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Water Characteristics of the Caribbean Sea

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ABSTRACT

The volume of Caribbean Sea water in bivariate classes of potential temperature vs. salinity has been estimated from 76 hydrographic stations. The resulting statistics are presented on a pair of characteristic diagrams. The outstanding feature of the diagrams is the strong mode; nearly half of all Caribbean water lies within 0.1°C and 0.02 per mil of the mode, at 3.9°C, 34.98 per mil. An envelope of all samples has been determined. The waters below 2000 m in each of the four large basins are compared by using only data from a single Crawford cruise. In each basin the deep water is remarkably homogeneous, but the deep waters are different in the eastern (Yucatan and Cayman) and western (Colombia and Venezuela) basins. There appears to be no inflow of deep water through Jungfern Passage, the deepest connection with the Atlantic Ocean, but there may be sporadic inflow through Windward Passage into the western basins. There appears to be no inflow of water at mid-depth above either sill.

Introduction. The first purpose of this study is to estimate quantitatively for the Caribbean Sea the amounts of water of different types according to temperature-salinity correlation. Studies of water characteristics of the world ocean were reported in a series of papers by Cochrane (1958), Pollak (1958), and Montgomery (1958). The present paper employs an extension of their methods to study the Caribbean Sea in detail. Potential temperature is used throughout, computed for each sample from Helland-Hansen (1930).

As in the earlier series of papers, the results are shown on diagrams having potential temperature and salinity as coordinates. A new feature of the present paper is the determination of an envelope of all samples.

The second purpose of the present study is to examine the temperature-salinity characteristics of the deep waters in the four major Caribbean basins (Fig. 1). Several features that should be explained by any theory of Caribbean deep-water renewal are discussed. The deep water is compared with oceanic water outside the sills. The principal difference between the present analysis

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Figure 1. Position of the 76 selected stations in the Caribbean Sea (Mercator projection). Stations denoted A are from ATLANTIS; the others are from CRAWFORD. The 2000-m isobath only is shown. Bathymetry near the Virgin Islands Basin is from Frasetto and Northrop 1957.
and previous ones is that water characteristics (i.e., salinity and potential temperature together) in the basins are compared with water characteristics in the adjacent Atlantic Ocean. The comparison indicates that deep water in the basins is being renewed through Windward Passage, the shallower of the two main passages, but not through Jungfern Passage as has been previously thought.

The data selected for the present study were obtained by the Woods Hole Oceanographic Institution during the International Geophysical Year (1957–1958), except for a 1954 ATLANTIS section, which is included for completeness.

| TABLE I. List of selected stations in the Caribbean Sea. Data from Fuglister 1960. |
|----------------------------------|-------------------------------|---------------------------------|---------------------------------|
| Vessel                          | Stations                      | Number | Year | Months |
| ATLANTIS                        | 5232–5235, 5557–5263          | 11     | 1954 | XII   |
| total                           |                               | 76     |      |       |

Method. The selected data consist of the 76 stations listed in Table I and mapped in Fig. 1. The ATLANTIS section was made under the leadership of L. V. Worthington, and the CRAWFORD stations under the leadership of W. G. Metcalf (Fuglister 1960). Values of potential temperature and salinity for each sample were used. Each of the 1356 samples was weighted in proportion to the thickness of the layer it was assumed to represent. This layer thickness was determined by the midpoints between samples (or by the boundaries). Each station was assigned a horizontal area of $37.7 \times 10^3 \text{ km}^2$, so that the total volume assigned to all samples would equal the volume of the Caribbean Sea according to Stocks (1938) $-6927 \times 10^3 \text{ km}^3$. The volumes assigned to each sample range from $1 \times 10^3 \text{ km}^3$ to $23 \times 10^3 \text{ km}^3$. To check the volume distribution in depth, volume sums for 500-m intervals were compared with the volume of Caribbean Sea water in each 500-m interval as determined from Stocks. The lack of agreement was greatest for the deep water, where one discrepancy was 1.6 per cent of the total volume, but for most volumes the agreement was much better.

