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SOME RECENT DEVELOPMENTS IN THE STUDY OF THE GULF STREAM

By

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INTRODUCTION

At Cape Hatteras the Gulf Stream leaves the Continental Slope, so that as far as the deep current is concerned its course is no longer confined. The current again approaches the Continental Shelf off Georges Bank and off the Grand Banks, but in neither area does it flow normally along the Continental Slope as a river pressing against its bank. The band of water which separates the Gulf Stream from the Continental Shelf in the sector between Cape Hatteras and the Grand Banks is usually called "slope water." The great body of water to the south and east of the Stream is known as the Sargasso Sea or Central Atlantic water. Although it is not a part of this paper to discuss the physical characteristics and the similarities or dissimilarities of these two masses of water, there is an important difference that must be mentioned. In the slope water, the main thermocline lies much nearer to the surface than it does in the Sargasso Sea. The depth of this thermocline does not gradually change from one body of water to the next but changes abruptly within a relatively short distance. The Gulf Stream occupies this transition belt where the midpoint of the thermocline drops from an average depth of 250 meters in the slope water to an average of 750 meters in the Sargasso Sea.

In the sector between Cape Hatteras and the Grand Banks, the Gulf Stream resembles a "river in the ocean" rather than a current pressed close against the margin of the ocean basin. For some purposes it is more convenient to think of the Gulf Stream as a transition belt or as a boundary phenomenon. The approximate mean position of this boundary, as taken from the U. S. Hydrographic Office chart No. 1412, is shown in Fig. 1. The dots in the figure show where the available subsurface temperature observations have indicated the abrupt change in the depth of the thermocline.

¹ Contribution No. 451 from the Woods Hole Oceanographic Institution.

