551.463(267)

Exploration of the Indian Ocean—Physical Oceanography

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(*Received 24 June 1960*)

1. Introduction

The Indian Ocean is the smallest and the least studied of all the oceans and occupies about one-fifth of the total area of the world oceans. Its exploration will provide a unique opportunity for studying many of the fundamental problems requiring solution in oceanography and in marine meteorology. This is mainly due to the fact that large variations of different oceanographic parameters occur only within this ocean. These variations essentially depend on two factors, *viz.*, (*i*) on the wide range of occurrence of different water characteristics and (*ii*) on meteorological conditions. For example, the surface salinity of sea water in the Bay of Bengal is almost the lowest of all oceans, whereas in the Arabian Sea, it is nearly the same as that at corresponding latitudes of other oceans. With its limited northward extent, the Indian Ocean experiences meteorological conditions which are very different from those of the other oceanic areas. Thus a regular half-yearly alteration of all the factors of weather conditions, and particularly of winds, plays an important role in the circulation of the surface layers in the monsoon regions from 10°S northward in the Indian Ocean. These wind systems, the monsoons, over the oceanic areas, if properly studied together with the physical oceanography of the region, can be expected to give satisfactory solutions to such problems as the energy exchanged between the sea and the atmosphere, the wind driven circulation etc. Such studies would also be useful both to test the extent to which the existing theories are applicable to the natural conditions occurring in the sea and the atmosphere, and to develop new methods for long range weather forecasts, forecasting of formation of cyclones, forecasting the depth of formation of thermocline and the like. Further the results obtained within this area could most profitably be applied for other oceanic divisions. Thus the Indian Ocean serves as a natural laboratory for studying various basic problems of general interest in different marine sciences and in meteorology.

Since the last quarter of the nineteenth century there have been about a score of expeditions to the Indian Ocean with different stages of development at instrumentation. And in the individual branches of the marine science, there were great differences in the techniques of observation employed in these expeditions. The total coverage of stations is poor, being on an average less than one observation per five degree square. Also there are vast regions in which observations have not been made. The inherent inaccuracy and uncertainty of the earlier observations together with the poor coverage of area do not permit any proper study of the Indian Ocean as a whole.

Oceanography embraces all aspects of scientific study of the oceans, *viz.*, physical, chemical, biological and geological, because anything that happens in the realm of any one of these branches affects the others. Therefore, for a proper understanding of the oceans the various branches should be studied together. Among these inter-related disciplines, physical oceanography occupies a unique position, its study being a necessity for the development of all the others. The physical oceanography of the Indian Ocean is mainly dealt with here.

Geographically the boundaries of the Indian Ocean broadly are India and Persia in the north, Arabia and Africa on the west, Burma, Malaya Peninsula, Sumatra, Java, Timor, Australia and Tasmania on the east. The boundary between the Atlantic and Indian Oceans runs from the Cape of Good Hope along the meridian 20°E, and that between the Indian and Pacific Oceans follows the meridian 147°E upto Antarctica which forms the southern limit. The demarcation of oceans in the absence of land boundaries is somewhat arbitrary. So, some attempts were made to find the so called 'natural boundaries' on a rational basis. Wüst has proposed a system of nomenclature based on the ocean bottom topography. Scholt (Sverdrup *et al.* 1942) and others have attempted to fix the boundaries taking such factors into consideration as the physical properties of the waters, the types of organisms that live within, the water circulations, the climatic conditions etc. A complete agreement of the boundaries defined by different characteristics cannot be expected. However, a comparison of such charts constructed from two different distributions, *viz.*, temperature—salinity relations (Sverdrup *et al.* 1942) and the zoo-geographical distribution of bottom fauna in the abyssal zone of the oceans (Vinogradova 1959) clearly indicates a discontinuity, within the Indian Ocean, at about 40°S. On the basis of the data obtained during the Discovery Expedition, Deacon (1937) has shown that this discontinuity is a line of convergence—the subtropical convergence—and that it is mainly related to the distribution of land and sea. From the oceanographic point of view, the region between the Antarctic Continent and the sub-tropical convergence can be considered as the Antarctic Ocean. It is seen, therefore, that the southern limit of the Indian Ocean extends only up to the sub-tropical convergence. However, it is to be clearly understood, that there is exchange of waters across this convergence and that the waters of the Antarctic origin can be traced in the Indian Ocean even to the north of the equator.

