anomalies.

The majority of the rings were found in the western, or the northwestern Sargasso Sea, where the highest data density was located. Nine rings (four in 1970, three in 1971, one each in 1972 and 1973) appeared to be formed between 60° and 70°W. Other rings might have formed in this region but were not observed. Four rings moved westward until they were within 200 miles of the Gulf Stream. Then they turned southwest and moved along a path parallel to the Gulf Stream and appeared to coalesce with the Stream near Florida. Six rings moved down this path during the four years under study, an average rate of one and a half per year. Since there may have been rings not observed, this should represent a minimum rate. If the rings were assumed to be formed between 60° and 70°W and moved with an average speed of 3 km a day, the average life span of rings following this path would be about two to three years.

Three rings were found south of 30°N in the western region and far away from the Gulf Stream. These rings also appeared to move southwest. Their motion may consist of a larger southward component into the Sargasso Sea compared to the westward motion discussed above. The fate of these rings remains unknown from these limited observations.

Three rings were found in the region east of 60°W which Parker (1971), using shallower mechanical BT's, had found to be devoid of rings. There is limited evidence that these rings also moved westward.[2] However, the low data density in this region prevents any detailed description of distribution and movement of rings there. No rings were found in an area south of 30°N and east of 65°W. Although there were some temperature anomalies in this region, the data were too sparse to meet the ring criteria. Thus, the question of whether rings are found in this region remains unresolved.

Rings moved with various speeds, ranging from 1 to 7 km a day (Figure 13). Speeds were estimated from the positions of the center of adjacent ring observations, sometimes rather subjectively, especially when there were few anomalies in a ring observation. Speed varied not only from ring to ring, but also along the path of the same ring. However, 82% of the speeds lie within 1 to 4 km a day, and the mean is 2.7 km a day which can be considered as typical mean ring translation rate.

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[2] Recent measurements in 1975 and 1976 (McCartney, 1975a) have confirmed these observations and indicated that large rings can be found in this region (see Appendix H).

Although most ring tracks appeared to be smooth, some rings made abrupt changes in speed and direction. The large time separation between consecutive ring observations and the difficulty in estimating the ring centers prevented details of the motion as was reported by Fuglister (1972).

In order to estimate the number of rings coexisting at a single time, the data was scrutinised for the time of highest data density and greatest number of rings and time-series. November 1971 was chosen because it was near the middle of the four-year period under study and, more important, it was the time of MODE-0 when numerous measurements were being made in the western Sargasso Sea. Ring positions during November 1971 were estimated, using the rings'apparent direction of motion and an average speed of 2.7 km a day. Eleven rings were found to exist at that time, mostly in the western Sargasso Sea (Figure 14, Table 4). The positions of a few single rings have not been extrapolated because of their unknown directions of motion. The low data density in the eastern and southeastern part of the region suggests the possibility that additional rings could have existed there and that the above number may be a low estimate.

Warm Eddies

Of the total data at 600 m, 2% were found to be warm temperature anomalies corresponding to a downward displacement of isotherms of at least 150 m (Table 5). Two warm "ring observations" satisfying the ring criteria were obtained; these will be termed warm eddies since warm rings are only found to the north of the Gulf Stream. There were five other observations each with two anomalies (Figure 15). Of these seven observations, two were close to the Gulf Stream and three near the MODE region.

The XBT traces of these warm observations showed a thick (several hundred meters) layer of water with a small temperature gradient (17° to 19°C) between 300 and 600 m; sometimes part of the layer was isothermal. The layer was accompanied by a deepening of the main thermocline. The two warm eddies near the Gulf Stream showed maximum vertical displacements of more than 200 m (Figure 16) while the displacement of others were near 150 m.

Efforts were made to analyse the 450-meter XBT's but special care was needed since a 150 m increase in depth of the isotherms at this level corresponds to a temperature change of less than 1.0°C. Only in two cases were there sufficient data to provide convincing evidence of the warm eddies. On one occasion more than 300 XBT's taken within a month in a region bounded by 33-38°N and 63-69°W made a detailed study of one of the eddies possible. Water of 18°C was found down to a depth of 450 m or more among three cold rings. It is impossible from the data to tell whether there was a corresponding dip in the main thermocline under this layer but unless the vertical temperature gradient was much larger than usual, the thermocline had to be deeper. When the data from October 20 to 24 and November 1 to 4 were combined, there was a suggestion that the warm eddy moved rapidly westward with a rate of 20 km a day.

These warm eddies are characterized by the extra thick layer of Eighteen Degree Water extending from 200 to 600 m, as compared with the usual depths of 200 to 400 m. Beneath the layer, there is a corresponding deepening of the main thermocline of more than 150 m. The extent of the 18° isotherm at 450 m, or 17° at 600 m, both of which correspond to about a 150 m height anomaly, suggests that these features have a horizontal scale of less than 100 km. However, no detailed survey of these warm eddies was made and the shape of them remains largely unknown. If geostrophy and a deep layer of zero velocity are assumed, a clockwise circulation in these eddies is obtained.

V. DISCUSSION

Cyclonic Gulf Stream Rings

From this study, it appears that there are two types of ring movement, both of which showed a net southwest displacement over long periods of time. Some rings moved westward until they came close to the Gulf Stream. On approaching the Stream, they turned abruptly and moved southwestward and appeared to coalesce with the Stream near Florida.[3] Other rings took a more southward direction into the Sargasso Sea after their formation. The results of this study, together with other observations (Fuglister, 1972; Parker, 1971; Stumpf, Strong and Pritchard, 1973; Richardson, Strong and Knauss, 1973) suggest that the first type of movement may be a common phenomenon. From the limited observations, it is not clear how typical is the second type of movement and what ultimately happened to the rings on this path. It is likely that they decayed to a point beyond recognition as Gulf Stream rings and may have appeared as "cold spots" in the southern Sargasso Sea (Draft Synoptic Atlas; Wunsch, 1975).

The processes that cause the movement of rings have not been determined. Rings may simply be advected by the general mean flow in the Sargasso Sea. On the other hand, the movement may be self-induced.

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[3] There have been no direct observations of a ring coalescing with the Gulf Stream in this region. Rings appear to consistently move towards Florida where they have been observed to be partially attached to the Stream (Cheney and Richardson, 1975; Richardson, 1976). The simplest explanation of the available data is that these rings eventually coalesce with the Gulf Stream.

Circulation in the North Atlantic is dominated by the subtropical gyre consisting of a narrow and fast Gulf Stream in the west and north and broad, slow southwestward flow in the Sargasso Sea (Iselin, 1936; Sverdrup, Johnson and Fleming, 1942; Worthington, 1977). Recent SOFAR float tracks in the northwestern Sargasso Sea provided further evidence of this southwestward flow (Cheney, et al., 1976). Part of the downstream increase in the transport of the Gulf Stream (Knauss, 1969) is thought to be recirculated by means of this return flow. Speeds of a few km per day are required in the inflow to the Stream to account for the transport increase. Thus the southwest movement of the rings in the Sargasso Sea is consistent with the speed and direction of the mean circulation of the region.

However, the abrupt change to a more southward direction of motion of the rings close to the Gulf Stream is puzzling. Countercurrents are known to exist on both sides of the Stream (Wust, 1936; Munk, 1950; Stommel, 1965). But the countercurrent is too narrow (about 50 km wide), swift (more than 20 cm/sec), shallow (about 200 m deep) and intermittent to account for the movement of rings there. Some unknown processes, probably from the interaction between the Stream and rings, may cause this type of movement.

Rings may be self-propelled through the surrounding fluid. Several theoretical studies have been made of the self-induced motion of the rings. Warren (1967) suggested the westward movement might be caused by the beta-effect and, similarly, by sloping bottom topography. The westward movement may also be explained by representing rings either as a packet of linear baroclinic Rossby waves (Flierl, in preparation) or as linear barotropic Rossby waves in a lateral shear (Yamagata, 1975). Flierl (in preparation) suggested the southward movement might be caused by the asymmetry of the rings. Stern (personal communication) suggested that the southward movement of rings may be related to the decay of the ring coupled with the conservation of potential vorticity. This theory agrees reasonably well with observations (Cheney and Richardson, 1976).

Since Gulf Stream rings probably do not extend to the bottom as coherent structures (Fuglister, 1972), except possibly during a short period immediately after their formation, bottom topography is probably not an important factor in determining their movement. However, the sudden change in direction of Ring 3 near Bermuda and the tendency of rings to coalesce with the Gulf Stream north of the Bahama Islands strongly suggest the presence of land masses does affect ring movement.

Rings east of 60°W

Three cold rings were found in a region east of 60°W which was found to be devoid of cold anomalies by Parker (1971). There is evidence that they also moved westward. McCartney (1975a) reported the recent discovery of several large cold features in this region. They have a 300 m uplifting of the main thermocline and a diameter of over 200 km. Worthington (1976) suggested calling them Gulf Stream Extension Rings. Some of these rings showed anomalously high oxygen content in the 12° to 17°C temperature range (Worthington, 1976). suggesting they were also rings with Slope Water cores. Recent studies associated with POLYMODE have added significantly to the data base, the number of anomalies and rings found in this area. These recent observations are analysed in Appendix H.

One Gulf Stream Extension Ring showed strong Mediterranean Water influence (McCartney, 1975a) possibly indicating an origin further east. A recent XBT transect (Seaver, 1975) across the Atlantic along 34° 30'N shows what may turn out to be large cold rings as far east as the Mid-Atlantic Ridge (35-40°W). However, the question of where and how they formed remains unexplained. The center core may contain Slope Water (Iselin, 1936) or Northern Gyre Water (Worthington, 1976). It appears that Gulf Stream Extension Rings move into the region west of 60°W. If so, it is very likely that some of the "ring observations" were actually these big rings.

Number and Spacing of Rings

Fuglister (1972) estimated that five to eight cyclonic rings are formed each year. If this number and an average life span of a ring of two to three years are assumed, ten to fifteen rings are expected to exist at a time. This estimate agrees closely with the eleven ring observations during November 1971 and the recent near-synoptic ring survey of the area (Cheney and Richardson, 1975). The low data density in the eastern regions suggests the possibility that additional rings could have existed there and that the above number may be a low estimate.

It appears that generally the spacing between centers of adjacent rings is about 300 to 400 km; sometimes the spacing between rings can be very small. The centers of Ring 2 and Ring 3 in November 1971 were less than 200 km apart. These two rings were exceptionally well documented so that it is clear they were spearate before December 1971. It is not known what happened to them after December. Did they merge into one or repel each other? There is indication that splitting of rings has occurred (Cheney, et al., 1976). Fuglister (1972) suggested his two rings came together and moved apart. The merging and splitting of rings (or Gulf Stream Extension Rings) should have profound influences on the dynamics of the rings and the neighboring fluid but it remains to be documented.

Warm Eddies

The results of this study, together with closely spaced XBT transects (Gulf Stream Monthly Summary; Noble, 1975) indicate that warm eddies with vertical displacements of more than 150 m exist in the Sargasso Sea although they occur less frequently than the Gulf Stream rings. Warm anticyclonic rings have been observed to break off on the shoreward side of the Gulf Stream (Saunders, 1971) but the Stream prevents them from moving into the Sargasso Sea. Thus the warm eddies found in this study have to be formed by mechanisms other than ring formation via Gulf Stream meanders.

Warm eddies appear to be similar to the anticyclonic "rotating lens" of Eighteen Degree Water observed by Swallow (1971). A deepening of more than 150 m of the main thermocline was found beneath the thick layer of Eighteen Degree Water. Velocities of about 50 cm/sec were observed in the Aries eddy (Swallow, 1971) which extended to a depth of 2000 m. There was no velocity measurement in the warm eddies found in this study but if geostrophy and a deep layer of no motion are assumed, an anticyclonic circulation is obtained. Other mid-ocean eddies observed by Swallow (1971), Koshlyakov and Grachev (1973), Gould, Schmitz and Wunsch (1974) and in MODE were of smaller displacement (about 50 m) and the thick layer of Eighteen Degree Water was absent.

Worthington (1959, 1971, 1972) suggested that the deepening of the main thermocline can be caused by the sinking of surface water as it is cooled by the Continental Polar Air in the winter. But his analysis only showed the Eighteen Degree Water influence in the upper 400 m. Sections across the warm eddies showed wavelike structures over a small region (about 100 km) instead of a general deepening of the main thermocline over a large area. In addition, no seasonal periodicity was found in the variation of thermocline depth. Therefore, Worthington's suggestion does not appear to explain the eddies.

Sources of mesoscale energy, and in particular, mid-ocean eddies, are being investigated by POLYMODE scientists and others. One of the possible sources are rings. Several theoretical studies have focussed on the interaction between ring-like features and the surrounding fluid and these studies have suggested features that could be interpreted as warm eddies. It was shown that westward moving obstacles generate meandering wakes in a stratified rotating fluid (McCartney, 1975b) and when the wakes become large enough, warm eddies are generated (McCartney, 1976). Flierl (in preparation) suggested that dispersed waves are left behind by moving and decaying rings, resulting in a series of highs and lows with decreasing amplitude east of the ring. The low could be interpreted as a warm eddy near the ring. Stern (1975) suggested the existence of a closely packed array of coupled cyclonic-anticyclonic systems called "modons", each with a minimal vorticity. This array can be viewed as cold rings intermixing with warm eddies.

Some of the warm eddies observed in this study might be associated with cold Gulf Stream rings. One eddy was found among three rings and Noble's (1975) warm eddy was between two rings. Thompson and Gotthardt (1971) reported a similar but opposite phenomenon: a cold "upwelling" region behind a warm ring north of the Gulf Stream in the Slope Water region. Thus there is a possibility that warm eddies could be generated by rings as some theories predict. It has been suggested that the evolution of these waves is slow, on the order of months, for baroclinic rings (Flierl, in preparation). This is consistent with the observation that warm eddies are not frequently found as rings. Transects across Gulf Stream rings may show these waves at earlier stages of development and hence the waves were not noticed. More detailed observations in the vicinity of rings are needed to explore the possible generation of eddies by rings.

VI. SUMMARY AND CONCLUSIONS

Approximately 50,000 temperature records, mainly XBT's, were obtained from the National Oceanographic Data Center and Fleet Numerical Weather Central and analysed to study the general distribution and movement of cyclonic Gulf Stream rings. The data were taken from 1970 through 1973 in the region bounded by 20-40°N and 50-80°W. Additional ring observations from other sources, including the Gulf Stream Summary (1970-73) and satellite photographs, were also used.

A "ring observation" was defined to consist of three or more height anomalies of 150 m within a five day period and within a diameter of 100 km. The height anomaly means a vertical displacement of the thermocline from its mean depth. Seventy ring observations were identified; they constitute twelve ring time-series, together with fifteen single rings. By extrapolating their movement in time and space, eleven rings were found to exist at one time (November 1971).

Rings were concentrated in the northwestern Sargasso Sea where the data was densest. Nine formed from the Gulf Stream between 60° and 70°W. They typically moved westward, turned southwestward when they were within 200 miles of the Gulf Stream and appeared to eventually coalesce with the Stream near Florida. A minimum of about one and a half rings moved down this path a year, with a mean speed of about 3 km per day and an estimated life span of two to three years. Some rings appeared to move in a more southward direction into the Sargasso Sea after their formation.

Some rings were found in a region east of 60°W which had previously been found devoid of rings (Parker, 1971). However, the low data density there prevented detailed study of the region, especially in an area south of 30°N and east of 65°W where the data were too scarce to meet the ring criteria.

Several warm eddies, with negative height anomalies of at least 150 m, were found in the data. They typically consisted of a thick layer of Eighteen Degree Water extending down to 600 m with a corresponding dip in the main thermocline. Anticyclonic circulation in these eddies was obtained if geostrophy and a deep layer of no motion are assumed. The eddies were found much less frequently than cold rings and because of the limited data, their distribution and movement cannot be inferred.

TABLE 1. Summary of the data.

Types of Records	Fleet Numerical Weather Central	National Oceanographic Data Center	Total Number
XBT's	29,194	18,421	47,615
STD stations	117	1,073*	1,190
Hydrostations	161	0*	161
	29,472	19,494	48,966

* The NODC data file does not distinguish between STD's and hydrostations.

TABLE 2. Summary of 150 m Height Anomalies at a depth of 450 m. The number in parenthesis is the 90% confidence limits (see text).

		1970	1971	1972	1973	Total
North-western Sargasso Sea	# of Data	3,194	3,268	1,627	1,822	9,911
	# of Anomalies	335	234	113	184	866
	Percentage	10.5	7.2	6.9	10.1	8.7(±0.5)
South-western Sargasso Sea	# of Data	722	2,605	1,171	797	5,295
	# of Anomalies	13	24	10	12	59
	Percentage	1.8	0.9	0.9	1.5	1.1(±0.2)
North-eastern Sargasso Sea	# of Data	261	411	330	222	1,224
	# of Anomalies	12	19	16	18	65
	Percentage	4.6	4.6	4.8	8.1	5.3(±1.1)
South-eastern Sargasso Sea	# of Data	40	126	92	115	373
	# of Anomalies	5	5	4	4	18
	Percentage	12.5	4.0	4.3	3.5	4.8(±1.8)

TABLE 3. Summary of 100 m Height Anomalies at a depth of 450 m. The number in parenthesis is the 90% confidence limits (see text).

		1970	1971	1972	1973	Total
North-western Sargasso Sea	# of Data	3,194	3,268	1,627	1,822	9,911
	# of Anomalies	437	320	164	235	1,156
	Percentage	13.7	9.8	10.1	12.9	11.7(±0.5)
South-western Sargasso Sea	# of Data	722	2,605	1,171	797	5,295
	# of Anomalies	31	96	23	19	169
	Percentage	4.3	3.7	2.0	2.4	3.2(±0.4)
North-eastern Sargasso Sea	# of Data	261	411	330	222	1,224
	# of Anomalies	22	29	28	18	97
	Percentage	8.4	7.0	8.5	8.1	7.9(±1.3)
South-eastern Sargasso Sea	# of Data	40	126	92	115	373
	# of Anomalies	5	5	5	6	21
	Percentage	12.5	4.0	5.4	5.2	5.6(±2.0)

TABLE 4. Observations of the 11 rings during November 1971.

Rings*	Last Day of Observation	Platform/ Agency	Observations	Remarks**
A(1)	November 5,9, 1971	Sumner, FNWC	3 XBT's	
B(2)	November 7, 1971	Lynch	15 XBT's	
C(3)	October 20-23, 1971	Steinaker	4 XBT's	
D(10)	October 19, 1971	FNWC	1 XBT	
E(5)	June 20,21,28 1971	J. Daniels	3 XBT's	southwest movement for 5 months
F(6)	August 6, 1970	FNWC	1 XBT	southwest movement offshore of the Stream for 15 months
G(S)	November 14, 1971	Lynch	5 XBT's	
H(S)	March 2,3, 1972	Chain	5 XBT's	westward movement for 4 months
I(S)	September 30, October 2, 1971	FNWC	6 XBT's	
J(S)	September 17, 18, 1971	Franconia	11 XBT's	southwest movement for 2 months
K(S)	August 14-17, 1971	Sims	8 XBT's	southwest movement for 3 months

* The letters identify the rings shown in Figure 15. Inside the parenthesis in the number of the time-series in which the ring observation belonged, or S if the observation was associated with a single ring.

** This indicates the assumed movement of the ring used in interpolating the result.

TABLE 5. Warm Anomalies at 600 m.

Year	Number of Data	Number Anomalies	Percentage
1970	1,020	24	2.3
1971	794	10	1.3
1972	698	16	2.3
1973	875	13	1.5
	3,387	63	1.9

REFERENCE AND BIBLIOGRAPHY

Cheney, R.E. 1976. A census of rings in the Gulf Stream system. NAVOCEANO Tech. Note 3700-44-76, 25 pp (unpublished document).

Cheney, R.E., W.H. Gemmill, M.K. Shank, P.L. Richardson, and D. Webb. 1976. Tracking a Gulf Stream Ring with SOFAR floats. J. Phys. Oceanogr., 6(5):741-749.

Cheney, R.E. and E.K. Khadouri. 1975. Synoptic Observations of two adjacent eddies in the Sargasso Sea. NAVOCEANO Tech. Note 6150-36-75, 20 pp (unpublished document).

Cheney, R.E. and P.L. Richardson. 1975. Distribution of Gulf Stream rings in the northwestern Sargasso Sea. MODE Hot Line News, Woods Hole Oceanographic Institution, 79:1 (unpublished document).

Cheney, R.E. and P.L. Richardson. 1976. Observed decay of a cyclonic Gulf Stream ring. Deep-Sea Research, 23:143-156.

Draft Synoptic Atlas, MODE I, 1974. (unpublished document).

Flierl, G.R. 1977. Gulf Stream ring dynamics, Part 1: Linear theory, J. Phys. Oceanogr. (submitted).

Fuglister, F.C. 1972. Cyclonic rings formed by the Gulf Stream, 1965-66. Studies in Physical Oceanogr., Vol. 1, Gordon and Breach, 137-167.

Fuglister, F.C. and L.V. Worthington. 1951. Some results of a multiple ship survey of the Gulf Stream. Tellus, 3(1):1-14.

Gotthardt, G.A. 1973. Gulf Stream eddies in the western North Atlantic. NAVOCEANO Tech. Note 6150-16-73, 42 pp (unpublished document).

Gotthardt, G.A. and R.A. Doblar. 1974. Cyclonic eddies observed in the western North Atlantic, January through June 1974. NAVOCEANO Tech. Note 6150-29-74, 21 pp (unpublished document).

Gould, W.J., W.J. Schmitz, and C. Wunsch. 1974. Preliminary results for a Mid-Ocean Dynamics Experiment (MODE-0), Deep-Sea Research, 21:911-931.

Hogg, N. and J. Dunlap. 1976. Beaufort-Bermuda GEK, XBT, and ship's drift sections. POLYMODE News, Woods Hole Oceanographic Institution, 7:1 (unpublished document).

Iselin, C.O'D. 1936. A study of the circulation of the western North Atlantic. Papers in Physical Oceanography and Meteorology, 4(4), 101 pp.

Iselin, C.O'D. 1940. A preliminary report on long-period variations in the transport of the Gulf Stream System. Papers in Physical Oceanography and Meteorology, 8(1), 40 pp.

Knauss, J.A. 1969. A note on the transport of the Gulf Stream. Deep-Sea Research, 16 (suppl.):117-123.

Koshlyakov, M.N. and Y.M. Grachev, 1973. Meso-scale currents at a hydrophysical polygon in the tropical Atlantic. Deep-Sea Research, 20:507-526.

Lai, D.Y. 1976. Distribution and movement of cyclonic Gulf Stream rings from historical data (1970-73). MS thesis. Univ. of Rhode Island, 116 pp.

Leetmaa, A. 1976. Recent observations of eddies southwest of Bermuda. POLYMODE News, Woods Hole Oceanographic Institution, 10:1 (unpublished document).

McCartney, M.S. 1975a. Big Babies in the northern Sargasso Sea. MODE Hot Line News, Woods Hole Oceanographic Institution, 74:1 (unpublished document).

McCartney, M.S. 1975b. Inertial Taylor columns on a beta-plane. J. Fluid Mechanics, 68(1):71-95.

McCartney, M.S. 1976. Eddy Parthenogenesis. POLYMODE News, Woods Hole Oceanographic Institution, 10:1 (unpublished document).

Molinari, R. 1970. Cyclonic ring spin-down in the North Atlantic. Ph.D. thesis. Texas A & M Univ. 106 pp.

Munk, W.H. 1950. On the wind-driven ocean circulation. J. of Meteorology, 7(2):79-93.

NAVOCEANO-1970-74. The Gulf Stream Monthly Summary. Vols. 5, 6, 7, 8, 9. U.S. Naval Oceanographic Office, Washington, D.C. 20373.

Newton, C.W. 1961. Estimates of vertical motions and meridional heat exchange in Gulf Stream eddies and a comparison with atmospheric disturbances. Journal of Geophysical Research, 66:853-870.

NOAA, National Weather Service (1975-76). Gulfstream, Vols. 1,2, Oceanographic Services Branch, Silver Spring, MD 20910.

Noble, M. 1975. XBT sections from R/V Chain 127. MODE Hot Line News, Woods Hole Oceanographic Institution, 84:4 (unpublished document).

Parker, C.E. 1971. Gulf Stream rings in the Sargasso Sea. Deep-Sea Research, 18:981-993.

Raschig, P. 1973. Surficial stratification and sound velocity field in the Sargasso Sea. Woods Hole Oceanographic Institution Technical Report, 73-23.

Richardson, P.L. 1972. Tracking of a Gulf Stream eddy. Maritimes, U.R.I. Graduate School of Oceanography publication, 16(3):14-16.

Richardson, P.L., R.E. Cheney, and L.A. Mantini. 1977. Tracking of a Gulf Stream ring with a free drifting surface buoy. J. Phys. Oceanogr., (submitted).

Richardson, P.L., A.E. Strong and J.A. Knauss. 1973. Gulf Stream eddies: recent observations in the western Sargasso Sea. J. Phys. Oceanogr., 3:297-301.

Saunders, P.M. 1971. Anticyclonic eddies formed from shorward meanders of the Gulf Stream. Deep Sea Research, 18:1207-1219.

Seaver, G. 1975. Two XBT sections in the North Atlantic. MODE Hot Line News, Woods Hole Oceanographic Institution, 84:1 (unpublished document).

Stern, M.E. 1975. Minimal properties of planetary eddies. J. Marine Res., 33(1):1-13.

Stommel, H.H. 1965. The Gulf Stream. University of California Press, 200 pp.

Stumpf, H.G., A.E. Strong and J. Pritchard. 1973. Large cyclonic eddies of the Sargasso Sea. Maritime Weather Log, 17(4):208-210.

Sverdrup, H.J., M.W. Johnson and R.H. Fleming. 1942. The Oceans. Prentice-Hall Inc., Englewood Cliff, 1087 pp.

Swallow, J.C. 1971. The Aires current measurements in the western North Atlantic. Phil. Trans. Roy. Soc. London A, 270:451-560.

Thompson, B.J. and G.A. Gotthardt. 1971. Life cycle of a North Atlantic eddy. Trans. Am. Geophys. Un., 52:241 (abstract).

Volkmann, G. 1975. Some XBT sections in the North Atlantic. MODE Hot Line News, Woods Hole Oceanographic Institution, 84:1 (unpublished document).

Vukovich, F.M. 1976. An investigation of a cold eddy on the eastern side of the Gulf Stream using NOAA 2 and NOAA 3 Satellite data and ship data. J. Phys. Oceanogr. 6(4):605-612.

Warren, B.A. 1967. Notes on translatory movement of rings of current in the Sargasso Sea. Deep-Sea Research, 14:505-524.

Worthington, L.V. 1959. The 18° Water in the Sargasso Sea. Deep-Sea Research, 5:297-305.

Worthington, L.V. 1971. Anticyclogenesis in the oceans as a result of outbreaks of Continental Polar Air. Studies in Physical Oceanography, Vol. 1, 169-178.

Worthington, L.V. 1972. Negative oceanic heat flux as a cause of water-mass formation. J. Phys. Oceanogr., 2(3):205-211.

Worthington, L.V. 1976. Further notes on Big Babies. POLYMODE News, Woods Hole Oceanographic Institution, 3:1. (unpublished document).

Worthington, L.V. 1977. On the North Atlantic Circulation. Johns Hopkins Oceanographic Studies, Baltimore, MD, Johns Hopkins Press.

Wunsch, C. 1975. A short summary of the present state of eddy art. Presented in the POLYMODE Assembly 1 in Brookline, MA. July, 1975.

Wust, G. 1936. Kuroshio and Gulfstrom. Veroff. d. Inst. f. Mooreskunde an d. Univ. Berlin, N.F. Reide A: Geogr.-naturwiss., Heft 29. 70 pp.

Yamagata, T. 1975. Rossby wave propagation in a lateral shear flow. MODE Hot Line News, Woods Hole Oceanographic Institution, 85:3. (unpublished document).

Figure 1. Schematic diagram of the formation of a cyclonic ring in June 1970 (based on data from the Gulf Stream Monthly Summary, 5(6), 1970). From Richardson, 1972.

Block 1:	10-11 May	Meander begins to form
Block 2:	20-21 May	Loop forms to south
Block 3:	1 June	Cold water mass is isolated
Block 4:	8 June	Ring is detached.

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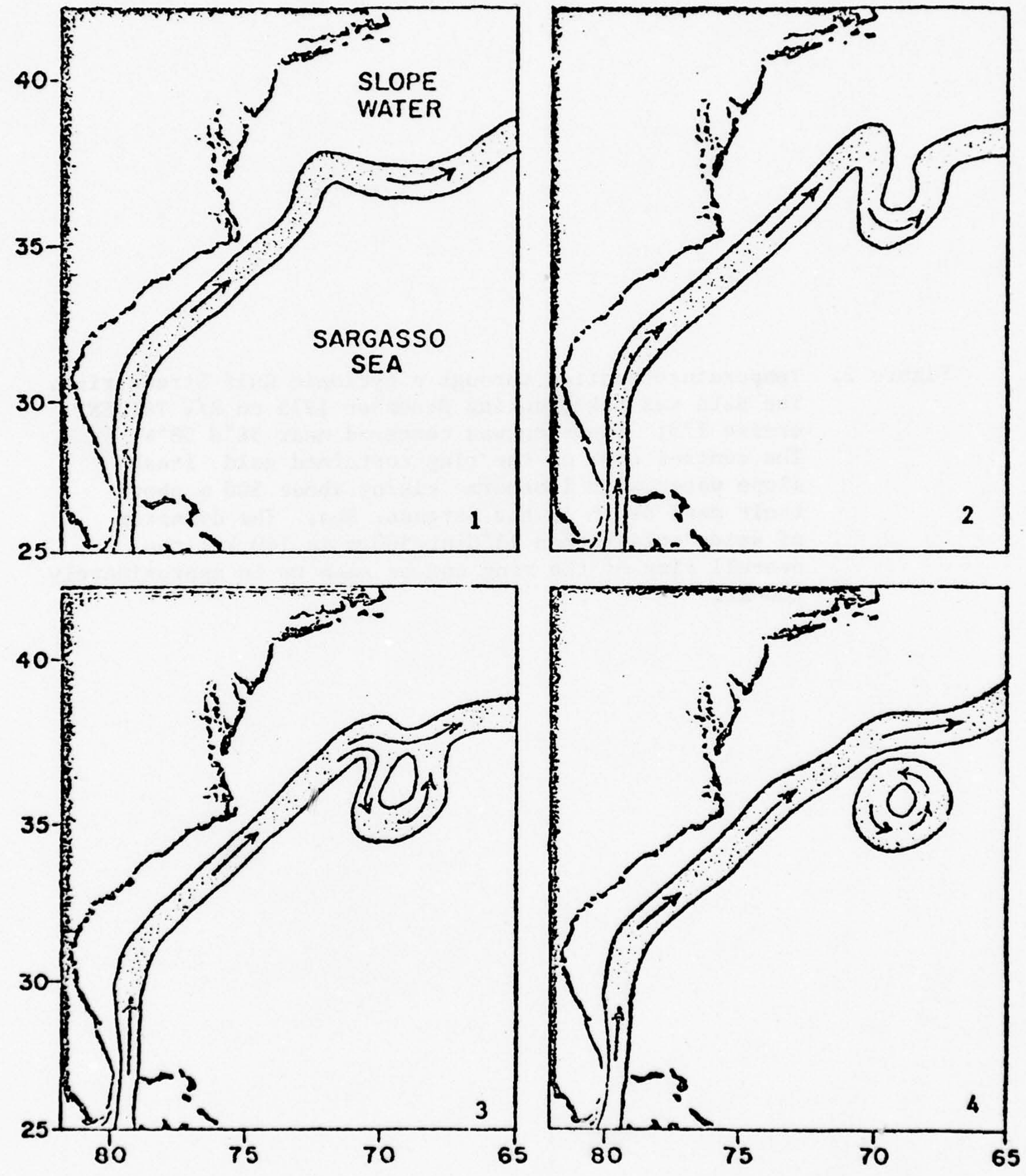


SLOPE WATER
SARGASSO SEA
40
35
30
25
1
2
3
4
80
75
70
65

Figure 2. Temperature section through a cyclonic Gulf Stream ring. The data was taken during December 1975 on R/V TRIDENT cruise 175; the ring was centered near 36°N 58°W. The central core of the ring contained cold, fresh slope water with isotherms rising about 500 m above their mean depth in the Sargasso Sea. The diameter of water colder than 15°C at 500 m is 140 km; the overall size of the ring can be seen to be approximately 200 km.

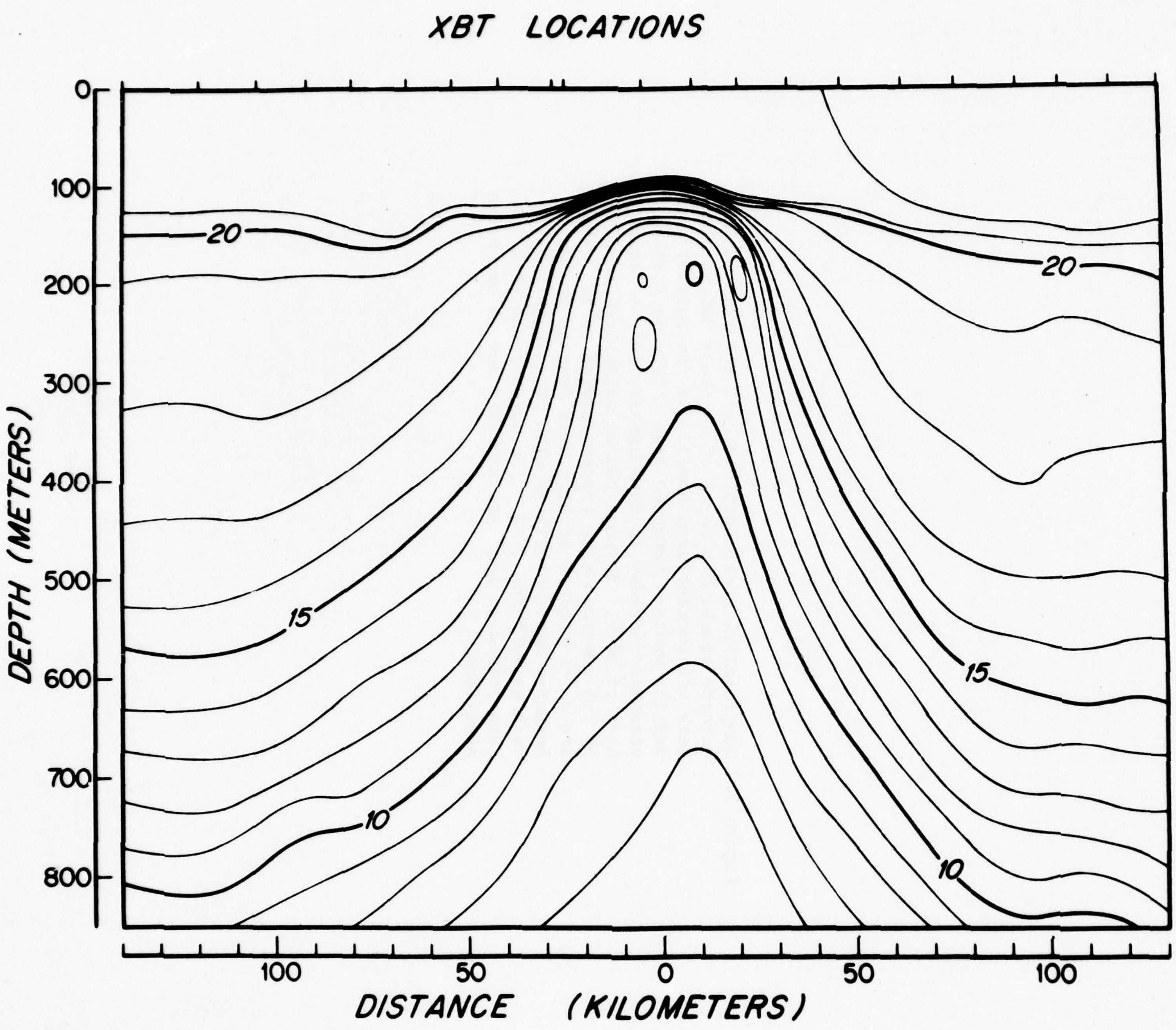

XBT LOCATIONS
0
100
200
300
400
500
600
700
800
DEPTH (METERS)
20
20
15
15
10
10
100
50
0
50
100
DISTANCE (KILOMETERS)

Figure 3. Geographical distribution of all the temperature records reaching a depth of at least 300 m. The data are concentrated heavily in the Gulf Stream and the western Sargasso Sea. There is a substantial decrease in data density in the region east of 65°W. Bermuda can be recognized easily by the numerous ship tracks leading to it. There are a few regions of high data density in the Sargasso Sea, associated with large experiments such as MODE and IWEX. The appearances of a few data points on land are probably due to erroneous positions.