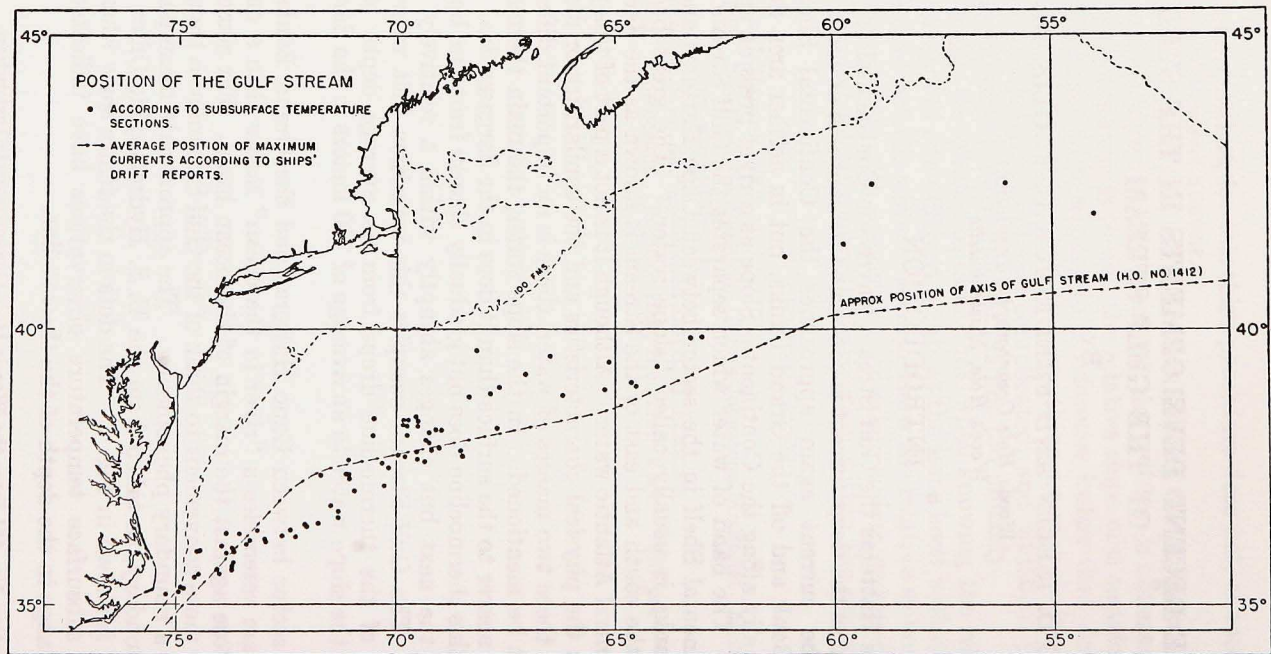


Figure 1. Comparison between the average path of the axis of the Gulf Stream as deduced from ship reports at the U. S. Hydrographic Office (arrows) and cross current temperature profiles (dots).

Our understanding of this part of the Gulf Stream system has come from three quite different sorts of studies, and only recently has a radically new attack on the problem been made. There is, first of all, a long series of studies in which average conditions in and near the Gulf Stream have been shown in various ways. The mean position of the axis of the Stream as given in Fig. 1 is an example. As more data became available, these plottings of the average physical characteristics of the current have been greatly improved, either by shortening the time intervals (Fuglister, 1947) or by combining several different types of information (Neumann and Schumacher, 1944). As will be shown below, although these observations were useful as a preliminary step in understanding the Gulf Stream, all such studies in the process of averaging the available data show the current as being considerably broader and weaker than it actually is at any given time. Of course, the defect has been generally understood by oceanographers, but how pronounced it could be has only recently been demonstrated.

A second general method, which was employed vigorously during the period 1930-1940, was the study of profiles of the Gulf Stream derived from lines of serial temperature and salinity observations. These Gulf Stream sections required only two or three days to complete and thus approached the synoptic ideal, but the interpolations, both vertical and horizontal, were relatively great. Especially when in and near the current, the observer experienced great difficulty in controlling the navigation of the research vessel, and the placing of the stations in relation to the current was always in doubt. This method when used under the most favorable circumstances provided considerable evidence (Iselin, 1940) that in cross section the current behaves just as would be predicted from the circulation theorem. However, because of the relatively wide spacing of the observations, calculations of the velocity could be regarded only as minimum values, and there remained even greater doubt as to the velocity at considerable depths below the surface. The total transport of the current could be computed from such observations with somewhat greater assurance. In these Gulf Stream profiles, marked distortions of the main thermocline layer on either side of the current were encountered. In the absence of reliable surface current observations such undulations of the isotherms could only be tentatively ascribed to eddies. Furthermore, in each case only a single profile was obtained.

At the same time that these subsurface studies were being made, the surface temperature records from commercial ships making regular runs across the area were being obtained. From these data, Church (1937) concluded that the Gulf Stream wandered or meandered to an increasing degree as it moved eastward from Cape Hatteras. Although

the surface temperature alone is not always an exact indication of the location of the swiftest current, this profitable line of study probably was not continued as long as it should have been.

A third approach to the problem of the Gulf Stream has stemmed from theoretical studies. The contribution of the basic ideas in the circulation theorem has already been mentioned. Rossby (1936) pointed out that the Gulf Stream, at least to some extent, must behave as a wake stream and that countercurrents and eddies should be found on both sides of it. More recently Stommel (1948) has contributed much to our understanding of why the great North Atlantic eddy, of which the Gulf Stream is a part, has been found to be so much swifter and narrower in the west than in other sectors. As will be shown below, the new observations are not inconsistent with these various theories, but as might be expected, they present us with a somewhat more complicated picture. It is hoped that in time the theory will be refined to meet the new aspects.

NEW INSTRUMENTS

During the war two new instruments were developed that allowed a different approach to the study of the Gulf Stream. These instruments were the bathythermograph, with which subsurface temperature data can be obtained while a ship is underway, and the loran, which makes it possible to obtain navigational fixes at any hour of the day or night.