2. Distribution of Temperature and Salinity

In the tropical regions of the Indian Ocean, temperature remains nearly constant in the topmost layer of thickness less than 100 m. The formation of this layer depends on the intensity of the solar radiation and of mixing resulting from wind action. This layer is often called the mixed layer. Below this, temperature decreases so rapidly with depth that the transition layer will generally have the characteristics of a discontinuity. The maximum fall of temperature occurs in about the next 200 m and this layer is known as 'thermocline'. At 500 m the temperature is about 10°C. Thereafter, temperature decreases rather slowly to about 1°C at the bottom, the average depth of the bottom being 3900 m. South of the equator, the formation of the mixed layer and the abrupt fall appear to be less marked. Also the bottom temperature, being of the order of —2°C, is less than in the tropical area.

The average salinity of the Indian Ocean, is about 34·76 per mille. Salinity in general increases with depth to give a salinity maximum within the equatorial waters at the top of the thermocline. Below this subsurface salinity maximum, the salinity gradually decreases down to the bottom. While above are the general conditions on an average, seasonal and even year to year variations in temperature and salinity may be expected, mainly in the upper 200 m of water, both in the equatorial and sub-tropical areas of the Indian Ocean. Pollak (1958) has shown that about one-third of the total volume of the Indian Ocean has temperature and salinity ranging between 0·5° to 2·0°C and 34·7 to 34·8 °/ₒₒ respectively and that this water forms the core of the Indian Ocean deep water. The potential temperature and salinity ranges of surface waters from different geographic locations are extracted from Pollak and are shown in Table 1, surface water being defined as that above the 200-m level.

Because of very limited data available for the above study, the ranges given above are to be considered only as approximate

TABLE 1

Geographic location of surface water	Range of salinity in ‰	Range of temperature in °C
Andaman Sea and Bay of Bengal	32·5 to 34·0	25·0 to 30·0
Equatorial and sub-tropical regions	34·0 to 36·0	20·0 to 30·0
Arabian Sea	36·0 to 36·5	15·0 to 27·5
Red Sea and Persian Gulf (all water)	38·5 to 41·5	20·0 to 27·5

Actually in the Bay of Bengal, observations north of 10°N were not included. Recent observations off the east coast of India show that surface salinities are often less than 20·00 per mille (Rama Sastry 1955).

The sea surface temperature increases northwards from the sub-tropical convergence to the equator. Within this area the isotherms are slightly inclined to the latitudes. But to the north of the equator the distribution is not as simple because of the influence of the prevailing water and wind circulations. In the southwest monsoon season, specific areas of surface maxima of temperature can be found in the region north of the equator. However, a detailed picture of the thermal changes both in time and space is not yet known. The distributions of temperature at 200 m and 400 m, given by Sverdrup (1942) indicate the existence at both the levels of a sub-surface maximum at 20°S and a minimum between 10°S and the equator. The bottom temperature, on the other hand, increases continuously northwards.

The distribution of surface salinity within the Indian Ocean is not as simple as that of the temperature. In general, it may be stated that west of 80°E salinity increases northwards of the sub-tropical convergence. Highest salinity is encountered in the Red Sea and in the Persian Gulf. Also, in the mid-regions of the Arabian Sea and to the west of Australia, salinity maxima are found at the sea surface. Lowest salinity occurs in the Bay of Bengal. Further, in the region to the northwest of Australia and to the south of the Malaya Peninsula sea surface salinity shows a minimum under the influence of the waters of Pacific origin.