Two scales are used to present the bivariate distribution of potential temperature and salinity characteristics. The entire volume is shown in Fig. 2 by coarse-scale classes measuring $2^\circ\text{C} \times 0.2$ per mil. The fine-scale presentation, Fig. 3, employs classes $0.2^\circ\text{C} \times 0.02$ per mil to show the most densely populated area of Fig. 2. The fine-scale presentation extends to $6.2^\circ\text{C}$ to include water of the salinity minimum corresponding to Antarctic Intermediate Water. Each diagram shows, by sums, the univariate distribution of potential temperature at the bottom, of salinity at the right, and of potential specific-volume

2. Wüst (1964) has used the name "Virgin Islands Passage" rather than Jungfern Passage. This passage should not be confused with Virgin Passage, between Culebra and St. Thomas islands.
anomaly at the top and left. The sum given for each interval of potential specific-volume anomaly is the sum of all classes having centers within the interval. The few classes whose centers lie within 0.01°C of a bounding isanostere are equally divided between the two intervals. For the summation, coarse-scale classes (2°C × 0.2 per mil) were divided into subclasses 0.5°C × 0.05 per mil. The bordering sums include classes outside the range of the fine-scale diagram (Fig. 3).

An envelope of all samples is shown in Figs. 2 and 3. To determine the envelope, all samples except those well within the boundary were plotted on an expanded scale, and the outer points were joined. The sample distribution was found to have small gaps, which are thought to result primarily from the practice of making observations at standard depths. The envelope was smoothed so as to avoid local concavities that would have been caused by the gaps.

Oceanographic samples frequently are taken only at depths of every few hundred meters, and samples are taken at very nearly the same depths at all stations; in this practice, extensive layers of water are never sampled. The present study would have been served better if the sample depths varied from station to station, so that each entire basin would be better sampled.
Figure 3. Caribbean Sea on a fine-scale diagram of potential temperature vs. salinity. Potential specific-volume anomaly is represented by curves. Oblique numbers, when multiplied by 1000 km³, represent the volume of water in each class 0.2°C × 0.02 per mil. Water outside the range of the diagram is represented by oblique numbers in the bordering band and in parentheses. The boundary is the smoothed envelope of all samples (except the one represented by the small circle, which deviated markedly from the others). Sums at bottom give the distribution by potential temperature, at right by salinity, and at left and top by potential specific-volume anomaly. The relative scale is the same as in Fig. 2.

In Fig. 2 the five samples shown as circles outside the envelope lie apart from the other samples and have been disregarded in the determination of the envelope. These five samples lay apart from the others by one envelope half-width or more as measured nearest the sample in question, although subsequent smoothing has enlarged the envelope slightly. Six other samples (questioned by the observer) were discarded because they were hydrostatically unstable. The discarded samples are listed in Table II.

**Table II. Samples discarded from the data because of hydrostatic instability.**

<table>
<thead>
<tr>
<th>Station</th>
<th>Depth (m)</th>
<th>Potential temp. °C</th>
<th>Salinity per mil</th>
</tr>
</thead>
<tbody>
<tr>
<td>376</td>
<td>3530</td>
<td>3.83</td>
<td>35.088</td>
</tr>
<tr>
<td>376</td>
<td>3830</td>
<td>3.83</td>
<td>35.068</td>
</tr>
<tr>
<td>377</td>
<td>3035</td>
<td>3.83</td>
<td>35.006</td>
</tr>
<tr>
<td>384</td>
<td>280</td>
<td>18.60</td>
<td>35.788</td>
</tr>
<tr>
<td>393</td>
<td>2805</td>
<td>3.85</td>
<td>35.013</td>
</tr>
<tr>
<td>5261</td>
<td>1330</td>
<td>4.17</td>
<td>35.013</td>
</tr>
</tbody>
</table>
An alternative to the present method would be the use of a smoothed temperature-salinity curve for each station, in conjunction with a temperature-depth curve, to find the depth interval for each class interval. This method was used by Masuzawa (1964). The present method is chosen to avoid the uncertainties of interpolation.

In the series of papers by Cochrane, Pollak, and Montgomery, boundaries on the bivariate diagrams contain certain fractions of the water volume. In the present paper, the envelope encloses all water types observed, and it encloses them in a smaller area than that of the bivariate classes containing the samples. In particular, the modal class on the coarse-scale diagram contains no samples colder than 3.79°C, although the class extends to 2.0°C. Several classes can be seen in which the number representing the volume in a class, printed at the center of that class, lies beyond the envelope. The samples themselves, of course, lie within the envelope. By the selection of boundaries of the proper bivariate classes, it is possible to determine a boundary that contains at least a given fraction of Caribbean water. For instance, the largest three classes on the fine-scale diagram give the least area within the 50 per cent boundary. That part of the envelope within those classes, however, gives a boundary that has less (sometimes much less) area than the boundary of the classes. As an example, the largest three classes on the coarse-scale diagram contain 74 per cent of the entire volume. The area of the envelope within those classes is less than one-fourth the area of the classes themselves.