With the bathythermograph, a nearly continuous temperature-depth profile can be obtained. Within a few minutes of the time of lowering this instrument, the observer has a clear picture of the temperature structure of the water through which the ship is passing. With this knowledge, he can maneuver the ship so as to remain close to any particular thermal structure that is to be studied. It is true that the instrument shows only the surface layer temperatures, to a depth of 900 feet with the latest model bathythermograph, but as will be shown, it is evident that even in this shallow layer the temperature structure reflects the current pattern.

The loran makes it possible to maneuver a ship in and out of a current over a period of days without becoming hopelessly involved in navigational problems. Unfortunately this does not hold for every portion of the Gulf Stream system. In many areas over the ocean, the loran coverage is poor or nonexistent, but it is fortunate that the coverage is extremely good over the area traversed by the Gulf Stream between Cape Hatteras and Georges Bank. Even in this region, a single loran fix should not be relied on, but if the instrument is in

operation continuously and if fixes are obtained at frequent intervals, the results are far more reliable and useful than the best dead reckoning and celestial navigation.

Other instruments have been and are being developed which will be of value in ocean current studies. For example, there are new electrical means of recording surface salinity, and the multiple sea sampler gives promise of providing practical means of observing the subsurface distribution of salinity at frequent intervals. It is hoped that these devices will be used in future surveys of the Gulf Stream, but since they were not employed in these studies, they are mentioned only briefly.

RECENT INVESTIGATIONS

The first studies of the Gulf Stream made with a bathythermograph were of rather limited scope (Spilhaus, 1940). As the instrument was further developed, a number of sections were run across the Stream, and it became quite clear that the temperature structure in the surface layer (450 or 900 feet) indicated the presence of the current. Fig. 2 shows two such temperature profiles, one made in August 1945 and the other in December 1947. A study of these and other sections shows that the depth of the 65° F. isotherm can be used conveniently to indicate the position of the Gulf Stream as well as large eddies and counter-currents. In the Sargasso Sea, the temperature of the water at a depth of 900 feet is at all seasons of the year between 64° and 65° F. There is no evidence of the water at this depth ever becoming appreciably warmer than this, but on the other hand a strong eddy or current may cause it to become several degrees cooler. In the swiftest portion of the Gulf Stream, the 65° isotherm abruptly moves up to the surface. During the coldest season of the year, all slope water is colder than 65°, while at other times of the year this isotherm is generally less than 200 feet deep. Anticyclonic eddies in the slope water area will cause the 65° isotherm to deepen, but rarely will it go to as great a depth as it occupies in the Sargasso Sea.

In spite of the fact that these temperature profiles are comparatively easy to obtain, only a few complete cross current sections are yet available. Shallow temperature profiles show where a strong current has been encountered, but they alone do not permit any calculations of velocity. With the introduction of the loran, not only was the problem of navigation near a current much simplified, but a means of approximating the velocity of the current at the surface was supplied. The loran data confirmed what had long been suspected on theoretical grounds; namely, that the sharp drop of the isotherms in the surface layer occurs where the current is swiftest.

