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HYDROGRAPHY OF THE WESTERN ATLANTIC;

Some Results of a Multiple Ship Survey of the Gulf Stream

by

F. C. Fuglister and L. V. Worthington

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Director

SOME RESULTS OF A MULTIPLE SHIP SURVEY OF THE GULF STREAM*

by

F. C. Fuglister and L. V. Worthington

INTRODUCTION

The first multiple ship survey of the Gulf Stream area between Cape Hatteras and the Grand Banks of Newfoundland took place during the period from the 6th to the 23rd of June 1950. The survey was given the code name "Operation Cabot" by the U. S. Navy Hydrographic Office which acted as headquarters during the planning and operational phases of the survey. The civilian scientist in charge of the technical phases of the program was Dr. Richard H. Fleming, Director, Division of Oceanography, U. S. Navy Hydrographic Office.

The purposes of Operation Cabot were:

(a) To obtain a synoptic plot of the Gulf Stream's path between Cape Hatteras and the Grand Banks;

(b) to determine the rate of change in the position of the Gulf Stream;

(c) to measure the surface velocities of the Gulf Stream;

(d) to observe what effect the Gulf Stream has on the conditions in the lower atmosphere;

(e) to observe the formation and some of the history of the eddies presumably formed when a larger "meander" or "wave" in the Gulf Stream is cut off;

(f) to obtain observations of the Gulf Stream from a plane and from ships simultaneously.

The following groups took part in the survey:

U. S. Navy Hydrographic Office, Washington, D. C.
U.S.S. SAN PABLO (AGS-30); Captain A. J. Peterson, Comdr., U.S.N.; Scientist in Charge, Dr. R. H. Fleming. This vessel acted as flagship for the fleet and Dr. Fleming was task unit chief scientist.
U.S.S. REHOBOTH (AGS-50); Captain R. V. R. Bassett, Jr., Comdr., U.S.N.; Scientist in Charge, Robert Abel.

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* Contribution No. 548 from the Woods Hole Oceanographic Institution.

Two PB4Y-2 Aircraft; Pilots Ensign F. M. Glazier, USNR and Lt. (j.g.) Stewart, USNR; Scientific Observer, W. V. Keilhorn.

Naval Research Establishment, Halifax, Nova Scotia.
H.M.C.S. NEW LISKEARD; Captain, Lt. W. W. Maccoll, R.C.N.; Scientist in Charge, Dr. William L. Ford.

U. S. Fish and Wildlife Service, Washington, D. C.
ALBATROSS III; Captain John Collins; Scientist in Charge, V. B. Colton.

Woods Hole Oceanographic Institution, Woods Hole, Mass.
R/V ATLANTIS; Captain Adrian K. Lane; Scientist in Charge, Martin J. Pollak.
R/V CARYN; Captain John F. Pike; Scientist in Charge, Dr. B. H. Ketchum.

Atlantic Oceanographic Group, St. Andrews, New Brunswick.
The original plans called for the participation of the CNAV WHITETHROAT. Because of last minute difficulties, the WHITETHROAT was unable to join in the survey. Dr. H. B. Hachey and Dr. L. M. Lauzier of the organization helped to plan the operation and Dr. Lauzier was on the scientific staff aboard the NEW LISKEARD.

Scripps Institution of Oceanography, La Jolla, California.
Dr. Walter H. Munk of this organization helped plan the operation and was on the Scientific Staff of the flagship.

U. S. Navy Office of Naval Research, Washington, D. C.
Lt. Comdr. R. L. Dahloff and J. K. Knauss of this organization helped plan the operation. Lt. Comdr. Dahloff was chief meteorologist of the task unit.

Although not an integral part of Operation Cabot the work done by the U. S. Coast Guard Research Vessel EVERGREEN, while on routine Ice Patrol for the International Ice Patrol, contributed valuable data. Mr. Floyd Soule was Scientist in Charge on the EVERGREEN.

Operation Cabot was a splendid example of cooperative effort and credit for the success of the survey must be distributed among all the many scientists and seamen who took part.

OPERATIONAL PLANS

The planners of Operation Cabot were faced with a new type of oceanographic investigation. Not only were six ships and a plane involved but new instruments for obtaining data with ships underway were to be used. A very large amount of data was to be collected and, although much of it would be collected automatically by seamen technicians, the scientific staffs would be kept busy supervising and evaluating the results.

Oceanographic surveys have traditionally been made according to a pre-arranged plan, and in an area such as the one under consideration, the measurements have been planned along "sections" or at points on a "grid". Recent surveys of the Gulf Stream (Iselin and Fuglister, 1948) have indicated that such a method is inherently wasteful of time and effort where answers to specific questions are sought, because many stations do not provide pertinent information. Nevertheless, detailed plans and instructions were formulated for Operation Cabot. This was done primarily because it was felt that without such pre-arranged plans the success of the survey would be entirely dependent on successful communications. Considering the variety of ships and equipment involved dependable communications were by no means certain. Also the planners realized that if communications were successful the flagship could alter the plans during the operation as might be desirable.

Briefly the plans for the survey were as follows. The first phase was to be a general reconnoitering of the Gulf Stream from Cape Hatteras to the Grand Banks. The ships would be deployed approximately 150 miles apart along the Gulf Stream, zig-zagging into and out of the current and underway continuously. Bathythermograph, Loran, and weather data were to be obtained at half-hour intervals. Surface current measurements were to be made every hour with the Geomagnetic Electrokinetograph (von Arx, 1950), hereafter referred to as the GEK. Positions of the Stream were to be transmitted every six hours to the flagship.

The second phase was to consist of simultaneous "sections" of hydrographic stations along pre-arranged meridians of longitude. Bathythermograph, Loran, and weather observations were also to be made along the "sections".

Phase three was to be a detailed study of a restricted area determined by the results of the first two phases.

Throughout the operation continuous sonic depth records were to be made, and a track chart maintained with the depth records referenced to the track chart by hourly markings.

Fortunately, communications were very nearly perfect during the entire operation. The first phase of the operation want off as scheduled and the scientific staff aboard the flagship was able to plot the position of the Gulf Stream from off Cape Hatteras to 50° west longitude. For the remainder of the Operation, the flagship directed the movements of all vessels and the pre-arranged plans were in a large part discarded.

An enormous amount of data were collected during the 17 days of the survey and the present paper will cover only a portion of the results.

DEFINITION OF TERMS

Early in the planning and operational stages of Operation Cabot it became evident that precise definitions were needed for the various terms used in association with the Gulf Stream. The frequent references to the "cold wall", "edge of the Stream", "warm core", and "front" led to a certain amount of confusion and misunderstanding. The term "inner edge" was most frequently used and most variously interpreted. This confusion is caused primarily because, although the words "Gulf Stream" denote a current, they also imply a distinct water mass and secondarily because water masses that may be motionless are included as part of the Stream because they lie below a surface current.

Since the Gulf Stream is a boundary or front in the western North Atlantic between the slope water and the Sargasso Sea we may define it as follows: it is a CONTINUOUS band stretching from the continental shelf off Cape Hatteras to the 50th meridian of longitude, south of the Grand Banks of Newfoundland. This band consists of a pronounced pressure gradient between the warm highly saline water to the south and the colder fresher water to the north. Using this definition then, the inner and outer limits or edges of the Gulf Stream can be defined as the points where this pressure gradient becomes zero. These points can be located only if deep, closely spaced temperature and salinity data are obtained and the crosscurrent pressure gradients calculated. Also, because of the large eddies found both north and south of the Stream, any section made across the area must be long enough to ascertain whether or not more than one pronounced pressure gradient exists. If only one is found it defines the Gulf Stream, but if more than one is located then the position of the Stream cannot be determined by that single section.

Not to be confused with the inner or left-hand edge of the Stream is the temperature-salinity boundary at the surface. This generally abrupt change that occurs to the left of the "warm core" may or may not coincide with the left-hand edge of the Gulf Stream as defined above. This applies also to the color boundary and the long thick lines of Sargassum frequently seen on the surface, all of these surface phenomena are apparently associated with shear zones to the left of the "warm core" but they are not necessarily coincident with the left-hand or inner edge of the Gulf Stream.

