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ANALYSIS OF CURRENT PROFILES BY A STUDY OF PYCNOMERIC DISTORTION AND IDENTIFYING PROPERTIES

By

A. E. PARR

Bingham Oceanographic Laboratory

It has, of course, always been recognized that one of the greatest uncertainties of dynamic oceanographic calculations is that which results from the necessity of selecting without definite evidence a surface of assumed zero motion to which the calculated relative velocities can be referred for evaluation in absolute terms. In the still most prevalent practice this uncertainty is further increased by the arbitrary assumption of a horizontal zero level, although it is *a priori* highly improbable that the true velocities should be so distributed in all verticals within any ocean area as to obtain zero values at the same absolute depth. The need for abandoning this arbitrary use of a fixed horizontal datum level in favor of a reasonably selected probable current boundary of variable depth has recently been so well stated by Wüst (1936, pp. 52–54) and by Dietrich (1937a, b) that no further discussion seems necessary on these pages. The argument has finally gained further strength from Rossby's theoretical demonstration of the probable occurrence of fairly strong gradient flow near bottom even in very great depths associated with the non-permanent features of ocean currents (Rossby, 1938).

In their search for a true current boundary of variable depth, the German investigators have emphasized the theoretical value and importance of the oxygen minimum distribution as an index to the quasihorizontal movements of the water. In recognition of the isopycnic character of liquid flow, it seemed natural to the present writer also to attempt to locate the current boundaries with reference to the vertical distribution of densities; and when

the conclusions reached from this line of approach, in the manner to be described in the following, are to a large extent found to be in perfect agreement with the results of Dietrich and Wüst this may perhaps be considered a most encouraging indication of the fundamental soundness of the method.

While comparing the presentations of the current situation south of the Newfoundland Bank obtained by dynamic topographies referred to a horizontal datum level and by the isopycnic distributions of the identifying properties (Parr, 1938a), the writer became interested in the possibility of finding evidence of the location of the true current boundaries by a study of the variations in the thickness of the density layers* through vertical profiles laid at right angles to the main direction of flow. In the following this method of attempting to discover the true current boundaries will be illustrated by application to two profiles across the Gulf Stream system, one from Cape Cod to Bermuda, and one off Cape Hatteras; and it might also be mentioned that the first experimental application of the method to several of the profiles in the region of Newfoundland Bank analyzed in other ways by Parr (1938a) gave equally as encouraging results as those to be described herein.

GENERAL REMARKS UPON THE METHOD AND DESCRIPTION OF THE PRELIMINARY PREPARATION OF THE DATA

The method to be suggested in these pages rests upon the assumption that the pycnomeric layers of a current will generally have a tendency to bank themselves to the right of the flow (on the Northern Hemisphere) due to a slight axial velocity downstream in excess of gradient values (Rossby, 1937).

Since currents and counter-currents can, of course, exist side by side in the same pycnomeric layer, it is in this connection necessary to distinguish between lateral current boundaries traversing the isopycnals between adjacent currents in opposite directions within the same pycnomeres, and basal current boundaries separating pycnomerically superimposed movements. While, on the principle of isopycnic flow (Rossby, 1936, Parr, 1938), the basal boundaries should serve to distinguish separate current systems (see also Dietrich, 1937), this is not a priori true of the lateral boundaries, which in the presence of eddy circulation may merely serve to separate opposite directions of motion within the same system. In such a system of eddies rotating in harmony with each other, the boundaries of motion will obviously overlap (alternate with) the boundaries of the eddies themselves, since the direction of motion is the same in the adjacent halves of two con-

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* Which for the sake of convenience we shall here designate as the pycnomeres, that is, the segments of the vertical column of water confined between two isopycnic surfaces.

tiguous eddies rotating in harmony with each other. These adjacent halves of two eddies rotating in harmony and therefore in opposite directions will consequently belong to the same area of motion in a profile differentiated only with reference to direction of flow, and the boundaries of the *areas of motion* must coincide with the *centers* of these eddies, and not with their own *peripheral boundaries*.

If the assumption is correct that the layers should thicken to the right, and longitudinal flow is isopycnic, a comparison of the increase in depth per unit increase in density $\left(\dfrac{\Delta D}{\Delta \sigma_t}\right)$ plotted against potential densities *in situ* (σ_t)* for adjacent station verticals in the same vertical section normal to the axis of the current system will show us, by the intercepts of these curves, the isopycnic surfaces along which no increase in thickness, that is, no distortion, occurs in either direction and above and below which such distortions take place. This isopycnic sheet of uniform thickness should then represent a *possible* boundary layer of zero motion since it gives no indication by distortion of being moved in either direction at right angles to our profile.†

This is of course not the same as to say that the uniform thickness of a pycnomere gives *positive* evidence that it is *not* in motion. On the contrary we shall in both of our examples be led to the assumption that certain pycnomeres of uniform thickness are actually moving in the direction of the main flow at the right side of the main current. The proposed method is not direct and absolute, but operates only indirectly by a process of elimination on the assumption that the pycnomeres which *do* show distortion are *not* likely to be static, and that in our search for the probable true current boundaries we may therefore limit our choice to the comparatively few surfaces in which no pycnomeric distortion is apparent, making our final selection with the fullest possible consideration of as many other factors as may have a bearing upon the problem.

The curves given in Figure 88, representing a profile from Cape Cod to Bermuda (above), and a profile across the Gulf Stream off Cape Hatteras

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* Although not a strictly correct expression for potential density *in situ* without adiabatic correction of the temperature *in situ*, σ_t has been considered sufficiently accurate for present purposes.

† Since $\dfrac{\Delta D}{\Delta \sigma_t}$ is simply (in first approximation) the inverse of the expression for vertical stability, our reasoning incidentally leads mathematically to the interesting suggestion that current divides should follow isopycnal surfaces of constant vertical stability. Since constant vertical stability in turbulent flow under otherwise equal circumstances indicates constant horizontal friction (see Parr, 1936; Rossby, 1936), this purely arithmetical result may under otherwise equal circumstances also have a reasonable explanation in fact.

(below),* are obtained simply by dividing the difference in depth between consecutive observations at each station by the difference in density (σ_t) between the same observations, and plotting the result against the linear average of the two densities used in the determination of each value. Figure 88 gives only the lower portions of the entire curves, containing most of the information with which we are here concerned. The complete curves are given in Figure 89 with the values for $\dfrac{\Delta D}{\Delta \sigma_t}$ drawn on a logarithmic scale for no other reason than the purely mechanical one that it proves absolutely impossible to give a readable picture of these complete curves by the use of a natural scale.

