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APPLICATION OF THE DISTRIBUTION OF  
OXYGEN TO THE PHYSICAL OCEANOGRAPHY  
OF THE CARIBBEAN SEA REGION

BY

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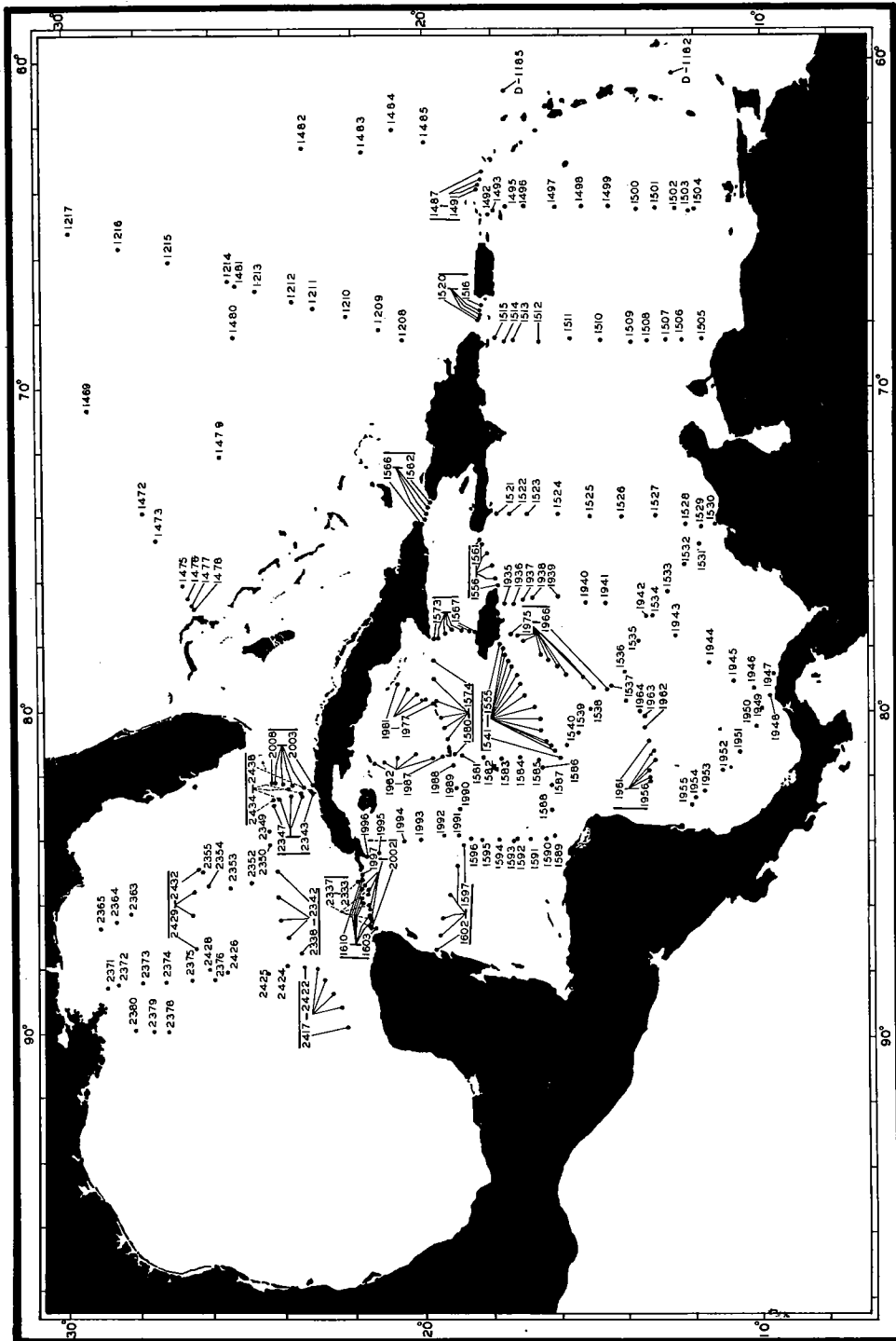


FIG. 1. "Atlantis" and "Dana" (D) stations in Caribbean Sea and adjacent region referred to in this report.

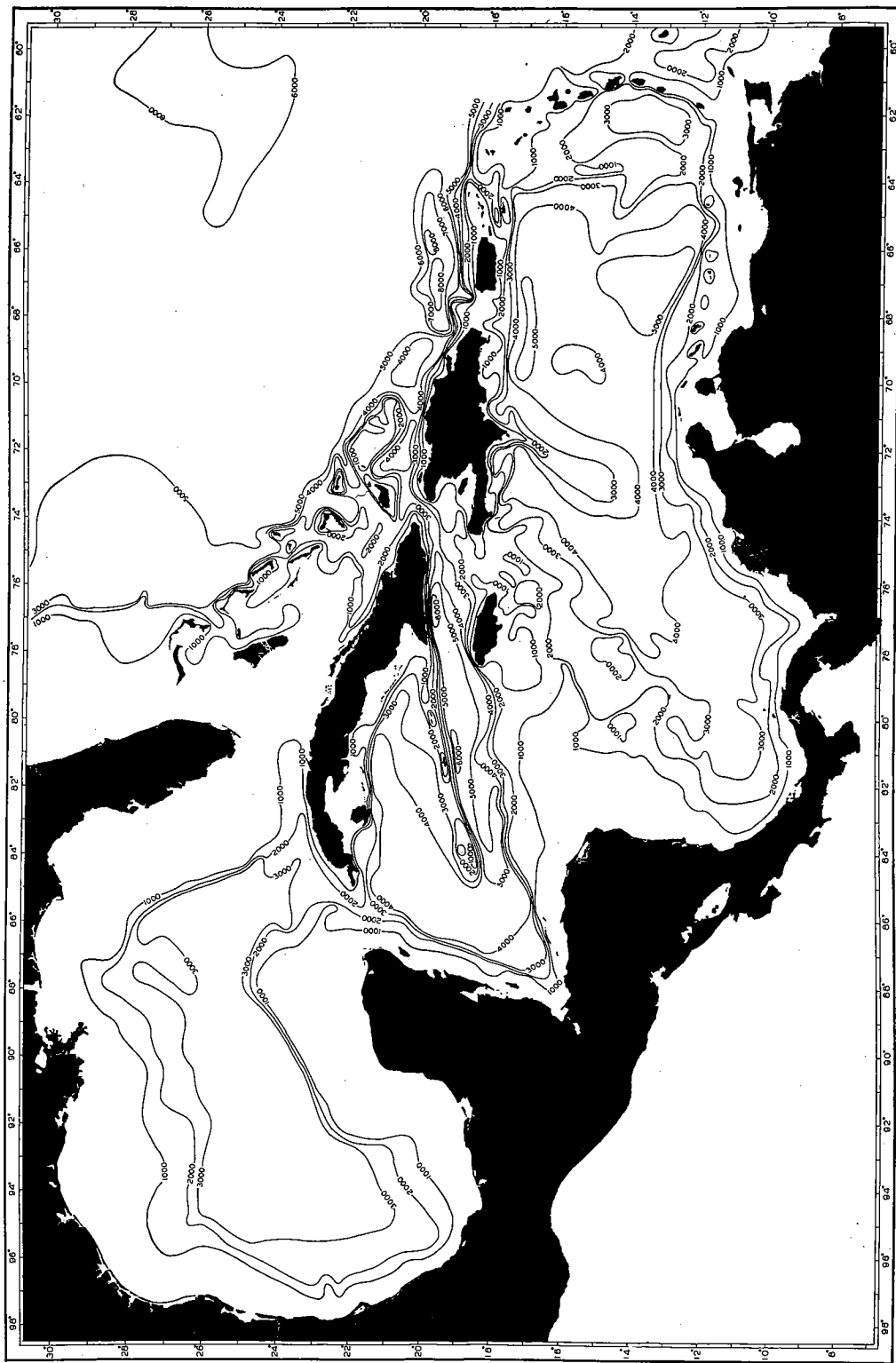


FIG. 2. Bathymetric chart of Caribbean Sea, Gulf of Mexico, and adjacent waters.

## INTRODUCTION<sup>1</sup>

Observational data for this discussion were obtained principally during the two cruises of the oceanographic research ship, "Atlantis," to the Caribbean Sea (Fig. 1) March 7 to May 5, 1933 (stations 1487-1610) and February 2 to March 2, 1934 (stations 1935-2002). The oxygen determinations, carried out on board, have been published in *Bulletin Hydrographique* (1934, 1935) together with other hydrographic data.

The Caribbean Sea region falls into two natural bathymetric subdivisions (Fig. 2): a western, lying between Yucatan Channel and a ridge extending from Honduras to Haiti via Jamaica, designated in this paper as the "Cayman basin," and an eastern, between this ridge and the lesser Antilles, here designated as the "Caribbean basin" (Fig. 3). "Cayman basin" has been used by Parr (1937) and by Rakestraw and Smith (1937), and, while antedated by "Yucatan basin" (Krümmel, 1907),<sup>2</sup> it seems that less confusion will arise if the term "Cayman" is used in this discussion.

The "Atlantis" observations supply for the first time the necessary information for a detailed study of the distribution of oxygen in the Caribbean Sea region. The 1933 and 1934 observations are here used indifferently; such a procedure seemed desirable since the data are insufficient for determination of annual or seasonal variations, particularly in view of the disturbing effect which may be caused by short period vertical oscillations of relatively large magnitude.

<sup>1</sup> The writer is indebted to Professor Henry B. Bigelow for considerable help with the descriptive part of this paper and to Professor H. U. Sverdrup for suggestions on the theoretical chapters.

<sup>2</sup> The designations Yucatan basin and Caribbean basin for the Caribbean Sea region were used by Krümmel (1907) in a discussion of certain hydrographic conditions based on the earlier observations of Agassiz (1888). Schuchert (1935) has proposed the name Antillean Sea for the eastern basin of the Caribbean Sea.

## REGIONAL VARIATION OF OXYGEN IN THE CARIBBEAN SEA REGION

### GENERAL DISTRIBUTION

The vertical distribution of oxygen in this region agrees, in its characteristic features, with other North Atlantic areas, notably in the fact that oxygen decreases from the surface downward to a minimum value in the 500-700 meter stratum, below which it again increases progressively with depth to a maximum value in the deepest water (Fig. 4). But, comparison of the oxygen content of the water of the neighboring Atlantic, as represented by "Atlantis" station 1210 ( $22^{\circ} 14' N$ ,  $67^{\circ} 50' W$ ; Fig. 1), and of Windward Passage (stations 1562-1556; Fig. 1) with that of the Caribbean and Cayman basins, shows decreasing values from the open ocean into the latter.

At depths less than 1000 meters differences in oxygen content for identical depths are, in large part, related to vertical displacement of the minimum of oxygen concentration as controlled by the vertical density distribution (page 40). Between the surface and 700 meters the recorded difference between Atlantic<sup>3</sup> and Caribbean waters was 0.8 to 1.0 cc per liter. At depths greater than 1000 meters the maximum difference was at the 1500 meter level where the concentration of oxygen in the Atlantic water (station 1210) was 5.88 cc per liter as contrasted with an average of 5.36 cc per liter for the Cayman basin, and 4.87 cc per liter for the Caribbean.

At 2000 meters the average oxygen contents of the Cayman and Caribbean basins were 0.2 and 0.9 cc per liter lower than at station 1210 respectively; 0.08 and 0.86 cc per liter lower at 3000 meters; 0.20 and 0.86 cc per liter lower at 4000 meters.

The average oxygen content of water in the Windward Passage (stations 1562-1556; 1933) proved intermediate between that of the Atlantic and of the Cayman basin, e.g., 0.4 to 0.5 cc per liter higher, for corresponding levels, than that of the latter in depths less than 500 meters, but practically identical deeper than 1000 meters. In 1933, also, the Windward Passage water averaged 0.2 to 0.4 cc richer per liter in oxygen than at similar levels in the Anegada Passage (stations 1487-1491).

Sections crossing the two channels leading from the Windward Passage into the Caribbean basin (Jamaica to Hispaniola; stations 1556-1561) and from the Windward Passage into the Cayman basin (Jamaica to Cuba; stations 1567-1573, Profile 4) showed practically identical values shoaler than 1500 meters, though at 2000 meters the Cayman entrance was 0.5 cc per liter richer (Figs. 4, 5).

Especially interesting is the fact that, during 1933-1934, the Cayman was the richer of the two basins by an average of 0.31 cc per liter between 100 and 500 meters, 0.07 cc between 750 and 1000 meters (Fig. 4), although the general circulation indicates that water of the upper levels flows into it from the Caribbean basin. The final oxygen condition of Caribbean water as it reenters the Atlantic is illustrated by sections across Straits of Florida (profile 9, Fig. 6).

The regional gradients between the Caribbean region and the surrounding Atlantic, as well as such as exist within the former, appear to have arisen primarily as a result of bathymetric features and of circulation rather than of differences in biochemical activity.

<sup>3</sup> For accounts of oxygen content of the Atlantic, see Wattenberg, 1929, 1933, and Seiwel, 1934.

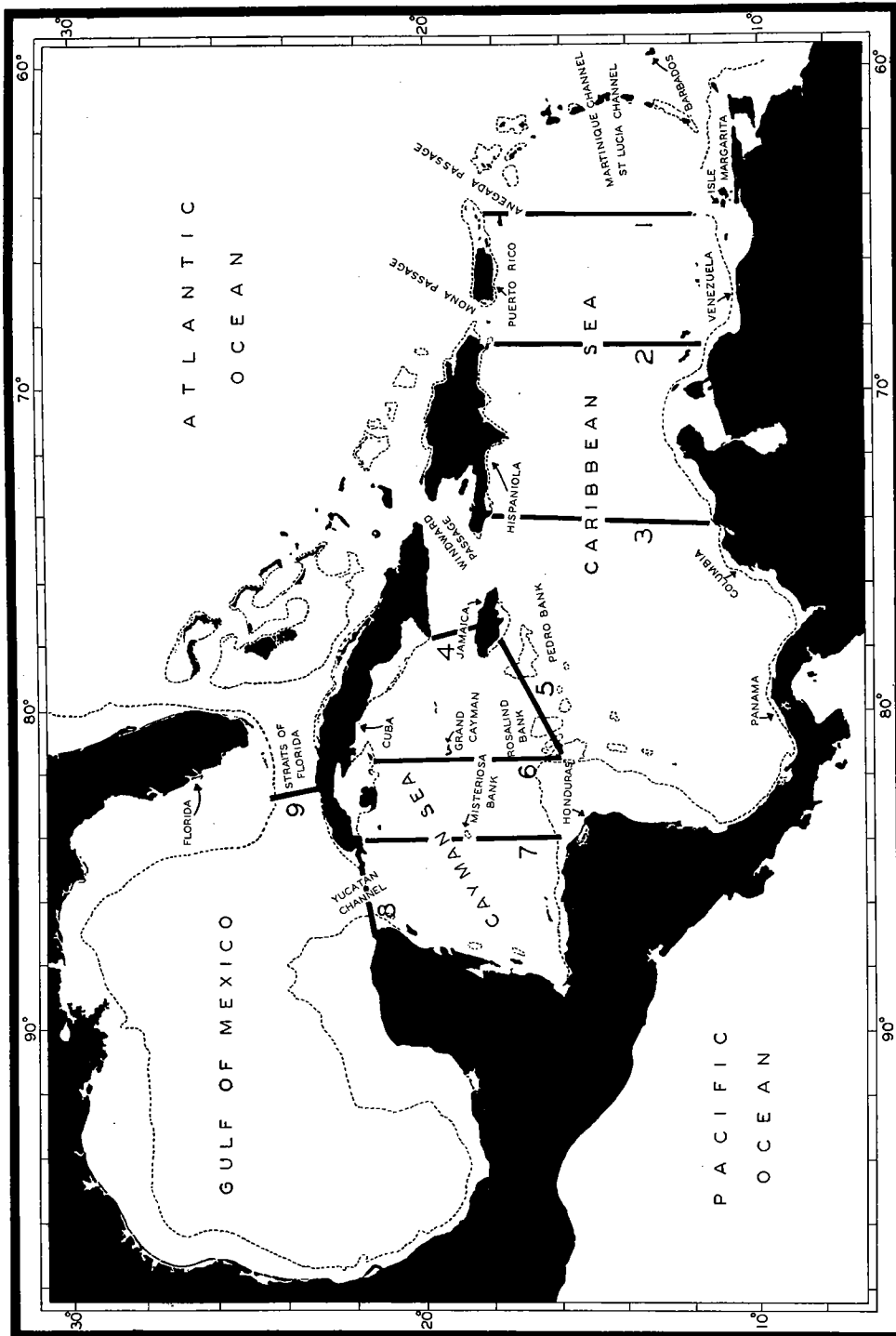


FIG. 3. Significant geographic localities in Caribbean Sea region, and locations of principal profiles.

Consequently, the logical division of the water column is into the stratum above and below the threshold depths of the basins. Decision as to the precise depth of threshold, for either basin, is somewhat arbitrary, but divergence in character between the deeper water of the Caribbean region and that of the adjacent Atlantic seems to be well established at 2000 meters.

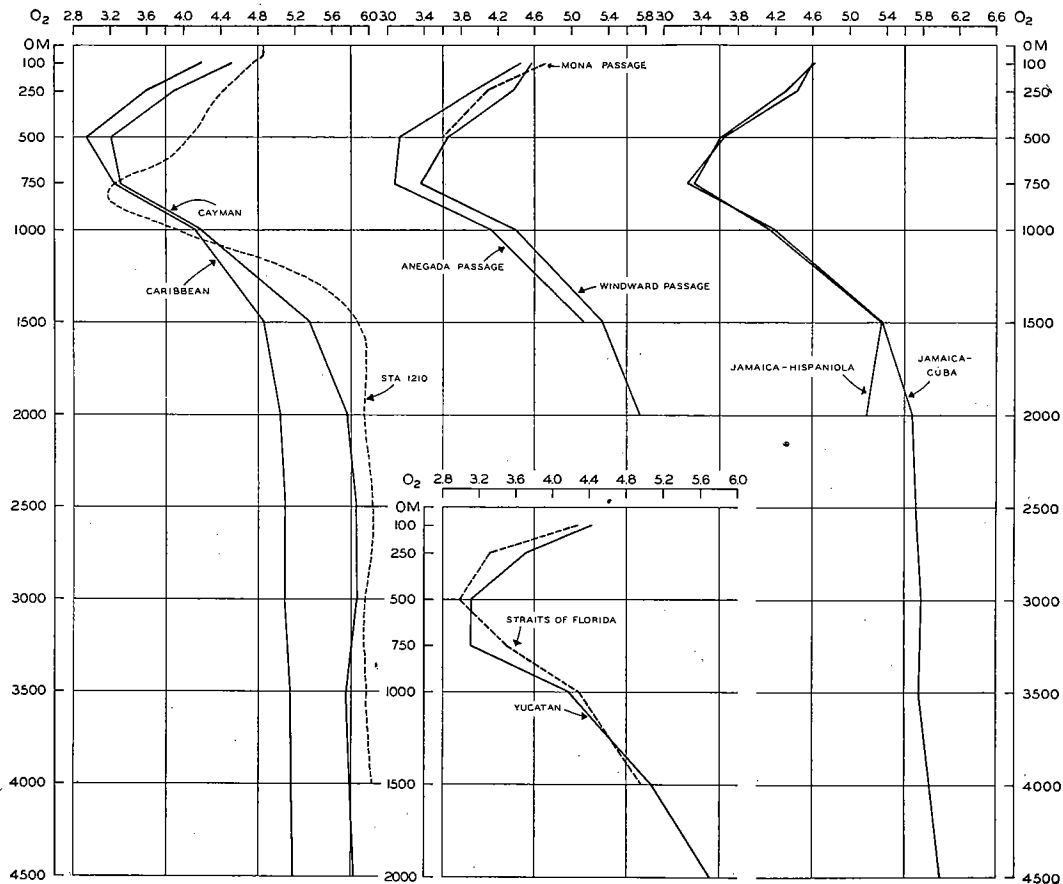


FIG. 4. Mean vertical distribution of oxygen in the Caribbean and Cayman basins and associated localities (based on 1933 and 1934 "Atlantis" data).

#### ABOVE THRESHOLD DEPTHS

During the winters of 1933-1934, the surface range of oxygen within the basins (4.6-5.0 cc per liter) was without any defined regularity, as was to be expected from the general rule that the oxygen dosage of the superficial stratum is ruled chiefly by biological processes combined with interchanges with the air.

Within the Caribbean region the first indication of definite regional variation in oxygen content was recorded at the 100 meter level where values decreased from north to south across both basins, and in the south from the Cayman basin into the Caribbean basin from a maximum of about 4.5 cc per liter to less than 3.5 cc (100%-61% saturated;



Fig. 7). At 250 meters (Fig. 8) the range of recorded values (4.8–3.1 cc per liter, 90%–50% saturated) about equals that already observed for this level in the neighboring Atlantic at corresponding latitudes and similarly decreases from north to south and from the Cayman basin into the Caribbean, suggesting a predominance of admixture of water entering through the passages, as illustrated by comparison of profiles crossing the

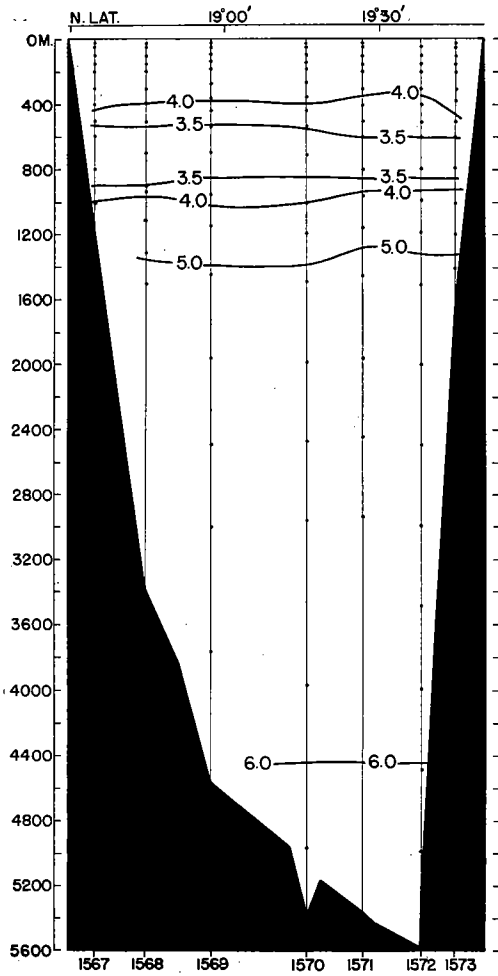
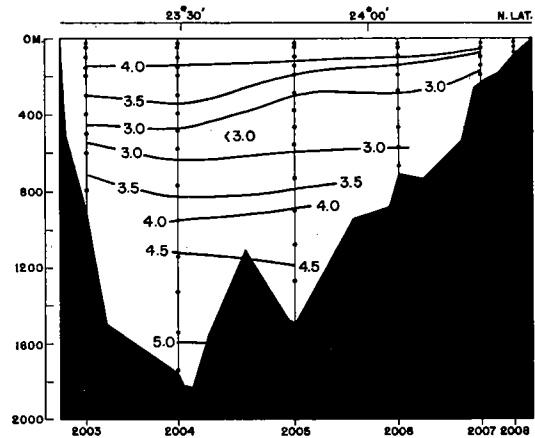
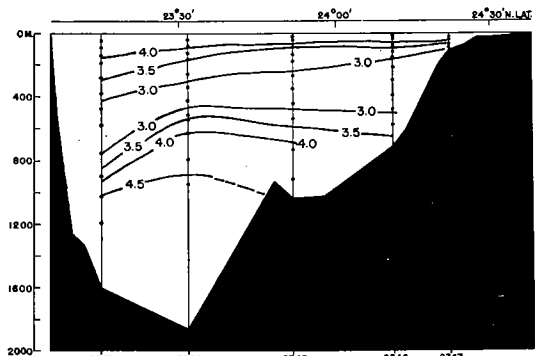


FIG. 5. Oxygen distribution (cc per liter) across extreme eastern part of Cayman basin (Jamaica to Cuba; stations 1567–1573); profile 4.



A



B

FIG. 6. Oxygen distribution (cc per liter) across Straits of Florida: A, based on 1934 "Atlantis" data (stations 2003–2008), and, B, based on 1935 "Atlantis" data (stations 2343–2347); profile 9.

east central Caribbean (Fig. 9) and east central Cayman (Fig. 10). These same profiles bring out the fact that the minimum oxygen concentration (the mean depth of which, in the Caribbean area as a whole, centers at about 600 meters) lay about 100 meters deeper in the northern side of the two basins than in the southern, resulting in the relatively strong horizontal gradient shown in Figure 11, as existing at the 500 meter level.