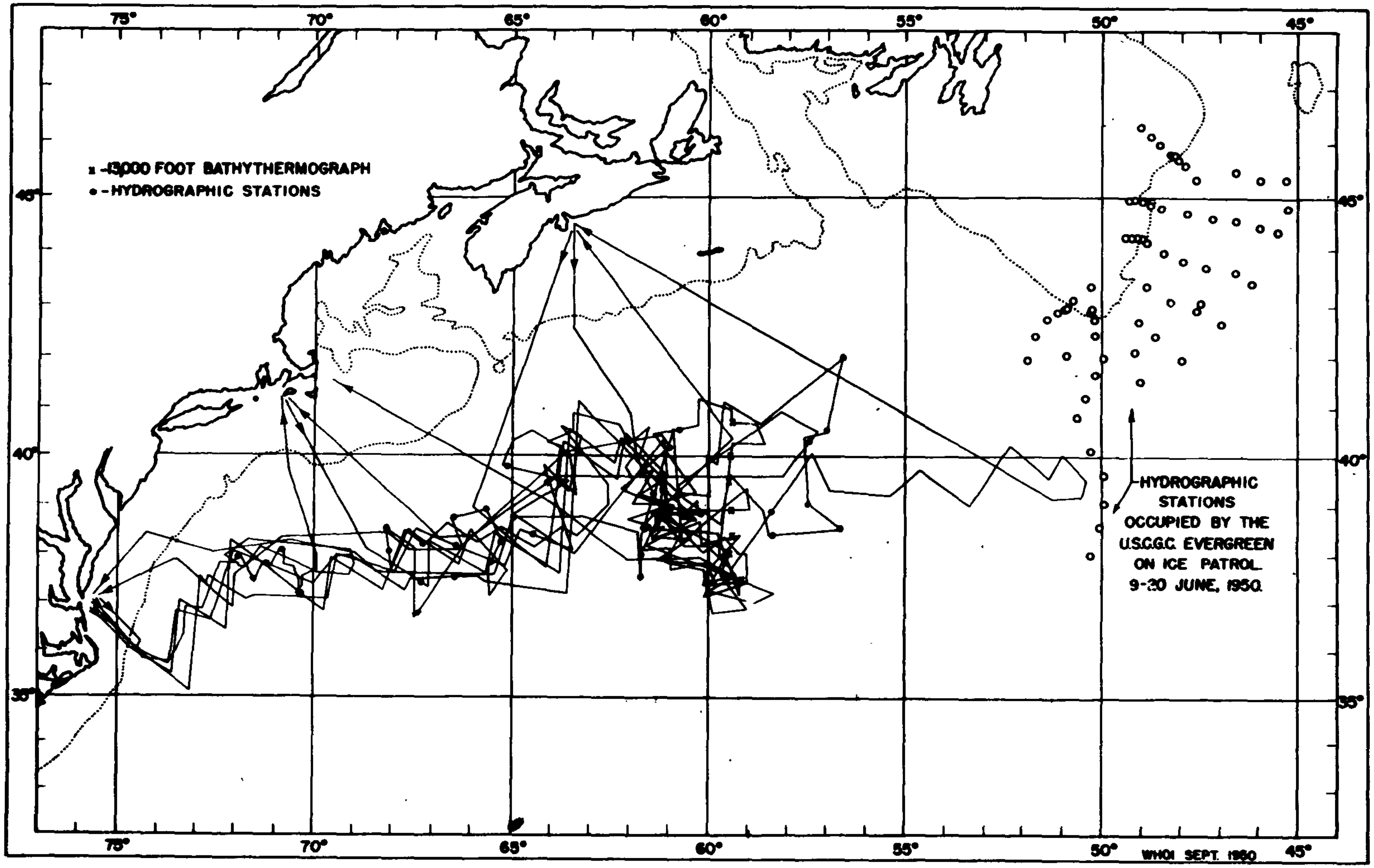
The "warm core" is defined here as that part of the Gulf Stream containing water warmer than the water at the same depth to the right, facing downstream, of the current. This "warm core" is generally 300 to 400 meters deep with the maximum temperature anomalies at a depth of about 100 meters.

The word "front" is considered synonymous with the pronounced pressure gradient and therefore with the Gulf Stream itself.

The term "cold wall" dates back to 1845 and is still frequently used to denote the "inner edge of the Stream" or, according to Church (1937), "the temperature gradient between the slope water and the Gulf Stream". According to these definitions, it could equally well be called the "warm wall" though in neither case do we have anything resembling a wall. This temperature gradient exists at different depths across the entire width of the Gulf Stream and therefore cannot be considered as something separate or adjoining the Stream. Because of the misleading connotations of the term "cold wall" it will not be used in this paper.

SYNOPTIC CHARTS

On this survey no attempt was made to locate, precisely, the inner and outer edges of the Gulf Stream. The area covered is shown in Figure 1. It is obvious that to obtain closely spaced, deep hydrographic stations over this large area, in the limited time available, was impossible even with six ships. However, a study of temperature-depth profiles made in the past and the results of recent surveys show that the limits of the Stream can be determined with a fair degree of accuracy from the temperature structure in the upper 200 meter layer. A temperature-depth profile across the Stream shows the following characteristics; facing downstream the left-hand edge of the Stream coincides with the point where the temperature at 200 meters reaches a minimum or levels off. The abrupt temperature boundary at the surface may or may not be directly over this point. To the right the isotherms slope downward until the "axis of the warm core" is reached.



SHIPS' TRACK ON OPERATION CABOT. GULF STREAM SURVEY 6-23 JUNE, 1950

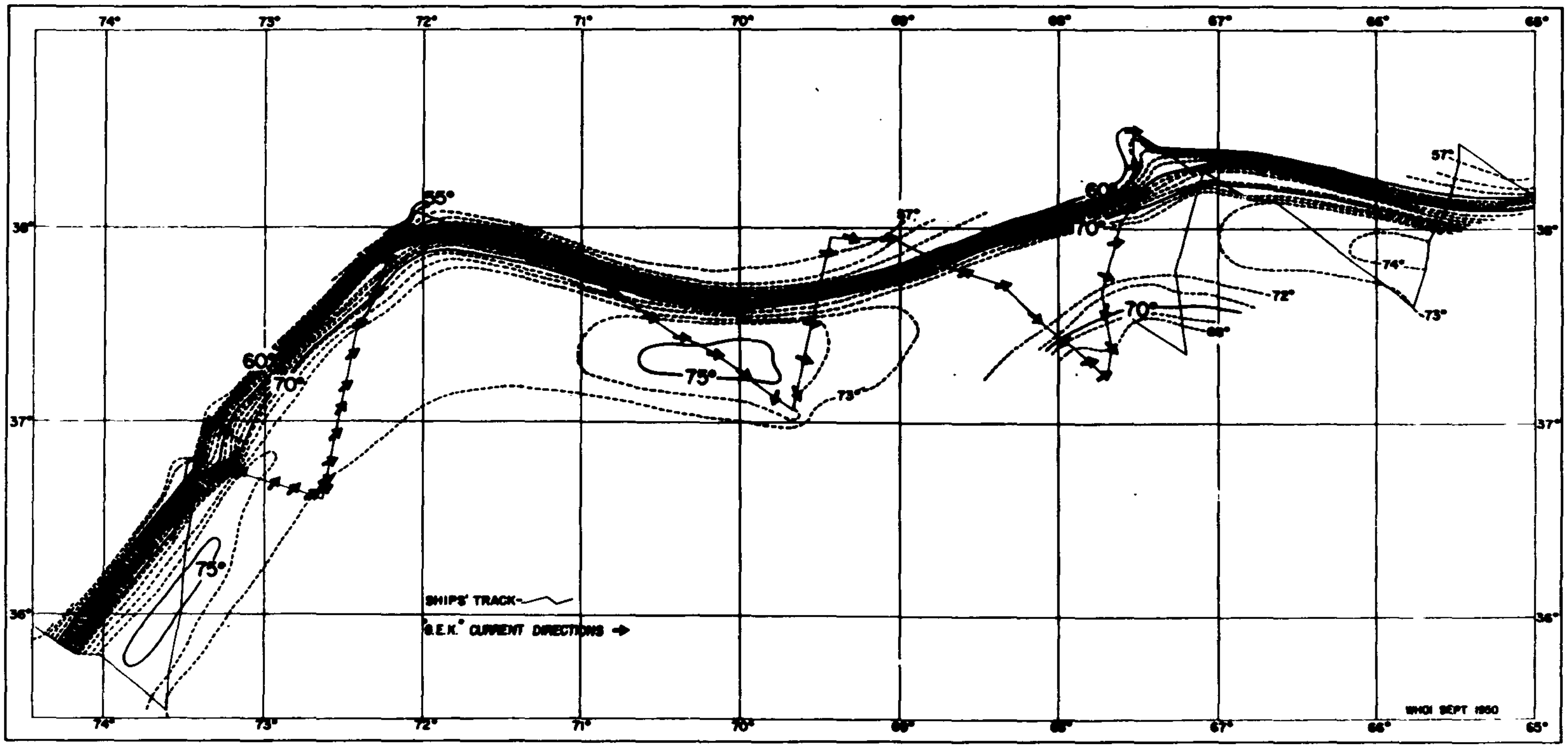
FIGURE I

This is the point where the mean temperature of the upper 200 meter layer is a maximum. Actually the "warm core" reaches to depths of 300 to 400 meters, but since the maximum anomalies are found at about 100 meters, it has proven convenient to use the mean of the upper 200 meter layer to show the position of this core. To the right of the "warm core" the isotherms in the surface layer rise until the temperature at a depth of 200 meters is again a minimum or levels off. This point is taken as the right-hand or outer edge of the Stream. The horizontal temperature and salinity gradients at all levels are quite gradual on this side of the Stream so that this "edge" is not nearly so well defined as the "inner edge".

In order to obtain synoptic charts of the Gulf Stream the first step was to calculate, for each bathythermogram, the mean temperature of the upper 200 meter layer. 3,521 bathythermograph observations were obtained during this survey and temperatures were read at eight points on 3,000 of these. Since the bathythermograph grids were in the Fahrenheit scale the labor involved in converting to the Centigrade scale was prohibitive. This explains the various scales used in this paper.