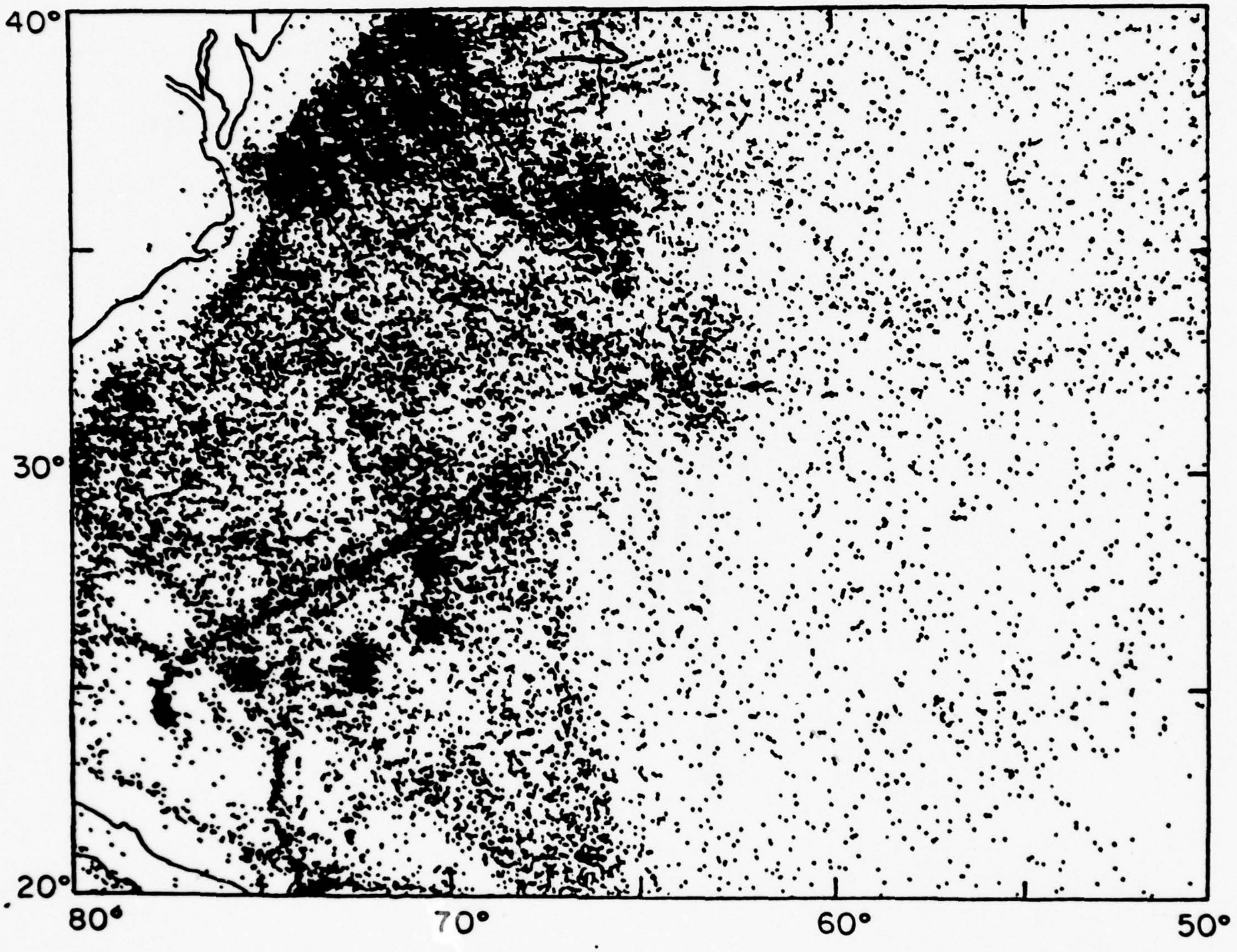

40°
30°
20°
80°
70°
60°
50°

Figure 4. Frequency distribution of terminal depth of the records. The distribution is trimodal; the peaks represent the surface temperature measurements, the 450 m and 750 m XBT's respectively. Since most of the data below the seasonal thermocline were 450 m XBT's, this level was chosen for the main analysis. Large fluctuations in sea surface temperatures due to seasonal and shorter period variability, prevented the effective use of surface temperature records in identifying ring anomalies.

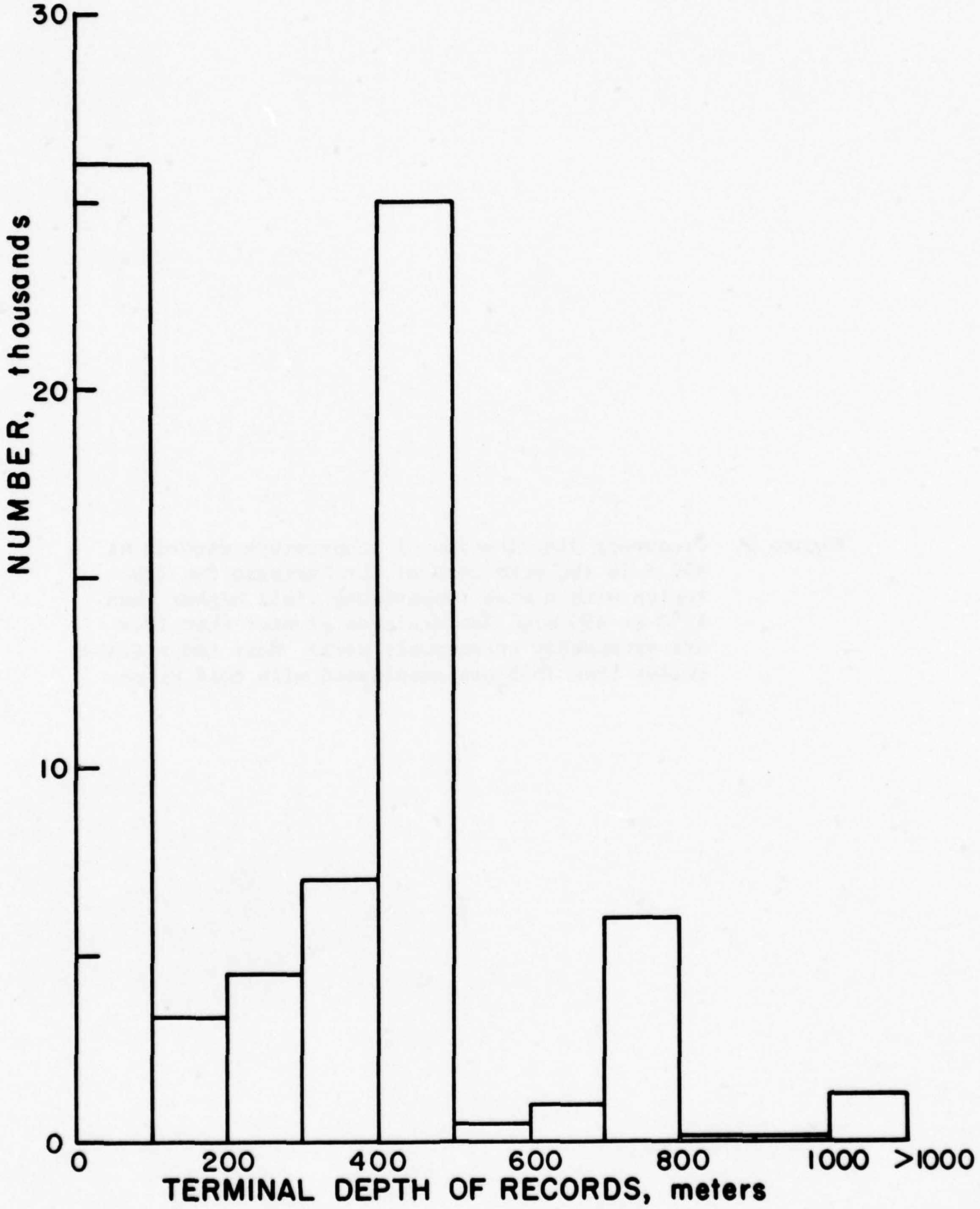

30
20
10
0
NUMBER, thousands
0
200
400
600
800
1000
>1000
TERMINAL DEPTH OF RECORDS, meters

Figure 5. Frequency distribution of temperature records at 450 m in the warm core of the Sargasso Sea (the region with a mean temperature field higher than 17°C at 450 m). Temperatures greater than 19.0 are presumably erroneously warm. Most temperatures colder than 15.5 are associated with cold rings.

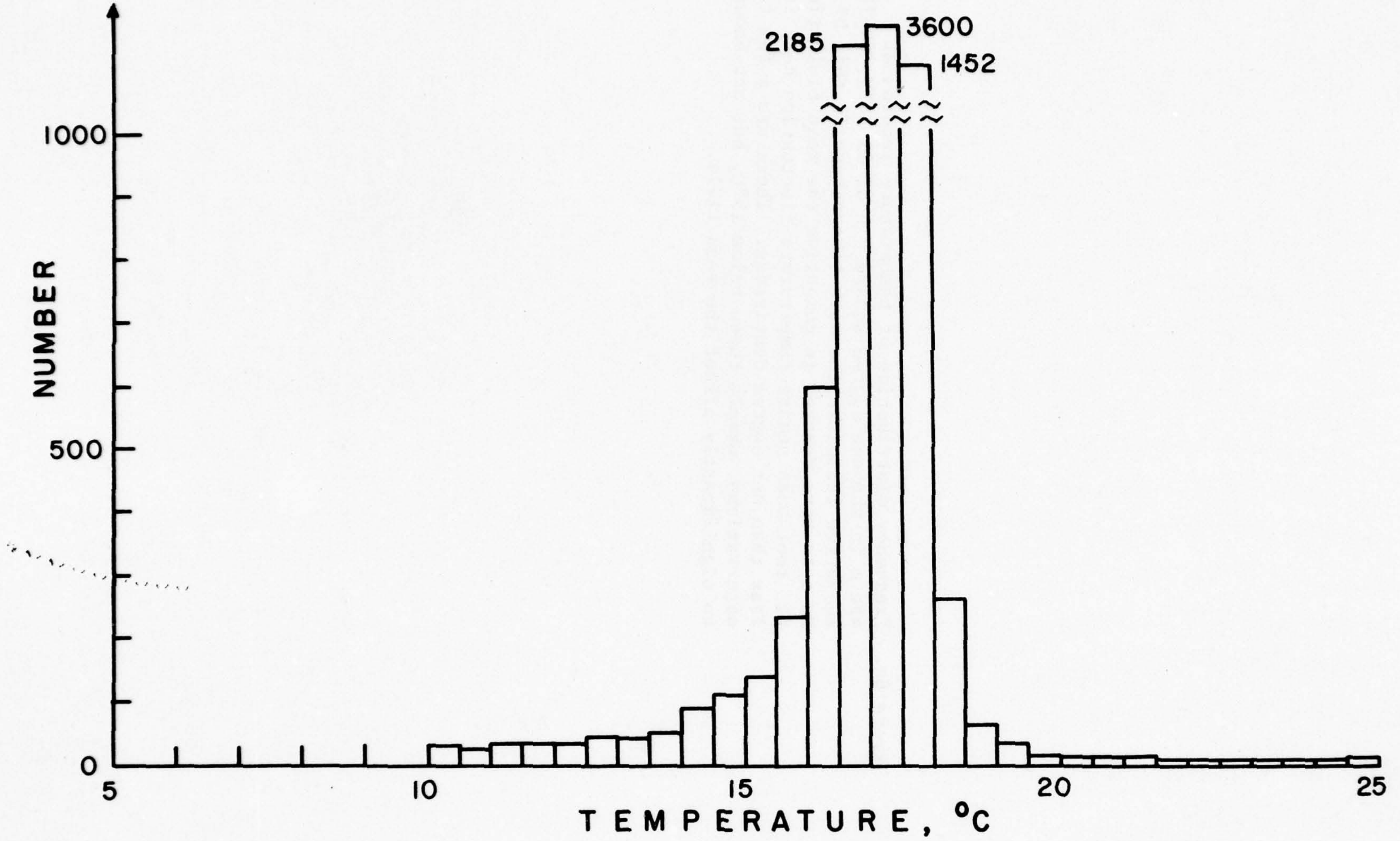
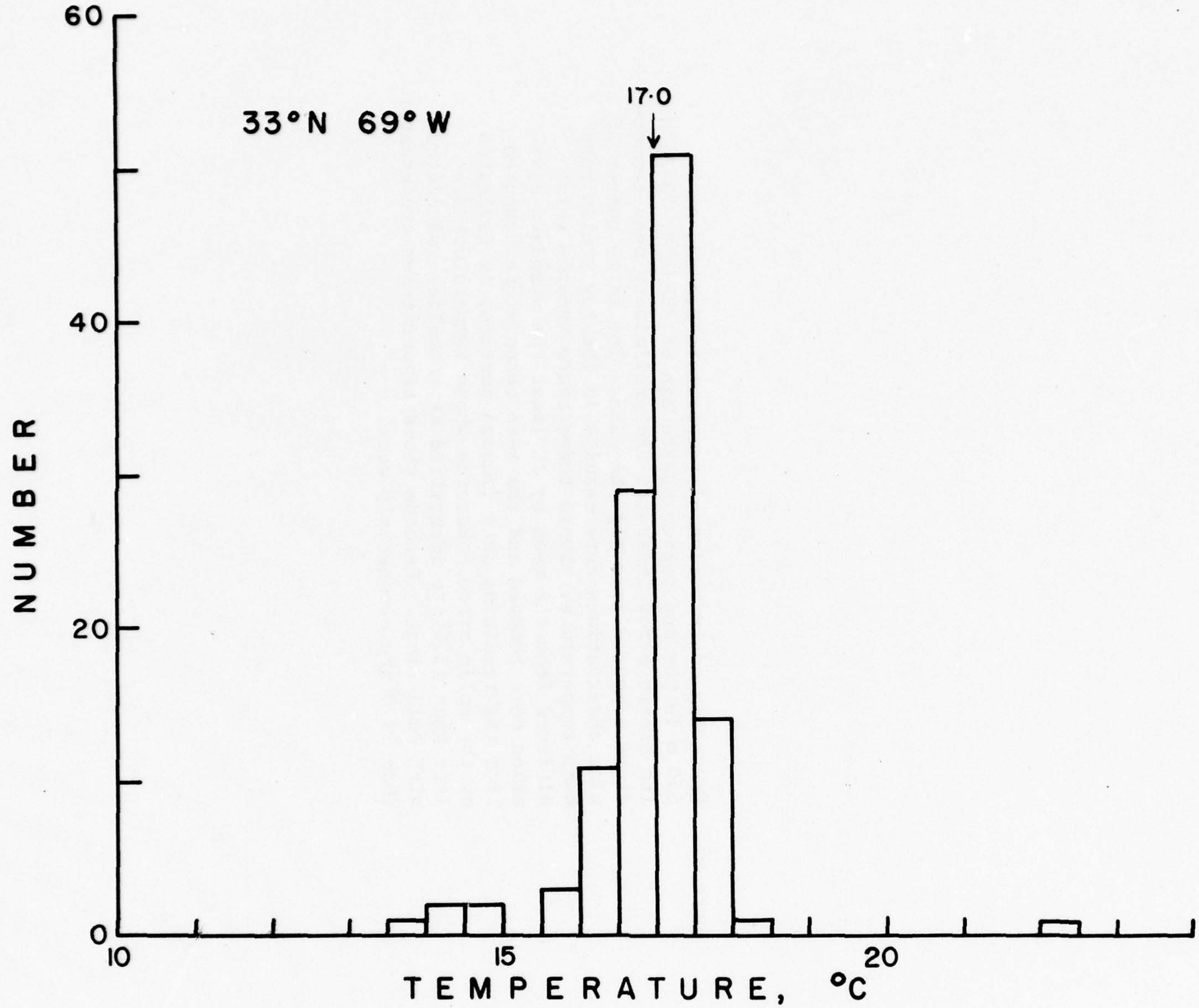
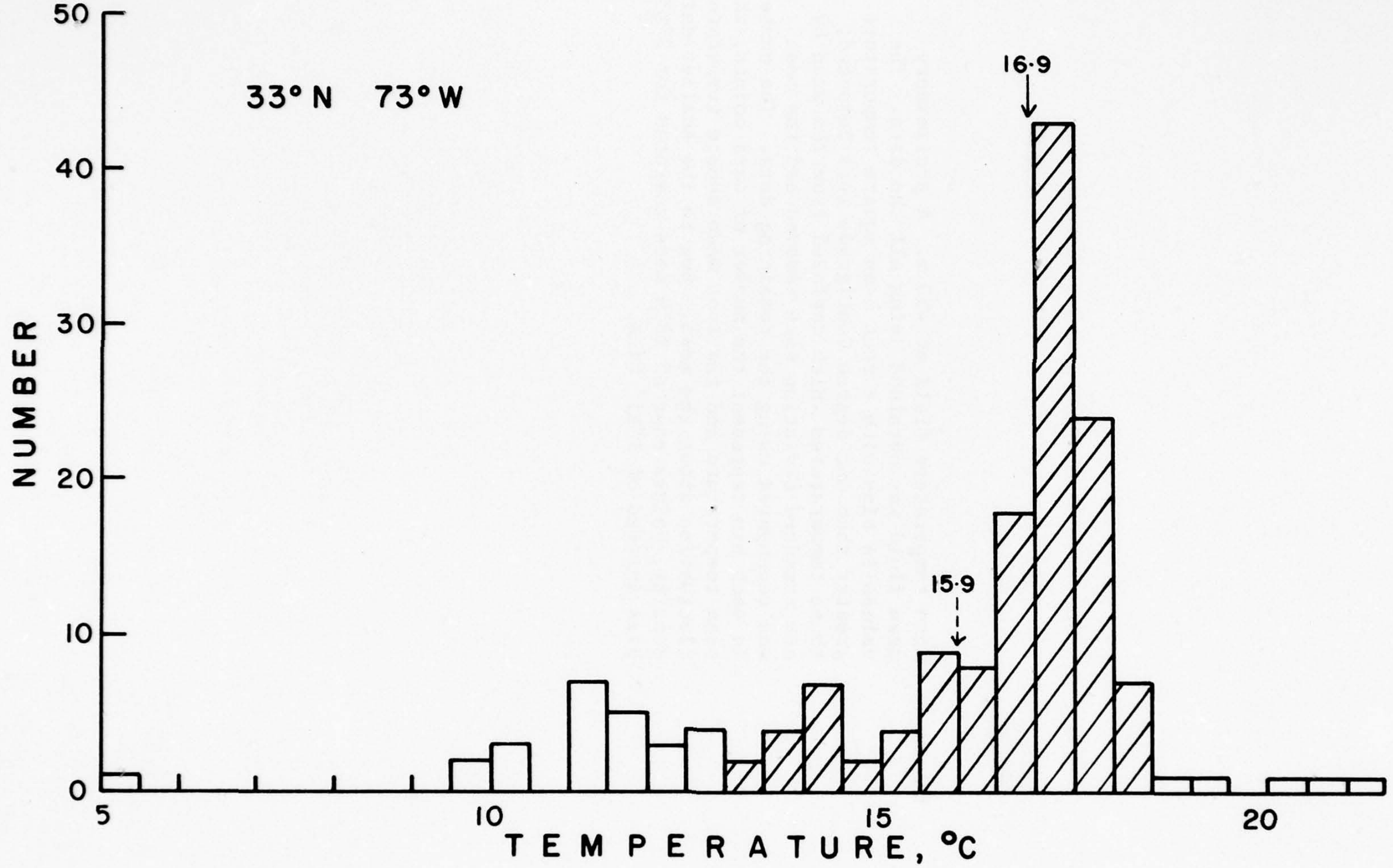

2185
3600
1452
1000
500
0
NUMBER
5
10
15
20
25
TEMPERATURE, °C

Figure 6a. Frequency distribution of temperature records at 450 m in the one degree square bin of 33-34°N, 69-70°W. The arrow indicates the mean temperature in this bin. No data were removed in computing the mean field since the root mean square temperature fluctuation here is less than one degree Centigrade. There are a few ring observations, namely those below 15°C, but not enough to significantly affect the mean field.



33°N 69°W
17·0
NUMBER
60
40
20
0
10
15
20
TEMPERATURE, °C

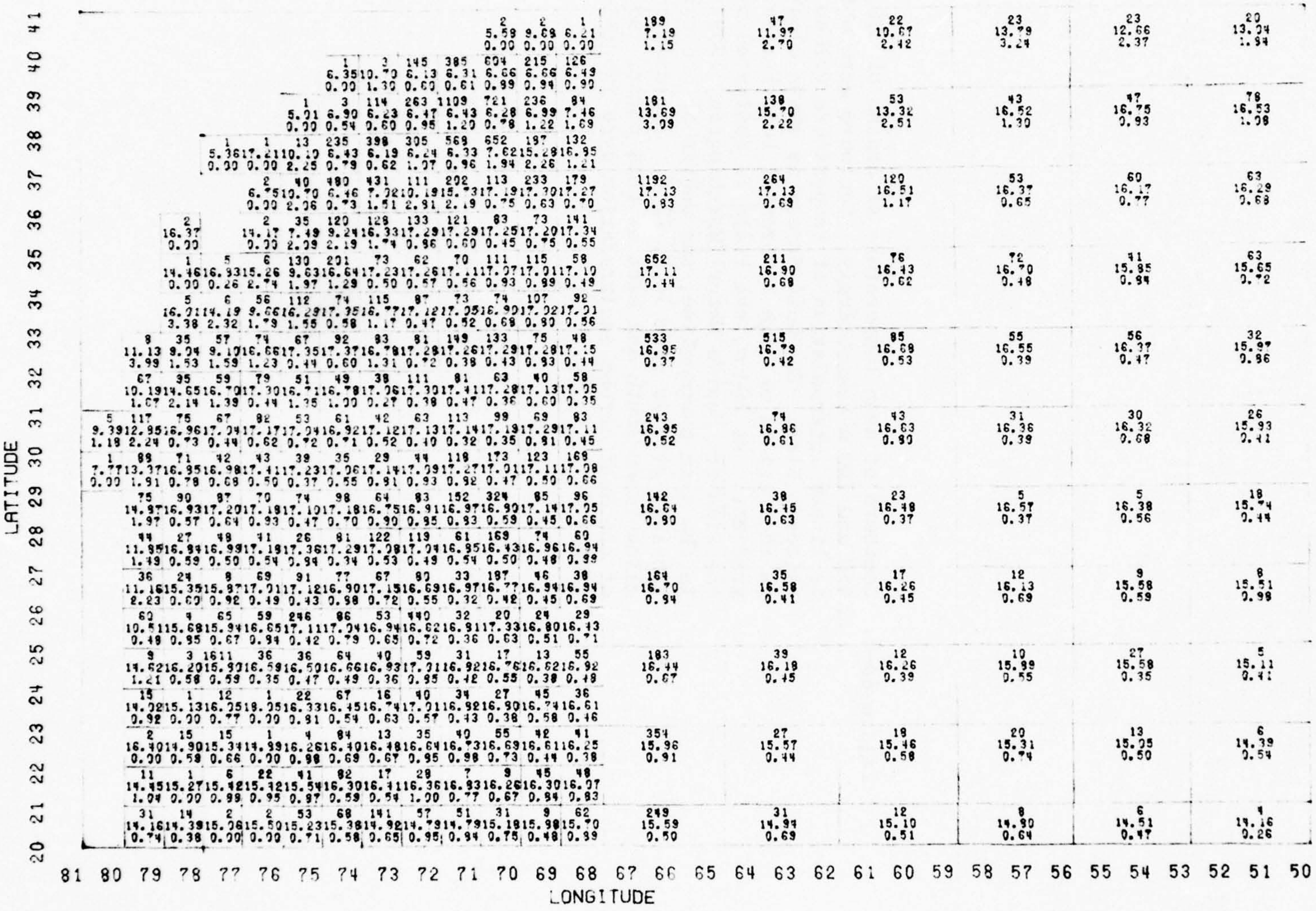
Figure 6b. Frequency distribution of temperature records at 450 m in the one degree square bin of 33-34°N, 73-74°W. The broken arrow indicates the preliminary mean temperature computed from all the data. The large number of ring observations here results in the low preliminary mean temperature. Those temperature records which differed from the mean by at least one standard deviation were removed and the mean temperature computed from the remaining data (shaded portion) is indicated by the solid arrow. Records whose temperature are less than 15.5° are identified as anomalies associated with cold rings. Records whose temperatures are greater than 19.0° are erroneously warm.



33° N 73° W
16·9
15·9
NUMBER
0
10
20
30
40
50
5
10
15
20
TEMPERATURE, °C

Figure 7. Mean temperature field at 450 m. A preliminary mean field was obtained using all the data. The values in bins with a root mean square temperature greater than one degree Centigrade were computed; those temperatures which deviated from the mean by one standard deviation were removed and the mean was recomputed using the remaining data. The numbers in each bin represent the number of data points, the *mean temperature* and the root mean square temperature fluctuation about the mean. Due to the smaller data density, values east of 68°W were computed for 2°X3° bins instead of 1°X1° bins.

DATA AT 450 METERS

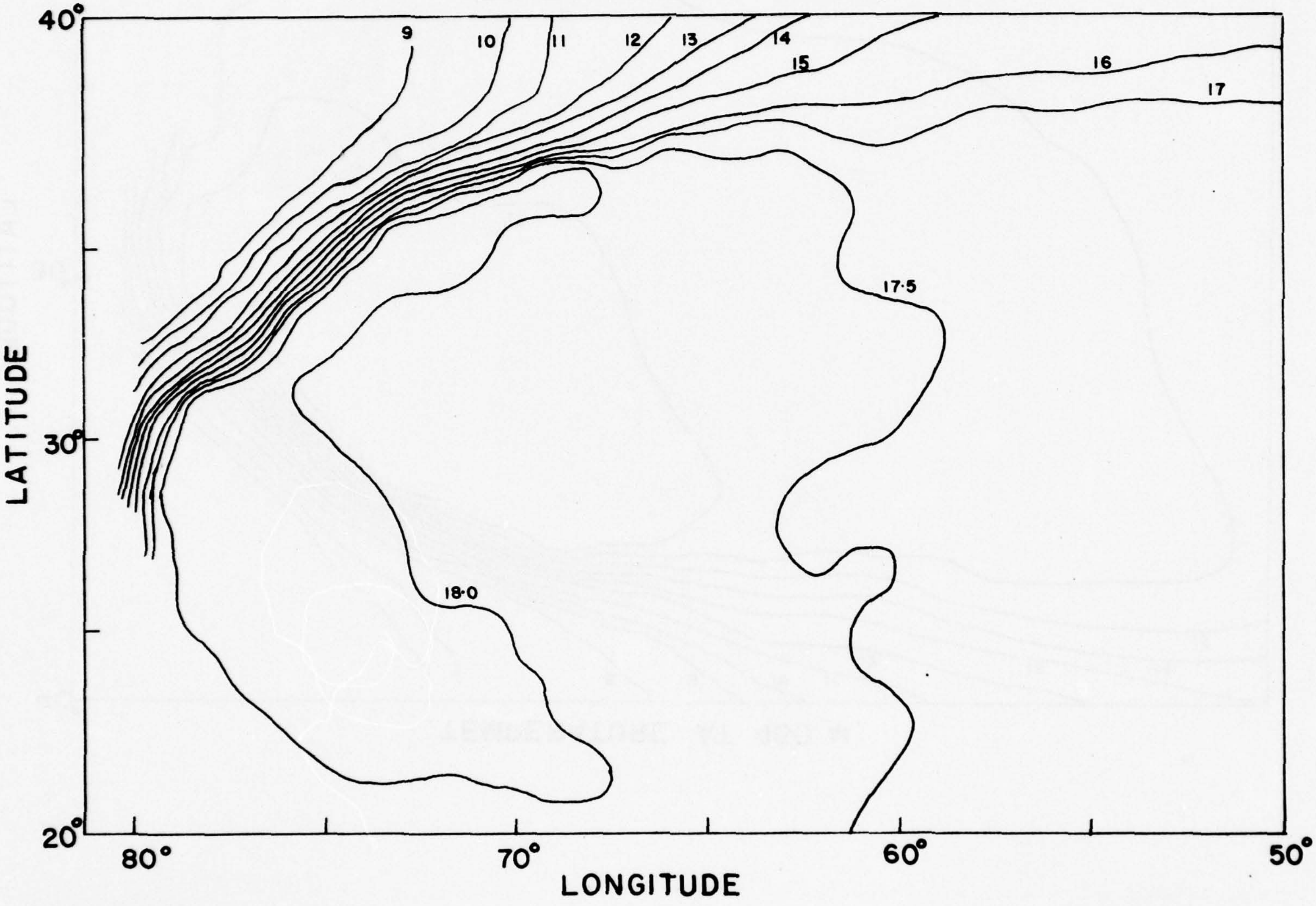


LATITUDE	80	79	78	77	76	75	74	73	72	71	70	69	68
41											2 5.59 0.00	2 9.69 0.00	1 6.21 0.00
40							1 6.35 0.00	3 10.70 1.30	145 6.13 0.60	385 6.31 0.61	604 6.66 0.99	215 6.66 0.94	126 6.49 0.90
39						1 5.01 0.00	3 6.90 0.54	114 6.23 0.60	263 6.47 0.95	1109 6.43 1.20	721 6.28 0.78	236 6.99 1.22	84 7.46 1.69
38				1 5.36 0.00	1 17.21 0.00	13 10.10 2.25	235 6.43 0.79	398 6.19 0.62	305 6.24 1.07	569 6.33 0.96	652 7.62 1.94	197 15.28 2.26	132 16.95 1.21
37					2 6.75 0.00	40 10.70 2.06	480 6.46 0.73	431 7.02 1.51	111 10.19 2.91	202 15.73 2.19	113 17.19 0.75	233 17.30 0.63	179 17.27 0.70
36			2 16.37 0.00		2 14.17 0.00	35 7.49 2.09	120 9.24 2.19	128 16.33 1.74	133 17.29 0.96	121 17.29 0.60	83 17.25 0.45	73 17.20 0.75	141 17.34 0.55
35			1 14.46 0.00	5 16.93 0.26	6 15.26 2.74	130 9.63 1.97	201 16.64 1.29	73 17.23 0.50	62 17.26 0.57	70 17.11 0.56	111 17.07 0.93	115 17.01 0.99	58 17.10 0.49
34			5 16.01 3.38	6 14.19 2.32	56 9.66 1.79	112 16.29 1.55	74 17.35 0.58	115 16.77 1.17	87 17.12 0.47	73 17.05 0.52	74 16.90 0.68	107 17.02 0.90	92 17.01 0.56
33		8 11.13 3.99	35 9.04 1.53	57 9.10 1.59	74 16.66 1.23	67 17.35 0.44	92 17.37 0.60	83 16.78 1.31	81 17.28 0.72	149 17.26 0.38	133 17.29 0.43	75 17.28 0.93	48 17.15 0.44
32		67 10.19 1.07	95 14.65 2.14	59 16.70 1.39	79 17.30 0.44	51 16.71 1.35	49 16.78 1.00	38 17.06 0.27	111 17.30 0.38	81 17.41 0.47	63 17.28 0.36	40 17.13 0.60	58 17.05 0.35
31	5 9.39 1.18	117 12.95 2.24	75 16.96 0.73	67 17.04 0.44	82 17.17 0.62	53 17.04 0.72	61 16.92 0.71	42 17.12 0.52	63 17.13 0.40	113 17.14 0.32	99 17.19 0.35	69 17.29 0.81	83 17.11 0.45
30	1 7.77 0.00	88 13.37 1.91	71 16.95 0.78	42 16.98 0.68	43 17.41 0.50	39 17.23 0.37	35 17.06 0.55	29 17.14 0.81	44 17.09 0.93	118 17.27 0.92	173 17.01 0.47	123 17.11 0.50	169 17.08 0.66
29		75 14.97 1.97	90 16.93 0.57	87 17.20 0.64	70 17.18 0.93	74 17.10 0.47	98 17.18 0.70	64 16.75 0.90	83 16.91 0.85	152 16.97 0.83	324 16.90 0.59	85 17.14 0.45	96 17.05 0.66
28		44 11.85 1.49	27 16.84 0.59	48 16.99 0.50	41 17.19 0.54	26 17.36 0.94	81 17.29 0.34	122 17.08 0.53	119 17.04 0.49	61 16.85 0.54	169 16.43 0.50	74 16.96 0.48	60 16.94 0.99
27		36 11.16 2.23	24 15.35 0.60	8 15.87 0.92	69 17.01 0.49	91 17.12 0.43	77 16.90 0.98	67 17.15 0.72	80 16.69 0.55	33 16.97 0.32	187 16.77 0.42	46 16.94 0.45	38 16.94 0.69
26		60 10.51 0.48	4 15.68 0.95	65 15.94 0.67	59 16.65 0.94	246 17.11 0.42	86 17.04 0.79	53 16.94 0.65	440 16.62 0.72	32 16.91 0.36	20 17.33 0.63	24 16.80 0.51	29 16.43 0.71
25		9 14.62 1.21	3 16.20 0.58	1611 15.90 0.59	36 16.59 0.35	36 16.50 0.47	64 16.66 0.49	40 16.93 0.36	59 17.01 0.95	31 16.92 0.42	17 16.76 0.55	13 16.62 0.38	55 16.92 0.48
24		15 14.02 0.92	1 15.13 0.00	12 16.05 0.77	1 18.05 0.00	22 16.33 0.81	67 16.45 0.54	16 16.74 0.63	40 17.01 0.57	34 16.92 0.43	27 16.90 0.38	45 16.74 0.58	36 16.61 0.46
23		2 16.40 0.00	15 14.90 0.58	15 15.34 0.66	1 14.99 0.00	4 16.26 0.98	84 16.40 0.69	13 16.48 0.67	35 16.64 0.95	40 16.73 0.98	55 16.69 0.73	42 16.61 0.44	41 16.25 0.38
22		11 14.45 1.04	1 15.27 0.00	6 15.42 0.99	22 15.32 0.95	41 15.54 0.97	82 16.30 0.59	17 16.41 0.54	28 16.36 1.00	7 16.93 0.77	9 16.26 0.67	45 16.30 0.94	48 16.07 0.83
21		31 14.16 0.74	14 14.39 0.38	2 15.06 0.00	2 15.50 0.00	53 15.23 0.71	68 15.38 0.58	141 14.92 0.65	57 14.79 0.95	51 14.79 0.94	31 15.18 0.75	9 15.98 0.48	62 15.70 0.39