Comparison of oxygen distribution over the series of banks separating the Caribbean and Cayman basins between Jamaica and Mosquito Bank (Fig. 12) suggests that the

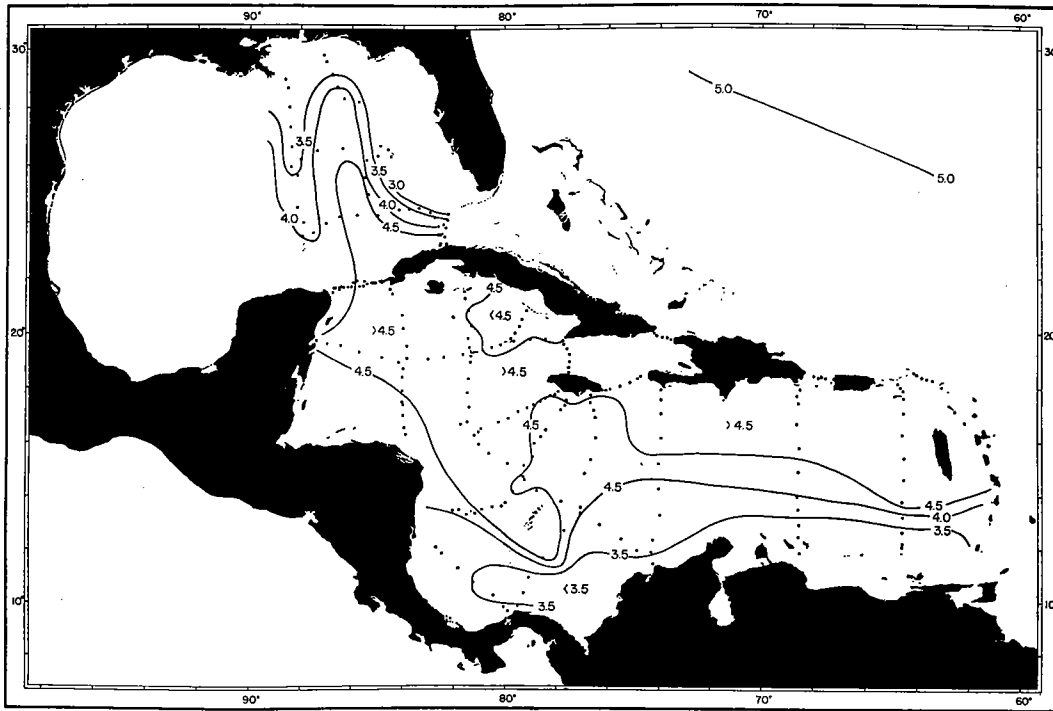


FIG. 7. Horizontal distribution of oxygen (cc per liter) at 100 meters depth (based on combined 1933 and 1934 "Atlantis" observations).

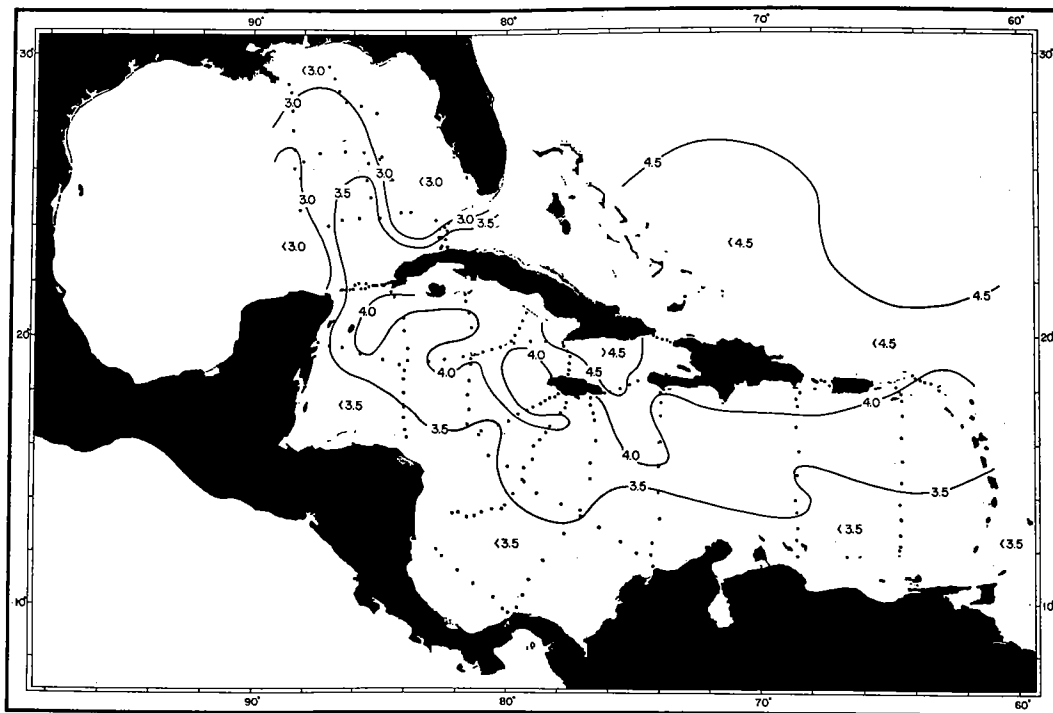


FIG. 8. Horizontal distribution of oxygen (cc per liter) at 250 meters depth (based on combined 1933 and 1934 "Atlantis" observations).

greater richness of the northern half of the Cayman basin arises primarily from admixture of the still richer water moving in through the Windward Passage, the main Caribbean current being thus enriched after it moves from the Caribbean into the Cayman basin. In fact, the profile between Jamaica and Cuba (Fig. 5) which crosses the intervening gully more than 5000 meters deep (Fig. 2), and is fully exposed to indrafts via the Windward Passage, not only showed the highest oxygen content for the entire Caribbean region, but the minimum concentration (3.19–3.31 cc per liter) here lay as deep as

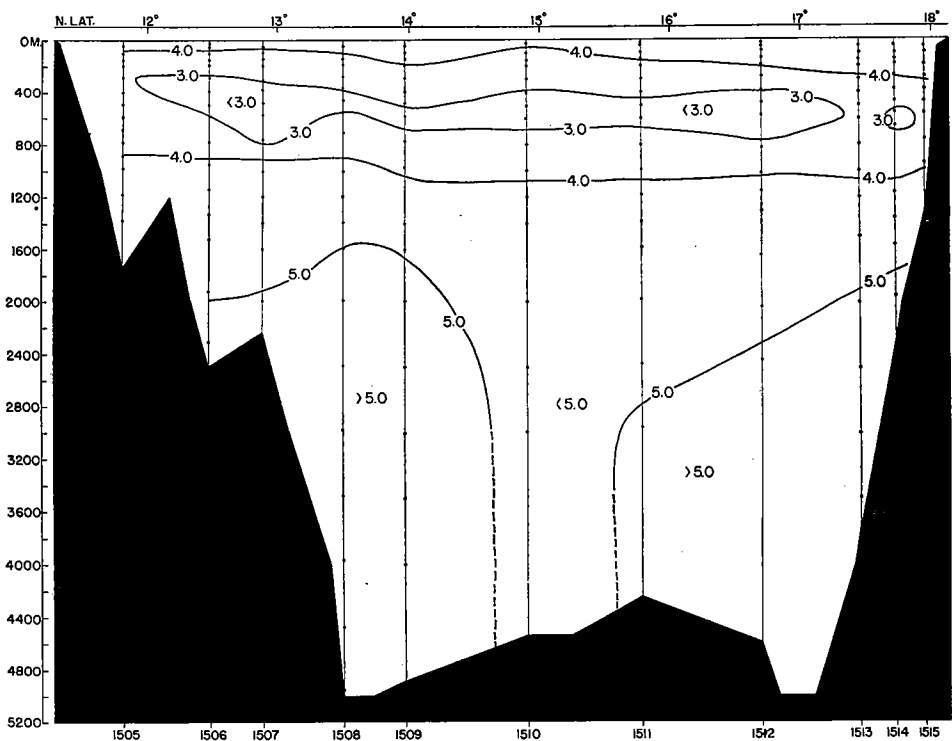


FIG. 9. Oxygen distribution (cc per liter) across east central part of Caribbean basin (stations 1505–1515); profile 2.

approximately 700 meters, contrasting with a depth of about 600 meters for the minimum (2.81–2.95 cc per liter) on the profile between Mosquito Bank and Jamaica (Fig. 12).

In both basins the minimum oxygen values (Fig. 13) agreed closely in magnitude with those observed in the surrounding Atlantic (Seiwell, 1937), richest, near the three northern inlets. Those of the Cayman basin form a continuation of the east-west increase in minimum oxygen already recorded for the western Atlantic between latitudes  $20^{\circ}$  and  $10^{\circ}$ N. Minimum values in the Caribbean basin were 0.1–0.2 cc per liter lower than in the Cayman, corresponding to the removal of the water masses from the influence of the Windward Passage, and toward the Yucatan Channel. And, this decrease continued into the eastern Gulf of Mexico and Straits of Florida, as illustrated in Figure 13.

Immediately below the level at which oxygen is poorest, the horizontal gradient of the Cayman basin (illustrated by the 750 meter level; Fig. 14) was much less pronounced

than at 500 meters though of the same order and with east-west decrease along the course of the Caribbean current still appearing in the western part of the basin in the form of a minimal tongue (less than 3 cc per liter). In the Caribbean basin, however, the horizontal gradient at 750 meters was, in general, the reverse of that at 500 meters. This situation suggests that the oxygen content of the water entering through the Windward

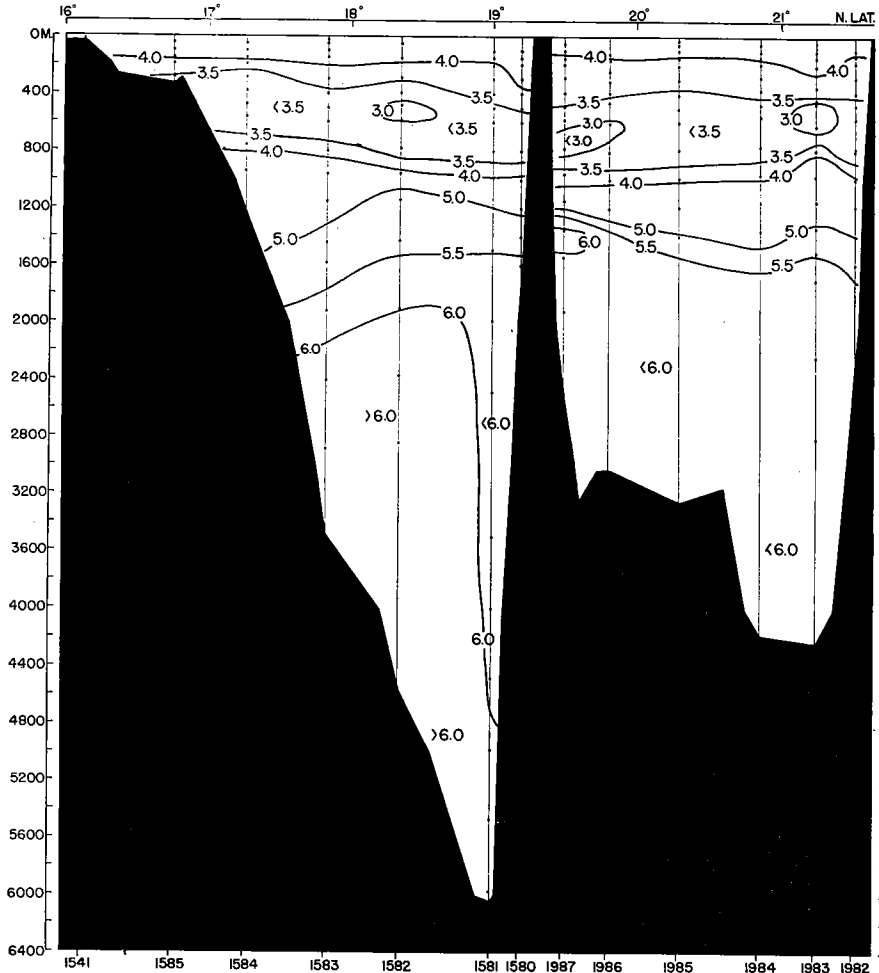


FIG. 10. Oxygen distribution (cc per liter) across east central part of Cayman basin (composite section based on "Atlantis" 1933 and 1934 data; stations 1982-1987, 1580-1585, and 1541); profile 6.

Passage at this level (Fig. 5) was not significantly different than that entering the Cayman basin, via the main Caribbean current, between Jamaica and Mosquito Bank (Fig. 12). Consequently, enrichment of the Caribbean current after it enters the Cayman basin (as shown for the 500 meter level) did not occur at 750 meters. A similar reversal in direction in the order of horizontal gradients was also encountered in the Yucatan Channel (Fig. 15) where lowest values were in the western side at 500 meters, but in the eastern at 750 meters. Likewise, in the Straits of Florida (Fig. 6), the lowest values lay on the

northern side just above the level of minimum oxygen, but in the southern side just below the latter. Furthermore, the minimum values were not only lower in the Straits of Florida (2.58–2.91 cc per liter) than in the Yucatan Channel (3.1–2.9 cc per liter), but lay shoaler in the former (375–580 meters) than in the latter (500–750 meters).

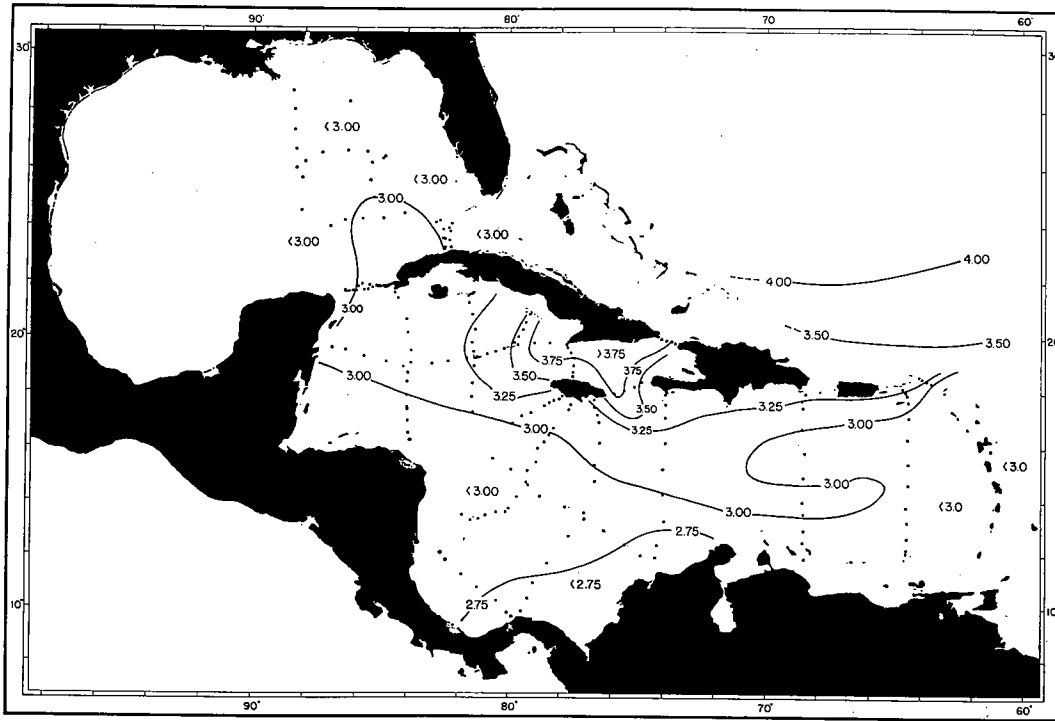


FIG. 11. Horizontal distribution of oxygen (cc per liter) at 500 meters depth (based on combined 1933 and 1934 "Atlantis" observations).

As depth increases below the 750 meter level, many of the passageways of the open Atlantic become successively closed off, until at 1000 meters apparently only four remain open, namely St. Lucia Channel, Martinique Channel, Anegada Passage and Windward Passage (Fig. 2). At this depth (Fig. 16) the horizontal distribution in the Caribbean basin (maximum in the south) was similar to that of 750 meters (Fig. 14). In the Cayman basin, however, the entrance of oxygen richer water through the Windward Passage was still shown with the presence of values greater than 4.25 cc per liter between Jamaica and Cuba (Fig. 16), while, further westward, the presence of a narrow tongue with less than 4 cc per liter indicates impoverishment along the main Caribbean current.

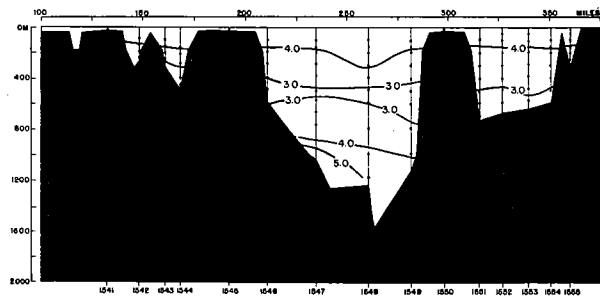


FIG. 12. Oxygen distribution (cc per liter) over series of banks separating deeper parts of Caribbean and Cayman basins (Jamaica to Mosquito Bank; stations 1541–1555); profile 5.

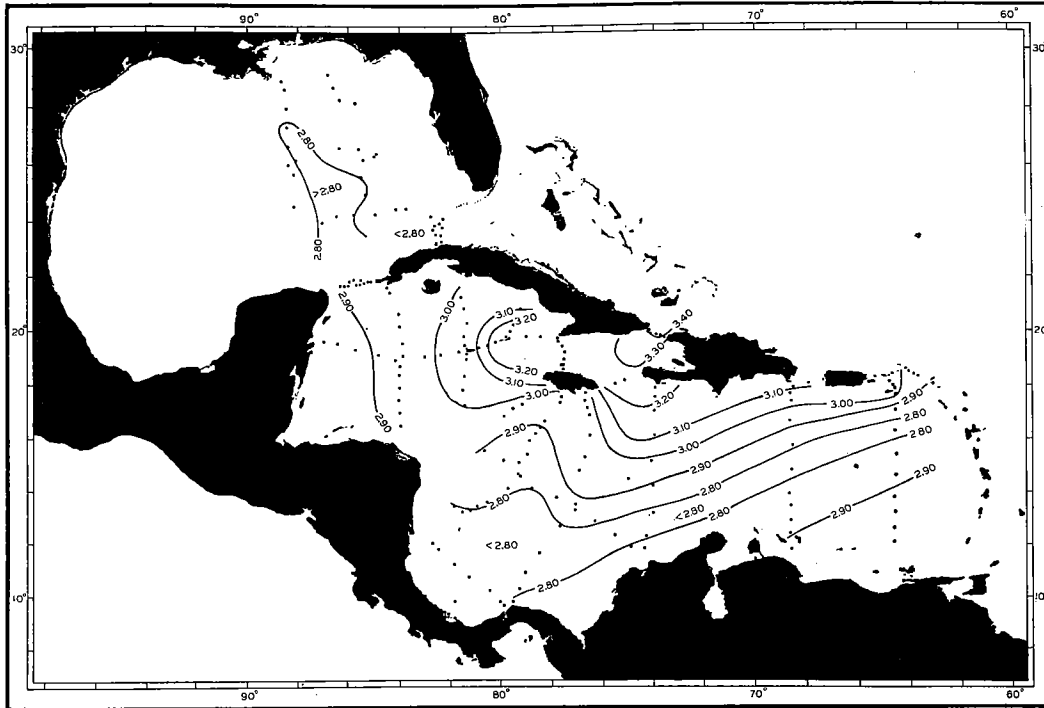


FIG. 13. Horizontal distribution of oxygen values at depth of the minimum oxygen concentration in the Caribbean Sea region.

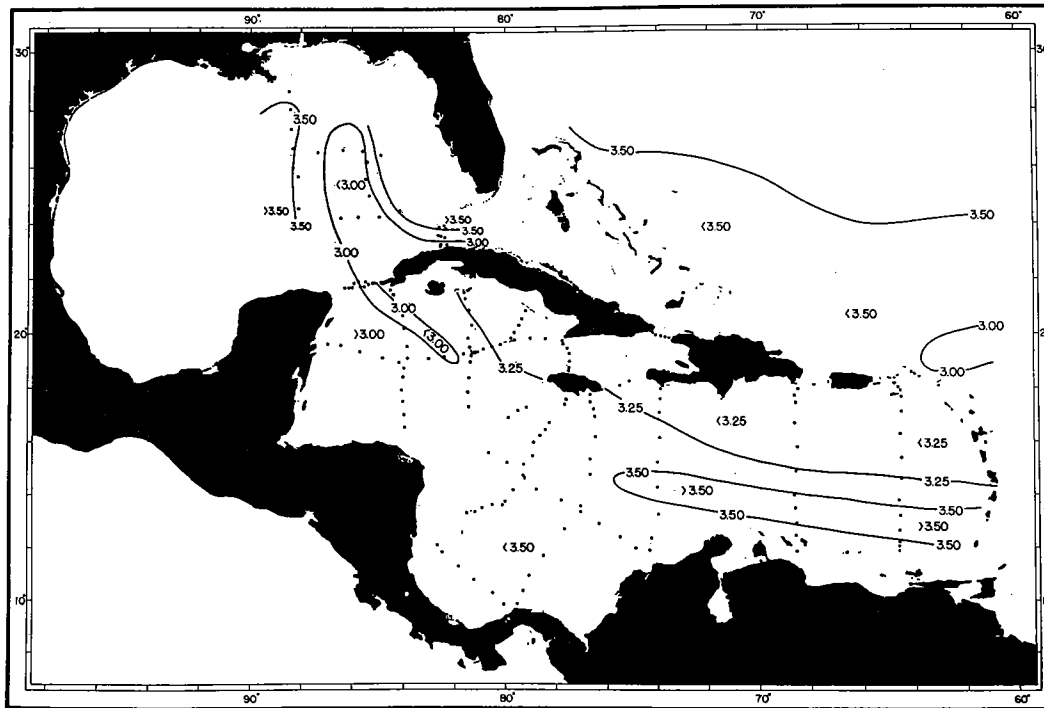


FIG. 14. Horizontal distribution of oxygen (cc per liter) at 750 meters depth (based on combined 1933 and 1934 "Atlantis" observations).

At 1500 meters (Fig. 17) separation of the Caribbean basin from the Cayman basin is almost complete, communication being confined to one narrow channel between Jamaica and Hispaniola, and to another between San Pedro and Rosiland Bank (Figs. 2, 12). At this level, water entering the Cayman basin from the Caribbean was more than 0.5 cc per liter poorer in oxygen than that entering through the Windward Passage (Figs. 5, 12), with the Cayman basin as a whole more than 0.5 cc per liter richer than the Caribbean, both basins being 0.5 to 1.0 cc per liter poorer than the adjacent Atlantic at corresponding latitudes.

#### BELOW THRESHOLD DEPTHS

At 2500 meters depth the separation of the two basins is complete, one from the other, and the Caribbean is completely isolated from direct communication with the open Atlantic; the Cayman, however, is apparently still in direct communication with the latter through the Windward Passage (Fig. 2).

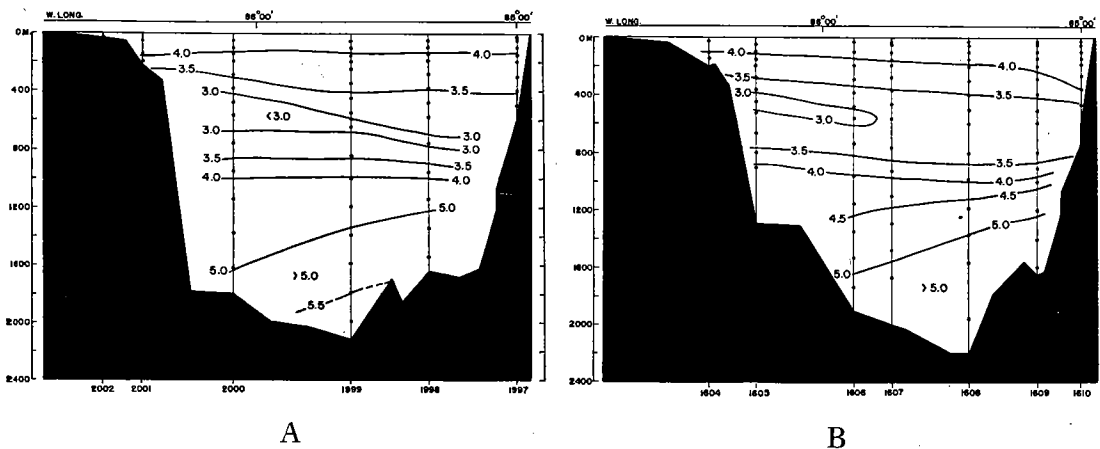


FIG. 15. Oxygen distribution (cc per liter) across Yucatan Channel: A, based on 1933 "Atlantis" data (stations 1604-1610), and, B, based on 1934 "Atlantis" data (stations 1997-2002); profile 8.