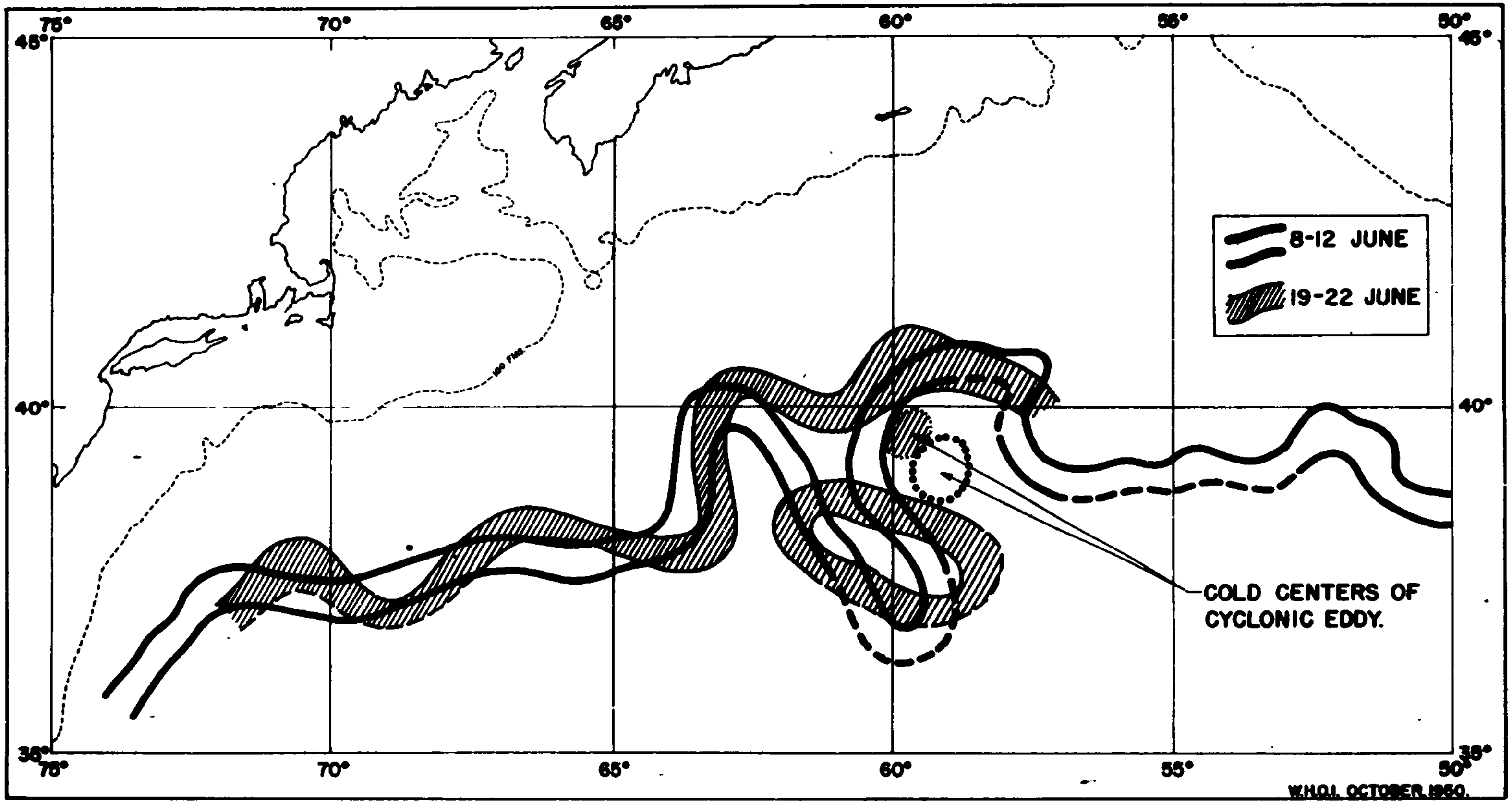
The positions and mean temperature (degrees Fahrenheit) of all bathythermograph observations were plotted geographically on daily charts and the results contoured. The mean temperature isotherms for the 8th of June, over the western portion of the Gulf Stream are shown in Figure 2. The solid lines in this figure show the ships' tracks and give an idea of the amount of interpolation that was generally necessary in drawing the curves. In relatively few of the 165 "sections" made was the entire width of the Gulf Stream covered, but in all cases the abrupt gradient to the left of the "warm core" was crossed. The sections that did cross the "warm core" indicate that it did not vary markedly in width throughout its entire length from Cape Hatteras to the 50th meridian. Figure 3 shows the positions of the "warm core" during the first and last periods of the survey. The most striking feature of this chart is, of course, the two large waves and the deep trough separating them in the center of the area. After the 12th of June the chief emphasis of Operation Cabot was to observe the changing conditions in and around this trough. As shown in the figure, the trough eventually "broke off" from the Stream forming, as it did so, an elongated cyclonic eddy to the south.

Although Operation Cabot was the first survey to cover the entire distance from off Cape Hatteras to 50° west longitude, other shorter surveys, show that large waves in the Gulf Stream may occur over a wide range of longitude and that



MEAN TEMPERATURE, °F, OF THE UPPER 200 METERS ALONG THE GULF STREAM FRONT ON THE 8TH OF JUNE, 1950.

FIGURE 2



POSITIONS OF THE WARM "CORE" OF THE GULF STREAM
DURING THE FIRST AND LAST PERIODS OF OPERATION CABOT.

FIGURE 3

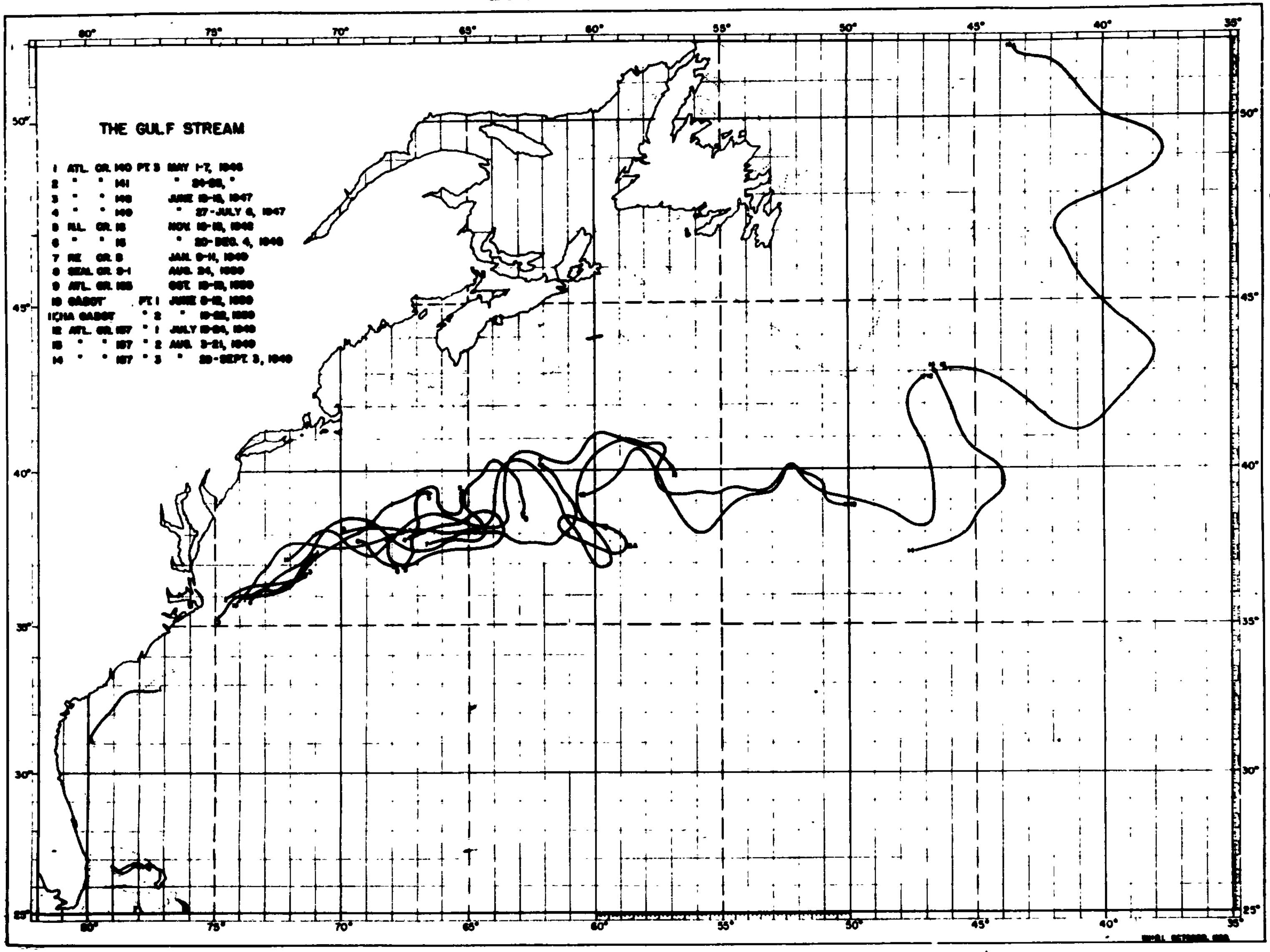
conditions, such as those found on "Cabot" are not exceptional. Figure 4 is a composite picture, showing the positions of the maximum horizontal temperature gradient at a depth of 100 meters, as obtained on all Gulf Stream surveys made since 1946. Besides the numerous large waves, this diagram shows another elongated, cyclonic eddy centering at 66° west similar to the one found on Operation Cabot.

The variable positions of the major waves in the Stream are stressed here because, during Operation Cabot, there was a strong feeling aboard the flagship that the bottom topography, near 39° north, 61° west, was the primary cause of the deep trough that existed in this area. Further investigation may show that the series of ridges and seamounts in this locality always affect the course of the Gulf Stream, but the occurrence of large waves and eddies in regions where the bottom is relatively flat indicates that bottom topography must be of secondary importance in the formation of such phenomena.

TEMPERATURES OF THE WARM CORE

Throughout the entire length of the Gulf Stream the mean temperature of the upper 200 meter layer in the warm core was greater than 68°F. An unpublished technical report by Fuglister on the monthly average temperatures in the region south of the Stream and north of Bermuda shows the mean temperature for this layer in June to be 67.8°F. Since the Stream moves in an easterly direction for a distance of about 1,200 miles it is evident that it must transport over this entire distance water from more southerly latitudes.

