Further study of a front in the Sargasso Sea

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ABSTRACT

A segment of an oceanic front in the vicinity of 30° N, 70° W is mapped, remapped and sectioned from temperature and salinity measurements. The moving front divides two stratified surface layers composed of uncorrelated water masses. These waters are virtually unmixed at their interface, despite even an incident of penetration, but a pool of mixed water is suggested below the front. A similarity in surface current (computed), frontal curvature and slope of the interface is noted with an earlier observation made in different circumstances.

Introduction

In May 1967 a detailed observation was made of a segment of an oceanic front in the vicinity of 30° N, 70° W. This work, initiated by John Beckerle on the cruise CHAIN 67, was stimulated by the recent documentation of the frontal activity in this region of the Sargasso Sea by Voorhis and Hersey (1964) and Voorhis (1965) and (1966). The result of the present work is to add to their surface current and shallow temperature studies a study of the temperature-salinity structure of the front and indications of its movement and influence on the surrounding waters. It further compliments the temperature sections of Voorhis and Hersey by showing the front in the stratified surface layer typical of the warmer months.

Geographically, the front is located in a relatively quiet area: away from the major wind and current systems. It is removed from continental margins and devoid of distinctive topographical features. In this context, a theory which adequately explains the presence of the front (reviewed by Neumann and Pierson, pp. 197–8, 1966) derives from the observation that the Sargasso Sea is bounded on the north by the prevailing Westerlies and on the south by the opposing Trades. These winds will persistently tend to drive the upper layers of the sea towards some central belt in the Horse Latitudes, the net Ekman transport being induced at right angles to the wind in the northern hemisphere. The confluence of surface waters will then establish an extensive front, with waters of different densities reflecting their origins on either side, and two mechanisms have been proposed which would counteract the apparent tendency for a local accumulation of water: a convection-like sinking and countercurrent (Defant, 1936, 1938) and/or an easterly geostrophic current (Iselin, 1936). Finally, by such displacement of waters from the interface, mixed waters are removed and a frontal structure is maintained.

It cannot be said that the above has been confirmed by direct observation, or even that its emphasis is necessarily correct. What it does provide is an overall view with which observations can be compared and, at the present time, it does suffice to explain all that is definitely known. For example, a front can usually be found between 25°–30° N. Hydrographic stations and temperature tows cutting across this belt to either side of 70° W almost invariably show some near surface discontinuity, and such discontinuities have proven to be an indication of a front on the few occasions they were followed.

Enumerating the most definitive results of the recent observations of fronts in this region one finds that they are interpretable by the same argument, though not excluding the possibility of an alternate explanation.

(1) A front can extend many hundreds of miles in an east–west direction, as would result from meridional water movement into the region: On two different occasions Voorhis

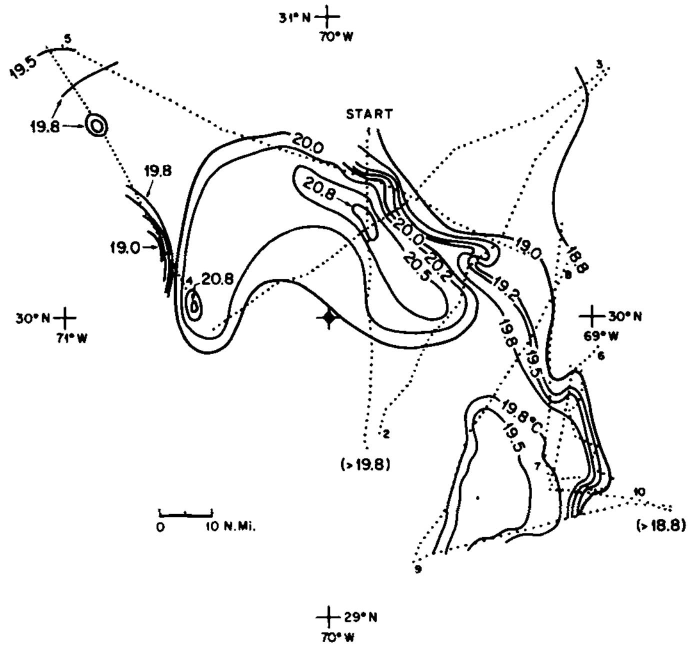

Fig. 1. The Front at 112 m. Track lines are shown dotted. The tows are numbered consecutively for future reference. Data were recorded continuously during the tows, May 14–19.

reported continuously tracing a front by contouring surface temperature: from 64° W to 72° W in January 1964 and from 62° W to 70° W in February 1965, as it meandered between 26° N and 29° N.[1]

(2) A front is limited to the upper waters, as would result from direct wind influence: In two temperature sections, during the winter months when the near surface water in this region is normally well mixed, Voorhis and Hersey found the depth of the front to correspond to the depth of the mixed layer: fifty and eighty meters (October and December 1962, respectively).