It will be noticed from these figures that nearly all station curves throughout the entire profiles, and absolutely all curves in the region of the main current, have intercepts or contact points with each other at an almost constant density value for all station intervals. Exactly similar general pictures were also obtained for the profiles off Newfoundland Bank on which the method was first tried out.† This finding that the indicated basal current boundary followed a virtually constant isopycnic surface through any transverse profile is patently in excellent agreement with reasonable expectations from the principle of generally isopycnic flow.

When we recall the fact that our curves of $\dfrac{\Delta D}{\Delta \sigma_t}$ are simply the inverse of the vertical stability curves, we further notice that the basal current boundaries indicated in Figure 88 coincide with a pycnomere which at all stations on the right side (low station numbers above, high station numbers below in Figure 88) of the main current, and also through the greater part of the left portions of the two profiles, is characterized by greater vertical stability than that of the surrounding pycnomeres both above and below.

From Figure 88 we may finally also notice that the relationship between adjacent station curves above and below the indicated basal boundaries are generally the reverse, that is, the basal boundary is identified with a true intercept between these curves. But in the station intervals at the extreme right the boundary is, on the other hand, only identified with contact points

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* For the original data see Bulletin Hydrographique 1932. Cons. Perm. Int. Expl. Mer. Copenhagen 1933.

† In the region of the Newfoundland Bank, the general absence of significant distortion occurred around σ_t 27.4–27.5. In the Cape Cod to Bermuda profile, it occurs around σ_t 27.3–27.4, and off Cape Hatteras usually around σ_t 27.2–27.3. Before this apparent trend for the boundary to descend gradually to slightly higher density values (deeper isopycnals) downstream has been abundantly confirmed by repeated applications of the pycnomeric distortion method, one must obviously refrain from drawing any definite conclusions. But if this trend should be confirmed, and not be shown to be merely accidental, it obviously has a considerable theoretical interest.
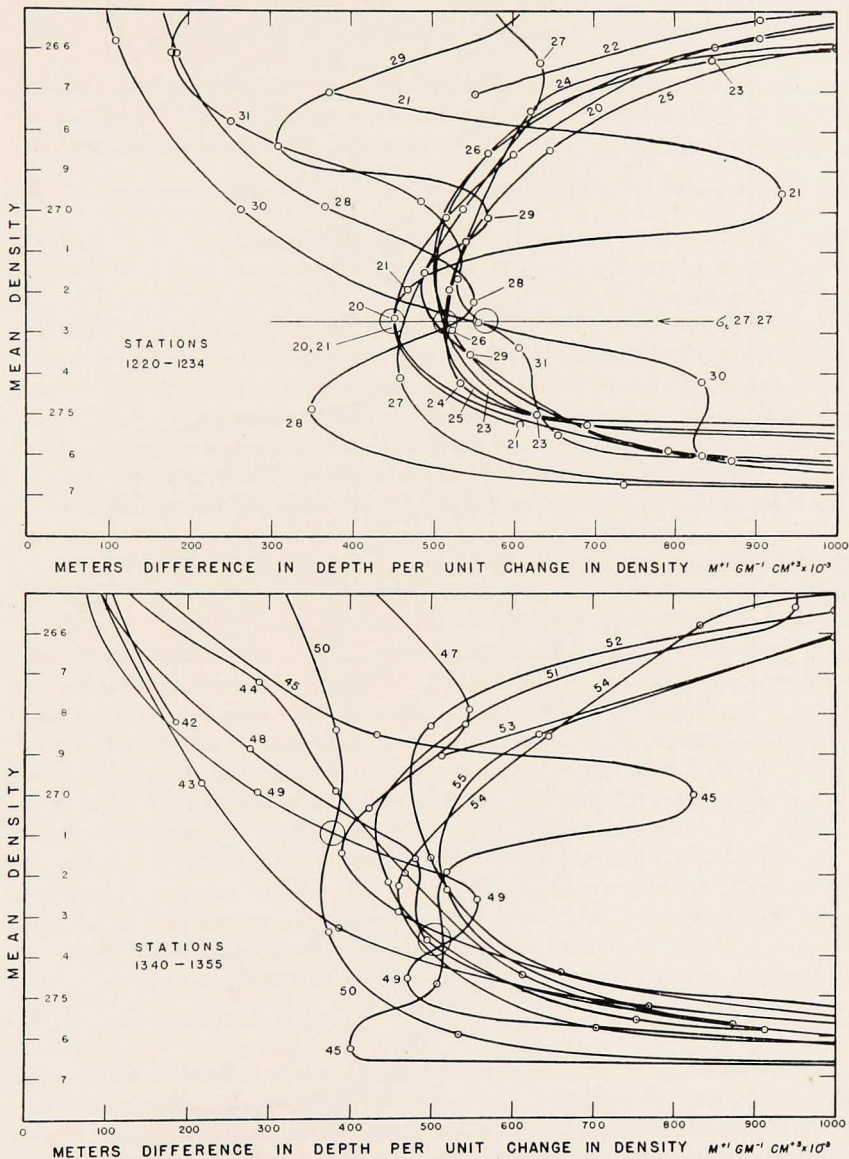
Figure 88.   Increase in depth (natural scale) per unit increase in density plotted against density *in situ* (σ_t) for Cape Hatteras profile, stations 1220-34 (*above*), and for Cape Cod–Bermuda profile, stations 1340-55 (*below*).
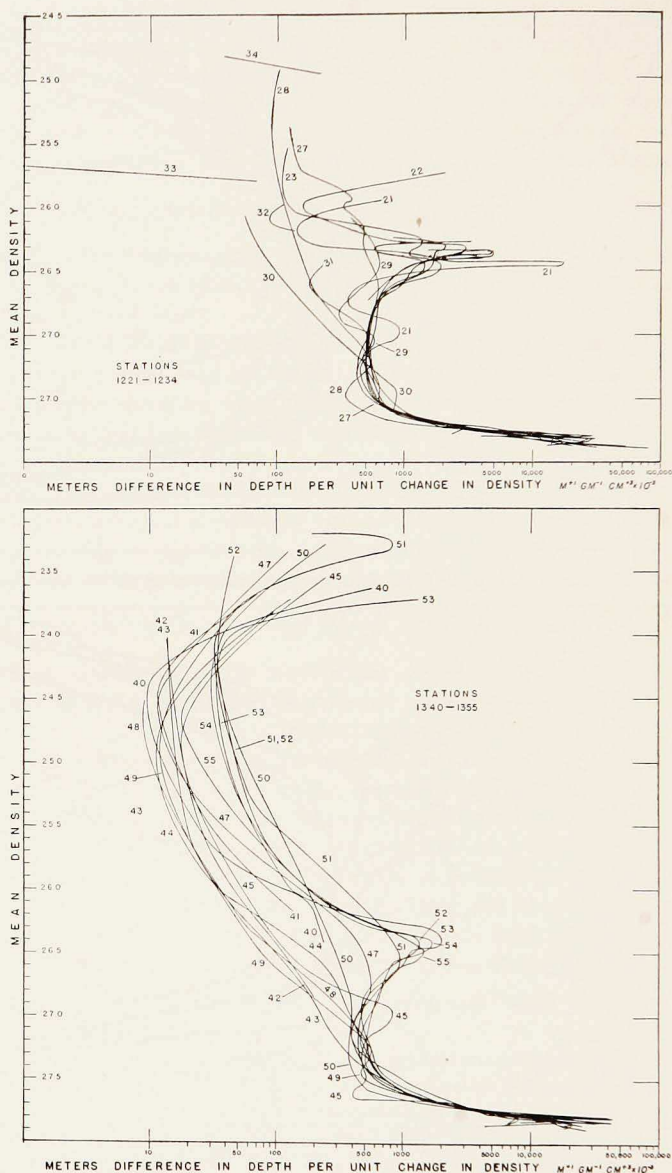
Figure 89.　Increase in depth per unit increase in density plotted on a logarithmic scale against density *in situ* (σ_t) for Cape Hatteras profile, stations 1220–34 (*above*) and for Cape Cod–Bermuda profile, stations 1340–55 (*below*).