The mean temperature at the axis of the "warm core" ranged from 68.3°F. to 75.5°F. As can be seen in Figure 2 these temperatures did not decrease uniformly downstream but what might be called "gobs" of warmer water showed up at intervals along the Stream. These "gobs" were observed as far east as the 57th meridian. The more consistent temperatures on either side of the "warm core" indicate that these "gobs" are not caused by internal wave action. If this is true, then these masses of warmer water, appearing at intervals in the Stream, may be evidence of a pulsing action in the current which in turn may have a bearing on the formation of waves and eddies. The pulsing could conceivably be caused by short period variations in the strength of the Trades or in variations in the barometric pressure over the Gulf of Mexico. If a series of temperature sections, say two a day for a period of a month, could be run across the Straits of Florida some of these speculations could be checked. An examination of existing bathythermograph sections in the Florida current between Key West and Cape Canaveral has not revealed any



POSITIONS OF THE MAXIMUM CROSS-CURRENT TEMPERATURE GRADIENTS
AT A DEPTH OF 100 METERS, FROM ALL SURVEYS, 1946 TO 1950

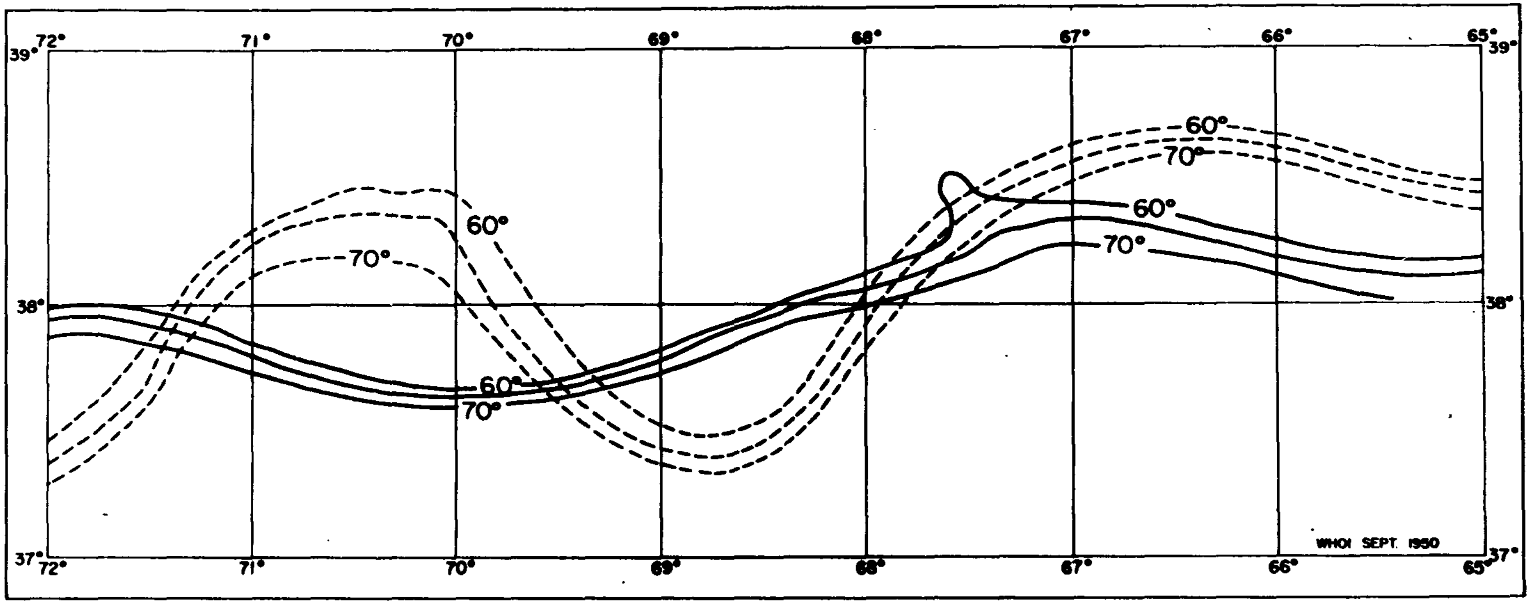
"gobs" but it is not possible, in view of the inadequacy of the data, to conclude that they do not occur there.

RATE OF CHANGE IN THE POSITION OF THE STREAM

In the first period of the survey four ships entered the Gulf Stream off Cape Hatteras at 24 hour intervals. During this interval the Stream shifted, at this point, at a rate of 4.5 miles a day toward the southeast. Numerous sections made near 72° west showed that the crest of the first wave in the path of the Stream moved toward the east at a rate of approximately 11 miles per day. The over-all change in positions of the western portion of the Stream, from the 8th to the 22nd of June, is shown in Figure 5. The daily synoptic charts, of the mean temperature in the upper 200 meter layer, show that all the changing positions of the Stream can be accounted for by lateral movements of not over 11 miles per day. The synoptic charts for the 18th and 19th of June, for the region around the trough (see Figure 6B), may at first glance indicate a lateral movement more rapid than 11 miles per day if the motion is considered as a north-south one. Actually, the water on either side of the trough converged at a rate less than 11 miles per day in cutting off the cyclonic eddy to the south.

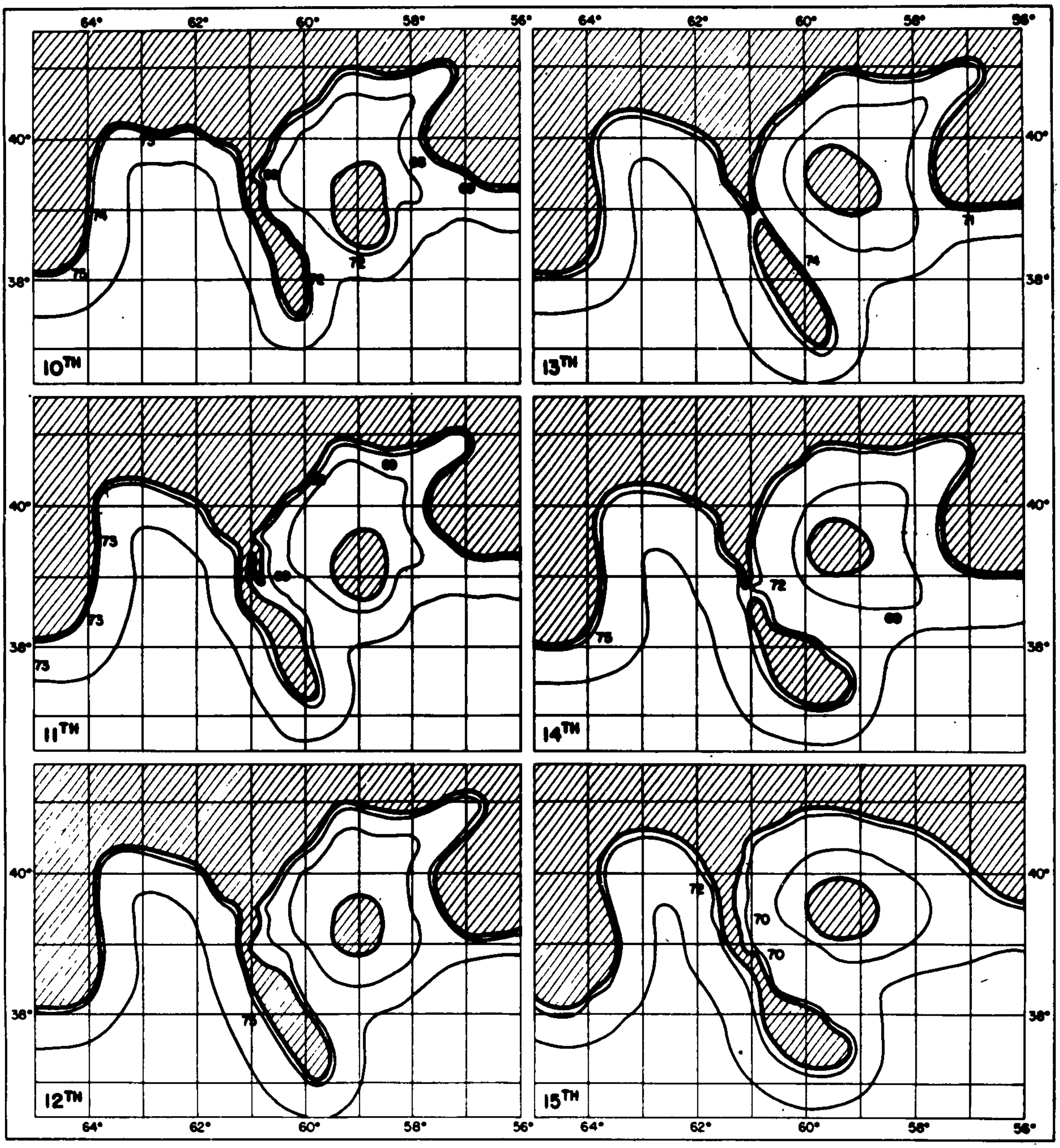
Various changes in the Gulf Stream position, are shown in Figures 5, 6A, and 6B. Considering the huge volume of the Stream, this shifting of its position by as much as 11 miles per day must produce large vertical motions in the water masses adjacent to the Stream. Although the evidence for these shifts in the Stream is based on observations of the upper 200 meter layer, a sufficient number of deep stations were made during Cabot and other recent Gulf Stream surveys to show that the water at least down to 2,000 meters is affected.

