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FURTHER OBSERVATIONS ON THE HYDROGRAPHY OF THE EASTERN CARIBBEAN AND ADJACENT ATLANTIC WATERS

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INTRODUCTION

In the observations made by the "Atlantis" in the eastern Caribbean during 1933, two interesting possibilities, requiring further investigation, seemed indicated, and in January 1937 an effort was made to obtain the necessary additional information during another cruise of the same research ship, jointly sponsored by the Woods Hole Oceanographic Institution and the Bingham Oceanographic Foundation of Yale University.

The first problem of the renewed investigation referred to the great discrepancy found to exist between the surface salinities determined within the eastern Caribbean during the 1933 cruise and those previously recorded by Jacobsen and others from the adjacent parts of the open Atlantic in the approach of the north equatorial current towards the Lesser Antilles (Parr 1937). On this point the new data provide a most valuable comparison with the previous observations.

The second purpose to be served by the 1937 visit to the eastern Caribbean was that of investigating further the possibility that this hydrographic region, when adequately examined, might provide a particularly instructive case for a study in nature of the relationship between vertical stability and lateral mixing. With reference to its primary objective, this second aspect of the new investigation has proved rather disappointing. Instead of giving sharper definitions of the mixing relationship, the more extensive material mainly shows a greater complication of detail; which was, of course, an equally probable expectation. It seems indicated that this type of problem must either be approached with a much closer spacing of observations, which under practical circumstances means on a much smaller scale,

*Joint contribution from Woods Hole Oceanographic Institution (No. 179) and Bingham Oceanographic Foundation, Yale University.
Figure 2. Surface salinities. Atlantis observations in January 1937.
almost to the surface on the southern side. Otherwise the 1937 observations show some very interesting variations from the situation observed in 1933. In the latter year no subsurface salinities lower than 36.00°/o were found in the series south from Virgin Islands, while the same profile in 1937 shows subsurface salinities of 35.5-35.6°/o in its middle portion and an isolated observation of surface salinities between 35.1 and 35.2°/o near its southern end. In the eastern series from 1937, salinities lower than 35.6°/o occurred both immediately outside and immediately inside the Antilles in the southern passage between Trinidad and Grenada. On the northern shelf immediately off Trinidad there is also a single surface observation of 34.57°/o and a questionable determination of 30.73°/o, but these are probably without great quantitative significance; and 35.5°/o can perhaps be set as the minimum significant surface salinity observation in 1937. This salinity, however, is .5°/o lower than the minimum significant surface salinity observed in 1933, and therefore in somewhat better agreement with the average salinities (34.85°/o at the surface and 35.14°/o at 25 meters) reported by Jacobson (1929) from area XIV in the north equatorial current approaching the Antillean Islands. A considerable difference still remains, however, and it is rather in the comparison of the distributions of surface and subsurface salinities in the Eastern Caribbean in 1933 and 1937, than in their absolute values, that our interest lies. When Figs. 3 and 4 are compared, it seems indicated that the surface water in the Eastern Caribbean may have been derived from quite different directions, by entirely different routes of invasion, in the two years. In 1933 (Fig. 4) we find a broad area of relatively saline (36.2-36.4°/o) surface water which has apparently entered over a wide front, mainly through the northeast passages of which, unfortunately, only the Anegada Passage was subject of observation in that year. In 1937 the northern part of the Eastern Caribbean contained neither surface nor subsurface waters with salinities as high as 36.0°/o and the distribution pattern is entirely different from that of 1933, without indication of invasion through Anegada Passage, but with a rather narrow tongue of salinities between 35.9 and 36.0°/o extending inward from the east between Antigua and Dominica; while a tongue of low salinity surface waters entering through the southern passages between the Lesser Antilles expand greatly to the northwest in their further westward flow. It thus seems indicated that the Eastern Caribbean in 1933 was largely covered by a surface layer of northern and northeastern origin, contrary to conditions in 1937, when the surface waters in this region mainly derived from the southeast with only a relatively small contribution through the more northern passages (excluding the Anegada?). Taking into account the much lower surface salinities found in the Western Caribbean and in the Cayman Sea in 1934 than in 1933 (see Parr 1937, Figs. 39 and 40, pp. 54-55), and the good agreement between the absolute values of 1934 and the Eastern Caribbean records from 1937, it seems probable that the 1937 situation in the Eastern Caribbean is likely to be more typical of the region than that observed in 1933.
Figure 3. Subsurface salinities recorded at first observation below the surface. January 1937.
Figure 4. Subsurface salinities in Caribbean and Cayman Sea in 1933. From Parr. 1937, fig. 30.
IDENTITIES AND RELATIONSHIPS OF WATER MASSES