Corresponding to this enclosure, complete for the one basin and nearly so for the other, oxygen distribution is horizontally more nearly uniform than at shoaler depths. Even in the Caribbean basin, however, the profiles (Figs. 10, 18, 19) in combination with horizontal projection (Fig. 20) show that significant regional horizontal gradients still persist even to 2500 meters, which may be summarized as a decrease westward in the southern part of this basin, contrasting with a general increase westward in the northern, which may have been brought about by admixture with Atlantic water entering the Windward Passage, the precise distribution being more easily represented by the isolines laid down on Figure 20, than verbally.

In the Cayman basin at this level oxygen content was in general 0.5-1.0 cc per liter higher than in the Caribbean (Fig. 4, 20) undoubtedly due to the influence of the Windward Passage. Within this basin significant differences in oxygen content were found in the deep water north and south of Grand Cayman, resulting evidently from the bathymetric features, and especially from the fact that the deep water (more than 3000 meters) between Cuba and Grand Cayman appears to have its principal communication with

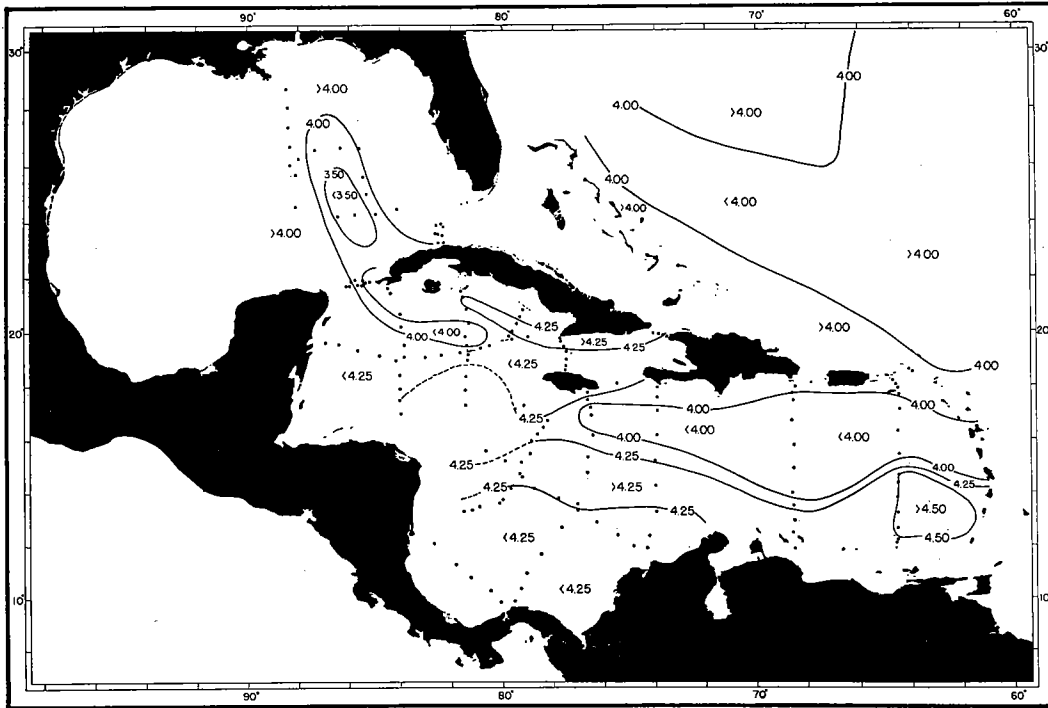


FIG. 16. Horizontal distribution of oxygen (cc per liter) at 1000 meters depth (based on combined 1933 and 1934 "Atlantis" observations).

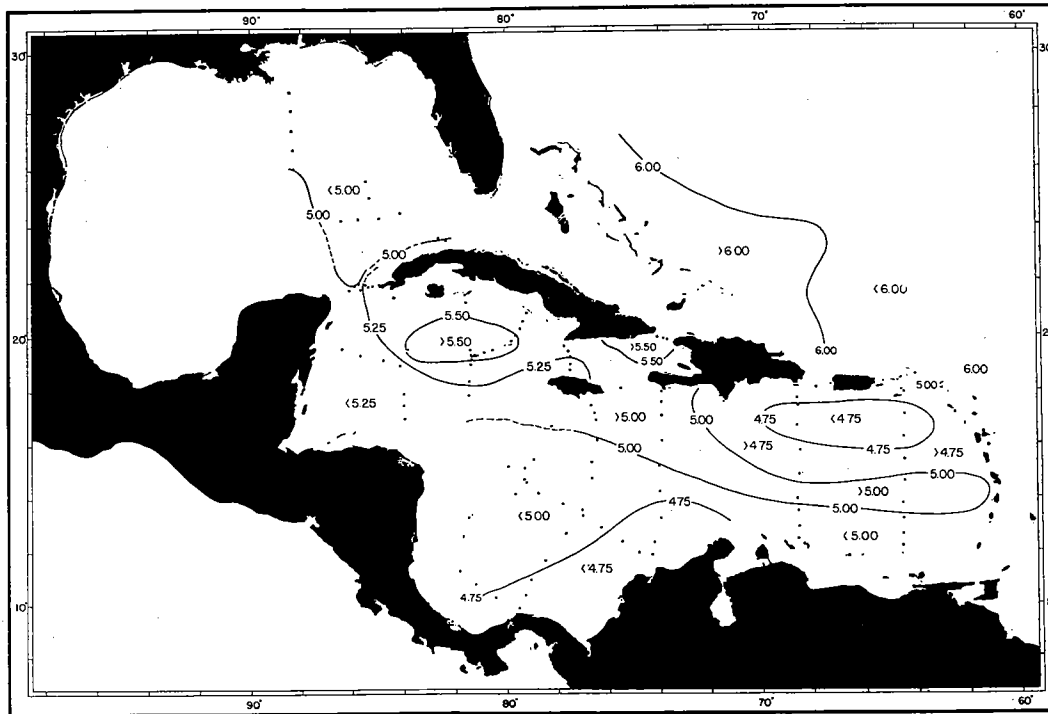


FIG. 17. Horizontal distribution of oxygen (cc per liter) at 1500 meters depth (based on combined 1933 and 1934 "Atlantis" observations).



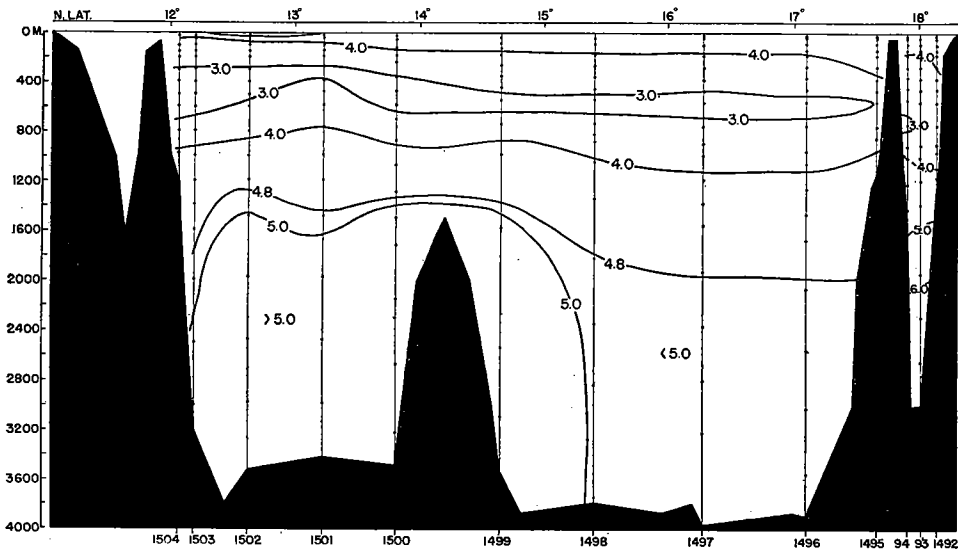


FIG. 18. Oxygen distribution (cc per liter) across eastern part of Caribbean basin (stations 1492-1504); profile 1.

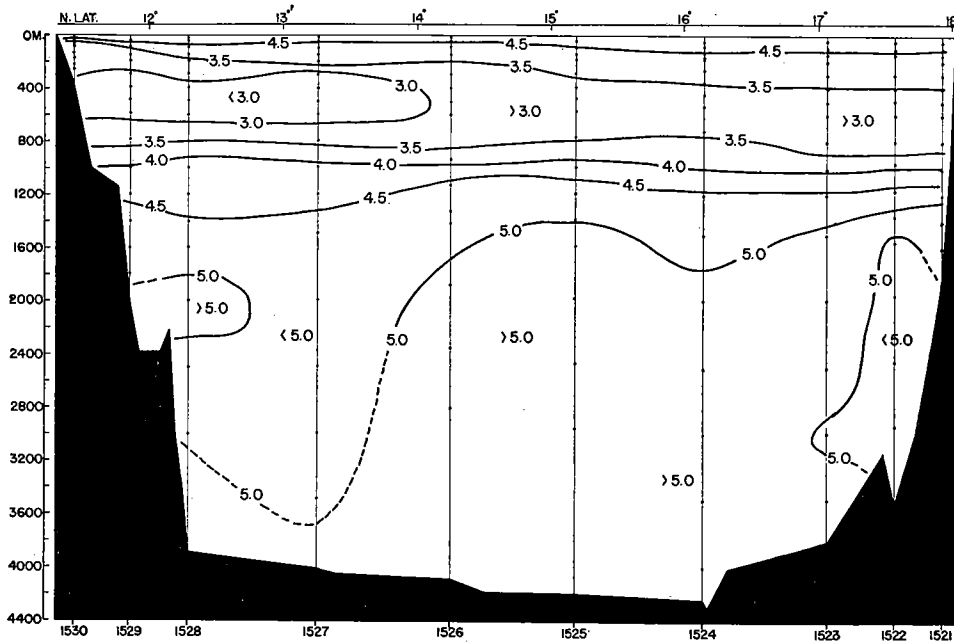


FIG. 19. Oxygen distribution (cc per liter) across west central part of Caribbean basin (stations 1521-1530); profile 3.

Windward Passage in a roundabout way, via the western end of the deep gully (more than 5000 meters deep) which extends transversely, south of Grand Cayman (Fig. 2). Thus, although at 2000 meters depth, oxygen content north of Grand Cayman was lower (less than 6.0 cc per liter) than that south of Grand Cayman (more than 6.0 cc per liter; Fig. 10), it was about equal to the oxygen content further west, north of Misteriosa Bank,

which, in turn was about 0.1–0.2 cc per liter lower than recorded south of Misteriosa Bank (Fig. 21). This condition seems to indicate that a certain amount of renewal takes place in the northern gully (Fig. 2) through the saddle depth (of more than 2000 meters) between Grand Cayman and Misteriosa Bank.

In the deepest parts of the two basins oxygen conditions may be illustrated by values recorded at 3500 meters and at 4500 meters. At these depths both basins are completely isolated not only one from the other, but from the surrounding Atlantic; horizontal

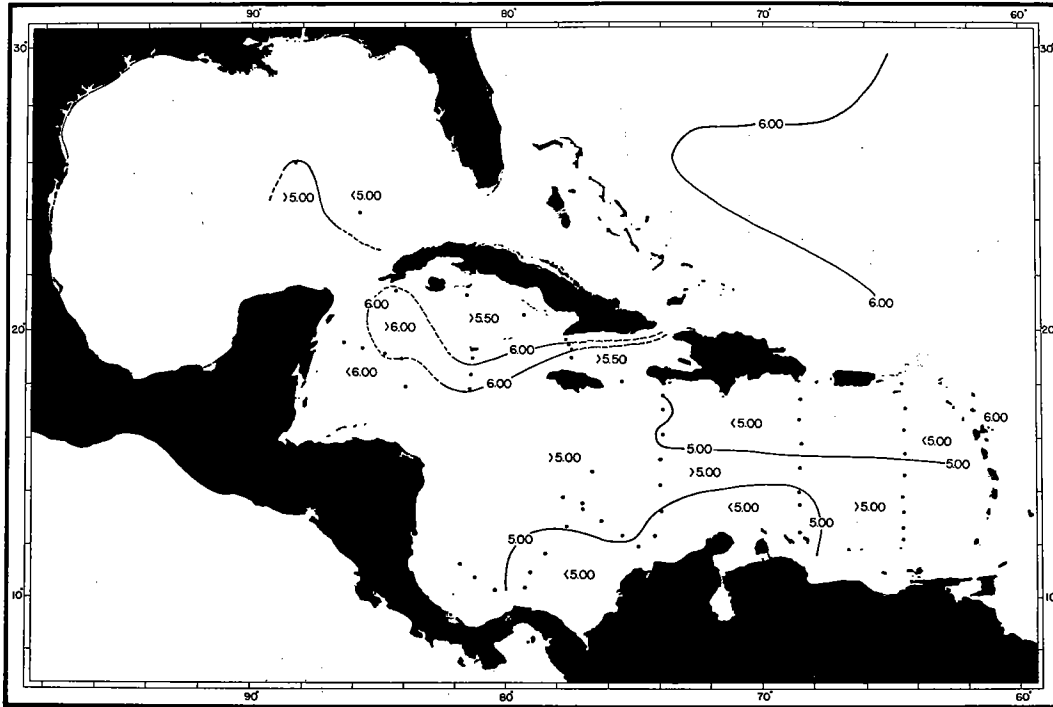


FIG. 20. Horizontal distribution of oxygen (cc per liter) at 2500 meters depth (based on combined 1933 and 1934 "Atlantis" observations).

gradients are, consequently, so small that the courses of the isolines shown on Figure 22 may have little meaning.

In the Caribbean basin a mean (calculated) oxygen content of 5.15 cc per liter for 3500 meters (Fig. 9) contrasts with 5.18 cc at 4500 meters, which last was 0.75 to 1 cc per liter less than for surrounding Atlantic waters. In the Cayman basin oxygen variation at great depths is illustrated by Figures 5, 10, and 21 as compared with Figure 22. The mean calculated oxygen content here was 5.76 cc per liter at 3500 meters and 5.84 cc per liter at 4500 meters, the latter only about 0.25 cc per liter less than that of neighboring Atlantic water.

In Yucatan Channel (through which the Caribbean water enters the Gulf of Mexico; Fig. 15) the average oxygen content (0–2000 meters) was 0.14 cc per liter lower in 1933 than that of the upper 2000 meters of the Cayman basin, while the average was slightly

lower still in the Straits of Florida (0-1500 meters; Fig. 6). Thus, the main Caribbean current, losing oxygen in the Caribbean basin, is enriched in the Cayman basin by inflow through the Windward Passage, after which its oxygen decreases continually as it moves through the Yucatan Channel and Gulf of Mexico.

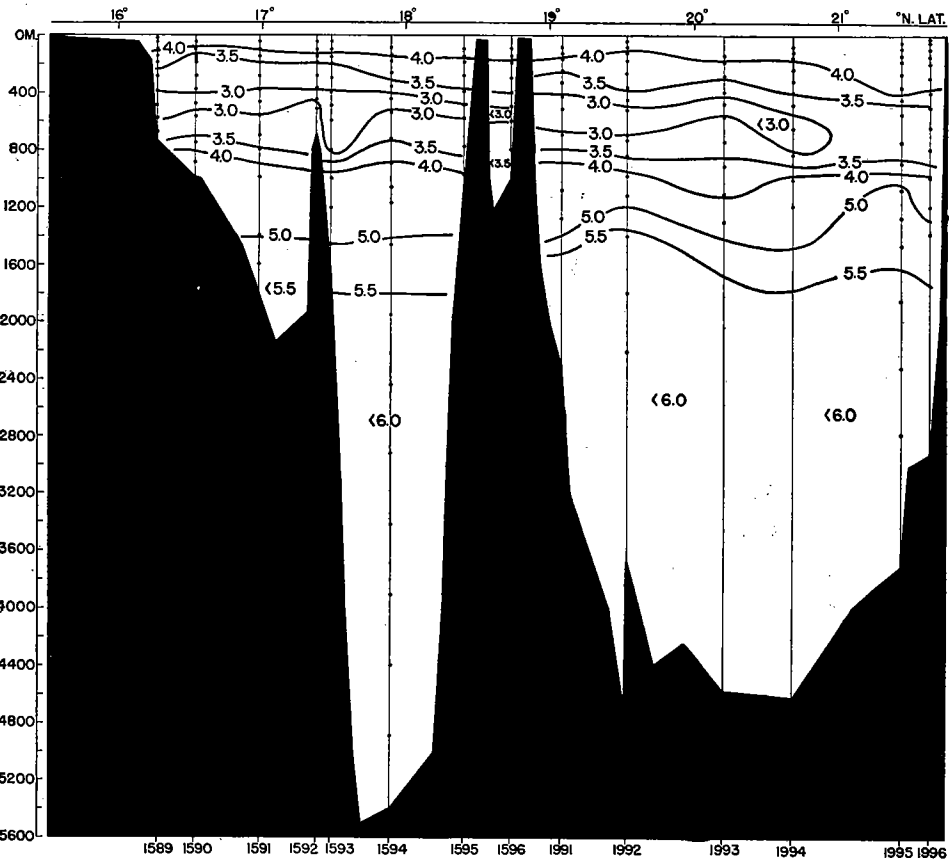


FIG. 21. Oxygen distribution (cc per liter) across west central part of Cayman basin (composite section based on "Atlantis" 1933 and 1934 data; stations 1991-1996 and 1589-1596), profile 7.

Beyond the Straits of Florida the Gulf Stream is characterized by a minimum oxygen concentration about 0.5 cc per liter lower than that of adjacent Atlantic water (Seiwell, 1934, 1937b). But, after leaving the Straits, the minimum oxygen increases downstream, in the current, until north of  $40^{\circ}\text{N}$  there is no significant difference, in this respect, between Gulf Stream and Sargasso Sea waters.<sup>4</sup>

<sup>4</sup> In this connection, see Rossby (1936) for discussion of lateral mixings.

## RELATION OF OXYGEN DISTRIBUTION TO PHYSICAL PROPERTIES OF THE WATER

### SUMMARY OF PHYSICAL PROPERTIES

Oxygen content of the sea is a consequence of amounts of oxygen utilized and oxygen supplied, and the observed distribution over large parts of the ocean basins may, in all probability, be taken to be constant as a result of the stability of adjustment between the existing biochemical and physical processes. Thus, in the Caribbean Sea region,

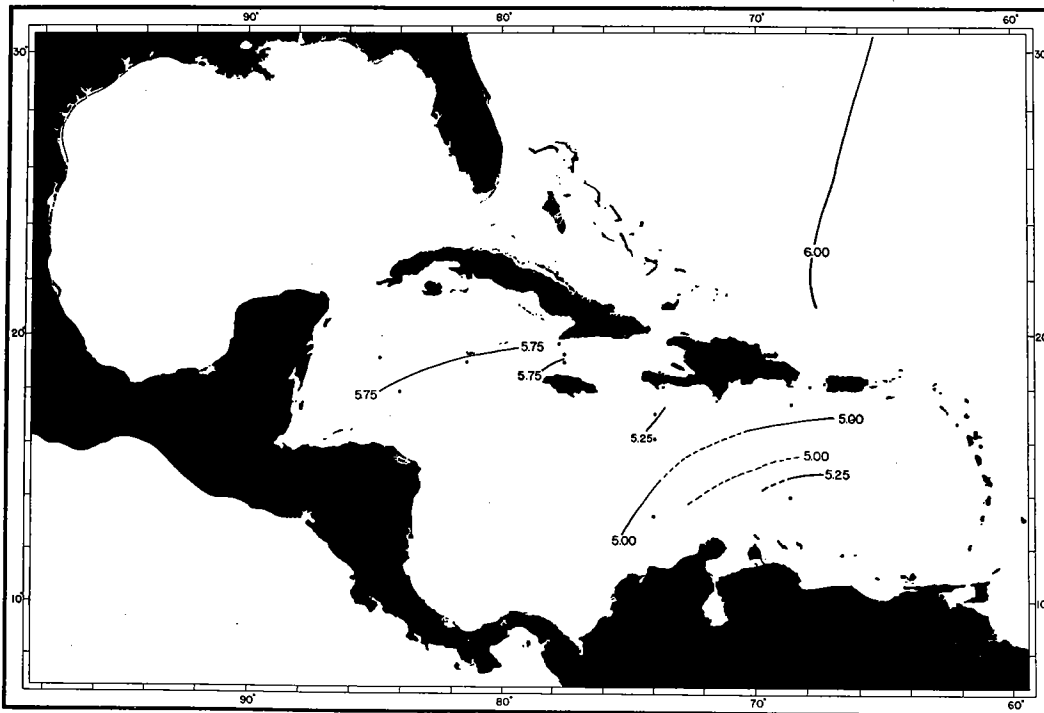


FIG. 22. Horizontal distribution of oxygen (cc per liter) at 3500 meters depth (based on combined 1933 and 1934 "Atlantis" observations).

characterized by definite regional oxygen variations, an effort is made to ascertain certain of the salient relationships between oxygen distribution and the hydrographical features (indicated by the conservative properties: temperature and salinity). Results are based partly on earlier investigations, and partly on "Atlantis" temperature and salinity data, recently discussed by Parr (1937).

#### *Temperature and Salinity*

Figures 23 and 24 illustrate that the rapid decline of temperature, beginning at approximately 100 meters (mean value  $24^{\circ}$  to  $26^{\circ}$ ), continued to 1000–1100 meters (usually  $4.5^{\circ}$ – $5^{\circ}$ ); below which the decrease continued at a much slower rate to a minimum value at approximately 2000 meters depth in the Caribbean and 2500 meters depth

in the Cayman basin. Below depths of 1200 meters, vertical variations of temperature were less than  $0.5^{\circ}$ ; between 1500 and 4000 meters the mean of all temperature observations (259), both from Caribbean and Cayman basins (obtained by "Atlantis" in 1933 and 1934), was  $4.107^{\circ}$ , with an average deviation of  $0.042^{\circ}\text{C}$ .<sup>5</sup>

Certain features in the salinity of the Caribbean Sea region are useful in associating its water masses with the adjacent Atlantic. In vertical distribution this property (Fig. 23) increased from the surface (about  $35.2\text{--}36.8\text{ ‰}$ ) downward to an intermediate maximum ( $36.5\text{--}37.0\text{ ‰}$ ) between 100 and 200 meters depth, suggesting water of origin to the north and east of the Caribbean (Jacobsen's (1929) area VI); and, in deeper water it declined to a minimum value ( $34.65\text{--}34.95\text{ ‰}$  at approximate depths of 700–800

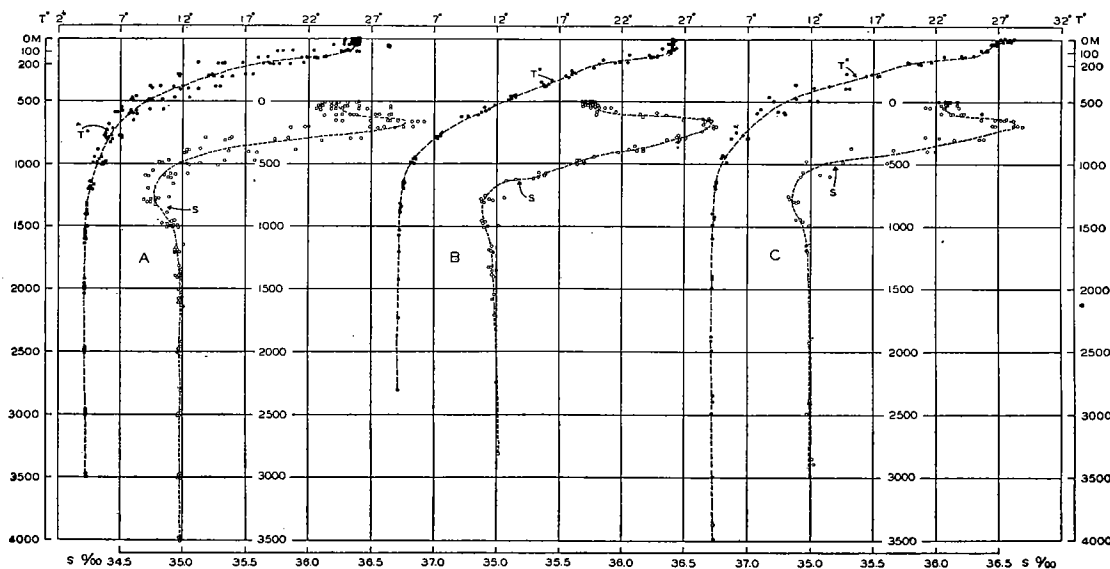


FIG. 23. Vertical distribution of temperature and salinity in Caribbean Sea: A= east central part of Caribbean basin (stations 1505–1515), B= northern east central part of Cayman basin (stations 1982–1987), C= southern part of east central Cayman basin (stations 1580–1584).

meters), apparently indicating water of subantarctic origin which has entered the Caribbean from the east.<sup>6</sup> In the still deeper water, salinity increased ( $0.3\text{ ‰}$  more) at first rapidly, and then less so, to depths of about 1100 meters, below which it was reasonably constant along any vertical. Between depths of 1500 and 4000 meters the average salinity of the entire Caribbean Sea region (245 observations) was calculated to be  $34.977\text{ ‰}$ , with an average deviation of  $0.012\text{ ‰}$ .