Because of the above measurements it is now possible to evaluate, with more confidence, the results of earlier Gulf Stream surveys made with single ships. The changes in positions of the Stream as found by the Canadian Research Vessel NEW LISKEARD in November 1948 and the large eddy, near 66° west longitude, surveyed by the ATLANTIS in June 1947 can be accounted for in detail by lateral shifts of the Stream of the order of 11 miles per day. It is obvious that several ships are required to obtain a synoptic picture of any very extensive portion of the Gulf Stream but, if it does not shift its position at a rate considerably greater than 11 miles per day, a single vessel can still be used to advantage in studying a limited area. In either case, however, the system of using a pre-arranged "grid" of hydrographic stations must be avoided. To obtain one section of closely spaced, deep



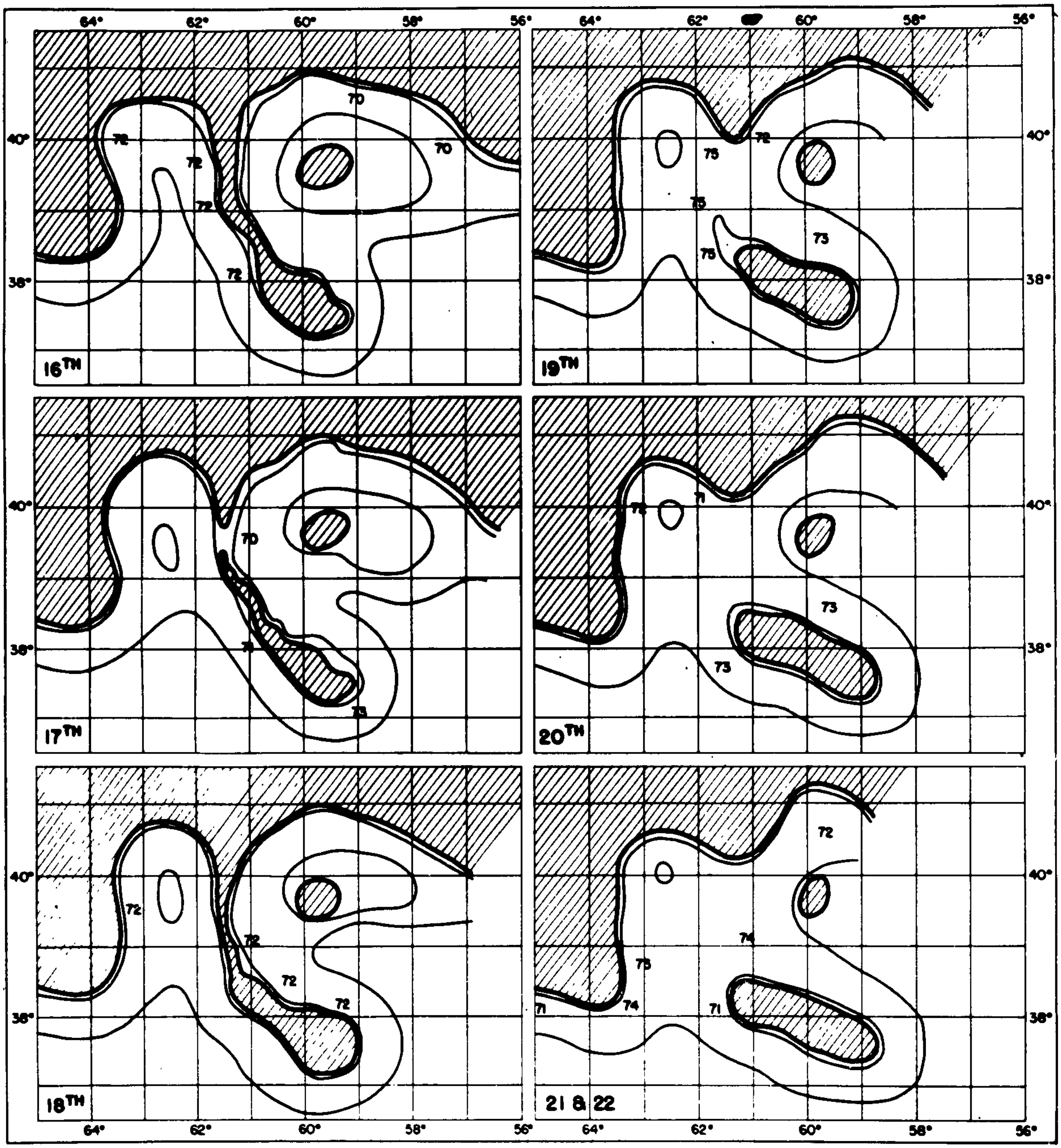
POSITION OF FRONT ON JUNE 8th, SOLID LINES, AND ON JUNE 21st–22nd, DASHED LINES. ISOTHERMS OF UPPER 200 METER AVERAGE TEMPERATURE.

FIGURE 5



POSITIONS OF THE "FRONT" (HEAVY LINE) JUNE 10th - 15th, 1950

FIGURE 6A



POSITIONS OF THE "FRONT" (HEAVY LINE) JUNE 16th-22nd, 1950

FIGURE 6B

stations across the Stream requires about 3 days time; a ship moving at 10 knots could make from 10 to 14 bathythermograph and GEK sections in this time.

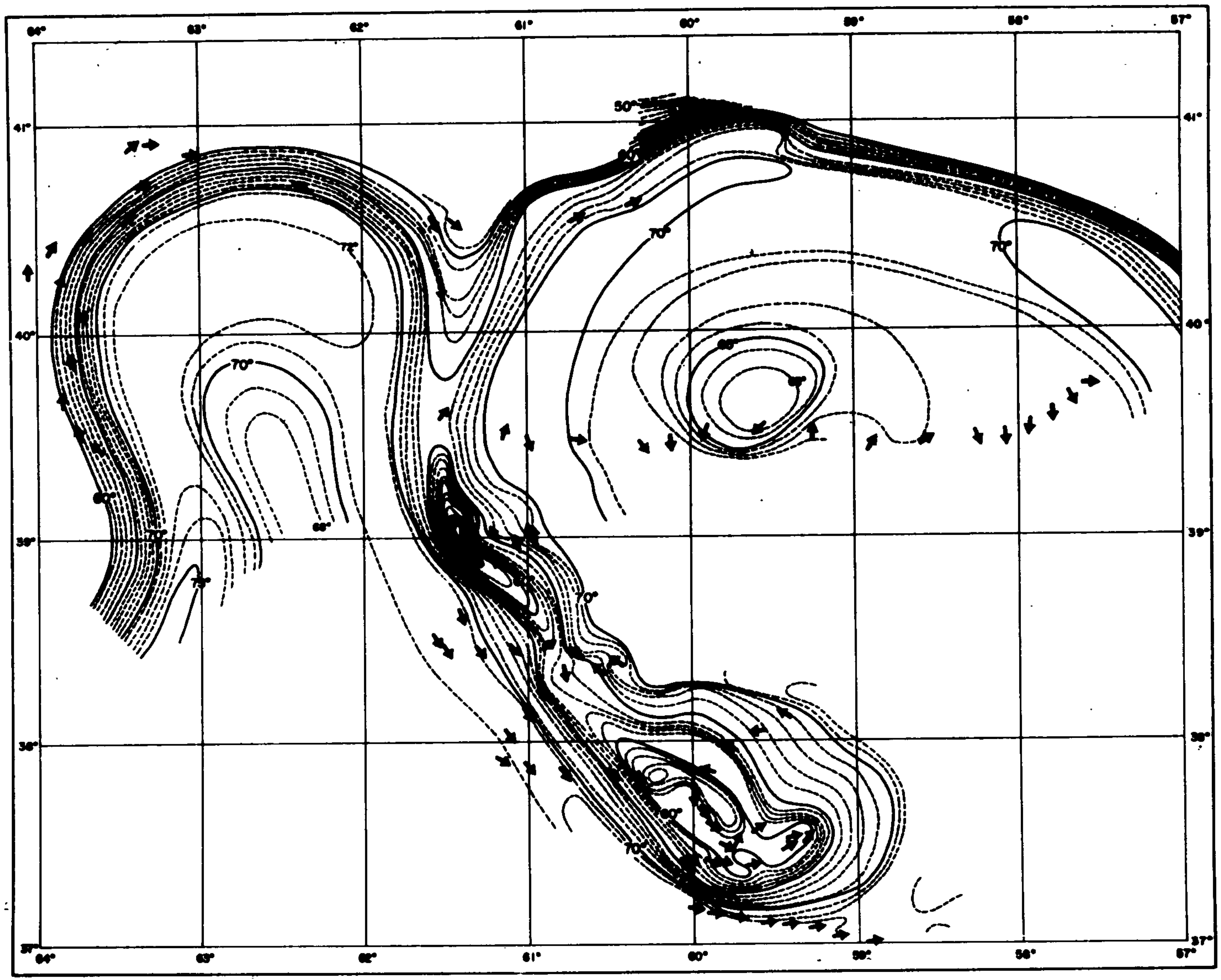
SURFACE CURRENTS

Up to this point, the positions of the Gulf Stream have been deduced from temperature observations and it has been assumed, first, that the pressure gradients coincide with the temperature gradients, and secondly, that the currents flow along the isobars. One of the most interesting results of Operation Cabot is the evidence that the surface current vectors and the isotherms (showing the mean temperature of the upper 200 meter layer) are parallel where the crosscurrent temperature gradient is sharpest.

As mentioned previously, the mean temperature of the upper 200 meter layer was plotted for each day. This was done without any reference being made to the observed current directions or speeds. At the completion of this work the current vectors, as computed by Mr. von Arx from the GEK data, were superimposed on the isotherms. Examples of the results are shown in Figures 2, 7, and 8. To the left of the warm core where the isotherms are most closely spaced it appeared, in nearly all cases, as though the isotherms had been drawn along the current vectors. Current vectors were obtained for 136 out of the 165 sections crossing this temperature gradient and the isotherms and vectors were parallel in 95% of the cases.

