ON THE NATURE, OCCURRENCE AND ORIGIN OF COLD LOW SALINITY WATER ALONG THE EDGE OF THE GULF STREAM[1]

By

W. L. FORD, J. R. LONGARD AND R. E. BANKS

ABSTRACT

In the left margin of the Gulf Stream, looking in the direction of flow, a narrow discontinuous band of relatively cold water is often found. This has been attributed to upwelling from the colder depths of the ocean, but recent investigations throw doubt on this explanation, since this water, which forms a thin layer close to the surface, may have a lower salinity than any water in the depths. Evidence is given that the only cold low salinity source is the so-called Shelf water, which is found in a broad band between the shore and a boundary off the Continental Shelf.

It is shown that the cold low salinity water in the margin of the Stream, when mixed with the warm high salinity water of its core, may form a product which is identical to the Slope water which lies between the Gulf Stream and the Shelf. It is postulated that this product is discharged to the left of the Stream to form a source of the upper layer of Slope water.

INTRODUCTION

It has been recognized for some time that unexpectedly cold water occurs at the surface along the left-hand edge of the Gulf Stream, but beyond this the phenomenon has received little attention. On the basis of thermograph records from merchant ships, Church (1937) reported that the temperatures on the northern edge are often a degree or more (°C) below those on either side and that sometimes these low temperatures are not matched within 40–80 miles to the north. He noted also that the occurrence is quite consistent during the colder half of the year but less so during the warmer half.

Spilhaus (1940) reported results of the first detailed study of the edge of the Stream, made possible by the Bathythermograph (BT) and Sea Sampler. A feature of his observations was the presence of a cold layer, with minimum temperature at about 200 feet, immediately adjacent to the warm water of the Stream; he attributed this cold layer to upwelling. The salinity observations obtained with the Sea Sampler did not happen to embrace the cold layer, and if they had, it is probable that remarkably low salinity values would have been obtained, too low in fact to be explained by upwelling from the depths, which contain water of relatively high salinity.

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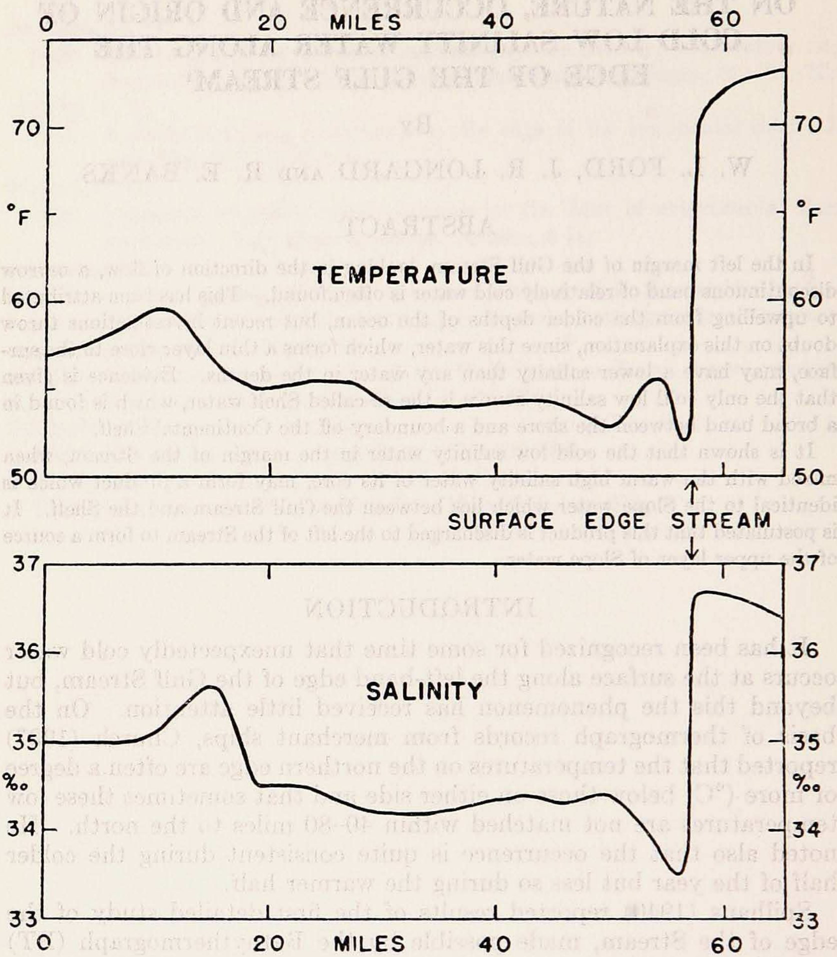


