SHOREWARDS UPSLOPE OF THE LAYER OF MINIMUM OXYGEN OFF BOMBAY: ITS INFLUENCE ON MARINE BIOLOGY, ESPECIALLY FISHERIES

By Dr. J. N. CARRUTHERS
National Institute of Oceanography, Wormley, Godalming, Surrey

S. S. GOGATE
Central Marine Fisheries Research Station, Bombay

J. R. NAIDU
Institute of Science, Bombay

AND

T. LAEVASTU
Fisheries Biology Branch, Food and Agriculture Organization, Rome

Earlier Knowledge of Upwelling in the Arabian Sea

THERE are two factors of particularly great interest in the Arabian Sea: the seasonal upwelling caused by the prevailing monsoons and their changes, and the well-developed tropical sub-surface layer of minimum oxygen. Both have pronounced effects on marine biology and especially on the seasonal nature of the local fisheries.

Upwellings along the Somali and South Arabian coasts and also around the southern tip of Ceylon during the south-west monsoon were indicated by Schott[1] on the basis of low surface temperatures then prevailing there. Upwelling could be expected to exist along the Bombay continental shelf during the north-east monsoon, and Jayaraman and Gogate[2] have earlier found indications which probably attest such between 20° and 22° N. latitude along this

coast. Their conclusion was also based on the distribution of temperature and salinity there.

Layer of Minimum Oxygen

The tropical subsurface layer of minimum oxygen in the Arabian Sea has been described in reports devoted to the *John Murray* expedition of 1933–34. Of all tropical seas the layer of minimum oxygen is most pronounced in the Arabian Sea, where the oxygen content is nearly nil at its mid-depth. The upper boundary of the layer is relatively sharp and coincides with the sharp thermocline or is slightly below it. The depth of the thermocline varies seasonally, dependent upon the seasonal upwelling or the coastal piling-up of the surface waters according to the prevailing monsoon. According to Schott[1], the layer of minimum oxygen is most pronounced off Bombay, where it is found generally at the depth of 50 metres.

Most usually it is found in the northern part of the Arabian Sea at the depth of 75 metres, but towards the equator it descends to reach a depth of about 150 metres. Salinity within the layer is relatively high, being in the north around 36 per mille and in the central Arabian Sea about 35·5 per mille with temperature at 22–23° C. It is noteworthy that the salinity maximum is found slightly below the layer of minimum oxygen. Gilson[3] found a high nitrite content in the layer of minimum oxygen, and immediately above it a high concentration of plankton was recorded.

The layer in question cannot fail to have a pronounced effect on marine life. It is to be expected that where it runs into the contour of the continental shelf, very little if any animal life will be possible beneath. Furthermore, in the event of upwelling raising the layer of minimum oxygen, animal life in the water above will be endangered. Proof of this has been recorded on several occasions. There is an area in the southern part of the Arabian Sea, between long. 60–65° E. and lat. 6–12° N., where mass mortalities of pelagic fish have often been reported during the month of June. This area being a divergence area of winds and of the drift currents caused by them (it is actually the centre of a gyral), upwelling of the layer of minimum oxygen there is to be expected. Mass mortality of fish has also been reported along the Arabian and Indian coasts in areas and seasons where and when upwelling of the layer is to be expected. Such mass mortalities might very well be caused by the upwelling of the layer of minimum oxygen alone or in conjunction with the accompanying 'red tides'.