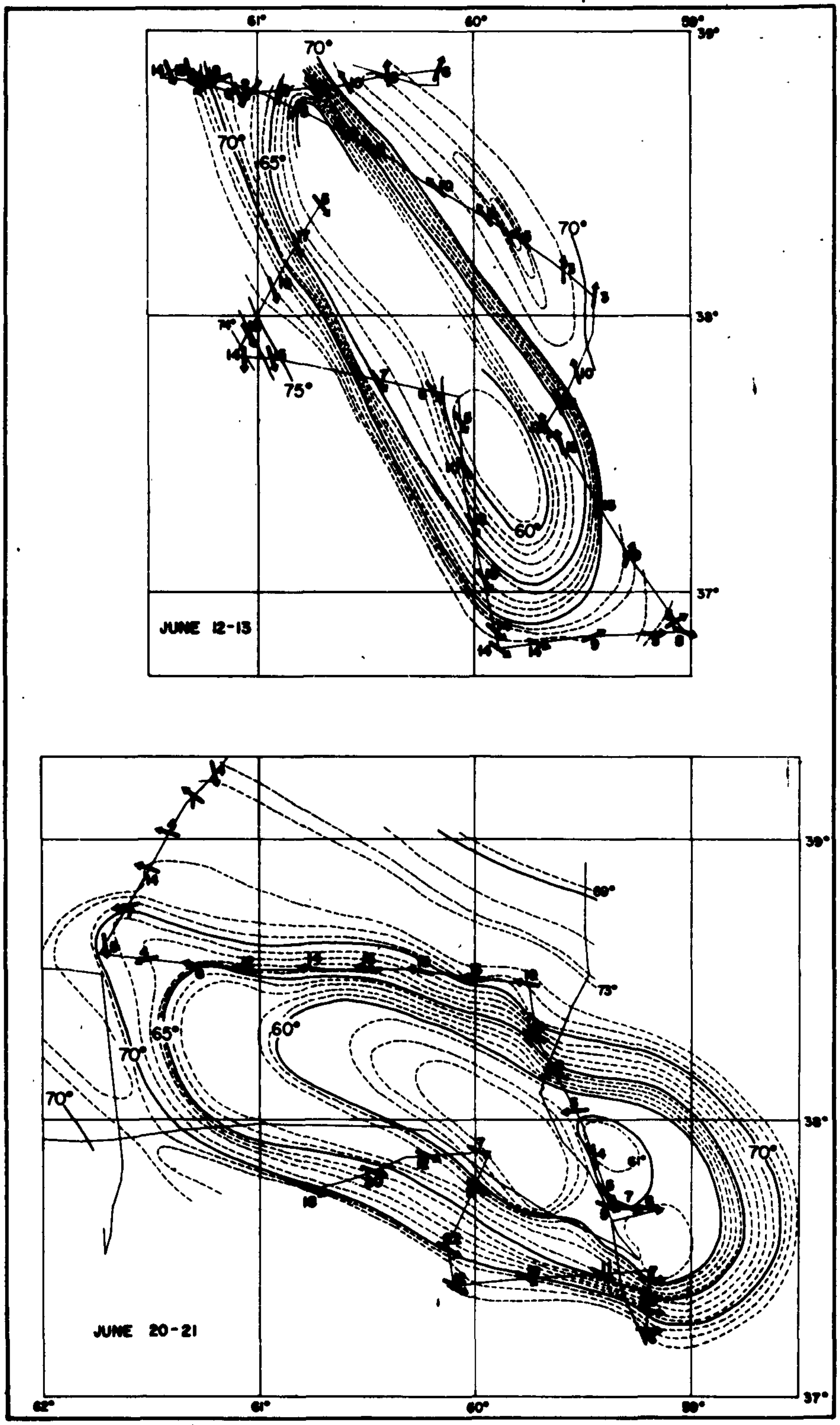
To the right of the warm core the direction of the current as obtained from the GEK data was extremely variable, on many occasions a narrow countercurrent being indicated. In one region, within the wave east of the trough, all sections that crossed the warm core showed a countercurrent. Actually, this current proved to be part of a cyclonic eddy with a cold core similar to, but not as cold as, that found in the larger eddy formed by the deep trough. It has not been determined whether this smaller cyclonic eddy originated as a broken-off segment of the Gulf Stream or was simply a countercurrent that became enclosed or cut off within the large wave to the east of the deep trough.

The current speeds obtained with the GEK are being subjected to a close analysis by Mr. von Arx. He reports that a correction must be applied, in the vicinity of the warm core, where the depth of the current affects the values obtained by his instrument. This correction factor has not been determined. The ships' drift data calculated from Loran observations, in the western half of the area, showed the



MEAN TEMPERATURE OF THE UPPER 200 METER LAYER ON 17th JUNE 1950. CURRENT ARROWS FROM THE "G.E.K."

FIGURE 7



"EDGAR" DURING THE FIRST AND LAST PERIODS OF OPERATION CABOT.
AVERAGE TEMPERATURE OF THE UPPER 200 METER LAYER.
CURRENT ARROWS FROM THE "G.E.K." SPEED IN DECIMETERS / SEC.

FIGURE 8

W.H.O.I. OCTOBER, 1960

band of maximum current speed to average between 4 and 5 knots. East of 60° the Loran data were not sufficiently accurate to justify current calculations by this method. The uncorrected GEK readings showed a falling off of velocities toward the east, the maximum south of the Grand Banks being 85% of the maximum found near Cape Hatteras. In general the maximum uncorrected velocities were found to the left of the axis of the warm core. The maximum shear was also observed to the left of the warm core. The uncorrected readings gave an average shear of 2.5 $10^{-4}sec^{-1}$ in the steepest part of the velocity profile.

EDDIES

For a number of years it has been noted that large cyclonic eddies are frequently encountered south of the Gulf Stream (Iselin, 1940, Iselin and Fuglister, 1948). In June 1947 the ATLANTIS circumnavigated one of these eddies. Centering at 66° west longitude it extended 200 miles east and west and 60 miles north and south. It was believed that these eddies were formed when a large loop or trough in the Gulf Stream became cut off and separated from the Stream. That this was indeed the case is shown by the observations made on Operation Cabot.

The day by day changes in the Gulf Stream's course in and around the trough at 61° west longitude are shown in Figures 6A and 6B. In these figures the water with a mean temperature in the upper 200 meter layer of less than 65°F. is indicated by shading. The heavy line is the 65°F. isotherm, the light line the 68°F. isotherm. The light lines are the approximate boundaries of the warm core. The maximum surface currents were observed where these two isotherms (the 65° and 68°) are shown close together, in other words the maximum speeds appeared to the left of the warm core. Details of the temperature and current pattern are shown in Figures 7 and 8.

For how long a period the trough existed before the 10th of June is not known but it is surprising that, considering the narrowness of the "neck", it took 9 days for it to break off. During this period the long narrow "neck" was meandering on a relatively small scale and the temperature characteristics in the cold central portion were continuously changing. Since there is comparatively little horizontal flow associated with the cold core these temperature changes must indicate vertical motion. On three occasions temperature profiles across the "neck" indicated that it was about to break off but each time subsequent observations showed the recurrence of colder water in the upper 200 meter layer. The final occlusion in this shallow layer occurred on the 19th of June and on the 20th a deep hydrographic station showed that the break had occurred at all levels.

Even before it broke off, the eddy, which was christened "Edgar" during the cruise, started to turn so that at the end of the survey its major axis was oriented east and west.

The smaller cyclonic eddy northeast of "Edgar" was crossed six times. Details of its size and shape are lacking but there is enough evidence to show that during the period it shrunk in size and moved steadily toward the northwest.

The following questions concerning these eddies were left unanswered by Operation Cabot. Do the eddies once they have broken away from the Stream move, and if so in what direction? How long do they last? Are elongated eddies typical? Do elongated eddies eventually break up into smaller, more nearly circular masses? Is there any preferred point of origin? If it is assumed that the region where "Edgar" was formed is such a "preferred point of origin", because of the ridges and sea-mounts, then the detached eddies must frequently move in an upstream direction, since they have been found as far west as 73° west longitude. If on the other hand we assume that the detached eddies remain motionless or move downstream then it is even more difficult to explain how an eddy such as "Edgar" could be formed in the relatively confined area near Cape Hatteras or south of it. All the available data show that the Gulf Stream does not start to meander until after it leaves the continental shelf at Hatteras.

An envelope drawn about the curves shown in Figure 4 indicates that it is not until the Stream reaches at least as far east as the 70th meridian that waves large enough to form an eddy could develop. Indeed, such an envelope would make it appear that, if waves of the size of those found on Operation Cabot are necessary to form an eddy, then they do not develop until the Stream reaches close to the longitude where "Edgar" was formed.

These considerations combined with what is known of the bottom topography indicate that the eddies formed by the Gulf Stream originate to the east of 63° west longitude and after being detached move in an upstream direction.

POSSIBLE BRANCHING OF THE GULF STREAM

Only two ships operated in the region east of 57° west longitude during this survey. The USCGC EVERGREEN made a bathythermograph and GEK section along the 50th meridian from the Grand Banks south to 38°30' north latitude then returning northward she made a series of hydrographic stations as well as bathythermograph and GEK observations. The HMCS NEW LISKEARD obtained bathythermograph and GEK sections into and out of the Gulf Stream to 50°20' west longitude. Both of these tracks are clearly seen in Figure 1.

The current map as calculated aboard the EVERGREEN from the data collected from the 9th to the 20th of June is shown in Figure 9. At about 42° north the EVERGREEN crossed a warm current flowing toward the east. This current was, in every respect, similar to the current that the Ice Patrol finds near this latitude each year. This current is referred to as the North Atlantic current (Soule, 1938). Continuing south the EVERGREEN crossed a minor countercurrent near 40° north and then at 39° it entered another easterly stream. Three days later the NEW LISKEARD showed that the southernmost current was the Gulf Stream which she had followed continuously from the west.

In August and again in September 1949, the Gulf Stream was located by the ATLANTIS at the 39th parallel south of the Grand Banks. An unpublished chart of the average depth of the 10°C. isotherm in the North Atlantic indicates that the Gulf Stream is south of 40° at this longitude. On the basis of these data and the records of the Ice Patrol it seems evident that at 50° west longitude there are always two easterly currents of major magnitude; one generally located near 41° north, the other at about 39° north. According to the definition given for the Gulf Stream it is quite evident that the southernmost current is the Stream. The data from Operation Cabot shows clearly that it forms part of a continuous current reaching from Cape Hatteras to 50° west longitude. What then is the origin of the current to the north and in what way are these two currents related? Is the one to the north a band or a branch of the Gulf Stream or is it entirely independent of the Stream?

The temperature-depth profile calculated from the bathythermograph and hydrographic station data collected by the EVERGREEN is shown in Figure 10. The current vectors as obtained by the GEK are plotted across the top of the profile. The deep observations were spaced approximately 30 miles apart while the temperatures down to 250 meters were obtained at 5 mile intervals. The right-hand or southern end of the section is a typical temperature profile across the Gulf Stream. The position of the warm core is evident. The narrow weak countercurrent on the right-hand side of the warm core is indicated by the vectors. The uncorrected current speeds (cm/sec) are shown above the vectors, the maximum speed of 167 cm/sec being to the left of the warm core.

