JOURNAL OF MARINE RESEARCH

The Journal of Marine Research, one of the oldest journals in American marine science, published important peer-reviewed original research on a broad array of topics in physical, biological, and chemical oceanography vital to the academic oceanographic community in the long and rich tradition of the Sears Foundation for Marine Research at Yale University.

An archive of all issues from 1937 to 2021 (Volume 1–79) are available through EliScholar, a digital platform for scholarly publishing provided by Yale University Library at https://elischolar.library.yale.edu/.

Requests for permission to clear rights for use of this content should be directed to the authors, their estates, or other representatives. The Journal of Marine Research has no contact information beyond the affiliations listed in the published articles. We ask that you provide attribution to the Journal of Marine Research.

Yale University provides access to these materials for educational and research purposes only. Copyright or other proprietary rights to content contained in this document may be held by individuals or entities other than, or in addition to, Yale University. You are solely responsible for determining the ownership of the copyright, and for obtaining permission for your intended use. Yale University makes no warranty that your distribution, reproduction, or other use of these materials will not infringe the rights of third parties.

This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. https://creativecommons.org/licenses/by-nc-sa/4.0/
Water Characteristics at 200 cl/t in the Intertropical Indian Ocean During the Southwest Monsoon

G. S. Sharma

Department of Earth and Planetary Sciences
The Johns Hopkins University
Baltimore, Maryland 21218

ABSTRACT

Depth, salinity, and oxygen on the 200-cl/t isanosteric surface have been mapped for the intertropical Indian Ocean during the southwest monsoon season. The data used for this study have come from 522 stations occupied during the International Indian Ocean Expedition. The most pronounced feature of the distribution is the transport of the low-salinity water from the Pacific through the Banda and Timor seas into the western Indian Ocean along the South Equatorial Current. The Equatorial Undercurrent could not be identified in the Indian Ocean during the southwest monsoon.

Introduction. The Indian Ocean is unique in that it is subject to an alternation in wind regimes, with the winds over the northern part reversing seasonally. The variation in the winds is reflected in the distribution of the properties and current structure of the water. A study of this effect is particularly fascinating relative to the southwest monsoon, when there are strong winds of 25–30 knots over the Arabian Sea. It is during this period that the strongest current (Somali) ever observed in any part of the ocean (7 knots) is present, with northward flow in the western Indian Ocean; also at that time the current pattern in the northern Indian Ocean is entirely different from that in the rest of the major oceans, viz., the Pacific and Atlantic. On the contrary, the northeast monsoon is less effective in its strength and continues over a shorter period of time; furthermore, the general features of the current structure in the northern Indian Ocean during this part of the year resemble those of the other major oceans. Because of the seasonal changes and because the northern Indian Ocean, during the southwest monsoon, differs in behavior from the

1. Accepted for publication and submitted to press 1 October 1971.
2. Present address: Central Marine Fisheries Research Institute, Cochin-16, Kerala, India.
Table I. See Fig. 1. List of stations, all from the International Indian Ocean Expedition.