between the adjacent station curves. That is to say, the station curve having higher values of $\dfrac{\Delta D}{\Delta \sigma_t}$ above the indicated boundary is reduced to values equal to those of the adjacent stations at the boundary itself, but again shows *higher* instead of lower values below, so that we find an increasing pycnomeric distortion below in the same direction as the distortion above. It seems probable that this equalization of the $\dfrac{\Delta D}{\Delta \sigma_t}$ values at adjacent stations on the right side of the illustrated profiles is simply a special feature of the general equalization of characteristics brought about by a very active lateral circulation along this particular surface of high vertical stability, which seems to become the true basal boundary surface at the left, but which does *not* separate layers of opposite directions of motion at the right. Since motion in the direction of the main current at the right thus seems to descend without actual interruption to much deeper isopycnals than that followed by the indicated current boundary at the left, we must therefore assume that the true current boundary itself also descends to these deeper isopycnals beyond the region of the main current on the right-hand side of the flow.

Apart from these deviations observed at the extreme right, we also notice in Figure 88 several instances of double intercepts between adjacent station curves, that is, of a second intercept occurring at more variable densities, but always above the general intercept at a nearly constant density value for all station intervals, which we have taken to indicate the true basal boundary of the upper current system. Most of these secondary intercepts above the indicated boundary are due to very minor undulations of the separate station curves, and it is obvious that if the actual curves should approach to fairly uniform values over a short density range immediately above the indicated current boundary, the sources of error in our calculation of the apparent curves would tend to introduce apparent double intercepts where none actually exist. These double intercepts may therefore in part be due to the inaccuracies of the method, but it is also possible that they may have some actual dynamic significance.

Our last paragraph introduces the question of the accuracy with which the $\dfrac{\Delta D}{\Delta \sigma_t}$ curves can be determined. It is obvious that the accuracy must decrease with a decrease of the absolute differences either in depth or in density between the two observations combined in each determination. Near the free surface the differences in depth are slight and the distorting effect of purely temporary influences from above may be very great. We may therefore take it for granted that a comparison between the upper portions of the station curves very near the free surface would not be of any great signifi-
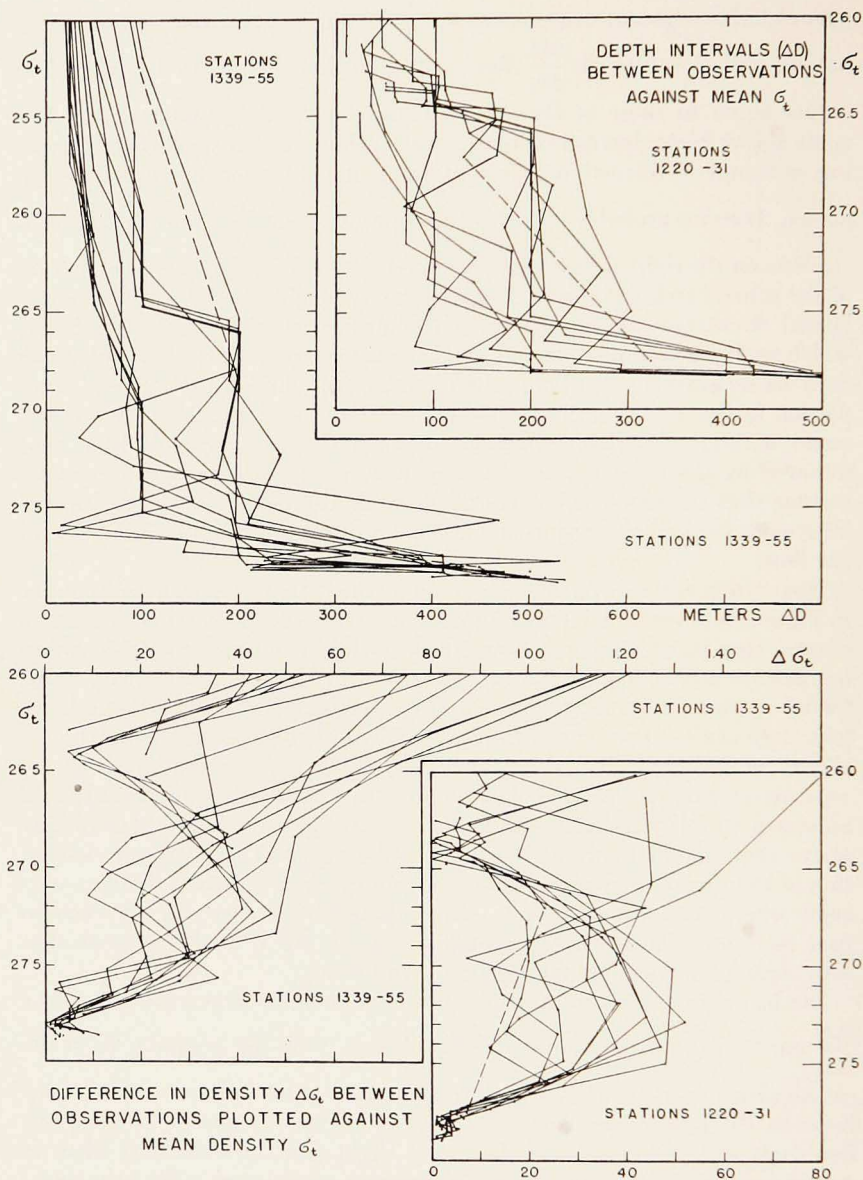
Figure 90. *Above:* Variations in the depth interval between observations plotted against density *in situ* (σ_t). *Below:* Variations in the absolute density difference between observations plotted against density *in situ* (σ_t).