Figure 1. A plot of continuous surface temperature and salinity recordings from the STD in a crossing of the edge of the Gulf Stream at 37° 20′ N. Lat. and 71° 35′ W. Long., ATLANTIS Cruise 137, December 13-14, 1945. Corrected values have been plotted. The main features in the curves are considerably larger than the uncertainty in the data, which for salinity is approximately ± 0.15 ‰, for temperature ± 0.2° F.

With the advent of detailed BT surveys of the Stream, accompanied on occasions by continuous recordings of the surface salinity and temperature by means of a Salinity-Temperature-Depth Recorder (STD), the temperature phenomenon was repeatedly observed (Jacobsen, 1948; Ford, 1949). The STD has shown that the temperature dip may be accompanied by a drop in salinity, sometimes to values lower than any observed in the Slope water to the north. An interesting example of this is given in Fig. 1, obtained during the first ocean cruise in which the STD was used.

Ford and Miller (1952), in a survey of the Stream in 1948 with the BT, STD and Sea Sampler (Spilhaus and Miller, 1948), noted the occurrence of cold water at several points along the Stream. It was shown that one occurrence of it, located just to the northeast of Cape Hatteras, originated from the Shelf or coastal water.

It is the purpose of this paper to examine the nature, frequency of occurrence, and origin of such cold low salinity water. Since the multiple ship survey of June 1950, "Operation Cabot," provided such exceptionally good coverage of the Gulf Stream, this paper is based for the most part on data from that survey. The reader is referred to a paper by Fuglister and Worthington (1951) for a description of the operation. It is to be noted that the present analysis is a by-product of the multiple ship survey and of previous surveys; it was not considered in the planning and execution stages. As a consequence, the character and amount of data available, particularly on salinity observations at depth, leave much to be desired.

THE NATURE OF THE WATER

The nature of the cold water can best be described by a detailed inspection of an example in which the phenomenon was not only well developed but for which relatively complete data were obtained. The surface characteristics are illustrated in Fig. 2. It shows how cold water may be found as a band at the edge of the Gulf Stream, which in this case is approximately defined by the 70° F isotherm.

In order to illustrate the structure and depth of the cold band, sections AA and BB in Fig. 2 are presented in vertical profile in Figs. 3A and 3B. The outstanding feature is the presence of a thin cold layer with minimum temperature at a depth of about 200 feet. The layer extends under the warmer surface water of the Stream. It is not only cold, but it has a very low salinity, as shown by three plots of temperature and salinity against depth in Fig. 4. The T-S diagram in the lower part of Fig. 4 emphasizes this point and shows that the cold low salinity water (curve 2) has quite different characteristics from the waters on either side of it. Of the many sea sampler and hydrographic stations made during Operation Cabot, only four produced samplings directly through the cold layer. In each of these the same T-S pattern was observed.

It will be assumed that a cold low salinity layer exists if a temperature inversion with a minimum of less than 55° F occurs in the upper

600 feet. From analysis of the available salinity data on cold layers, this rather arbitrary upper limit appears to be a conservative one. Temperature inversions greater than 55° F were not considered, since too little is known of their salinity to have any confidence that they could be identified properly.

