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Transequatorial movement of water masses in the Indian Ocean

by G. S. Sharma

ABSTRACT

Interrelationships of potential temperature-salinity and potential temperature-oxygen are presented for 31 stations along 5°N, the equator, and 5°S during the southwest monsoon, and the volumes of water in bivariate classes of potential temperature against salinity are estimated throughout each section. The sources of different water types and their flow pattern are discussed. The water below the equator is the most homogeneous and that of the northern section is the most heterogeneous. The influence of the Persian Gulf water is insignificant even in the northern region. There is no large flow of the Red Sea water across the equator except very near the African coast. In the depth range of 100-1,000 m the flow is primarily zonal; thus the equatorial Indian Ocean water acts as a barrier to transequatorial movement. The deep water in all the regions is of antarctic origin.

1. Introduction

Rochford (1964) used oceanographic data collected mainly during the northeast monsoon, when the Equatorial Undercurrent in the Indian Ocean is present, (Swallow, 1967; Taft, 1967; Taft and Knauss, 1967; Sharma, 1968) and interpreted the salinity maxima as showing southward flow.

As a result of the flow of high-salinity water from west to east along the Equatorial Undercurrent, a salinity maximum is formed in the core of the undercurrent (Swallow, 1967; Taft, 1967; Taft and Knauss, 1967; Sharma, 1968). Furthermore, the inflow of low-salinity water from the Pacific into the western Indian Ocean (Wyrtki, 1957, 1961; Taft, 1963; Sharma, 1972) and the incursion of the Banda Sea Intermediate Water at about 800-900 m (Rochford, 1966), must give rise to salinity maxima at different levels in the equatorial Indian Ocean during the northeast monsoon, in addition to the salinity maximum of the Red Sea water. In contrast, the salinity distribution in this region during the southwest monsoon shows nearly uniform salinity with a vertical variation of less than 0.30‰ in the upper 1,000 m (Sharma, 1972).

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Warren, Stommel and Swallow (1966) believe that the core method affords a satisfactory method of determining the qualitative flow features when the motion itself is more or less steady; but when, as in the Indian Ocean, the surface circulation is known to reverse periodically, property distributions on horizontal charts may not indicate the sense of motion unambiguously. In this paper, it is proposed to examine critically the transequatorial movement of water masses in the Indian Ocean during the southwest monsoon from water characteristics and flow pattern at different steric surfaces.

2. Treatment of the material

To study the water characteristics along 5°N, the equator, and 5°S, oceanographic data from 31 stations (Fig. 1) distributed as uniformly as possible, were chosen. With few exceptions the stations chosen were worked during the southwest monsoon (June-September) of 1962 or 1964.

For each station potential temperature for each sample was computed using the nomograms prepared by R. B. Montgomery and M. J. Pollak from Helland-Hansen's computations (1930). Potential temperature is plotted against depth, salinity and oxyty on a grid with overprinted isopleths of thermosteric anomaly. The values of potential temperature, salinity and oxyty are read directly from the station curves at the levels of 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 180, 200, 240, 280, 320, 360, 400, 440, 480, 520, 580, 640, etc., cl/t, and at the surface and deepest sampling level. Scatter diagrams for $\theta$-S and $\theta$-O$_2$ (Potential temperature-oxyty) are plotted for the stations along 5°N, the equator, and 5°S (Figs. 2a-2c). This method is advantageous in that the number of representative points is the same for each station, and the relative distribution of properties at each steric level is well depicted.

By the use of the station curves, the volume of water in each class with potential temperature range of 1.0°C and with salinity range of 0.1‰ is computed for the upper 2,000 m. The frequency distributions in terms of $10^3$ km$^3$ are given for the northern, equatorial, and southern sections separately as well as for the entire region covering the area 7°30'N to 7°30'S and 50°E to 98°E (Figs. 3a-3d). Montgomery
(1958) critically discussed the superiority of the quantitative evaluation by volumetric inventories over the qualitative assessment of T-S characteristics for identification of water masses. The total volume of water estimated is higher than that actually encountered because the islands and the projection of ridges above 2,000 m are not accounted for in the evaluation of the volume of water. This has been done deliberately to avoid the undue weightage of representation for any one region. However, the expected difference is negligible compared to the total volume of water.