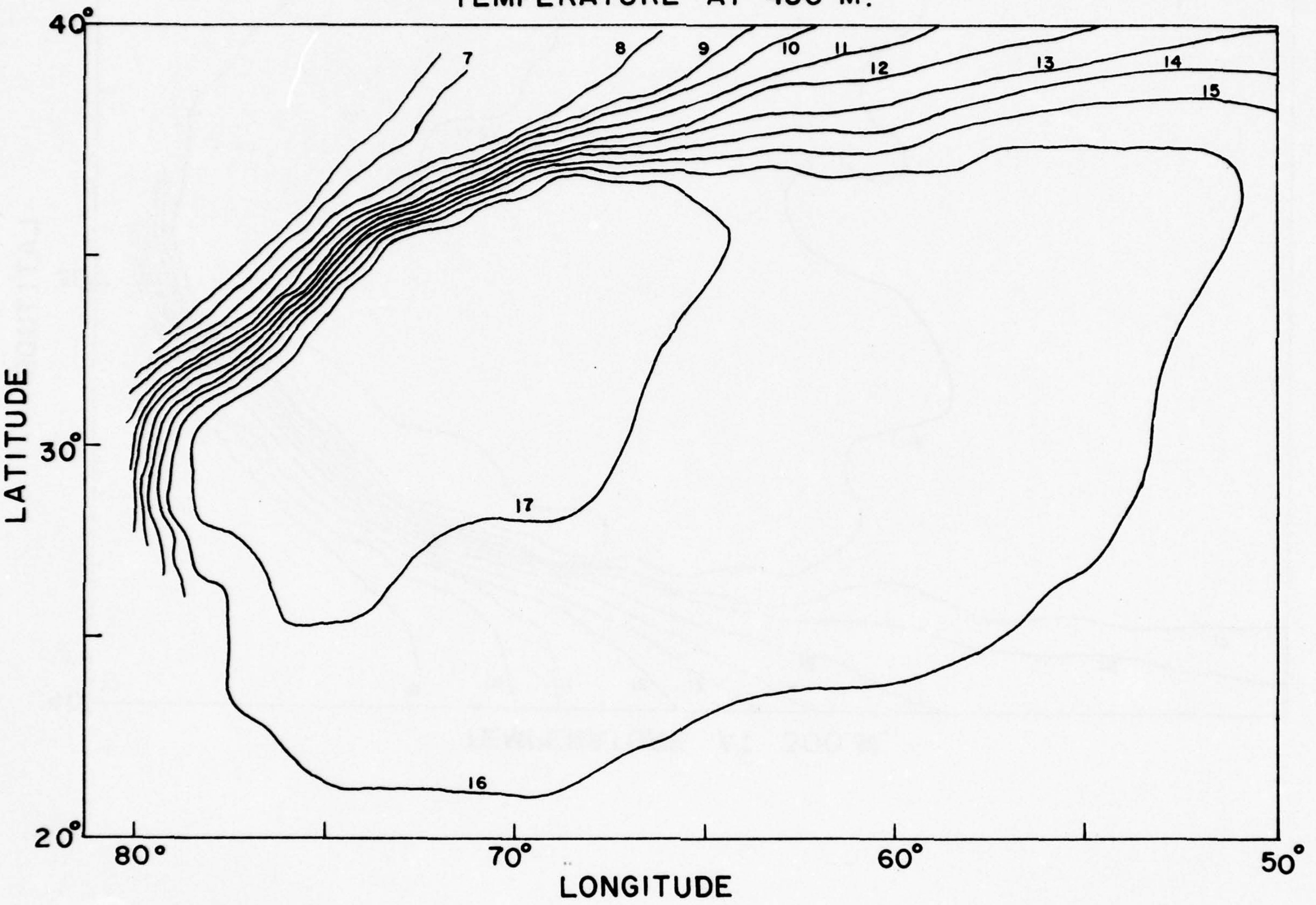
LATITUDE	66	63	60	57	54	51
41	189 7.19 1.15	47 11.97 2.70	22 10.67 2.42	23 13.79 3.24	23 12.66 2.37	20 13.04 1.94
39	181 13.69 3.09	138 15.70 2.22	53 13.32 2.51	43 16.52 1.30	47 16.75 0.93	78 16.53 1.08
37	1192 17.13 0.83	264 17.13 0.69	120 16.51 1.17	53 16.37 0.65	60 16.17 0.77	63 16.29 0.68
35	652 17.11 0.44	211 16.90 0.68	76 16.43 0.62	72 16.70 0.48	41 15.85 0.94	63 15.65 0.72
33	533 16.95 0.37	515 16.79 0.42	85 16.69 0.53	55 16.55 0.39	56 16.37 0.47	32 15.97 0.86
31	243 16.95 0.52	74 16.86 0.61	43 16.63 0.80	31 16.36 0.39	30 16.32 0.68	26 15.93 0.41
29	142 16.64 0.90	38 16.45 0.63	23 16.48 0.37	5 16.57 0.37	5 16.38 0.56	18 15.74 0.44
27	164 16.70 0.94	35 16.58 0.41	17 16.26 0.45	12 16.13 0.69	9 15.58 0.59	8 15.51 0.98
25	183 16.44 0.67	39 16.19 0.45	12 16.26 0.39	10 15.99 0.55	27 15.58 0.35	5 15.11 0.41
23	354 15.96 0.91	27 15.57 0.44	18 15.46 0.58	20 15.31 0.74	13 15.05 0.50	6 14.39 0.54
21	249 15.59 0.50	31 14.94 0.69	12 15.10 0.51	8 14.90 0.64	6 14.51 0.47	4 14.16 0.26

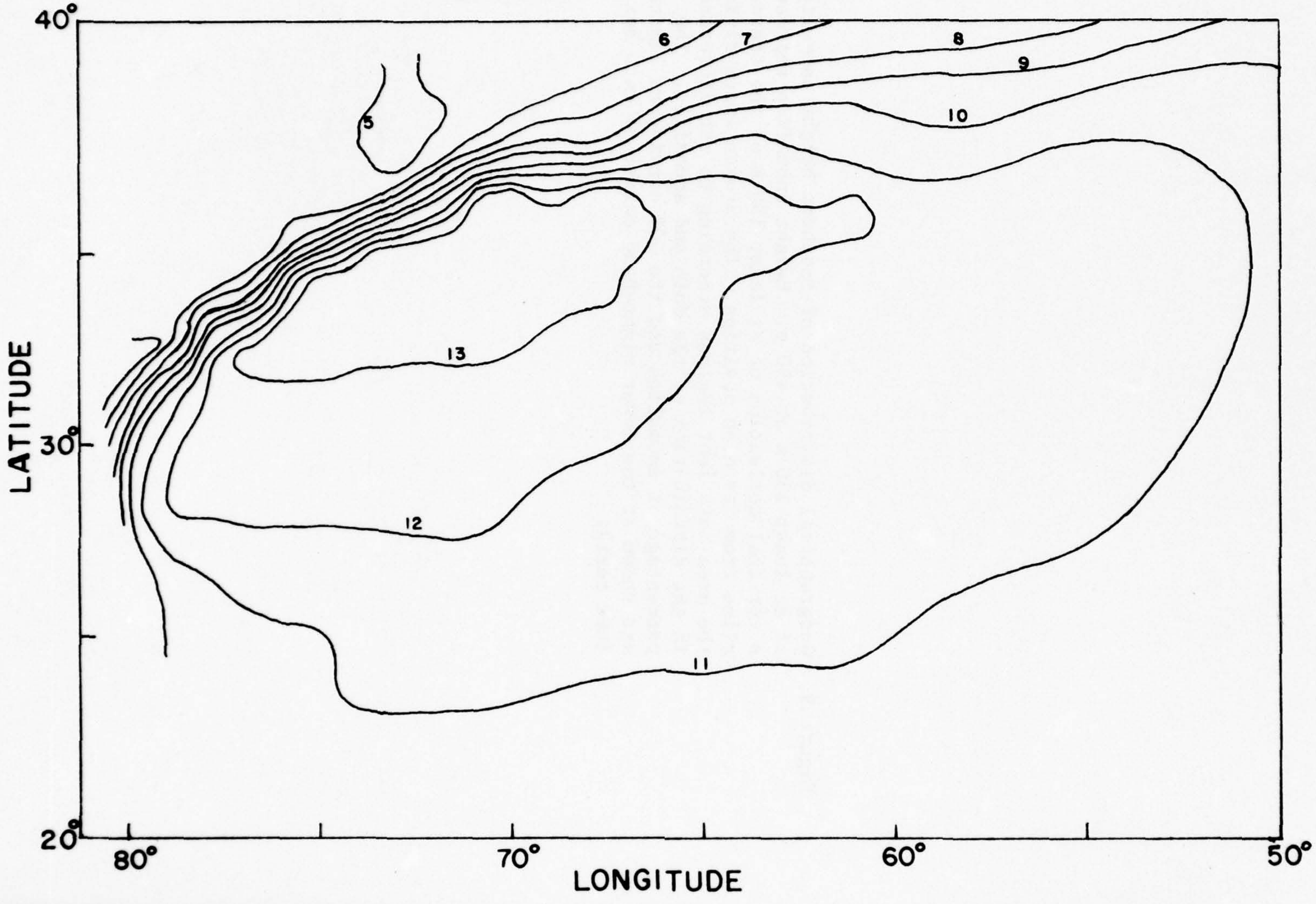
Figure 8a-c. Contours of mean temperature at depths of 300, 450 and 700 m respectively. Contours were obtained by linear interpolation of temperature values of adjacent bins. The Gulf Stream is shown clearly as the regions of high horizontal temperature gradient. At 300 m, the field is dominated by the Eighteen Degree Water (Worthington, 1959). In the main thermocline, the center of the subtropical gyre is near 34°N, 72°W. The main thermocline rises south and east of this point, indicative of the Gulf Stream recirculation gyre (Worthington, 1976).

TEMPERATURE AT 300 M.



TEMPERATURE AT 450 M.





TEMPERATURE AT 700 M.

Figure 9. Geographical distribution of isotherm height anomalies of at least 150 m at 450 m. Height anomalies represent a vertical deflection of at least 150 m of the thermocline from its mean position. The broken lines divide the area into four regions according to the differences in the distribution of the data and anomalies. The percentage of anomalies and the 90% confidence limits are shown at the lower right-hand corner of each box (see text).

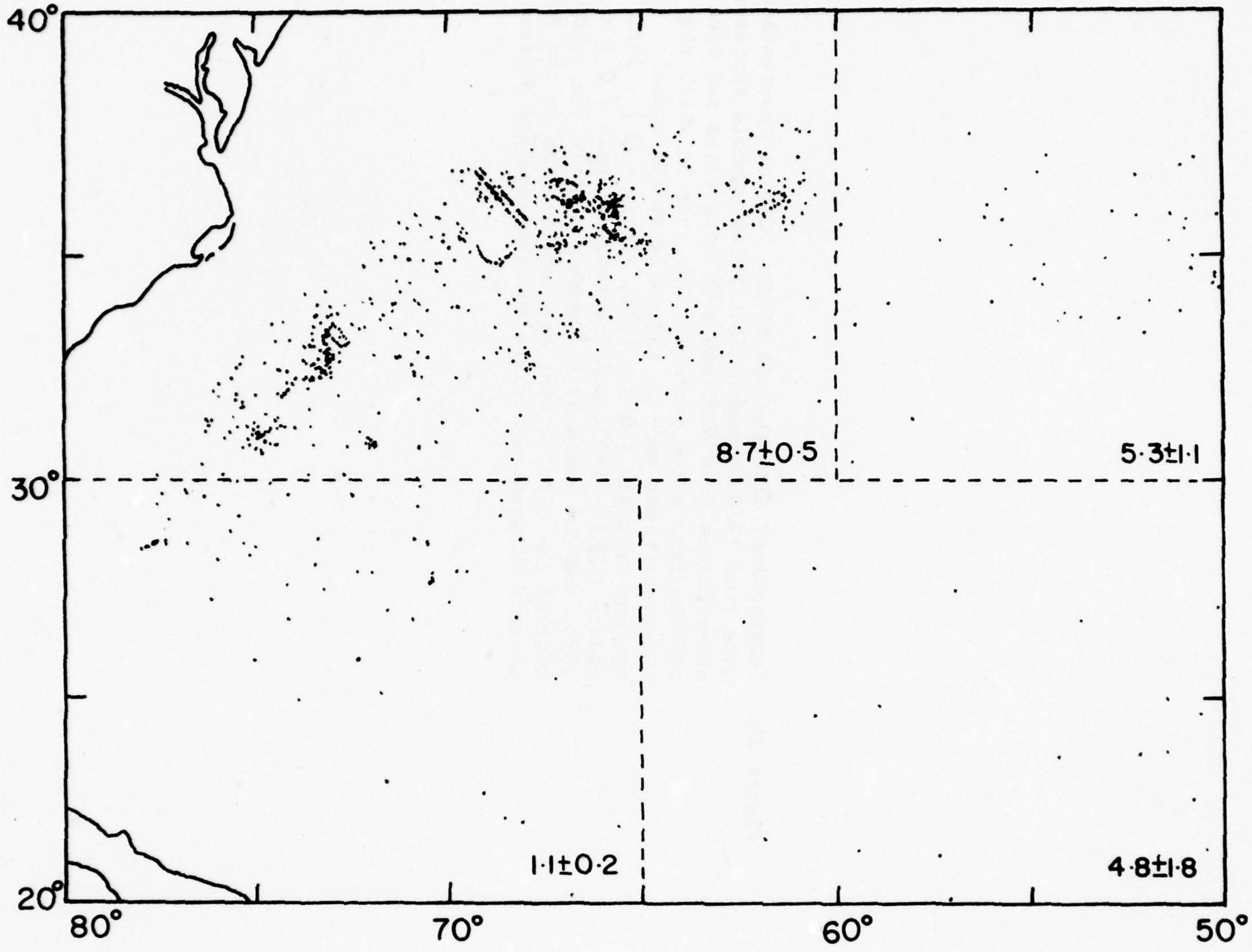

40°
30°
20°
80°
70°
60°
50°
8·7±0·5
5·3±1·1
1·1±0·2
4·8±1·8

Figure 10. Geographical distribution of the 70 ring observations made from 1970 through 1973. Solid symbols represent observations from NODC and FNWC data files and open symbols from other sources. The year in which the observation was made is indicated by the symbol: upright triangle (△) - 1970, circle (○) - 1971, square (□) - 1972, and inverted triangle (▽) - 1973, and the month by the number next to the symbol. Most of the observations are concentrated in the northwestern Sargasso Sea where the data are the densest.

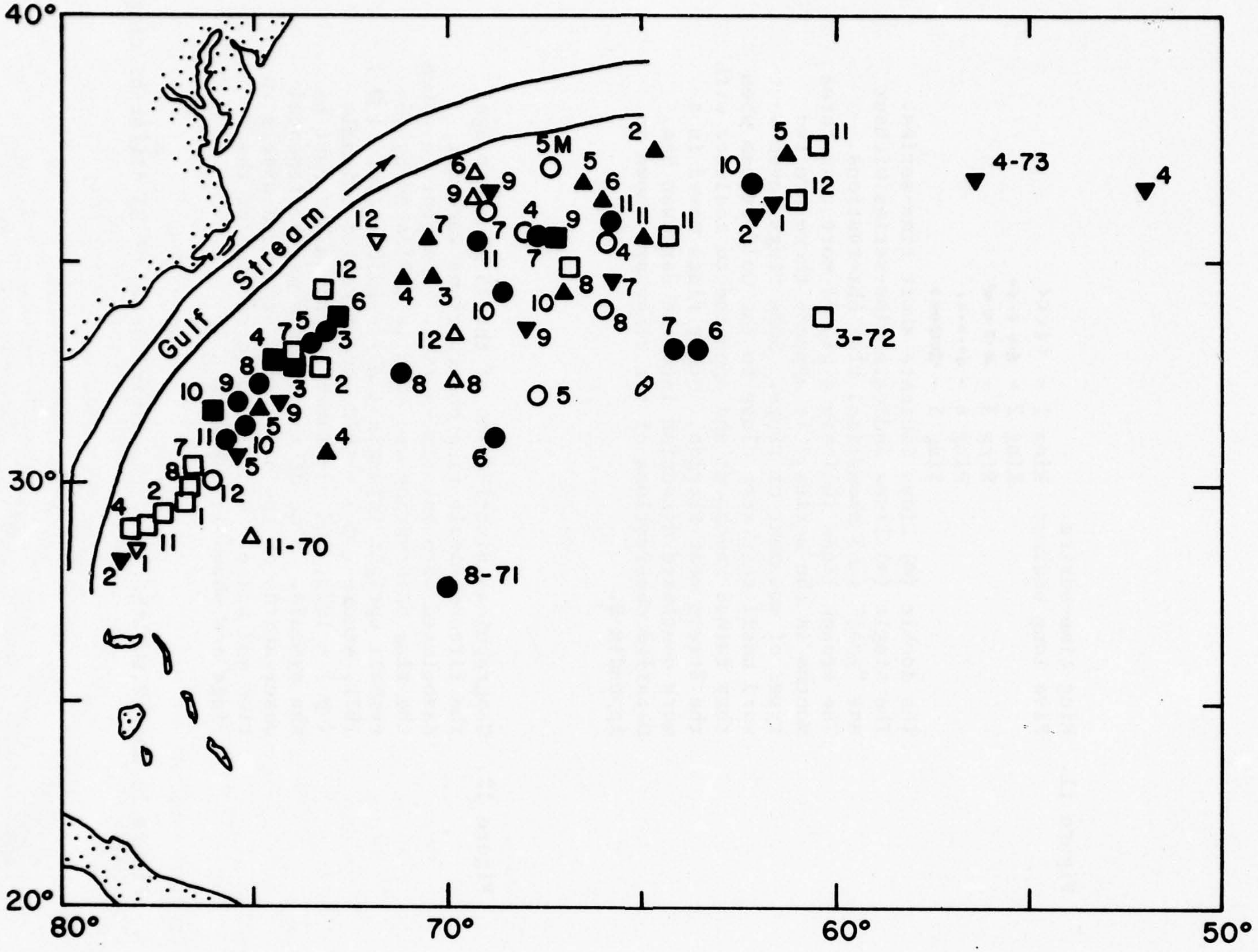
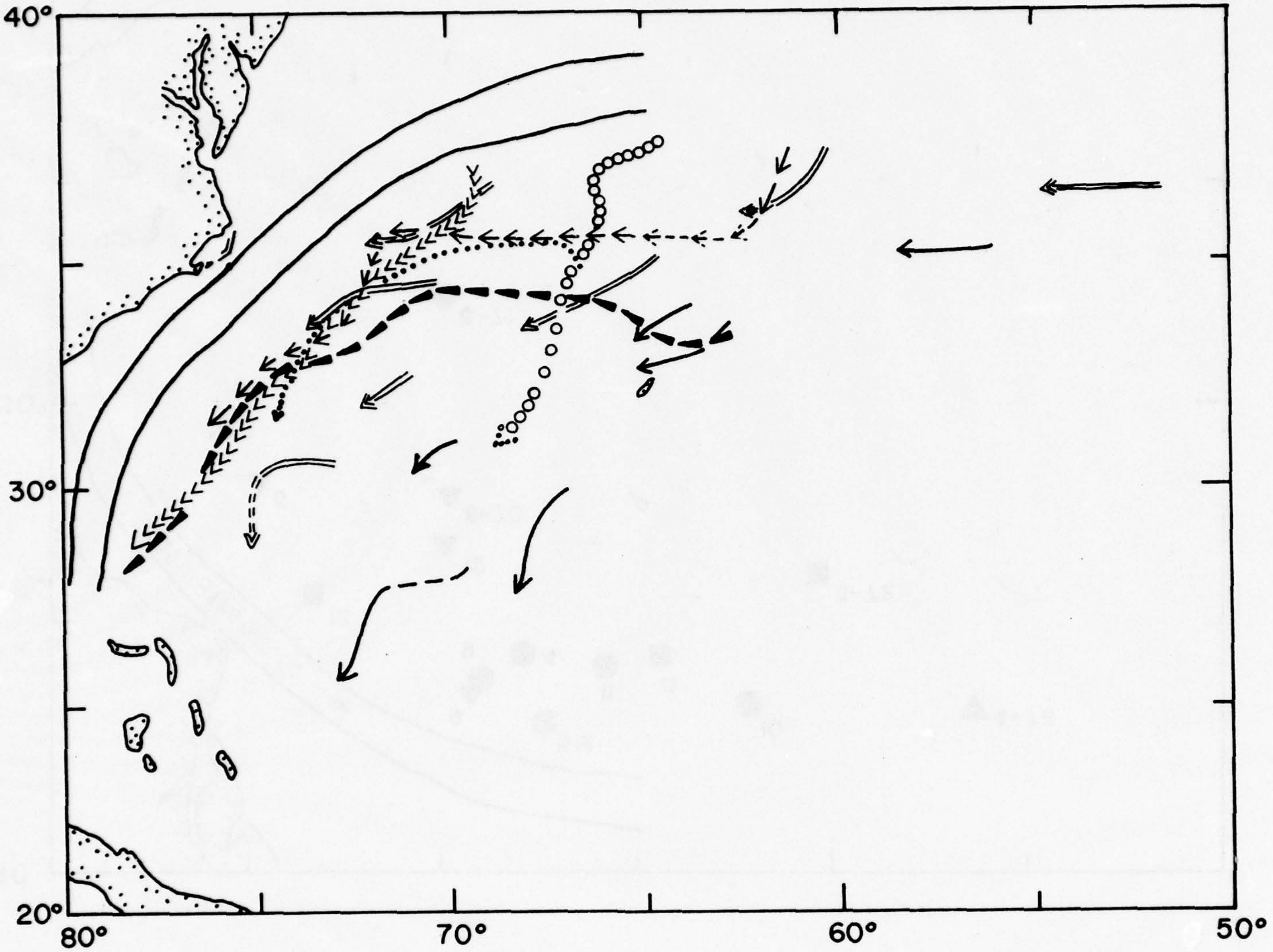

40°
30°
20°
80°
70°
60°
50°
Gulf Stream
5M
11-70
8-71
3-72
4-73

Figure 11. Ring time-series.
Five long series: Ring 1 - <<<<<
Ring 2 - ←←←←
Ring 3 - ◀◀◀◀
Ring 4 - ←••••••
Ring 5 - ◁oooooo

The double (⇒) lines indicate short time-series. The single (→) lines indicate time-series without any "good" (>3 anomalies) ring observations. The broken lines indicate a gap of more than three months in the series. It appears there are two types of movement of rings. Some rings moved westward until they were close to the Gulf Stream when they turned southwest and appeared to coalesce with the Stream near Florida. Other rings moved in a more southward direction into the Sargasso Sea. Detailed observations of the rings are shown in Appendix B.

Figure 12. Geographical distribution of the 15 single rings. The fifteen single ring observations were not associated with any time-series. The year in which the ring observation was made is indicated by the symbol: upright triangle (▲) - 1970, circle (O) - 1971, square (◘) - 1972, and inverted triangle (▼) - 1973, and the month by the number next to the symbols. Some of these rings may be repeated observations of the same rings separated widely in time and space. Detailed observations of the rings are shown in Appendix B.

Figure 11 and 12 together show the distribution of 23 different rings.


40°
30°
20°
80°
70°
60°
50°

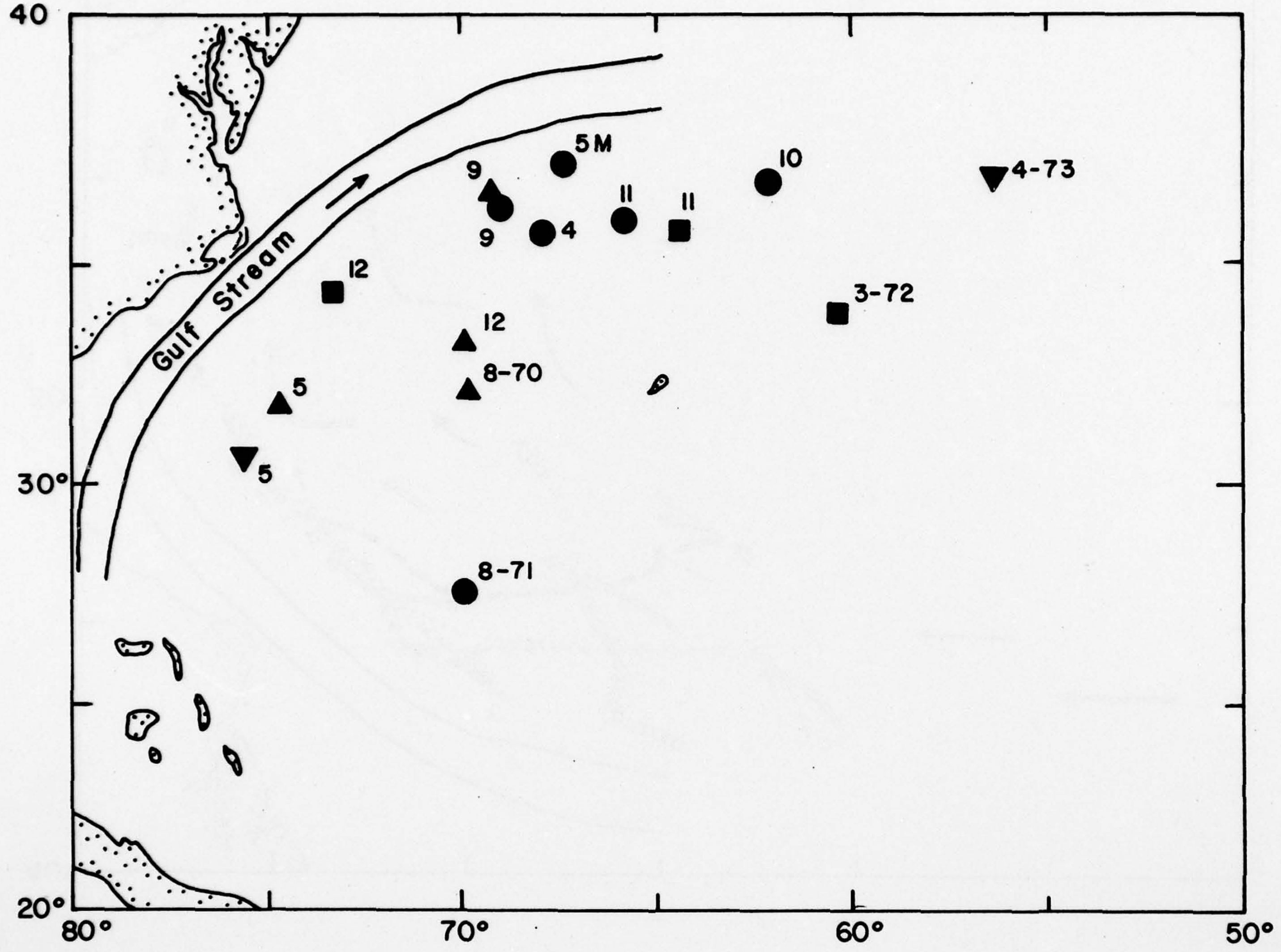

40
30°
20°
80°
70°
60°
50°
Gulf Stream
5M
10
4-73
9
9
4
11
11
12
3-72
12
8-70
5
5
8-71

Figure 13. Frequency distribution of ring speed. Each speed is estimated from the positions of adjacent ring observations, sometimes rather subjectively, especially when only one single anomaly was available. The mean speed is 2.7 km per day, with 82% of the speeds between 1 to 4 km per day.

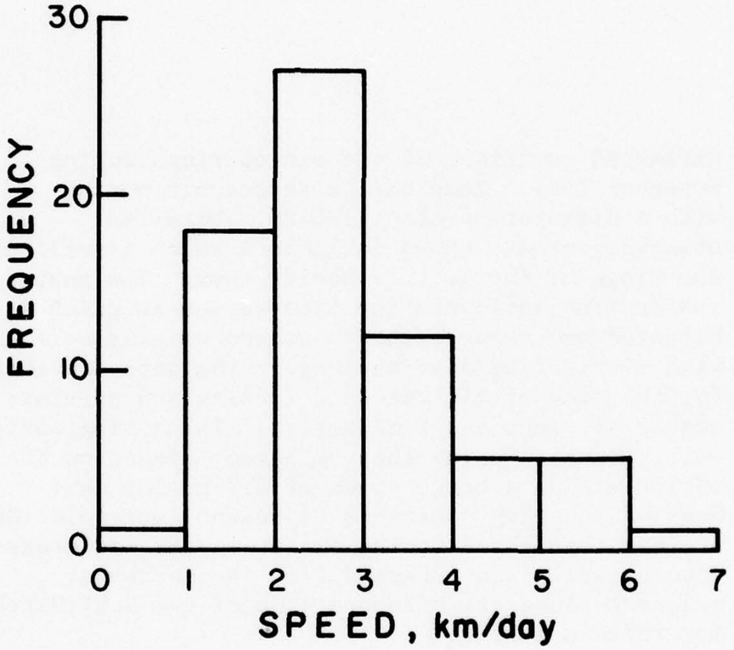

30
20
10
0
FREQUENCY
0
1
2
3
4
5
6
7
SPEED, km/day

Figure 14. Estimated positions of the eleven rings during November 1971. Each circle represents a ring with a diameter of about 100 km. Detailed observations are shown in Table 4 which identifies the rings by the letters beside them. The number inside ring indicates the time-series in which it belonged and those without numbers were associated with single ring observations. The date was chosen for the time of highest data density and greatest number of rings and time-series. These ring positions were estimated using their apparent direction of motion and an average speed of 2.7 km per day. Most of the ring positions represent interpolation of less than three months except ring F (in broken circle) which was inferred from the southwest movement along the offshore side of the Gulf Stream for fifteen months.

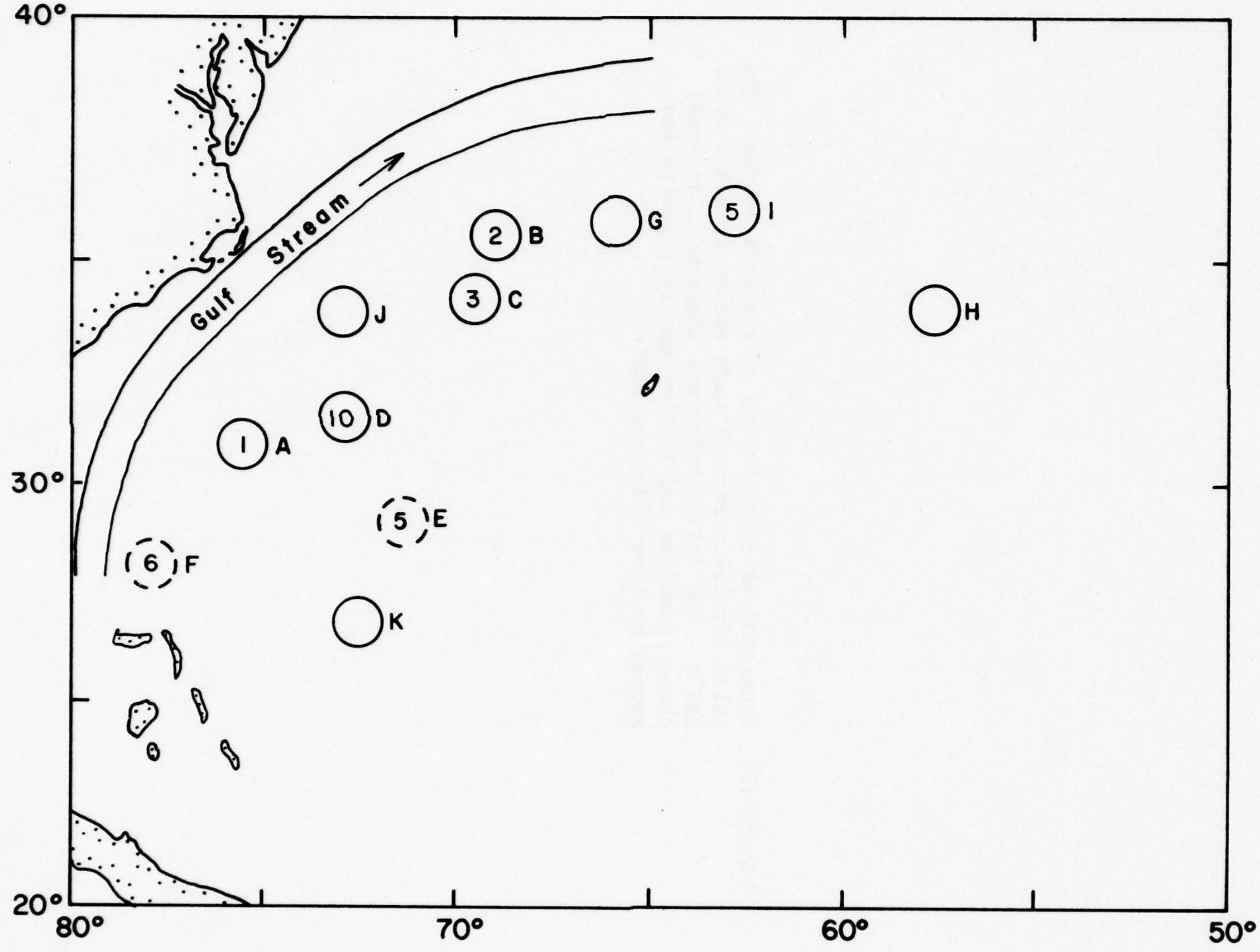

40°
30°
20°
80°
70°
60°
50°
Gulf Stream
1 A
2 B
3 C
10 D
5 E
6 F
G
H
5 I
J
K

Figure 15. Geographical distribution of the warm eddies. The solid circles represent warm eddies from 450 meter XBT's. The full circles are those with at least three anomalies and the broken circles with two anomalies from 750 meter XBT's.