In Figs. 3A and 3B it will be seen that a tongue of the cold low salinity water extends to the surface and is reflected in the surface temperature and salinity plot. Although this sample is quite typical,

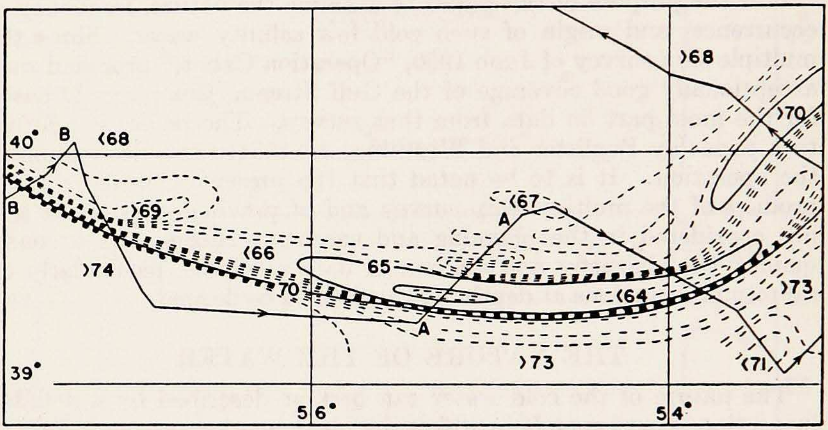
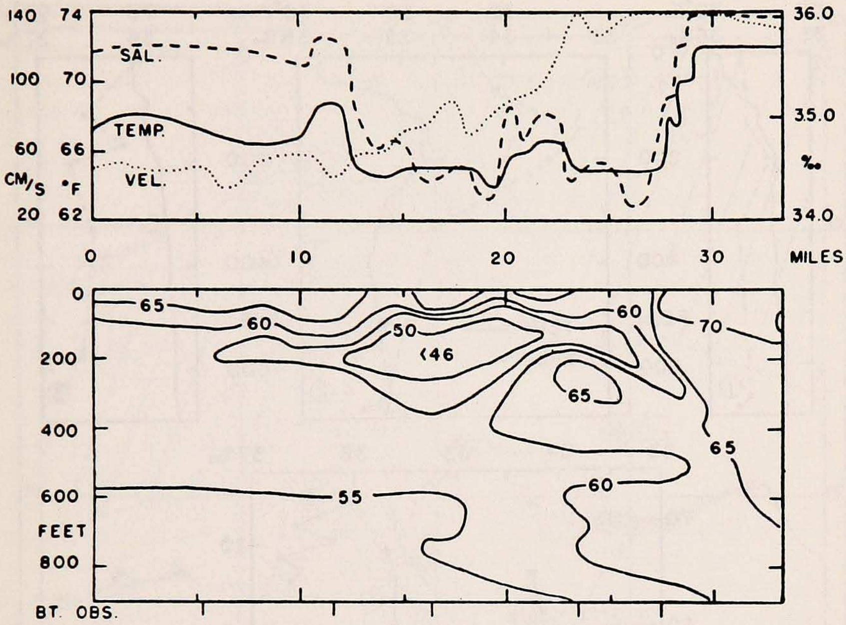


Figure 2. Surface temperature contour plot from STD data of H. M. C. S. New Liskeard. Ship's course is shown as arrowed lines. Sections AA and BB cross the Stream at an angle of about 60° to the current which parallels the isotherms.

not all cold layers exhibit this surface manifestation. Thus, of 19 consecutive crossings of the Stream made by H. M. C. S. New Liskeard between 64° and 51° W. Long. during Operation Cabot, eight contained a subsurface cold layer, only five of which gave a significant dip of surface temperature and salinity as observed by the STD. On the other hand, six of the 19 crossings showed a marked drop in surface values in the absence of a subsurface cold layer. In these cases a narrow cold layer might have been present between successive BT observations, or the recorded minimum temperature might not have been as low as 55°. The decrease in surface salinity and temperature with reference to the relatively steady values observed in nearby Slope water varied between 0.4 and 2.2 °/₀₀ and 1° and 6° F, respectively.