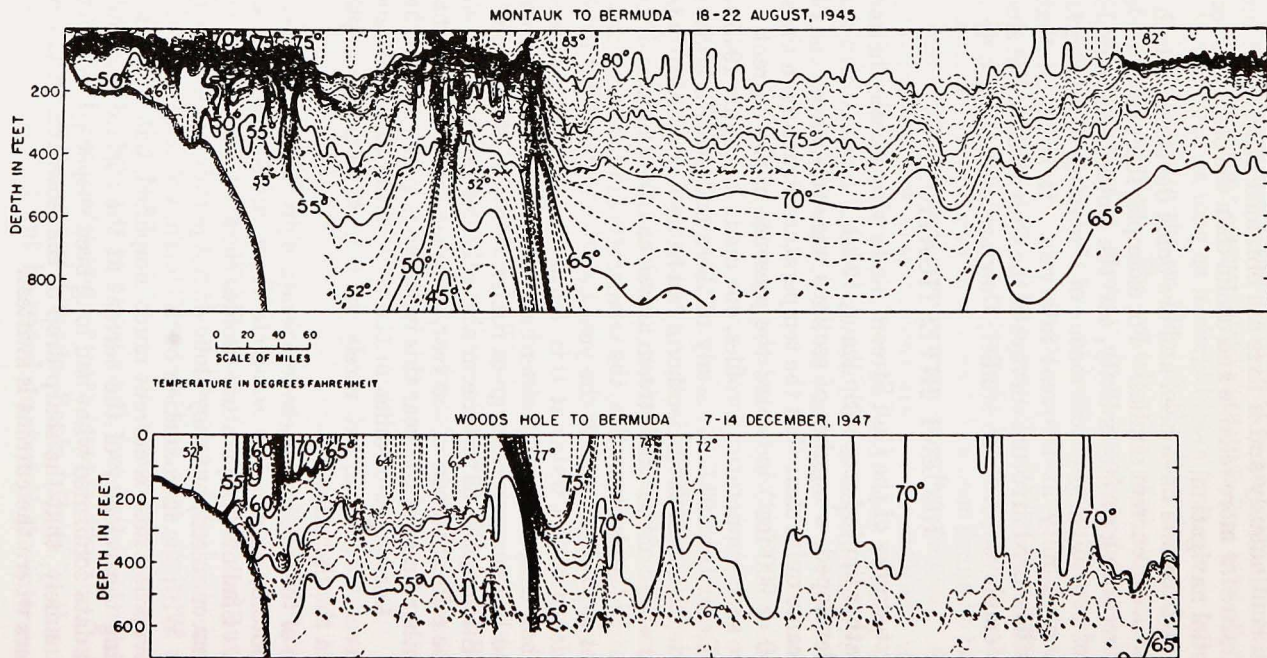


Figure 2. Bathythermograph profiles across the Gulf Stream off southern New England. The diagonal marks indicate the greatest depth achieved on each lowering. In the upper section the 450-foot instrument was used alternately with the 900-foot instrument.