Periodicity of salinity of surface water in the Bay of Bengal and the Andaman sea was noticed by Sewell (1957) and the same was attributed to the periods of the seiches occurring within that region. For a unimodal seiche in the Andaman sea the period is about 18 days. For a bimodal seiche in the Bay of Bengal the respective periods in the long and transverse axes are about 15·5 and 6 days. Associated with these seiches of the upper layers, probably deep water seiches are also present in the Indian Ocean, at least in certain closed basins. Corresponding periodicity of temperature is not reported. But periodic fluctuation of temperature in the Bay of Bengal with a period very nearly equal to that of a tide was reported by La-Fond and Poornachandra Rao (1954). Also recent observations by the author show the presence of internal waves both in the Bay of Bengal and the Arabian Sea.

3. Circulation in the Surface Layers

As mentioned earlier, the circulation within the surface layers (of about 200-m thickness) results mainly from the prevailing wind systems. In the tropical regions of the Indian Ocean, particularly to the north of the equator the surface waters are driven by the alternating northeast and southwest monsoons. During the northeast monsoon south of 10°N the current is mainly westerly. But in the rest of the Bay of Bengal and the Arabian sea east of 60°E anti-clockwise circulations exist. Also to the west of 60°E the current is directed into the Red Sea and the Persian Gulf. The current directions are reversed during the southwest monsoon while in the remaining parts of the year the circulation is in transition. Because of the regular half yearly change in the direction of these systems, the surface currents within this area are weak. In fact, except the Agulhas stream in the Indian Ocean there are no strong currents.

In the tropical and sub-tropical regions of the South Indian Ocean, the surface water drifts along the southeast trades and forms the equatorial current of the Indian Ocean. Between the north equatorial (near the equator) and the south equatorial (at about 20°S) currents, an equatorial counter-current will be encountered. The seasonal variation of these currents with regard to their position and intensity is not known.

Further to the south, *i.e.*, between 20°S and 40°S and between Africa and Australia there are indications of an anticlockwise circulation. The southernmost arm of this circulation merges with the 'west-wind drift' and flows from the region south of Africa towards east and finally enters the Pacific continuing its eastward flow south of Australia. The northern branch of this gyral joins the south equatorial current near the Australian and the Malayan coasts. During the southern winter, waters from the Pacific enter the Indian Ocean to the north of Australia and join this system. Thus the south equatorial current gains strength and flows westwards. However, in the southern summer the currents in the region north of Australia are reversed. But in both the seasons the south equatorial current divides into two streams to the north of Madagascar. One of these branches turns to the north to form the Somali stream which is particularly strong in the southwest monsoon season. The other branch turns to the south and flows between Africa and Madagascar. This is further reinforced by that part of the south equatorial current which sweeps round the southern end of Madagascar. These two masses of water combine to form the great Agulhas stream which flows southwards along the African coast. A part of this stream continues its southward journey till it breaks into a number of eddies on meeting the west wind drift. The other branch, probably a smaller portion, flows westwards round the Cape of Good Hope and enters the Atlantic. The Agulhas stream extending only to about 100 km from the African coast transports according to Dietrich (Sverdrup *et al.* 1942) nearly 20 million m^3/sec of water. The available data from the Indian Ocean are so scanty that similar transports by other current systems cannot be computed.

On an ocean wide scale, below the tropical discontinuity the circulation is not known. But from considerations of oxygen distribution, Sverdrup infers that no strong currents exist and that only a sluggish flow takes place in the region to the north of the equator. Recent studies off the Indian coasts by the author (1960) support the above view. Also they show subsurface reversals in the circulation pattern.

Secondary circulations

In addition to the general circulations as described above, secondary vertical circulations are found in different parts of the Indian Ocean. The detailed character of these motions are yet to be investigated. In the following, a short resume of only a few instances of such circulations is given.