#### Density

Immediately below the homogeneous layer (between 100 and 200 meters) occurred the most stable part of the water column, with a maximum stability at approximately 150 meters where the mean vertical variation of  $\sigma_t$  per centimeter for the two basins was

<sup>5</sup> Values not corrected for adiabatic warming.

<sup>6</sup> This water, identified by an intermediate salinity minimum, found everywhere throughout the Caribbean Sea region (page 34) may represent the last remnant of water of subantarctic origin which has entered from the North Atlantic (see Wüst, 1936).

approximately:  $\Delta\sigma_t/\Delta z = 2.4 \times 10^{-4}$  (Fig. 24). Below depths of 200 meters the mean value of  $\Delta\sigma_t/\Delta z$  declined to  $3.5 \times 10^{-5}$  at 300 meters; to  $1.6 \times 10^{-5}$  at 500 meters; below 600 meters it was  $1.2 \times 10^{-5}$  or less; at 1000 meters depth the mean value of  $\Delta\sigma_t/\Delta z$  was approximately  $5 \times 10^{-6}$ . In still deeper water, observed values of  $\sigma_t$  varied still less; between depths of 1500 and 4000 meters the mean density (based on observed temperatures and salinities from both basins) was calculated to be:  $\sigma_t = 27.780$ , with an average deviation of only 0.011.

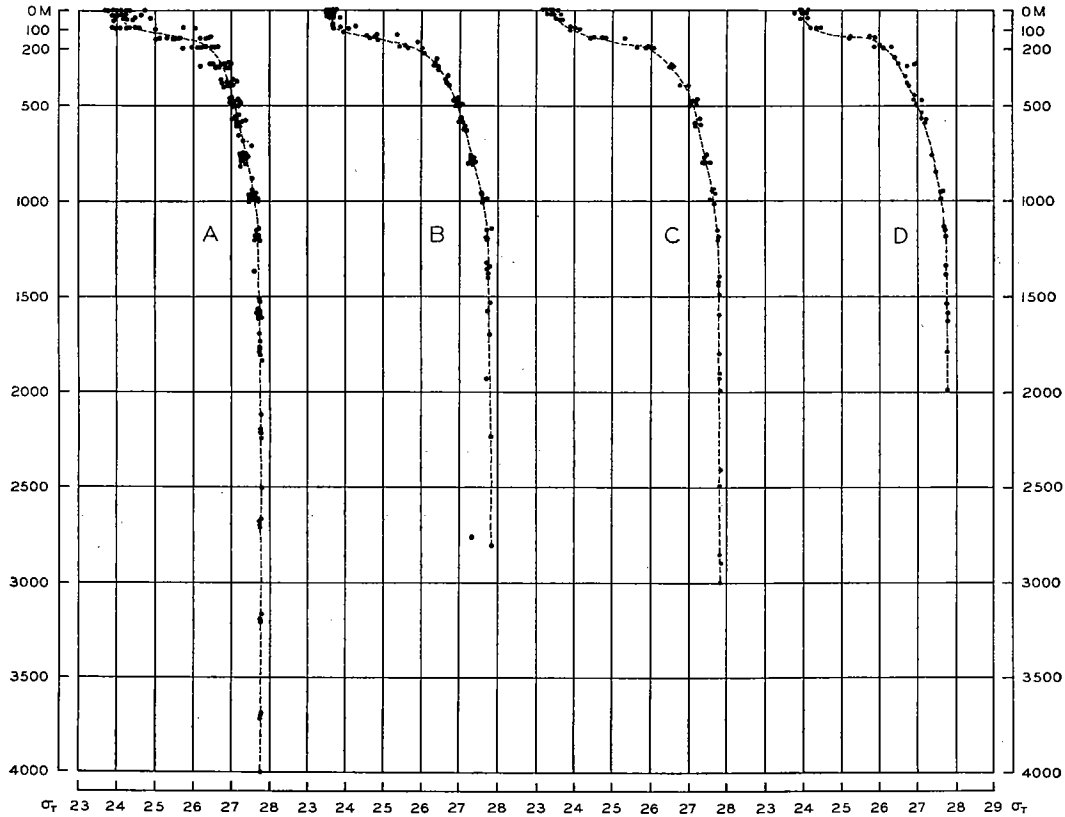


FIG. 24. Vertical distribution of density in Caribbean Sea: A= east central part of Caribbean basin (stations 1505-1515), B=northern east central part of Cayman basin (stations 1982-1987), C=southern east central part of Cayman basin (stations 1580-1584), D=Yucatan Channel (stations 1997-2000).

The horizontal spread of temperature, salinity, and density values particularly in the upper levels (Figs. 23 and 24) is associated with a transverse tilting of the isothermal, isohaline, and isopycnal surfaces. For purposes of later discussion (page 41) the transverse density situation across the east central Caribbean basin (as shown by stations 1505-1515; Fig. 25) is considered briefly. The south-north downward tilting of the isopycnal surfaces was confined principally to the upper 1000 meters of the water column; thus, on the northern side of the basin the 25.00 isopycnal surface lay approximately 80 meters deeper, the 26.00 surface approximately 120 meters deeper, the 27.00 surface approximately 160 meters deeper, and the 27.50 surface approximately 140 meters deeper. Transversal changes in vertical stability arise as a result of different inclinations

of the isopycnal surfaces; as for instance, the 25.00 and 26.00 surfaces are separated by intervals of about 40 meters on the southern side and by about 80 meters on the northern side, while the 26.00 and 27.00 surfaces are separated by approximately 230 and 270 meter intervals respectively.

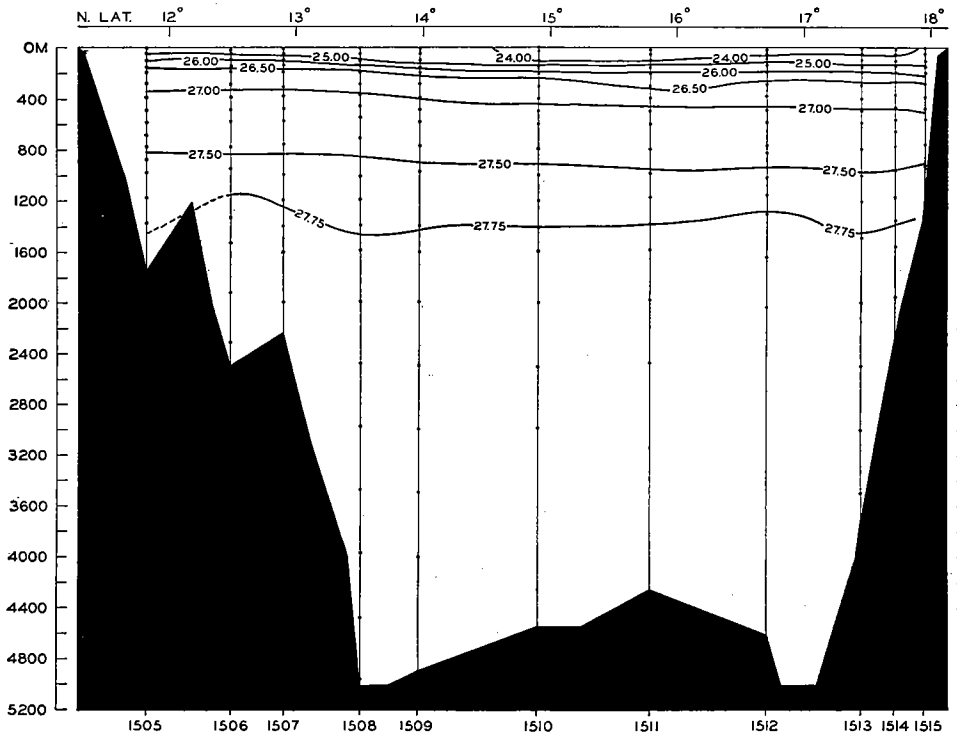


FIG. 25. Density ( $\sigma_t$ ) distribution across east central part of Caribbean basin (stations 1505-1515); profile 2.

## GENERAL OXYGEN SALINITY RELATIONSHIPS

### *Introduction to the Method*

The use of identifying properties of sea water (temperature, salinity, oxygen, etc.) in various combinations is frequently helpful in supplementing and corroborating results obtained from application of the Bjerknes' dynamic method, and, under certain circumstances, as for instance, in strata identified by secondary maxima or secondary minima (of one or both of the properties involved in the relationship) is useful in tracing the mean trajectories when the time factor involved is sufficiently large. A distinct advantage possessed by a combination of identifying properties is that the actual relationship is independent of the depth scale so that the hydrographic picture is not distorted by, for instance, short period vertical movements of the water masses as may be the case when properties of the water are studied as functions of depth (Seiwell, 1937a).

The oxygen salinity relationship in hydrographical investigations finds its counterpart in the temperature salinity correlation introduced by Helland-Hansen (1918) and used extensively by him (1926, 1930) and other oceanographers in circulation studies of the Atlantic. The use of oxygen salinity relationships as a means of characterizing water masses appears to have been suggested by Jacobsen (1929) and has been used by Rossby (1936) as a means of indicating the mass exchange between the Gulf Stream and its surroundings in the western North Atlantic.<sup>7</sup> A sharp distinction, based on conservatism, separates the use of identifying properties of sea water into two categories. The choice of the oxygen-salinity or of the temperature-salinity relationship for hydrographical purposes should, therefore, depend on the existing circumstances; the latter combining two conservative properties, being applicable, chiefly, to the study of variations resulting from mixing of water masses having different physical properties, whereas, the former, which forms a non-conservative combination, is useful in the study of small variations in a water mass of more uniform properties.

Thus, combination of oxygen and salinity values to form an oxygen salinity relationship is useful in tracing certain principal horizontal water movements, between depths of approximately 200–1000 meters, in the Caribbean Sea region. The part of the water column to which the method is applicable is determined by certain disturbing factors (such as phytoplanktonic growth and contact with the atmosphere) which, above depths of approximately 200 meters, may cause complex local variations; and by the magnitude of salinity variations which, below depths of approximately 1000–1200 meters, are too small to permit the relationship to be of differential value. In the Caribbean region these limitations have not caused serious concern since the main horizontal movement of its water masses involves chiefly the upper 1000 to 1200 meters.

Within that part of the sea shut off from contact with the atmosphere the non-conservatism of oxygen is due to the biological activity of the water mass, and since plant growth, the only known chemical means by which the oxygen content of the seas can be increased, is limited to the topmost layer of the sea, the average concentration of oxygen in the greater part of the water mass will decrease with time because of oxidation of its suspended organic matter. The rate of consumption of oxygen from the deeper parts of the sea has been estimated for the central North Atlantic (along the 40th meridian), between 0° and 35°N (Seiwell, 1934), to be approximately 0.42 cc per liter per year for the oxygen poor layer (mean depth 700–800 meters) at mid-depths (containing less than 60 per cent of the amount required for saturation) and 0.103 cc per liter per year for the deeper water between the position of the lower 60 per cent isoline of relative oxygen saturation (1200–1300 meters) and 2000 meters depth. However, the loss of oxygen from this deeper water is not entirely due to consumption, in situ, but in part, to an upward transport by eddy motion of the water.

#### *The Atlantic Waters North and East of the Caribbean*

The oxygen salinity relationships of neighboring localities, north and east of the Caribbean, from whence water masses enter the various passageways among the Antillean islands showed a consistent north south decline in oxygen content along the isohaline surfaces, to depths of approximately 1000 meters (Fig. 26A) as illustrated by stations

<sup>7</sup> Dietrich (1937) has studied oxygen temperature relationships in the western North Atlantic in connection with his study of the origin of the Gulf Stream waters. Methods involving oxygen salinity or oxygen temperature combinations should give essentially the same results.



1208 ( $20^{\circ} 38'N$ ,  $68^{\circ} 36'W$ ), 1210 ( $22^{\circ} 14'N$ ,  $67^{\circ} 50'W$ ) and 1212 ( $23^{\circ} 46'N$ ,  $67^{\circ} 24'W$ ), lying approximately 150 to 350 miles north of Mona Passage. There was no evidence of a salinity minimum concentration at mid depths and in still deeper water, oxygen salinity relationships tended to become constant. A mid depth salinity minimum concentration, which has a great significance in the Caribbean region, first appeared further south, in the waters, just northeast of the Caribbean ("Dana" station 1185:  $17^{\circ} 41'N$ ,  $60^{\circ} 58'W$ ), between depths of 800–1000 meters, marking the principal divergence, in oxygen salinity relationship, from that of the waters immediately to the north. Still further south, just

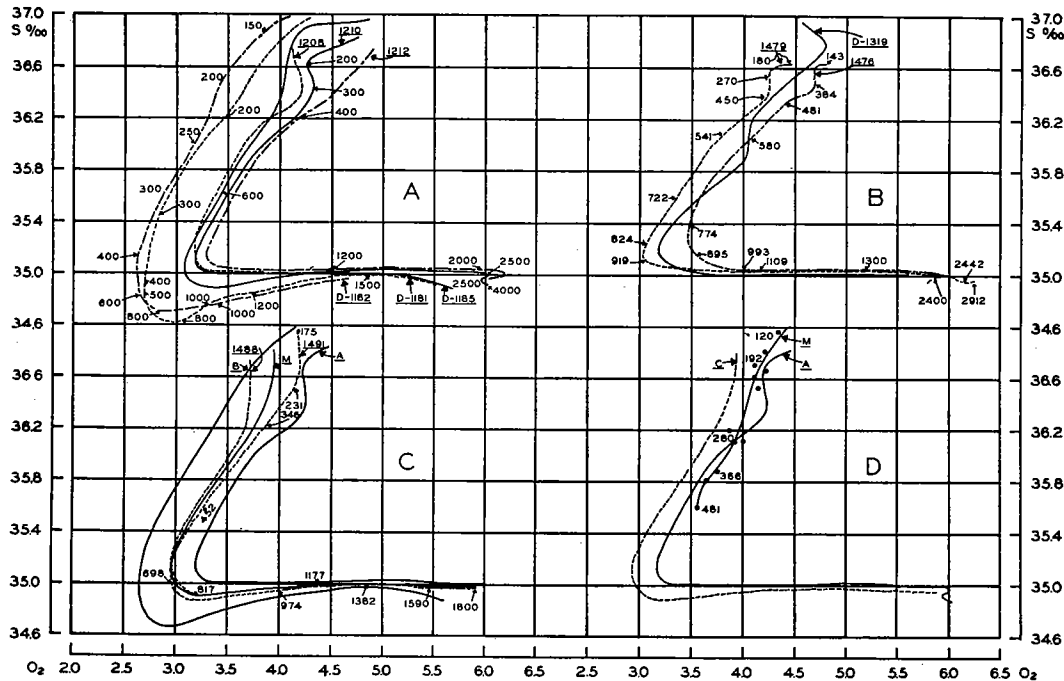


FIG. 26. Oxygen salinity relationships in Caribbean basin and adjacent waters. A=immediately north of Caribbean ("Atlantis" stations 1208,  $20^{\circ} 38'N$ ,  $68^{\circ} 36'W$ ; 1210,  $22^{\circ} 14'N$ ,  $67^{\circ} 50'W$ ; and 1212,  $23^{\circ} 46'N$ ,  $67^{\circ} 24'W$ ), and immediately east of Caribbean ("Dana" stations D-1181,  $13^{\circ} 07'N$ ,  $57^{\circ} 20'W$ ; D-1182,  $13^{\circ} 03'N$ ,  $59^{\circ} 50'W$ ; and D-1185,  $17^{\circ} 41'N$ ,  $60^{\circ} 58'W$ ). B=other localities north of Caribbean ("Atlantis" stations 1476,  $26^{\circ} 42'N$ ,  $76^{\circ} 32'W$ ; 1479,  $25^{\circ} 47'N$ ,  $72^{\circ} 10'W$ ; and "Dana" station 1319,  $22^{\circ} 43'N$ ,  $61^{\circ} 43'W$ ). C=comparison of mean relationships for water north of Caribbean ("Atlantis" stations 1208 and 1210, curve A) and of water east of Caribbean ("Dana" stations D-1181 and D-1182; curve B) with those for Anegada Passage (stations 1489–1491; points indicate observed values for which curve M is the mean relationship). D=comparison of oxygen salinity relationship of "Atlantis" stations 1208 and 1210 (curve A) and the mean for Anegada Passage (curve M); points indicate observed values for Mona Passage; numerals along curves indicate depths of observed values.

east of the Caribbean ("Dana" stations 1181:  $13^{\circ} 07'N$ ,  $57^{\circ} 20'W$  and 1182:  $13^{\circ} 03'N$ ,  $59^{\circ} 50'W$ ), distinct differences in the oxygen salinity relationship result from lower oxygen contents (approximately 0.5 cc per liter, above 1200 meters) for similar salinities, and from pronounced salinity minima.

Thus, the water masses which apparently enter the Caribbean Sea region from the east, through the passages among the lesser Antilles (in particular Martinique and St. Lucia Channels) showed an oxygen salinity relationship different from that of the waters which apparently enter the region from the north (through Mona and Anegada Passages). This difference is due both to transition of oxygen content along the isohaline surfaces

and to the presence or absence of a minimum salinity concentration at mid depths. The latter, which has been used by Wüst (1935) to represent the range of subantarctic influence is not detectable in the Atlantic waters adjacent to the Caribbean north of latitude 18°N.

In the Atlantic water immediately north of the Caribbean, a definite, although less pronounced transition in oxygen salinity relationship, appears to take place east to west in the upper 1000 meters (Fig. 26B). The manner in which this occurred is clarified by comparing charts of horizontal distribution of oxygen showing an east west oxygen gradi-

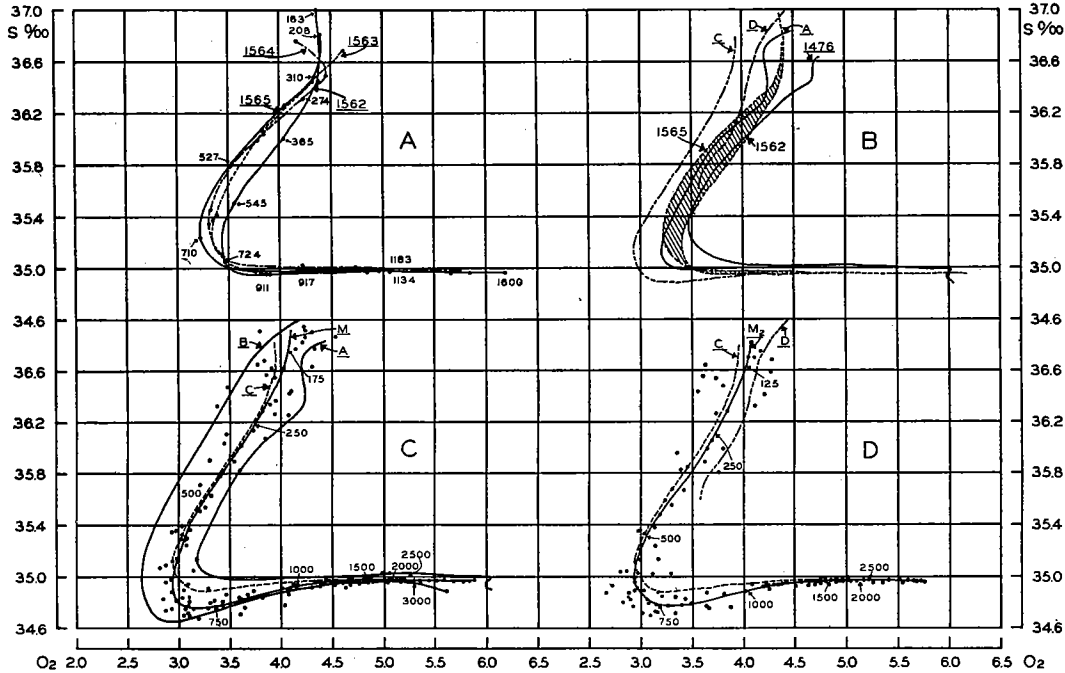


FIG. 27. Oxygen salinity relationships for Caribbean basin and its passages to the open Atlantic. A=Windward Passage (stations 1562-1565). B=comparison of oxygen salinity relationships of Windward Passage (between stations 1562 and 1565; shaded area) with mean of stations 1208 and 1210 (curve A), the mean of Mona Passage (curve D), mean of Aneгада Passage (curve C) and station 1476. C=eastern Caribbean (stations 1492-1504; mean of observations given by curve M) compared with the mean of station 1208 and 1210 (curve A), the mean of stations D-1181 and D-1182 (curve B), and the mean of Aneгада Passage (curve C). D=east central Caribbean basin (stations 1505-1515; mean given by curve M) compared with mean of Mona Passage (curve D). Depths of observed values indicated along curves.

ent at practically all levels immediately north of the Caribbean (Seiwell, 1934) with charts of horizontal distribution of salinity (Wüst and Defant, 1936), showing similar salinity gradients in the same locality although not sufficiently great to offset a transition in the oxygen salinity relationship.

#### *The Passageways Communicating between the Atlantic and Caribbean Sea Region*

The oxygen salinity relationships in Aneгада Passage (based on "Atlantis" stations 1489-1491) occupied an almost central position between the means for stations 1208 and 1210 (characterizing the Atlantic water to the north) and stations D-1181 and D-1182 (to the east; Fig. 26C) with a well defined intermediate salinity minimum which did not exist in the Atlantic water to the north. This indicates that the water masses of this

passage are mixtures of the waters from the east with the more saline and oxygen richer waters from the north.

The mean oxygen salinity relationship for Mona Passage (based on stations 1516 to 1518), as compared with the mean for stations 1208 and 1210, and for Anegada Passage (Fig. 26D) gives no definite indication of mixture with the water from the east of the Caribbean, but suggests a close relationship with the Atlantic water north of the Caribbean. The oxygen content of Mona Passage (to depths of about 500 meters) was about 0.3 cc per liter higher than in Anegada Passage.

The oxygen salinity relationships for four stations (1562-1565), extending in an almost east west direction across the narrowest part of Windward Passage showed a greater spread of values than for the other two passageways (Fig. 27A); also, a definite west to east gradient between depths of approximately 300 and 800 meters, with the lowest oxygen values on the western side of the isohaline surfaces. This represents a transition from the mean of stations 1208 and 1210 to that of station 1476 (Fig. 27B). Between depths of 300 and 500 meters, the mean oxygen salinity relationship was approximately the same for Windward Passage as for Mona Passage, while its oxygen content was 0.3 to 0.4 cc per liter higher at depths above 800 meters than that for identical salinities in Anegada Passage. But, at depths below 800-900 meters oxygen salinity relationships appeared to be practically identical for the two deep passages, both having slightly lower salinities than the Atlantic water to the north.

#### *The Caribbean Basin*

The analysis of data for this basin is based on oxygen salinity relationships from four "Atlantis" sections: eastern Caribbean (stations 1492-1504; March 11-15, 1933; Fig. 27C), east central Caribbean (stations 1505-1515; March 21-24, 1933; Fig. 27D), west central Caribbean (stations 1521-1530; March 28-31, 1933; Fig. 28A), and northwest Caribbean (stations 1556-1561; April 15-16, 1933; Fig. 28B), the first three of which extended in a north to south direction across the basin, and the latter in an almost east west direction across the Windward Passage entrance into the Caribbean (Fig. 1).