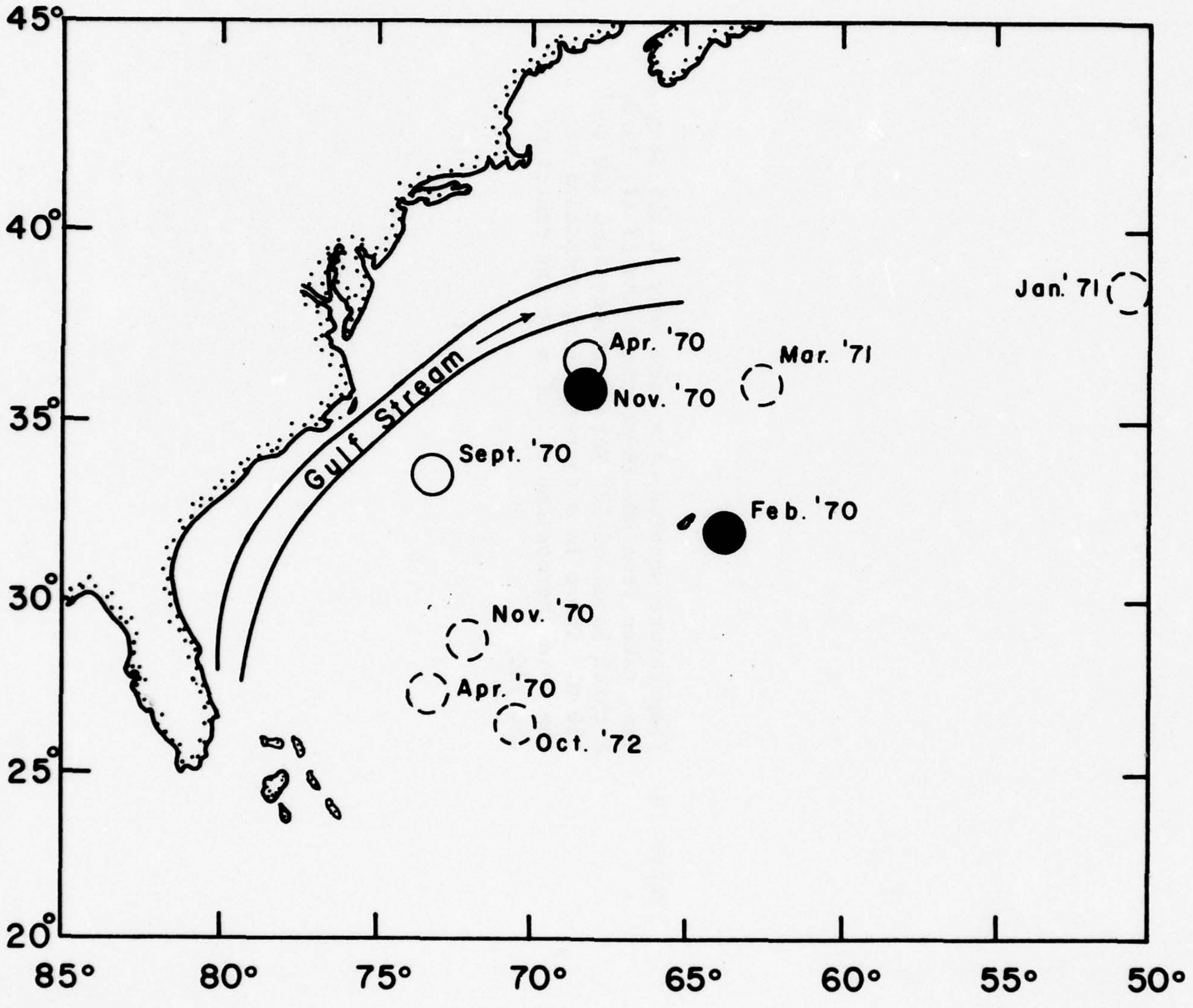
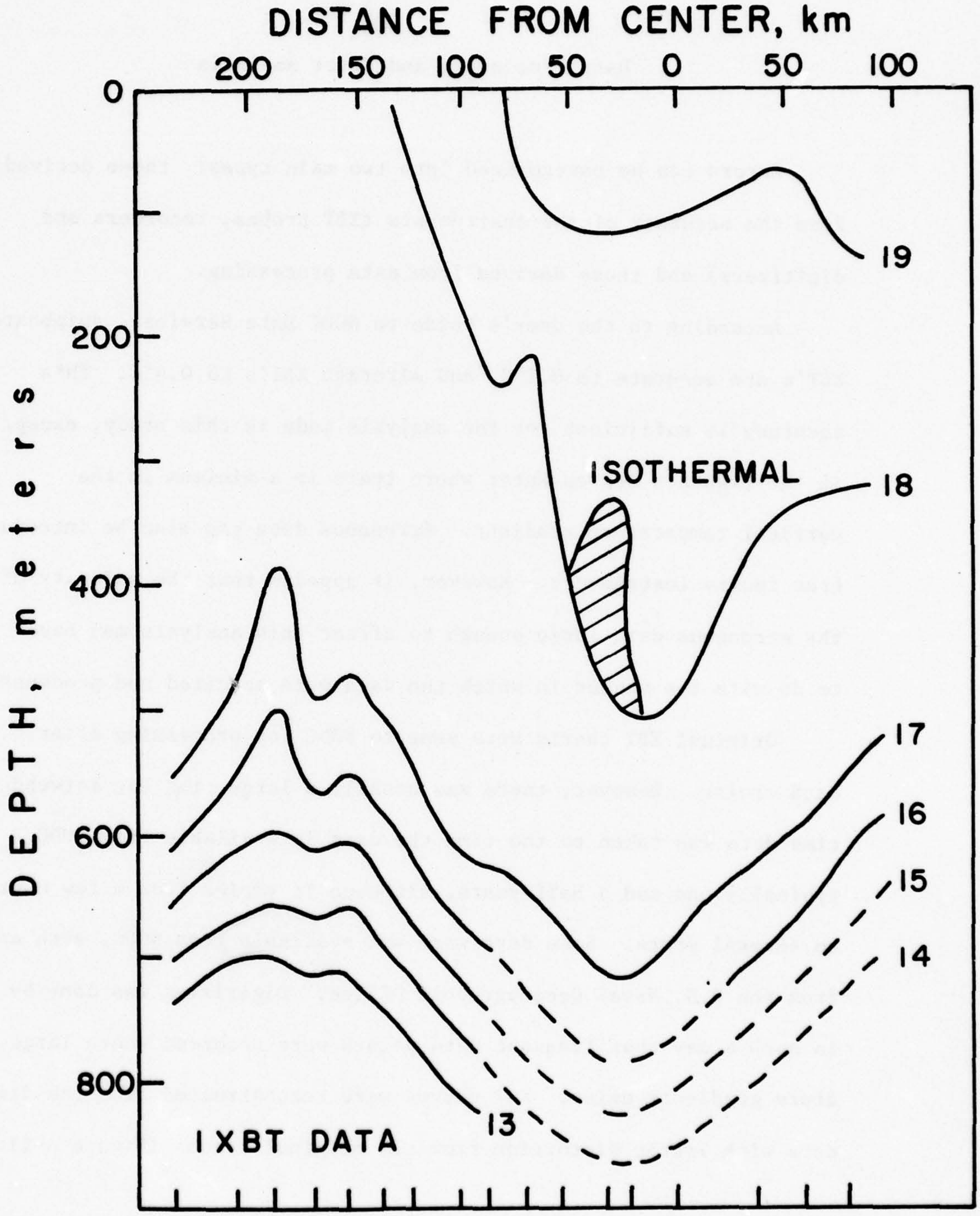

45°
40°
35°
30°
25°
20°
85°
80°
75°
70°
65°
60°
55°
50°
Gulf Stream
Apr. '70
Nov. '70
Mar. '71
Jan.' 71
Sept. '70
Feb. '70
Nov. '70
Apr. '70
Oct. '72

Figure 16. Temperature section of a warm eddy in the Sargasso Sea, taken from RMS FRANCONIA on April 17, 1970. A thick layer of 18° Water extends from 200 to 600 m. There is a corresponding deepening of the main thermocline of 200 m at the center of the eddy.


DISTANCE FROM CENTER, km
200
150
100
50
0
50
100
DEPTH, meters
0
200
400
600
800
19
18
ISOTHERMAL
17
16
15
14
13
IXBT DATA

APPENDIX A

Data Processing and Error Analysis

Errors can be categorized into two main types: those derived from the accuracy of the instruments (XBT probes, recorders and digitizers) and those derived from data processing.

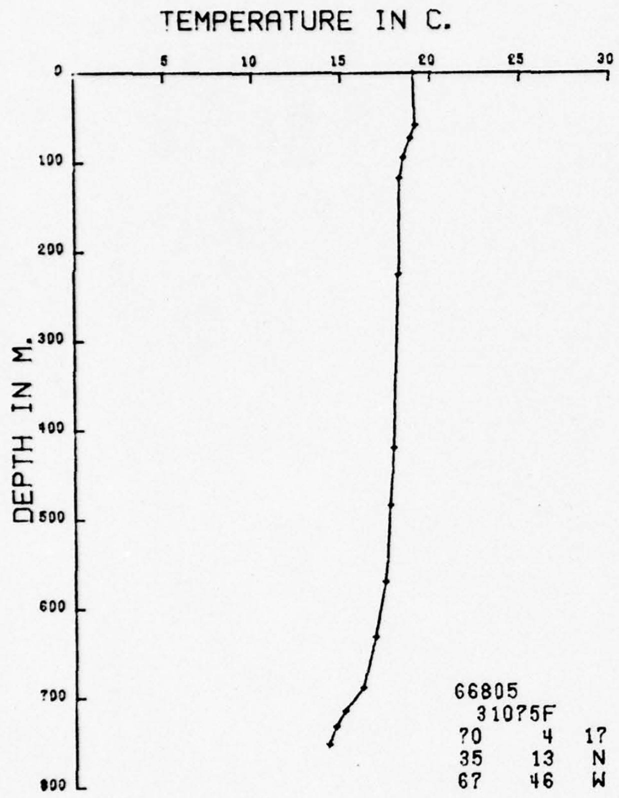
According to the User's Guide to NODC Data Services, shipboard XBT's are accurate to 0.1°C, and aircraft XBT's to 0.4°C. This accuracy is sufficient for the analysis made in this study, except in the Eighteen Degree Water where there is a minimum in the vertical temperature gradient. Erroneous data can also be introduced from faulty instruments. However, it appears that the majority of the erroneous data large enough to affect this analysis may have to do with the manner in which the data were acquired and processed.

Original XBT charts were sent to NODC for processing after each cruise. However, there was usually a large time lag between the time data was taken to the time the data is available from NODC, typically one and a half years, although it varies from a few months to several years. Some data were not available from NODC, such as those from the U.S. Naval Oceanographic Office. Digitizing was done by machines in such a way that frequent data points were recorded where large temperature gradients exist. XBT curves were reconstructed from the digitized data with little distortion from the original traces (Figure A-1). The digitized data were stored on magnetic tapes and are available upon request to NODC.

The data processing scheme in FNWC varied considerably from that of NODC. Although some of the original XBT charts were digitized in the same manner as described above, a large number were digitized at sea and wired to FNWC. Points were read off at nonstandard and arbitrary intervals and sometimes the digitized data do not reflect details of the real XBT traces (Figure A-2). Further errors may be introduced by recording the wrong depths, temperatures, and even dates and positions.

It was very difficult in this study to be sure whether the anomalous features were real or consisted of erroneous data. Presumably data processors at NODC and FNWC have also had an equal difficulty in eliminating bad data. Extra precautions, some rather subjective, were used to offset the effect of bad data. The ring criterion of three anomalies was used to provide corroboration of the identification of a ring. Individual temperature profiles were checked for possible errors (incorrect positions, inversions, spikes) and those traces that looked suspicious were not used. Ring observations were checked by comparing them to non-anomalous observations; if there was a conflict, the ring observation was discarded.

Figure A-1. Examples of XBT's from NODC. Traces were reconstructed from digitized values indicated by the small crosses. Digitization was done in such a way that frequent data points were recorded where a large temperature gradient existed. At the lower right-hand corner of each plot, the numbers indicate the code number of the XBT, the code of the ship, the year, month and day, the longitude and latitude at which the data was taken. Trace 61400 was taken in the Sargasso Sea and trace 66805 in a warm eddy. Due to the small temperature gradient in the extra thick layer of Eigtheen Degree Water, there are only four digitized points between 200 and 600 m in the trace taken in the warn eddy as compared with fifteen points in the one taken in the Sargasso Sea where larger temperature gradients exist at such depths.


TEMPERATURE IN C.
0
5
10
15
20
25
30
100
200
300
400
500
600
700
800
DEPTH IN M.
66805
31075F
70 4 17
35 13 N
67 46 W

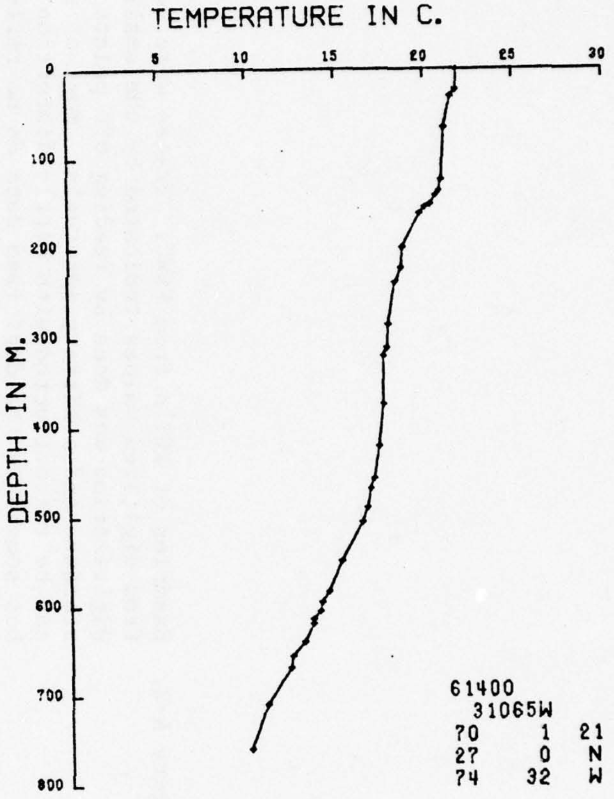
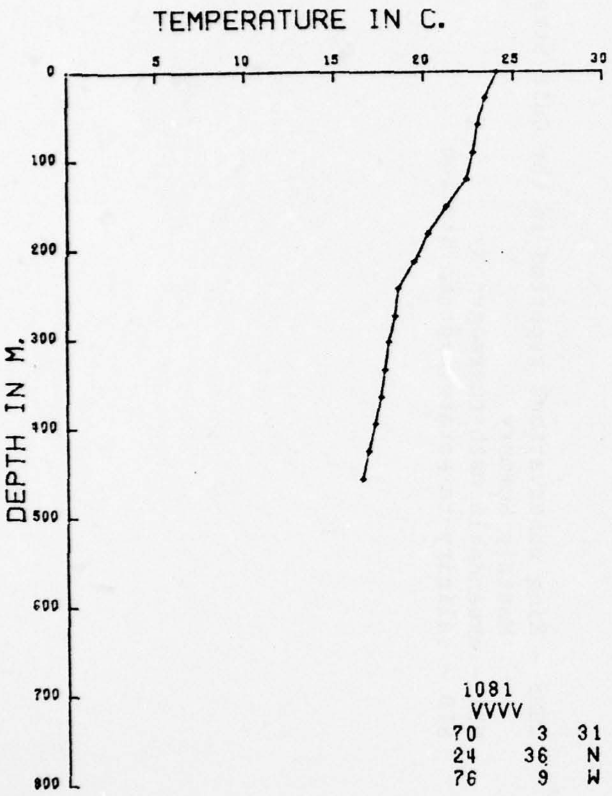
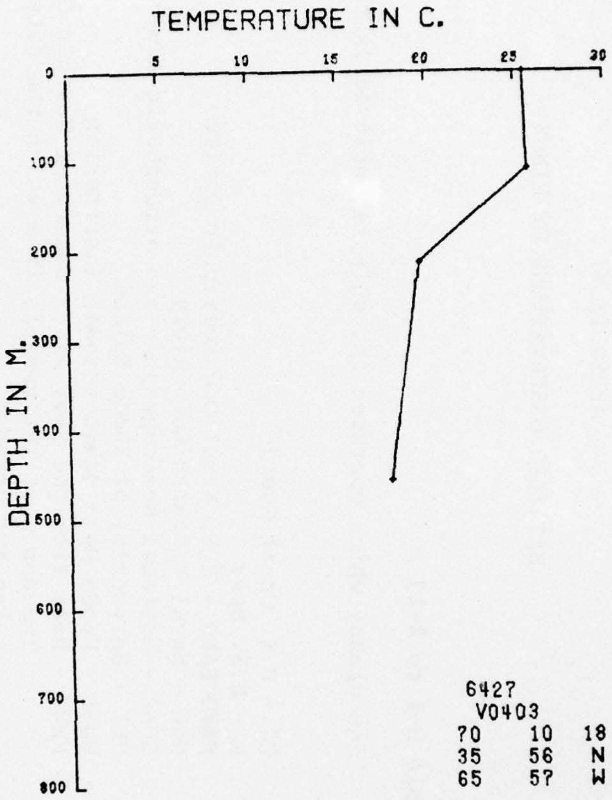

TEMPERATURE IN C.
0
5
10
15
20
25
30
100
200
300
400
500
600
700
800
DEPTH IN M.
61400
31065W
70 1 21
27 0 N
74 32 W

Figure A-2. Examples of XBT's from FNWC, Traces were reconstructed from digitized values indicated by the small crosses. Digitization was done by reading off points at non-standard and arbitrary intervals. Most of the traces can be reconstructed with little distortion (trace 1081) but sometimes the digitized data do no reflect details of the real XBT traces due to insufficient points (trace 6427).


TEMPERATURE IN C.
5
10
15
20
25
30
DEPTH IN M.
0
100
200
300
400
500
600
700
800
1081
VVVV
70 3 31
24 36 N
76 9 W


TEMPERATURE IN C.
5
10
15
20
25
30
DEPTH IN M.
0
100
200
300
400
500
600
700
800
6427
V0403
70 10 18
35 56 N
65 57 W

APPENDIX B

DETAILED OBSERVATIONS OF RINGS

Table B-1 to B-13

* The agency which operates the ship is enclosed in parenthesis.

CG - U.S. Coast Guard
N - U.S. Navy
NAVOCEANO - U.S. Naval Oceanographic Office
NRL - Naval Research Laboratory
NOAA - National Oceanographic and Atmospheric Administration
URI - University of Rhode Island
WHOI - Woods Hole Oceanographic Institution
FNWC - Data from the Navy Fleet Numerical Weather Central. The names of the vessels from which the data were taken are unknown.

**
GSMS - Ring observations reported in the Gulf Stream Monthly Summary
XBT - expendable bathythermography
STD - salinity-temperature-depth station

TABLE B-1. Observations of Ring 1.

Date	Platform/Agency*	Observations**
1970		
June 1	Franconia (NAVOCEANO)	reported in GSMS
June 12, 18	Vogue (N), FNWC	2 XBT's
July 18	Rockaway (CG)	2 STD's, 1 hydrostation
August 18	FNWC	1 XBT
1971		
March 23	Ingham (CG), FNWC	6 XBT's
April 12-14		satellite data
May 12		satellite data
May 10, 11, 18	Trident (URI)	65 XBT's, 3 hydrostations
June 1		satellite data
July 16, 25	FNWC	2 XBT's
August 4,20,28	FNWC	3 XBT's
September 20,26,29	Little Rock (N)	3 XBT's
October 21-24	Trident (URI)	28 XBT's, 5 STD's
November 5,9,14	Sumner (N), FNWC	3 XBT's
December 10	Kane (NAVOCEANO)	3 XBT's
1972		
January 8	Wilkes (NAVOCEANO)	10 XBT's
January 19	Evergreen (CG)	2 XBT's
February 19	Mizar (NRL)	17 XBT's
March 3	Bordelon (N)	2 XBT's
April 8,9	Researcher (NOAA)	22 XBT's

TABLE B-2. Observations of Ring 2.

1970		
May 1,14,15	F. Sherman (N)	3 XBT's
July 20	Rockaway (CG)	1 STD, 1 hydrostation
October 30,31	Cromwall, Evergreen (N)	8 XBT's
1971		
April 2		reported in GSMS
April 18	Cromwall (N)	2 XBT's
July 22,25,26,29	E. McDonald, Browning	16 XBT's
September 29	FNWC	1 XBT
November 7	Lynch (NAVOCEANO)	15 XBT's
1972		
January 6	FNWC	1 XBT
February 28	FNWC	1 XBT
June 8,13	W.H. Standley (N)	3 XBT's, satellite data
July 27	FNWC	1 XBT, satellite data
August 8,14	FNWC	2 XBT's
October 25	X.D. Yarnel (N)	3 XBT's

TABLE B-3. Observations of Ring 3.

Date	Platform/Agency*	Observations**
1971		
May 8	Norwalk (N)	1 XBT
June 16, 17	Ingham (N)	3 XBT's
June 25, July 8	J. Daniels	4 XBT's
July 22	FNWC	1 XBT
August 29,30		reported in GSMS
September 21	FNWC	1 XBT
October 20,22,23	Steinaker (N)	4 XBT's
December 16	J. Daniels (N)	1 XBT
1972		
February 15,25	FNWC	2 XBT's, in GSMS
February 28	Blandy (N)	6 XBT's
March 1,3,8		
April 27	Garcia (N), Knorr (NOAA)	9 XBT's
June 17	FNWC	1 XBT
July		satellite data
August		satellite data
December	Trident (URI)	7 XBT's
1973		
January		satellite data
January 30,31	Albatross IV (CG)	9 XBT's
February 4,6		

TABLE B-4. Observations of Ring 4.

1972		
August 13		reported in GSMS
September 23	Atlantis II (WHOI)	26 XBT's
November 7	Chain (WHOI)	1 XBT
1973		
February 8	X.D. Yarnell (N)	1 XBT
March 7	Koelsch (N)	2 XBT's
April 5,15	Whiting (N)	2 XBT's
June 5,6	Morton (N)	2 XBT's
July 11,17	FNWC	2 XBT's
August 14	FNWC	1 XBT
September 14,17	FNWC	3 XBT's

TABLE B-5. Observations of Ring 5.

Date	Platform/Agency*	Observations**
1970		
February 28	Koelsch, McCloy Vogue (N)	8 XBT's
May 20-24	Vogue, Koelsch (N)	109 XBT's
June 10-18	Koelsch, Mc Cloy, Vogue (N)	107 XBT's
October 22,23	Intrepid (N)	12 XBT's
1971		
May		
June 20,21,28	J. Daniels (N)	3 XBT's

TABLE B-6. Observations of Ring 6.

1970		
March 1,7	Chain (WHOI)	2 STD's, 1 hydrostation
April 27,28	Atlantis II (WHOI)	4 XBT's
May 16,19	FNWC	1 hydrostations, 1 XBT
July 3,12	Victor (N)	2 XBT's
August 6	FNWC	1 XBT

TABLE B-7. Observations of Ring 7.

1972		
November 8		reported in GSMS
December 8		reported in GSMS
1973		
January 14-19	Lynch (NAVOCEANO)	25 XBT's
February 5-13	Lynch (NAVOCEANO)	14 XBT's

TABLE B-8. Observations of Ring 8.

1970		
April 27	Atlantis II (WHOI)	1 STD
June 27	C.R. Ware (N)	1 XBT
November	Androscoggin (CG)	Several STD's

TABLE B-9. Observations of Ring 9.

Date	Platform/Agency*	Observations**
1973		
June 7	FNWC	1 XBT
July 20	Ambassador (NAVOCEANO)	6 XBT's
September 8.11	FNWC	13 XBT's

TABLE B-10. Observations of Ring 10.

1971		
August 20,24,31	Norwalk (N), FNWC	2 XBT's, 3 STD's
September 13	FNWC	1 XBT
October 19	FNWC	1 XBT

TABLE B-11. Observations of Ring 11.

1973		
August 31	Ambassador (NAVOCEANO)	30 XBT's
September 9,14		
October 7,19	FNWC	2 XBT's
November 27,28		reported in GSMS

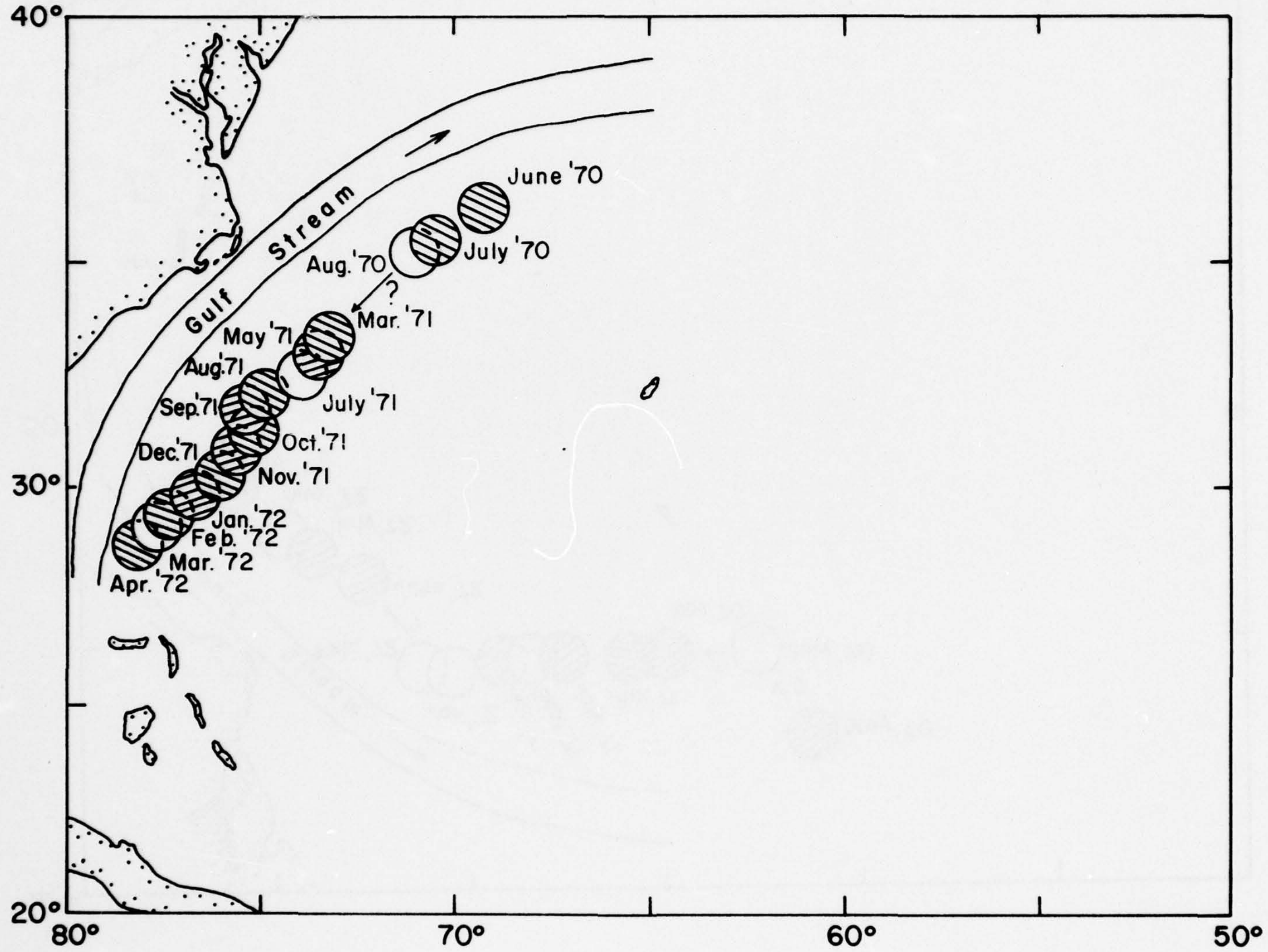
TABLE B-12. Observations of Ring 12.

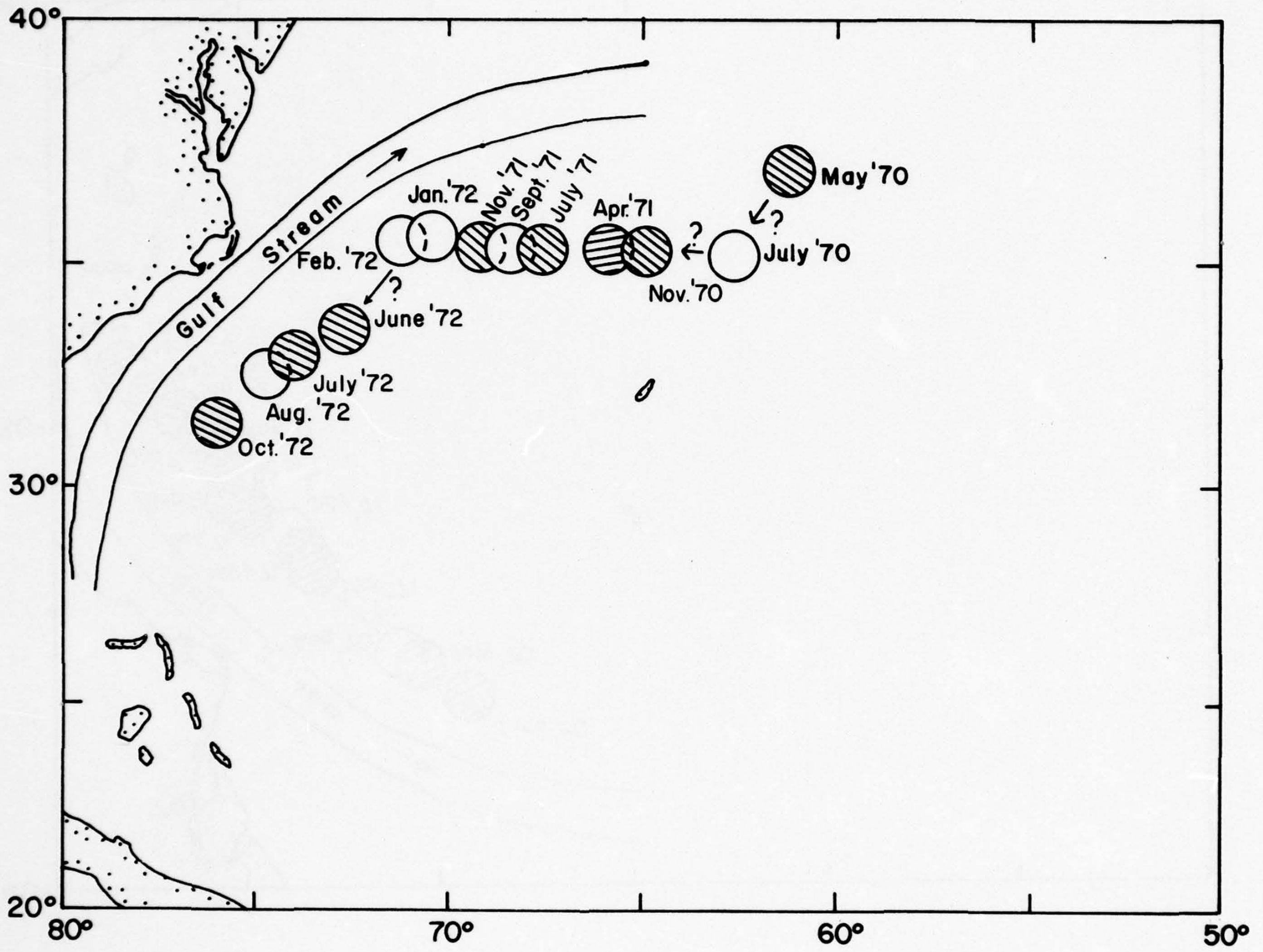
1973		
April 14	FNWC	3 XBT's
May 22, 29	Morton (N)	2 XBT's
July 21,22	FNWC	1 XBT

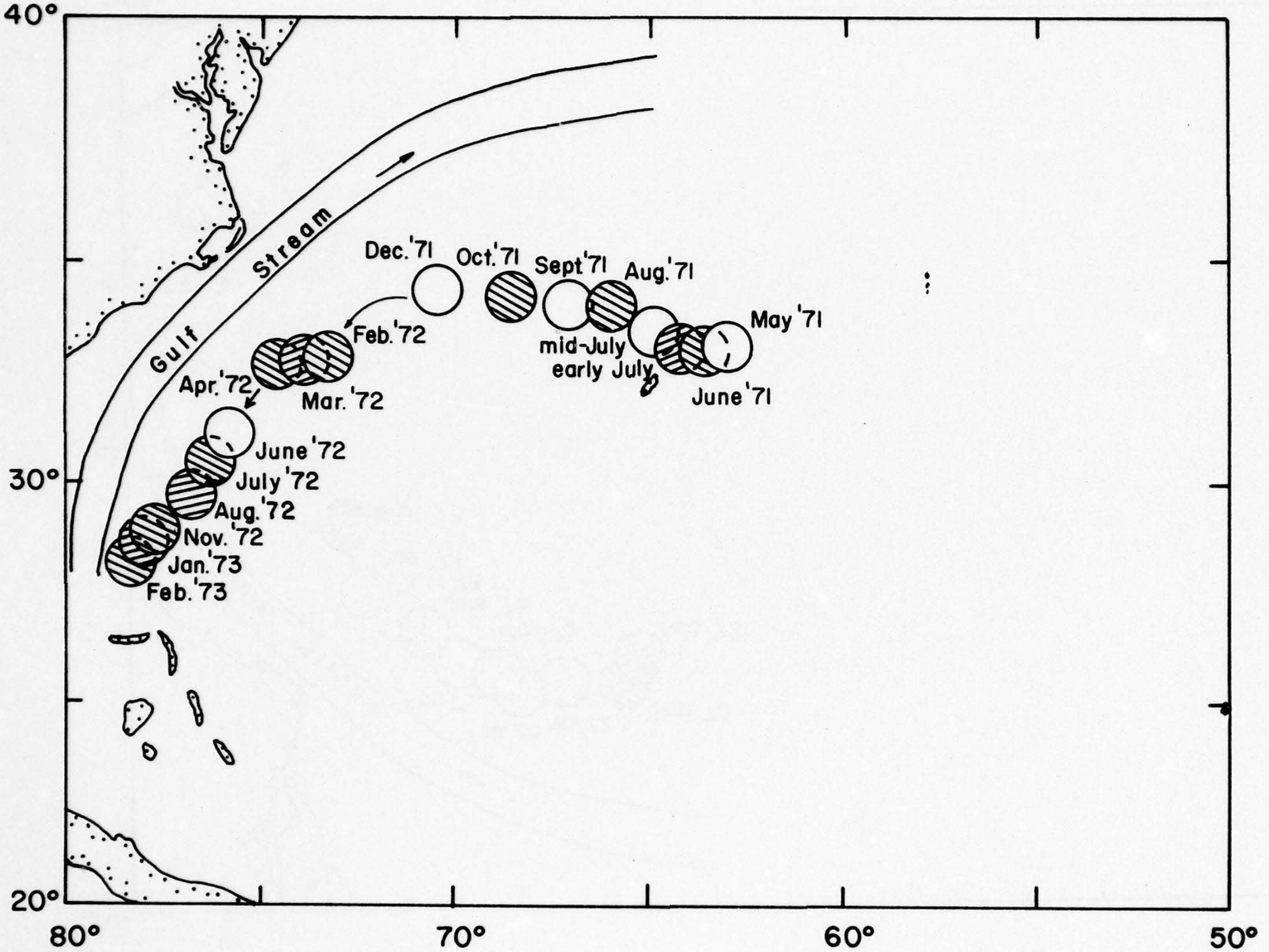
TABLE B-13. Observations of Single Rings

Date	Platform/Agency*	Observations**
1970, September 27		reported in GSMS
1970, May 5,6,13	Tsxin, X.D.Yarnell (N)	4 XBT's
1970, August	Absecon (CG)	several STD's
1970, December	Chincoteague (CG)	several STD's
1971, April 25,26,30	Franconia (NAVOCEANO)	reported in GSMS
1971, May 24	Franconia (NAVOCEANO)	reported in GSMS
1971, September 17,18	Franconia (NAVOCEANO)	reported in GSMS
1971, September 30 October 2	FNWC	6 XBT's
1971, November 14	Lynch (NAVOCEANO)	5 XBT's
1971, August 14-17	Sims (N)	8 XBT's
1972, March 2,3	Chain (WHOI)	5 XBT's
1972, November 6		reported in GSMS
1972, December	Trident (URI)	
1973, April 13,21	Morton (N)	4 XBT's
1973, May 28,31	FNWC	3 XBT's

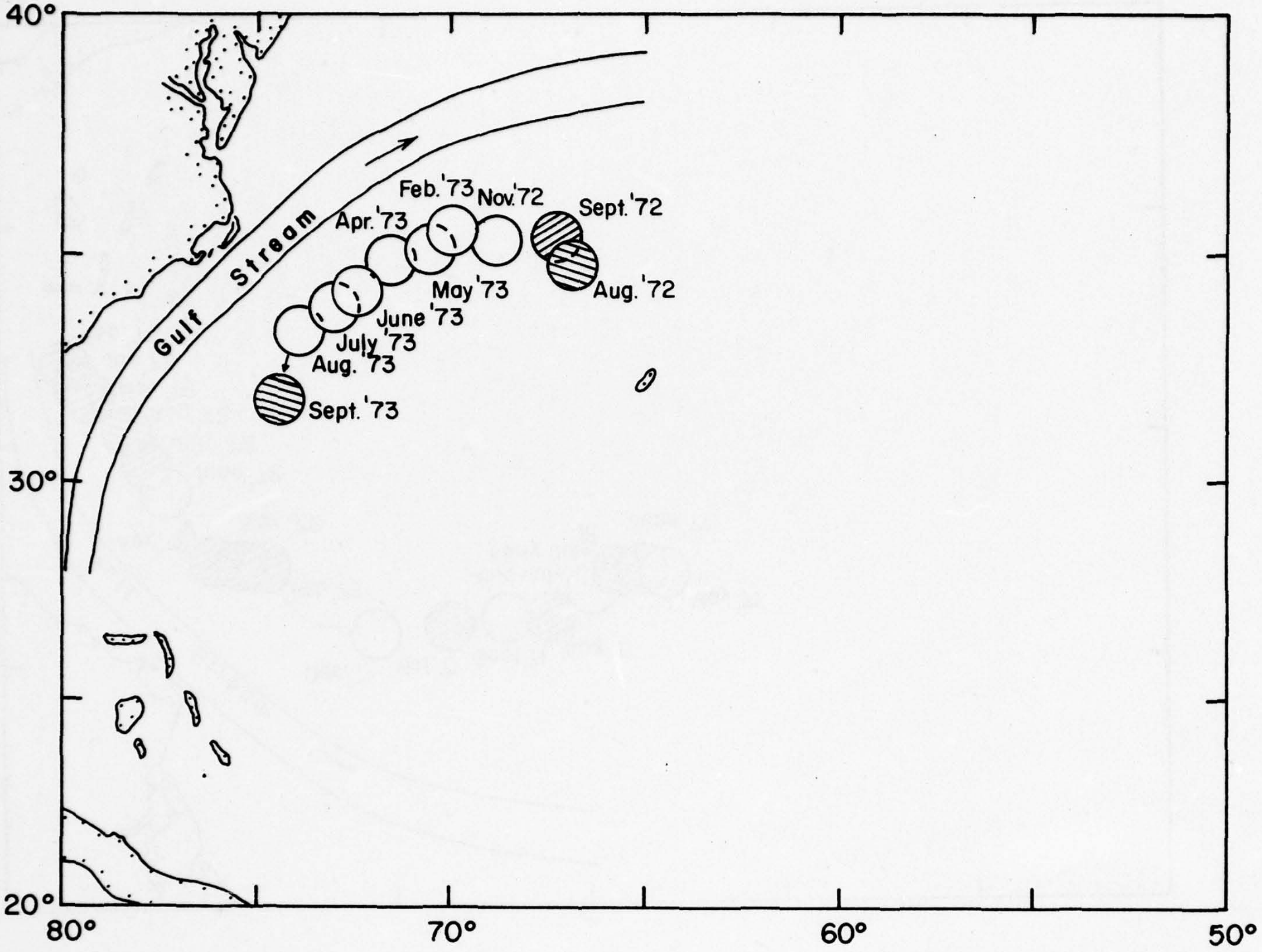
Figure B-1 to B-7.
The observed positions of the ring time-series. The shaded circles indicate ring observations of at least three anomalies. Question marks indicate data gaps of more than three months. Figure B-7 shows the ring time-series which consist of ring observations only with one or two anomalies.