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Cruise</th>
<th>Stations used</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANTON BRUUN</td>
<td>Cr. 1</td>
<td>6</td>
<td>May 1, 1963 to May 2, 1963</td>
</tr>
<tr>
<td>ANTON BRUUN</td>
<td>Cr. 2</td>
<td>32</td>
<td>May 23, 1963 to July 17, 1963</td>
</tr>
<tr>
<td>ANTON BRUUN</td>
<td>Cr. 3</td>
<td>9</td>
<td>Aug. 13, 1963 to Sept. 4, 1963</td>
</tr>
<tr>
<td>ANTON BRUUN</td>
<td>Cr. 4</td>
<td>5</td>
<td>Sept. 25, 1963 to Sept. 30, 1963</td>
</tr>
<tr>
<td>ANTON BRUUN</td>
<td>Cr. 6</td>
<td>21</td>
<td>May 17, 1964 to June 24, 1964</td>
</tr>
<tr>
<td>ANTON BRUUN</td>
<td>Cr. 7</td>
<td>7</td>
<td>Aug. 3, 1964 to Aug. 17, 1964</td>
</tr>
<tr>
<td>ARGO</td>
<td></td>
<td>96</td>
<td>June 1, 1962 to Sept. 21, 1962</td>
</tr>
<tr>
<td>ATLANTIS II</td>
<td>Cr. 8</td>
<td>115</td>
<td>Aug. 4, 1963 to Oct. 27, 1963</td>
</tr>
<tr>
<td>DIAMANTINA</td>
<td>Cr. 2/60</td>
<td>24</td>
<td>Aug. 21, 1960 to Sept. 23, 1960</td>
</tr>
<tr>
<td>DIAMANTINA</td>
<td>Cr. 3/61</td>
<td>7</td>
<td>July 26, 1961 to Aug. 21, 1961</td>
</tr>
<tr>
<td>DIAMANTINA</td>
<td>Cr. 2/62</td>
<td>41</td>
<td>July 19, 1962 to Aug. 21, 1962</td>
</tr>
<tr>
<td>DIAMANTINA</td>
<td>Cr. 3/63</td>
<td>11</td>
<td>July 14, 1963 to Aug. 7, 1963</td>
</tr>
<tr>
<td>DISCOVERY</td>
<td>IIOE Cr. 1</td>
<td>19</td>
<td>June 25, 1963 to Aug. 16, 1963</td>
</tr>
<tr>
<td>DISCOVERY</td>
<td>IIOE Cr. 3</td>
<td>73</td>
<td>May 1, 1964 to Aug. 29, 1964</td>
</tr>
<tr>
<td>PIONEER</td>
<td>Cr. 442</td>
<td>11</td>
<td>May 26, 1964 to June 30, 1964</td>
</tr>
<tr>
<td>VITYAZ</td>
<td>Cr. 35</td>
<td>45</td>
<td>July 15, 1964 to Sept. 19, 1964</td>
</tr>
</tbody>
</table>

Total number of stations used....... 522

Pacific and Atlantic, this study is limited to one season, viz., the southwest monsoon.

This paper presents the distributions of salinity and oxyty on the surface of constant thermosteric anomaly 200 cl/t (sigma-t 26.02 g/l) as well as the depth of this surface in the intertropical Indian Ocean during the southwest monsoon.

The 200-cl/t surface is one of a series of surfaces being studied: namely, 400, 300, 200, and 100 cl/t. Maps showing the distributions of salinity, oxyty, and depth have been prepared for each surface. Results of the entire work will be published later. The present paper presents some of the results concerning only the 200-cl/t surface.

In this study, data collected during the International Indian Ocean Expedition at 522 hydrographic stations have been used. Table I lists all of the stations, and Fig. 1 shows the geographical position of each station. Except for a few stations (ATLANTIS II Sts. 170–198), all were occupied during the southwest monsoon, from May to September. The ATLANTIS II stations were occupied in October and formed two latitudinal sections along 5°S and 10°S, but the seasonal variation in the region of the October stations is not significant.

Because of the unique relationship between temperature and salinity for a given isanosteric surface, the salinity distribution can alternately be interpreted for temperature. Corresponding values of temperature and salinity contoured on the map are listed in Table II. The depth of the constant thermosteric anomaly and the distribution of salinity and oxyty are shown in Figs. 2–4, respectively.
Figure 1. Stations used in the present study. See Table I.
Figure 2. Depth in meters of the 200-cl/t thermosteric-anomaly surface.
Figure 3. Salinity in per mille on the 200-cl/t thermosteric-anomaly surface.
Figure 4. Oxyty in milliliters per liter on the 200-cf/t thermosy-tic-anomaly surface.
Table II. Corresponding values of temperature and salinity on the 200-cl/t surface.