A secondary purpose of the 1937 cruise was to attempt to trace closer to its origin the shuffling of Sargasso Sea maximum salinity waters in between surface and minimum salinity layers derived from the North Equatorial Current. The probable occurrence of this phenomenon was first suggested by Nielsen (1925) and was found to be confirmed by the "Atlantis" observations of 1933 (Parr 1937, p. 82 and 85). In Figs. 5–7 the T–S correlations in the 1937 profile through the open Atlantic immediately east of the Antillean Islands are shown in three sections from north to south. Fig. 5 shows the observations made in the first part of the series entirely to the north (northeast) of the Antillean ridge (see...
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Figure 6. T-S correlations in the Atlantic along the northern half of the Lesser Antilles. See legend for fig. 5.

Fig. 1). A comparison with Jacobsen's average curves clearly shows this region to contain only waters of Jacobsen's southern Sargasso Sea type (VI) at all levels and at all stations without exception. In the next series of stations (Fig. 6), extending about half-way southward off the eastern side of the Lesser Antilles, the maximum salinity layer appears to be still of exclusively southern Sargasso Sea type, while the minimum salinity layer shows a great variety of values intermediate between those characteristic of the southern Sargasso Sea and those of the North Equatorial Current (Jacobsen's area XIV). The disappearance of the Sargasso Sea characteristics from the minimum salinity layer and from the isopycnic surface of \( \sigma_t = 27.365 \) is most strikingly shown in figure 20, page 24. The layers between maximum salinity and the isothermal surface of about 12° C. are also entirely of Sargasso Sea type, with only one single exception at the northern end (Station 2735, see also figure 18, page 22), where the characteristics are rather surprisingly of the southeastern kind (Jacobsen's
area XIV). There is no intrinsic evidence of errors in the determination at this station, and the deviations from neighboring stations are consistent through several depths of observation. The values have therefore been fully accepted in the plotting of the synoptic charts shown in Figs. 12-16.

In the southernmost series of observations in the Atlantic profile east of the Lesser Antilles (Fig. 7), we finally note a similar diversity of curves through intermediate values between those of the Sargasso Sea and North Equatorial type around maximum salinities as that which was found around minimum salinity values in the intermediate section of the Atlantic profile (Fig. 6). In the southernmost section (Fig. 7), however, the minimum salinity values are as uniformly North Equatorial as they were uniformly of Sargasso Sea type in the northernmost section (Fig. 5).

It is thus evident that the southward penetration of maximum salinity waters of southern Sargasso Sea type above minimum salinity waters of North Equa-
Editorial characteristics is largely accomplished even before the layers reach to the eastern entrances to the Caribbean. In fact, only a very narrow streak of maximum salinity water of the type identified by Jacobsen from area XIV seems to penetrate into the Caribbean at all, although it is still clearly observable at two of the southernmost stations in our first North–South profile through the open waters of the eastern Caribbean (Fig. 10). In a study of the further westward movement of the maximum salinity layer, however, we must also bear in mind that vertical mixing through a layer of southern Sargasso Sea type will tend to reduce its salinities and change its T–S curve towards a North Equatorial character ("compensation mixing," see p. 15), a development which has already previously been referred to (Parr 1937, p. 79, Fig. 55). On the whole, it seems indicated that the maximum salinity layer throughout the Central American basins must be mainly derived from the southern Sargasso Sea (Nielsen 1925, Parr 1937), and if this should be true, and it should also be true.
that the North Equatorial Current in the Atlantic is actually transporting a considerable volume of maximum salinity water of the type described by Jacobsen from area XIV, we patently have a very interesting problem in relation to the fate of the North Equatorial maximum salinity layer, which, however, is beyond the scope of the present report.