Figure 3. Details of Sections AA (3A) and BB (3B) of Fig. 2. Upper section of each gives surface temperature and salinity from STD and the uncorrected surface velocity component normal to the ship's course from GEK. Lower sections give the temperature profiles from BTs.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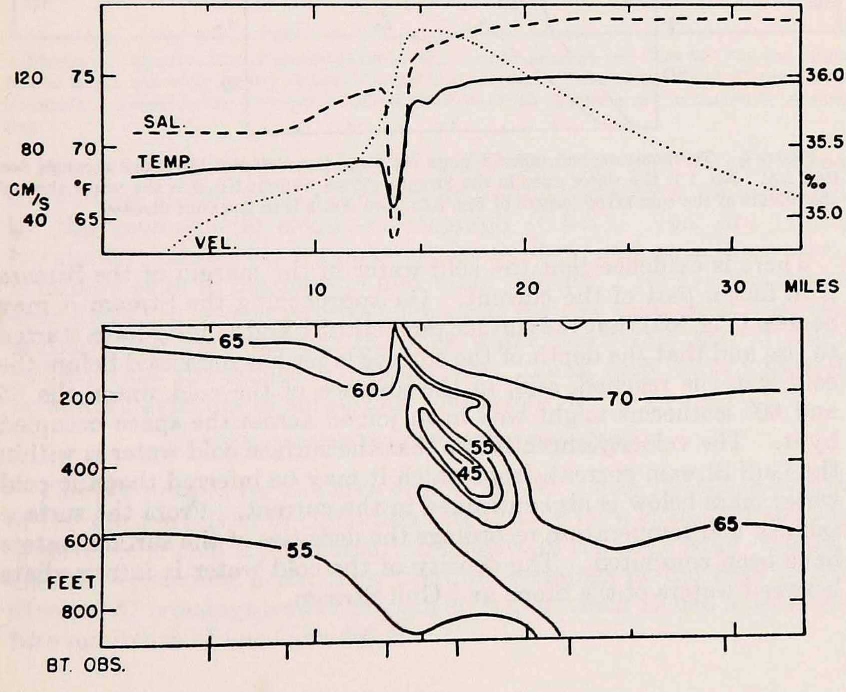
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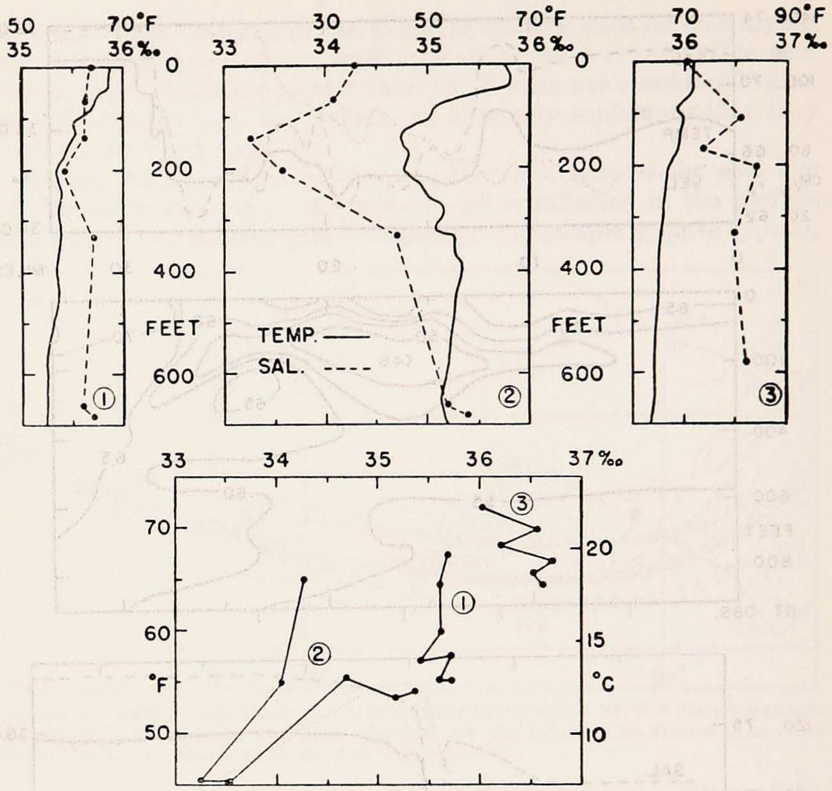

Figure 4. Temperature and salinity plots for three Sea Sampler lowerings through Section AA. No. 1 is the water outside the Stream (Slope water); No. 2 is the water through the middle of the cold layer (centre of Fig. 3A); and No. 3 is in the Gulf Stream.