<table>
<thead>
<tr>
<th>Salinity (%oo)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.6</td>
<td>13.4</td>
</tr>
<tr>
<td>34.8</td>
<td>14.2</td>
</tr>
<tr>
<td>35.0</td>
<td>16.2</td>
</tr>
<tr>
<td>35.2</td>
<td>15.6</td>
</tr>
<tr>
<td>35.4</td>
<td>16.2</td>
</tr>
<tr>
<td>35.6</td>
<td>16.9</td>
</tr>
<tr>
<td>35.8</td>
<td>17.5</td>
</tr>
<tr>
<td>36.0</td>
<td>18.2</td>
</tr>
</tbody>
</table>

Results. The isanosteric surface shows a trough along 18°S, with the maximum depth exceeding 250 m. A ridge extends from the African coast to 75°E and then bends northeastward. The depth of the ridge is less than 150 m. In the region north of the equator the contours mostly run parallel to the coast and there are a few cells of lesser and greater depth.

A striking feature of the salinity distribution is a tongue of low salinity, with values of less than 35.0%oo, extending from the Banda Sea in the east to 50°E in the west. Southward from the low-salinity tongue the salinity increases rapidly. The highest salinity in the region is encountered in the north-central Arabian Sea. North of the equator, low-salinity water exists in the Bay of Bengal.

In the equatorial region the water is nearly isohaline, with slight variation from 35.0 to 35.2%oo.

The isolines of oxyty, in general, follow the parallels of latitude except near the coasts; oxyty decreases northward, from 4.5 ml/l near 20°S to about 0.5 ml/l along 10°N. Low-oxygen water, with oxyty of less than 0.2 ml/l, predominates in the northern Arabian Sea and Bay of Bengal. The lowest values, with only traces of dissolved oxygen, are encountered in the central Arabian Sea.

In the northern hemisphere, the 200-cl/t surface lies below the naviface. In the southern hemisphere, the 200-cl/t surface intersects the naviface at 32°S–40°S all the year round. In the winter the latitude of intersection is 32°S in the east and 37°S in the west; in the summer there is a shift southward by about 4°.

Discussion. Water of relatively low salinity (below 35.4%oo), with an oxygen content of 2.5 ml/l, prevails off the Somali Coast. Judging by the salinity distribution alone, this water might originate in either the Bay of Bengal or the Pacific Ocean. But it is evident from the oxyty distribution that the water in the Somali Basin is definitely not from the Bay of Bengal, as the oxyty in the Bay water on the 200-cl/t surface is less than even 0.5 ml/l. Between the waters in the Somali Basin and in the Eastern Archipelago between Java and Australia, there is not much difference in oxyty. Furthermore, the tongue structure indicates a flow of low-salinity Pacific Ocean water through the Archipelago. Then the low-salinity water is carried into the Somali Basin by the South Equatorial Current.

Warren et al. (1966) have pointed out that the oxyty values of the water in the Somali Basin are higher than those in the Banda Sea; consequently they concluded that the Archipelago can not be the principal source of the relatively low-salinity water in the Somali Basin. But the present study indicates that the
difference in oxyty of these two waters is only around 0.5 ml/l. It is probable that the oxyty of the water is increased through mixing with high-oxyty water from the south during its flow to the west. The present observations confirm Taft’s (1963) findings that the low-salinity water of the Pacific penetrates the Indian Ocean through the Banda and Timor seas.

Waters south of 17°C on this isanosteric surface show a salinity of 35.6‰; this requires a temperature near 17°C. Hence, there is warm saline water at depths between 200 m and 300 m. This water, which also shows high oxyty, appears to form at the surface near the Tropic of Capricorn and to sink to deeper layers. The high salinity is due to an excess of evaporation over precipitation in these latitudes.

In the equatorial Indian Ocean, almost isohaline water, with salinities around 35.1‰, exists extensively between depths of 140 m and 180 m. A cursory glance at the station curves (not included in this paper) reveals that the salinity from the surface to a depth of about 1000 m varies from only 35.3 to 35.0‰, indicating vertical extension of isohaline water in the equatorial region. This water seems to have been formed by the mixing of warm saline water from the Arabian Sea with cold low-salinity water from south of the equator.