cance. In great depths, on the other hand, the vertical variations in density from one observation to the next become so slight (within 0–5, generally only 0–4, in the second decimal place in the customary notation of σ_t) as to be only very low multiples of the probable errors of determination, if not even less than this error. For the deepest layers our comparisons therefore also become entirely unreliable, and when we reach the conclusion that the true basal boundary on the extreme right descends from its intermediate location at the left to surfaces of very high density, our method does not enable us to determine its precise continuation at the right in terms of isopycnic surfaces, and we have to revert to the old procedure of using a horizontal datum level for the parts of the profiles to which this conclusion applies (see page 285).

From the preceding considerations it is clear that our evidence derived from a consideration of the $\dfrac{\Delta D}{\Delta \sigma_t}$ curves will be of greatest accuracy and significance where both the density differences and the differences in depth between observations have a fairly high value. It is therefore very reassuring to note from Figure 90 that both ΔD and $\Delta \sigma_t$ between observations are of relatively great absolute magnitudes around the densities with which we have identified our indicated current boundary. With reference to the density differences between observations, there is indeed a tendency for these to develop an intermediate maximum value around σ_t 27.2–27.4, of 0.12–0.50, with an average around 0.30, in the customary notations for σ_t; while the depth intervals vary from 100 to 300 meters. We thus obtain our indications of a basal current boundary in the density zone in which our determinations should have a maximum accuracy and significance.

As the final step in the preparation of the data the curves for relative salinities against σ_t have been drawn in accordance with the procedure previously described (Parr, 1938b). These curves, which are not illustrated, form the basis for the determination of the relative salinity profiles used in the following considerations.

PROFILE ANALYSIS

Having prepared the data for the single stations in the manner described in the preceding, we may now turn our attention to the study of the entire profiles, beginning again with a description of the further procedure.

PROCEDURE USED FOR THE DEVELOPMENT OF INDICATED CURRENT PROFILES

In Figure 92 all details of procedure are indicated in a manner which will, of course, be entirely superfluous by a routine use of the method herein suggested. The information drawn upon comes under two separate headings:
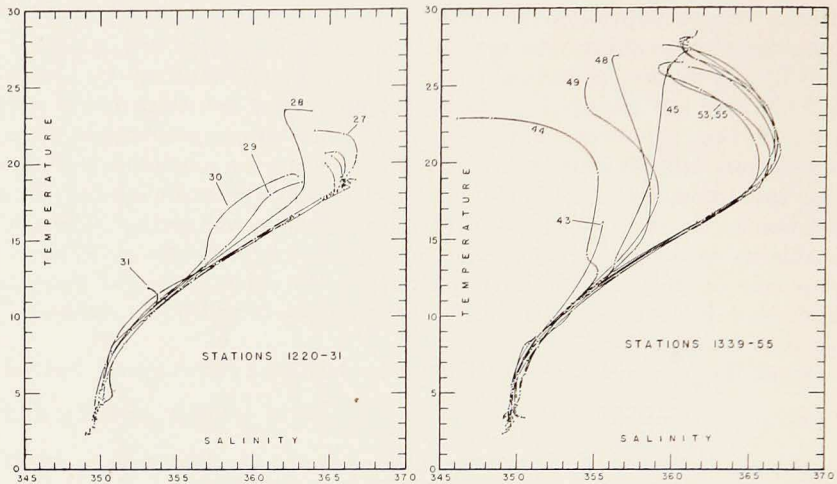
Figure 91.   Temperature-Salinity correlation curves in the Cape Hatteras profile (*left*) and in the Cape Cod–Bermuda profile (*right*).
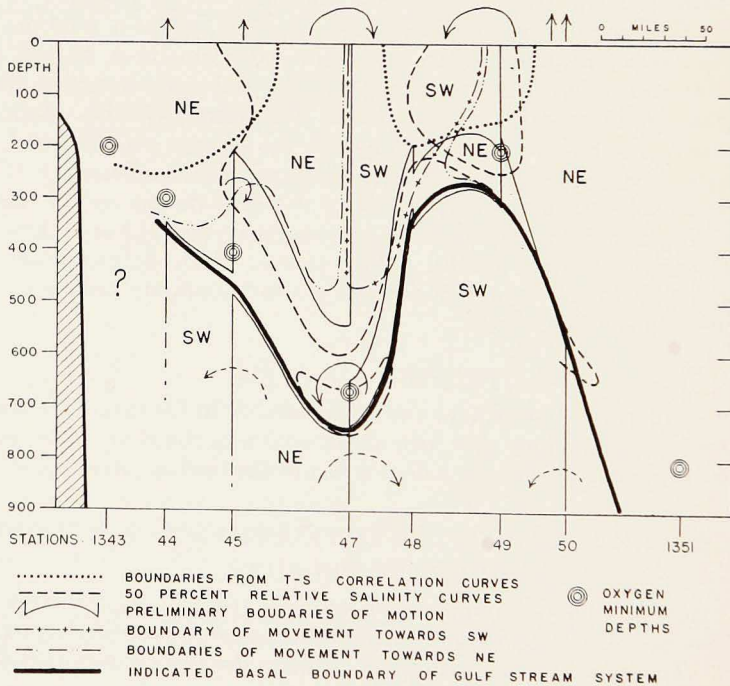