(3) There is a horizontal current at the interface: At the former front Voorhis and Hersey reported a narrow 60 cm/sec easterly surface current (measured by a towed GEK) coincident with the time of crossing.

The present data will be presented in three phases: a broad track survey which locates and maps a segment of the front and provides the necessary orientation for subsequent measurements, a front-following exercise to establish the degree of permanency of the front and, finally, a series of hydrographic stations through and around the front. The paper concludes with a discussion of the data and their contribution to the cumulative description of a front in this region.

Phase 1. Mapping of the frontal region

In order to locate and map the frontal region, a temperature sensor mounted in the nose of a one ton fish was towed at a nominal speed of nine knots and a depth of 112 ± 3 meters. In this manner an area of three one-degree-squares was broadly covered by ten track line. Each crossing of the front was clearly marked by a sharp gradient separating the different temperature levels on either side, and this information was utilized when drawing temperature

[1] Whether these observations represent an eastern limit is an open question. Schroeder (1965) suggested, from averaged bathythermograph data, that a thermal disturbance appeared in the upper layers from 50 °W, but in a wider meridional expanse than we are considering. In the same vein, it is yet to be established whether this region of the Sargasso Sea is streaked by one or more fronts further south, as records of surface temperature discontinuities often imply.

contours between diverging tracks. The resulting contour diagram is shown as Fig. 1.

The segment of front was mapped as extending from NW to SE. Tow no. 4 may have crossed an extension of it. The colder side is seen to be extremely uniform, the temperature being confined to the narrow range of 18.8–19.0°C. In contrast, the warm side temperature had large scale features, the most prominent being a hot spot immediately behind the front with a recorded maximum temperature of 21.0°C. This is a degree warmer than what appears to be the warm water temperature at this depth as evidenced by moving further from the front.

During several of the longer tows bathythermograph sections were made. Two are shown in Fig. 2. The thermal disturbance due to the front is present to below 200 meters depth. The two features of the contour plot of Fig. 1, constant temperature on the cold side and warmest water immediately on the warm side, are seen in Fig. 2 to be characteristic of a wide range of depths, 75–200 meters.

During most of this first phase a temperature sensor was mounted in the hull of the ship, about five meters below water level. An example of the records, compared to the corresponding deep tow, is shown in Fig. 3. While no tow was really typical of all, Tow no. 3 illustrates many of the common features. The break from one water to the next was always very sharp at both depths. In contrast to the deep tows, at hull depth the temperature usually rose again on the cold side. The hull depth temperature showed much more variation. Crossing tracks did not repeat the same temperatures faithfully and an attempt to contour isotherms at this shallow depth was unsuccessful.

When the front divides stratified waters, estimates of the inclination of the front cannot be based on the slope of a particular isotherm. The sharp break before the temperature rise is now the best indication of the front at both depths. The time delay between these jumps varied from the 39 minutes shown in the figure, to two hours for Tow no. 5. As Tow no. 3 was as close to a normal crossing as was made, its time delay provides the best estimate of slope: 1.0×10^{-2}, or about a half of one degree.

Immediately after these tows a broad survey was made of the area by airborne infrared de-