For the eastern Caribbean, the mean oxygen salinity relationship curve (indicated by  $M_1$  in Fig. 27C) followed closely the mean curve for stations D-1181 and D-1182 (representing Atlantic water east of the Caribbean) to depths of approximately 1500-2000 meters, where the eastern Caribbean and the Anegada curves again fall together. The divergence of the eastern Caribbean curve from the Anegada Passage curve below 600 meters is primarily a result of the marked salinity minimum (about 750 meters) characterizing the former, and may be taken as evidence that inflow of water into the eastern Caribbean basin through Anegada Passage (and other passages along the northern border of the Caribbean) diminished in the vicinity of 600 meters depth; and, in still deeper water, the inflow of Atlantic water from the east and southeast predominated, only to diminish at about 1500 meters and to be replaced in the greater depths by water from the Atlantic north of the Caribbean. This concept, in general, supports previous conclusions that the upper water masses of the Caribbean are derived from the waters of Jacobsen's (1929) area VI which enters through Anegada and other passages between the greater Antilles, whereas, the major portion of the deeper layers around the salinity minimum are derived from Jacobsen's area XIV entering between the lesser Antilles<sup>8</sup> (chiefly Martinique and St. Lucia Channels).

<sup>8</sup> Curve B (Fig. 27C) represents the mean of stations D-1181 and D-1182 located in Jacobsen's (1929) area XIV, and curve A (Fig. 27C) represents the mean of stations 1208 and 1210 located in Jacobsen's area VI.

Oxygen salinity correlation for the east central Caribbean (the mean curve of which is compared with means from Anegada and Mona Passages in Fig. 27D) was, with the exception of a slight withdrawal of the minimum salinity concentration (at approximately 750 meters depth), almost identical with that for the eastern Caribbean. In spite of the proximity of this locality to Mona Passage, the oxygen richer water of the latter appears to have exerted a perceptible influence only in its immediate vicinity.

The mean oxygen salinity relationship of the west central Caribbean (stations 1521-1530; Fig. 28A) was, with the exception of a continual weakening of the minimum

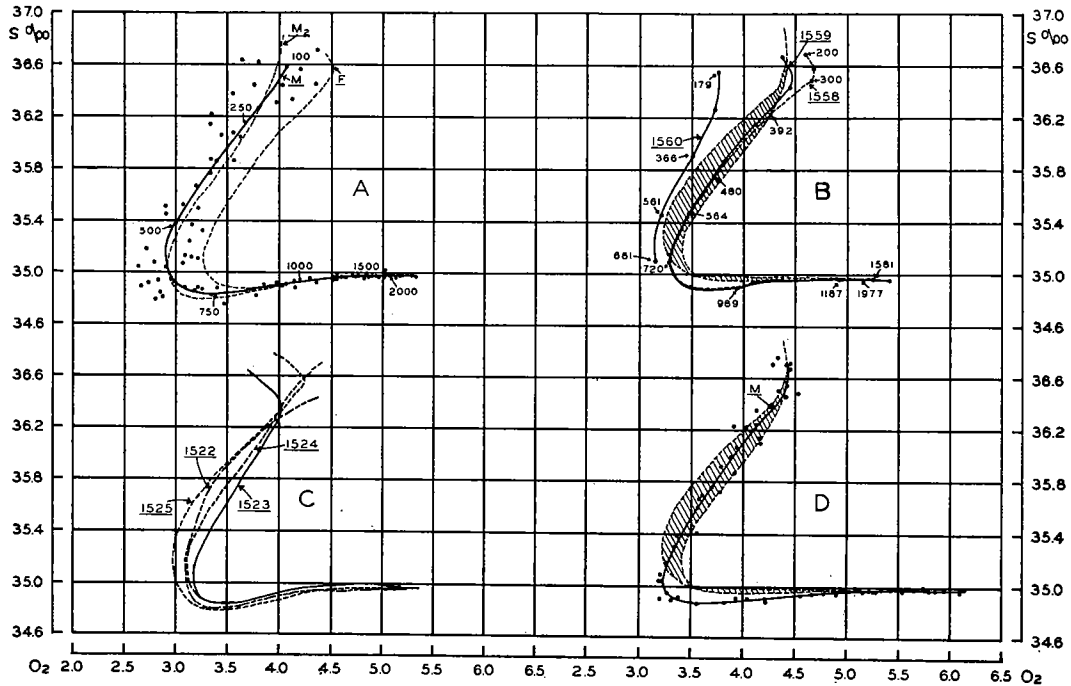


FIG. 28. Oxygen salinity relationships for Caribbean basin and its passages to the open Atlantic. A=west central Caribbean basin (stations 1521-1530; mean given by curve M) compared with the mean for east central Caribbean (curve M<sub>2</sub>) and the mean for stations 1558 and 1559 (between Hispanola and Jamaica; curve F). B=waters between Hispanola and Jamaica (stations 1558-1560) compared with the oxygen salinity range for Windward Passage (shaded area). C=northern half of the west central Caribbean (stations 1522-1525). D=waters between Jamaica and Cuba (stations 1567-1572; mean given by curve M) compared with the Windward Passage (shaded area). Depths of observations are indicated along curves.

salinity concentration (the result of continuous mixing with adjacent water masses; page 34), but little different from that demonstrated for the east central Caribbean basin. Hence, the oxygen richer water over the central part of Jamaica Hispaniola ridge (approximate depth 1500 meters; stations 1558 and 1559), which, except in the vicinity of the salinity minimum,<sup>9</sup> has essentially the same oxygen salinity relationship as Windward Passage (Fig. 28B), appeared to exert only a small influence in the Caribbean basin proper (brought out by a comparison of its mean oxygen salinity relation curve with that for the west central Caribbean basin). The maximum modification by Windward Passage

<sup>9</sup> The divergence of oxygen salinity relationship of the water masses over the Jamaica Hispaniola Ridge, from that characterizing Windward Passage, in the vicinity of the minimum salinity concentration, may arise as a result of marked influence of subantarctic water in interrupting inflow from the open Atlantic at mid depths.

water (along the west central Caribbean section) occurred in the area represented by station 1523 (Fig. 28C).

It is significant that the water in Windward Passage, which has been shown to possess a higher oxygen content along its isohaline surfaces than that in any other passage opening to the Atlantic, should contribute so little to the Caribbean basin, but have such a marked influence on the circulation of the Cayman basin. Thus, the Atlantic water masses moving in through Windward Passage appear to be mainly deflected to the right and to enter the Cayman basin between Jamaica and Cuba.

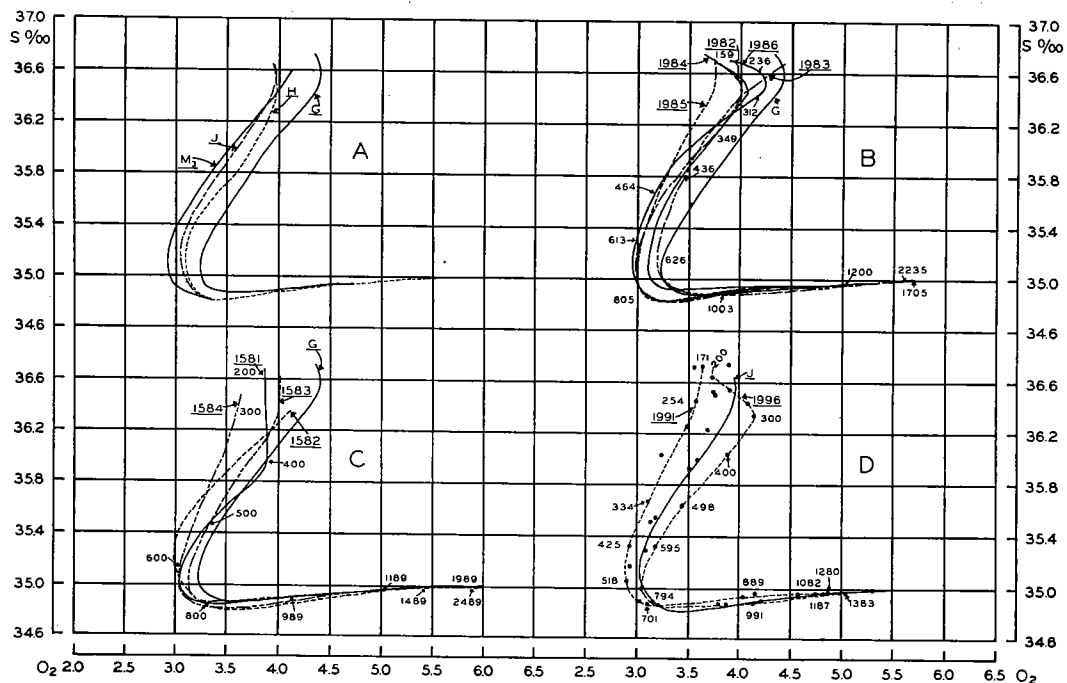


FIG. 29. Oxygen salinity relationships in the Cayman basin. A = comparison of mean values of west central Caribbean basin (stations 1521-1530; curve  $M_3$ ), of waters between Jamaica and Cuba (stations 1567-1572; curve G) of the southern east central Cayman basin (stations 1580-1584; curve H), and of the northern east central Cayman basin (stations 1982-1987; curve J). B = northern east central Cayman (stations 1982-1986) compared with the mean between Jamaica and Cuba (curve G). C = southern east central Cayman basin (stations 1581-1584) compared with the mean between Jamaica and Cuba (curve G). D = northern west central Cayman basin (stations 1991-1996) compared with the mean for the southern east central Cayman (curve J).

### The Cayman Basin

Oxygen salinity relationship in the extreme eastern Cayman basin (indicated by a line of stations, 1567-1573, extending northward from Jamaica to Cuba; Fig. 28D) was essentially the same as recorded for Windward Passage with the exception of a divergence occurring at the depth of the salinity minimum concentration (page 34). In the east central part of this basin Figures 29A, 29B, 29C show the influence of inflow through Windward Passage in raising the oxygen content along isohaline surfaces of the main Caribbean current moving from the Caribbean to the Cayman basin. The Windward Passage inflow, however, appears to be reduced in the vicinity of the salinity minimum.

As previously shown (page 15), the nature of the local circulation produces distinct

differences in oxygen content of the water masses north and south of Grand Cayman, and comparison of the mean oxygen salinity relationships on both sides of Grand Cayman (Fig. 29A) indicates that to depths of the salinity minimum the waters to the south (represented by stations 1580 to 1584; Fig. 29C) possessed slightly higher oxygen contents along corresponding isohaline surfaces, and, consequently, the mean value of the oxygen salinity relationship was closer to that characterizing the water near the Windward Passage entrance (indicated by stations 1567-1572). Thus, the conjecture, that in the eastern part of the Cayman basin the maximum oxygen enrichment (brought about by Atlantic water entering through Windward Passage) occurred south of Grand Cayman

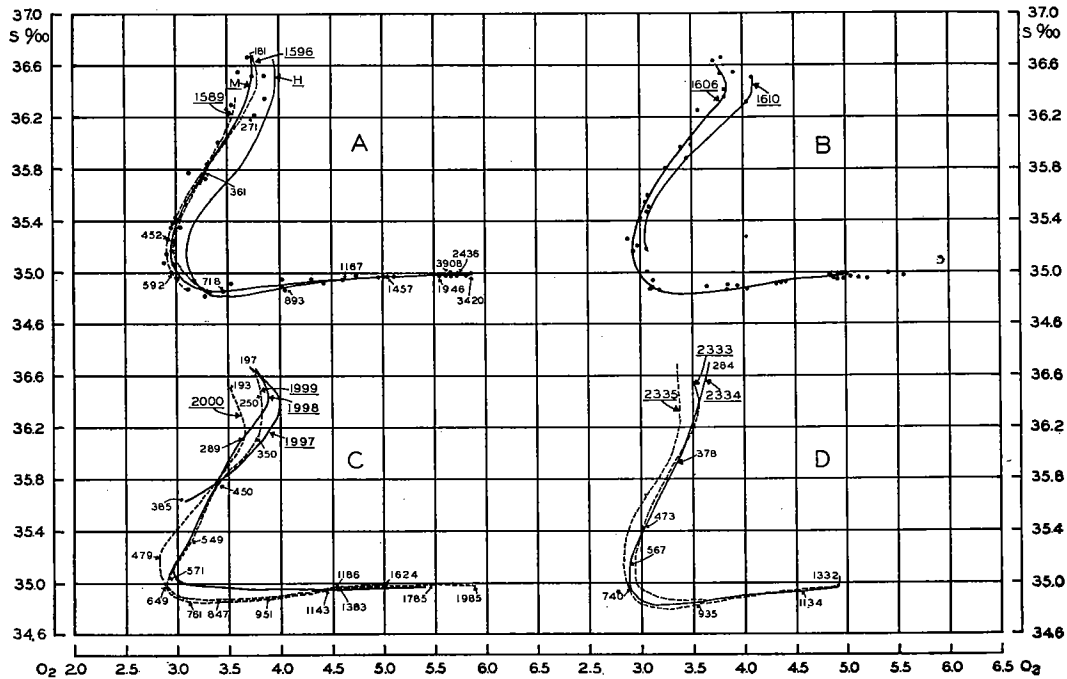


FIG. 30. Oxygen salinity relationships for the Cayman basin and Yucatan Channel. A=southern west central Cayman basin (stations 1589-1596; mean value indicated by curve M) compared with the mean for the southern east central Cayman basin (curve H). B=Yucatan Channel in 1933 (stations 1605-1616). C=Yucatan Channel in 1934 (stations 1997-2000). D=Yucatan Channel in 1935 (stations 2333-2335).

rather than north of it is substantiated. In the waters north of Grand Cayman (represented by stations 1982-1985; Fig. 29B) oxygen salinity relationships fell in a relatively narrower ribbon than did those characterizing the waters to the south; and, above depths of the salinity minimum, exhibited a definite north-south variation, with oxygen values increasing northward along isohaline surfaces.

In the west central part of the Cayman basin oxygen salinity relationships (Fig. 29D) north of Misteriosa Bank were less uniform than those north of Grand Cayman although a similar south-north gradient existed (as for the eastern group); above the salinity minimum, oxygen values along isohaline surfaces became increasingly higher towards the north for corresponding isohaline surfaces. High oxygen values recorded for station 1996 (Fig. 29D) indicate an excessive oxygen richness of the water immediately south of western Cuba, the reason for which, however, does not appear clear from a study of the

oxygen salinity relationships of the adjacent waters (possibly due to a scarcity of observations).

Oxygen salinity relationships of the water masses south of Misteriosa Bank (stations 1589 to 1596; Fig. 30A) showed significantly less horizontal scattering than those to the north, and comparison with the mean oxygen salinity curve for the southern part of the east central Cayman area (stations 1581-1584) shows that (above the salinity minimum) oxygen values along the isohaline surfaces averaged about 0.3 cc per liter lower. Thus, since the oxygen salinity relationship of the water masses north of Misteriosa Bank are more closely correlated with that characterizing the water masses south of Grand Cayman it seems likely that the water south of Misteriosa plays a less prominent part in the

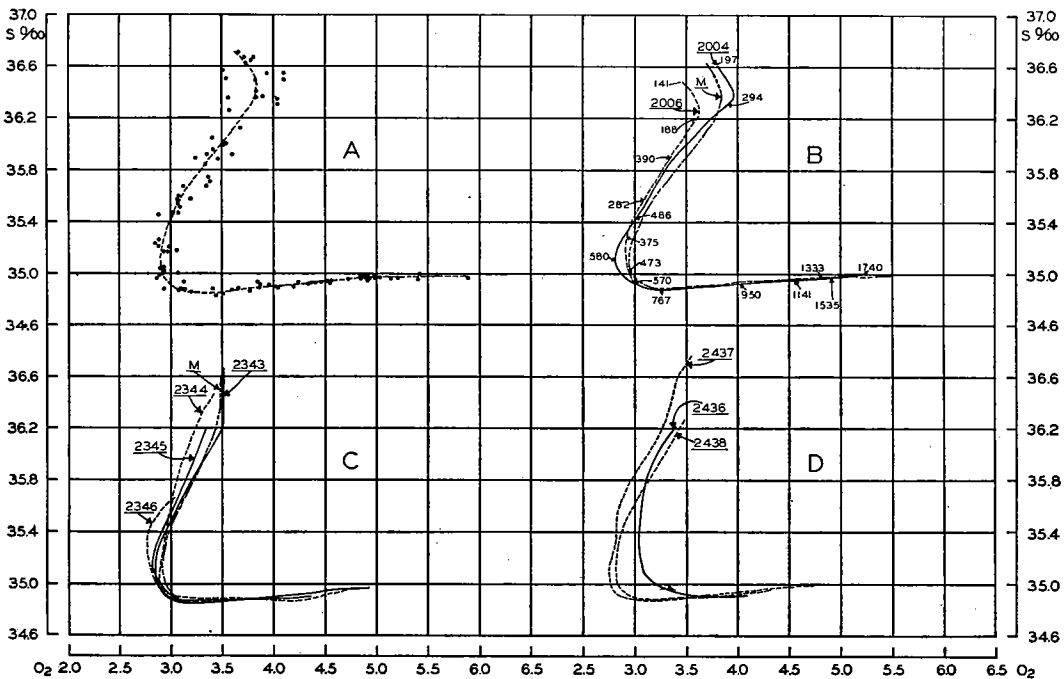


FIG. 31. Oxygen salinity relationships in Yucatan Channel and Straits of Florida. A=combined oxygen salinity relationships for Yucatan Channel in 1933, 1934, and 1935. B=Straits of Florida (stations 2004 and 2006; 1934), compared with the 1934 mean value in Yucatan Channel (curve M). C=Straits of Florida (stations 2343-2346; 1935), compared with the 1935 mean (curve M) for Yucatan Channel. D=Straits of Florida (1935 "Atlantis" data; stations 2436-2438).

main drift of the upper water layers through the Cayman basin. This is not contradictory to the general circulation scheme of the Cayman basin (outlined on page 51).

#### *The Yucatan Channel*

Oxygen salinity relationships in the Yucatan Channel, derived from "Atlantis" observations in three successive years (Figs. 30B, 30C, 30D) showed good agreement although, in 1935, oxygen values for identical salinities (above depths of the oxygen minimum) were slightly lower than those for 1934 or 1933. Data for each year illustrate the same transversal gradient; along corresponding isohaline surfaces (above depths of the salinity minimum) oxygen values on the eastern side of the channel were 0.2 to 0.3 cc

per liter higher, and, on the western side, the mid depth salinity minimum concentration was more pronounced, suggesting that outflow of the main Caribbean current is principally confined to the western (left) part of the Yucatan Channel. Oxygen values in Yucatan Channel were slightly lower, and the mid depth minimum salinity concentration slightly less pronounced, than in the northern part of the west central Cayman basin.

### *The Straits of Florida*

Oxygen salinity relationships in the Straits of Florida (Figs. 31B, 31C, 31D) show that (above depths of the oxygen minimum) oxygen values for identical salinities were slightly lower (0.2 to 0.4 cc per liter) in 1935 than in 1934 (as for Yucatan Channel). A comparison with Yucatan Channel indicates that oxygen content of similar isosaline surfaces in the Straits of Florida was slightly lower (particularly above depths of the salinity minimum); a result of excess of oxygen consumption (by oxidation of organic matter) over that gained by mixing of super- and subadjacent water masses as the water masses move from Yucatan Channel to the Straits of Florida.

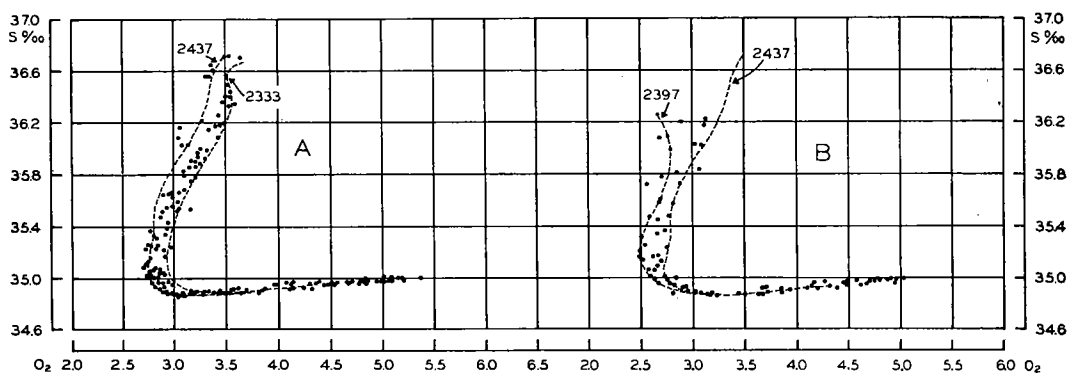


FIG. 32. Oxygen salinity relationships in the Gulf of Mexico. A= eastern Gulf of Mexico (based on "Atlantis" 1935 data) and station 2437 in Straits of Florida. B= western Gulf of Mexico (based on "Atlantis" 1935 data) and for station 2437 in Straits of Florida. For explanation see text.

The path over which water transfer between Yucatan Channel and Straits of Florida takes place has been suggested by Rossby (1936) not to be direct, but that probably the water masses on leaving Yucatan Channel break up into large eddies in the eastern Gulf of Mexico and later become reestablished near the western entrance of the Straits of Florida. Evidence in favor of this suggestion is given, first, by patterns of the horizontal distributions of oxygen (Figs. 7, 8, 11, 14, 16) which indicate the presence of a large eddy in the eastern Gulf of Mexico, and, second, by consideration of oxygen salinity relationships from the eastern Gulf of Mexico (based on 25 "Atlantis" 1935 stations; Fig. 32A), practically all of which lay between the maximum value of the relationship found in Yucatan Channel (1935 station No. 2333) and the minimum value found in the Straits of Florida (1935 station No. 2437). In the western Gulf of Mexico, oxygen salinity relationships were distinctly separate (Fig. 32B), illustrating that the oxygen contents along isohaline surfaces are (above 800-1000 meters) almost invariably lower than the minimum recorded for the Straits of Florida. The low oxygen salinity relationship of station 2397 (Fig. 32B) was located in the northwest Gulf of Mexico.



*Summary of Horizontal Movements in the Caribbean Sea Region as Shown by Oxygen Salinity Relationships*

The oxygen salinity relationship of the adjacent Atlantic waters have, before entering the various passages to the Caribbean, definite regional distinctions which permit the establishment, within the Caribbean Sea region, of a fundamental pattern, the minor modifications of which are characteristic of the circulation. Thus, in the Caribbean basin, oxygen salinity relationships, based on three transverse sections, reveal almost similar latitudinal variations, and significant changes of pattern in the direction of the principal water movement of the upper layers are brought about, in particular, by small decreases in oxygen content at the depth of the oxygen minimum concentration, and by increases

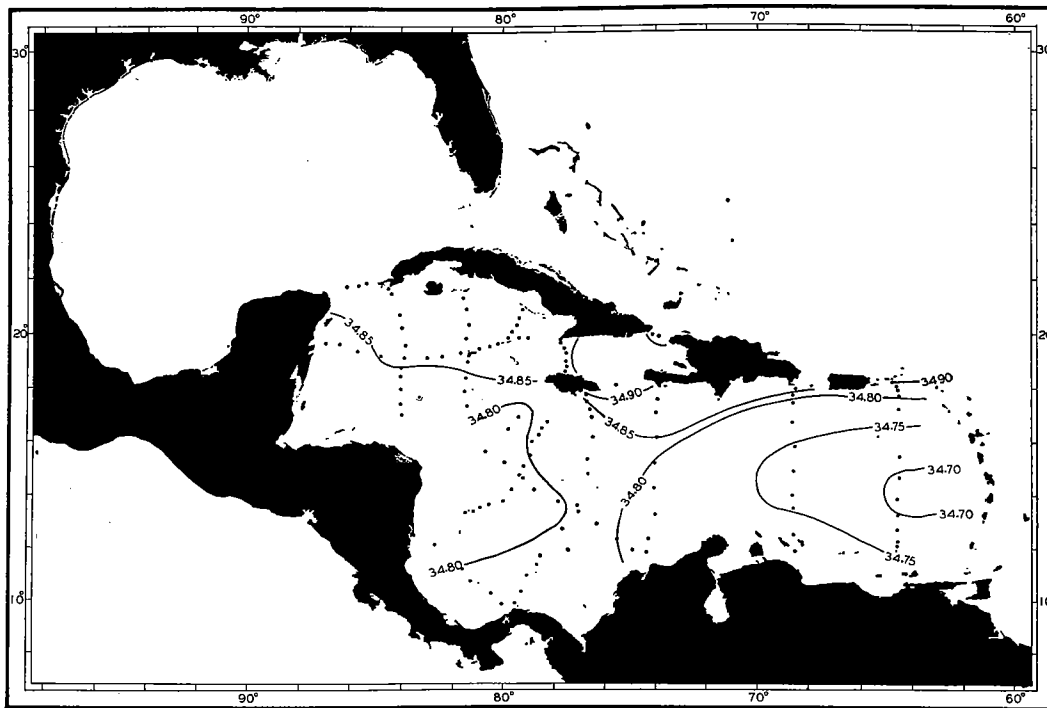


FIG. 33. Horizontal distribution of salinity at depth of the principal salinity minimum in the Caribbean Sea region.

in salinity at the depth of the salinity minimum concentration (the decline of oxygen represents an excess of biological consumption over the gain by mixing). The apparent widespread influence of subantarctic water in the Caribbean region appears to be indicated by the intermediate salinity minimum; and comparisons of oxygen salinity relationships in the Caribbean Sea region with those characterizing the adjacent Atlantic waters suggests that, in the former, the water masses derived from the Atlantic to the north and northeast are largely replaced at mid depths by water masses derived from the Atlantic to the east and southeast. These inferences as remarked on page 21 are in accordance with previous conclusions (Nielsen, 1925; Parr, 1937).