There is evidence that the cold water in the margin of the Stream is in fact a part of the current. On approaching the Stream it may be seen (Fig. 3B) that the surface temperature and salinity have started to rise and that the depth of the surface layer has increased before the cold water is reached, and, in the absence of the cold water, the 65 and 60° isotherms might well have joined across the space occupied by it. The velocity curve shows that the surface cold water is within the Gulf Stream current, from which it may be inferred that the cold water mass below is also entrained in the current. From the surface salinity and temperature recordings the densities of the surface waters have been computed. The density of the cold water is intermediate between waters of the Slope and Gulf Stream.

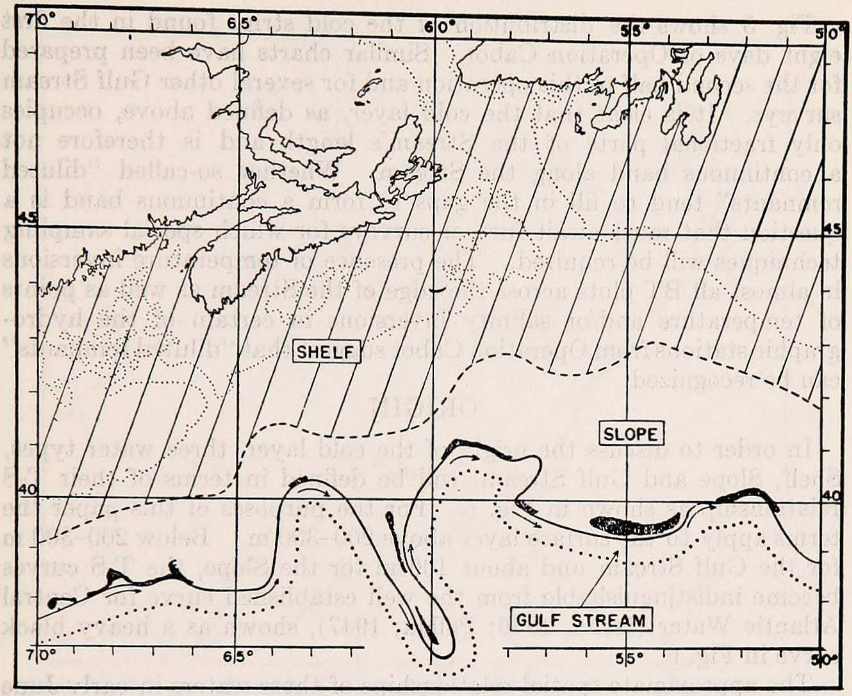

Figure 5. Distribution of temperature inversions with minima less than 55° F in the upper 200 m along the edge of the Stream during the first eight days of operation Cabot (cross hatched). Approximate southern limits of Shelf water at this time are indicated by dashed line.

It may be noted also in Figs. 3A and 3B that the cold water reached the surface at the point of maximum velocity gradient, as measured by the geomagnetic electro-kinetograph (GEK). Von Arx (1951) has shown that this is a region of maximum shear and, as in these cases, is usually close to the point of maximum velocity. He has also shown that slicks are associated with such shear regions, and, on at least one occasion, we observed that the slick water was colder and of lower salinity than the adjacent ruffled water. Thus, such slicks may well be surface evidence of subsurface cold layers.

FREQUENCY OF OCCURRENCE

The BT profiles for the area east of 70° W. Long. obtained by five of the ships involved in Operation Cabot have been examined and the occurrence of cold layers noted. Exclusive of the large eddy "Edgar" and its connecting neck, there were 97 crossings of the edge of the Stream; 57 crossings contained cold layers, of which 19 had a temperature minimum of less than 50° F.