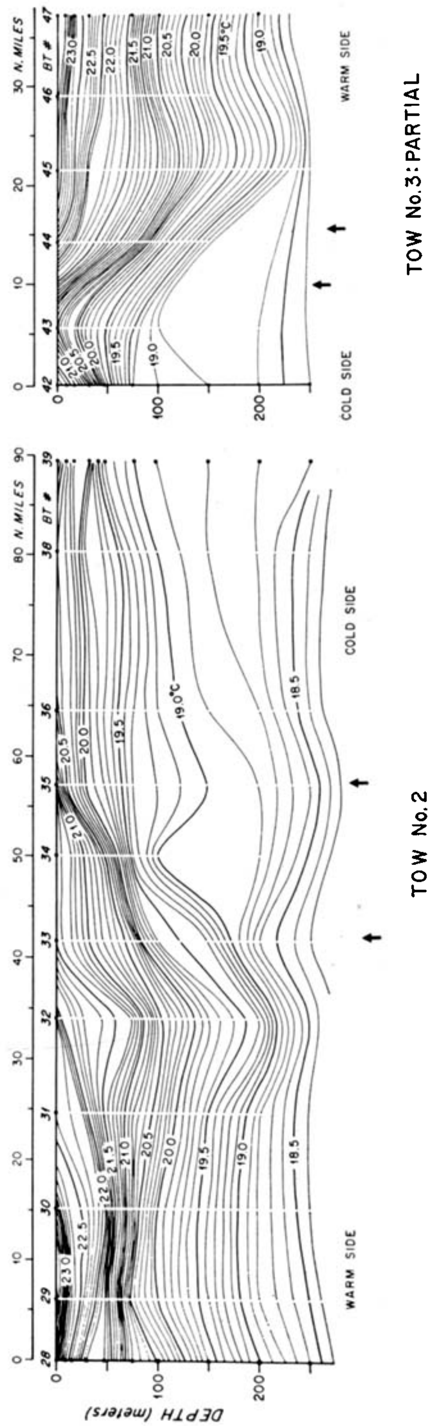

Fig. 2. Temperature Sections during Tows nos. 2 and 3. The arrows note the ranges where the front had been crossed at 5 m and 112 m, as indicated by the hull thermometer and towed sensor. The sections were developed by the usual technique of reading the slides at discrete depths (black dots on either side) and interpolating in between. The result is a smoothing of the front which can be thought of only as a representation, the details of the front (its location, slope, etc.) being best measured by other techniques.

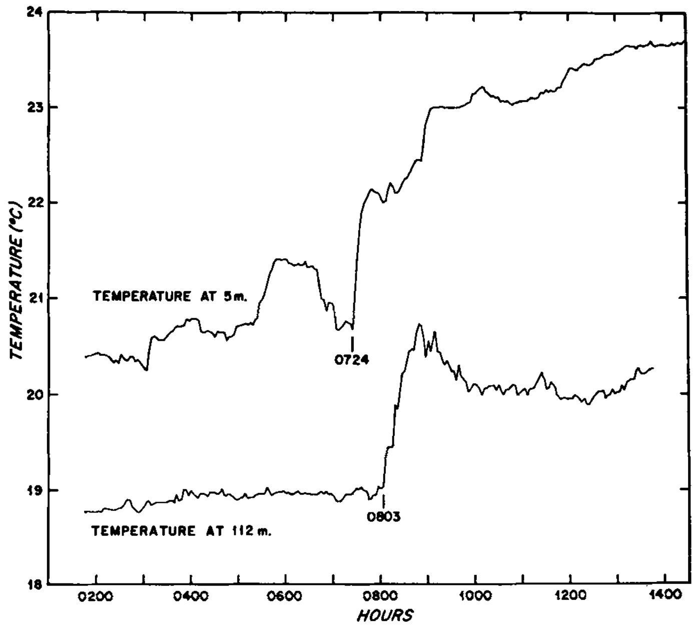

Fig. 3. Comparison of Temperature Records at 5 m and 112 m from Tow no. 3.

tector.[1] Out of the many tracks made during four days of flying in a rectangular grid, only three tracks showed evidence of a discontinuity in surface temperature. The strongest of these occurred in the immediate area under observation from the CHAIN; the other two along north–south tracks to the east. They showed the front extending to the SE from 30°30′ N, 70° W to 28° N, 67° W, or over 200 miles. No data was taken further west and the data further east was inconclusive.

Phase 2. Retracing the front

Upon completion of the ten tows through the front, the CHAIN was turned around and the frontal zone was retraced with only the temperature sensor being towed at 112 m. The objective was to get a more detailed picture of its shape and, by comparison with the previous map, the movement of the front. This phase of the work was made with the assumption that we were in the vicinity of a front whose general location was now well known and which could be recognized by a characteristic temperature band centered around 19.5°C. The resulting

[1] This work was performed by the Weather Reconnaissance Squadron Four, Jacksonville, Florida.

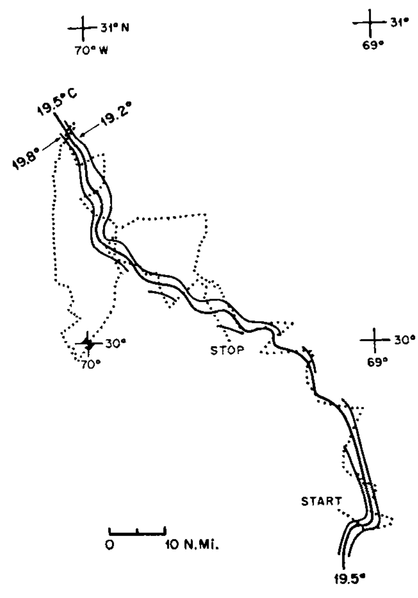

Fig. 4. A Second Map of the Front at 112 m. Track lines are shown dotted. The SE corner repeats Fig. 1. New data were recorded continuously while towing, May 19–21. Track charts are based on Loran C.

front of 110 n.m. arc length is shown in Fig. 4 where only three critical isotherms were contoured, and these only where sufficient data were available.