A systematic study of oxygen salinity relationships in the Cayman basin indicates that the higher oxygen content of its upper layers is due to oxygen richer Atlantic water

which, moving in through Windward Passage, is deflected chiefly to the right to mix with the main Caribbean current in the Cayman basin. Still further west, after removal from the vicinity of Windward Passage the principal water masses of the main Caribbean current are traced by their oxygen salinity relationships out through the Yucatan Channel and into the eastern Gulf of Mexico (where they appear to form a large clockwise eddy), finally moving out through the Straits of Florida to flow northward (after uniting with other water masses of the North Atlantic) as the Gulf Stream.

#### GENERAL OXYGEN RELATIONSHIP TO MINIMUM SALINITY

The minimum salinity concentration which occurs at mid depths throughout the entire Caribbean Sea region is closely related to the oxygen distribution as previously shown (page 23). Its average depth, 775 meters, is approximately 150 meters deeper than the minimum oxygen concentration, and combination of these two minima have afforded a convenient basis for discussion of turbulence at mid depths in the Caribbean basin (page 44).

In his investigation of the circulation of the Atlantic, Wüst (1935) used the mid depth salinity minimum concentration as an indicator of the "kernschicht" (nucleus) of the subantarctic intermediate water, and then traced the movements and mixing of this "nucleus" (so identified) between the approximate latitudes of 48°S (salinity minimum at about 100 meters depth) and 20°N (salinity minimum about 800 meters depth). It is most definitely marked on the western side of the Atlantic basins, and, whereas, in the North Atlantic it peters out at latitudes 17°-20°N (the northern boundary of the subantarctic water according to Wüst) it can be traced into the Caribbean and Cayman basins and out through the Straits of Florida. Thus, the characteristics of the water at the depth of the salinity minimum in latitude 48°-50°S are:

Salinity	= 33.80 ‰
Temperature	= 2.20°
Density ( $\sigma_t$ )	= 27.01
Oxygen	= 7.4 cc/l

and at latitudes 17°-20°N these have altered to:

Salinity	= 34.95 ‰
Temperature	= 6.60°
Density ( $\sigma_t$ )	= 27.45
Oxygen	= 3.1 cc/l

It is apparent that the water at the depth of the salinity minimum concentration in the North Atlantic which later enters the Caribbean basin has a relatively low oxygen content.

The smoothed distribution of minimum salinities in the Caribbean region (based on the 1933 and 1934 "Atlantis" data; Fig. 33) illustrates the continuous change in concentration brought about by mixing with super- and subadjacent waters from the time the water at mid depths enters the Caribbean region at its eastern end (minimum value = 34.69 ‰) until it leaves through the Straits of Florida (minimum value = 34.88 ‰), and progressive variations in its significant physical and chemical properties are indicated by consideration of mean values in the main direction of flow. Thus, in the Carib-

bean basin, mean values of significant characteristics at the depth of the salinity minimum (based on the three transverse sections of 1933) were:

Salinity	= 34.78 ‰
Density ( $\sigma_t$ )	= 27.36
Depth	= 766 meters
Oxygen	= 3.31 cc/l

The lowest observed minimum salinity at the eastern end of this basin (34.69 ‰, at 744 meters depth) had an accompanying density ( $\sigma_t$ ) value of 27.33; and, the highest minimum salinity in the west central part of the basin (34.88 ‰, at 800 meters depth) was accompanied by a density ( $\sigma_t$ ) value of 27.36. The mean interrelationships of oxygen, salinity, and density of the Caribbean basin agree with those established by Wüst (1935) for the "kernschicht" of the subantarctic intermediate water in the western North Atlantic, where the minimum salinity value of 34.78 ‰ corresponded approximately

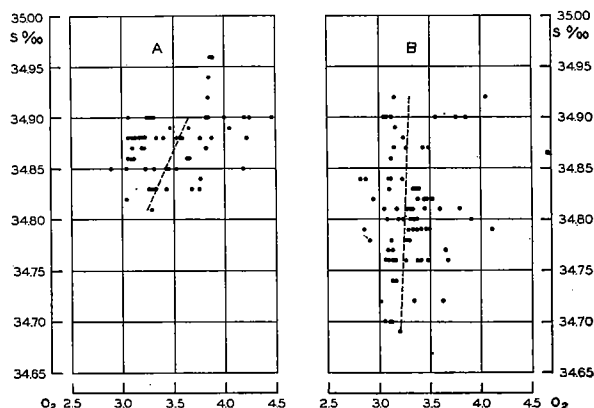


FIG. 34. Oxygen salinity correlation at depth of salinity minimum in Caribbean Sea region. A=Cayman basin,  $O_2$  (cc/l) =  $4.6 \times S$  ‰ - 156.89; B=Caribbean basin,  $O_2$  (cc/l) =  $0.4 \times S$  ‰ - 10.68.

to a density ( $\sigma_t$ ) value of 27.38 and an oxygen concentration of 3.2 cc per liter. In the Cayman basin, mean values of significant characteristics at the depth of the salinity minimum (based on two composite transverse sections of 1933 and 1934) were:

Salinity	= 34.87 ‰
Density ( $\sigma_t$ )	= 27.39
Depth	= 789 meters
Oxygen	= 3.35 cc/l

showing increased concentrations and depth over the Caribbean basin. Still further west, as the water masses flow through Yucatan Channel, the characteristics underwent but slight modification (indicated by the 1933 observations; stations 1605-1609) thus:

Salinity	= 34.87 ‰
Density ( $\sigma_t$ )	= 27.40
Depth	= 799 meters
Oxygen	= 3.38 cc/l

The small, but continuous, average increase in density and oxygen content at the depth of the salinity minimum concentration, from east to west, suggests that (as far as vertical turbulence is concerned) mixing with the subadjacent strata is slightly in excess of mixing with the superadjacent. The relationships between oxygen and salinity for the Caribbean basin (at the depth of the salinity minimum; Fig. 34) as given by the best straight lines fitting the data was (salinity range,  $34.69\text{‰}$ – $34.92\text{‰}$ ):

$$O_2 \text{ (cc/l)} = 0.4 (s \text{ ‰}) - 10.68$$

and for the Cayman basin (salinity range,  $34.81\text{‰}$ – $34.90\text{‰}$ ):

$$O_2 \text{ (cc/l)} = 4.6 (s \text{ ‰}) - 156.89.$$

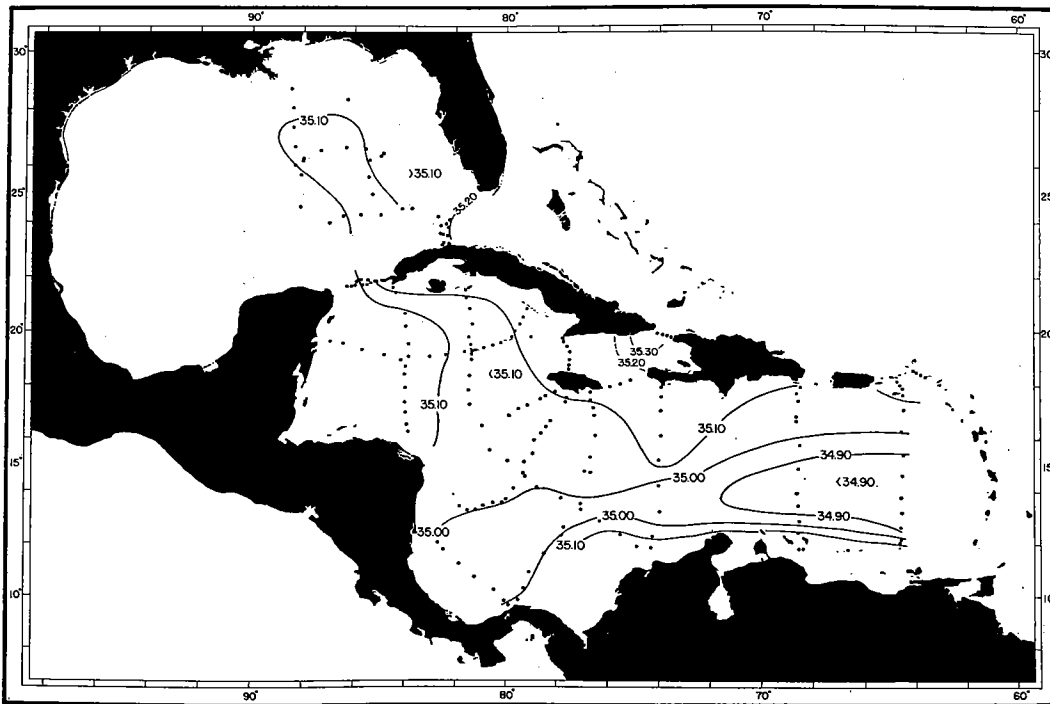


FIG. 35. Horizontal distribution of salinity at depth of the minimum oxygen concentration in the Caribbean Sea region.

#### MINIMUM OXYGEN CONCENTRATION IN RELATION TO SALINITY ANOMALY

The interdependence existing between variations of minimum oxygen concentration and the variations of the associated salinities is such that only a very general similarity existed between their horizontal patterns (Figs. 13 and 35); this situation being probably the combined result of the non-conservatism of oxygen and of the local circulation. Features common to both patterns show that in the northern parts of both basins the higher salinities were accompanied by higher oxygen concentrations, and, also, that in the eastern part of the Caribbean basin, lowest salinities coincided with lowest oxygen values.

The relationships between horizontal variations in minimum oxygen concentration and characteristics of the various water masses in the Caribbean Sea region (as opposed

to the dependence of horizontal variation of oxygen concentration on biological processes) may be brought out by consideration of deviations from the mean salinity anomaly ( $D$ ) at the depths concerned. This method, used to establish similar relationships in the western North Atlantic (Seiwell, 1937b) has been developed as follows.

From Helland-Hansen's (1930) normal temperature salinity relationship for northern North Atlantic water:

$$(1) \quad S_t \text{ ‰} = 34.737 + 0.038t + 0.0029t^2$$

the salinity anomalies at the depth of the minimum oxygen concentration have been calculated:

$$(2) \quad \text{S.A.} = 100 (S \text{ ‰} - S_t \text{ ‰})$$

(where  $S$  is the observed salinity and  $S_t$  the calculated normal salinity). Then, by subtracting the mean anomaly from each individual anomaly, a series of deviations ( $D$ ) from the mean have been obtained, thus:

$$(3) \quad D = (\text{S.A.} - \overline{\text{S.A.}})$$

(where S.A. is the calculated salinity anomaly and  $\overline{\text{S.A.}}$  the mean value of all salinity anomalies in the Caribbean region at the depth of the minimum oxygen concentration). The quantity,  $D$ , is based on the original form of the temperature salinity correlation as deduced by Helland-Hansen; positive values indicate that the water contains more salt than normal, with respect to a given temperature, whereas, negative values of  $D$  characterize water with less salt than is normal for a given temperature. The values are relative for this particular region only.

Values of the salinity anomaly (S.A.) associated with the minimum oxygen concentration (calculated from equation 2) ranged between  $-7$  and  $-40$ , showing the preponderance of low salinity water (as compared with the northern North Atlantic) and apparently confirming the presence of water of subantarctic origin at the depths in question (page 34). The mean value of the salinity anomaly (for 227 observations at the depth of the oxygen minimum) was calculated to be  $-23$ ; subtracting this from each individual anomaly (equation 3) gave a series of deviations from the mean anomaly ( $D$  values), the horizontal distribution of which is plotted in Figure 36.

Mixing of the water masses in the Caribbean region is such that a transition of  $D$  values occurred along the principal axes of the two basins, and comparison of the horizontal pattern (Fig. 36) with the pattern of minimum oxygen values (Fig. 13) would seem to indicate that the control of the magnitude of the minimum oxygen concentration by the circulation is frequently offset by biological processes. It is clear that in the Caribbean Sea region, at localities close to sources of oxygen richer Atlantic water (entering through the northern inlets), the increasing saltiness of the minimum oxygen stratum is accompanied by increased oxygen content, but where the water masses are sufficiently far removed from such sources, the gain of oxygen by mixing of the water masses is eventually offset by biological activity and thus discrepancies are produced between the relations of the two properties. As an example of this change of control the situation in the northern half of the Cayman basin may be considered since there, in a westerly direction, the definite decline in minimum oxygen concentration was not paralleled by a similar change in  $D$  values, indicating that here the oxygen pattern resulted chiefly because dynamic processes (producing the salinity anomaly variations) were gradually exceeded

by biological processes. In Yucatan Channel, the salinity anomaly, more than 20 units greater than that characterizing the eastern Caribbean basin, represented one of the highest positive deviations from the mean in the Caribbean Sea region (excluding localities adjacent to the northern inlets), but the accompanying oxygen content was only about 0.1 to 0.2 cc per liter greater than that of the eastern Caribbean basin. For the entire Caribbean Sea region the highest minimum oxygen concentrations (Fig. 13) were found in Windward Passage where the accompanying salinity anomalies were 25 to 30 units higher (positive direction) than in the eastern Caribbean basin.

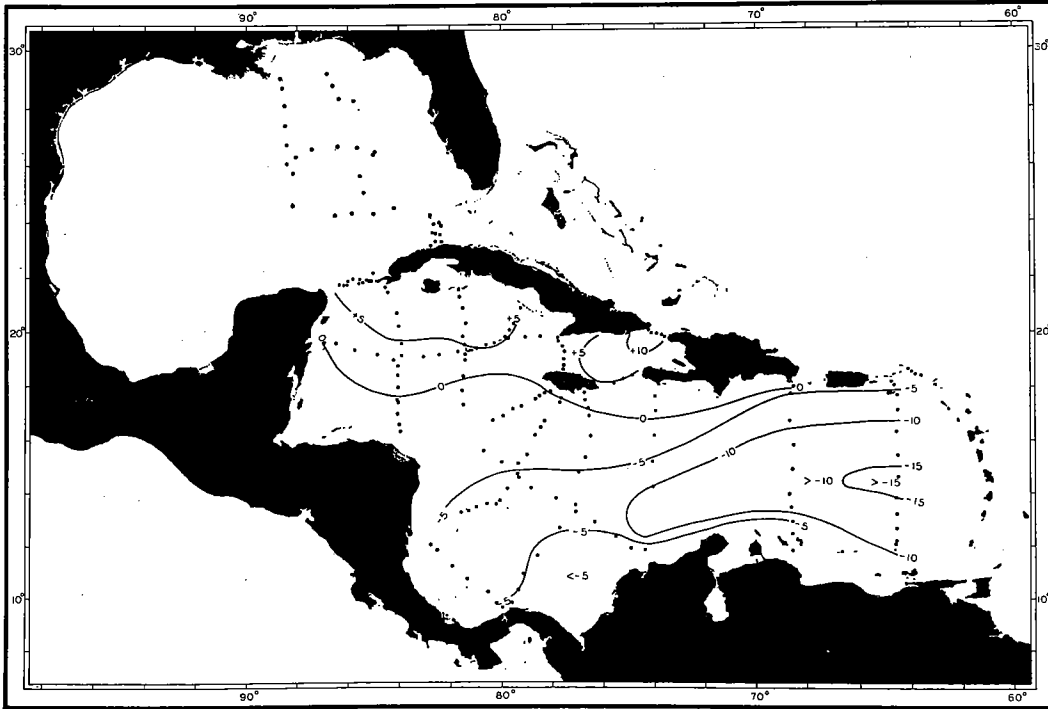


FIG. 36. Horizontal distribution of  $D$  values (deviations from the mean salinity anomaly) at depth of minimum oxygen concentration.

To estimate the average extent to which the horizontal variation of minimum oxygen values in the Caribbean Sea region (Fig. 13) may be dependent on mixing of the water masses, the minimum oxygen- $D$  relationships are separately considered for the two basins (Fig. 37). Thus, for the Caribbean basin (81 pairs of values), the standard deviations of the minimum oxygen values ( $\sigma_{O_2}$ ) and of the  $D$  values ( $\sigma_D$ )<sup>10</sup> were:

$$\sigma_{O_2} = 0.1360$$

$$\sigma_D = 5.84$$

and the correlation coefficient was:

$$r = 0.387.$$

<sup>10</sup> The calculation includes only values for the Caribbean basin; observations across the inlets opening to the Atlantic have been omitted.

The probability that this observed correlation arose because of random sampling of an uncorrelated population is:<sup>11</sup>

$$P > 0.01$$

indicating the correlation to be significant. Similarly, in the Cayman basin, standard deviations of the variables (59 pairs) were:

$$\sigma_{O_2} = 0.143$$

$$\sigma_D = 3.89$$

and the correlation coefficient was:

$$r = 0.323.$$

As, in the previous case, the probability that the correlation is due to the random sampling of an uncorrelated population is:

$$P > 0.01$$

indicating this correlation to be significant also.

The significance of these results may be seen by comparing them with a similar calculation for the western North Atlantic (Seiwell, 1937b) where the effect of influx of Mediterranean water on the minimum oxygen concentration between latitudes 25°N and 35°N was investigated. In this case, however, the statistics:

$$\sigma_{O_2} = 0.178$$

$$\sigma_D = 4.06$$

$$r = 0.782$$

showed that a much better correlation existed between deviations from the mean salinity anomaly of the region and values of the minimum oxygen concentration. Thus, while standard deviations of the quantities for the Caribbean and Cayman basins and the central western North Atlantic were in fair agreement, the lower correlation coefficients showed less dependence of minimum oxygen concentration of the Caribbean region on dynamic processes than was the case in the western Atlantic. Such a differentiation would seem to arise as a natural result of the restricted exchange between the water masses of the Caribbean region.

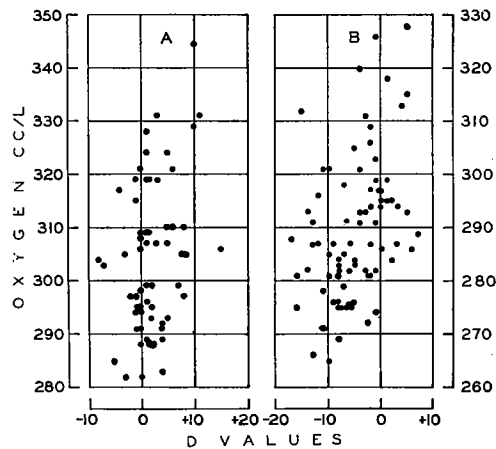


FIG. 37. Oxygen-D correlation in Caribbean Sea region. A=relationship in Cayman basin, correlation coefficient,  $r=0.321$ ; B=relationship in Caribbean basin, correlation coefficient,  $r=0.387$ .

<sup>11</sup> Significance of the correlation was determined by the method outlined by Fisher (1932).

## MINIMUM OXYGEN CONCENTRATION IN RELATION TO DENSITY

The density ( $\sigma_t$ ) associated with the observed minimum oxygen concentration in the Caribbean Sea region (as observed during the 1933 and 1934 "Atlantis" cruises) ranged from  $\sigma_t = 26.85$  to  $\sigma_t = 27.44$ ; grouping of these values into a frequency table (Table I) suggests that the data were normal, or nearly so, and that the observed variations in density of the minimum oxygen concentration were chiefly a result of the sampling. To test the significance of this assumption and to calculate the modal value of density of the minimum oxygen concentration, a procedure similar to that used on oxygen data in the western basin of the North Atlantic (Seiwell, 1935) was used.<sup>12</sup>

TABLE I

CLASS INTERVAL	BERNOULLI CLASS MARK	OBSERVED FREQUENCY	GRADUATED FREQUENCY
26.85 26.89	0	1	0.4
26.90 26.94	1	2	1.6
26.95 26.99	2	4	4.4
27.00 27.04	3	7	9.7
27.05 27.09	4	18	17.3
27.10 27.14	5	30	24.6
27.15 27.19	6	30	27.9
27.20 27.24	7	21	25.2
27.25 27.29	8	12	18.2
27.30 27.34	9	13	10.4
27.35 27.39	10	7	4.8
27.40 27.44	11	2	1.8

The statistical constants calculated from the data showed it to be only slightly skew, thus:

$$\text{Skewness, } S = 0.01476$$

$$\beta_2 = 2.9273 \neq 0.2725$$

$$\text{Kurtosis, } E = \beta_2 - 3 = -0.0727$$

(the latter lying well within the probable error of  $\beta_2$ ). From the standard deviation of the data:

$$\sigma = 2.1039$$

and the average:

$$A = 6.0204$$

(both of which are referred to Bernoulli class marks); the normal frequency curve (slightly skew) best fitting the distribution in Table I is:

$$y = 69.8702 e^{-0.01476(x-6.0204/2.1039)} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(x-6.0204/2.1039)^2}$$

To test for the goodness of fit between the observed and the theoretical density frequency distribution (both given in Table I), the chi squared function<sup>13</sup> was calculated to be:

$$\chi^2 = 7.5094$$

and the Pearson probability:

$$P = 0.7554$$

<sup>12</sup> The details of the Caribbean calculation are to be published in a separate paper by Seiwell and Coker.

<sup>13</sup> See Pearson (1930) for explanation.



from which it is concluded that 75.5 times out of 100 we should get a fit as bad, or worse, in random sampling as that observed if the real distribution were normal. Hence, the theoretical curve is a very good representation of the observed frequency distribution of  $\sigma_t$  associated with the minimum oxygen concentration in the Caribbean Sea region (Fig. 38).

The modal value of  $\sigma_t$  at the minimum oxygen concentration in the Caribbean Sea region has been calculated from data to be:

$$\text{Mode} = 27.171 \neq 0.007.$$

$$\delta_T = 90.5 \text{ d.f.}$$

Since variations of three times the probable error are only rarely exceeded the most probable modal class within which the value of  $\sigma_t$  at the minimum oxygen concentration oscillates has the limits:

$$\sigma_t = 27.15 \text{ to } 27.19.$$

Thus, from a probability viewpoint, the observed density variations associated with the minimum oxygen concentration in the Caribbean Sea region chiefly resulted from random sampling, and the existence of a unique mechanism which tends to make the lowest oxygen value occur everywhere along the same density surface regardless of depth, is suggested. However, in this respect, the possibility is not excluded, by the foregoing results, that variations in this fundamental mechanism may occur to vary the minimum oxygen density surface; and that some such process may actually exist to produce small significant latitudinal variations of the modal value of the minimum oxygen density over a large oceanic area is probable.

A further analysis of the density associated with the minimum oxygen concentration in the Caribbean basin was carried out for the purpose of determining if, because of the transverse tilting of the isopycnal surfaces (Fig. 25), significant variations within the modal class were produced. Thus, the depth of the minimum oxygen concentration showed a definite latitudinal variation (Fig. 39) across the Caribbean basin; the observations<sup>14</sup> when fitted by the best straight line had the equation:

$$z = 450 + 27x$$

(where  $z$  is the depth in meters and  $x$  = degrees of latitude minus  $12^\circ$ ), indicating a mean northward increase in depth of the minimum oxygen concentration (between latitudes

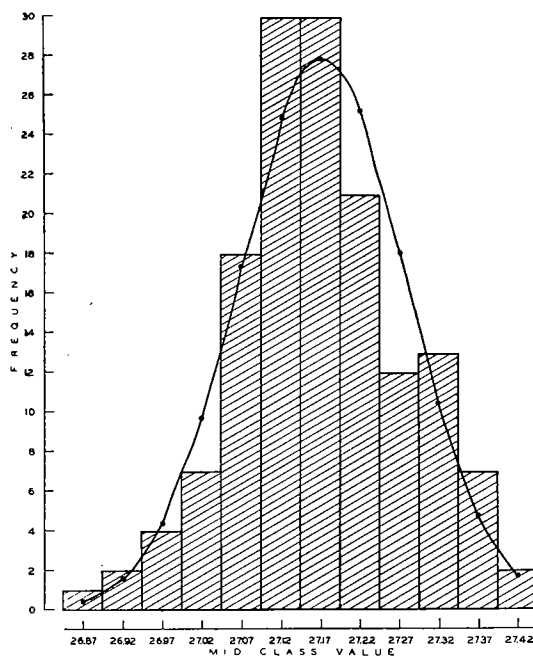


FIG. 38. Frequency distribution of density ( $\sigma_t$ ) values at depth of minimum oxygen concentration; observed frequency (histogram) compared with theoretical frequency.