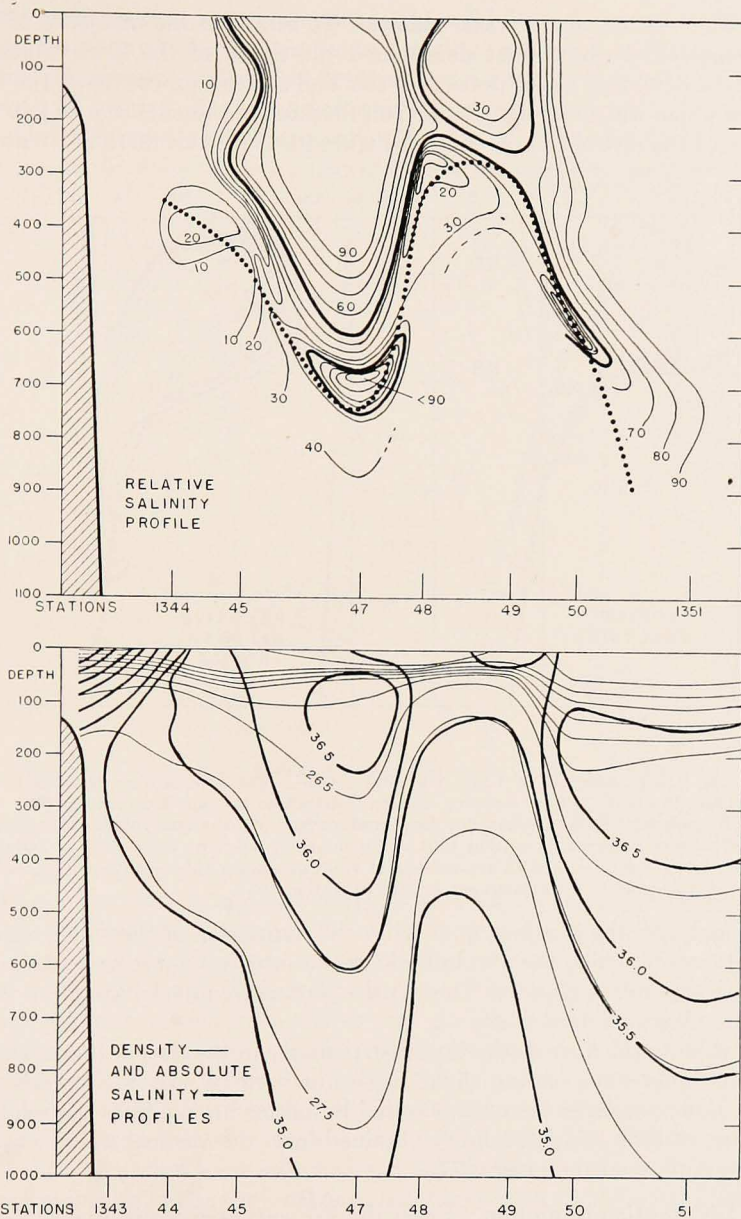Figure 92.   Analysis of the Cape Cod–Bermuda profile.   See text.

Figure 93. *Above:* Relative salinity distribution in the Cape Cod–Bermuda profile. Heavy contour line for 50% relative salinity. Light lines for every 10%. Dotted curve represents indicated basal current boundary. *Below:* Density and absolute salinity distributions in the Cape Cod–Bermuda profile.

(1) The identity of the water masses. To establish the identities of the water masses, we have first determined the depth of the T–S values at which the deviating upper portion of the T–S correlation curves at the stations in which waters foreign to the Gulf Stream are present seem to join the pattern of the rest of the curves (see Figure 91). By this method we do, of
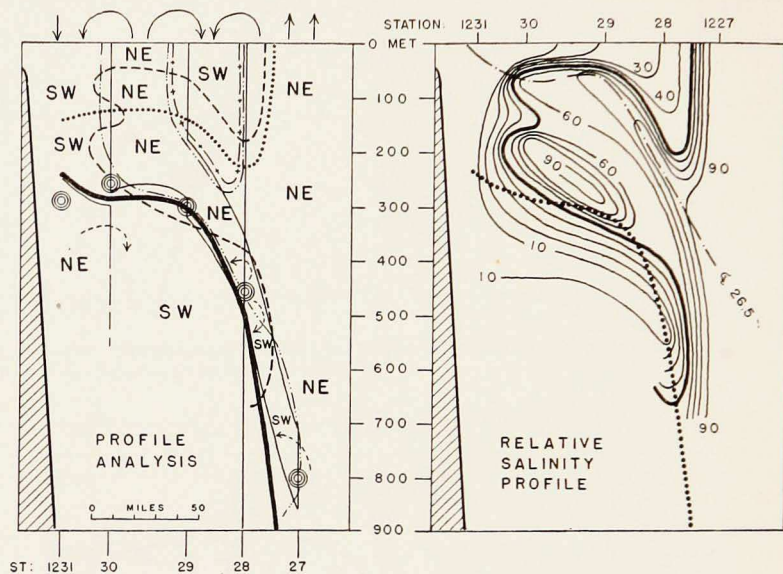

Figure 94. *Left:* Analysis of Cape Hatteras profile. For explanation of symbols see figure 92 and the text. *Right:* Relative salinity distribution in Cape Hatteras profile. See legend of figure 93. In and below the isopycnal surface of $\sigma_t = 26.5$ minimum isopycnic values of salinity occurred at station 1231 throughout the column; while relative salinities above the isopycnal of $\sigma_t = 26.5$ are calculated from minimum values obtained at station 1230, since the upper isopycnals do not extend to station 1231.

course, only get the roughest qualitative differentiation of the water masses in the layers in which the absolute differences are very large and conspicuous at a superficial glance. The depths thus determined have been connected by heavy dotted lines.

To evaluate the finer distinctions, particularly in the deeper layers where the total differences are too slight to be analyzed by the T–S correlation curves alone, we have then also entered in lighter broken lines the relative isohalines of 50% relative salinity obtained from the vertical relative salinity curves mentioned on page 277.