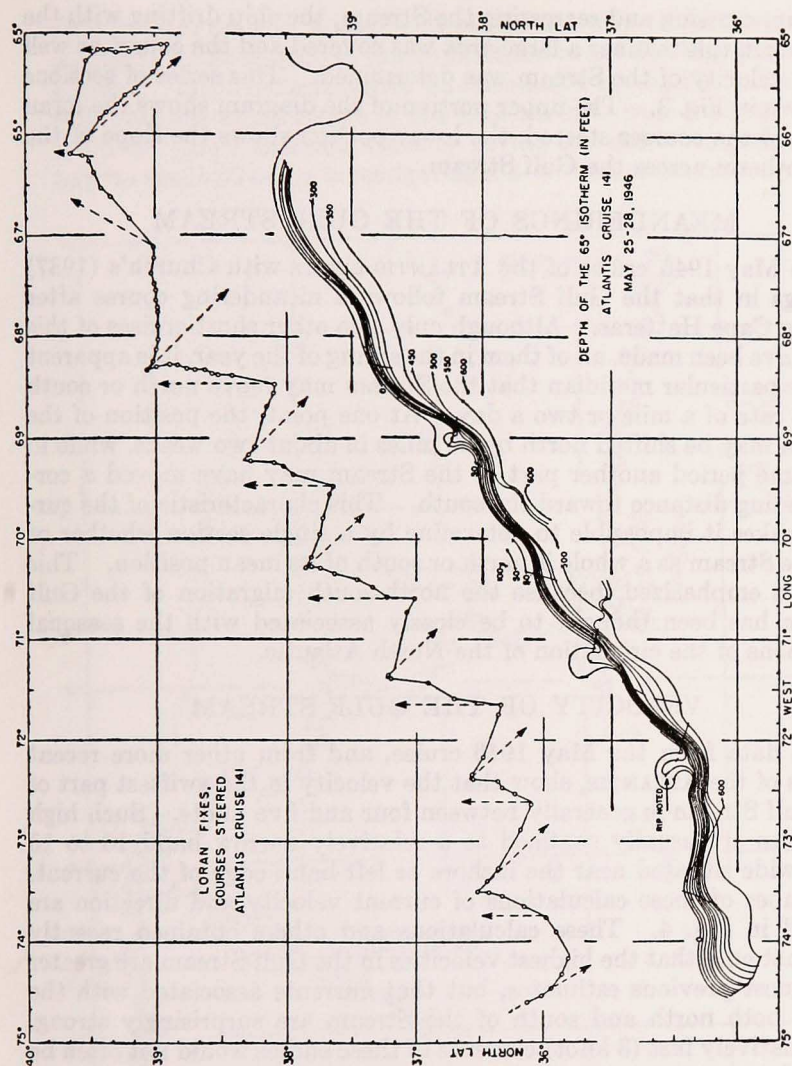


Figure 3. Survey of the northern edge of the Gulf Stream showing the departure between dead reckoning and observed positions (above) and the probable depth contours of the 65° F. isotherm (below).

In May 1946, the two new instruments were used aboard the research ketch *ATLANTIS* in a new type of survey of the Gulf Stream.² Instead of observing an individual section, a series of short sections

² This survey, as well as the collection of much of the other data presented here, was carried out under Contract No. N6onr-277 with the Office of Naval Research.

was run, crossing and recrossing the Stream, the ship drifting with the current; in this manner a large area was covered and the course as well as the velocity of the Stream was determined. This series of sections is shown in Fig. 3. The upper portion of the diagram shows the loran fixes and the courses steered, the lower portion shows the slope of the 65° isotherm across the Gulf Stream.

MEANDERINGS OF THE GULF STREAM

The May 1946 cruise of the *ATLANTIS* agrees with Church's (1937) findings in that the Gulf Stream follows a meandering course after leaving Cape Hatteras. Although only two other short cruises of this type have been made, all of them in the spring of the year, it is apparent at any particular meridian that the Stream may move north or south at the rate of a mile or two a day. At one point, the position of the Stream may be shifted north by 20 miles in about two weeks, while in the same period another part of the Stream may have moved a corresponding distance toward the south. This characteristic of the current makes it impossible to determine by a single section whether or not the Stream as a whole is north or south of its mean position. This point is emphasized, because the north-south migration of the Gulf Stream has been thought to be closely associated with the seasonal variations of the circulation of the North Atlantic.

VELOCITY OF THE GULF STREAM

The data from the May 1946 cruise, and from other more recent cruises of the *ATLANTIS*, show that the velocity in the swiftest part of the Gulf Stream is generally between four and five knots. Such high velocities are usually confined to a relatively narrow band 10 to 15 miles wide situated near the inshore or left-hand edge of the current. A number of these calculations of current velocity and direction are plotted in Fig. 4. These calculations and others obtained recently show not only that the highest velocities in the Gulf Stream are greater than most previous estimates, but that currents associated with the eddies both north and south of the Stream are surprisingly strong. The relatively fast (3 knot) currents of these eddies would not often be noticed in general navigation, since for each current moving in one direction there is an opposite current of equal, or nearly equal, velocity near by. It is for this same reason that when crossing the Gulf Stream the ships' drift records show the velocity as less than it actually is. The countercurrents near the Stream are usually indistinguishable from the main flow in the navigational record. Because of the meanderings, eddies and countercurrents which are characteristic of the

Gulf Stream area, it would be difficult for a ship to maintain a course so that it would remain in the swiftest, eastward flowing, portion of the current. Drift records, based on infrequent celestial fixes from a ship following the mean course of the Gulf Stream, would almost certainly not show the maximum velocity of the current. Recently the ATLANTIS spent 36 hours investigating a 3- to 4-knot countercurrent near