**MIXING**

Figs. 12-16 give the synoptic distribution of temperatures in four isopycnic surfaces, one \((\sigma, 25.4)\) corresponding very closely to the maximum salinity surface, one \((\sigma, 27.365)\) similarly located with reference to minimum salinity, and the other two representing intermediate surfaces between maximum and minimum salinity values (see density intercepts of T-S correlation curves in Figs. 5-11). The distribution pattern of maximum and minimum salinities are also

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**Figure 9.** T–S correlations in the Caribbean along the northern half of the Lesser Antilles. See legend for fig. 5.
Presented in Figs. 13 and 17, for comparison with Figs. 12 and 16. Isopycnic temperatures were selected in preference to isopycnic salinities for the reason that, due to the angles of intercept between the T–S correlation curves the isopycnic temperatures are less affected by uncertainties of interpolation than are the salinities, at the same time as the ratio between a unit on the temperature scale in our T–S correlation curves, and the limit of accuracy for the actual temperature determinations is ten times as great as the ratio between the salinity units and the accuracy of the salinity titrations.

From Figures 12–16, it is clear that the situation with reference to the “streakiness” of various layers was of the same general nature in 1937 as in 1933 (Parr 1937) with the streakiness relatively persistent in the intermediate layers (σt 26.5 and σt 27.0), while it rapidly disappeared into a comparatively uniform north-south gradient in the maximum and minimum salinity layers and in the
corresponding isopycnic surfaces of $\sigma_t$ 25.4 and $\sigma_t$ 27.365. This is perhaps even more strikingly evident in a comparison of the transverse isopycnic temperature curves given in Figures 18–20. In the 1937 observations, however, we are able to extend our comparisons beyond the Antillean Islands to the eastward, and by so doing we find that the streakiness with which the salinity minimum layer and the isopycnic surface of $\sigma_t$ 27.365 arrive off the eastern side of the Antilles is almost obliterated in the passage between the Antillean Islands (see Figures 16 and 17). In this passage the streakiness, or transverse variability, in the maximum salinity layer and in the isopycnic surface of $\sigma_t$ 25.4 is also greatly reduced, although not nearly obliterated (Figures 12 and 13), while the reduction in the streakiness and transverse range of variation in the intermediate isopycnic surfaces of $\sigma_t$ 26.5 and $\sigma_t$ 27.0 is relatively slight (compare the curve for Stations 2735–50 with Stations 2780–51, Figs. 18–19). It thus seems indicated that factors coming into play in the passage of the water between the Antillean
Islands have induced a greater amount of mixing in the isopycnic surfaces around maximum and minimum salinity values, than in the isopycnic surfaces between. One might immediately suggest a relationship to the great vertical stability around maximum salinity, and to the relative proximity to the topographic complications of the bottom around minimum salinity. But first it will be necessary to consider to what extent the reduction of streakiness might be due to vertical, instead of lateral, mixing alone. In this connection a serious objection to the previous use of the example of the maximum and minimum salinity layers in the eastern Caribbean as a possible illustration of the relationship between vertical mixing and horizontal stability (Parr 1936) has since occurred to the writer. Since the isopycnic surfaces of \( \sigma_v = 26.5 \) and \( \sigma_v = 27.0 \), both intercept virtually straight portions of the T-S curves (Figs. 5-11), it is evident that a change in the distribution of identifying properties in these isopycnic surfaces can only be due to lateral and not in a significant degree to vertical mixing (Parr 1938). To the extent that the streakiness of these intermediate isopycnic surfaces has been reduced by the passage between the Antillean Islands, the phenomenon may therefore be ascribed to lateral mixing. But in the isopycnic surfaces around maximum and minimum salinities the identifying properties involved in the determination of density (temperatures and salinities) may both be very significantly changed by vertical mixing alone. Since furthermore the rate of change in either identifying property per unit vertical mixing (that is, per unit vertical exchange of volume) at an inflection point in the vertical distribution curve for one of the properties affecting density, will decrease as the vertical mixing progresses and the radius of curvature of the vertical distribution curve increases, we may have a downstream "mixing compensation," quite comparable with the biological phenomenon of "compensation growth" as interpreted by Hodgson (1929). Assuming a uniform intensity of vertical mixing throughout, the cumulative curve of change in identifying properties around a maximum or minimum value in the course of the downstream movement would thus take a form similar to that of the curves shown in Fig. 21, p. 24 (modified from Hodgson’s illustration in explanation of compensation growth). If the difference between laterally adjacent streaks (A, B, C; in profile I, Fig. 21) is mainly one of more or less advanced or deferred vertical mixing, it is evident from our figure, in which the three curves are identical, that there will be a gradual obliteration downstream of the differences between the lateral streaks, even in the complete absence of lateral mixing and with a uniform vertical mixing in all streaks. For this reason the choice of maximum and minimum salinity layers or corresponding isopycnic surfaces for a comparison with isopycnic surfaces intercepting straight portions of the T-S curve in illustration of the possible relationship between vertical stability and horizontal mixing was obviously an unfortunate one which has to be discarded.