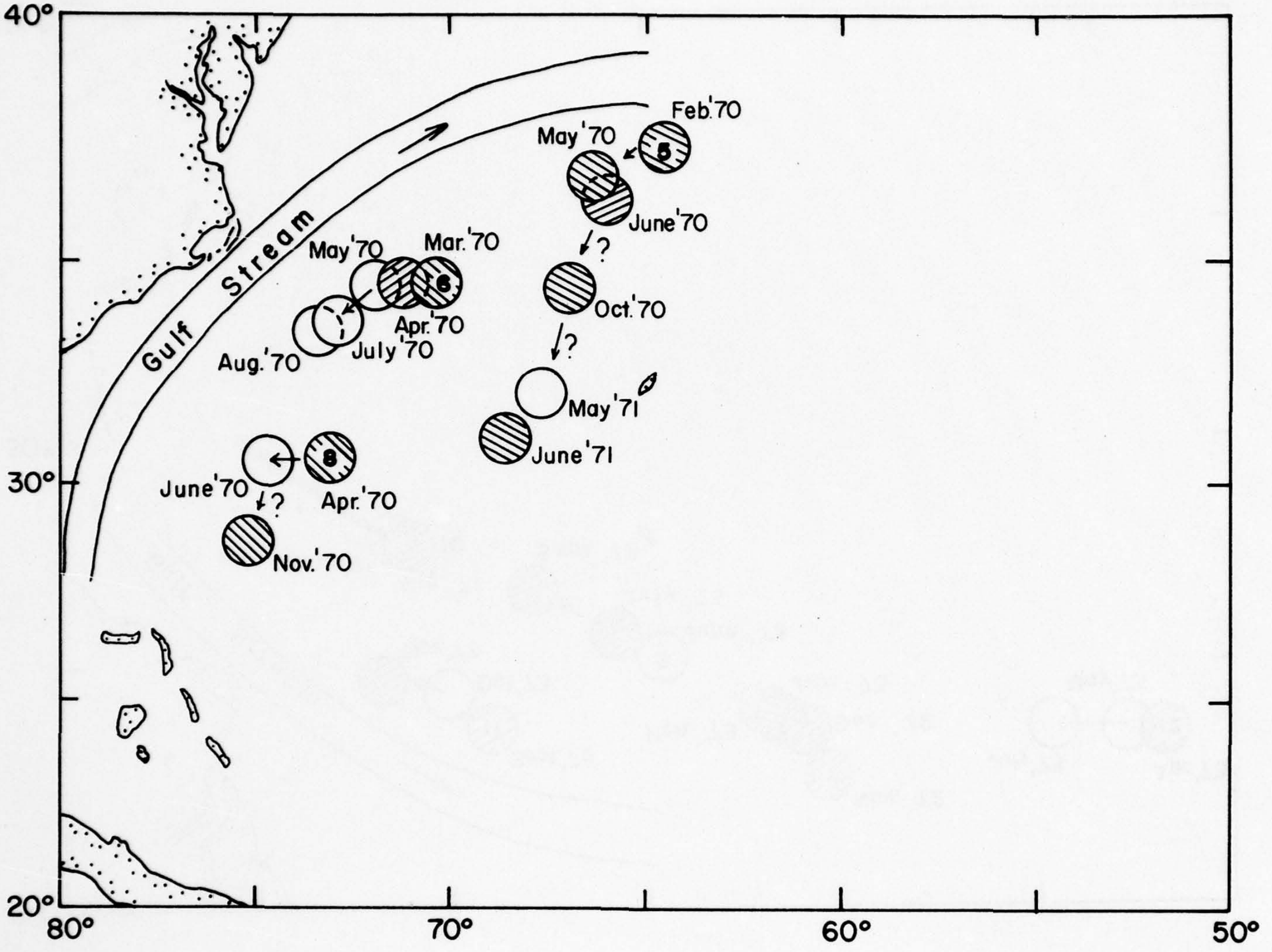

40°
30°
20°
80°
70°
60°
50°
Gulf Stream
June '70
July '70
Aug. '70
?
Mar. '71
May '71
Aug.'71
July '71
Sep.'71
Oct.'71
Dec.'71
Nov.'71
Jan.'72
Feb.'72
Mar.'72
Apr.'72

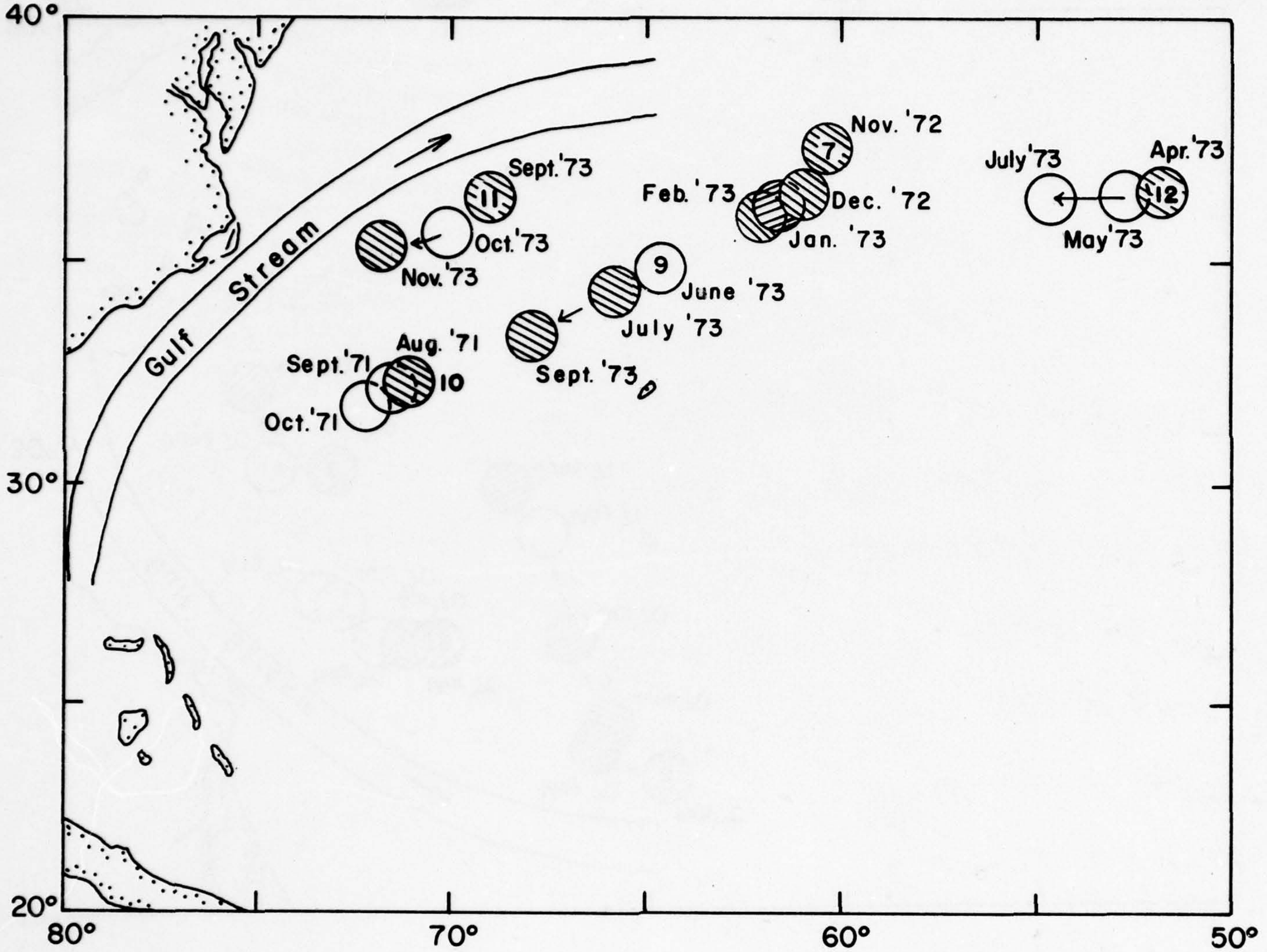

40°
30°
20°
80°
70°
60°
50°
Gulf Stream
May '70
July '70
Nov. '70
Apr. '71
July '71
Sept. '71
Nov. '71
Jan. '72
Feb. '72
June '72
July '72
Aug. '72
Oct. '72
?
?
?

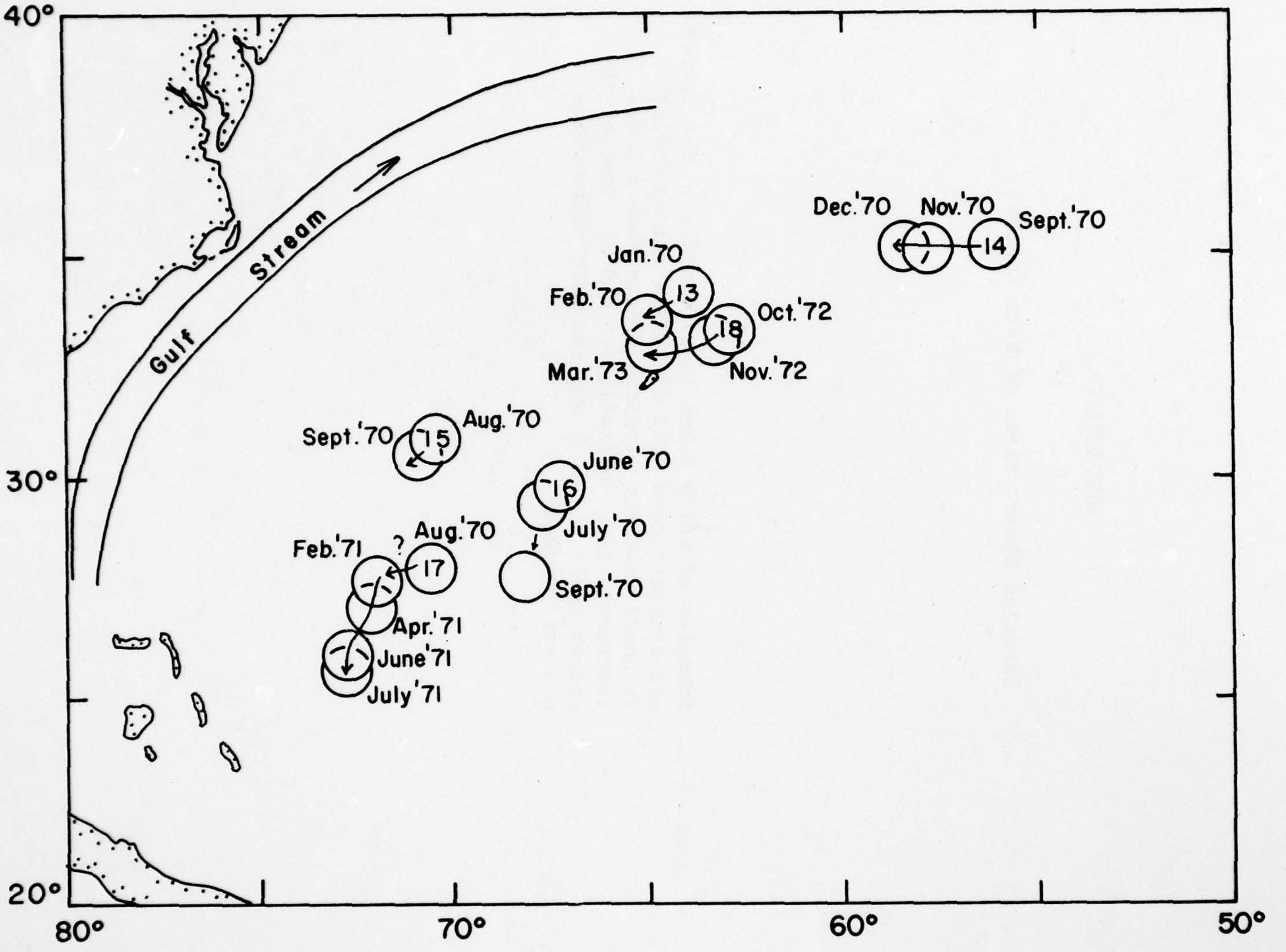


40°
30°
20°
80°
70°
60°
50°
Gulf Stream
Dec.'71
Oct.'71
Sept.'71
Aug.'71
May '71
mid-July
early July
June '71
Feb.'72
Mar.'72
Apr.'72
June '72
July '72
Aug.'72
Nov.'72
Jan.'73
Feb.'73


40°
30°
20°
80°
70°
60°
50°
Gulf Stream
Feb.'73
Nov.'72
Sept.'72
Apr.'73
May '73
Aug.'72
June '73
July '73
Aug. '73
Sept.'73


40°
30°
20°
80°
70°
60°
50°
Gulf Stream
Feb.'70
5
May '70
June '70
?
Oct.'70
?
May '71
June '71
May '70
Mar.'70
6
Apr.'70
July '70
Aug.'70
8
June '70
Apr.'70
?
Nov.'70


40°
30°
20°
80°
70°
60°
50°
Gulf Stream
Sept.'73
11
Oct.'73
Nov.'73
Aug.'71
10
Sept.'71
Oct.'71
9
June '73
July '73
Sept. '73
Nov. '72
7
Dec. '72
Feb. '73
Jan. '73
July'73
Apr.'73
12
May'73


40°
30°
20°
80°
70°
60°
50°
Gulf Stream
Dec.'70
Nov.'70
Sept.'70
14
Jan.'70
13
Feb.'70
Oct.'72
18
Nov.'72
Mar.'73
Sept.'70
Aug.'70
15
June'70
16
July'70
Sept.'70
Feb.'71
?
Aug.'70
17
Apr.'71
June'71
July'71

AD-A036 334 RHODE ISLAND UNIV KINGSTON GRADUATE SCHOOL OF OCEANO--ETC F/G 8/3
DISTRIBUTION AND MOVEMENT OF CYCLONIC GULF STREAM RINGS.(U)
FEB 77 D Y LAI, P L RICHARDSON N00014-68-A-0215-0003
UNCLASSIFIED URI/GSO-REF-77-1 NL

2 OF 2
AD
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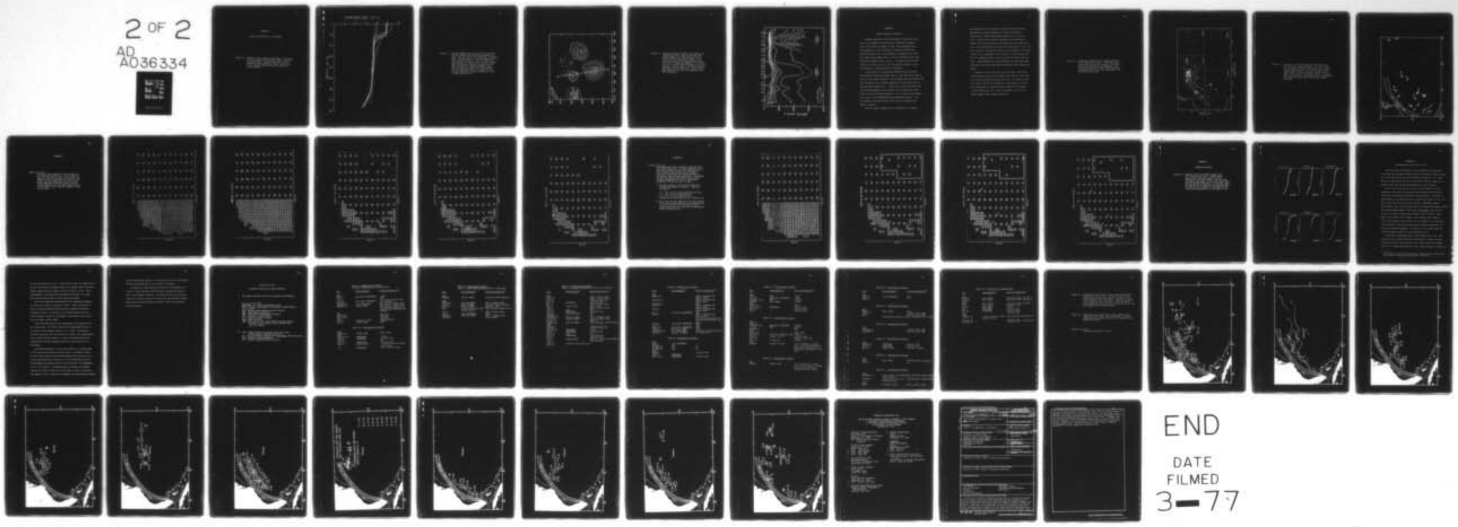


END
DATE
FILMED
3-77

APPENDIX C

Detailed Observations of Warm Eddies

Figure C-1. Examples of XBT's taken in warm eddies. The traces are reconstructed from digitized values indicated by small crosses. Typical traces show a thick isothermal layer extending to 600 m. Some of the traces ended at 450 m and the main thermocline was not reached.

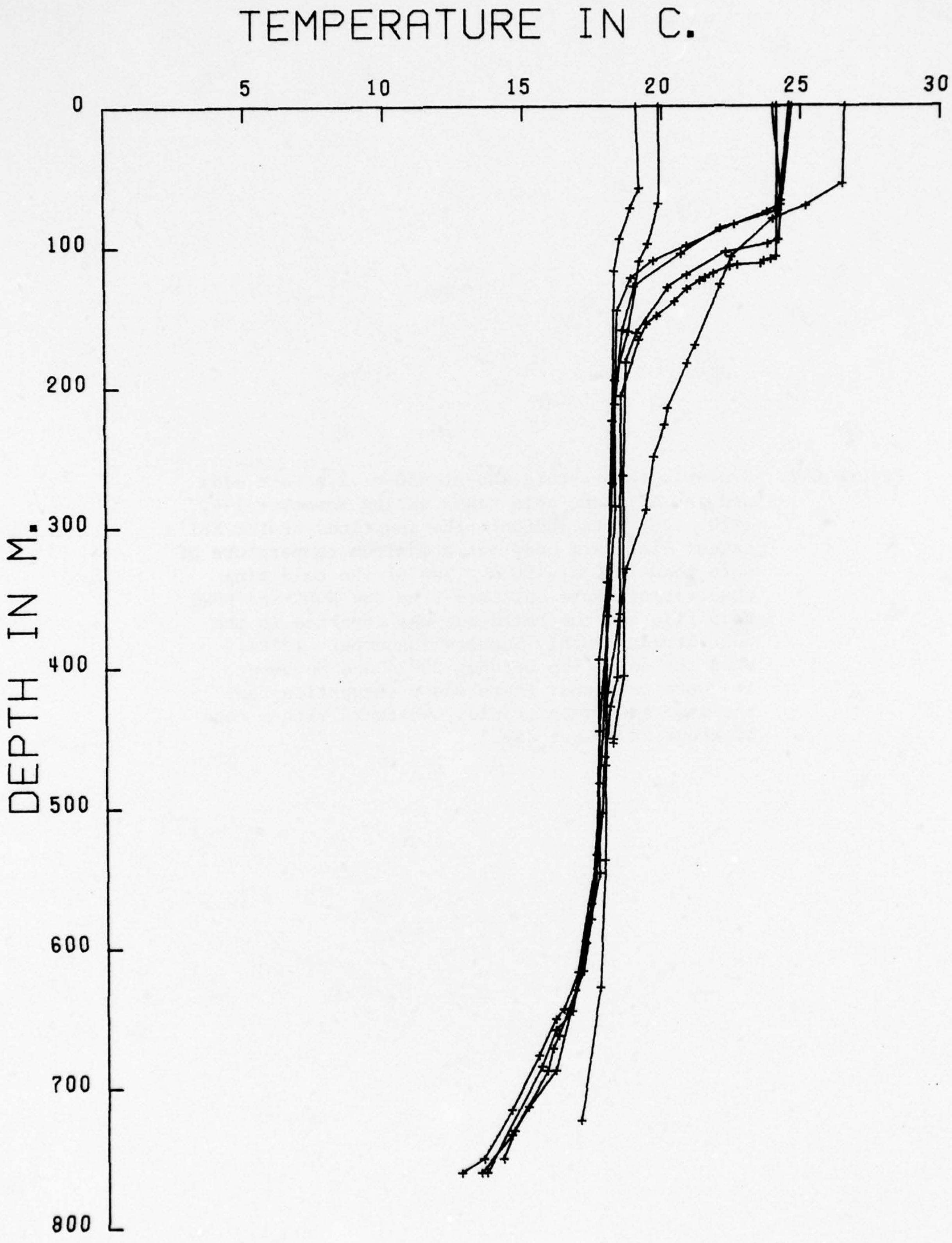
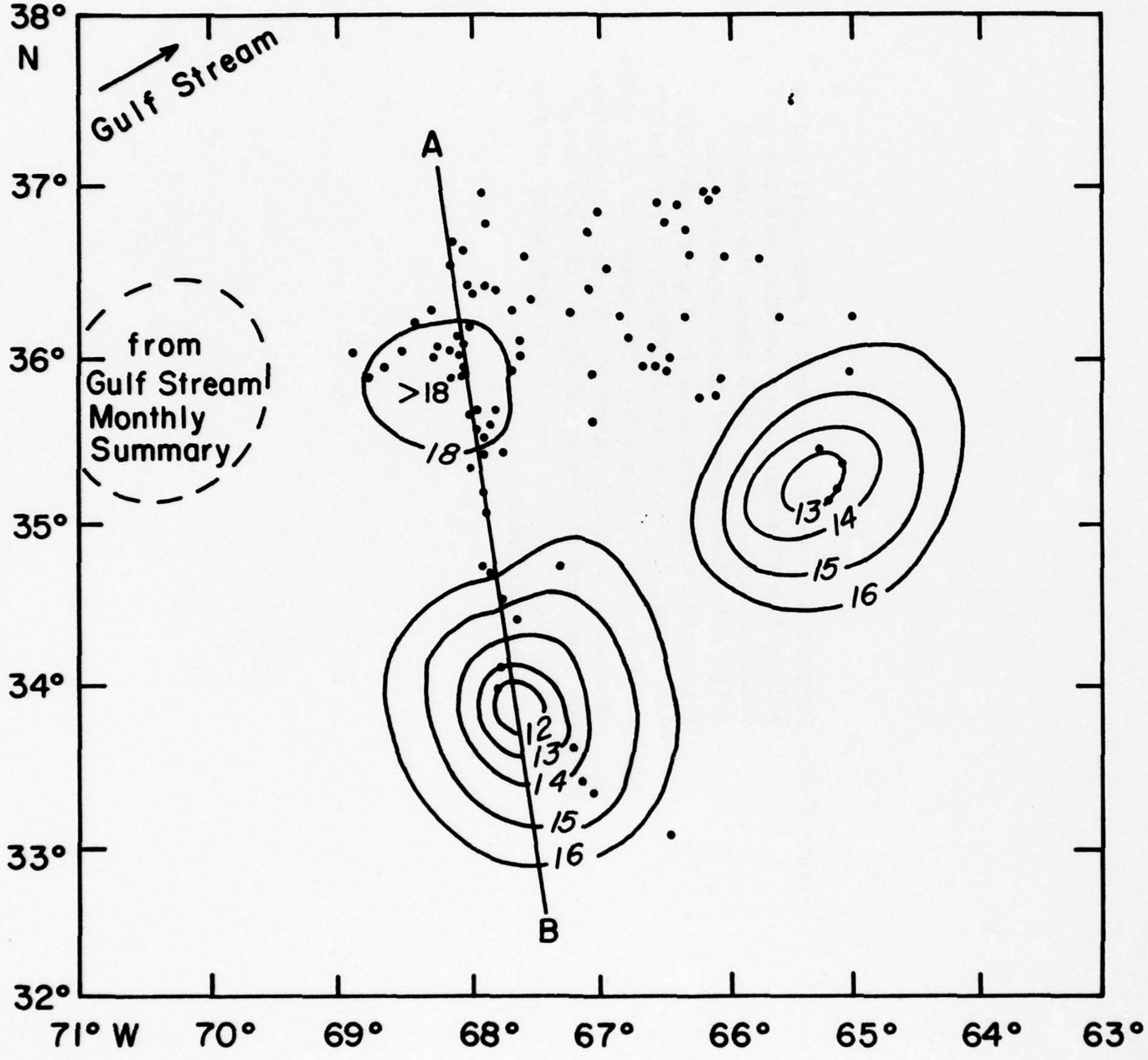
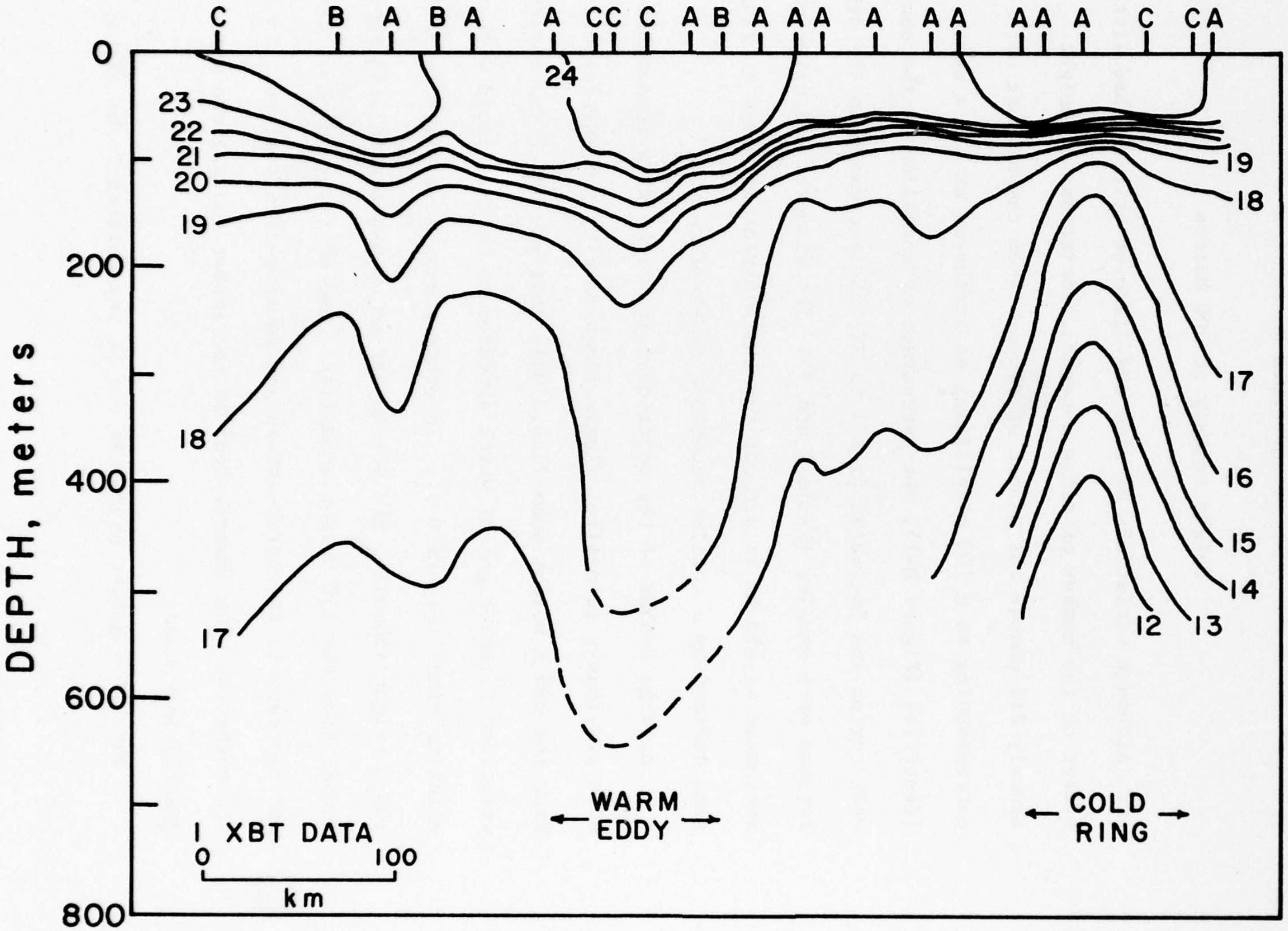

TEMPERATURE IN C.
0
5
10
15
20
25
30
DEPTH IN M.
100
200
300
400
500
600
700
800

Figure C-2. Synoptic temperature map at 450 m of a warm eddy and the adjacent cold rings during November 1-4, 1970. The dots indicate the positions of the XBT's taken. The warm eddy has a maximum temperature of more than 18°C at 450 m. Two of the cold ring observations were obtained from the NODC and FNWC data file and the third one was reported in the Gulf Stream Monthly Summary (December, 1970). When the data from October 20-24 and November 1-4 were combined, there was a suggestion that the warm eddy moved rapidly westward with a rate of about 20 km per day.



Gulf Stream
from
Gulf Stream
Monthly
Summary
A
B
>18
18
12
13
14
15
16
13
14
15
16
38°
N
37°
36°
35°
34°
33°
32°
71° W
70°
69°
68°
67°
66°
65°
64°
63°

Figure C-3. Temperature section through a warm eddy and an adjacent cold ring. This section was taken during November 1-4, 1970 along the line AB (Figure C-2) by several Navy vessels. The letter indicates the ship from which the XBT was taken; A stands for INTREPID, B for McCLOY and C for data from FNWC (the names of the ships unknown). A thick layer of 18° Water indicates the presence of the warm eddy. The 450 meter XBT's used did not reveal the deepening of the main thermocline.