Fig. 5 shows the distribution of the cold strips found in the first eight days of Operation Cabot. Similar charts have been prepared for the second half of this operation and for several other Gulf Stream surveys. It is clear that the cold layer, as defined above, occupies only fractional parts of the Stream's length and is therefore not a continuous band along the Stream. Whether so-called "diluted remnants" tend to fill in the gaps to form a continuous band is a question that must await further surveys for which special sampling techniques will be required. The presence of temperature inversions in almost all BT plots across the edge of the Stream as well as points of temperature and/or salinity inversions in certain of the hydrographic stations from Operation Cabot suggest that "diluted remnants" can be recognized.

ORIGIN

In order to discuss the origin of the cold layer, three water types, Shelf, Slope and Gulf Stream, will be defined in terms of their T-S relationship as shown in Fig. 6. For the purposes of this paper the terms apply to the surface layer above 200–300 m. Below 200–300 m for the Gulf Stream and about 100 m for the Slope, the T-S curves become indistinguishable from the well established curve for Central Atlantic Water (Iselin, 1936; Pollak, 1947), shown as a heavy black curve in Fig. 6.

The approximate spatial relationships of these waters in early June 1950, i. e., during the first half of Operation Cabot, are shown in Fig. 5. The term Shelf has been applied to all of the relatively cold and low salinity water between the shore and a boundary separating it from Slope water. It is preferred to the term Coastal, which has been used in the literature, since the water in question is hardly coastal, extending, as it does, well beyond the Continental Shelf. The boundary between Shelf and Slope was taken as the seaward limit of the Shelf cold layer, which limit was found to be coincidental with the 50° isotherm. The Shelf boundary is drawn on the basis of six separate BT sections between 50 and 70° W. Long., made during the first half of June 1950. The Gulf Stream is essentially as given by Fuglister and Worthington (1951).

The T-S plots are based on data from Operation Cabot, with the exception of those for the Shelf, which include data collected during May, July and August 1950, since there was insufficient coverage for June alone. The restriction of the data to a short period of time is necessary since T-S relationships cannot be applied satisfactorily to surface layers in which seasonal changes have occurred.

The Gulf Stream and Slope envelopes contain approximately 250 observations of temperature and salinity from hydrographic stations

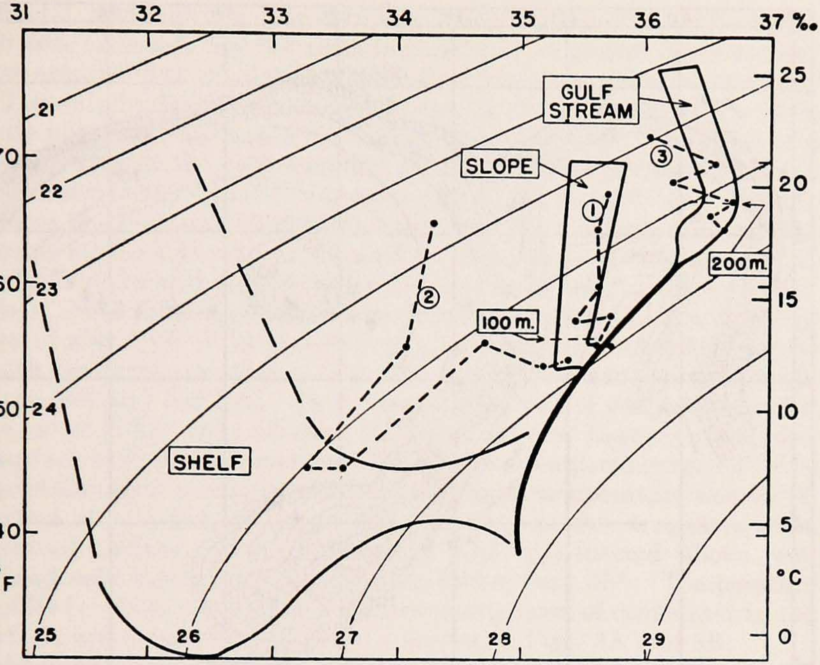

Figure 6. **T-S envelopes of Gulf Stream, Slope and Shelf waters. Surface layer Shelf water is shown dashed. Curves 1, 2 and 3 are those of Fig. 4, indicating cold water of No. 2 to be of Shelf water origin.**

and sea sampler lowerings distributed over the area under consideration. Only those observations that were definitely in the Gulf Stream or in the Slope were used. The Shelf envelope is based on 140 observations.