Discussion of Coarse-scale and Fine-scale Diagrams. The oceanographic features of the Caribbean Sea have been described by Parr (1937), Dietrich (1939), and others. The main topographic features are two deep basins separated by the Jamaica Ridge (Fig. 1). The western basin has a deep trench reaching to 7600 m and the eastern basin is deeper than 5400 m. Both the western and the eastern basins have passages connecting them with the Atlantic Ocean to the north. The effective sill depth is approximately 1500 m; 54 per cent of the total volume (computed from Stocks 1938) is below this depth. Each of the two principal basins is subdivided as shown in Fig. 1; between the subdivisions there is free communication at depths well below sill depth.

The upper water motion is dominated by inflow at the eastern rim. Fig. 2 shows the warm surface waters that are characteristic of these latitudes. Values warmer than 27°C are typical of these (winter) data. The subsurface salinity maximum represents Tropical Water (sometimes called "Subtropical"). Salinity at the maximum decreases westward as the flow travels the length of the Caribbean Sea. Antarctic Intermediate Water appears as the salinity minimum near 6°C. The minimum is found at depths of 700 m to 800 m,
and its salinity increases westward. The spottiness of the fine-scale diagram, Fig. 3, in the region of this minimum results partly from limited sampling, but the small volume there indicates that the minimum is a weak feature of the distribution. The deep water (3.8°C to 4.0°C) has characteristics well within the range of North Atlantic Deep Water but is warmer than its modal temperature of 2.25°C (Montgomery 1958).

Because all deep water in the Caribbean Sea must have entered over the sills, it is not surprising to find a heavy mode corresponding to the deep water. On the coarse-scale diagram, the two largest classes, at 4°C, 34.9 per mil, contain nearly 70 per cent of all the water. The mode stands out as the dominant feature of each univariate distribution. The largest class is in the salinity distribution; over 75 per cent of all Caribbean water is in the class 34.8 per mil to 35.0 per mil. The mode is also well defined in the distribution of potential temperature.

The secondary mode, near 17°C, 36.2 per mil, represents water in the Cariaco Trench (see Richards 1960), on the southern rim of the Venezuela Basin. The maximum depth in the trench is approximately 1450 m. Although disproportionately many stations were made there (Sts. 348-353), only two of them are in the deep portion. The mode, although exaggerated, appears to be a real feature of the water characteristics. The secondary mode also appears in the distribution of potential specific-volume anomaly, between 140 cl/t and 160 cl/t, and of potential temperature.

The detached fresh, warm limb is due entirely to stations at the northern end of the 1954 Atlantis section.

A feature of the results that is attributed to the sampling method is the scarcity of water having potential specific-volume anomaly near 320 cl/t. This water is found at a depth of roughly 130 m, a depth that is poorly represented in these data.

On the fine-scale diagram, nearly half the water is contained in two classes centered on the mode, at 3.9°C, 34.98 per mil. Homogeneity of the deep water is discussed in the next section, but it should be emphasized here that such a large fraction of the water has a range of only 0.2°C x 0.04 per mil.

The salinity of samples colder than 4°C varies only from 34.965 per mil to 34.996 per mil. Parr (1937), in discussing the deep water, noted that salinity varied between 34.96 per mil and 34.99 per mil, but in his figures a salinity greater than 35 per mil is shown occasionally. In the Cayman Basin, just inside Windward Passage, Worthington (unpublished data, Crawford 1963) has found salinities greater than 35 per mil; these values are higher than any of the present values for deep water. Earlier stations inside Windward Passage were examined (Atlantis Sts. 1569, 5073; Bull. hydrogr. Copenhagen. 1933, 1953), but no values of salinity as great as 35 per mil could be found below 1000 m.
It is desirable to mention the two small basins that are not represented in the selected data. The Virgin Islands Basin, between Anegada Passage and Jungfern Passage\(^3\), has a deeper sill toward the Atlantic Ocean than toward the Venezuela Basin, as was pointed out by Dietrich (1939) on the basis of potential temperature. Deep samples in the Virgin Islands Basin (CRAWFORD St. 330, Fuglister 1960) are colder than any samples used in the present study. In the Grenada Basin (on the eastern rim of the Caribbean Sea), examination of ATLANTIS St. 5282 (Bull. hydrogr. Copenh. 1955) shows that the deep water has characteristics of the modal class of the fine-scale diagram, but that water at temperatures of 4.5°C to 10°C is fresher than the envelope. This freshness is attributed to a larger fraction of Antarctic Intermediate Water at the eastern end of the Caribbean Sea.