C
B
A
B
A
A
CC
C
A
B
A
A
A
A
A
A
A
A
A
C
C
A
0
200
400
600
800
DEPTH, meters
24
23
22
21
20
19
18
17
19
18
17
16
15
14
13
12
WARM EDDY
COLD RING
I XBT DATA
0
100
km

APPENDIX D

Height Anomaly of 100 Meters

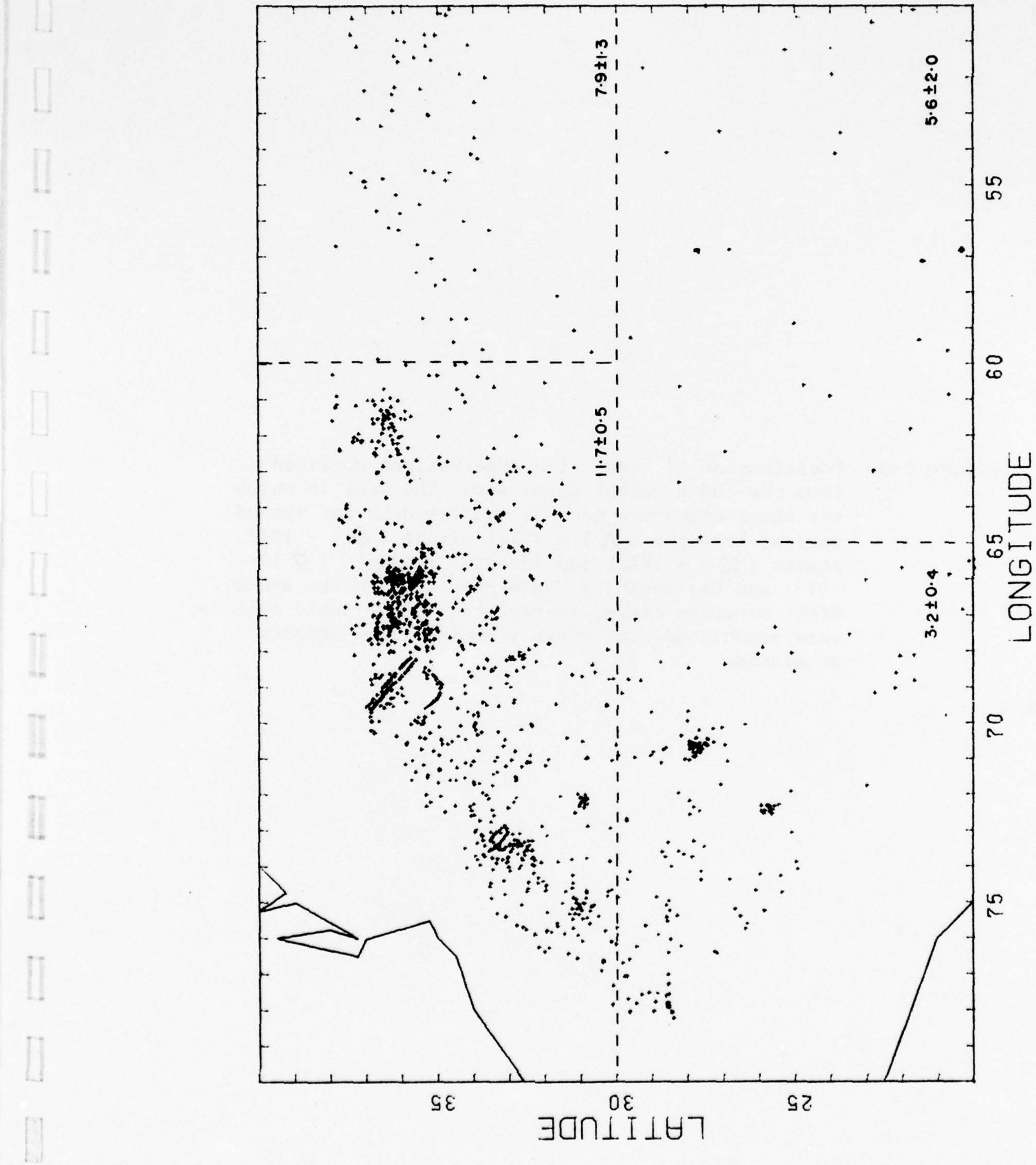
Although variations of time and diameter criteria had little effect on the number of rings observed, variations in height anomaly did change the number of rings. When temperature data corresponding to a 100 m uplifting of isotherms at 450 m were identified (Figure D-1), the percentage of anomalies in the southwest region was increased from 1 to 3%; the increases in the other regions were smaller (Table 2 and 3). The diameter criterion was increased to 150 km to account for the apparent increase in ring size defined by a smaller anomalous temperature.

A large number of the additional anomalies were associated with previously identified single rings or ring time-series obtained from the 150 m height anomalies. Only thirteen new "ring observations" were identified, eight of which appeared to be associated with the existing rings (Figure D-2). In other words, five rings formed from 100 m height anomalies did not appear to be associated with those formed from the 150 height anomalies. One of these was near Bermuda, and two each in the northeastern and southwestern regions. Thus, the number of ring observations in the latter two regions were greatly increased.

The 100 m height anomalies can be interpreted to be either measurements close to the edges of strong Gulf Stream rings or measurements of weaker phenomena (old rings, MODE eddies) consisting of a smaller displacement amplitude of the order of 100 m. Since most of the 100 m anomalies in the northwestern Sargasso Sea were associated with existing rings, the same may be true in the northeastern region where the data density is low. However, because of the high data density and low number of ring observations in the southwestern region, there is the possibility that the 100 m anomalies observed there were mid-ocean eddies and not rings. These anomalies may also be remnants of Gulf Stream rings which moved into this region and whose amplitude have decreased in height.

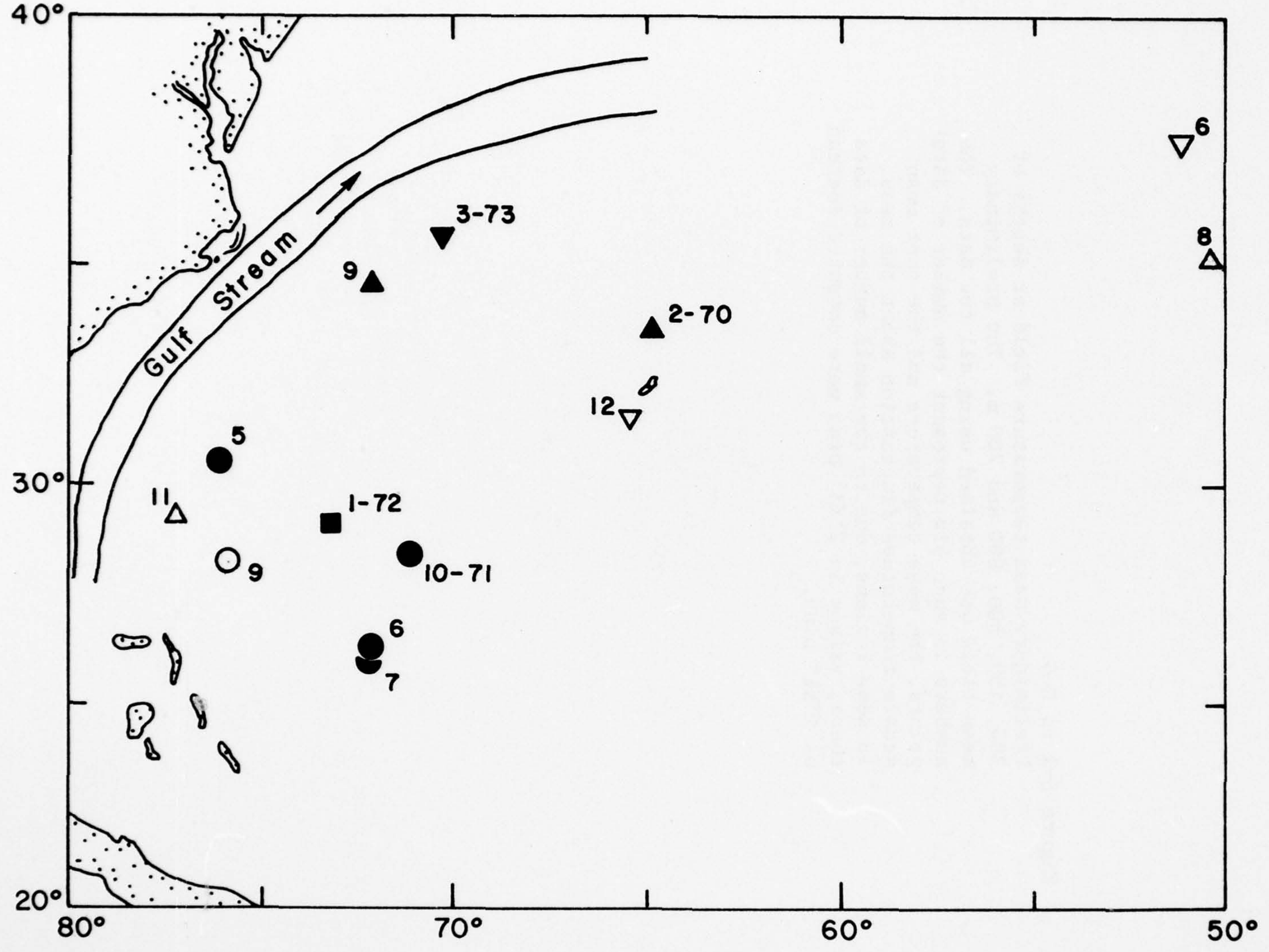
Attempts to infer ring time-series from these single 100 m "ring observations" and other anomalies which did not satisfy the ring criteria were made but proved fruitless. The series formed were either too short (involving only a few anomalies) to be of much significance, or involved numerous subjective decisions as to which anomalies to use. Thus, the movement of these 100 m height anomaly "rings" remains unresolved.

Figure D-1. Geographical distribution of height anomalies of at least 100 m at 450 m. The broken lines divide the area into four regions, according to the distribution of data and anomalies. The percentage of anomalies and the 90% confidence limits are shown at the lower right-hand corner in each box (see text).



LATITUDE
35
30
25
LONGITUDE
55
60
65
70
75
7·9±1·3
11·7±0·5
5·6±2·0
3·2±0·4

Figure D-2. Positions of 13 "new" ring observations obtained from the 100 m height anomalies. The year in which the observation was made is indicated by the symbol: upright triangle (△) - 1970, circle (○) - 1971, square (□) - 1972, and inverted triangle (▽) - 1973, and the month by the number next to the symbol. Eight of these rings, represented by the solid symbols, were associated with rings from the 150 m height anomalies.

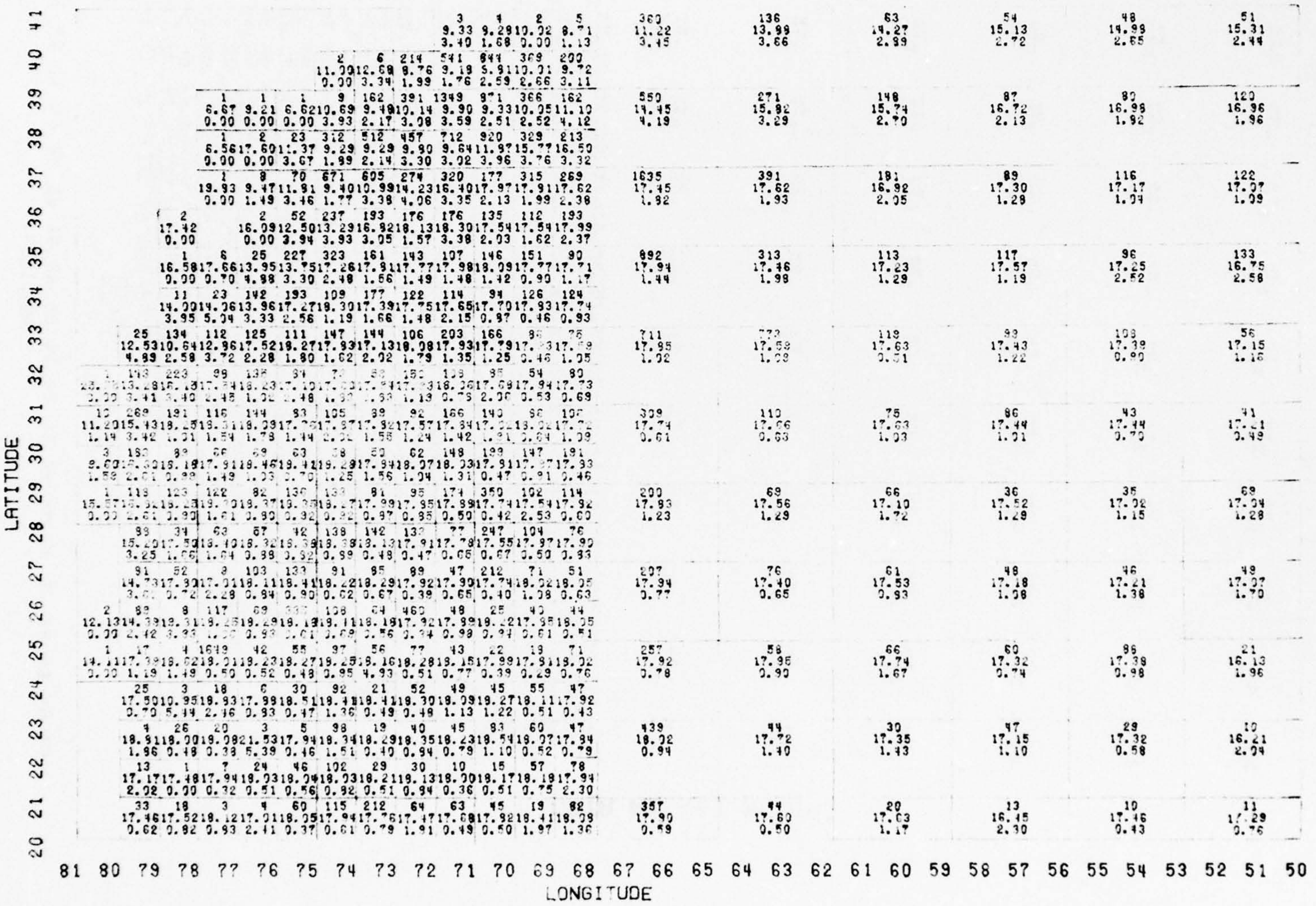

40°
30°
20°
80°
70°
60°
50°
Gulf Stream
3-73
9
2-70
12
6
8
5
11
1-72
9
10-71
6
7

APPENDIX E

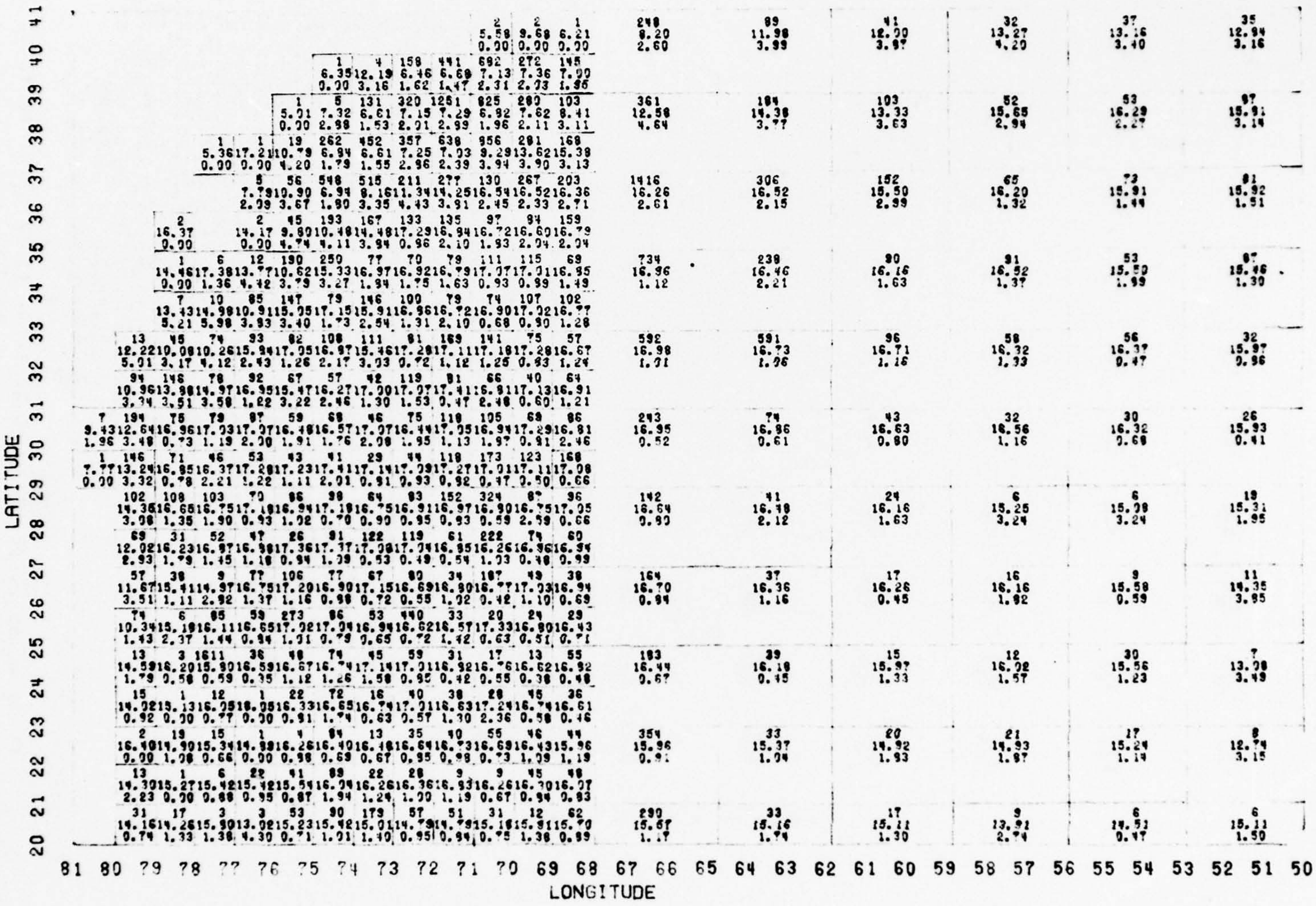
Figure E-1 to E-5.

Preliminary mean temperature field at depths of 300, 450 500, 600 and 700 m. The preliminary mean field was obtained using all the data. The numbers in each bin represent the number of data points, the mean temperature and the root mean square temperature fluctuation about the mean. In some regions, due to the small number of data there, values in 2°X3° bins were computed instead of 1°X1° bins.

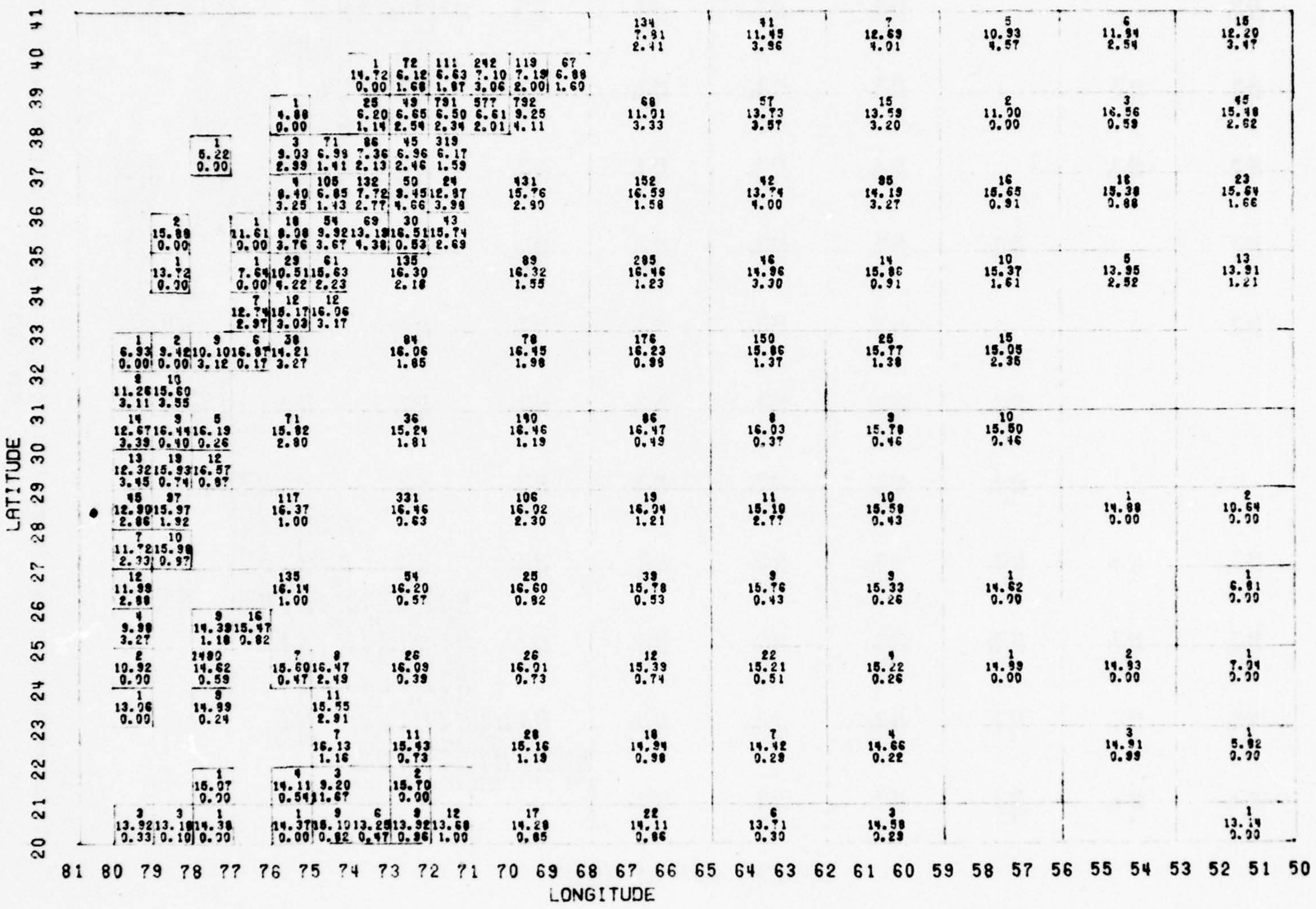
DATA AT 300 METERS



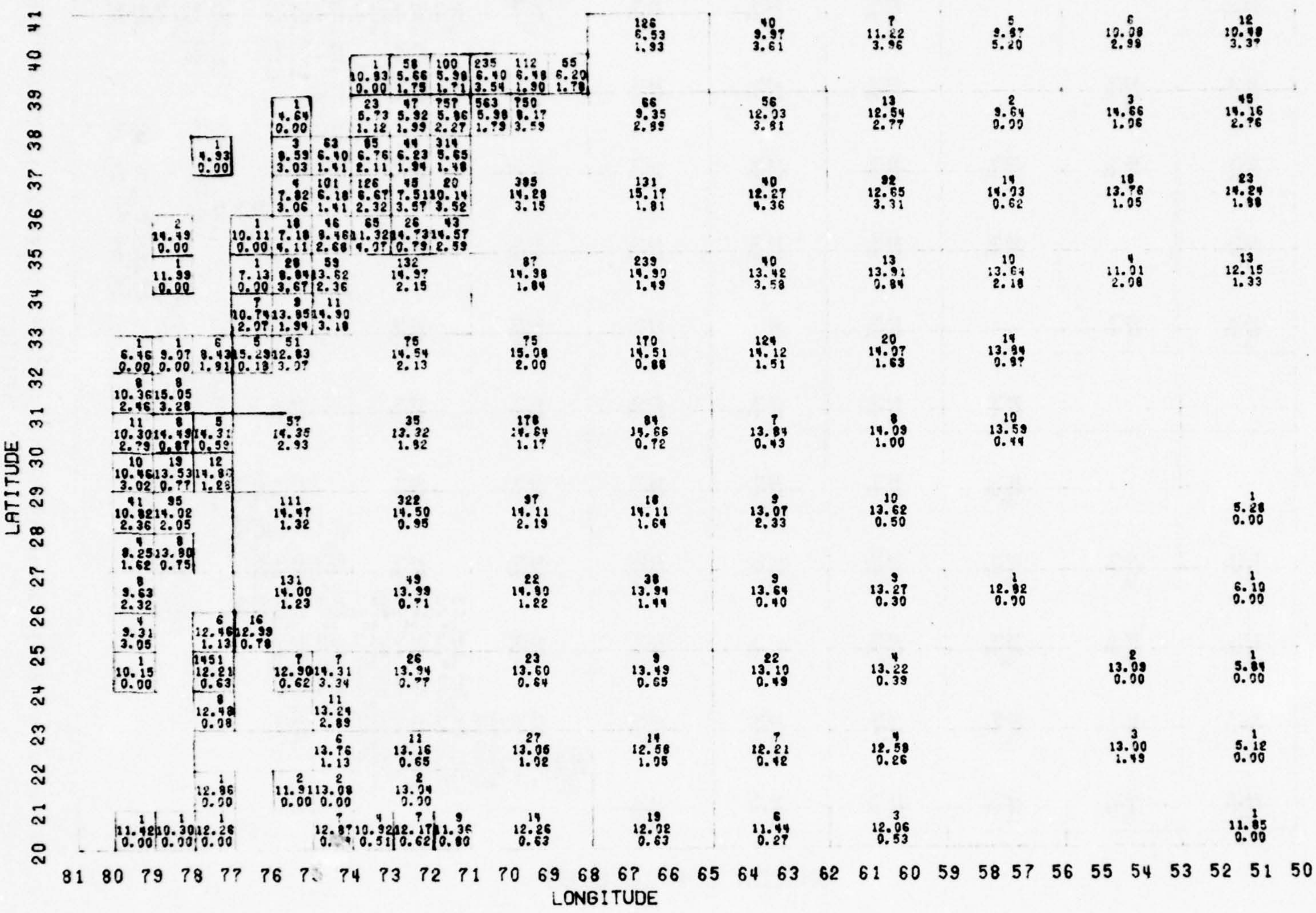
DATA AT 450 METERS



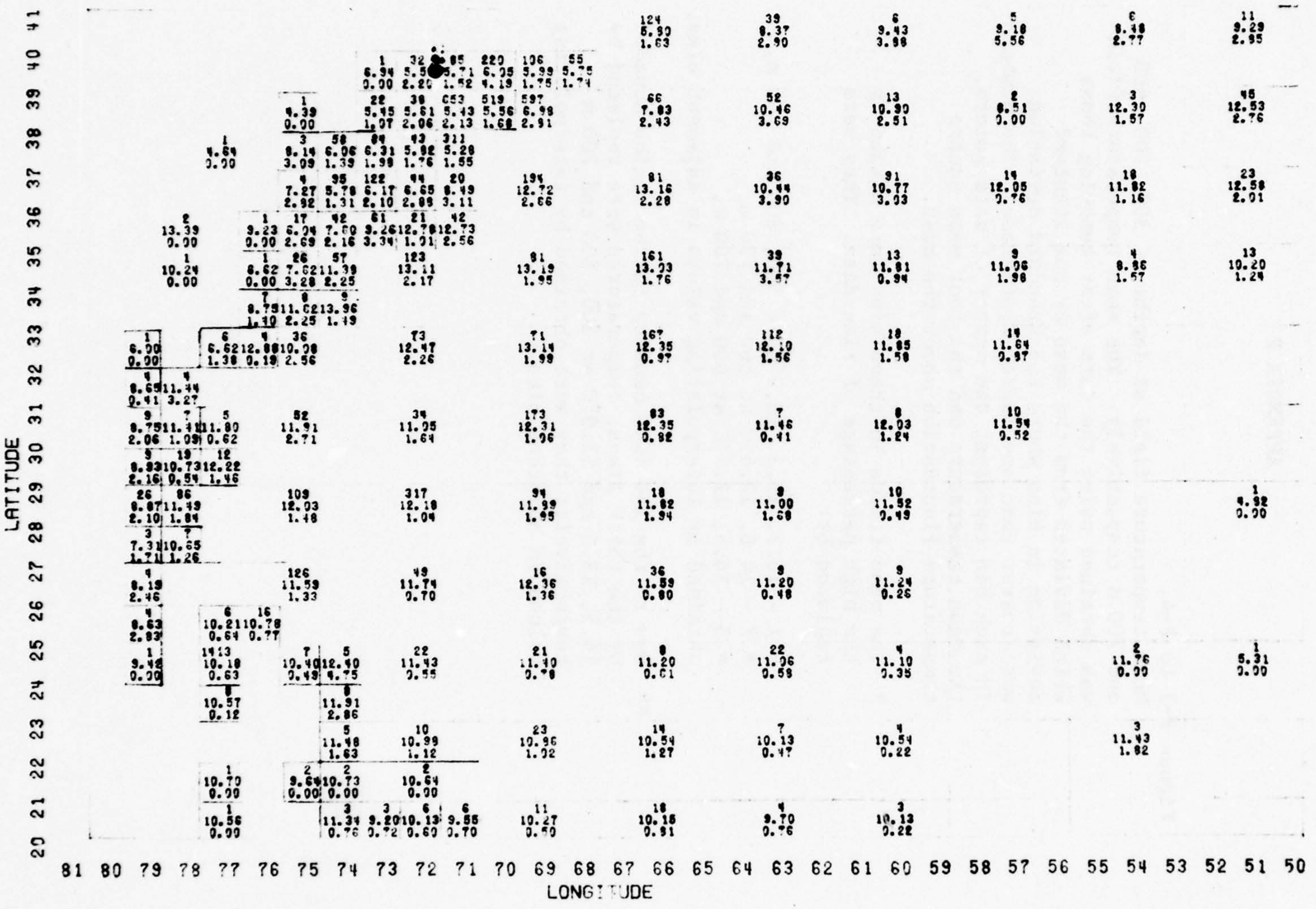
DATA AT 500 METERS



DATA AT 600 METERS



DATA AT 700 METERS



APPENDIX F

Figure F-1 to F-4.

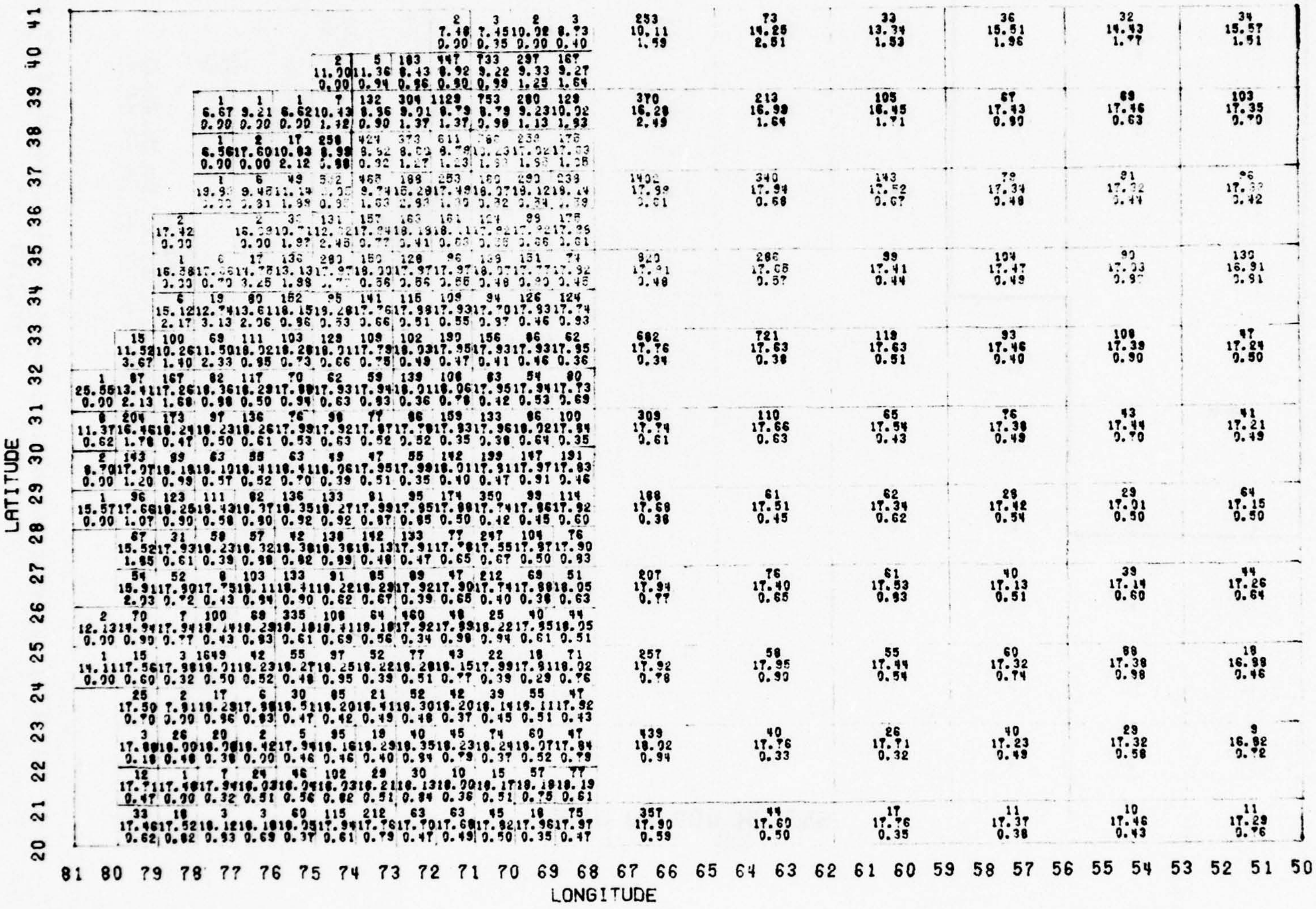
Mean temperature field at depths of 300, 500, 600 and 700 m respectively. The mean temperature field was obtained using the data after removing those which deviated from the mean by one standard deviation in bins where the standard deviation was greater than one degree Centigrade. The numbers in each bin represent the number of data points, the mean temperature and the root mean square temperature fluctuation about the mean.

* The mean fields in these bins were biased by the high percentage of ring data. They were replaced by:

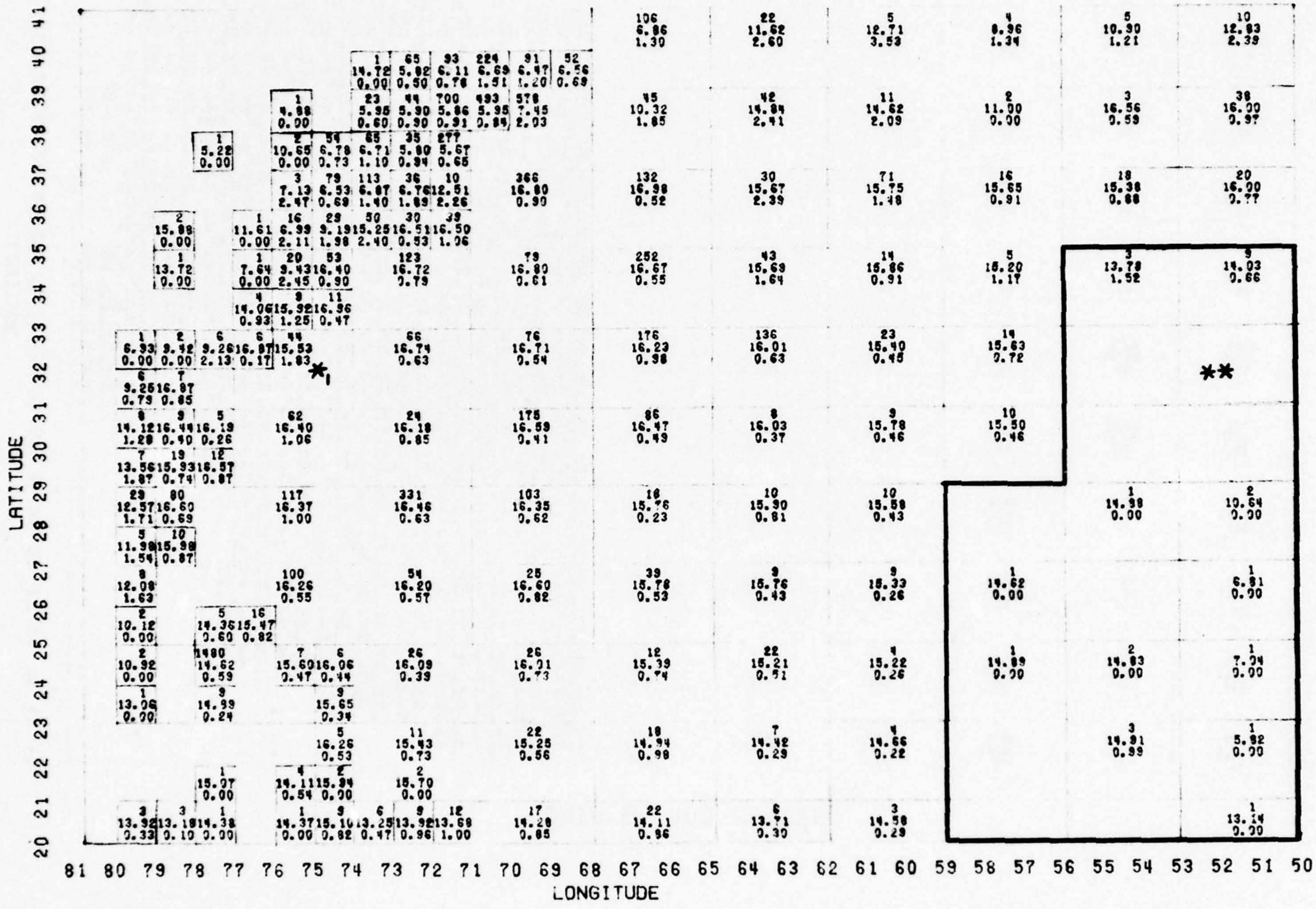
* 1 - 16.7, 15.3, 13.5°C at 500, 600 and 700 m,
* 2 - 14.8, 12.6°C at 600 and 700 m,
* 3 - 14.5, 12.7°C at 600 and 700 m,
obtained by interpolating values in adjacent bins.