(2) Distribution of motion. From the $\dfrac{\Delta D}{\Delta \sigma_t}$ curves given in Figure 88 we have determined the σ_t values for the intercept between these curves for ad-

jacent stations, and have entered in light solid lines the course of the corresponding isopycnals between the two station verticals, as a first indication of the presumable boundaries between movements in opposite directions above and below. The presumable directions of motion above and below have been entered according to the direction of distortion shown by the relationship between the two adjacent station curves on the assumption that
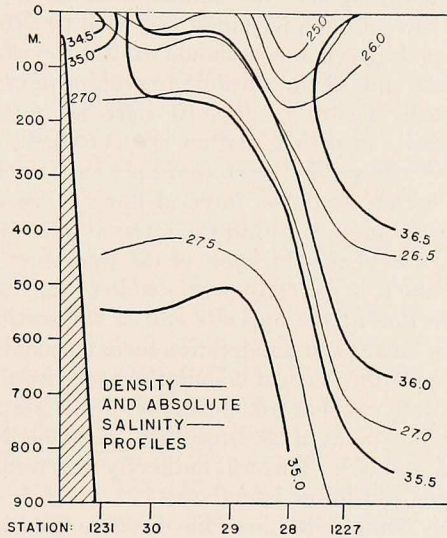

Figure 95.   Density and absolute salinity distributions in Cape Hatteras profile.

the thickening of the pycnomeric sheet indicated by higher values of $\left(\dfrac{\Delta D}{\Delta \sigma_t}\right)$ must occur on the right side of the flow.

When a station is in opposite relations to its two nearest stations on either side with reference to indicated directions of flow, a straight vertical boundary of motion has been drawn at the location of such a station through the depth interval over which such opposite trends are indicated.

Through this procedure we have now divided our profile into areas of indicated movements in opposite directions separated from each other laterally by straight vertical lines, and above and below by undulating isopycnals. It will be noticed from Figures 92 and 94 that even in this discontinuous presentation of separate areas of motion (shown in light solid lines) the lower boundaries approach a confluent pattern in a most encouraging manner even in the very complicated profile from Cape Cod to Bermuda (Figure 92). Nevertheless a proper method of smoothing must be introduced and described.

In this smoothing we have as our main source of freedom the fact that an indicated thickening of pycnomeres at one station compared with the nearest adjacent station merely implies that *greater* thickening has occurred at the former point of observation than at the latter. That is to say, the thickening of the pycnomere at one station as compared with its thickness at the next station gives us no guarantee that this pycnomere is moving in one single direction throughout the station interval concerned. On the contrary, a lateral current boundary may very well be situated between the two stations, so that the pycnomeres should exhibit the effects of thickening due to motion at *both* ends of the station interval, or in other words so that thickening has actually occurred *both to the right and to the left*, indicating movements in opposite directions within the station interval. The only rule which has to be followed is therefore simply that the interpolation of a current boundary within a station interval must be so carried out as to indicate that the *major* motion within the interval must be in the direction shown by a comparison of the thickness of the pycnomeres at the two stations considered, while it is perfectly permissable to suggest a *minor* motion in the opposite direction at the opposite end of the station interval, when other considerations make such a suggestion seem reasonable. On this basis we may therefore move the vertical boundaries away from the exact, but in this connection entirely haphazard, positions of our stations towards the corresponding inflection point of the isopycnals in reasonably drawn density profiles (Figures 93 and 95). This will indirectly also result in a freedom of smoothing the upper and lower boundaries.

Smoothed current boundaries have thus been entered in Figures 92 and 94, with a heavy solid line indicating the probable basal boundary of the entire Gulf Stream system in these profiles.

Having thus arrived at a reasonable analysis of our profiles with reference to directions of motion, we still have to assign these directions of motion to reasonable circulation patterns, and we now have recourse to the differentiation of the water masses indicated by our dotted and broken lines, and shown in greater detail in the relative salinity profiles (Figures 93 and 94). On this point we may be governed by the simplifying assumption that when eddies are indicated each eddy will usually (not necessarily always) rotate without significant change in the identity of its water masses along its closed trajectories. That is to say, each type of water must as a rule form an eddy of its own, and when an area of motion in one direction is divided by a boundary with reference to the identity of the moving water masses, the two parts into which the area of motion is thus differentiated must belong to separate and opposite eddy circulations moving in harmony with each other. It is notable in our Figure 92 that the counterpart (opposite side) of every eddy indicated in this manner is also always suggested in an appropriate spacial relationship.

DISCUSSION OF RESULTS

Two specific purposes have been aimed at in the above described attempt to analyze hydrographic profiles by a study of the distortion of the pycnomeres correlated with an analysis of identifying properties, one being concerned with the selection of a datum surface for dynamic calculations, the other having for its goal a qualitative description of the probable eddy patterns transsected by the profile, and in general the distribution of directions of motion.

With reference to the datum surface, or the basal boundary of zero motion, the results indicated in Figure 88 on the whole places this surface at very consistent density values without significant recourse to smoothing. In both profiles the motion in the direction of the main current would appear to descend to deeper isopycnic surfaces (below σ_t 27.6) at the extreme right of the segment shown in the illustration, as one gets below and beyond the main current on the surface to the open oceanic waters on the right, where the direction and velocities are probably more constant and stable throughout, and therefore capable of building up a cumulative influence to greater depths. Through the left, and probably more variable part of the system, including the region of the main current, the indicated boundary runs consistently through densities varying only between 27.26 and 27.33 in the profile off Cape Hatteras (through stations 1228–1230 inclusive, Figure 92), and between 27.32 and 27.38 in the cross-section between Cape Cod and Bermuda (through stations 1345–1349 inclusive, Figure 94). In both profiles the indicated boundary rises to lower density values at the extreme left (σ_t 27.16 at station 1231, Figure 94; σ_t 27.11 at station 1344, Figure 92). Only one single deviation from this regular pattern is indicated, namely at station 1350 (Figure 92) where the boundary as drawn by our method rises to σ_t 27.10, but this is scarcely of any great significance.

It thus seems indicated that there is a tendency for the surface of discontinuity with reference to motion to follow a constant isopycnic surface over a considerable part of the width of the current. When we again recall that the curves of $\dfrac{\Delta D}{\Delta \sigma_t}$ are in first approximation simply the reverse of the vertical stability curves, we further notice that the indicated basal current boundary in both profiles extends to the left along the continuation of an isopycnic surface identified with a pronounced intermediate vertical stability maximum at the right. Moving from the right-hand side towards the portions of the profiles shown in Figures 92 and 94 we find this intermediate stability maximum at density values corresponding to the basal current boundary in the left portions strongly developed through stations 1220–1227 (Figure 88) referring to the right approach to Figure 94, and through stations 1355–1351 (Figure 88) referring to the right approach to Figure 92. This interme-

diate stability maximum also remains quite pronounced through several of
the nearest station intervals at the left (station 1229, Figures 88 and 94;
stations 1345 and 1347, Figures 88 and 92) and it is even more or less dis-
tinctly suggested by double inflections (?) at all the remaining stations
considered in Figure 88, with the only exception of station 1344 (Figures
88 and 92) which forms a single continuous curve through the layers of
densities higher than 27.00.