Investigations off Bombay during October–November 1958

Some modest investigations were made off Bombay during the latter part of October and the beginning of November 1958 by the personnel of a refresher course in marine biology sponsored by the United Nations Educational, Scientific and Cultural Organization. Because the north-east monsoon starts in October, an accompanying upwelling of the layer of minimum oxygen along this coast should be expected then because of the direction of the wind. This was in fact found, the layer with an average oxygen content of 0·7 ml./l. occurring at an average depth of about 18 m. some 18 nautical miles out from the coast. The slope of the discontinuity layer was upwards towards the coast (Figs. 1–3). The salinity

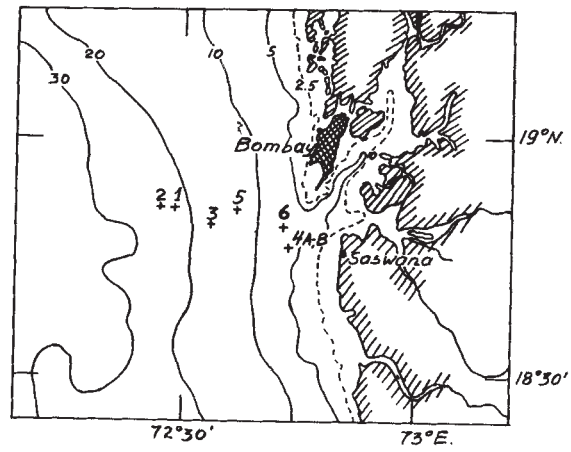

Fig. 1. Depth contours (in fathoms) and position of stations off Bombay

in this layer of minimum oxygen was about 36·0 per mille and the temperature around 24° C. The phosphate content was also relatively high (greater than 1 μgm. at./litre). In a zone 7–10 nautical miles from the coast, the layer of minimum oxygen practically reached the surface. The oxygen content there was very low from surface to bottom (see Station 4). An intensive mixing by tides takes place in this zone, where the water was found to be rather turbid. Inshore of it there was coastal water which was also thoroughly mixed by the tides and which contained higher amounts of oxygen. This coastal water was extremely muddy because of the intensive tidal mixing and the soft nature of the bottom. Pronounced colour changes were noticed in the water. Near the coast it was brownish grey out to about 7 miles offshore. Seawards of this for some 3 miles the hue was greenish-grey. Still farther out the colour of the water graded into blue. Because the effects of the upwelling in

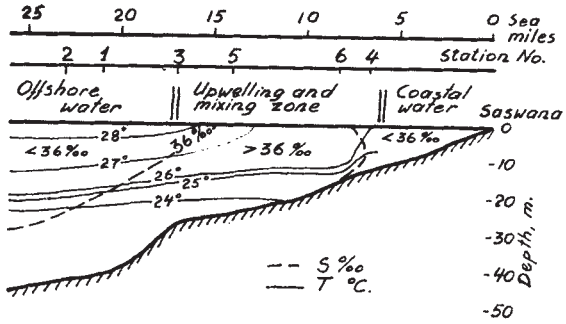

Fig. 2. Distribution of temperature and salinity off Bombay (beginning of November 1958)

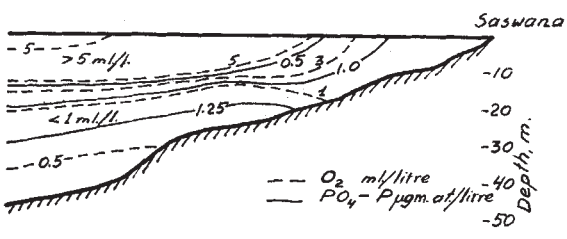

Fig. 3. Distribution of dissolved oxygen (ml./l.) and phosphate phosphorus (μgm. at./l.) off Bombay (beginning of November 1958)

respect of high salinity and high plankton production were detectable as far out as our Station 3 (17 miles offshore), the 10-mile-wide belt of water outside Station 4 (itself 7 miles from the coast) could be regarded as the 'upwelling and mixing zone'.