In the Antarctic region of the Indian Ocean in addition to the sub-tropical convergence to which reference has already been made, Deacon (1937) has shown a region of another convergence—the Antarctic convergence—at about 50°S. Large scale sinking of surface waters occurs mostly at these convergences. The various stages of sinking between the sub-tropical convergence and the Antarctic Continent lead to the formation of the Antarctic water masses. Among these, the Antarctic circumpolar water, sub-Antarctic water, Antarctic intermediate water and the Antarctic bottom water are of importance in the Indian Ocean north of 40°S. Some of these water masses can be traced even to the north of the equator.

During the southwest monsoon the equatorial current flowing towards the east coast of Africa turns northwards. Further, under the influence of strong monsoon winds water from the Somali coast is drifted away leading to a large scale upwelling along the coast.

In the mid-regions of the Arabian Sea evaporation exceeds precipitation to such an extent that the surface water sinks to about 400 m within that area to form a water type which can be traced even to the south of the equator as pointed out by Thomsen (1933).

Off the east coast of India, under the influence of prevailing winds upwelling occurs from February to April and sinking from September to November (LaFond 1954). Along the west coast upwelling seems to occur during different parts of the year in different portions. Off the west coast south of 16°N, upwelling inshore takes place towards the end of the southwest monsoon (Rama Sastry and Myrland 1959). Also it occurs from greater depths than off the east coast. But further north along this coast, it appears that upwelling takes place in February.

The arid climatic conditions of the region in which Red Sea is located would result in tremendous evaporation from the sea surface. Since there is no run off into the Red Sea from rivers, the salinity goes up as high as $50 \cdot 00\,^0/_{00}$ in certain limited locations within this area. The surface water, therefore, sinks. Also from the existing water and wind circulations it can be inferred that large scale sinking in the Red Sea leads to the formation of the Red Sea water which is characterised by very high temperatures and salinities.

In recent times it is being realised that the Arabian Sea forms one of the regions of richest biological productivity in the world oceans. However, studies pertaining to the general distribution of the nutrient salts in this area are not available. But it is reasonable to assume, *a priori*, that large scale vertical circulations should be indirectly responsible for the distribution of the nutrients and the fertility of waters therefrom. This serves to emphasise the fact that in the Indian Ocean, there are vast regions of large scale upwelling which are yet to be discovered.

4. Water masses and Deep Water circulation

The surface layer is influenced by environmental conditions so that the water masses within this layer are subjected to great variations both in space and time and, therefore, are of local significance only. Just below this layer the Indian central and Indian equatorial waters are found.

The Indian central water is formed by sinking of surface water just to the north of the sub-tropical convergence within the Indian Ocean. Its horizontal extent can be traced up to the equatorial regions. The formation of the Indian equatorial water is not clearly understood. But it is believed that it is formed by the processes of subsurface mixing. A critical examination of the T-S curves at a few Dana stations (1929) by Thomsen has indicated mixing of two water types in the north equatorial Indian Ocean, particularly in the Arabian Sea. These water masses are the Indian Ocean bottom water ($T=1 \cdot 20°C$ and $S=34 \cdot 74\,^0/_{00}$) and the other at relatively shallow depths of 400 m with temperature 11°C and salinity 35·15. As the Red Sea water normally sinks to about 1000 m, Thomsen doubted the existence of any possible relation of the other water with the Red Sea water. An examination of a large number of T-S relations within the Laccadive Sea and off the west coast of India by the author indicates nearly linear relationship from about 100 m to 400 m. Also a salinity maximum is found between 400 m and 500 m in most parts of the year. This salinity maximum can be related to the central regions of the Arabian Sea surface water where a salinity maximum is found. Also a large number of sub-surface salinity maxima are noticed in the Arabian Sea near the Persian Gulf as revealed by the data of the John Murray Expedition 1933-34. Thus, sinking of the surface water in different parts of the Arabian Sea and consequent sub-surface mixing would lead to the observed linear relationships just below the surface stratum. A minor portion of the Red Sea water also participates in these mixing processes as is clear from the John Murray stations in the Arabian Sea.