Also plotted in Fig. 6 are the T-S curves of Fig. 4 which result from three Sea Sampler lowerings made (1) north of the Stream, (2) in the edge of the Stream, and (3) in the core of the Stream. Curves (1) and (3) fall approximately within the envelopes for Slope and Gulf Stream waters. However part of curve (2) falls within the envelope for Shelf water. Thus it seems quite evident that the Shelf water in this case is the source of the cold low salinity layer found in the edge of the Gulf Stream.

By definition the cold water considered in this paper is marked by a temperature inversion in the upper 200 m. The presence of such an inversion suggests that there is also a corresponding salinity inversion, in accordance with T-S diagram relationships; otherwise a condition of extreme density anomaly and consequent instability must be

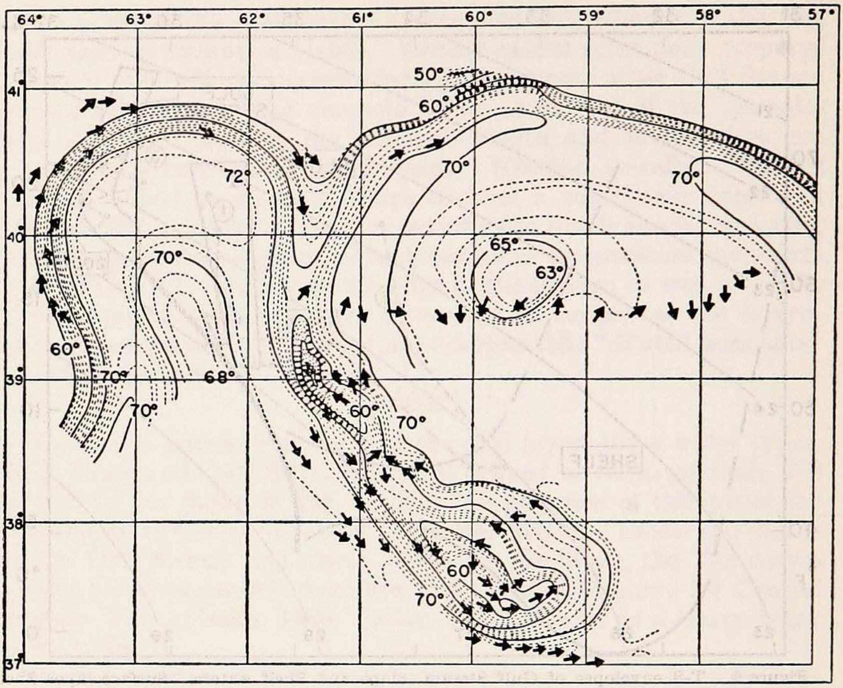

Figure 7. Plot of average temperatures in upper 200 m in vicinity of "Edgar" on June 17, showing cold water in neck and main body of eddy. Current arrows are from G. E. K. From Fuglister and Worthington (1951) by courtesy of Tellus and the Woods Hole Oceanographic Institution.

postulated. The minimum salinity to be found in the depths below the Stream and adjacent waters is 34.9 °/₀₀. From T-S diagrams, temperatures below 50° F found in the upper 200 m should be associated with salinities considerably less than 34.9 °/₀₀ if density anomalies are to be avoided. Hence, in the few cases for which salinity samples were obtained and also in the many cases where temperatures only were available, cold layers with temperatures in the vicinity of 50° F found in the upper 200 m must be of Shelf water origin rather than the result of upwelling.