<sup>14</sup> Based on data from three transverse sections across the Caribbean basin: stations 1492-1504; 1505-1515; 1521-1530.

12°–18°N) of approximately 27 meters per degree of latitude. Now, the problem is to determine whether this latitudinal depth transition is significantly different from that determined by the transverse tilting of isopycnal surfaces ( $\sigma_t = 27.15$  to 27.19) in the region (Fig. 25); the latitudinal variation of observed density associated with the minimum oxygen concentration (as given by the best straight line (Fig. 39) which can be fitted to the data) had the equation:

$$\sigma_t = 27.150 + 0.007x$$

(where  $x$  = degrees of latitude minus 12°). The indication is that a northerly increase of density (at a rate of 0.007  $\sigma_t$  units per degree of latitude) accompanied the minimum

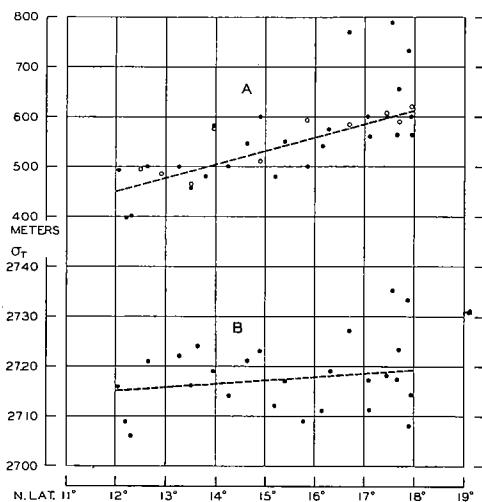


FIG. 39. Latitudinal variation of minimum oxygen concentration across Caribbean basin. A = transverse depth variation of minimum oxygen concentration. B = observed transverse density ( $\sigma_t$ ) variation at depth of minimum oxygen concentration.

oxygen concentration across the Caribbean basin. However, because of considerable scattering of the points about the fitted line, its slope is doubtful; and, when tested by estimating the significance of the difference between mean  $\sigma_t$  values at both ends of the line (for latitude 12.5° mean  $\sigma_t = 27.13$ ; for latitude 17.5° mean  $\sigma_t = 27.20$ ) the odds in favor of reality of this northerly density increase of 0.007  $\sigma_t$  units per degree of latitude are only 1 in 9.<sup>15</sup> Hence, as far as is indicated by the data at hand, the transversal variation in depth of the minimum oxygen concentration across the Caribbean basin is dependent on the transversal tilting of the 27.17 ( $\neq 0.007$ ) isopycnal surface and deviations therefrom (due to other causes) are not significant.

The modal value of the minimum oxygen density in the Caribbean Sea region (27.17  $\neq 0.007$ ) was slightly lower than that ( $\sigma_t = 27.237 \neq 0.008$ ) previously calculated for the western basin of the North Atlantic, between the equator and 50°N latitude (Seiwell, 1937b). It is to be noted, however, that in the calculation for the western North Atlantic, the majority of data were obtained from latitudes north of 20°N, so that the existing difference of approximately 0.07 units of  $\sigma_t$  in the modal values may represent a definite latitudinal variation in the modal value of the density of the minimum oxygen concentration, when considered over a large area of the North Atlantic. It appears likely that small latitudinal variations in the modal value of the density at the minimum oxygen concentration might be expected, particularly, if the vertical position of the minimum oxygen concentration in the water column was influenced as a result of interrelationship between vertical distribution of density in the sea and the density of sinking, oxidizable organic debris,<sup>16</sup> which may conceivably result from small latitudinal variations either in the initial sizes or densities of the sinking, decomposing, organic particles. However, analysis of the situation in other regions of the Atlantic are needed to substantiate such an inference.

<sup>15</sup> Estimation of the significance of means was determined by McEwen's (1929) extension of "Student's" method.

<sup>16</sup> For discussion of the mechanism involved in the sinking of organic debris in the sea see Seiwell (1937b) and Seiwell and Seiwell (1937).

# OXYGEN DISTRIBUTION AND RELATED PROPERTIES AS EVIDENCE OF EDDY DIFFUSION

## INTRODUCTION TO THE METHOD

The significance of turbulent motion to the vertical (and possibly horizontal) transfer of properties of the ocean is universally accepted by students of oceanic circulation, and while little is known about the details of turbulent motion itself its effects on the average properties of the water column have been studied and there appears no need to elaborate the point here. The formulation of factors governing the activity of turbulence in the sea and the attempts to calculate its magnitude under a variety of conditions have been made by Ekman (1905, 1928), Taylor (1931), Jacobsen (1913, 1916, 1929, 1930), Helland-Hansen (1930), McEwen (1919), Defant (1930, 1935), Sverdrup (1930, 1933), Schmidt (1925), Seiwel (1934, 1935) etc.

The fundamental differential equation regulating the distribution of substances in the sea by both vertical and lateral (down stream and cross stream) turbulence is:

$$(1) \quad \rho \frac{d\alpha}{dt} = \frac{\partial}{\partial x} \left( A_x \frac{\partial \alpha}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_y \frac{\partial \alpha}{\partial y} \right) + \frac{\partial}{\partial z} \left( A_z \frac{\partial \alpha}{\partial z} \right)$$

or expanding to show local changes within a fixed unit volume we have:

$$(2) \quad \rho \frac{d\alpha}{dt} = \frac{\partial}{\partial x} \left( A_x \frac{\partial \alpha}{\partial x} \right) - u \frac{\partial \alpha}{\partial x} + \frac{\partial}{\partial y} \left( A_y \frac{\partial \alpha}{\partial y} \right) - v \frac{\partial \alpha}{\partial y} + \frac{\partial}{\partial z} \left( A_z \frac{\partial \alpha}{\partial z} \right) - w \frac{\partial \alpha}{\partial z}$$

Considering only the vertical component of turbulence, and motion only in the  $X$  direction:

$$(3) \quad \frac{\partial \alpha}{\partial t} = \frac{\partial}{\partial z} \left( A_z \frac{\partial \alpha}{\partial z} \right) - u \frac{\partial \alpha}{\partial x}$$

and for a steady state:

$$(4) \quad 0 = \frac{\partial}{\partial z} \left( A_z \frac{\partial \alpha}{\partial z} \right) - u \frac{\partial \alpha}{\partial x}$$

In the application of equations 1-4 to the sea, distinction need first be made as to the disposition of the property concerned. For the conservative properties (such as salinity) the value of  $d\alpha/dt$  may be taken as the observed change, but for non-conservative properties (such as oxygen) the value of  $d\alpha/dt$  must be corrected for variation resulting from biological activity. Thus, for the vertical component of turbulence alone we may write:

$$\frac{d\alpha}{dt} = \frac{\partial}{\partial z} \left( A_z \frac{\partial \alpha}{\partial z} \right) - C$$

where  $C$  represents the effect of biological activity on the non-conservative property; in the case of oxygen,  $C$  is the rate of oxygen consumption.

Of the various methods developed, those of Jacobsen (1927) and Schmidt (1925) are considered here. Thus, using curves, from two localities, of temperature salinity rela-

tionships in a steady current, Jacobsen's (1927) method graphically computes the eddy diffusion coefficient. And, on the assumption that requirements are fulfilled, this method may be applied to compute the eddy coefficient at the depth of the salinity minimum between station 1499 (east Caribbean) and station 1510 (east central Caribbean); by noting the amount of depth ( $S$ ) intersected on the temperature salinity curve of station 1499 by a tangent to the point of minimum salinity concentration (point of inflection) on the temperature salinity curve of station 1510 (Fig. 40). Thus:

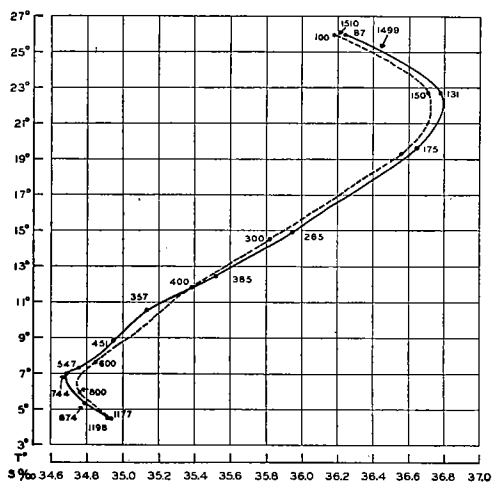


FIG. 40. Temperature salinity relations for stations 1499 and 1510 in the eastern part of the Caribbean basin.

which may, with certain assumptions, be applied to the deeper layers of the Caribbean basin.

In view of the extensive distribution and close vertical relationship of the salinity and oxygen minimum concentrations (page 34) both of these properties have been utilized in an investigation of the vertical eddy diffusion coefficients at mid depths in the Caribbean basin. And, in the following, as an example of the mean vertical eddy coefficient at mid depths, its average value in the layer (approximately 100 meters thick) between the oxygen and salinity minimum concentrations has been calculated. Oxygen and salinity data in the vicinity of each respective minimum concentration from the eastern Caribbean (profile I: stations 1492-1504) and the east central Caribbean (profile II: stations 1505-1515) have been used (Figs. 40 and 41). It is assumed, for purposes of calculation, that only small vertical variations of horizontal velocity occurred within the stratum concerned, and, also, as a first approximation, it was further assumed that the only eddy component producing a measurable diffusion was that acting along the vertical. Hence, changes in concentration of the oxygen minima (Fig. 41) between profiles I and II were considered to result from the combined effects of biological activity and vertical eddy diffusion,<sup>17</sup> whereas, changes in concentration of the salinity minimum are considered to be due solely to vertical diffusion.

<sup>17</sup> Between profiles I and II the average concentration of the oxygen minimum decreased, showing an excess of consumption by biological activity over that gained by turbulence.

$$(5) \quad A = \frac{\rho}{8t} S^2$$

where,  $t$ , is the time required for the water at the depth of the salinity minimum to move from station 1499 to 1510, and,  $\rho$ , is the mean sea water density.

A second method for calculating the vertical eddy diffusion component,  $A$ , based on the loss of oxygen per unit time ( $\Delta O / \Delta t$ ) (from the deeper layers of the North Atlantic (Seiwell, 1934), makes use of the equation (developed by Schmidt, 1925):

$$(6) \quad A = \rho \frac{\frac{\Delta O}{\Delta t}}{\frac{\partial^2 O}{\partial z^2}}$$

## VERTICAL DIFFUSION

The consumption of oxygen at the depth of its minimum concentration during the time ( $t$ ) it takes this water to move horizontally from section I to II would be:

$$Ct = O_1 - O_2 + \frac{\Delta O}{\Delta t} t$$

where,  $C$ , is the rate of oxygen consumption per unit times,  $O_1 - O_2 =$  the difference in the observed mean minimal oxygen concentrations of profiles I and II, and  $\Delta O/\Delta t$  is the amount of oxygen supplied per unit time due to vertical mixing (changes due to the lateral eddy components were neglected). We get from equation (6)

$$\frac{\Delta O}{\Delta t} = \frac{A}{\rho} \frac{\partial^2 O}{\partial z^2}$$

and thence by substitution:

$$(7) \quad O_1 - O_2 + t \left( \frac{A}{\rho} \frac{\partial^2 O}{\partial z^2} - C \right) = 0.$$

Since the value of  $C$  may be approximated (see below) this equation contains two unknowns,  $t$  and  $A$ , and was solved by a consideration of the minimum salinity concentrations at mid depths of profiles I and II (as represented by stations 1499 and 1510, Fig. 40). Thus, the application of Jacobsen's equation to the temperature salinity relationship of the layers adjacent to the salinity minima of stations 1499 and 1510 (assuming a steady state as the water moves from profile I to II) would give:<sup>18</sup>

$$(8) \quad t \frac{A}{\rho} = \frac{S^2}{8}.$$

It may be accepted that the relative functional relationships of temperature and salinity of profiles I and II, in the vicinity of the salinity minimum, are represented with sufficient accuracy, by those for stations 1499 and 1510 (which lay at approximate mid points of their respective sections), so that there is no need to use mean values as was done for the less accurate oxygen values. Equations (7) and (8) may be combined into a simultaneous system and solved for,  $t$ , and,  $A$ , (on the basis of previous assumptions these quantities both in equation (7), involving the minimum oxygen concentration, and equation (8), involving the minimum salinity concentration, are taken to be equivalent), thus:

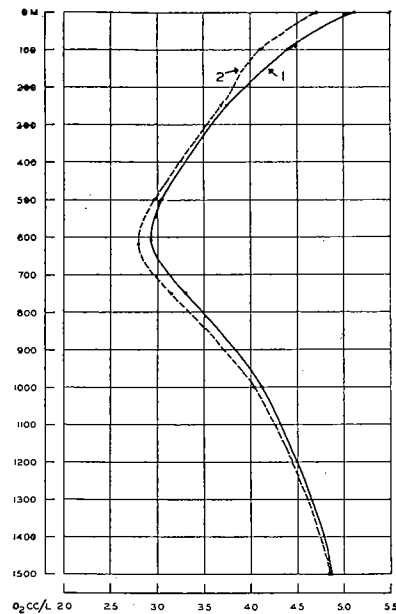


FIG. 41. Mean vertical distribution of oxygen (cc per liter) for profile I (stations 1492-1504) and profile II (stations 1505-1515) in the eastern part of the Caribbean basin).

<sup>18</sup> The density of sea water ( $\rho = 1.02$ ) is not utilized in the practical application of the diffusion equations.

$$t \left[ \frac{A}{\rho} \frac{\partial^2 O}{\partial z^2} - C \right] = O_2 - O_1$$

$$t \frac{A}{\rho} = \frac{S^2}{8}$$

which gives on solving:

$$(9) \quad t = \frac{O_1 - O_2}{C} + \frac{\partial^2 O}{\partial z^2} \frac{S^2}{8C}$$

Equation (9) may be evaluated with the aid of data plotted in Figures 40 and 41. The difference in mean minimum concentration ( $O_1 - O_2$ ) between profiles I and II was 0.16 cc per liter =  $1.6 \times 10^{-4} \text{ cm}^3 \text{ g}^{-1}$  and the mean value of  $\partial^2 O / \partial z^2$  at 615 meters (mean depth of oxygen minimum concentration) for profiles I and II, was:

$$\frac{\partial^2 O}{\partial z^2} = 2.40 \times 10^{-12} \text{ cm}^3 \text{ g}^{-1} \text{ cm}^{-2}$$

The value of  $S = 2.25 \times 10^4$  cms was determined graphically from the combined temperature salinity relationships of stations 1499 and 1510 (Fig. 32). The value of oxygen consumption per unit time,  $C$ , was taken to be  $1.35 \times 10^{-11} \text{ cm}^3 \text{ g}^{-1} \text{ sec}^{-1}$  (0.42 cc per liter per year), the mean value of oxygen consumption (page 24) previously calculated for the oxygen poor layer<sup>19</sup> at mid depths of the tropical mid Atlantic (Seiwell, 1934). Substitution of these values in equation (9) would give:

$$t = 2.3 \times 10^7 \text{ secs} = 0.7 \text{ year}$$

and the mean vertical eddy diffusion coefficient characterizing the water column at mid depths, between the salinity and oxygen minima in the eastern Caribbean, would then be:

$$A = 2.8 \text{ C.G.S. units.}$$

The distance,  $X$ , between stations 1499 and 1510 (both of which are located near the mid points of their respective profiles) is approximately the same as the mean distance between profiles I and II, or  $X = 4.45 \times 10^7$  centimeters. Thus, the mean horizontal velocity in the layer bounded by the minimum salinity and minimum oxygen concentration was calculated to be:

$$u = \frac{\Delta x}{\Delta t} = 2.0 \text{ cms sec.}^{-1}$$

The calculated values of  $A$  and  $u$  depend on the amount of error involved in neglecting lateral diffusion (page 51) and especially on the value of  $C$ , which may be only of correct order of magnitude. It is readily seen from equations 8 and 9 that as  $C$  increases  $t$  becomes smaller with corresponding increases in the values of  $A$  and  $u$ , and vice versa.

<sup>19</sup> This assumption seems justified since it is probable that at mid depths biological conditions of the Caribbean Sea region are sufficiently similar to those at similar latitudes of the mid North Atlantic.

Hence, the calculated values of  $A$  and  $u$  are to be considered as only approximate, but quite probably of correct order of magnitude, being within the limits established by other investigators for mid depths of the ocean basins.

The plausibility of the calculated values for  $A$  and  $u$  may be tested in a manner similar to that used by Defant (1930, 1935) for estimating the relation of the eddy diffusion coefficient to the horizontal velocity in the deeper parts of the South Atlantic. On assumption of steady motion, the existence of the relation involving only the vertical eddy component:<sup>20</sup>

$$(10) \quad \frac{A}{u} = \rho \frac{\frac{\partial \alpha}{\partial x}}{\frac{\partial^2 \alpha}{\partial z^2}}$$

allows calculation of the ratio,  $A/u$ , where  $\partial\alpha/\partial x$  denotes horizontal variation of the property in direction of flow and  $\partial^2\alpha/\partial z^2$  the vertical variation of a conservative transferable property,  $\alpha$ ; the coordinate system being oriented so that the  $X$  axis points in the direction of flow, velocities in all other directions are assumed to be zero. Thus, applying equation (10) to salinity data from the vicinity of the salinity minima of stations 1499 and 1510 (Fig. 41) would give:

$$\frac{A}{u} = \frac{1.35 \times 10^{-12}}{10^{-12}} = 1.35$$

as the ratio existing in the vicinity of the salinity minimum; this result is in good agreement with the ratio,  $A/u = 2.8/2.0 = 1.4$ , from results of the previous calculation in the vicinity of the oxygen minimum. In fact, when it is considered that the values of the two ratios (although based on the same data) separately involve biological and dynamical considerations the agreement is good.

Further application of the fundamental differential equation regulating diffusion of substances in the sea by vertical turbulence alone (page 43) to the temperature and salinity data in the vicinity of the oxygen minimum at stations 1499 and 1510 supports the value,  $A = 2.8$  C.G.S. units, as approximately correct for the existing circumstances. Thus, denoting observed temperature ( $t^\circ$ ) and salinity ( $S$ ) values (at the depth of the oxygen minimum) for station 1499 (profile I) by subscript I and for station 1510 (profile II) by subscript 2, we have:

$$S_2 - S_1 = 9 \times 10^{-5} \text{ g. g}^{-1}$$

$$t_2^\circ - t_1^\circ = 3.5 \times 10^{-1} \text{ deg.}$$

showing that increases both in salinity and temperature have taken place by mixing processes as the water at mid depths (at depth of the principal oxygen minimum), near the central axis of the Caribbean basin, moves westward from station 1499 (profile I) to station 1510 (profile II). The average oxygen content at the depth of its minimum concentration actually decreased between profiles I and II, showing an excess of oxygen

<sup>20</sup> This form of the diffusion equation is obtained from equation (4) as shown on page 43; stationary motion is assumed and velocities are admitted only in the  $X$  direction.

*This is the same as the ratio of the two ratios calculated above.*

consumption (by biological processes) over that gained by mixing; the mean difference in oxygen content between profiles I and II was calculated<sup>21</sup> to be:

$$O_2 - O_1 = -1.6 \times 10^{-4} \text{ cm}^3 \text{ g}^{-1}$$

Mean values for the second derivatives of the vertical salinity, temperature, and oxygen gradients for stations 1499 and 1510 at the depth of the oxygen minimum concentration are:

$$\frac{\partial^2 S}{\partial z^2} = 10.0 \times 10^{-13} \text{ g. g}^{-1} \text{ cm}^{-2}$$

$$\frac{\partial^2 t^\circ}{\partial z^2} = 5.7 \times 10^{-9} \text{ deg. cm}^{-2}$$

$$\frac{\partial^2 O}{\partial z^2} = 2.40 \times 10^{-12} \text{ cm}^3 \text{ g}^{-1} \text{ cm}^{-2}$$

And, the time rates of changes as computed from the equation:

$$(11) \quad \frac{d\alpha}{dt} = \frac{A}{\rho} \frac{\partial^2 \alpha}{\partial z^2}$$

when  $A = 2.8$  C.G.S. units, are:

$$\frac{dS}{dt} = 2.80 \times 10^{-12} \text{ g. g}^{-1} \text{ sec}^{-1}$$

$$\frac{dt^\circ}{dt} = 1.60 \times 10^{-8} \text{ deg. sec}^{-1}$$

$$\frac{dO}{dt} = 6.74 \times 10^{-12} \text{ cm}^3 \text{ g}^{-1} \text{ sec}^{-1}$$

Integrating between the limits,  $t=0$  and  $t=2.3 \times 10^7$  seconds (the time calculated for the water to move from station 1499 to 1510, page 46) gives the amount of change in temperature, salinity, and oxygen resulting from vertical diffusion as the water at the depth of the oxygen minimum moves from station 1499 to 1510 (the results are entered in Table 2)

TABLE 2

PROPERTY	OBSERVED CHANGE	COMPUTED CHANGE	COMPUTED-OBSERVED
Oxygen	$-1.6 \times 10^{-4}$	$1.5 \times 10^{-4}$	$3.1 \times 10^{-4} \text{ cm}^3 \text{ g}^{-1}$
Temperature	$3.5 \times 10^{-1}$	$3.7 \times 10^{-1}$	$2 \times 10^{-2} \text{ deg.}$
Salinity	$9.0 \times 10^{-5}$	$6.4 \times 10^{-5}$	$-2.6 \times 10^{-5} \text{ g. g}^{-1}$

Comparison of observed and computed change in concentration of identifying properties at depth of minimum oxygen concentration between stations 1499 and 1510 in Caribbean basin. Difference between computed and observed oxygen value represents the approximate amount of oxygen consumed by biological processes between section I and II Thus:

$$\frac{3.1 \times 10^{-4} \text{ cm}^3 \text{ g}^{-1}}{2.3 \times 10^7 \text{ sec}} = 1.35 \times 10^{-11} \text{ cm}^3 \text{ g}^{-1} \text{ sec}^{-1}$$

(See page 46).

<sup>21</sup> This decrease in oxygen content is due to its non-conservatism. The actual (positive) time rate of change of this property due to eddy diffusion should be calculated as shown on page 43.



Because the agreement between observed and calculated change in the two conservative properties (temperature and salinity) is sufficiently good it may be concluded that the value of 2.8 C.G.S. units for the vertical eddy transfer coefficient is approximately correct.

#### LATERAL DIFFUSION

In the above discussion of eddy diffusion, only the effects produced by vertical components of turbulent motion have been considered, any effect from lateral turbulence has been neglected in order to simplify the treatment. Likewise more information is available on the lateral diffusion accompanying fluid motion of the atmosphere than of the ocean, and, in the former, the order of magnitude of horizontal diffusivity coefficients have been calculated to be (according to investigations of Defant, 1921, and Richardson and Proctor, 1926) approximately between  $10^{11}$  and  $10^9$   $\text{cm}^2 \text{sec}^{-1}$ , or expressed as eddy viscosities approximately between  $10^8$  and  $10^6$   $\text{g. cm}^{-1} \text{sec.}^{-1}$ . In the ocean, the effects of the two lateral diffusion components (down stream and cross stream components) and of the vertical diffusion component have not been isolated and separately studied, but it is evident (at least in so far as the Caribbean basin is concerned) from the preceding discussion of the vertical and horizontal gradients of the transferable substances, that to be significant in diffusing substances the lateral turbulent components must exceed greatly the magnitude of the vertical diffusion component. Recently, Rossby (1936) in connection with studies of the Gulf Stream circulation investigated theoretically the dynamics of horizontal diffusion but did not publish numerical values for the magnitude of the viscosity coefficients.