3. Water characteristics

The $\theta$-S, $\theta$-$O_2$ characteristics (Figs. 2a-2c) offer a useful view of qualitative description of waters in the three regions—along 5°N, the equator, and 5°S. The most striking difference is that the distribution along 5°N is the most heterogeneous, and along the equator the most homogeneous. The influence of the high-salinity water of the Arabian Sea and the low salinity water of the Bay of Bengal account for the wider scatter in the upper layers, along 5°N. Although the east-west contrast in the water properties is evident in all the regions with relatively higher salinity in the west, the origins of low-salinity waters in the east are different in different regions. In the north the low salinity has its origin in the Bay of Bengal and in the south it is due to the advection of equatorial Pacific Ocean water that flows along the South Equatorial Current to the western Indian Ocean (Wyrtki, 1957, 1961; Taft, 1963; Sharma, 1972). In the intermediate depths where $\delta_0$ is 100-120 cl/t, there is less scatter probably because of lateral mixing. Below this layer there is more scatter where the Red Sea water spreads. Underneath the 40-cl/t surface the scatter in all the regions is almost uniform, with slightly higher salinity in the northern region, and uniformly increasing oxygen with depth.

4. Volumetric inventories

The three regions can be compared with regard to the number of frequencies enclosed by the 75% and 90% boundaries.

<table>
<thead>
<tr>
<th>Region</th>
<th>75%</th>
<th>90%</th>
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<tbody>
<tr>
<td>Northern (Fig. 3a)</td>
<td>16</td>
<td>30</td>
</tr>
<tr>
<td>Equatorial (Fig. 3b)</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Southern (Fig. 3c)</td>
<td>12</td>
<td>29</td>
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<tr>
<td>Combined (Fig. 3d)</td>
<td>20</td>
<td>29</td>
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The 75% boundary reveals the northern region to be the most heterogeneous and the 90% boundary indicates the equatorial water to be the most homogeneous (Figs. 3a, 3b). It is interesting to note that the 75% boundary of the southern region constitutes only 12 frequencies while the additional 15% accounts for 17 frequencies (Fig. 3c) probably because of different water masses from the east and
south. In the upper layers of the northern region (Fig. 3a), high-salinity water of the Arabian Sea and low-salinity water of the Bay of Bengal are distinctly separated from moderately saline equatorial Indian Ocean water. One striking feature of the northern region is the bimodal distribution brought about by the 75% boundary (Fig. 3a). The primary mode at 3.5°C, 34.85‰ and 35 cl/t represents the deep water between 1,600 and 1,800 m. The secondary mode at 9.5°C, 35.15‰ and 90 cl/t is the consequence of the Red Sea water. The mode at 26.5°C, 33.35‰ and 680 cl/t within 90% boundary represents the surface water of the Bay of Bengal. In the equatorial region, the mode is the same as the primary of the northern region and in the southern region the mode at 2.5°C, 34.75‰ and 35 cl/t represents the circumpolar water.

Within the 90% boundary, there are five frequencies accounting for a total volume of $164 \times 10^3$ km$^3$ with salinity 35.25‰ in the northern region (Fig. 3a), while there is no frequency present within this boundary either in the equatorial or southern regions with salinity greater than 35.20‰ (Figs. 3b, 3c). Of these, two frequencies below 100 cl/t with 9.0°C are essentially of the Red Sea origin, and the other three are from the Arabian Sea.
Figure 3. Frequency distribution in terms of $10^3$ km$^3$ of the upper 2,000 m of water in each class of the potential temperature range of 1.0°C and with salinity range of 0.10%. Solid line boundary encloses 75% of the total and dashed line boundary encloses 90%. Sums at bottom give the distribution by potential temperature and at right by salinity.

(a) northern region between 50°E and 98°E, and 7°30'N and 2°30'N.
(b) equatorial region between 50°E and 98°E, and 2°30'N and 2°30'S.
(c) southern region between 50°E and 98°E, and 2°30'S and 7°30'S.
(d) all the three regions combined between 50°E and 98°E, and 7°30'N and 7°30'S.
In the univariate distribution of salinity at the right of the diagrams, the primary mode at 34.85‰ (Fig. 3c) in the southern region is partly due to the equatorial Pacific Ocean water, and in the equatorial region the mode is at 34.95‰ (Fig. 3b). But in the northern region there is no predominant primary mode and the salinity is widely scattered with almost uniform distribution between 34.80‰ and 35.20‰. In the univariate distribution of potential temperature at the bottom of the diagrams, the primary mode at 5.5°C in the northern region may represent the admixture of various water masses from the northern and southern hemispheres and the secondary mode at 9.5°C is due to the Red Sea water. In the other two regions the primary mode at 3.5°C represents the upper deep water of the subpolar origin and the secondary mode at 8.5°C in the equatorial region is the effect of the Red Sea water. There is no prominent secondary mode in the southern region.