The layer of minimum oxygen shallows up the continental slope and intersects the bottom at about 7 fathoms depth. In consequence, demersal fish are forced to migrate shorewards during the upward movement of the layer. This results in notable concentrations of fish during the period October–December between the 'upwelling and mixing zone' (see Fig. 2) and the 'coastal zone' at about 13 miles out from Bombay harbour, that is, about 7 miles offshore from Saswan along the line of stations. Seawards of the upwelling and mixing zone there was a warm surface layer with relatively high phosphate and high oxygen contents. The upper boundary of the layer of minimum oxygen seems to rise and fall with the tides (see the observations from Stations 4*A* and 4*B* in the accompanying tables). This can be expected to cause up-and-down migrations of the fish concentrated in the area where the layer of minimum oxygen intersects the bottom contour. These vertical fish movements are known to the local bag-net fishermen. An abundant growth of plankton was found in the 'upwelling and mixing zone' which is likely to exhaust the nutrients from the surface layer rather quickly, and in fact a decreasing phosphate content was found going offshore. Also the oxygen content of the upper surface water showed a decrease farther offshore, which might be ascribed to the consumption of oxygen due to the decomposition of the organic matter produced in the upwelling and mixing zone and in its vicinity. Both the decrease of nutrient content in the surface layer and the downwards sloping of the thermocline and layer of minimum oxygen will probably continue as one goes farther offshore. Gilson[3] found in December and January off Bombay (at the edge of the continental slope) that the thickness of the surface layer was 50–60 metres and that it was completely depleted of nutrients.

The bulk of the standing crop of plankton was found above the discontinuity layer. The main phytoplankton organisms were: *Coscinodiscus*, *Trichodesmina* and *Ceratium* species. Of zooplanktonts the chief were copepods and sagittas. Scarcely any benthic animals were found in the depths where the oxygen content of the bottom water was less than 0·5 ml. per litre. In shallow water, benthos consisted mainly of hermit crabs, *Jibia curba* shells and a few nereid and polychaete worms.

The seasonal upwelling and the associated up-and-down movement of the layer of minimum oxygen caused by the changing monsoons have various important effects on the local fisheries. During the south-west monsoon the surface mixed layer will be rather thick and the layer of minimum oxygen correspondingly deep in the water off Bombay due to the piling up of surface waters. During the north-east monsoon the layer of minimum oxygen will gradually ascend into shallower depths because the surface waters will be blown seawards, so causing upwelling from below. The demersal fish which were distributed during the south-west monsoon over a large area on the relatively shallow continental shelf off Bombay will have to move into shallow water to escape lethal low-oxygen conditions. This chain of events will lead to the occurrence in shallow water during the north-east monsoon of fish concentrations easily available to the local fishermen and, in fact, there was a glut of landings soon after the start of the north-east monsoon in 1958.

Station 1. I.N.S. *Ranjit*. October 24, 1958
Lat., 18° 51′ N.; long., 72° 29′ E.; depth, 42 m.

Depth of sample	Temperature (°C.)	Salinity (per mille)	Phosphate phosphorus (μgm. at./l.)	Dissolved oxygen (ml./l.)
Surface	28·5°	35·35	0·39	—
9 m.	28·1°	35·70	0·43	5·21
22 m.	24·0°	36·45	1·25	0·67

Station 2. I.N.S. *Madras*. November 4, 1958
Lat., 18° 51′ N.; long., 72° 27′ E.; depth, 43 m.

Surface	28·0°	35·66	0·45	2·90
5 m.	27·8°	35·86	0·40	5·11
15 m.	26·5°	35·95	0·53	3·00
25 m.	23·4°	35·99	1·20	0·87
32 m.	23·4°	36·13	1·25	0·68
39 m.	23·2°	36·04	1·35	0·45

Station 3. I.N.S. *Madras*. November 4, 1958
Lat., 18° 49′ N.; long., 72′ 34′ E.; depth, 26 m.