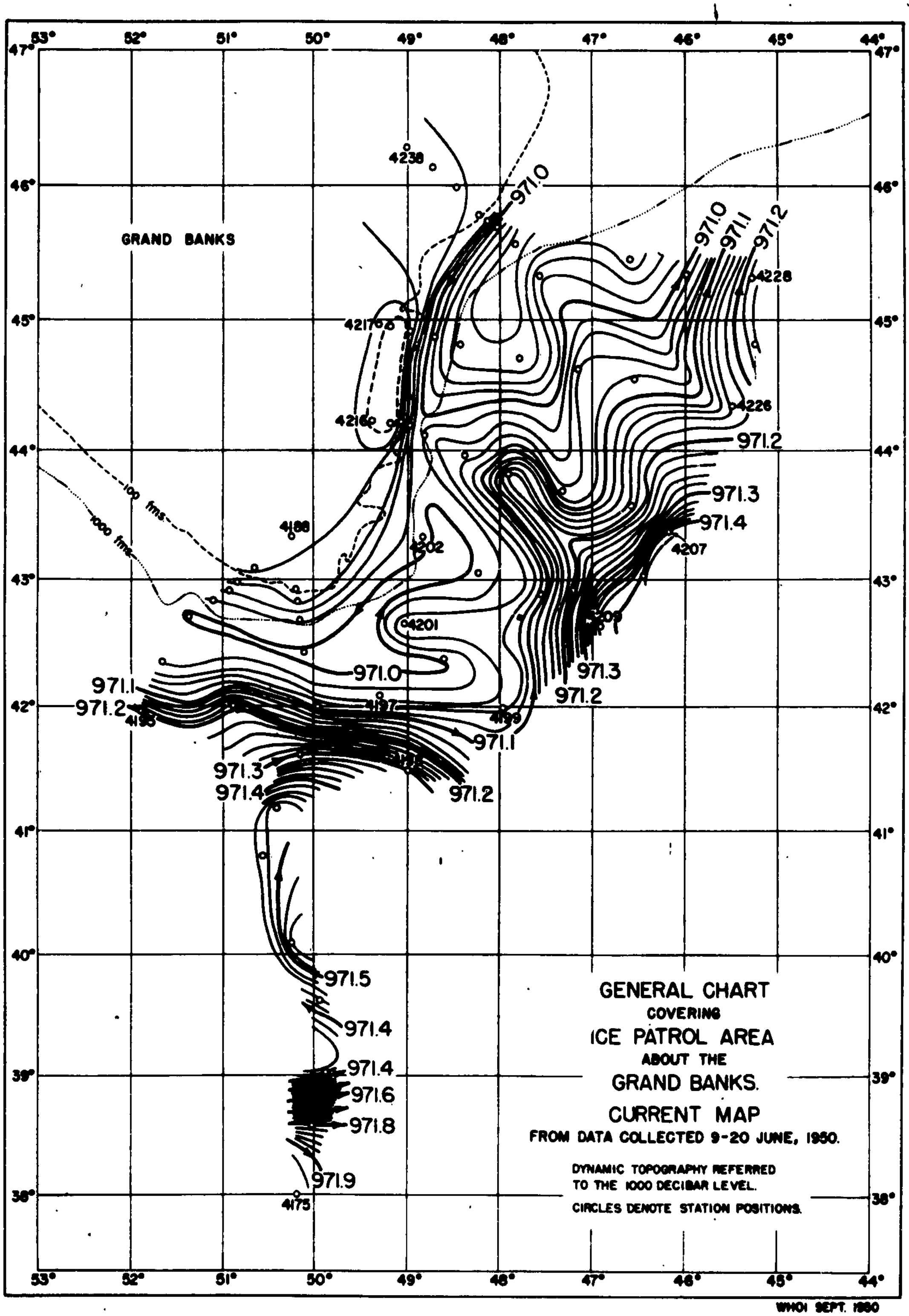
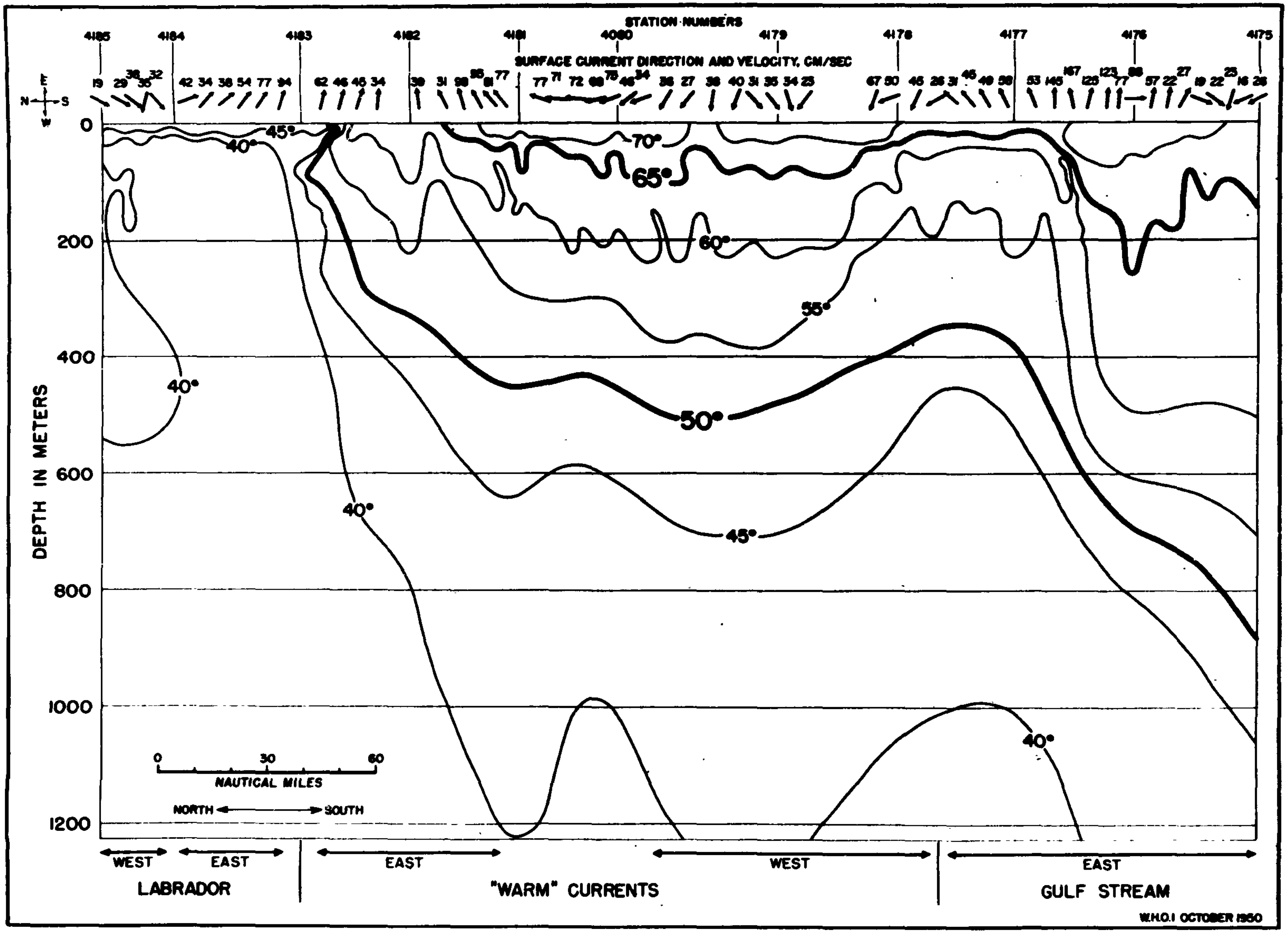

GRAND BANKS
GENERAL CHART
COVERING
ICE PATROL AREA
ABOUT THE
GRAND BANKS.
CURRENT MAP
FROM DATA COLLECTED 9-20 JUNE, 1950.
DYNAMIC TOPOGRAPHY REFERRED
TO THE 1000 DECIBAR LEVEL.
CIRCLES DENOTE STATION POSITIONS.
100 fms
1000 fms
971.0
971.1
971.2
971.3
971.4
971.5
971.6
971.8
971.9
4238
4228
4217
4216
4226
4188
4202
4207
4201
4197
4199
4195
4175
53°
52°
51°
50°
49°
48°
47°
46°
45°
44°
47°
46°
45°
44°
43°
42°
41°
40°
39°
38°
WHOI SEPT. 1950

FIGURE 9



TEMPERATURE (°F) PROFILE ALONG THE 50th MERIDIAN SOUTH OF THE GRAND BANKS.

FIGURE 10

The northern end of the profile shows the cold waters of the Labrador current. Between the Gulf Stream and the Labrador current this profile could be interpreted as showing a large anticyclonic eddy that may have been formed originally by a wave in the Gulf Stream breaking off on its northern side. However, the Ice Patrol current maps, over a period of years, have indicated that this current near 41° north latitude is of a permanent character and flows generally from the northwest and therefore it cannot be part of an eddy detached from the Gulf Stream.

The other possibility is that the northernmost current is a band or branch of the Stream. The authors' interpretation of the data obtained on this survey does not show any such branching of the Gulf Stream although, because of the relative scarcity of observations east of the 58th meridian, it does not preclude the possibility. The most simple interpretation is that the northernmost current coincides with the pressure gradient between the slope water and Labrador current water and the two easterly currents at 50° west are independent of each other.

OTHER OBSERVATIONS

The continuous sonic depth records obtained during the survey have been turned over to the U. S. Navy Hydrographic Office to be incorporated in their bottom topography charts. During the cruise the U.S.S. SAN PABLO surveyed two seamounts not shown on the Hydrographic Office charts. The first located at approximately 38°54' north and 60°28' west had a least depth of 725 fathoms. This was tentatively named San Pablo Seamount. The second at approximately 37°29' north and 59°52' west was flat-topped with an elongated zone some 8 miles long and 3 miles wide, and less than 700 fathoms. The minimum recorded depth was 675 fathoms. This was tentatively named Cabot Seamount. Both seamounts were explored by running at least three sections across them on different headings. The seamount shown on the charts at approximately 39°00' north and 61°00' west was found to have depths somethat less than indicated and that it too was flat-topped at a depth of about 500 fathoms.