**Sill Depths.** Depths of the major sills leading to the Caribbean basins have recently been estimated. Frassetto and Northrop (1957) concluded from their bathymetric survey that the depth of Jungfern Passage sill is 1960 m. On the basis of distributions of oxygen and potential temperature, however, Wüst (1964) estimated this sill depth to be only 1725 m to 1775 m. Wüst also estimated, on the same basis, that the depth of Windward Passage sill is 1600 m to 1625 m and that the depth of Dominica Passage sill is 1400 m. McLellan and Nowlin (1963) estimated, on the basis of potential temperature, that the sill depth in Yucatan Channel is less than 1900 m.

The eastern and western basins are separated by the Jamaica Ridge. Wüst has estimated that the sill depth there is approximately 1500 m.

Except for the work of Frassetto and Northrop, no published bathymetric surveys exist for any of the critical sills of the Caribbean Sea. Accurate surveys of these regions should be considered an important objective so that a better interpretation of observed water characteristics can be made.

**Comparison of Deep Waters in the Individual Basins.** The 1954 ATLANTIS section is excluded from the remainder of the present study to give the data maximum internal consistency.

For each of the four major basins, all samples below 2000 m are plotted in Figs. 4 and 5. Values of potential temperature and salinity for standard depths were obtained by linear interpolation for each station, and averages for each basin are given in Table III. Because of the small number of stations in the Yucatan and Cayman basins, data from them have been combined. Table IV contains a summary of the range of characteristics in the deep water of each basin.

The three main features of the waters below 2000 m are described here. Conclusions drawn from these features are discussed in the next section.

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3. See footnote, p. 149.
First, the degree of homogeneity increases with distance from Windward Passage. Fig. 4 shows that samples from the Cayman Basin have the greatest scatter, and those from the Venezuela Basin have the least scatter.

The degree of homogeneity in the deep waters of all Central American basins is remarkable (see Table IV). Values for the Gulf of Mexico are included to show that homogeneous deep water is a common feature of all large Central American basins. Deep water in the Gulf of Mexico differs from
Figure 5. Potential temperature vs. depth, in meters, for all samples below 2000 m in the individual basins of the Caribbean Sea. ATLANTIS stations have been excluded.


<table>
<thead>
<tr>
<th>Depth m</th>
<th>Potential temperature °C</th>
<th>Salinity per mil</th>
<th>Potential specific-volume anomaly, cl/t*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yucatan and Cayman</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Colombia</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Venezuela</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>3.95</td>
<td>34.987</td>
<td>30.8</td>
</tr>
<tr>
<td>2500</td>
<td>3.86</td>
<td>34.989</td>
<td>29.7</td>
</tr>
<tr>
<td>3000</td>
<td>3.84</td>
<td>34.988</td>
<td>29.6</td>
</tr>
<tr>
<td>3500</td>
<td>3.83</td>
<td>34.990</td>
<td>29.3</td>
</tr>
<tr>
<td>4000</td>
<td>3.83</td>
<td>34.990</td>
<td>29.3</td>
</tr>
</tbody>
</table>

* Absolute value of the digit after the decimal point is not significant.
TABLE IV. RANGE OFRecorded characteristics below stated levels in the Central American basins. The stated levels are those where vertical gradients of potential temperature very nearly vanish. Values in the Gulf of Mexico are taken from McLellan and Nowlin (1963: figs 3, 4).

<table>
<thead>
<tr>
<th>Basin</th>
<th>Level m</th>
<th>Potential temp., °C</th>
<th>Salinity per mil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gulf of Mexico</td>
<td>2200</td>
<td>4.00-4.05</td>
<td>34.970-34.976</td>
</tr>
<tr>
<td>Yucatan</td>
<td>2800</td>
<td>3.81-3.85</td>
<td>34.982-34.996</td>
</tr>
<tr>
<td>Cayman</td>
<td>2800</td>
<td>3.80-3.84</td>
<td>34.971-34.995</td>
</tr>
<tr>
<td>Colombia</td>
<td>2300</td>
<td>3.82-3.86</td>
<td>34.970-34.990</td>
</tr>
<tr>
<td>Venezuela</td>
<td>2300</td>
<td>3.83-3.86</td>
<td>34.976-34.986</td>
</tr>
</tbody>
</table>

the deep water of the adjacent Yucatan Basin but has characteristics that lie completely within the fine-scale envelope (Fig. 3).