The large undulations of the front contoured in the first phase now appear smaller and since the wavelength of each were comparable in scale to the distance between crossings of the front one can only conclude that no small scale shimmering of the front can be reliably reported. Ignoring the smaller scale, a definite meander remains, changing the sign of its curvature once in the length observed. A mean radius for each half is on the order of 50 n.m. The continual crossing of the front in small steps also provided the resolution to comment that the thickness of the front, at this depth well below the surface, remained essentially constant. The normal distance between the 19.2°C and 19.8°C isotherms was a relatively constant 2–3 n.m.

To indicate the movement of the front at this depth, the position of the 19.5°C isotherm during the two phases are redrawn together on Fig. 5. Taking into consideration that the data were essentially taken from northwest to southeast and then back again, a steady translation of the front would take the form of a rotation about its southern extremity. Fixing attention to the two segments furthest separated by time, west of 69°30′ W, the elapsed time from the last tow during the first phase which contributed to the contours in this region to the first relevant data of the second phase was 90 hours. The

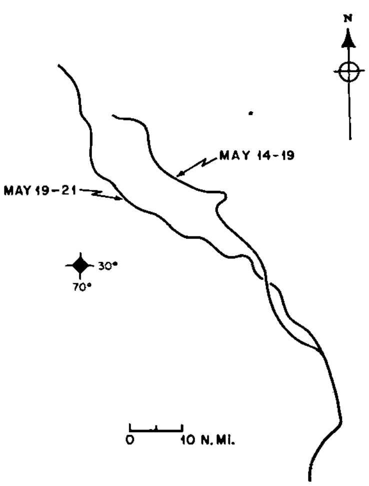

Fig. 5. Movement of the Front as Indicated by the 19.5°C isotherm at 112 m.

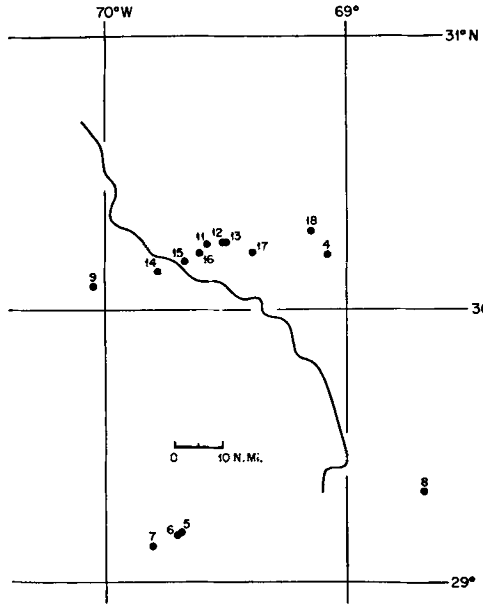

Fig. 6. Locations of Temperature–Salinity Lowerings Relative to the Front. The front is indicated by the 19.5°C isotherm of Fig. 4. Its location on the surface at the same time would be estimated at 6 n.m. along the normal on the cold side, but neither is static. The dates of the lowerings were as follows:

Date (May 1967)	17	18	19	20	23	24
Lowering no.	4	5–7	8	9	11–13	14–18

normal distance in this range is estimated as 7 n.m., which results in a maximum average translation at 0.08 knots in a southwesterly direction. Though the calculation is crude, it is qualitatively clear from a comparison of the figure that a movement was occurring during these seven days and that it was accumulatively to the west or southwest.

Phase 3. Probing the frontal zone and its surroundings

Fourteen lowerings were made with a conductivity-temperature-pressure system (HY-TECH Model no. 9006) down to 1500 m. The positions of the lowerings, relative to the front, are shown in Fig. 6. Of these, Lowerings nos. 11–18 were executed in a twenty-four hour period along a fifty mile line crossing the front at roughly forty degrees to the normal. If, as suspected, the temperature and salinity contours at a given depth near the front run

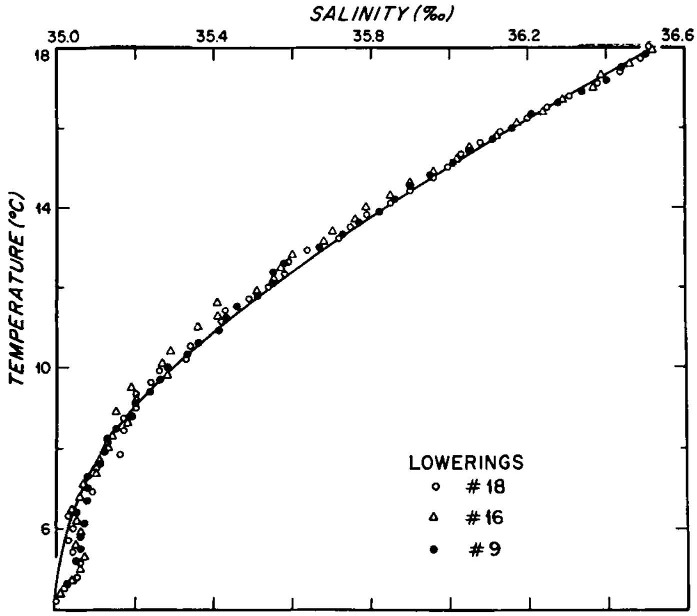

Fig. 7. Temperature–Salinity Correlation for Water Below the Frontal Zone. The three sets of data are typical of all in the section. The solid line is the Sargasso Sea correlation after Iselin (1936). The divergence between the two below 6°C can be attributed to how Iselin resolved the scatter in his data at this depth.