The number of frequencies within the 75% boundary for the whole region shows more heterogeneous nature than even the northern region (Fig. 3d) because of the wider range covered in the three regions. However, the 90% boundary indicates a similar number of frequencies as those of the northern and southern regions. The mode at 4.0°C, 34.85‰ and 40 cl/t accounts for nearly 17% of the total volume of the water. The 90% boundary shows a bimodal nature, and the secondary mode at 13.5°C, 35.15‰ and 160 cl/t represents the Arabian Sea water.

5. Flow pattern

In order to understand the movement of water masses in the equatorial Indian Ocean, the flow pattern, in the light of distribution of the water properties on the various steric surfaces presented by Taft (1963), Wyrtki (1971), and Sharma (1972), is briefly summarized.

The upper layers are subject to large seasonal variation due to periodic reversal of the surface circulation in the North Indian Ocean. A feature common to most of the steric surfaces is that the isohalines, depth contours, and oxyspleths run parallel to the latitudes, suggesting that the main transport is zonal except near the boundaries. The in-flow of low-salinity water from the Pacific Ocean along the South Equatorial Current, at intermediate depths above 100-cl/t surface is conspicuous. Transport function charts (Wyrtki, 1971) indicate a northward flow in the upper layers near the African coast while there is a southward transport in the offshore region. In the deeper layers, below 100-cl/t surface along the western boundary, the relatively high-salinity Red Sea water flows southward. There is an indication that the transport north of the equator is primarily zonal between 50°E and 80°E, east of which the flow takes a southerly turn crossing the equator (Wyrtki, 1971; Sharma, 1972). This cross-equatorial transport in the eastern boundary is common on all the surfaces.
6. Sources of water masses

Some of the transequatorial sections in the International Indian Ocean Expedition Atlas (Wyrtki, 1971) are made for transition periods between the two monsoons and some are for the northeast and southwest monsoons. As a result of semiannual variation of currents, there is less consistency between sections. To avoid ambiguity, sections corresponding to the southwest monsoon season are used to arrive at the sources of water masses.

The shallow salinity maximum of the Arabian Sea extends to 6°S in the depth range of 50-200 m in the western region. In the east the low-salinity water of the Bay of Bengal is extensive in the upper 200 m. The effect of the Red Sea water at depths varying from 600 m to 800 m can be seen as far as 5°S-6°S as a salinity maximum (34.9‰). The water from the northern hemisphere is associated with low oxyty. The high-salinity water from 28°S-35°S (Tropical High-salinity Water, invariably known as the Subtropical Water) sinks and protrudes as a tongue to about 13°S in the depth range of 100-500 m. Underneath this high-salinity water, the low-salinity water from the subpolar belt, known as the Antarctic Intermediate Water, sinks to about 1,500 m at 35°S-40°S, and then slopes up northward to about 600 m at 13°S. Surprisingly, the salinity minimum of the Antarctic Intermediate Water or the Subtropical Subsurface Water (both appear to be the same, although Warren et al., 1966, draw a distinction between these two) is associated with low oxyty, probably because this water has a longer stay at the intermediate depths underneath the Tropical High-salinity Water which is associated with high oxyty. Between 10°S and 15°S, there is a break-up in the salinity structure with low-salinity water separating the two high-salinity tongues from the northern and southern hemispheres (Wyrtki, 1971; Sharma, 1972). This particular feature is more conspicuous in the eastern sections where the incursion of the Pacific Ocean water is predominantly felt. Another interesting feature in the meridional sections is the relatively homogeneous water in the equatorial region, vertically extending from 100 m to 1,000 m within which the salinity variation is less than 0.30‰ (Wyrtki, 1971, pp. 400-512).

7. Discussion

The heterogeneous nature of the northern region in the frequency distribution of potential temperature and salinity as well as in the $\theta$-S scatter is the consequence of the extreme salinities in the Arabian Sea and the Bay of Bengal. The diverging water characteristics of the east and west are confined only to the upper layers. At intermediate depths (500-800 m), it is accounted for by the Red Sea water and mixing of low-salinity water of the southern hemisphere as well as the westward flowing Pacific Ocean water entering the Indian Ocean through the Banda and Timor seas at 10°S.
The five frequencies with salinity greater than 35.20%, within the 90% boundary in the northern region, are purely due to mixing of the Red Sea water below 100-cl/t surface and that of the Arabian Sea water above 140-cl/t surface. The Persian Gulf water is expected to be present on 140-cl/t surface. In the northern region, there is no water with salinity higher than 35.20% on 140-cl/t surface, and this confirms that the effect of the Persian Gulf water, even in the northern region, is small. The total volume of the Persian Gulf water is $6 \times 10^3$ km$^3$ (Evans, 1966) and the area of the northern region considered in the present paper is about $3 \times 10^6$ km$^2$. The average salinity of the Persian Gulf water is 38.00% (Evans, 1966), and if we assume the average salinity of the northern region water to be 35.00% and the entire volume of the Persian Gulf water is flushed out and spread in this region over a thickness of 20 m, the salinity of the resulting mixture would be higher than that of the northern region water by not more than 0.30%. Obviously, then, the spreading of the Persian Gulf water to south of 10°S as indicated by Rochford (1964) and Wyrtki (1971), is unlikely to increase the salinity of the water by a measurable quantity. This is also consistent with Sverdrup et al. (1942) who note that the Persian Gulf is so shallow that any exchange between it and the adjacent Gulf of Oman is of small significance.