Second, the western basins differ from the eastern basins with regard to salinity of the deep water. Salinity is higher and potential specific volume is lower in the Cayman and Yucatan basins than in the Colombia and Venezuela basins (Fig. 4, Table III). The average difference in salinity is approximately 0.01 per mil. This difference is two or three times the precision of measurement. Furthermore, the samples from each basin show a marked central tendency, with little overlap of values for the western and eastern basins.

Third, the depth at which potential temperature becomes nearly constant is greater in the western basins than in the eastern basins (as was noted by Worthington 1955). Fig. 5 shows that potential temperature becomes nearly constant at 2300 m in the eastern basins but at 2800 m in the western basins. This order is opposite to that of the usually assumed sill depths; the deeper sill (Jungfern) leads into the eastern basins.

Concerning the Renewal of Deep Water. Previous studies of deep water in the Caribbean Sea have been made by Dietrich (1939) and Wüst (1964), among others. They relied primarily on the distributions of oxygen and potential temperature. They concluded that deep water in the western basins is renewed through Windward Passage, and in the eastern basins through Jungfern Passage. Using potential temperature and, independently, salinity, Wüst found renewal of “near Bottom Water” through both Windward and Jungfern passages, but he found no flow from the western basins into the eastern basins. On the basis of the distribution of dissolved oxygen, however, Wüst has indicated (plates xxxiv et seq.) that a deep inflow through Windward Passage continues over the Jamaica Ridge into the eastern basins.

Worthington (1955) has suggested that the eastern and the western basins were filled from a single source, through Windward Passage. His arguments rest heavily on the oxygen values from the 1954 ATLANTIS section; as these
have been questioned, the strength of his arguments is reduced. Nevertheless, the other bases of his arguments (similarity of water types on each side of the ridge, warming of the deep water, climatological evidence) remain valid, and his ideas merit careful consideration.

The Crawford data indicate that there is inflow at sill depth through Windward Passage but not through Jungfern Passage. The principal evidence is that water having the characteristics of oceanic water is found only in the western basins. The data used in the present study are more precise than those used by Dietrich and are internally consistent to a greater extent than the data used by Wüst. In the present study, moreover, bivariate characteristics (i.e., potential temperature and salinity, together) are compared. Note that continuous isotherms, drawn on a vertical section through a passage, may imply a continuity of water types that does not necessarily exist.

Fig. 6 presents oceanic water characteristics for depths of approximately 1300 m to 1800 m near the sills, for comparison with water inside the basins. The oceanic samples are from 14 Crawford stations to the north, east, and southeast of the Caribbean Sea. All samples within the temperature range of the figure are included. Boundaries for the eastern and western basins are based on Crawford samples used in the present study.

Fig. 6 shows that water characteristics in the western basins are continuous with the characteristics of oceanic water. This continuity is consistent with inflow at Windward Passage sill. The western basins are certainly not simply filled with unmixed oceanic water, but some renewal seems likely. (The depth of the 3.80°C isotherm at the selected stations in the ocean varies from 1425 m to 1675 m.)

Fig. 6 also shows that in the eastern basins there is no continuity of water characteristics with oceanic water. The lower left-hand corner of the “Eastern” boundary is biased by a single sample in the Colombia Basin (see Fig. 4); the remaining samples have a boundary even farther removed from the “Atlantic” boundary. This lack of continuity of water characteristics is a strong indication that there is no inflow through Jungfern Passage (based on conditions in 1958). It is improbable that such extreme homogeneity could exist in the Venezuela Basin if there were inflow of oceanic water having noticeably different characteristics.

Dissolved oxygen should be lower in the eastern basins than in the western basins if there is presently no renewal through Jungfern Passage. Seiwell (1938) found that dissolved oxygen in the waters below 2500 m in the eastern basins was 0.7 ml/l lower than in the western basins. On the Crawford (1958) cruise that provided the data employed here, dissolved oxygen also was deter-

4. Crawford Sts. 320–326 extend from the northern end of the Atlantis section to 25°N (refer to Fig. 1); Crawford St. 369 is north of Windward Passage at 21°54′N, 73°15′W; Crawford Sts. 307–309 extend to 57°W from the eastern end of the Caribbean Sea at about 16°N; Crawford Sts. 177, 178, 183 lie near the coast of South America at 8°N. All stations are from Fuglister (1960).
Figure 6. Water characteristics (potential temperature vs. salinity) in the eastern and western basins of the Caribbean Sea compared with water characteristics in the adjacent Atlantic Ocean. The small circles represent samples from 14 CRAWFORD stations to the north, east, and southeast of the Caribbean Sea. The upper boundary of "Atlantic" water is an estimate of the freshest oceanic water at each temperature outside the sills. Boundaries for the basins are based on CRAWFORD (1958) samples. Potential specific-volume anomaly is approximated by the sloping line. The relative scale is the same as in previous figures.