parallel to the front, then the section will have elongated the changes across the front by thirty per cent. This will be ignored and the distances between stations thought of as relative ranges. Adding to the discussion are Lowerings no. 4 and no. 9, which were made several days earlier than the others.

The data are divisible into two parts, that above and that below a value of about 18.5°C (found between 150–250 m). Below 18°C, the water was the same at all locations along the section and a single temperature-salinity correlation could be composed from all the lowerings.[1]

This is demonstrated in Fig. 7, using several sets of data. The comparison with Iselin's (Fig. 53, 1938) accumulative Sargasso Sea correlation establishes that it is typical of a very wide area.

Above 19°C two distinct water masses are observed. The purest examples of these are found at the extremes of the section and are shown in Fig. 8. The branches are designated north and south, according to their presumed origins. The branch point at 19.0°C, 36.62 ‰, consists of waters at 70 and 170 m, to the north and south respectively. The limit curves drawn on the figure provide a measure with which to interpret the intermediate lowerings and obtain a rather precise picture of the interface in this particular instance. These comparisons are made in Fig. 9. Lowerings nos. 14 and 4 reproduce Fig. 8, neither of the two giving any

[1] This is equally true for Lowering no. 8, but Lowerings no. 5 – no. 7 were very different from the others, as well as any the author has seen in the files from this general area. They were so exceptional that the data might have had to be discarded due to some unknown equipment malfunction except that they were reproduced three times, during both lowerings and raisings, and that the expendable bathythermographs clearly indicated that the region was indeed anomalous at the shallow depths. As it is, we will satisfy ourselves by reporting that the data from these lowerings indicated a layer of water from 300–700 m, which was colder and denser than normal, and a deep layer of water below which was considerably warmer and lighter than normal. The basic feature was a truly anomalous 200 m of practically constant temperature (14.75°C) and salinity (36.13 ‰) beginning at the cross over depth of 700 m. The expendable bathythermographs, which could be read to only 500 m, showed that this region and extending over five casts and twenty miles towards the front along the track of Tow no. 9, had a minimum temperature at 500 m of 15.6°C, which is a degree colder than any of seventy other bathythermographs made during the study. It is possible that a very interesting anomaly was probed and that it might be related to the front.

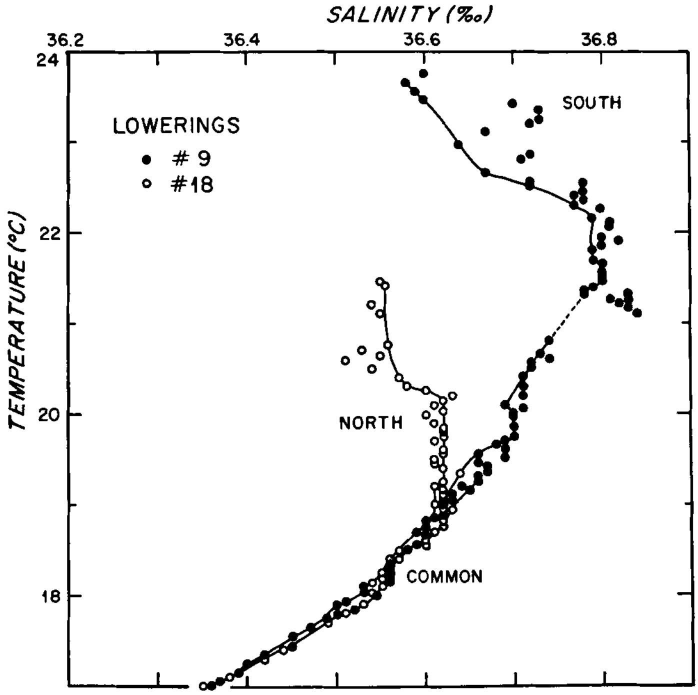

Fig. 8. Temperature–Salinity Correlations in the Upper 500 meters on either Side of the Frontal Zone. The solid lines are drawn to delineate the separation between the two sets of data in the region where they were distinctive. The data gap for a few tenths of a degree about 21°C was a recording failure and should be disregarded, both here and in the next figure.