In connection with the present investigation of turbulent transfer in the Caribbean basin it is desirable to consider the lateral (along constant density surface) as well as the vertical gradients for available identifying properties in order that comparison of their respective curvatures may furnish information on the magnitude of the horizontal diffusivity coefficients required to produce a measurable effect in their concentrations as a result of lateral diffusion. For this object, lateral and vertical distributions of oxygen, salinity, and temperature at the depth of the minimum oxygen concentration in the vicinity of stations 1499 and 1510 have been compared. The density of the minimum oxygen concentration in the area concerned is so nearly constant that for practical purposes associated properties may be considered to lay along an isopycnal surface.<sup>22</sup>

We are now concerned with the fundamental differential equation, regulating diffusion in the sea both by lateral and vertical turbulence (page 43). The last two terms of the right hand side referring to the down stream and cross stream components may be combined into an average value for the lateral component so that the equation would read:

$$(12) \quad \rho \frac{d\alpha}{dt} = A \frac{\partial^2 \alpha}{\partial z^2} + A' \frac{\partial^2 \alpha}{\partial N^2}$$

where  $A'$  would represent an average value for the two lateral turbulent components and  $\partial^2 \alpha / \partial N^2$  the average gradient over a constant density surface. Values of  $\partial^2 \alpha / \partial z^2$  have been given for oxygen,  $\partial^2 O / \partial z^2$ , salinity,  $\partial^2 S / \partial z^2$ , and temperature,  $\partial^2 t^\circ / \partial z^2$ , at the depth of the oxygen minimum concentration between stations 1499 and 1510 (page 48);

<sup>22</sup> Such an adjustment may be obtained by plotting the property ( $\alpha$ ) as a function of density and scaling for its value at the density value  $\sigma_t = 27.17$ . For explanation see page 41.

and mean values for the second derivative of the horizontal gradient,  $\partial^2\alpha/\partial N^2$ , with reference to the same depth are given in Table 3.

TABLE 3

Property	$\frac{\partial^2\alpha}{\partial N^2}$	Ratio: $\frac{\frac{\partial^2\alpha}{\partial z^2}}{\frac{\partial^2\alpha}{\partial N^2}}$
Oxygen	$\frac{\partial^2 O}{\partial N^2} = 2.15 \times 10^{-18} \text{ cm}^3 \text{ g}^{-1} \text{ cm}^{-2}$	$\frac{\frac{\partial^2 O}{\partial z^2}}{\frac{\partial^2 O}{\partial N^2}} = 1.1 \times 10^6$
Salinity	$\frac{\partial^2 S}{\partial N^2} = 1.75 \times 10^{-18} \text{ g. g}^{-1} \text{ cm}^{-2}$	$\frac{\frac{\partial^2 S}{\partial z^2}}{\frac{\partial^2 S}{\partial N^2}} = 5.7 \times 10^5$
Temperature	$\frac{\partial^2 t^\circ}{\partial N^2} = 6.85 \times 10^{-15} \text{ deg. cm}^{-2}$	$\frac{\frac{\partial^2 t^\circ}{\partial z^2}}{\frac{\partial^2 t^\circ}{\partial N^2}} = 8.4 \times 10^5$

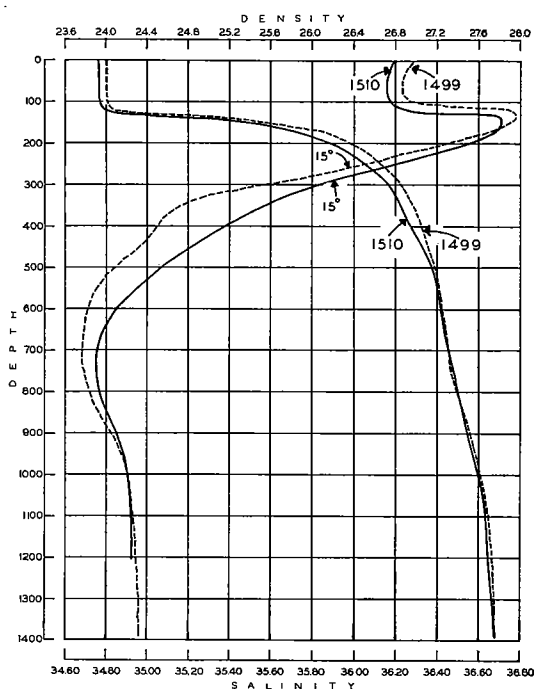


FIG. 42. Vertical distribution of density ( $\sigma_t$ ) and salinity ( $S$  ‰) for stations 1499 and 1510 in the eastern part of the Caribbean basin.

Since the ratios of the second derivatives of mean vertical to mean horizontal gradients at the oxygen minimum concentration are approximately  $10^6$ , a horizontal eddy diffusion coefficient having a value up to  $10^5$  may exist, and yet produce no measurable effect in the concentrations of the transferable substances. Thus, for example, the amounts of change in concentrations of oxygen, salinity, and temperature calculated from a horizontal eddy diffusing coefficient of  $10^5$  C.G.S. units (based on data in Table 3) for the time interval as the water at the depth of the minimum oxygen concentration moves (along an isopycnal surface) from station 1499 to 1510 are given in Table 4. The results are also expressed as percentages of the observed change of concentration ( $\alpha_2 - \alpha_1$ ) and of the change brought about by vertical turbulence (taking  $A = 2.8$  C.G.S. units). In all cases for this area, the horizontal diffusion which might be brought about by a lateral turbulent coefficient approximately  $10^5$  times the vertical component is slight.

TABLE 4

Property	$10^5 \int_0^{2.3 \times 10^7} \frac{\partial^2 \alpha}{\partial N^2} dt$	$100 \frac{\alpha \text{ lateral}}{\alpha \text{ observed}}$	$100 \frac{\alpha \text{ lateral}}{\alpha \text{ vertical}}$
Oxygen	$4.95 \times 10^{-6} \text{ cm}^3 \text{ g}^{-1}$	—	3%
Salinity	$4.03 \times 10^{-6} \text{ g. g}^{-1}$	4%	6%
Temperature	$1.57 \times 10^{-2} \text{ deg.}$	4%	4%

Calculation of the amount of lateral diffusion brought about by a lateral eddy coefficient of  $10^5$  C.G.S. units at the depth of the minimum oxygen concentration (calculated from data in Table 2) as the water moves from station 1499 to 1510 ( $t = 2.3 \times 10^7$  secs).

Thus, while the above calculations do not necessarily demonstrate the existence of lateral diffusion they do suggest that lateral diffusion coefficients of the order of magnitude of  $10^5$  may exist (at the depths concerned) without producing a measurable diffusion effect. In fact, part of the difference between the observed change of salinity concentration and that calculated to result from vertical diffusion between stations 1499 and 1510 may be due to a proportionately greater lateral diffusion of salinity, resulting from the reduced ratio between vertical and horizontal gradients.

Regarding any relation between lateral and vertical turbulence little is known. In the region under discussion consideration of vertical salinity gradients (as represented by stations 1499 and 1510; Fig. 42) shows that second derivatives are greater at depths of maxima or minima, thus producing more favorable conditions for vertical transport, than (as for instance) at the depth of the  $15^\circ$  isotherm (Fig. 42). The situation is brought out in Table 5.

TABLE 5

Level	$\frac{\partial^2 \alpha}{\partial z^2}$
Salinity maximum	$\frac{\partial^2 S}{\partial z^2} = -3.3 \times 10^{-11} \text{ g. g}^{-1} \text{ cm}^2$
$15^\circ$ isotherm	$\frac{\partial^2 S}{\partial z^2} = 7.0 \times 10^{-13} \text{ g. g}^{-1} \text{ cm}^2$
Salinity minimum	$\frac{\partial^2 S}{\partial z^2} = 10.0 \times 10^{-13} \text{ g. g}^{-1} \text{ cm}^2$

### OXYGEN AND THE GENERAL CIRCULATION

Previous investigations of the Caribbean Sea have developed a general picture of the main circulation pattern. Large quantities of water from the open Atlantic to the east and southeast entering the eastern Caribbean region through the passages among the lesser Antilles (to depths of 1000–1500 meters approximately) are modified within the Caribbean and Cayman basins by admixture of more northern Atlantic water entering through the three northern passages (Mona, Anegada, and Windward); the effects of mixing of super- and subadjacent water masses are noticeable in particular at the depth of the salinity maximum (which may be largely derived from the Atlantic water to the north and northeast), and at the depths of the salinity minimum (which may represent the last traces of subantarctic water injected into the North Atlantic ocean; page 34). The latter which persists everywhere in the Caribbean and Cayman basins, the Yucatan Channel, and the Straits of Florida, would seem to indicate a powerful and wide reaching influence of subantarctic water in the Caribbean region and is discussed on page 33.

In the deeper parts of the Caribbean and Cayman basins (below approximately 1500 to 2500 meters depth) separate circulations are maintained whereby water filling the greatest depths probably chiefly enters through the two deeper northern passages (Anegada and Windward). On the basis of oxygen content (page 6), it seems likely that renewal of the deeper parts of the two basins is fairly frequent and takes place principally at or close to the bottom whereby a vertical circulation is induced by means of which the deepest water is carried off eventually by the main Caribbean current out through the Yucatan Channel and the Straits of Florida.

Application of the Bjerknes' dynamic method for calculation of dynamic topography to the "Atlantis" data from the Caribbean Sea may give results not as satisfactory as when this method is applied to oceanographic data obtained in a shorter time interval in a smaller area.<sup>23</sup>

Nevertheless, Parr's (1937) calculations of dynamic topography in the Caribbean Sea (based on "Atlantis" 1933 and 1934 observations) relative to the 1200 decibar surface, showed a general good agreement with ideas of its circulation as derived from other sources. Thus, in the upper 1200 meters, the principal flow, as shown by dynamic calculations, followed approximate west and northwest directions through the Caribbean and Cayman basins out through the Yucatan Channel. South of the main axis of flow there was evidence of a large eddy between Honduras and Colombia and, to the north, evidence of a similar large eddy south of Jamaica, while between Cayman Island and Cuba there appeared to be a complex system of eddies.

### OXYGEN AND THE ORIGIN OF THE DEEP WATER

The most striking feature in the oxygen distribution of the Caribbean Sea region is that it increases continuously below threshold depths down to the bottom. This fact alone is evidence that (in both basins) renewal of the deep water occurs at, or close to, the very bottom, and while similar circumstances are known to occur in other inclosed seas, the Caribbean basins are unique in their class, in that the deepest water cannot have been aerated at the immediate surface there, as a consequence of which the mechanism of renewal is distinctly different from other seas of its type and presents a puzzling problem.

Thus, while in the Mediterranean, and adjacent seas, oxygen content likewise increases below threshold depths all the way to the bottom, both Jacobsen (1912) and Nielson (1912) have shown that in certain parts of the Mediterranean seasonal cooling of the surface water is sufficient to induce a mass sinking effective to the bottom. At the surface of the Mediterranean, conditions determining oxygen absorption are such that its deep water contains lower quantities of the dissolved gas than the Caribbean deep water. Likewise, in the Red Sea (lying at approximately the same latitudes as the Caribbean) the recent data of van Riel (1932) indicates an increasing oxygen content below threshold depths to the bottom (lower absolute values than in the Mediterranean), but here also a reasonable explanation is afforded by seasonal mass sinkings resulting from the combined effect of evaporation and chilling of the surface water in the coldest season (Krümmel, 1911). That this renewal is very weak appears to be indicated by the uniformly low oxygen content at great depths (apparently less than 2.5 cc per liter).<sup>24</sup>

Thus, the problem of renewal of the deep water of the two Caribbean basins is distinctly different from that characterizing other seas of this general type, but whatever the mechanism may be it remains in fairly frequent operation. The relatively high oxygen content of the deep water suggests an origin at the surface at high latitudes (unlike that of the Mediterranean or Red Sea), and furthermore difference in oxygen contents of the

<sup>23</sup> See Bjerknes' (1910) discussion of quasi static state in the ocean.

<sup>24</sup> In certain regions the mechanism of aeration is insufficient to offset stagnation in the deeper water as for instance apparently occurs in places off the Arabian coast where Sewell (1934) reports a slight trace of hydrogen sulphide in a bottom deposit (green mud) and, likewise, in the Black Sea where below 200 meters there is a complete absence of oxygen (Krümmel, 1911). Other bodies of water whose deeper parts are closed off by thresholds may exhibit a seasonal stagnation, as the Norwegian oyster basins, described by Helland-Hansen (1908) and Gaarder and Spärck (1932).

two Caribbean basins indicates that their deeper parts are independently supplied by the instreaming through the various passages. It is here suggested that the mechanism of renewal may be associated with vertical oscillations of the water column (both short and long period) which are known to exist to great depths in the ocean, and by which a periodic raising of the water column in the Atlantic adjacent to the Caribbean inlets may cause a periodic entrance of heavier water which immediately sinks to the bottom of the deep basins.<sup>25</sup> It is not possible to elaborate further on this idea at present, but it is logical that some such mechanism exists in order that water of slightly greater density may frequently enter the Caribbean basins over its thresholds. The remarkable uniformity of physical properties of the water masses within the Caribbean, below threshold depths, are ideal for the maintenance of such a situation; between depths of 1500 and 4000 meters this uniformity of oceanographic characteristics as illustrated by the following average values (based on "Atlantis" 1933 and 1934 observations) is:

Salinity average: 34.977 ‰; average deviation: 0.012 ‰. Temperature average: 4.107°; average deviation: 0.042°; Density average ( $\sigma_t$ ): 27.780; average deviation: 0.011. Below depths of 1700 meters the surrounding Atlantic water<sup>26</sup> became increasingly colder and heavier than that of the Caribbean Sea basins; at depths of 4000 meters temperature of Atlantic water<sup>27</sup> was approximately 1.7° lower and its density 0.12 units of  $\sigma_t$  greater.

Comparison of the oxygen content of the Caribbean Sea region (average values in Table 6) with that of the Atlantic water to the north (as indicated by "Atlantis" station 1210, 22° 14'N, 67° 50'W; Seiwel (1934)) showed that between depths of 2000 to 4500 meters the Caribbean basin was 0.82 to 0.99 cc per liter lower and Cayman basin 0.08 to 0.21 cc per liter lower. Hence (assuming no significant differences in biological activity), the deeper water of the Caribbean Sea basins was renewed less frequently than that of the open Atlantic.

TABLE 6

DEPTH	OXYGEN cc/LITER		TOTAL AVERAGE	VARIABILITY COEFFICIENT
	CARIBBEAN AVERAGE	CAYMAN AVERAGE		
1500	4.87	5.36	5.16	0.05
2000	5.05	5.77	5.39	0.07
2500	5.10	5.87	5.43	0.07
3000	5.10	5.88	5.43	0.07
3500	5.15	5.76	5.56	0.06
4500	5.18	5.84	5.72	0.04
5000	—	—	5.77	0.06

The bathymetric features of the Caribbean passages are not precisely known, but as far as can be determined, direct contact with the surrounding Atlantic water is apparently completely shut off at depths of approximately 2000 meters in the Caribbean basin, and at approximately 2500 to 3000 meters in the Cayman basin; the deepest passages connect both basins with Atlantic waters to the north. The lowest level at which direct exchange of water between the Caribbean region and the surrounding Atlantic takes place has been assumed by Parr (1937) to be indicated by the depth of the lowest

<sup>25</sup> Short period vertical oscillations in the Atlantic ocean have been studied by various investigators both from practical (Helland-Hansen and Nansen, 1909; Helland-Hansen, 1930; Defant, 1932; and Seiwel, 1937) and theoretical standpoints (Fjelstad, 1933). Likewise, in this connection, a somewhat similar question appears to arise regarding the renewal of the water below threshold depths in the fjords of east Greenland (remarked on by Jakelln, 1936).

<sup>26</sup> To compare temperature, salinity, and density values of the Caribbean Sea basins with the surrounding Atlantic waters see also Wüst's (1936) charts of horizontal distribution of these characteristics.

<sup>27</sup> Temperature values are not corrected for the effect of adiabatic warming.

temperature, in situ, which, in the Caribbean basin, has an average depth of slightly more than 2000 meters and, in the Cayman basin, slightly more than 2500 meters (these depths approximately coincide respectively with the previously estimated threshold depths of the two principal passages opening to the Atlantic). On the other hand, estimations, obtained by comparing vertical distributions of potential temperatures within the deep parts of the Caribbean Sea region with those of adjacent Atlantic water, appear to give somewhat higher threshold levels (approximately 1800 meters in the Caribbean basin and 1600 meters in the Cayman basin, according to Dietrich's (1937) estimates). In this case, however, the use of potential temperatures as identifying properties may give a false impression of threshold depth because the water masses from the Atlantic after entering the Caribbean region may, in part, lose their identities by some mixing with warmer water before reaching the bottom. And, in particular, since, below depths of 1500 meters, vertical temperature gradients are everywhere small, a slight variation of temperature may cause a significant variation in an estimation of threshold depth; or specifically, a rise in temperature of a water mass (by mixing) after it has entered the Caribbean Sea region will, on the basis of potential temperature identity, appear to have originated at a higher outside level (in the Atlantic) than it actually did.

Likewise, Dietrich's (1937) inadvertent employment of oxygen to associate certain strata of the Caribbean Sea region with the adjacent Atlantic, gives threshold depths of insufficient depth, which is a logical consequence from using oxygen as an identifying property without the necessary consideration of its non-conservatism (page 23). Hence, conclusions, whereby threshold depths are fixed by assuming continuous hydrographic connections between the Caribbean Sea and the adjacent Atlantic, along a stratum identified by identical oxygen content, will in all probability be too shallow, since water masses (below the depth of the minimum oxygen concentration) in the Caribbean Sea may reasonably be expected to have originated from the deeper levels of higher oxygen content in the open Atlantic. Consequently, while there appears to be as yet no completely satisfactory method for establishing the depth to which direct exchange between the Caribbean basins and the surrounding Atlantic waters takes place, the use either of potential temperatures or dissolved oxygen content for the purpose appears to be undesirable.

### RÉSUMÉ

The Caribbean Sea region (lying approximately between latitudes  $10^{\circ}$ – $20^{\circ}$ N and longitudes  $61^{\circ}$ – $87^{\circ}$ W) is divided into two natural bathymetric subdivisions by a ridge (in places less than 1000 meters depth) extending from Honduras to Haiti via Jamaica; the eastern basin is here termed the Caribbean and the western the Cayman. Connection between the Caribbean basin and the adjacent Atlantic is maintained by passages among the lesser Antilles (generally less than 1000 meters depth), through Mona Passage (less than 1000 meters depth), and through Anegada Passage (1500–2000 meters depth). The Cayman and Caribbean basins are connected over the above mentioned ridge by two channels of not more than 2000 meters depth and connection of the former with the open Atlantic is through Windward Passage, whose greatest depth appears to be slightly greater than 3000 meters. The waters of the Caribbean Sea region flow through Yucatan Channel (greatest depth just over 2000 meters) into the eastern Gulf of Mexico where they are isolated from the deeper parts of the open Atlantic by a threshold of less than

1000 meters depth across the Straits of Florida. Since large areas of the Caribbean basin are more than 4000 meters deep and depths of more than 6000 meters occur in the Cayman basin a large part of each basin has no direct contact with the adjacent Atlantic.

Oxygen content in the upper 100 meter layer (controlled chiefly by biological activity) was 4.0 to 5.0 cc per liter below which it decreased to minimum values (2.8 to 3.2 cc per liter) in the vicinity of 600 meters; in the Cayman basin minimum values were 0.1 to 0.2 cc per liter higher than in the Caribbean. In still deeper water (below the minimum), oxygen contents of both basins increased, at first rapidly to depths of 1500 to 2000 meters and then more slowly to the bottom. The Cayman (the richer of the two basins) averaged 0.5 cc per liter higher at 1500 meters and 0.71 cc per liter higher between 2000 and 4500 meters than the Caribbean. The waters of both basins characteristically contained less oxygen in depths below 1000 meters than the surrounding Atlantic waters at the same depths; at 1500 meters the Cayman averaged about 0.5 cc per liter less, the Caribbean about 0.9 cc per liter less.

The combinations of oxygen and salinity values to form oxygen salinity relationships were useful in tracing certain principal water movements (between depths of 200 to 1000 to 1200 meters) in the region investigated. Thus, oxygen salinity relationships of adjacent Atlantic waters, which, entering the Caribbean Sea region, have definite regional distinctions, permitted the establishment within the Caribbean Sea region of a fundamental pattern, the minor modifications of which are characteristic of the circulation. In the Caribbean basin, oxygen salinity relationships, based on three transverse sections, reveal almost similar latitudinal variations; significant changes of pattern in direction of the principal water movements of the upper layers are brought about, in particular, by small decreases in oxygen content at the depth of the oxygen minimum concentration, and by increases in salinity at the depth of the salinity minimum concentration. The apparent widespread influence of subantarctic water in the Caribbean region appears to be indicated by the intermediate salinity minimum; and, comparisons of oxygen salinity relationships in the Caribbean Sea region with those characterizing the adjacent Atlantic waters suggest that, in the former, the water masses derived from the Atlantic to the north and northeast are largely replaced at mid depths by water masses derived from the Atlantic to the east and southeast.

In the Cayman basin, oxygen salinity relationships indicate that the higher oxygen content of its upper layers was due to richer Atlantic water which, moving in through Windward Passage, was deflected chiefly to the right to mix with the main Caribbean current. Still further west, after removal from the vicinity of Windward Passage, the principal water masses of the main Caribbean current were traced by their oxygen salinity relationships out through the Yucatan Channel and into the eastern Gulf of Mexico (where they appear to form a large clockwise eddy), finally moving out through the Straits of Florida to flow northward as the Gulf Stream.

Because of the extensive distribution and close vertical relationship of the principal salinity and oxygen minimum concentrations, both properties have been utilized in an investigation of the vertical eddy diffusion coefficient at mid depths in the Caribbean basin. The calculation, based on the change in oxygen and salinity in the eastern part of this basin, gave a value of  $A = 2.8$  C.G.S. units for the vertical turbulent coefficient, and the mean horizontal velocity of the water at mid depths was calculated to be  $u = 2.0$  cms  $\text{sec}^{-1}$ . The ratio  $A/u$  obtained in this manner was confirmed by a second method and appears to be approximately correct for the depths concerned; also, the calculated

changes in salinity and temperature resulting from a vertical turbulent coefficient of 2.8 C.G.S. units show good agreement with observed changes. The effect of lateral turbulence at mid depths in this region appears to be very small and application of the lateral diffusion equation (to the case under consideration) showed that lateral turbulent coefficients of  $10^5$  C.G.S. units may actually exist and produce only 4 per cent of the observed change of temperature and salinity (or an unmeasurable amount).

The minimum oxygen concentration was lowest in regions farthest removed from the inlets, the decline being due to excess of oxygen consumption over the gain by turbulent mixing, and was, in general, higher in the Cayman than in the Caribbean basin. To estimate the dependence of the minimum oxygen concentration on the circulation, a comparison of its horizontal variation with deviations from the mean salinity anomaly showed a correlation coefficient of 0.387 for the Caribbean basin and a coefficient of 0.323 for the Cayman basin. From these results it was concluded that the actual value of the minimum oxygen concentration was more dependent on the biological activity than on the circulation. A statistical treatment of the frequency distribution of density of the water column at which the minimum oxygen concentration was observed (in both basins) indicates that the observed variation of density is a result of the random sampling. The modal value of the density ( $\sigma_t$ ) level at which the minimum oxygen concentration occurred in the Caribbean Sea region was calculated to be:  $\sigma_t = 27.171 \pm 0.007$ ; which is in close agreement with a similar value previously calculated for the western North Atlantic basin.

The bathymetric isolation of the Caribbean Sea region is such that a divergence of oceanographic characteristics from those of the open Atlantic was well established at 1500 meters (in both basins) and continues all the way to the bottom. In the case of oxygen, both basins had a lower concentration than the adjacent Atlantic, the Cayman being higher than the Caribbean; at 4500 meters the Cayman averaged 5.8 cc per liter and the Caribbean 5.18 cc per liter, the latter having approximately 0.9 cc per liter of dissolved oxygen less than the water of the adjacent Atlantic. In both basins, oxygen content (below the minimum concentration) increased down to the bottom.

This oxygen distribution suggests certain circumstances surrounding the unique origin of the deep water in the Caribbean Sea basins. They are: first, the relatively high oxygen contents of both basins are sufficient evidence to indicate that the deepest water masses were originally formed at the surface of high latitudes, from whence they have entered the region by instreaming through the various passages among the islands; second, the difference in oxygen contents of the deeper parts of the Caribbean and Cayman basins (combined with bathymetric considerations) may indicate that the deeper parts of these basins are independently supplied (probably the Caribbean, chiefly through Anegada Passage, and the Cayman, through Windward Passage) and also that the rate of renewal of the Cayman basin is slightly in excess of that in the Caribbean; and, third, since below the depth of minimum oxygen concentration, dissolved oxygen content in both basins (in general) increased downward to the bottom, would appear to be evidence that a supply of oxygen richer water takes place at or close to the bottom. This latter condition implies that water of somewhat greater density, than exists inside the Caribbean basins at threshold depths, enters through the various passages and immediately sinks to the bottom. The mechanism for bringing about this renewal of water is suggested to be associated with the short period vertical oscillations of the sea.



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