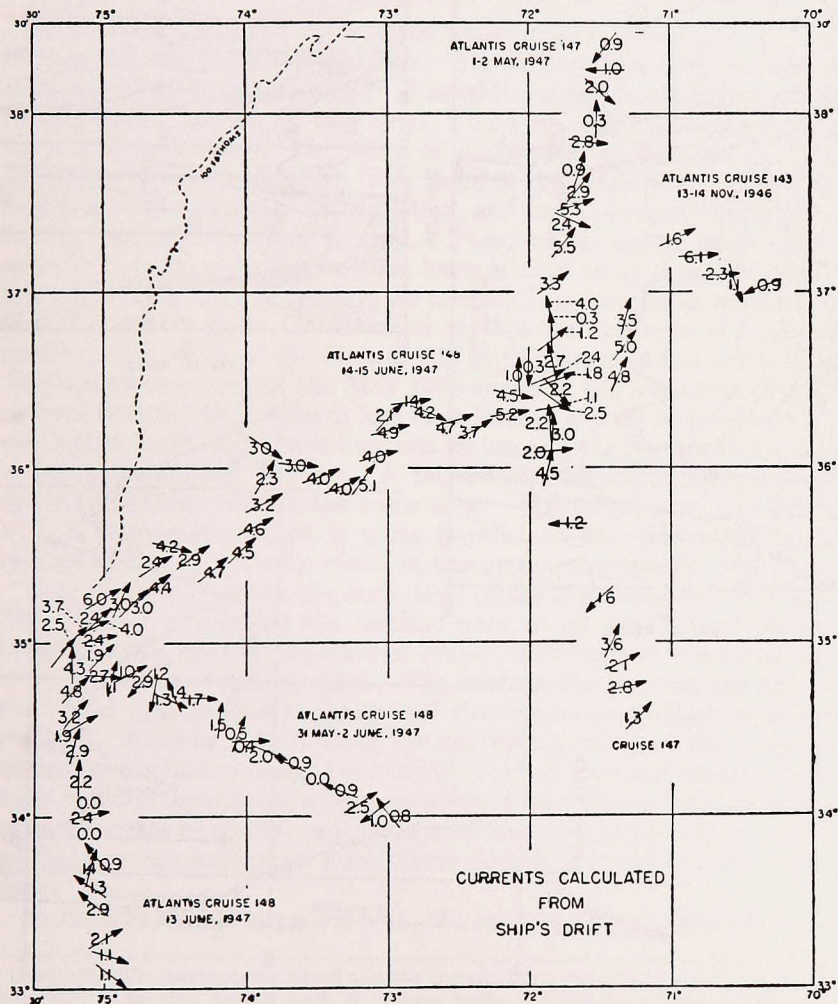
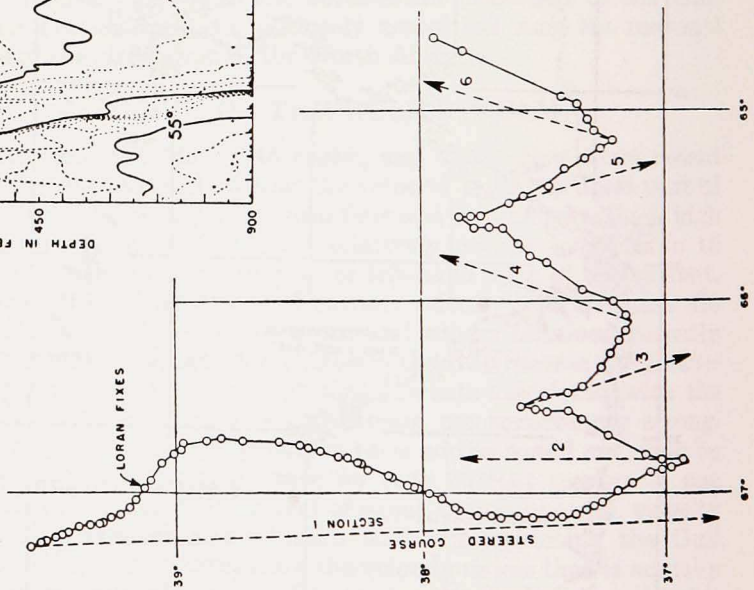
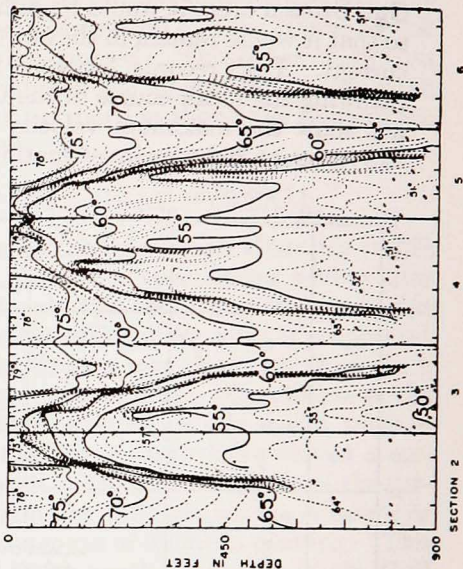
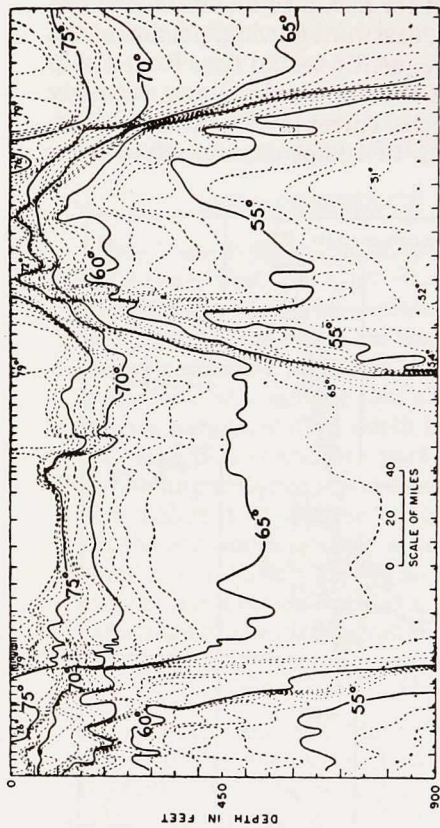