indication of crossing from one water mass to another. Lowering no. 17 at best suggests some mixing with the warmer water in the first 15 m, but this is questionable for the reason noted in the legend. The remaining three lowerings, covering ten miles of the oblique traverse of the front, give indications of both T–S correlations. Of these, Lowering nos. 13 (and 11 and 12 were identical) shows the clear distinct jump from one correlation to the other during the course of the lowering. The interface is seen to be a very sharp discontinuity. Within the rate of data acquisition, every two meters, no mixed

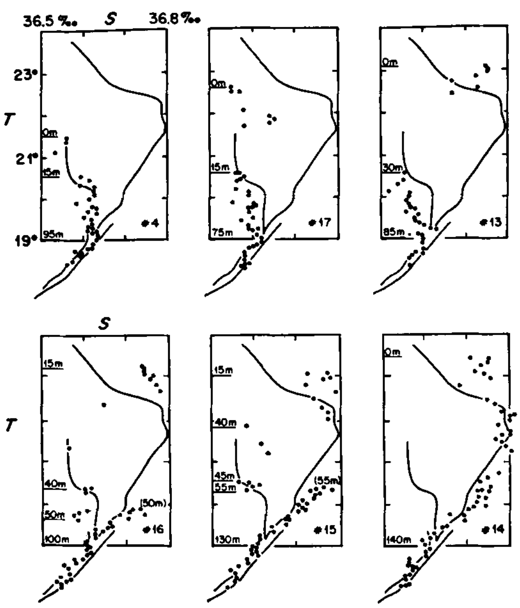

Fig. 9. Temperature–Salinity Diagrams for the Intermediate Lowerings. The solid lines are the limits established in Figure 8. The depth at which a particular water was found is indicated on the left and in the parentheses. Lowerings nos. 11, 12 and 13 yielded identical data, despite the fact that Lowering no. 11 appeared to have been made significantly further towards the warm side, and only the latter is presented. The first fifteen meters were excluded for Lowerings nos. 15 and 16 because they were obviously disturbed by a squall. It may also have affected no. 17.

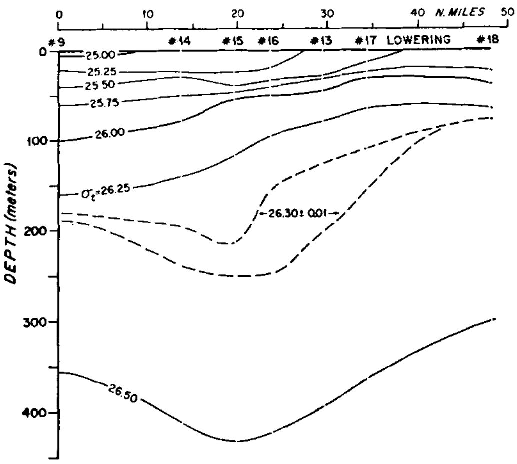

Fig. 10. Density Section to 450 m through the Frontal Zone. Dashed lines outline a variable depth layer of constant density. In the layer salinity was virtually constant at 36.60 ‰; temperature was 18.85 ± 0.05°C.

layer (as would be indicated by water not identifiable with either the north or south branches) separated the two sides. Lowerings nos. 15 and 16 introduce a new feature: a 10–15 m layer of northern water projecting into the southern water at a depth of about 45 m, still without much evidence of mixing. In passing back from northern to southern water, a slight temperature inversion is stabilized by the salinity differences. No further crossing to northern water is observed at deeper depths, suggesting that these stations were exclusively on the warm side of the front.

The different waters are of different densities and from this comes the expectation of surface currents associated with the front. Fig. 10 shows a density (σ_t) section of the upper 450 m. The isothermal layer on the cold side of the front, evident throughout the mapping phase, is found to be of constant salinity as well. It appears here as a constant density layer. The waters are disturbed well below the surface region containing the frontal zone. Though not shown in the figure, a small disturbance appeared to persist down to the bottom of the thermocline at about 1250 m. Arbitrarily using the deepest measured depth, 1500 m, as a depth of no motion, the currents were calculated and the resulting surface currents are shown in Fig. 11. A comparison of this calculation with the GEK measurements of Voorhis and Hersey, which is admittedly a comparison derived from different kinds of observations under very different circumstances, shows a similarity in both magnitude and scale.

Discussion

The earlier thermal observations of frontal activity in this area have been supplemented by the temperature–salinity correlation which establishes the existence of an oceanic front: a separation between two distinct water masses. The interface was vertically probed and no mixing was apparent down to the finest scale of the measurements. Within a few meters one passed from one water mass to the other and any transition water in between was undetectable with the equipment and technique used. Such a sharp interface is taken as an indication of water transport along the interface, either parallel to the sea surface or down its slope.