(Turn to page 22)
Figure 12. Synoptic chart of temperature distribution in isopycnal surface of $\sigma_t = 25.4$, near salinity maximum. Isotherms for every $0.2^\circ$C.
Figure 13. Synoptic chart of temperature distribution in isopycnic surface of $\sigma_t = 27.365$, near salinity minimum. Isotherms for every $0.1^\circ C$. 
Figure 14. Synoptic chart of temperature distribution in isopycnic surface of $\sigma_z = 26.5$. Isotherms for every .2°C,
Figure 15. Synoptic chart of temperature distribution in isopycnic surface of σ₁ = 27.0. Isotherms for every 0.2°C.
TEMPERATURES IN ISOPYCNAL SURFACE OF $\sigma_z = 27.365$

NEAR SALINITY MINIMUM

JANUARY 1937

ISOTHERMS FOR EVERY 0.1°C

Figure 16. Distribution of maximum salinities. Isobalines for every .1°/o.
MINIMUM SALINITIES
JANUARY 1937
ISOHALINES FOR EVERY 0.05%.

Figure 17. Distribution of minimum salinities. Isohalines for every .05%. 
To avoid the confusing aspect of mixing compensation just discussed, one might attempt to make comparisons between different isopycnic surfaces within the straight portion of the T–S curve, such as the surfaces of σ1 26.5 and σ1 27.0 for which synoptic charts are given in Figs. 14 and 15. But in so doing we would be reduced to a consideration of quantitative instead of simple qualitative differences in the synoptic patterns, requiring an accuracy of observations and a precise evaluation of all factors involved which can certainly not be obtained from a system of stations as widely spaced as those here reported upon. The
factor of lateral shearing stresses, which would be a function of lateral variations in longitudinal velocities, and is of an importance equal to that of vertical stability, would have to be determined with an accuracy which the present uncertainties in the practical applications of the velocity equation, caused among other things by the guesswork involved in selection of a datum surface, would certainly not permit. Average vertical stabilities would also have to be evaluated in accurate figures along isopycnic surfaces in proportion to the lateral variations in velocities along the same surfaces, which, as we have just mentioned, can hardly themselves be accurately determined. What seemed of interest and possible significance in the comparison between the distribution patterns of various layers in the Eastern Caribbean, was therefore not to be found in precise quantitative estimates, but in the fact that qualitative differences in these patterns would appear to be associated with a close proximity to positive deviations in vertical stability. The integration of the effects of

Figure 19. Transverse temperature curves for isopycnic surfaces of $\sigma = 25.4$ (near salinity maximum) and $\sigma = 27.365$ (near salinity minimum). Upper series in the Atlantic along Lesser Antilles. Second series in Caribbean immediately inside of Lesser Antilles, with positions of Islands indicated by hatched blocks. Lower two series through open Caribbean. Datum lines refer to $25^\circ C.$ for $25.4$ and $6^\circ C.$ for $\sigma = 27.365$. Scale of deviations in $^\circ C.$ at left. Degrees latitude at bottom (does not apply to the last stations at the left in the second series, see station chart on page 2).
Figure 20. Profiles of maximum and minimum salinities (open circles, dot and dash) and of temperatures (solid lines, black dots) in the isopycnic surfaces of $\rho = 27.365$ for entire Atlantic profile. Latitude in °N. at bottom.