This relationship between the indicated current boundary and the loca-
tion of an intermediate vertical stability maximum can, in the writer's
opinion, be considered an independent verification of the method here sug-
gested, since a greater vertical stability should mean a greater lateral free-
dom of motion through reduced vertical transfer of momentum (Parr, 1936).
The break between opposite currents above and below should therefore
naturally be expected to occur along the surface in which the vertical eddy
viscosity would be at a minimum in comparison with the nearest adjacent
zones of oppositely directed movements above and below. And when the
break has once developed, the discontinuity with reference to the origin and
derivation of the water masses above and below tends to become self-
perpetuating.

In this instance the source of the main motion can obviously be assigned
to the light water masses on the right, which carry the momentum of the
Florida Current (Rossby, 1936). Where this type of water extends uni-
formly to great depths, we have already mentioned that we also find the
indicated current boundary descending to deeper isopycnals below the
intermediate vertical stability maximum. But at the left where this lighter
water carrying its momentum with it extends inward towards the shore
above heavier water reaching fairly high levels underneath, we find the
indicated current boundary immediately rising to the isopycnal surface
*along which the upper part of the uniformly moving water column at the right
can be most easily displaced laterally against its lower portion.* Since this
variation from right to left in the relationship between the indicated current
boundary and the intermediate vertical stability maximum is exactly what
one would be led to expect from the preceding considerations, it would seem
to lend further support to the validity of the method of current analysis
here suggested.

If we now turn to a comparison with the results obtained by Dietrich's
method (Dietrich 1937a, b) of using the oxygen minimum surface as the
lower boundary of the Gulf Stream system, we find an indeed surprisingly
close agreement, as shown by the triple circles entered in Figure 94, to indi-
cate the depths of oxygen minimum as determined by interpolation from
reasonably drawn vertical oxygen curves. These oxygen minimum depths
show no significant deviation from the indicated current boundary at any
point except at the extreme right where they follow the intermediate

stability maximum surface, rather than the indicated surface of zero motion. But this deviation at the right is obviously in equally perfect agreement with our expectations as is the coincidence throughout the left portion in accordance with the interpretation offered in the preceding paragraph.

Dietrich (1937a) has further also found support for the use of the oxygen minimum surface as the lower boundary of the Gulf Stream system through a consideration of transverse movements, and here again his evidence is abundantly confirmed by the transverse circulations indicated by the relative salinity profile shown in Figure 94.

We may thus apparently claim confirmation of the actual validity of the indicated current boundary obtained by the pycnomeric method herein described from no less than four entirely independent sources. (1) From the logical premises of the method itself, which rest upon the requirement for a distortion of the pycnomeres caused in a definite manner by the actual movement itself. (2) From the fact that the indicated current boundary is located in accordance with reasonable expectations in relation to the vertical distribution of vertical stability, which is an arithmetically fortuitous result entirely independent upon the method used for determining the probable current boundary. (3) Through the perfect agreement below the main current with the results obtained by the entirely independent oxygen minimum method used by Dietrich (1937a, b), for reasons which have been fully discussed by him. (4) From the equally good agreement with the picture obtained from a study of transverse movements.

To this we may finally add a fifth qualitative confirmation from a consideration of quantitative relationships. Using the oxygen minimum surface for reference between stations 1225 and 1231 (see Figure 94, stations 1225–26 are beyond the picture to the right), Dietrich (1937, p. 512) gave a volume transport estimate for the Gulf Stream system through this profile of 31.75 million cubic meters per second. This figure agrees entirely with the estimates of the flow through the Central American Seas previously made by the present writer on the basis of four separate profiles through the Caribbean and Cayman Seas and the 24-hour averages for five anchor stations across the Straits of Florida, which all together gave as a result 30–34 million cubic meters per second (Parr, 1937, p. 48). Whether this agreement is accidental or has any dynamic significance is impossible to say, however, since it has been stipulated by Rossby (1936) that there must be an increase in volume transport downstream, which should come into effect between the Straits of Florida and the location of the profile here considered off Cape Hatteras. And this required increase is available in the results of the method here proposed.

It has already been mentioned (p. 277) that the indicated lower current boundary on the right side descends from its isopycnal on the left, which continues through the right portion as the isopycnal of minimum oxygen

and intermediate maximum vertical stability only. Between stations 1228 and 1227, and likewise between stations 1227 and 1226 (beyond Figure 94 to the right) the relationships of the $\frac{\Delta D}{\Delta \sigma_t}$ curves indicate by actually determined values fairly strong movement in the direction of the main flow down to the deepest isopycnals (densities higher than 27.6, see p. 283). Still farther to the right conditions become vague and the differences between the $\frac{\Delta D}{\Delta \sigma_t}$ curves below σ_t 27.5 are not uniquely determined by actual observations, but largely due to "reasonable" interpolations of smooth curves, and are therefore without definite significance. Beyond station 1227 to the right, we can therefore not obtain a useable reference surface by the method here suggested, but nevertheless have definite indication of "Gulf Stream flow" down to great depths at least between stations 1227 and 1226, much deeper than the oxygen minimum surface on this side. From station 1227 to the right (and also between station 1228 and 1227) we must therefore make an addition to the estimate arrived at by Dietrich, who used the oxygen minimum surface for reference also through the right portion of the series to station 1225. If we therefore follow Dietrich's method for stations 1231–1227,[*] but use the 2000 decibar surface as our datum level for station 1227–1225, we arrive at an indicated total volume transport of about 50 million cubic meters per second.[†] If we change our reference surface from the oxygen minimum to the 2000 decibar level already at station 1228, our estimate indicates about 69 million cubic meters per second (only about 65 million cubic meters per second according to Dietrich's Table 2, see footnote † below) with the gross transport in the Gulf Stream direction not very significantly higher than the net transport. Since it is indicated that the basal current boundary departs from the oxygen minimum layer between stations 1228 and 1227, the correct value for the volume transport should probably lie between these two figures, at say about 60 million cubic meters per second.