The 200-cl/t layer in the Arabian Sea lies between the salinity maximum of the Arabian Sea surface water and the salinity maximum that originates through the mixing of the Persian Gulf water. The water in this layer shows a lower salinity than that in either the Arabian Sea surface water or the Persian Gulf water; also, the temperature is lower than in either of these two. Hence, this water must be a mixture of cold low-salinity water from the equatorial region with either the Arabian Sea surface water or the Persian Gulf water, or both.

In the zone 10°S–20°S, the distributions of salinity and oxyty are strongly zonal, so that there is no clear evidence of northward flow. This feature is in agreement with the maps of Rochford (1958) and Taft (1963).

Off the Somali Coast, the northward flow of the Somali Current and its eastward flow beginning at about 7°N, 55°E are shown clearly on the depth chart of the isanosteric surface. On the maps of Swallow and Bruce (1966), the turn of the Somali Current eastward takes place to the northwest at about 9°N, 52°E; on Bruce’s maps (1968) it turns at about 5°N, 55°E. According to Bruce (1968), the surface topography off the Somali Coast during the summer of 1964 differed from that during the summer of 1963, with a resultant turning of the Somali Current eastward in 1964. Probably, the picture obtained in the present study is the average of the pictures reported in the above 1966 and 1968 studies.

Unlike the Pacific (Tsuchiya 1968), the Indian Ocean during the southwest monsoon shows no evidence of an Equatorial Undercurrent on the 200-cl/t surface. This result agrees with Sharma’s (1968) inference that the Equatorial Undercurrent is absent in the Indian Ocean during the southwest monsoon
but is present during the northeast monsoon. Direct measurements of the current velocity and water properties aboard the Argo, along the equator in the Indian Ocean from June 28 to September 24, 1962, and from February 16 to May 15, 1963 (Taft 1967, Taft and Knauss 1967), show that the Equatorial Undercurrent was measured at the end of the northeast monsoon (March–April 1963). An unstable current, similar to the Undercurrent in some respects, was observed on the eastern side of the Indian Ocean in September 1962 (during the southwest monsoon), but the instability of the velocity and the large associated meridional components do not seem to be representative of the Undercurrent. The Undercurrent was not present on either side of the Indian Ocean in July 1962 and was not present on the western side in August 1962.

The ridge from Sumatra to 6°S, 75°E and thence along 6°S to the African Coast appears to be the boundary between the Monsoon Current and the westward-moving South Equatorial Current. The trough near 17°S seems to be the southern boundary of the South Equatorial Current and the northern boundary of the eastward-flowing subtropical anticyclonic gyre in the southern Indian Ocean.

Conclusions. 1. The salinity distribution indicates an incursion of low-salinity water into the western Indian Ocean along the South Equatorial Current. This water appears to come from the Pacific through the Banda and Timor seas.
2. The waters of neither the Red Sea nor the Persian Gulf could be detected on the 200-cl/t surface.
3. A striking feature of the oxyty distribution is the low-oxyty water in the northern region of the Arabian Sea and the Bay of Bengal.
4. The distribution maps do not suggest the presence of an Equatorial Undercurrent in the Indian Ocean during the southwest monsoon.

Acknowledgments. I express sincere thanks to R. B. Montgomery for his invaluable assistance throughout the course of this study and for making arrangements for my stay at The Johns Hopkins University. This study was supported by the National Science Foundation through Grant GA-11047 and by the Office of Naval Research through contract No0014-67-A-0163-0006. Contribution No. 165 from the Chesapeake Bay Institute, The Johns Hopkins University, Baltimore, Maryland 21218.
REFERENCES

BRUCE, J. G.

ROCHFORD, D. J.

SHARMA, G. S.

SWALLOW, J. C., and J. G. BRUCE

TAFT, B. A.

TAFT, B. A., and J. A. KNAUSS

TSUCHIYA, MIZUKI

WARREN, BRUCE, HENRY STOMMEL, and J. C. SWALLOW