The homogeneous nature of the equatorial region is shown to be due to various water types from northern and southern hemispheres, and the Pacific Ocean, coming into juxtaposition, resulting in lateral as well as vertical mixing. The admixture of these water masses, with properties different from any one of them, can be delineated as the equatorial Indian Ocean water with the least vertical variation of properties. From the vertical sections (Wyrtki, 1971; Sharma, Ms.) it is apparent that the equatorial Indian Ocean water acts as the southern boundary of water masses from the northern hemisphere and as the northern boundary of those from the southern hemisphere in the depth range of 100-1,000 m, and thus appears as a zone where they meet and mix. Furthermore, the absence of any frequency with salinity greater than 35.20% either in the equatorial or southern regions (Figs. 3b, 3c) within the 90% boundary confirms that there may not be any major flow that crosses the equator southward except very near the coastal boundaries. The salinity maxima on the T-S curves, probably, cannot be taken as a conclusive evidence of the flow of the Red Sea, Persian Gulf, or Arabian Sea waters, as considered by Rochford (1964), but only as the effect of mixing of these waters, unless they are confirmed by the distribution pattern on isosteric surfaces.

A comparison of station curves along 5°S shows that below 100-cl/t surface the salinity maxima of the stations from the east are higher than those of the central region. The distributions of water properties at these steric levels reveal the flow to be zonal between 50°E and 80°E. Such a situation implies that the mixing of the Red Sea water in the eastern zone of the equatorial Indian Ocean is more than that in the central zone. However, this does not warrant any major flow of the Red
Sea water across the equator. But very near the African coast the southward flow of the Red Sea water is obvious from higher salinity and lower oxyty noticed in station curves along 45°E, and it is further confirmed by the distribution of properties on the steric surfaces.

As the Red Sea or the Arabian Sea waters flow south and eastward, they are found to be present on lower steric levels (Wyrtki, 1971). The steric surfaces below 100 cl/t slope down southward in the equatorial Indian Ocean (Taft, 1963; Wyrtki, 1971). Therefore, the Red Sea water as it flows southward should deepen. Ambiguously, by the core method Rochford (1964) comes across a situation where the Red Sea water ascends as it moves south and east, and then again deepens with further southward and eastward movement.

Although the Red Sea and Antarctic Intermediate waters have the same density at their sources, the density of the former increases while the density of the latter decreases as they come in close proximity in the equatorial Indian Ocean, probably because the Antarctic Intermediate Water is warmed substantially by mixing while the Red Sea water is not changed much. Hence, the Antarctic Intermediate Water glides over the Red Sea water as they come in juxtaposition near the African coast.

Water, below 40 cl/t in all the three regions, cooler than 4.0°C with salinity between 34.70‰ and 34.80‰, must be of circumpolar origin. The relatively higher salinity and lower oxyty of the northern region at these levels seem to be the consequence of vertical mixing between the water of the circumpolar origin, and the higher salinity and lower oxyty water of the Red Sea origin.

8. Conclusions

a. The admixture of the various water masses of the northern and southern hemispheres, and the water mass of the Pacific Ocean, forms the equatorial Indian Ocean water which is nearly vertically homogeneous in the depth range of 100-1,000 m.

b. Due to basically zonal flow the equatorial Indian Ocean water checks the free transequatorial movement of water masses at 100 to 1,000 m depth.

c. The influence of the Persian Gulf water even in the northern region up to 5°N is small.

d. During the southwest monsoon there is no major cross-equatorial flow of the Red Sea water other than that near the African coast.

e. Although the Red Sea and Antarctic Intermediate waters have the same density at their sources, the density of the former increases while that of the latter decreases. When these waters come in juxtaposition near the African coast, the Antarctic Intermediate Water glides over the Red Sea water.

f. Below 40 cl/t, the water in the whole area is of circumpolar and Atlantic origin.
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REFERENCES


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