Some excellent colored photographs showing shear zones, long thick lines of Sargassum, abrupt changes in wave types, clouds and color changes associated with the Gulf Stream were obtained from the aircraft. The reports of the Stream's positions, based on such visual evidence, were generally in close agreement with shipboard observations. The abrupt changes in the appearance of the sea surface did not, however, always coincide with the inner edge of the Gulf Stream as defined in this paper. Although dye marker experiments carried out by the plane showed clearly that the visual boundary was both a velocity discontinuity and a line of convergence, the ships' observations showed that there may be more than one such surface boundary, none of which necessarily coincide with the inner edge of the Stream.

Near 41°00' north 63°00' west, while following a long dense line of Sargassum, the plane encountered the U.S.S. SAN PABLO as it was crossing from south to north through the line of weed. The temperature-depth profile as obtained by the ship on this section is shown in Figure 11. The line of Sargassum indicated convergence at the sea surface. Visual observations of the ship's wake and GEK data showed that there was an abrupt change in velocity at this line but both the temperature profile and the GEK showed that the ship was still in the current after it had passed to the north side of the weed. Figure 11 shows that the line of Sargassum was about 5 miles from the abrupt temperature change at the surface and about 20 miles from the "inner edge" of the Gulf Stream as defined by the pressure gradient.

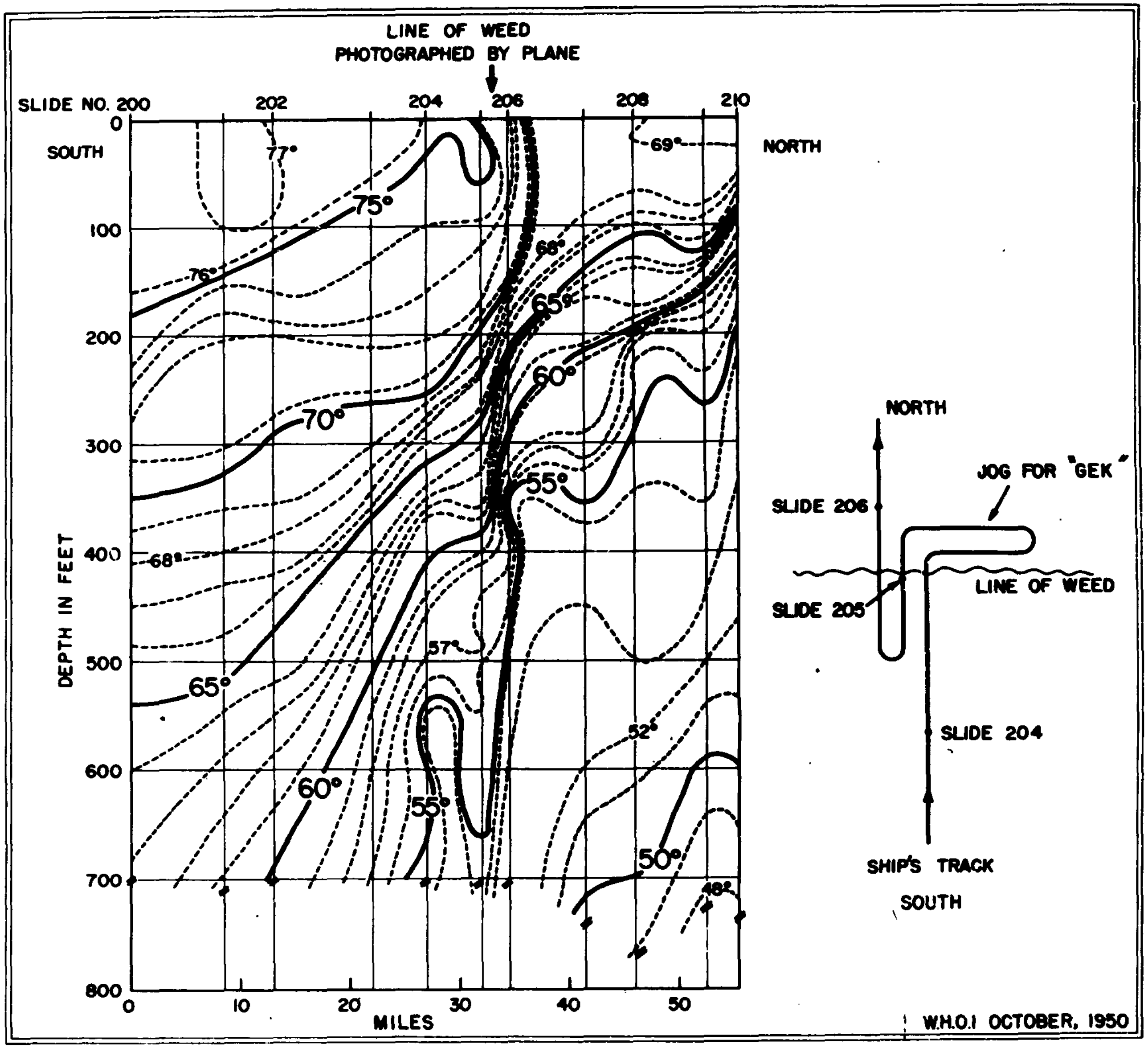
Color differences associated with the Gulf Stream were apparent to the plane only in the westernmost area, west of 71° west longitude. East of this point lines of weed, differences in wave type, and formations of "typical" Gulf Stream cumulus clouds had to be depended upon to locate the Stream. Neither the cumulus clouds nor the weed were always present and the wave patterns, of course, depended on the wind velocities and were most pronounced with moderate winds blowing against the current. In general, visual observations failed to identify the Stream east of the 65th meridian.

The authors hope that Mr. Kielhorn, the observer on the plane, or the Hydrographic Office will publish a complete report on the aircraft participation in Operation Cabot reproducing some of the excellent photographs obtained.

The large amount of weather data collected by the planes and ships during the survey have not as yet been studied. These data, the sea surface temperature data, and more details of the surface current data will form the basis of future reports.

SUMMARY

Operation Cabot, the first oceanographic survey of its kind to date was successful mainly because:



GULF STREAM PROFILE JUNE 10, 1950

FIGURE 11

(a) Communications were maintained between all ships and the flagship throughout the survey, enabling the staff aboard the flagship to direct and coordinate the movements of the various vessels as the synoptic picture of the Gulf Stream developed.

(b) Instruments for taking numerous and rapid measurements were available; Loran for navigation, the bathythermograph for water temperatures, the geomagnetic electrokinetograph for current velocities, and the planes for visual observations of the Gulf Stream's positions.

(c) Highly qualified scientific personnel were available to man the six ships and the plane.

In this paper the Gulf Stream has been defined as the continuous band, reaching from the continental shelf off Cape Hatteras to the 50th meridian, where a pronounced pressure gradient exists between the warm, highly saline water to the south and the colder, fresher water to the north. The inner and outer edges of the Stream are the points where this pressure gradient becomes zero. Abrupt changes in temperature and current velocities that occur at the surface do not necessarily coincide with these boundaries.

Daily synoptic plots of the Gulf Stream show that the current may shift its position at a rate of 11 miles per day. Two synoptic plots of the Stream are shown; one for the first and one for the last periods of the survey. The outstanding feature of the first plot is the two large waves separated by a deep trough near 61° west. The second plot shows that the trough became cut off and formed a cyclonic eddy south of the Gulf Stream. The breaking off of the trough was observed in detail and confirmed the theory that the large cyclonic eddies frequently found south of the Gulf Stream are formed in this manner.

A smaller, weaker cyclonic eddy was observed to the east of the deep trough. Although it is assumed that this eddy was formed in the same manner as the larger one, it is pointed out that it may be a portion of the countercurrent found on the outer side of the Stream, that became enclosed and cut off within the large wave east of the deep trough.

Eddies are probably always formed when the waves in the Gulf Stream reach a certain optimum size. It is estimated that the waves cannot become large enough to form eddies west of longitude 70° and probably not west of longitude 63°. There is the further possibility that the waves only reach this critical size in regions where ridges in the bottom topography affect the course of the Stream.

There is evidence that the cyclonic eddies broken off to the south of the Stream move in a westerly or upstream direction.

The surface currents are shown to flow parallel to the isotherms where these isotherms are closely spaced in the region to the left of the warm core of the Gulf Stream. In the right-hand portion of this core the current directions are variable, frequently showing a narrow weak countercurrent.

Temperatures of the warm core indicate that the Gulf Stream transports water from south of Cape Hatteras to the longitude of the Grand Banks, the mean temperature of the upper 200 meter layer decreasing approximately 6°F. over this 1,200 mile distance. "Gobs" of warmer water, possibly indicating a pulsing action of the Stream, were found at intervals in the warm core from Cape Hattèras to 57° west longitude.

To the south of the Grand Banks two easterly currents are found and the southern one is shown to be the Gulf Stream. No evidence was obtained on this survey to show that the northerly current was in any way connected with the Gulf Stream.

ACKNOWLEDGMENTS

Obviously this, or any other paper to be published dealing with Operation Cabot owes its existence to the efforts of the scientists and seamen who took part in the survey. The authors wish to thank these men, and also Dr. Rossby of the University of Chicago, Dr. Iselin and Mr. Stommel of the Woods Hole Oceanographic Institution for their many helpful suggestions. Thanks are also due to Miss Evangeline Tollios and Mr. Columbus Iselin, Jr., who did such a fine job of plotting and calculating.

ILLUSTRATIONS*

11. Temperature profile across the Gulf Stream, 10th of June 1950.

* Figure numbers are on the backs of the prints.

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