Figure 21. Vertical mixing compensation. See text, page 15.
generally decreasing vertical stability, and undoubtedly also decreasing lateral shearing stresses towards the depths did apparently not result in a uniformly decreasing curve of lateral mixing, but on the contrary, gave indication of two separate maxima of such mixing each closely associated with a major or a minor positive deviation from the general trend of decreasing vertical stability (see Figs. 22–23).

It has been stated by Dietrich (1937) that there is no vertical stability maximum around minimum salinity values. Although the wide vertical spacing of observations (100–200 meters apart) in these depths make precise determination of the form of the density curves through the layers concerned a virtual impossibility, it is nevertheless by various methods quite possible to show that an actual increase in vertical stability must occur in, or very near to, the minimum salinity surface. From a consideration of the derivation of the \( \sigma_t \) values alone, the probability of this occurrence is immediately indicated. By standard methods the value of \( \sigma_t \) is determined by the empirical equation:

\[
\sigma_t = \sigma_z - D
\]

With the value of \( D \) steadily decreasing towards the depths, with decreasing temperatures, and the value for \( \sigma_z \) first decreasing towards the salinity minimum and then increasing again towards greater depths, it is evident that if this change from a negative to a positive rate of change of \( \sigma_z \) around salinity minimum should not find expression in a secondary increase in the vertical gradient of \( \sigma_t \) at and below salinity minimum, there would have to be a corresponding and compensating irregularity in the vertical temperature gradient of which there is no general indication in the data. An actual case (from 1937) is shown in Fig. 22. It is evident from the form of the vertical curves for \( D \) and \( \sigma_z \) that the increase in vertical stability should normally be expected to begin slightly above the salinity minimum and reach its maximum somewhat below. If we choose the apparent (interpolated) depth of minimum salinity at each station as our zero level and plot the observed densities according to their height above or depth below this level, we also find that there is, on the average, a definite inflection in the vertical density curves around or immediately below salinity minimum, both in the 1933 and in the 1937 observations from the Eastern Caribbean.

Since the salinity minimum values, and therefore also the distribution pattern of the salinity minimum surface, according to the manner in which the vertical curves are drawn and read, must necessarily also be indicative and indirectly representative of salinities and salinity distributions immediately below, it seems entirely proper to claim association between the salinity minimum distribution pattern and the secondary vertical stability maximum. Finally, it should perhaps also be mentioned at this point that the principle that vertical stability and horizontal mixing should be in direct relationship to
Figure 22. Vertical density curve ($\rho$) for station 2802 (Atlantis 1937) and its derivation from vertical curves for salinity (Sal.), temperature (Temp.), $\sigma$, and $D$.

Figure 23. Curves of $\Delta\sigma_t$ for stations 1505 and 1512 (Atlantis 1933). See text. Insert: Curves of salinities, $\sigma$, and approximate curve of vertical stability at "Atlantis" station 2955. See page 27. Observations made in 2 overlapping series.
each other does not require any vertical stability in the layer in which lateral mixing occurs, but merely that this layer should be in fairly close contact with one or confined between two vertically stable boundaries.