The exact regions of sinking of these waters and the subsequent mixing are not clear. Thus, it appears that the Indian equatorial water forms in the Arabian Sea. Also the vertical extent of the Indian equatorial water is greater than that of the central water. The above are the important water masses occurring in the Indian Ocean at depths less than 1000 m.

The water masses in the depths of the Indian Ocean as presented by Möller (1929) and further studied by Thomsen (1933) and Sverdrup *et al.* (1942) are—(*i*) Antarctic Intermediate water having low temperatures and salinities with its axis at about 1200 m. In the Indian Ocean, it initially flows to northwest and there changes to northeast and finally mixes with the north Indian deep current. (*ii*) North Indian deep water which is warm and more saline and occurs between 1300 and 2000 m. It was considered to have a southerly flow by Möller but such a movement was doubted by the later authors and (*iii*) the Antarctic bottom water with low temperatures and salinities flowing towards north which gradually loses its characteristics near the equator.

Red Sea water and that part of the central water which is less saline than the equatorial water at temperatures less than 10°C can be traced in the equatorial regions also. This portion of the central water is sandwiched between the sub-Antarctic water and the Antarctic intermediate water. An analysis of some deep sea observations, within the Indian equatorial regions by the author in 1960 has shown that the Red Sea water is not carried directly southwards across the equator, particularly giving rise to a salinity maximum in the Indian deep water. Further, there is no appreciable southward transport of the north Indian deep water across the equator. Both the intermediate and bottom waters move in a northerly direction, but the motion of the latter is influenced by the bottom topography as was shown by Sewell (1957), from whom the following paragraph is quoted.

"The mid-Indian ridge splits the Antarctic bottom drift ino two streams the one to the west of the ridge passes northwards till it comes in contact with the Mauritius-Seychelles bank which splits into two streams that pass respectively to the east and west of this curved mountain chain into the north and south Somali basins. The western stream flows towards the northwest......till it meets the African coast, where it is deflected towards the northeast and finally passing Cape Guardafui and Socotra flows in part into the Gulf of Aden while the last traces of it run parallel to the Arabian Coast and so enter the Gulf of Oman. The eastern branch appears to be deflected towards the surface and serves to augment the equatorial counter current. East of the mid-Indian ridge between Kerguelen Plateau and Australia the second stream of the Antarctic bottom water flows northeastwards and meeting the curve of Malayan arc swings northwards to the entrance of the Bay of Bengal, where meeting the Carpenter's ridge it splits into two streams one passing into the Bay of Bengal and the other towards Ceylon, where further splitting takes it into the Laccadive Sea and possibly across the Maldive ridge into the Arabian basin. In the Bay of Bengal the entrance of the Antarctic bottom water sets in circular motion......".

5. Conclusion

If the movement of water constitutes the central theme in oceanography, as is rightly claimed, it is clear from the above how imperfect our knowledge is in this sphere with regard to the Indian Ocean. Our information on the biological and geological aspects also is very scanty. No biological sampling has been done in about half of the ocean and depth soundings in most regions are absent. Thus, all the major problems pertaining to the Indian Ocean are mostly unexplored. Further, the increasing need for protein-rich food from the sea, the demands of advancing civilisation requiring the disposal of radioactive wastes and the necessity for better understanding of the energy transfer processes between the sea and the atmosphere as an aid to long range weather forecasting and study of climatic changes, require a fuller understanding of all marine sciences and their inter-relationships. Here it may be stated that detailed International Oceanographic expeditions to the Indian Ocean have been planned by the Special Committee for Oceanic Research (SCOR) of the International Council of Scientific Unions (ICSU) of which Krishnan (1960) has already given a very brief account. This international expedition in which many nations will take part will no doubt yield results of considerable scientific and economic importance.

6. Acknowledgement

I thank Shri P. R. Krishna Rao, Director General of Observatories, for encouraging me to write this article.

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