Water movement normal to the interface was also indicated. A tongue of pure northern water was observed to stably protrude into southern water for miles, with little evidence of mixing.

Summarizing the section of the front, an interpretative sketch is presented in Fig. 12. The front appears not much deeper than 100 m,

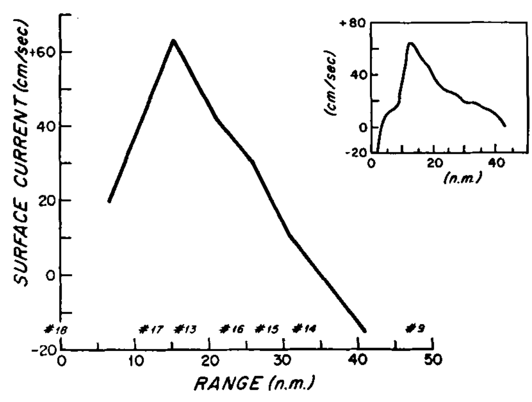

Fig. 11. Geostrophic Surface Current Across the Front. Calculations based on an assumption of no motion at 1500 m. Positive velocities are SSE, normal to the section, and represents an underestimate of maximum velocity if one assumes the flow parallel to the front. The insert reproduces the direct measurements of Voorhis and Hersey (1964).

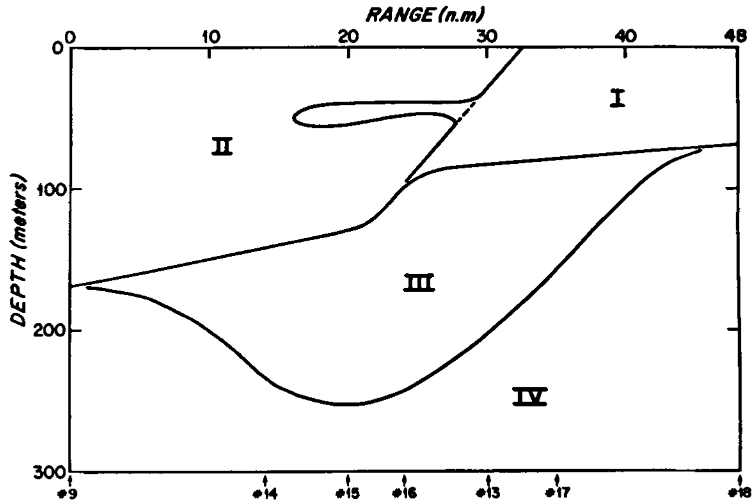

Fig. 12. Schematic Section of Front. Region I = Northern water. Region II = Southern water. Region III = Mixed water common to both. Region IV = Original subsurface water. The slope of the front is based on its presence during Lowering no. 13 and its absence on all others. The upper boundary of Region III is the beginning of 19° water, from Figs. 8 and 9, and the interface between Regions III and IV is the bottom boundary of the constant density layer of Fig. 10.

which is an intermediate depth between the supposed undisturbed thickness of the two distinct surface waters. Below these waters a common temperature-salinity correlation was obtained, but this region appears divisible into two: one where commonality is thought to have resulted from lateral mixing and the other representing the sub-surface water of this area. The latter has probably undergone some vertical displacement.

Confirmation that there is indeed a boundary between regions II and III comes from the fact that the tows at 112 meters were inadvertently mapping a short and apparently linear extension of the front rather than the front itself. The homogeneous water found on the cold side was not the northern surface water as supposed; it was the mixed layer. What was depicted by the convergence of isotherms of more than a half of a degree (and a salinity discontinuity of more than 0.05‰; estimated from the hydrographic section) was the beginning of the mixed layer.

Although the tows were below the actual front, i.e., the interface between regions I and II, it is valuable to be able to ascertain what it was mapping. The extension appears so intimately related to the front, it may only be the definition which divides them. Certainly its mapping yielded the desired information to relate the lowerings to the front and it would be difficult to argue, a priori, that its movement and curvature did not correspond to that of the front. In discussing the tow data, the distinction between the front and its extension has been ignored.

The geostrophic current calculation attempted suffered from the usual difficulty of selecting a level of no-motion typical to such calculations, but, selecting a shallower depth below the front as reference, would have left the peak at the crossing of the front. With this in mind, it is noted that the magnitude and variation of the resulting surface current were found comparable to that reported by Voorhis and Hersey. In addition, they roughly estimated a radius of curvature of 100 km for their section of front, which is the same order of magnitude as the present estimate of 50 n.m. These similarities between two fronts were observed in different seasons and were therefore found to be in very different water structure near the surface: mixed in the one case, stratified in the other. The comparison may have an explanation in that a steady uniform current will tend to meander, because of the action of the Coriolis force on it, such that the wave length will vary with latitude and relative current velocity (Rossby, 1939). Identifying the radius of curvature with wave length as length scales of the disturbance, then curvature and current are interrelated as suggested by the favorable comparison. The wave speed of the perturbation to the current would then be interpreted as a movement of the front and provide the explanation for the observed translation. The similarities in current speed and curvature of the front result in a similar Rossby number, 0.1, implying that the basic flow was probably geostrophic as assumed in the calculation.