** Due to the low data density in the region bounded by the thick lines, temperatures were replaced by 14.5, 13.0 and 11.0°C at 500, 600 and 700 m respectively; they were obtained by interpolating values in adjacent bins.

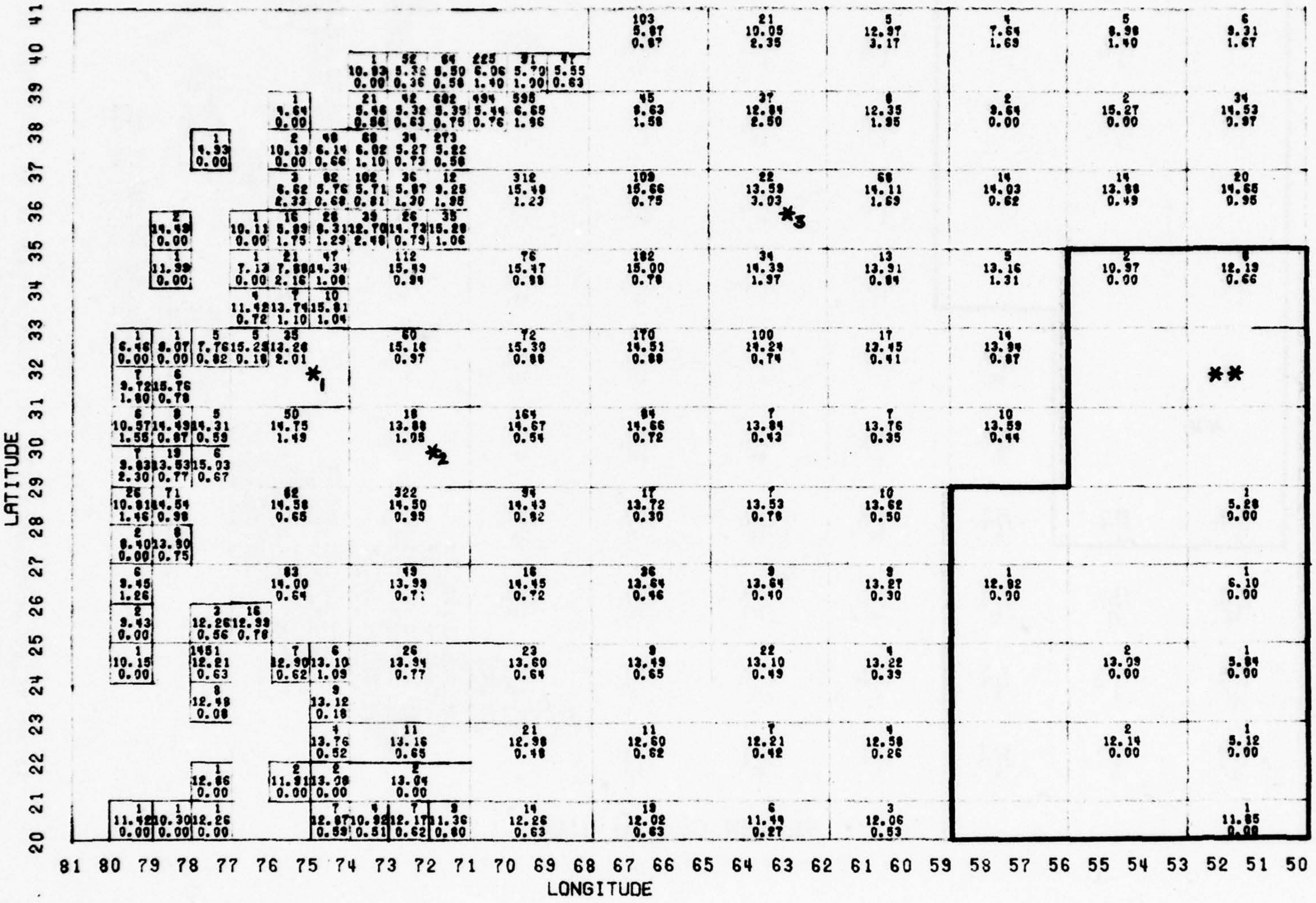
DATA AT 300 METERS



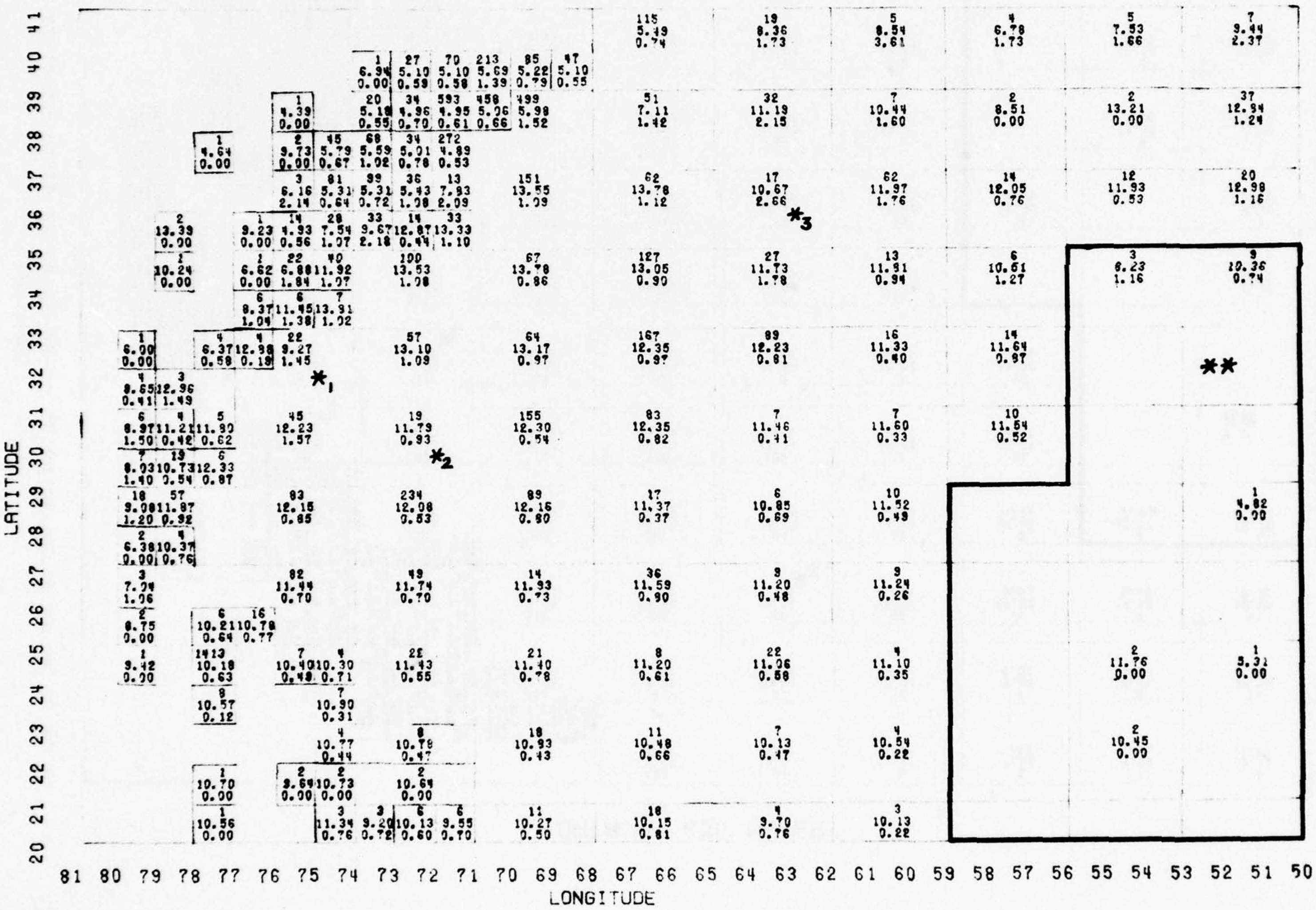
DATA AT 500 METERS



DATA AT 600 METERS



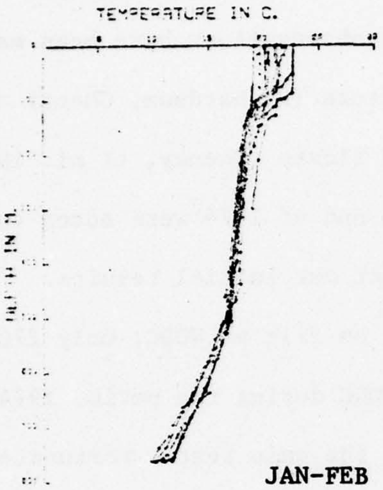
DATA AT 700 METERS



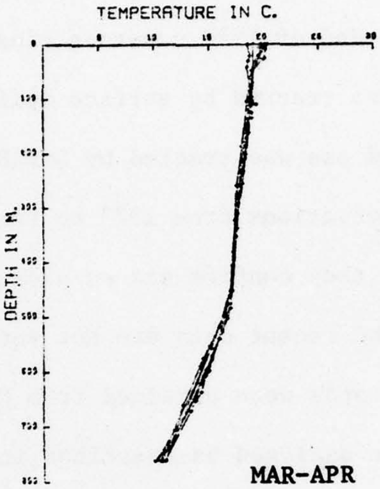
APPENDIX G

Seasonal Variations

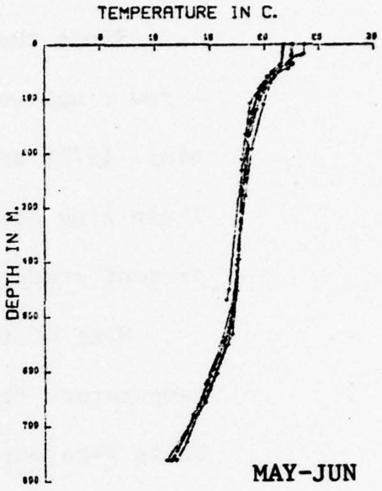
Figure G-1. Bimonthly plots of the XBT's taken in the 1°X 1° bin of 29°N, 69°W. The XBT traces were reconstructed from digitized values indicated by the small crosses. The plots show the annual development of the surface mixed layer and the seasonal thermocline. No seasonal signal was observed in the temperature field below 400 m. If there is such a signal, it was masked by the "noise" whose amplitude is on the order of 50 m.



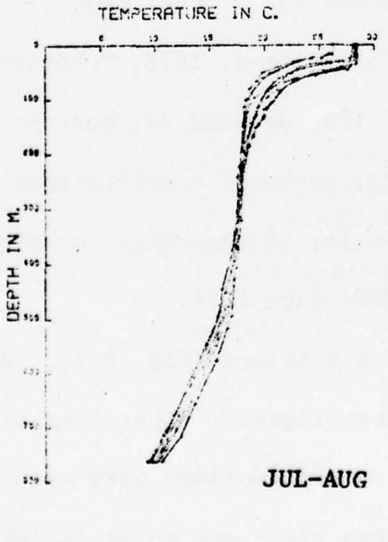
JAN-FEB



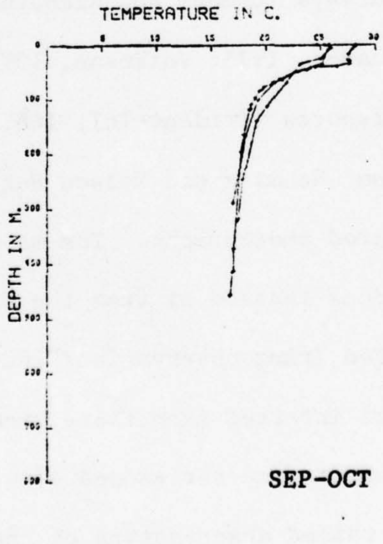
MAR-APR



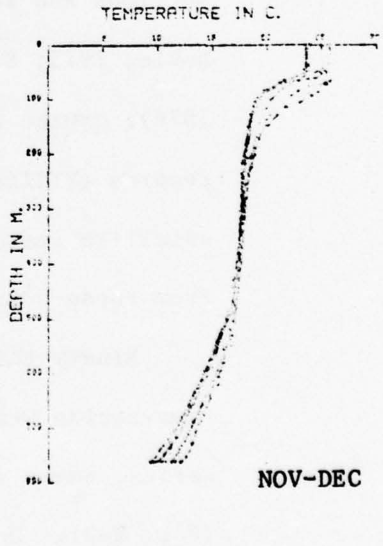
MAY-JUN



JUL-AUG



SEP-OCT



NOV-DEC

APPENDIX H

Ring Observations from 1974 to 1975

Since the end of 1973 numerous ring observations have been made. A few rings were tracked by surface drifters (Richardson, Cheney and Mantini, 1977) and one was tracked by SOFAR floats (Cheney, et al. 1976). These ring observations from 1973 to the end of 1976 were added to the present study; they confirm and supplement our initial results.

Most of the recent data are not yet on file at NODC; only 1700 temperature records were obtained from NODC during the period 1974-76. These data were analysed as described in the main text. Fortunately a large number of ring observations were obtained from other sources. The main sources that we used were the following: NAVOCEANO technical notes (Cheney, 1976; Gotthardt and Doblar 1974; Cheney and Khadouri, 1975); Gulf Stream Monthly Summary (1974) and the Gulfstream (1975-76); XBT sections and surveys (Cheney and Richardson, 1975; McCartney, 1975a; Noble, 1975; Seaver, 1975; Volkmann, 1975; Leetmaa, 1976; Vukovich, 1976), cruise reports (Trident-161, 168, 175; Oceanus-7), current meter records (William Schmitz and Nelson Hogg, personal communcation) and satellite infrared photographs. The majority of the rings found came from these sources instead of from the NODC data file.

Ninety-three "ring observations" were obtained (Fig. H-1). Ring time-series were inferred from these observations.[1] Eight long time-series, seven short time-series and eleven single rings were obtained (Fig. H-2). Detailed observations of these rings are shown in Tables H-1

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[1] During 1974-76 there are practically no single anomalies, which were very useful in establishing time-series in 1970-73.

to H-16 and figures H-3 to H-11. During 1974 to 1976, six rings were observed to move along the familiar path on the offshore side of the Gulf Stream, constituting an average of about two rings in a year. These rings appeared to coalesce with the Stream near Florida. Two rings were actually found attached to the Stream near Florida.

Most of the rings were concentrated in the northwestern Sargasso Sea, but eight rings were found east of 60°W. Some of them were the large Gulf Stream Extension Rings reported by McCartney (1975a) and Worthington (1976). At least one of these moved westward into the western Sargasso Sea and its twelve-month track appears to be consistent with those of other rings.

Since 1974 there have been two experiments to continuously track Gulf Stream rings. The first consisted of launching SOFAR floats in two rings at various depths (Cheney, et al., 1976). One ring was followed continuously for three months as it moved to the westnorthwest with a speed of 6cm/sec (ring A). A second ring seeded with floats coalesced with the Gulf Stream near 60°W only three months after it had formed.

The second experiment to track rings consists of a program using satellite-tracked free-drifting surface buoys. Preliminary results in three rings indicate that one moved westward for one month, one is moving southwestward just offshore of the Gulf Stream and one moved northeastward and coalesced with the Gulf Stream near 55°W (Richardson et al., 1977) (ring I). Although we need to continue the tracking program to be able to reveal the typical paths of rings, two results have emerged. One is a qualitative agreement with the analysis presented here from temperature records. The second is that rings can coalesce with the Gulf Stream after a life of only a few months.

In general the ring time-series from 1974 to 1976 appear to be similar to those observed in previous years although they appear to have a more "wriggly" character. We think this is due to the better resolution of the positions of the rings plus their probable looping motion which has been observed by Fuglister (1972) from continuous ring observations.

Table H-1 to H-16

Detailed Observation of Rings (1974-76).

* The agency which runs the ship is enclosed in parenthesis.

CG - U.S. Coast Guard
NAVOCEANO - U.S. Naval Oceanographic Office
NOAA - National Oceanographic and Atmospheric Administration
N - U.S. Navy
NESS - National Environmental Satellite Service
NRL - Naval Research Laboratory
WHOI - Woods Hole Oceanographic Institution
URI - University of Rhode Island
RTI - Research Triangle Institute
DUKE - Duke University
FNWC - Data from the Navy Fleet Numerical Weather Central The names of the vessels in which the data were taken are unknown.

** GSMS - Ring Observations reported in the Gulf Stream Monthly Summary, NAVOCEANO publication
GS - Ring observations reported in the <u>Gulfstream</u>, NOAA publication.
XBT - expendable bathythermography
STD - salinity-temperature-depth stations.

TABLE H-1. Observations of Ring A.
(tracked by SOFAR floats for three months)

Date	Platform/Agency*	Observations/Sources**
1974		
June 17	Sea Venture (NAVOCEANO)	5 XBT's
July 14		GSMS
July 30	Sea Venture (NAVOCEANO)	In several transects from NY to Bermuda.
August 30		
September 30	Lynch (NAVOCEANO)	XBT, STD and 3 SOFAR floats
December 10	Trident (URI)	XBT, STD and 2 SOFAR floats The ring was tracked by two floats between September and December.
1975		
February 10		Navy Ship
March 23-26		satellite
April 7		satellite
April 9	Advanced II (RTI)	Vukovich (1976)
June 1	Trident (URI)	XBT's

TABLE H-2. Observations of Ring B.

1975		
December 8	Trident (URI)	XBT's, STD's
1976		
February 18	(NAVOCEANO)	4 XBT's
March 8	(NAVOCEANO)	satellite data
March 27		GS
April 14	(NAVOCEANO)	satellite data
June 12	Oceanus (WHOI)	A surface buoy was launched in the ring.
July	(NAVOCEANO)	XBT's, satellite data

TABLE H-3. Observations of Ring C.
(This is a Gulf Stream Extension Ring or a "Big Baby").

Date	Platform/Agency*	Observations/Sources**
1974		
November	Knorr-43 (WHOI)	McCartney (1975) Big Baby 3
1975		
January 24	Chain-118 (WHOI)	XBT's Volkmann (1975)
March 25	Knorr-48 (WHOI)	McCartney (1975) Big Baby 5
April 6	Knorr-49 (WHOI)	McCartney (1975)
May 1	current meters with temperature records.	Hogg (personal communication)
June 17		AXBT's, Cheney (1976)
July 5	Lynch (NAVOCEANO)	XBT's
September	Chain-127 (WHOI)	XBT's, Volkmann (1975)
October 14		Cheney (1976)

TABLE H-4. Observations of Ring D.
(This is the Ring D referred to by some ring scientists).

Date	Platform/Agency*	Observations/Sources**
1975		
March 24		AXBT's, Cheney (1976)
April 14		AXBT's, Cheney (1976)
April 24		satellite data, GS
May 12	(NOAA/NESS)	satellite data
May 21		AXBT's, Cheney (1976)
June 7	Trident (URI)	XBT's, STD's
June 17		AXBT's, Cheney (1976)
June 25	Lynch	XBT's
July 28	(NAVOCEANO)	satellite data
August 8	Chain-125 (WHOI)	XBT's
September 2		GS
September 30	Chain-127 (WHOI)	XBT's, Volkmann (1975)
October 14	Eastward (DUKE)	Hogg and Dunlap (1976)
October 29		AXBT, GS
November 20	Knorr-53 (WHOI)	Wiebe (personal communication)
1976		
January 6		satellite data, GS
February 5		satellite data, GS
February 18	(NAVOCEANO)	AXBT's
March 1	(NOAA/NESS)	satellite data
March 31	(CG)	GS
April 14	(NAVOCEANO)	satellite data
May 20		satellite data
June 6	Oceanus (WHOI)	XBT's, a surface buoy launched
June 13		satellite data
July 14	tracked by the surface buoy	
August 14		

TABLE H-5. Observations of Ring E.

Date	Platform/Agency*	Observations/Sources**
1974		
January 28		AXBT's, Gotthardt and Doblar (1976)
February 2-5		AXBT's, Gotthardt and Doblar (1976)
February 27		GSMS
April 16		AXBT's, Gotthardt and Doblar (1976)
April 27		AXBT's, Gotthardt and Doblar (1976)
May 30	Sea Venture (NAVOCEANO)	XBT
June 14		AXBT's, Gotthardt and Doblar (1974) The ring coalesced with the Gulf Stream and formed a new ring.
June 30	Sea Venture (NAVOCEANO)	XBT's
July 19		GSMS
August 16	Sea Venture (NAVOCEANO)	XBT's
August 19	Atlantis II (WHOI)	XBT's
September 24-27	Lynch (NAVOCEANO)	coalescence with Stream with six floats in it.
October 6	Atlantis II (WHOI)	

TABLE H-6. Observations of Ring F.

1975		
July 2	Lynch (NAVOCEANO)	
November 2	(CG)	GS
November 20	(CG)	GS
December 26	(CG)	GS
1976		
February		satellite data
March 31	(NAVOCEANO)	
April 11-14	(NOAA/NESS)	satellite data

TABLE H-7. Observations of Ring G.

Date	Platform/Agency*	Observations/Sources**
1973		
June 7	FNWC	1 XBT
July 20	Ambassador (NAVOCEANO)	6 XBT's
September 8,11	FNWC	13 XBT's
December	Knorr (WHOI)	10 XBT's
1974		
January 29		AXBT's
April 12, 16	(NOAA/NESS)	satellite data
April 30		satellite data
May 5		satellite data

TABLE H-8. Observations of Ring H.

1973		
August 31		
September 9,14	Ambassador (NAVOCEANO)	30 XBT's
October 7	FNWC	2 XBT's
November 27		GSMS
1974		
January 26		AXBT's, GSMS
February 21	Fiske (N), Marshfield (N)	2 XBT's
March 25	Advance II (RTI)	Vukovich (1976)
March 30		satellite data, GSMS
April 20	J. Hewes (N)	3 XBT's
1975		
November	Trident-175 (URI)	It was tracked by a surface buoy. It moved northeastward and finally coalesced with the Gulf Stream. (Richardson et al. 1976).

TABLE H-9. Observations of Ring I.

1975		
November	Trident (URI)	It was tracked by a surface buoy for four months. It moved northwestward and finally coalesced with the Stream.

TABLE H-10. Observations of Ring J.

Date	Platform/Agency*	Observations/Sources**
1975		
June 28	Lynch (NAVOCEANO)	XBT's
August 4		GS

TABLE H-11. Observations of Ring K.

1974		
March 26	Knorr (WHOI)	XBT's
April 17		satellite data, GSMS
May 1		satellite data, GSMS
	northwestward movement possible coalescence with Stream.	

TABLE H-12. Observations of Ring L.

1974		
September 11		satellite data, GSMS
September 27		satellite data, GSMS

TABLE H-13. Observations of Ring M.

1975		
February 13	(NOAA/NESS)	satellite data
March 23	(NOAA/NESS)	satellite data
May 25	Trident (URI)	attached to Stream

TABLE H-14. Observations of Ring N.

1975		
March	Knorr (WHOI)	McCartney (1975, Big Baby 6
May 3-9		GS

TABLE H-15. Observations of Ring P.

1975		
September 15	current meters with temperature records	Hogg (personal communication)
November 5	current meters with temperature records	Hogg (personal communication)
1976		
April	Researcher (NOAA)	XBT's, Leetmaa (1976)

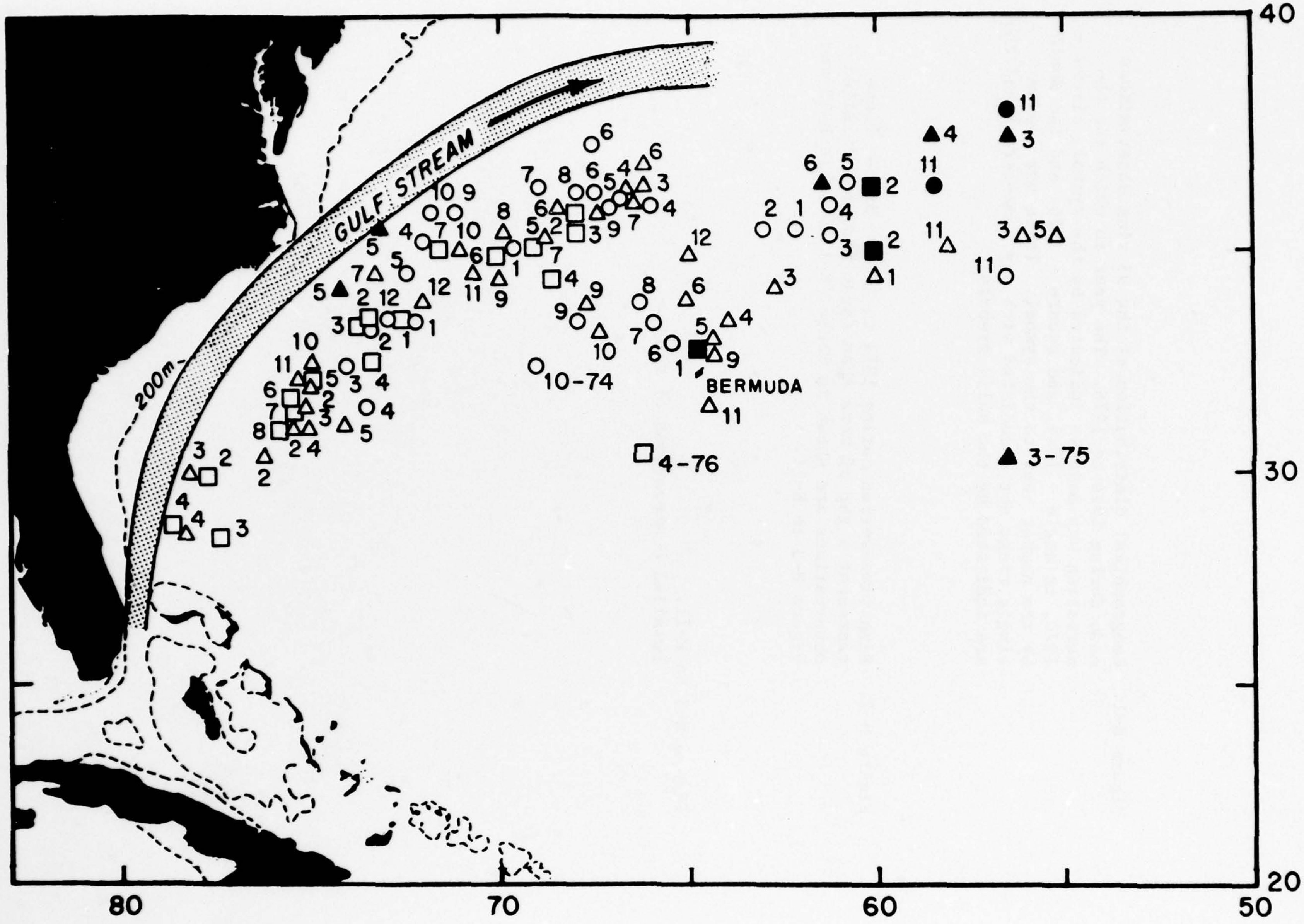
TABLE H-16. Observations of Single Rings.

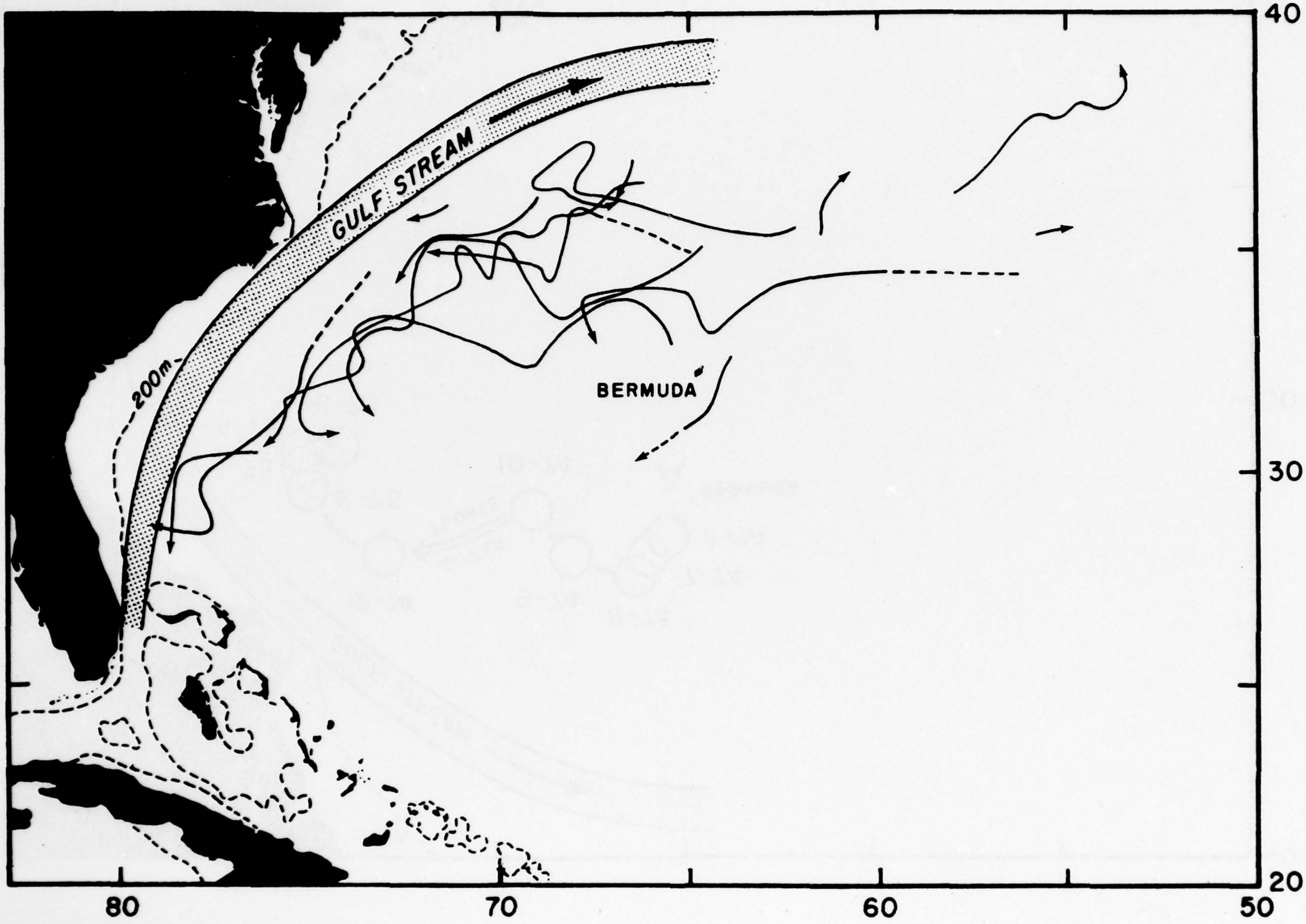
Date	Platform/Agency*	Observations/Sources**	
1974			
November	Knorr (WHOI)	McCartney (1975), Big Baby 1	
November	Knorr (WHOI)	McCartney (1975), Big Baby 2	
1975			
March	Knorr (WHOI)	McCartney (1975), Big Baby 4	
March 4	Knorr (WHOI)	McCartney (1975)	
April 4	Knorr (WHOI)	5 XBT's	
May 5	(NAVOCEANO)	satellite data	
May 10	(NAVOCEANO)	satellite data	
June		satellite data	
1976			
January 20	current meters with temperature records	Hogg (personal communication)	
February 28		satellite data	a double ring
February 28		satellite data	

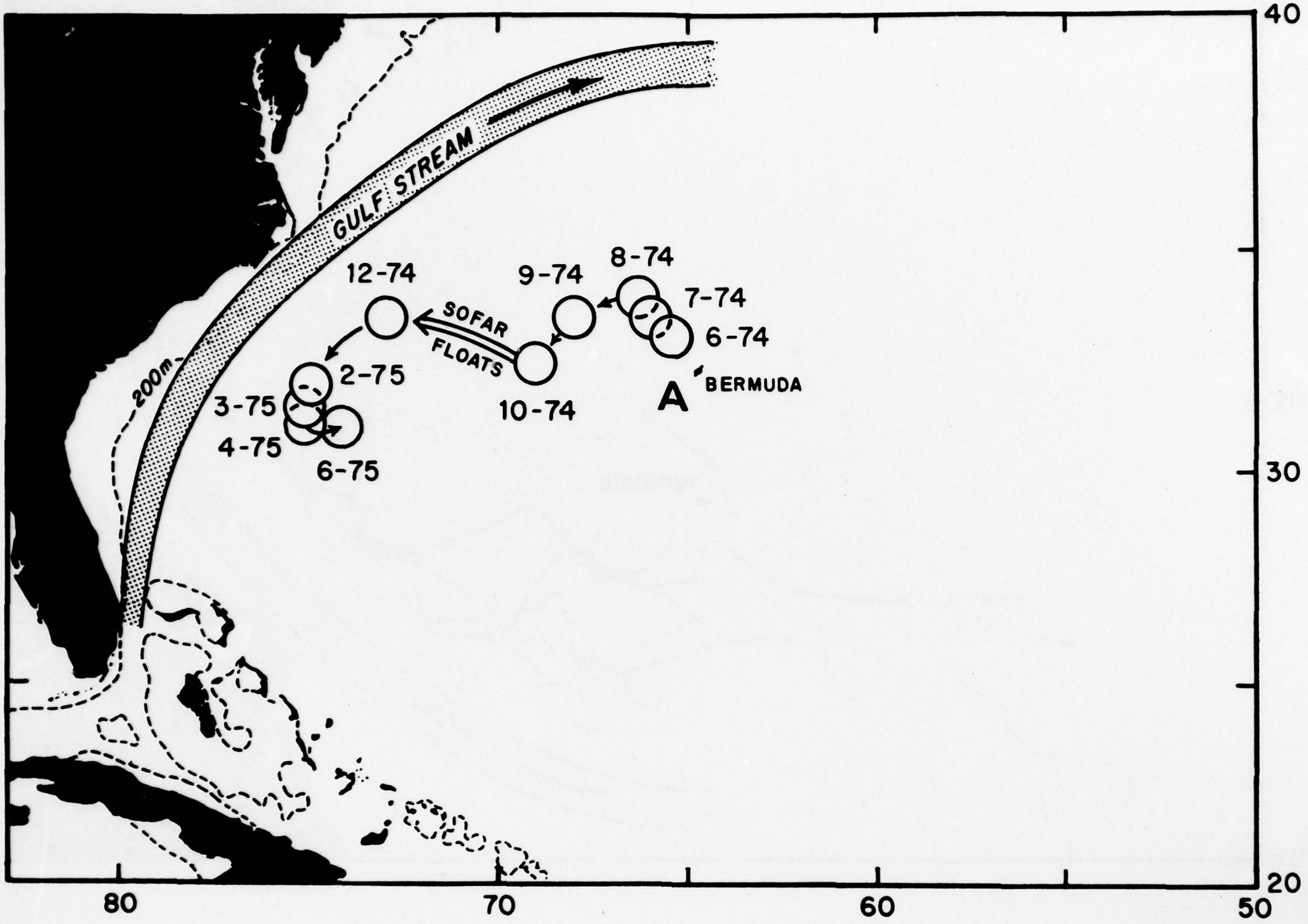
Figure H-1. Geographical distribution of the 93 ring observations made during 1974 to 1976. The year in which the observation was made is indicated by the symbol: circle - 1974, triangle - 1975, and square - 1976, and the month by the number next to the symbol. There are eleven single rings not associated with any time-series and they are indicated by the solid symbols.