Figure 4. Currents calculated from the departure between the observed and dead reckoning positions during recent Gulf Stream surveys.



the usual axis of the Gulf Stream, and during this time several freighters bound for Europe were sighted. Since these ships must have been bucking this countercurrent for at least six hours, their calculated drift toward the east for a 12-hour period could not have come to more than one or two knots, even if they had spent the remainder of the time in the swiftest part of the easterly-flowing, true Gulf Stream.

EDDIES ASSOCIATED WITH THE GULF STREAM

The eddies that have been found both north and south of the Gulf Stream fall into two general classes. The *first* are frictionally-driven or shear-zone eddies, often roughly 17 miles in diameter. Spilhaus (1940) found smaller eddies of this type, which he called parasite eddies, having dimensions of the order of magnitude of four miles. The *second* are radically different from these in that they are considerably larger, rotate in the opposite direction, and are frequently found many miles away from the Gulf Stream. These eddies appear to be actual segments of the main stream that have broken away from the parent body when the Gulf Stream, in its meandering, formed an excessively large loop in its path. This would explain the existence of large cyclonic eddies south of the Stream and anticyclonic eddies north of it. The last two sections of the May 1946 cruise of the ATLANTIS (Fig. 3) showed that the Gulf Stream had then formed a large loop toward the south that could easily have been cut off later by the Stream re-forming across the northern portion. A more fully developed example was observed in June 1947 in the same area. Apparently, we are dealing with a phenomenon that is quite parallel to that observed in the regions of strong westerly winds in the upper atmosphere.

Part of the data from the June 1947 cruise is summarized in Fig. 5. The diagram illustrates the method used in all recent Gulf Stream investigations, that is, the steered course, the frequent loran fixes and the temperature-depth profiles. The relationship between the drift of the vessel (the surface current) and the temperature-depth profile is evident. Sections 2 to 6 along the southern portion of the eddy are typical of profiles crossing the swiftest part of the Gulf Stream itself. As this cruise developed, it became evident that the cyclonic eddy was over 200 miles in length, east-west, and about 60 miles wide. It was partially circumnavigated three times during a period of about eight days.