The geostrophic current alone is probably not sufficient to explain how a front can extend continuously for hundreds of miles. Though not observable in this study some mixing must be supposed at the interface and the current can be thought of preventing an accumulation of mixed waters in any one region of the front. Further downstream, however, the mixed waters being carried there would tend to obliterate the front and result in a fragmentation contrary to observation. To avoid this, one is encouraged to look for evidence of a small vertical component to the current at the interface. The interface would then be swept horizontally and drained vertically, the first maintaining the abruptness of the separation and the second removing out of the frontal zone waters already mixed. The dipping of the isotherms on the warm wide of the front (Fig. 2) and the related hot spot at 112 m (Fig. 1), observed in the same region as the section, provide the suggestion of a movement of water sliding down the interface. Below the front the water might be expected to mix with the water it finds there and then spread horizontally. This would be region III of Fig. 12, a variable depth mixed layer which is clearly centered under the front and thins at either side.

Summarizing this study in the context of the earlier observations, they are found to be complimentary. The reach of the front appears to have been more limited on this occasion, but the matter was not pursued. Observing a front between two stratified surface layers gives evidence that the presence of the front is independent of surface conditions.

The depth of the front was once again limited to the first hundred meters. The distinctiveness of the two branches on the temperature–salinity diagram provides important evidence that the front is not a local phenomenon. To arrive at such a state each of the waters had to evolve independently and then come together in a front, as has been generally supposed.

Geostrophic current calculations supported the earlier surface current measurements, and curvature and slope estimates of the front were in close agreement between studies. The result is a similarity which will require further observations to decide what part of the agreement was coincidental. To the extent that each of these parameters are mutually dependent on the density contrast between the waters across the front, one might expect that they will vary more than in this particular comparison, but not so much as to result in a very different description of the front.

Acknowledgements

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REFERENCES

Defant, A., 1936. Die Troposphäre, Deutsche Atl. Exped. "Meteor" 1925–27. *Wiss. Erg.*, *6*, 1, pp. 289–411 (Berlin).

Defant, A., 1938. Aufbau und Zirkulation des Atlantischen Ozeans. *Sitz. Ber. Preuss. Akad. Wiss., Phys.-Math. K1.*, *14*, pp. 145–171.

Iselin, C. O'D., 1936. A study of the circulation of the western North Atlantic. Papers in *Phys. Oceanogr. and Meteorol.*, *4*, 4, 104 pp.

Neuman, G. & Pierson, W. J., Jr., 1966. *Principles of Physical Oceanography*, 545 pp., Prentis-Hall Inc., Englewood Cliffs, N. J.

Rossby, C. G. & Collaborators, 1939. Relation between variations in the intensity of the zonal circulation of the atmosphere and the displacements of the semi-permanent centers of action. *J. Mar. Res.*, *2*, 1, pp. 38–55.
Schroeder, E. H., 1965. Average monthly temperatures in the North Atlantic Ocean. *Deep-Sea Research*, *12*, pp. 323–343.
Voorhis, A. D., 1965. Thermal fronts, unpublished manuscript. Woods Hole Oceanographic Institution Ref. No. 65–13, Woods Hole, Massachusetts 02543, p. 172.
Voorhis, A. D., 1966. Thermal front surveys, unpublished manuscript. Woods Hole Oceanographic Institution Ref. No. 66-3, Woods Hole Massachusetts 02543, p. 228.
Voorhis, A. D. & Hersey, J. B., 1964. Oceanic thermal fronts in the Sargasso Sea. *J. Geophys. Res.*, *69*, 18, pp. 3809–3814.

ДАЛЬНЕЙШЕЕ ИЗУЧЕНИЕ ФРОНТА В САРГАССОВОМ МОРЕ

По измерениям температуры и солености найден и выделен участок океанического фронта вблизи 30 с. ш. и 70 з. д. Этот движущийся фронт разделяет два стратифицированных поверхностных слоя, водные массы которых некоррелированы друг с другом. Эти массы фактически не перемешиваются на их поверхности раздела, даже несмотря на один случай проникновения воды из одного слоя в другой, но предполагается, что основная масса перемешанных вод находится ниже фронта. Отмечается сходство вычисленных поверхностного течения, кривизны фронта и наклона поверхности раздела с более ранними наблюдениями, произведенными при других обстоятельствах.