mined (Metcalf 1959). The average oxygen content of the water below 2500 m is 0.55 ml/l lower in the eastern basins than in the western basins. (No significant difference was found between averages for the Yucatan and Cayman basins, or between those for the Colombia and Venezuela basins.) The averages are: western basins, 47 samples, 5.24 ml/l; eastern basins, 85 samples, 4.69 ml/l.

The present results indicate that the deep water in the eastern basins could have been supplied through Jungfern Passage in the past. Because oceanic waters near depths of the sills decrease in salinity with increasing depth, the deeper sill would admit (colder) water of slightly lower salinity. The observed average salinity difference between the western and eastern basins corresponds closely to the salinity associated with depths of the sills. Water in the eastern basins could have been warmed from below, causing the present temperatures nearly to coincide with those in the west. Estimates of bottom heat flow (e.g., $1.4 \times 10^{-6}$ cal cm$^{-2}$ s$^{-1}$, Gerard et al. 1962) indicate that the rate of temperature increase in the water below 2500 m, assuming no renewal, is about
0.03°C per 100 yr. This rate is essentially equal to that noted by Worthington (1955: table 2).

Some deep water may occasionally flow across the Jamaica Ridge from the western to the eastern basins. The conditions that suggest this flow are: the similarity of temperature-salinity characteristics in the east and west (except for the most saline water in the west), the increase in homogeneity with increasing distance from Windward Passage, and the decrease in oxygen content from west to east.

The similarity of temperature-salinity characteristics suggests a single source for both basins, as proposed by Worthington. The salinity difference, however, suggests previous inflow through Jungfern Passage, if Jungfern Passage is deeper than Windward Passage, as has been assumed. Previous filling of the eastern basins from the ocean and present renewal from the western basins are consistent with all the present results. More definite assertions should be withheld until the passages have been surveyed.

As discussed above, there appears to be no deep inflow at Jungfern Passage. Furthermore, there appears to be no inflow at depths below roughly 1000 m through either passage to the north, except for the inflow at sill depth through Windward Passage. The fine-scale diagram, Fig. 3, shows that at depths above the sills Caribbean water becomes fresher with increasing temperature; water outside the sills, however, becomes saltier with increasing temperature, as shown in Fig. 6. In order to study water characteristics at depths above the sills, salinity on the potential-specific-volume-anomaly surface 33.5 cl/t was mapped (not presented). This surface lies at a depth of roughly 1400 m in the basins and 1200 m to 1400 m outside the sills. Salinity on this surface was between 34.963 per mil and 34.977 per mil in the basins, but was greater than 35 per mil in the ocean. Within the basins the scatter from station to station was almost as large as the total range of values. At these depths, above sill depth, no inflow is indicated.

This result indicates that the horizontal pressure-gradient force is directed outward (from the basins to the ocean), at all depths between roughly 1000 m and the sills. Renewal of the deep water occurs, presumably, only when storm surges or other disturbances (e.g., internal waves) force oceanic water across the sill at Windward Passage. The eastern basins are not renewed from the ocean by these surges, because oceanic water that crosses the sill in Anegada Passage is apparently trapped in the Virgin Islands Basin.

Worthington (1955) has suggested that the deep northern sills are “considerably shallower” than 1600 m—and they may be; a pressure-gradient force that is directed outward at the sills, however, indicates that the depth of the sills cannot be determined by a simple comparison of potential temperatures in the basins with those in the ocean. There remains the pressing need for a bathymetric survey of all the deep sills.
Note Added in Proof. All salinities used in this study were determined by measurement of electrical conductivity. It has been learned that salinities of Crawford samples from the Venezuela Basin (Sts. 333–353) were determined aboard ship, but that those from the other basins (Sts. 354–400) were determined subsequently at Woods Hole. In the published data (Fuglister 1960), no distinction is made between the different methods, but conceivably this difference contributes to the change in homogeneity between the basins. It is of interest that more recent data (Crawford 1963; L.V. Worthington, personal communication) confirm the greater homogeneity in the eastern basins.

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