[*] Using the values given in Dietrich's Table 2 (Dietrich, 1937, p. 512) for the volume transport with reference to the oxygen minimum surface.

[†] If we use the values given in Dietrich's Table 2 (see footnote above) for the volume transport both with reference to the oxygen minimum surface and with reference to 2000 decibars at the right, the procedure gives only about 45 million cubic meters per second. The total net volume transport with reference to 2000 decibars calculated for the entire profile (stations 1231- 1225) is given by Dietrich as 68.32 million cubic meters per second. Using end stations only, with the values of anomalies of dynamic height given in Dietrich's Table 1, we obtain a little over 73 million cubic meters per second, which seems in fair agreement with Iselin's estimate of 82 million cubic meters per second gross flow in the Gulf Stream direction (Iselin, 1936).

In other words, by taking into account the fact that the indicated boundary departs at the right from the oxygen minimum layer which it follows at the left, we find that there must have been an increase in volume transport between the Straits of Florida and our profile off Cape Hatteras probably amounting to somewhere around 30 million cubic meters per second, which, since it fulfills an independent theoretical requirement not fulfilled by the oxygen minimum method alone, gives a fifth independent verification of the validity of the proposed method.

Although the probable net volume transport arrived at for the Hatteras profile is thus about twice as great as that obtained by the oxygen minimum method alone, it is still only about 75% of that calculated by Iselin by referring the motion to the 2000 decibar surface throughout (82 million cubic meters per second, Iselin, 1936, p. 75). This reduction from Iselin's estimate greatly facilitates our understanding of the current profile, particularly by virtually cancelling the need for such cumbersom explanations as that which is required to interpret the volume transport through area E as given in Iselin's diagrammatic analysis of the profile (Iselin, 1936, Figure 49, p. 78), namely, that the water masses passing through this area *in the center* of the current have been about 50% diluted in the course of only 600 miles of northward flow.

The new interpretation of the current profile off Cape Hatteras thus seems to give a completely reasonable presentation both from the quantitative as well as from four different and independent qualitative points of view.

EDDY CIRCULATION PATTERN

It has been pointed out by Iselin (1938, see also Iselin, 1936, pp. 24–25, 69) that the occurrence of a system of eddies along the left side of the current seems to be the normal rather than the unusual state of affairs in the passage of the Gulf Stream along the Atlantic coast of the United States. This conclusion is also in accordance with the theoretical expectations of Rossby (1936) and the findings of Parr (1937) and is amply confirmed by the result of our study of pycnomeric distortion.

By assigning direction of motion to eddy systems differentiated by their identifying properties as mentioned in our description of procedure (p. 282), we find two major upper eddies rotating in harmony with each other and with the steady flow at the right, and the apparently also steady flow in the same direction at the left in the profile from Cape Cod to Bermuda (Figure 92). It should be noted that velocities calculated with reference to a horizontal datum level applied to a system of this sort would indicate *only one single* eddy rotating in conflict with a steady motion at the right. In the Cape Hatteras profile (Figure 94) in which dynamic calculations with reference to a horizontal datum level would not indicate any eddy at all, our

method brings out the existence of three eddies, all rotating in harmony with each other, and with the steady current at the right and the presumably steady counter-current at the left. Iselin's findings are thus fully substantiated by the results of the pycnomeric distortion method, and the pictures offer no difficulties with reference to conflicting directions of motion.

In both Figures 92 and 94 we notice a relatively narrow, but fairly consistent belt immediately above the indicated current boundary, in which the indicated movement is generally in the opposite direction of the movement in the much deeper and quantitatively far more important upper eddies. As mentioned on page 275 the appearance of this intermediate belt may partly be due simply to the inaccuracies of the computed values in this density region where the absolute differences between the $\frac{\Delta D}{\Delta \sigma_t}$ curves are slight. But since this belt is characterized by intermediate maximum vertical stability and is closely associated with the surface along which lateral translation of the upper water masses in relation to the lower bodies of water is indicated, it is perfectly reasonable to expect a relatively thin zone of very complicated eddies. Indeed, it would seem suspicious if such eddies were not suggested by our analysis. But probably the comparatively thin eddies in this contact zone are actually much more complicated than the comparatively widely spaced stations will permit us to discover.

Below the indicated boundary, there are also laterally adjacent zones of apparently opposite movements, and slow eddying probably also occurs here, but for the deeper isopycnal surfaces our evidence becomes gradually vaguer (see p. 286) and it seems wise to refrain from drawing any definite conclusions with regard to conditions below the Gulf Stream system (see also Dietrich, 1937, p. 514).

In conclusion, it is necessary, however, to make the reservation that neither dynamic calculations as expressed in profiles of dynamic height or in dynamic topographies, nor studies of pycnomeric distortions can ever give unequivocal *a priori* evidence of the direction of motion in any eddy system, or even of the mere existence of an eddy circulation. If a body of lighter water occurs in an isolated position surrounded by heavier water on both sides (as at station 1347, Figure 92) both pycnomeric distortion and dynamic calculations with reference to any reasonable datum surface would indicate the presence of an eddy circulation, even if the isolated body was completely stationary without any rotation or any other form of motion. It is only on the assumption that such isolated bodies cannot occur in the absence of rotation without dispersing to form a uniform light surface layer that either the pycnomeric or the dynamic method can be applied. On this assumption the dynamic method alone may, as we have seen, fail to indicate the full number of rotations present, thereby suggesting conflicting movement in the contact zones, while the pycnomeric method in conjunction with

the assignment of motion according to the distribution of identifying properties will always indicate a system of eddies in harmonious rotation.

But even when we thus obtain a reasonable and harmonious picture of eddy circulation around an isolated light or heavy body of water, there will still always remain one final uncertainty in view of the fact that both the dynamic and the pycnomeric method can only indicate *rotation in one single direction* around such a body, even if this body in its historical origin has actually been split off from its parent body with a *rotation in the opposite direction* to that indicated by either method of analysis. For this difficulty there would seem to be no solution except by actual observations, and lacking such observations there is always the possibility that indicated direction of rotation may be entirely reversed in any particular instance. But such occurrences will, let us hope, in all probability not be very frequent, and lacking direct observations we must proceed on the assumption that the indicated direction of rotation will, as a general rule, correspond to the actual direction in nature.

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