THE COLD CORE OF THE EDDY AND ITS NECK

So far we have dealt only with crossings of the Stream exclusive of the eddy. The position of this eddy and the cold water found near its centre and in the neck during the period June 8–13 is indicated in Fig. 5; for a later stage of the development of the eddy, June 17, see Fig. 7, reproduced here by courtesy of Fuglister and Worthington

(1951). Although Fig. 7 gives the average temperature of the upper 656 feet (200 m), the BT records show that the cold water masses were associated as usual with temperature inversions within this depth.

The only hydrographic station to sample the cold core of the eddy or its neck was that made by U. S. S. San Pablo on June 14 in the eastern edge of the cold water of the neck. The minimum salinity observed was 34.7 °/₀₀ with a temperature of 56° F at 230 feet. Several records of abnormally low surface salinities were obtained from STD records by both the Atlantis and H. M. C. S. New Liskeard. In the area of the cold core of the neck of the eddy (see Fig. 7) from June 5 to 17, both ships observed surface salinities of 33.0 °/₀₀ at a temperature of about 60° F in association with a well defined cold layer in which temperatures of less than 50° F, minimum 43°, extended between 250 and 550 feet. In the main body of the eddy on June 19, i. e., after it had split off from the Stream, New Liskeard recorded a surface salinity minimum of 32.9 °/₀₀ at a temperature of 62° F in association with a cold layer whose minimum temperature was 43° F centred at 425 feet. Also, in other sections in this area both ships observed surface salinity minima of 34.5 °/₀₀ located above well defined cold layers containing water colder than 55°. Temperature profiles for these cases, showing upward extension of cold water to the surface, are quite parallel to those shown in Figs. 3A and 3B.

As in the main Gulf Stream, such cold low salinity water can be only of Shelf origin, and with the splitting off of the eddy, which occurred toward the end of Operation Cabot, this Shelf water was in a remarkable position, namely in the Sargasso Sea, seaward of the Gulf Stream.

DISCUSSION

It is of interest at this point to discuss what part the cold low salinity strips may play in maintaining the temperature and salinity characteristics of the system. Consider first certain aspects of the dynamics of the system as given by Rossby (1936), who has shown from theoretical consideration that the Gulf Stream on its eastward path assimilates water from its right side (i. e., from the high salinity mass of the Sargasso Sea) and discharges it on its left side (i. e., into the lower salinity Slope water) and that there should be a Slope counter current adjacent to the Stream. Supporting experimental evidence of this lateral transport from right to left is given for the surface layer by Ford and Miller (1952) and by data from Operation Cabot, during which the upper 200 m was repeatedly sampled, both in the Stream and in the nearby Slope from 66° to 50° W. Long., a distance along the Stream of over 800 miles. From west to east there was a significant shift in the surface layer of the Stream towards higher salinity (+ 0.2 °/₀₀) and lower temperature (− 3° F) which suggests the absorption of water from the more saline cooler area to the right. On the other hand *no* significant change in the T-S characteristics of the Slope water was observed. In support of Rossby's prediction of a counter current, Fuglister (1951) gave a plot of the 200 m temperature contours based on all available data; this plot indicates a counter movement of Slope water running adjacent and parallel to the Stream.

If cold low salinity water is introduced into this system and if it is assumed that it is entrained in the current and consequently mixes mainly with Gulf Stream water, the resulting product will be discharged into the Slope area in accordance with the theory. From the mixing relationships evident in the T-S diagram in Fig. 6 it follows that this product can have the properties of, and may be a source of, Slope water. Such a product is not only possible but necessary. If the Rossby process is considered as operating in the absence of this product, then the discharged Gulf Stream water would cause a progressive change towards higher salinity and temperature in the Slope water counter current from east to west. Such, however, is not the case. In fact, as mentioned above, the T-S characteristics of the surface layer of the Slope water are unchanged over a considerable distance alongside the Stream.

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Page 106, last sentence of the first paragraph in the Abstract should read:

"The salinity is on the average *lower* on the right side of the estuary (looking downstream) than on the left.