In 1945, in almost the same area, the schooner VALOR had drifted in

Figure 5. The navigational record and the corresponding bathythermograph profiles for a crossing of the Gulf Stream south of Georges Banks and also for a large cyclonic eddy (Section 1). Sections 2 to 6 extend along part of the southern edge of this eddy, the center of which was characterized by relatively cold water at all depths.

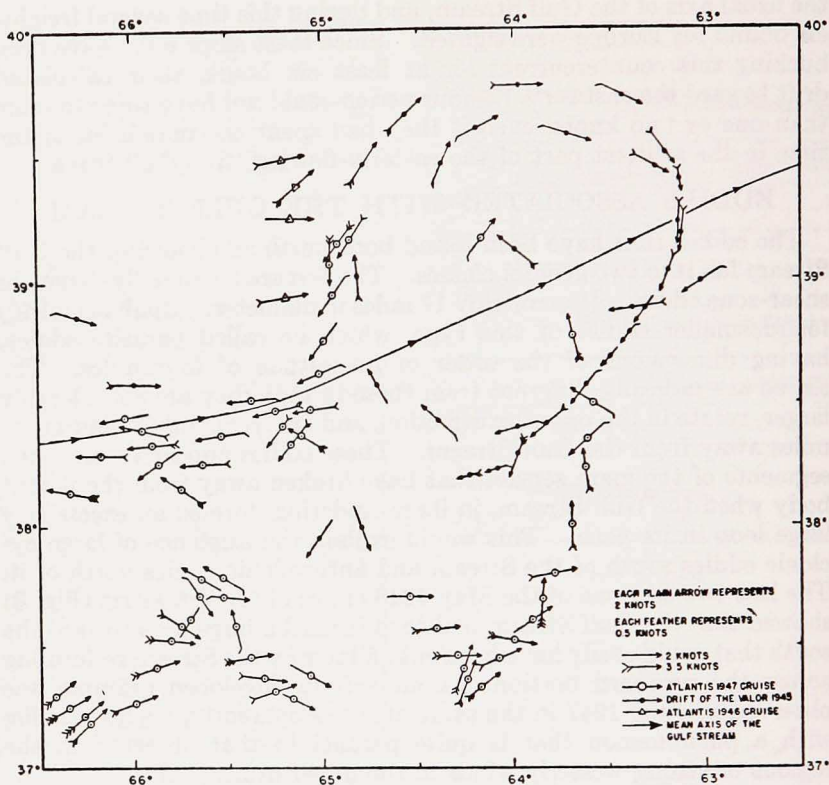


Figure 6. Comparison between the currents observed on three recent cruises and the supposed mean track of the Gulf Stream.

a powerful anticyclonic eddy for about 10 days. We are indebted to Lieut. D. T. Parson, USNR, for 48 loran fixes obtained during this period. These, plus his careful records of the drift of the vessel through the water while hove to, have enabled us to make reliable calculations of the velocities encountered. Fig. 6 combines the VALOR and ATLANTIS data. To avoid confusion, only calculated velocities of two knots or more are shown. These observations cover a considerable area through which the Gulf Stream presumably flows normally, yet only a few of the arrows point toward the east. It just happens that on all three occasions the Gulf Stream had been violently displaced; at the time of the 1945 observations it was far to the south; in 1946 the strongest current was about 50 miles north of the mean track. Admittedly, these are probably exceptional observations. The aver-

age current charts from which the normal axis of the Gulf Stream has been deduced combine many thousands of less accurate observations. Yet Fig. 6 clearly illustrates the great weakness of such charts. The average current, and the current at any one time, may be very different indeed. Strong currents flowing in deep water are subject to considerable dislocations, and moreover, these strong currents, at least in the western part of the oceans, are considerably narrower than has generally been supposed. If the Gulf Stream is typical of such currents, and it probably is, only by rapid survey techniques can we hope to gain a reasonably reliable picture of its typical behavior. Averaging data merely blurs the details which are the key to its more complete understanding.

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