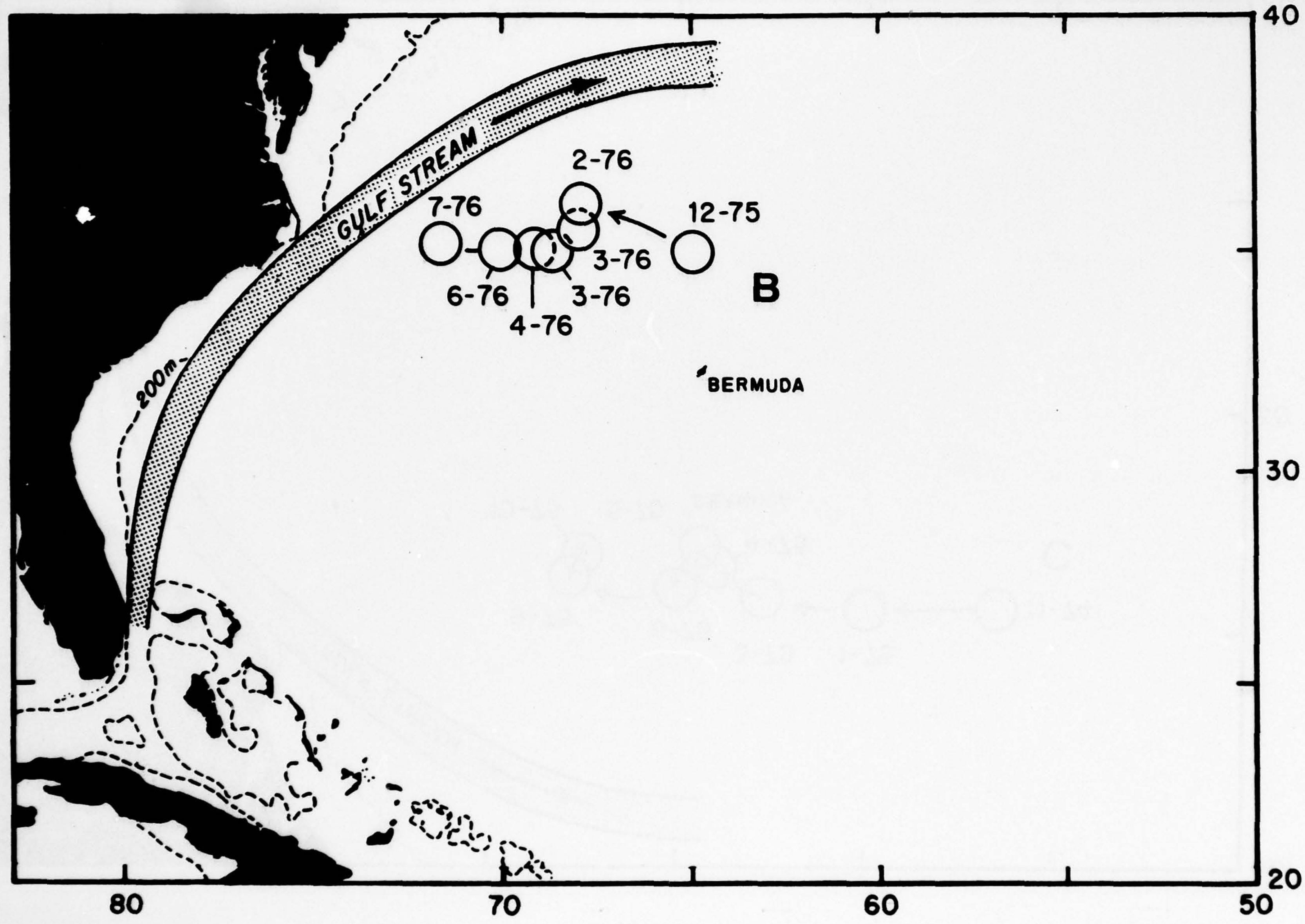
Figure H-2. Ring time-series during 1974 to 1976. Broken lines represent a gap of more than three months. Detailed observations are shown in Table H-1 to Table H-15 and Figure H-3 to H-11.

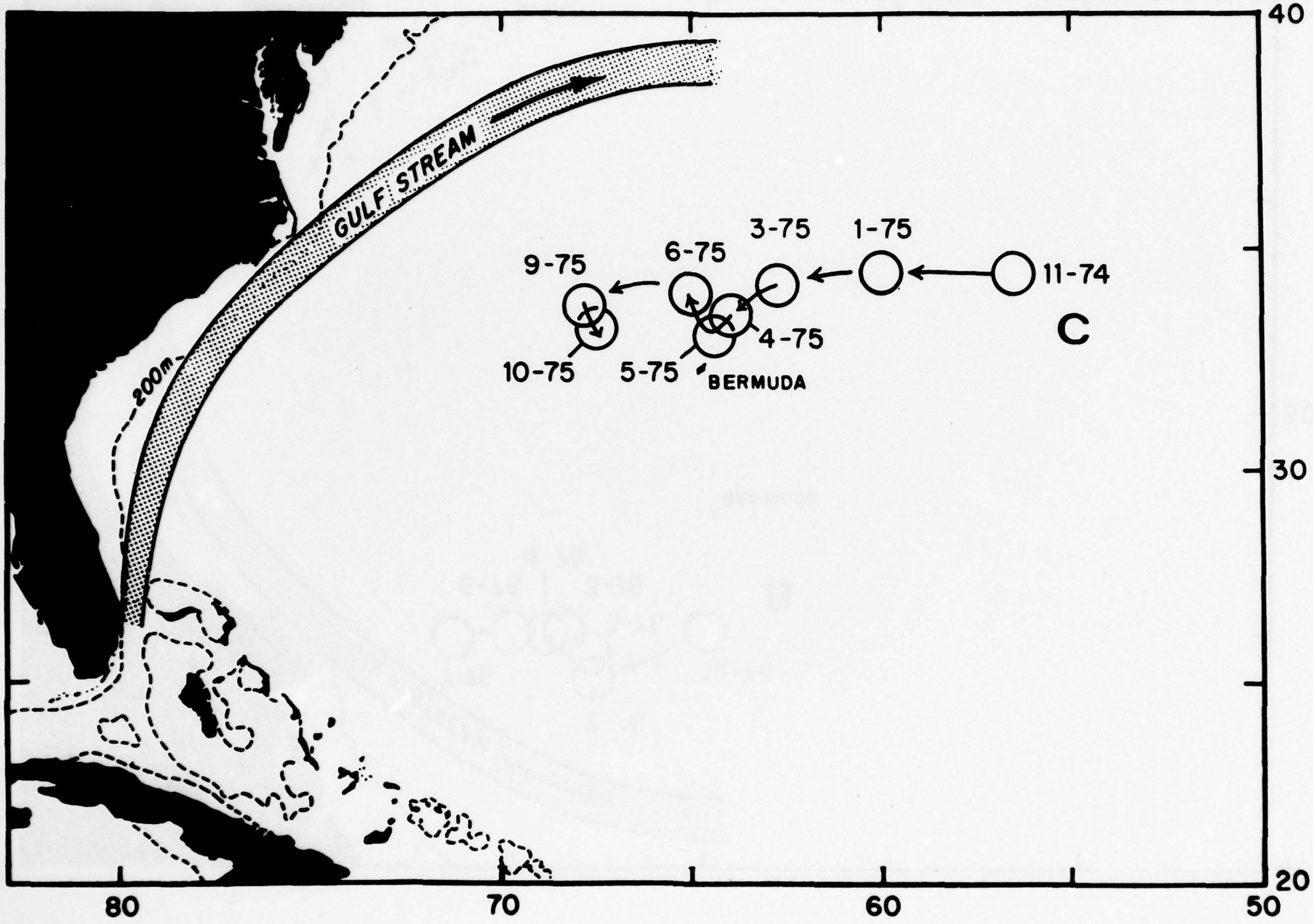
Figure H-3 to H-11.
Detailed observations of rings.

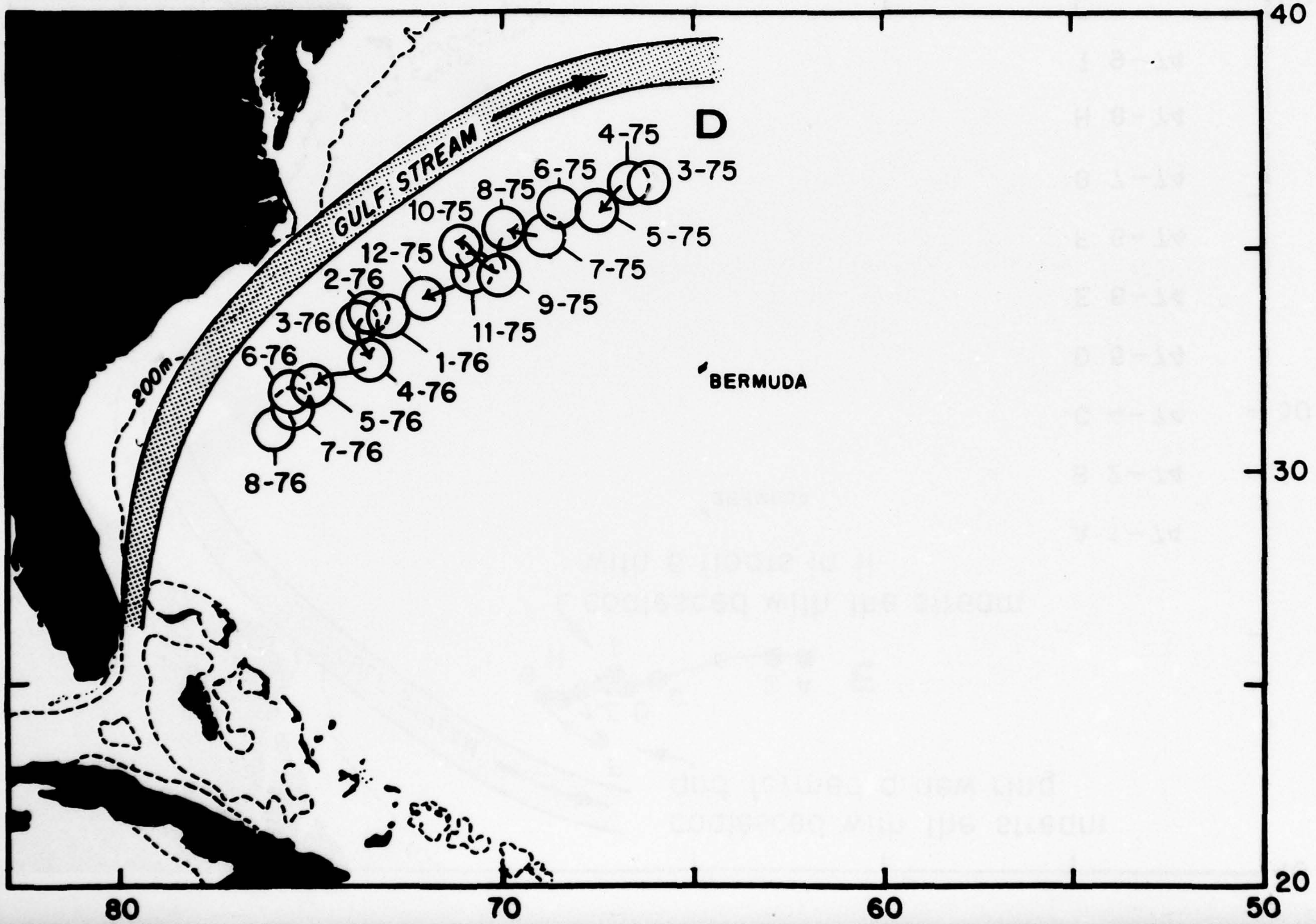

GULF STREAM
200m
BERMUDA
10-74
4-76
3-75
40
30
20
80
70
60
50

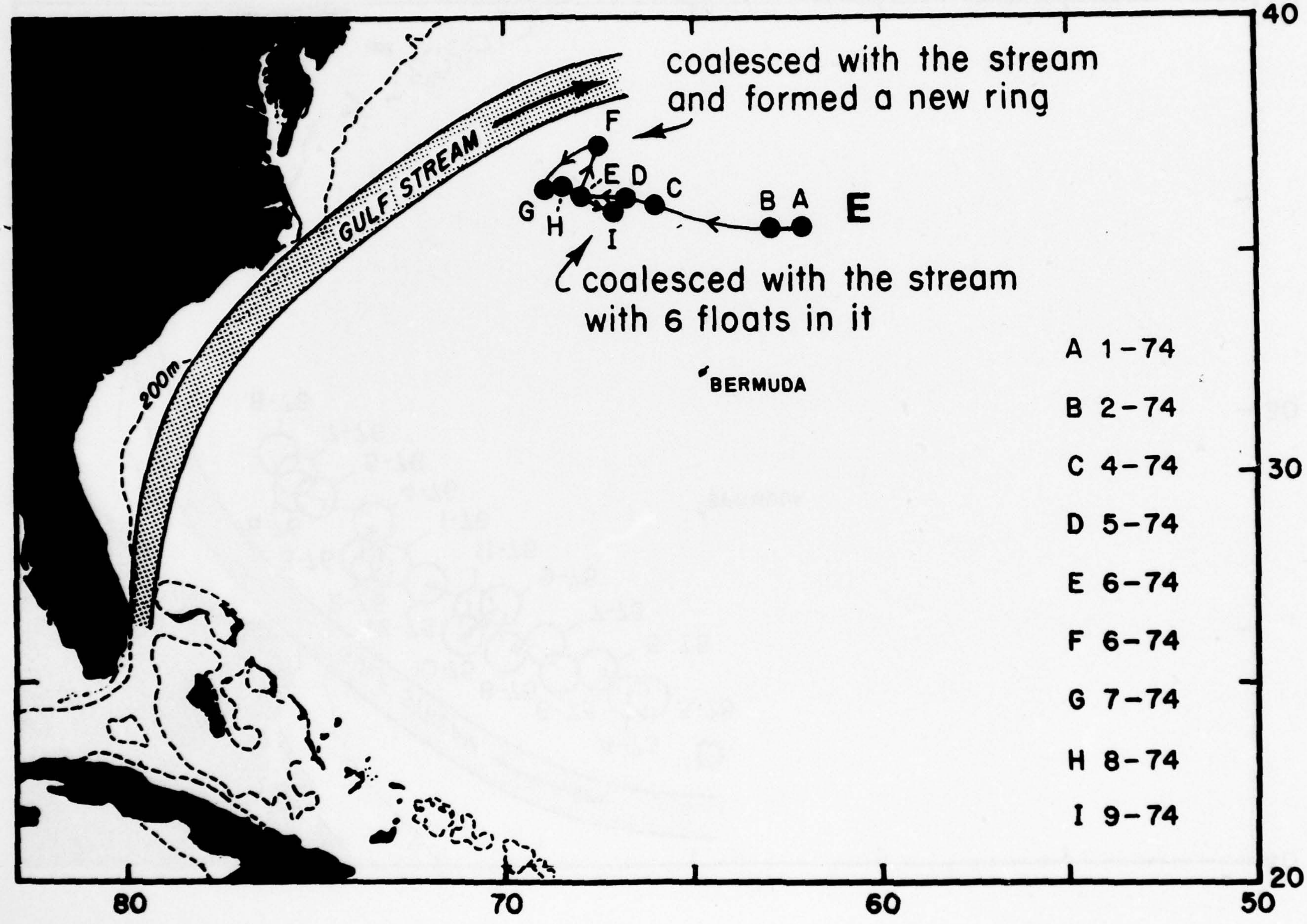

40
30
20
80
70
60
50
GULF STREAM
200m
BERMUDA

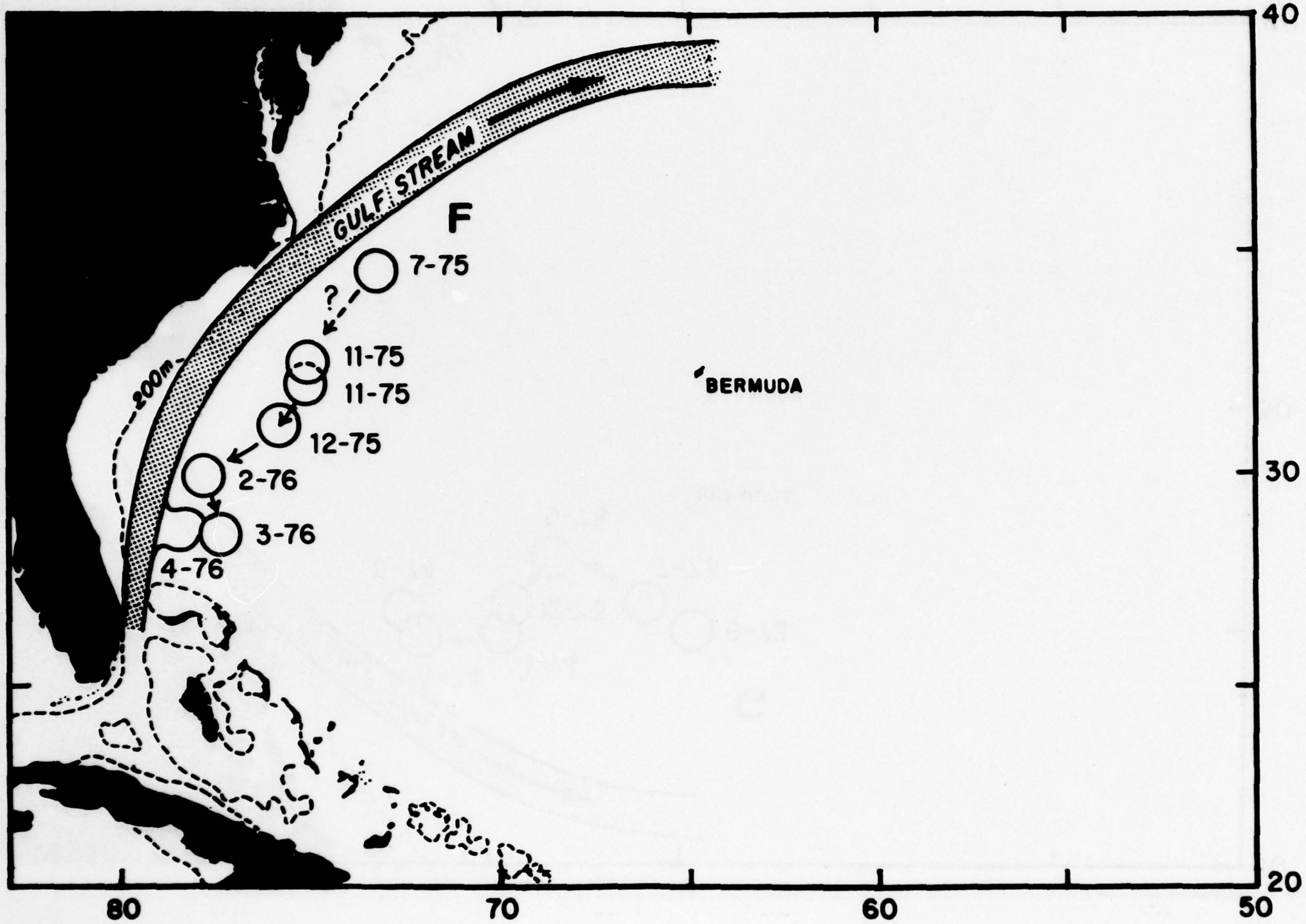

40
30
20
80
70
60
50
GULF STREAM
200m
12-74
9-74
8-74
7-74
6-74
10-74
SOFAR
FLOATS
2-75
3-75
4-75
6-75
A
BERMUDA

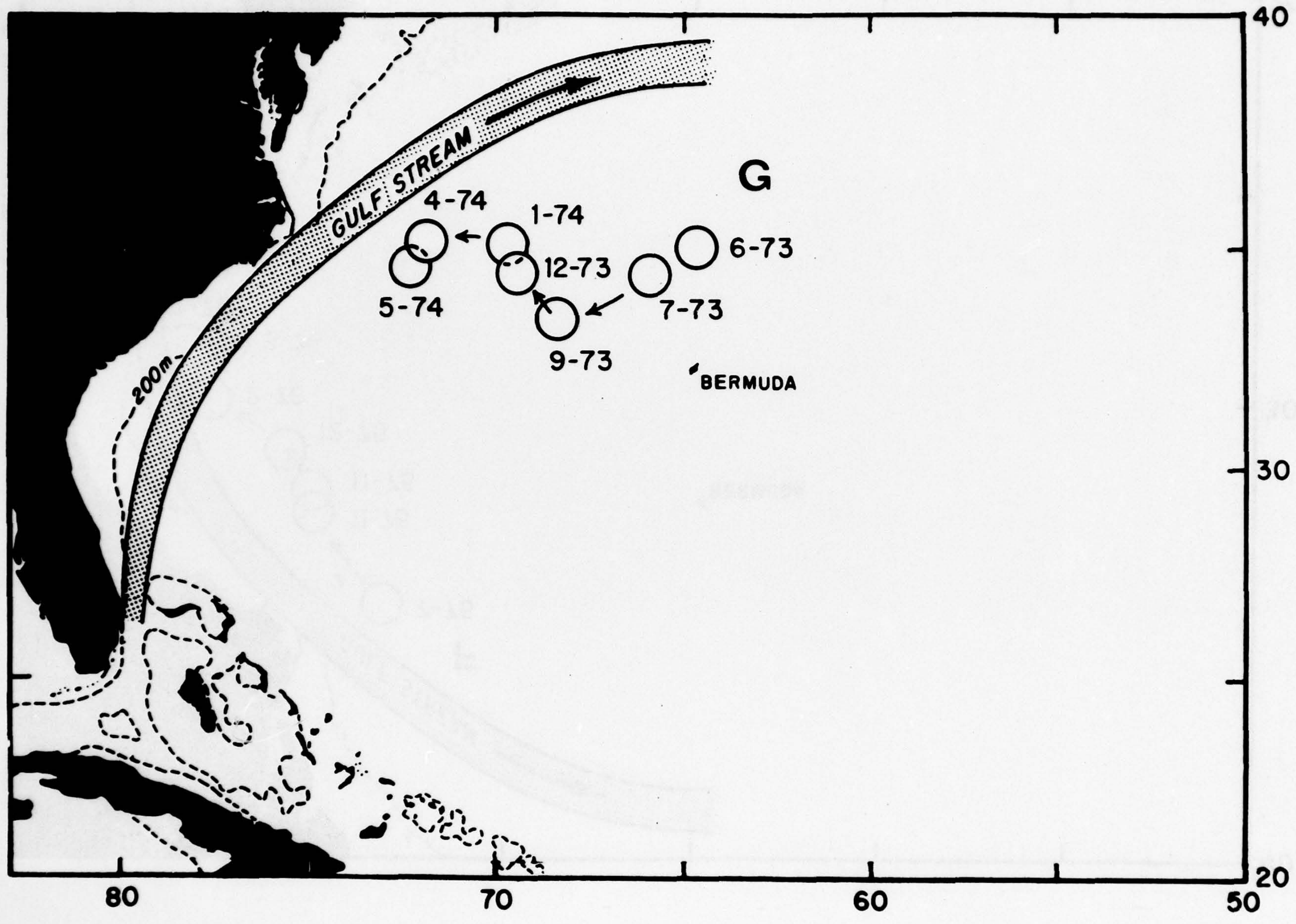

GULF STREAM
2-76
7-76
12-75
3-76
6-76
3-76
4-76
B
BERMUDA
200m
40
30
20
80
70
60
50

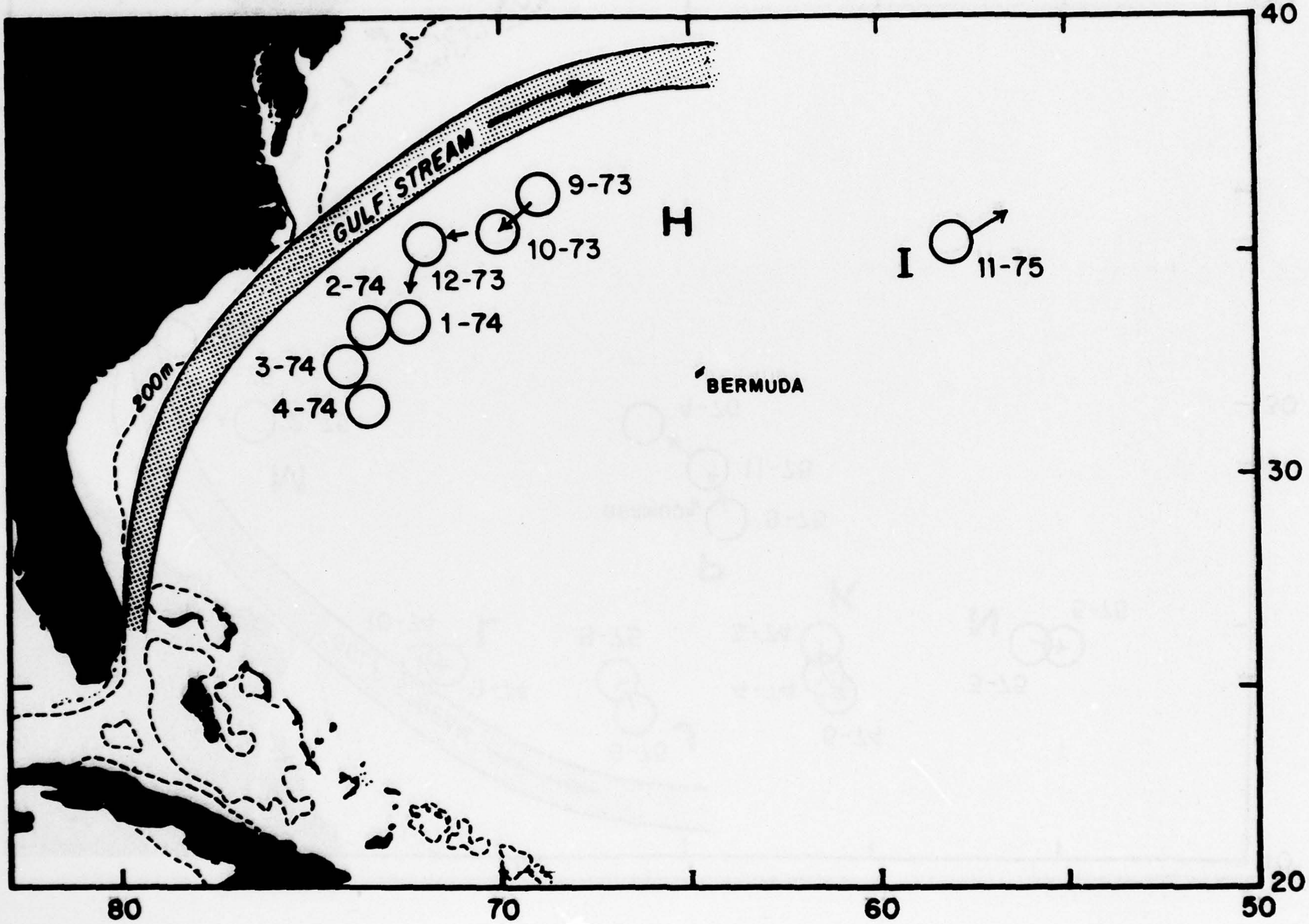

GULF STREAM
200m
9-75
10-75
6-75
5-75
3-75
4-75
1-75
11-74
BERMUDA
C
40
30
20
80
70
60
50

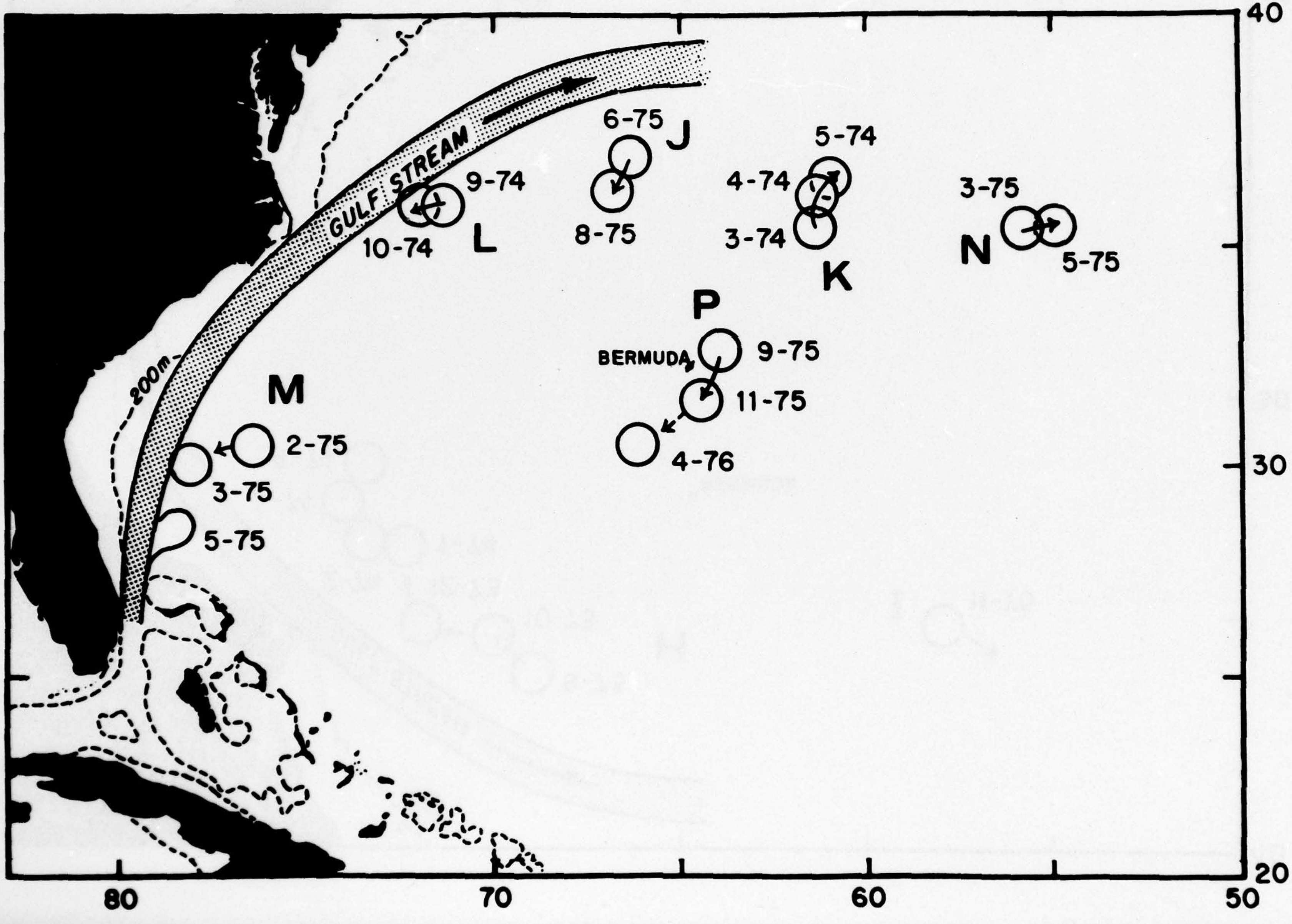

D
GULF STREAM
200m
BERMUDA
3-75
4-75
5-75
6-75
7-75
8-75
9-75
10-75
11-75
12-75
1-76
2-76
3-76
4-76
5-76
6-76
7-76
8-76
40
30
20
80
70
60
50


40
30
20
80
70
60
50
GULF STREAM
200m
coalesced with the stream
and formed a new ring
F
E D
C
B A
E
G
H
I
coalesced with the stream
with 6 floats in it
BERMUDA
A 1-74
B 2-74
C 4-74
D 5-74
E 6-74
F 6-74
G 7-74
H 8-74
I 9-74


40
30
20
80
70
60
50
GULF STREAM
F
7-75
?
11-75
11-75
12-75
2-76
3-76
4-76
200m
BERMUDA


G
GULF STREAM
200m
4-74
1-74
5-74
12-73
6-73
7-73
9-73
BERMUDA
80
70
60
50
40
30
20


40
30
20
80
70
60
50
GULF STREAM
200m
9-73
10-73
12-73
2-74
1-74
3-74
4-74
H
I
11-75
BERMUDA


GULF STREAM
200m
M
2-75
3-75
5-75
L
9-74
10-74
J
6-75
8-75
P
BERMUDA
9-75
11-75
4-76
K
5-74
4-74
3-74
N
3-75
5-75
80
70
60
50
40
30
20

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A study of the general distribution and movement of cyclonic Gulf Stream rings was made by analysing 50,000 temperature records obtained from the National Oceanographic Data Center and Fleet Numerical Weather Central. The data were taken from 1970 through 1973 in the region bounded by 20-40°N and 50-80°W. Additional ring observations from other sources were also used. Twelve ring time-series, together with fifteen single ring observations were obtained; approximately eleven rings were found to exist at one time. They

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typically moved westward, turned southwest when close to the Gulf Stream and appeared to coalesce with the Stream near Florida. On the average, about one and a half rings a year moved down this path, with a mean speed of three km a day and an estimated life span of two to three years. Although rings were concentrated in the northwestern Sargasso Sea, a few were found east of 60°W. However, the low data density in the eastern region prevented detailed analysis there. Several warm eddies, with at least a 150-meter deepening of the main thermocline, were also found.