With regard to the actual values of the secondary vertical stability maximum, it is evident that the great vertical distance between observations makes it impossible to arrive at accurate figures and also that the increase in the vertical density gradient and accordingly also in the vertical stability curve must be minimized in proportion to this distance between observations. Therefore, if the transverse isopycnals around salinity minimum were forming a parallel system, we would be entitled to regard the maximum estimated vertical stability around salinity minimum as a minimum value for the actual stability of this layer. And it was noted in the 1933 observations that there seemed to be a tendency for the more closely spaced observations around salinity minimum to show greater vertical stability values in the secondary maximum. The \( \sigma_{\Delta h} \) curves for the two stations in the transverse profile on which the previously used average T-S curve was based (Parr 1930, Fig. 3; 1937, Fig. 45) at which observations were most closely spaced around salinity minimum are given in Fig. 23. At Station 1512 the observations were more closely spaced in these depths (only 51 meters apart around salinity minimum) than at any other station made in the Eastern Caribbean, and this station also showed the highest estimated vertical stability value in the secondary stability maximum. Unfortunately the premise that the transverse isopycnals should run parallel around salinity minimum does not hold true. Although the maximum estimated vertical stability can therefore not a priori be used as a minimum value for all actual values in nature, the probability remains that the maximum actual vertical stability in the secondary maximum must be greater than the maximum estimated from our discontinuous observations.

During the 1938 cruise to the Central American Seas, a special set of observations was made by the "Atlantis" in the Cayman Sea just south of Cuba, with the instruments more closely spaced (only 25 meters apart) in the depths around the salinity minimum. The records of these observations have just come to hand and are presented in the insert in figure 23, which again confirms the existence of an increased vertical stability in and immediately below the minimum salinity layer. At Station 2965 the average for the first 121 meters below salinity minimum \( \left( 2.1 \text{ g} / \text{cm}^3 \right) \) is nearly twice the average \( (1.1) \) for the first 175 meters above. It should also be kept in mind that Station 2965 is located in a region with relatively high minimum salinity values \( (34.83^\circ /o) \) and great thickness of the layers (right side of current) in which the increase in vertical stability associated with the increase in salinities below must therefore be considerably less than the average for the Central American Seas.
On the basis of the preceding, it therefore definitely seems valid to repeat that the peculiarities of the salinity distribution in the maximum and minimum salinity layers, and in corresponding isopycnic surfaces, as compared with the synoptic patterns of the intermediate isopycnals (particularly when we consider $\sigma$, 27.0) is clearly associated with positive deviations from the general trend of decreasing vertical stability. Since, however, the possibility of a mixing compensation already discussed on page 15 introduces a further complication not previously taken into consideration, it nevertheless seems advisable to give up the attempt to extract definitive evidence from a case as complicated as that of the Eastern Caribbean, and to withdraw this previously used illustration of a possible application of the principle concerning the relationship between vertical stability and lateral mixing from further consideration until much more precise information may become available. In so doing, however, the author wishes to emphasize the fact that this withdrawal of an ambiguous, but definitely not contradictory, illustration in no manner affects his confidence in the previously enunciated principle, for which unequivocal evidence is probably more easily obtainable by meteorological research and experimental investigations of liquid dynamics for which apparatus is now under construction.

SUMMARY

The 1933 records from the Eastern Caribbean showed a very great discrepancy with previous observations from adjacent parts of the open Atlantic, with reference to salinities in the surface layer. In the 1937 observations herein reported upon, this discrepancy is greatly reduced and considerable variations in Caribbean surface salinities are thus indicated.

With reference to the deeper layers, the 1937 data confirm the findings of 1933 previously reported upon (Parr 1937). It seems indicated that the intrusion of a maximum salinity layer of Southern Sargasso Sea origin between surface and minimum salinity layers mainly derived from the North Equatorial Current (Nielsen 1925, Parr 1937) is largely completed before the water masses enter the Eastern Caribbean.

Synoptic temperature charts are given for four isopycnic surfaces, one corresponding very closely to the maximum salinity surface, another to the minimum salinity layer and the remaining two to intermediate layers between these.

With reference to "streakiness" these synoptic charts give general confirmation of the comparison previously made between the distributions of maximum and minimum salinities and salinities in the isothermal surface of 15°C. The possibility of an elimination of streakiness by compensating cumulative effects of simple vertical mixing is brought out, and in view of the uncertainties introduced by this factor, which has not previously been taken into consideration, it is considered advisable to disregard all comparisons between layers identified...
with inflection points on the T-S correlation and to resort to meteorological and experimental hydrodynamic methods instead for the further study of the relationship between vertical stability and lateral mixing.

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**Nielsen, T. N.:**


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