Surface	28·2°	35·37	0·42	5·12

Station 4*A*. Fishing vessel *Machwa*, KRJ 478. November 9–10, 1958
Lat., 18° 47′ N.; long., 72° 44′ E.; depth, about 14 m.
Start of rising tide

Surface	26·5°	35·88	0·93	2·6
5 m.	25·3°	35·91	1·09	1·75
10 m.	25·2°	(36·02)	1·06	1·25
12·5 m.	25·2°	35·91	1·09	1·2

Station 4*B* (same as Station 4*A*). End of rising tide

Surface	27·0°	36·22	0·56	1·25
5 m.	25·7°	36·17	1·09	1·20
10 m.	24·8°	36·04	1·13	1·4
12·5 m.	24·7°	35·82	1·16	0·5

Station 5. I.N.S. *Madras*. November 11, 1958
Lat., 18° 51′ N.; long., 72° 37′ E.; depth, 25 m.

Surface	27·0°	36·26	0·33	5·2
4 m.	26·9°	36·24	0·40	4·94
5 m.	26·55°	36·33	0·83	5·11
10 m.	26·25°	36·27	0·86	3·42
13 m.	24·85°	36·36	1·06	0·97
15 m.	24·4°	36·36	1·20	0·86
20 m.	24·4°	36·42	1·25	(1·00)

Station 6. I.N.S. *Madras*. November 11, 1958
Lat., 18° 49′ N.; long., 72° 44′ E.; depth, 12 m.

Surface	26·8°	36·26	0·71	3·30
5 m.	26·5°	36·24	0·86	3·14
8 m.	26·1°	36·11	1·31	4·29
10 m.	26·1°	36·09	0·71	3·03

The upwelling during the north-east monsoon causes also a high production of plankton off the Bombay coast, because nutrient-rich water is brought close to the surface, and it is naturally expected that pelagic fish would migrate into this area to feed on the rich standing crop of plankton then existing there. However, *Rastrelliger*, tunas, and Indian oil sardines do not come close to the coast in the Bombay area. It seems that these pelagic fish remain outside the 'upwelling and mixing zone' because of the low oxygen content of its water. Schools of pelagic fish were in fact sited at about 25 nautical miles off Bombay at the time to which this report relates.

The origin of the layer of minimum oxygen in the Arabian Sea is not yet fully understood, but it is associated with high salinities and relatively high temperatures, and several authors believe that it originates through the outflow of the Red Sea and Persian Gulf waters.

The seasonal behaviour of the surface layers of the Arabian Sea is not fully known. It would also be interesting to know the changes in intensity of the upwelling off Bombay during the north-east monsoon. From January onwards, the north-east monsoon

turns along the Indian Coast to north and north-west. This turning might cause considerable changes in the conditions to be found during October–November and described above for the period here concerned.

Currents

Very obviously it would help greatly in the understanding of the oceanographical situations discussed above if it were possible to make observations of the speed and direction of the bottom water movements at regular and frequent intervals around the clock—say, every half-hour for a lunar day on a number of separated occasions. We had certain suitable apparatus of great simplicity for making such current observations, but time did not serve. Only a few spot observations were possible using the very simple instruments developed by one of us (J. N. C.), but a notable current one-third knot in speed was measured running towards about 210° magnetic. This was at the position lat. 18° 51′ N., long. 72° 29′ E., and served to show at least that the bottom water was not setting constantly towards the coast at the time. Perhaps it might have been found to set dominantly shorewards later after the north-east monsoon had become more strongly established. If so (and the matter should certainly be investigated), a mechanism explaining the shorewards uptilt of the layer of minimum oxygen would be to hand.

We wish to thank the participants in the refresher course in marine biology who were engaged in the collection of the observations; the Indian Navy for the provision of shipboard facilities, and Mr. K. Koli, who kindly allowed us to use his boat.

[1] Schott, G., "Geographie des Indischen und Stillen Ozeans" (Boysen, Hamburg, 1935).

[2] Jayaraman, R., and Gogate, S. S., *Proc. Ind. Acad. Sci.*, **45**, 151 (1957).

[3] Gilson, H. C., "The Nitrogen Cycle", Rep. John Murray Exp., **2** (2), 21 (1937).