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Environmental changes associated with monsoon induced upwelling, off central wetst coast of India

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Coastal upwelling of nutrients during and after the southwest monsoon has been considered to support rich pelagic and demersal fisheries off the west coast of India. Studies indicate occurrence of coastal upwelling associated with Ekman transport in response to prevailing equatorward winds. High salinity ocean waters of rich nutrient contents were observed at the coast in some locations. However, the effect of upwelling on the surface distribution of properties was reduced to some extent due to coastal runoff which gives the region a patchy distribution of properties.

It is a well known fact that the inshore waters off the central and southwest coast of India support rich fisheries during the postmonsoon period September to December. Earlier studies from this area suggest a close link between the presence of high salinity nutrient rich waters at the surface during monsoon and the high biological production during the subsequent postmonsoon season. In order to study the impact of the monsoon on the fertility of this region a study was undertaken onboard *R. V. Gaveshani* during the southwest monsoon of 1991 (August 10 to 22) in the inshore waters off the central west coast of India between Ratnagiri and Mangalore. The present work reports these broadscale surveys of water chemistry in this area during the monsoon.

Materials and Methods

Water samples from surface and at 10 m depth intervals were collected from each of the 17 stations spread over 5 transects normal to the coast, extending 25 km offshore (Fig. 1), using Niskin water samplers. In few cases, however, samples were also collected from 5 m and 15 m depths. The samples were analysed onboard within 3 hours of collection, for dissolved oxygen[1], phosphate[2] and nitrate[3]. Salinity was measured in the shore laboratory using Mohr-Knudsen titration technique, (due to some mistake the nitrate samples of stations G_3 and G_4 of Mormugao section were lost and could not be analysed).

Results and Discussion

Figures 2 and 3 depict the vertical distribution of chemical variables at two representative sections off Ratnagiri and off Karwar respectively. At the Ratnagiri section the salinity was low ($< 33 \times 10^{-3}$), extending a considerable distance offshore, and this was associated with high oxygen

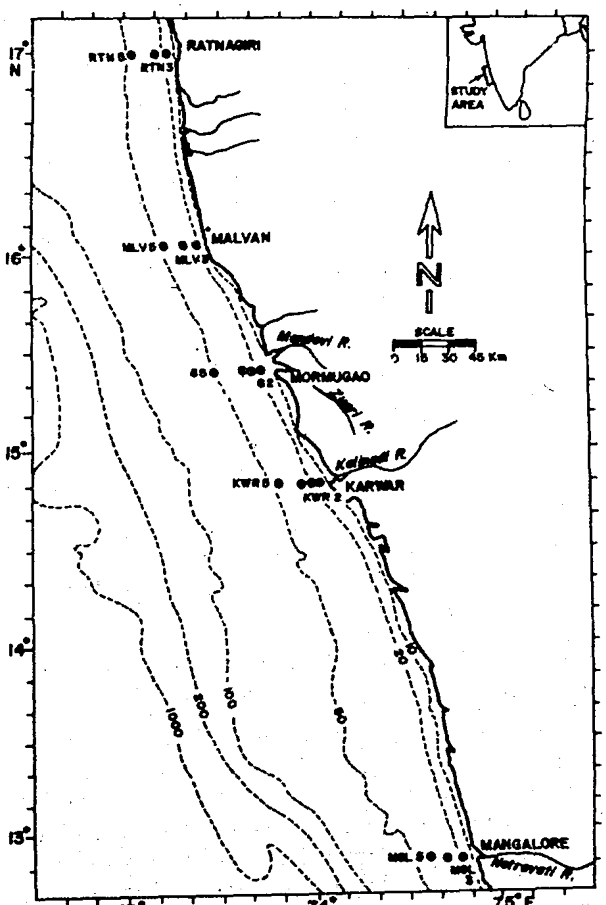

Fig. 1—Map showing locations of stations

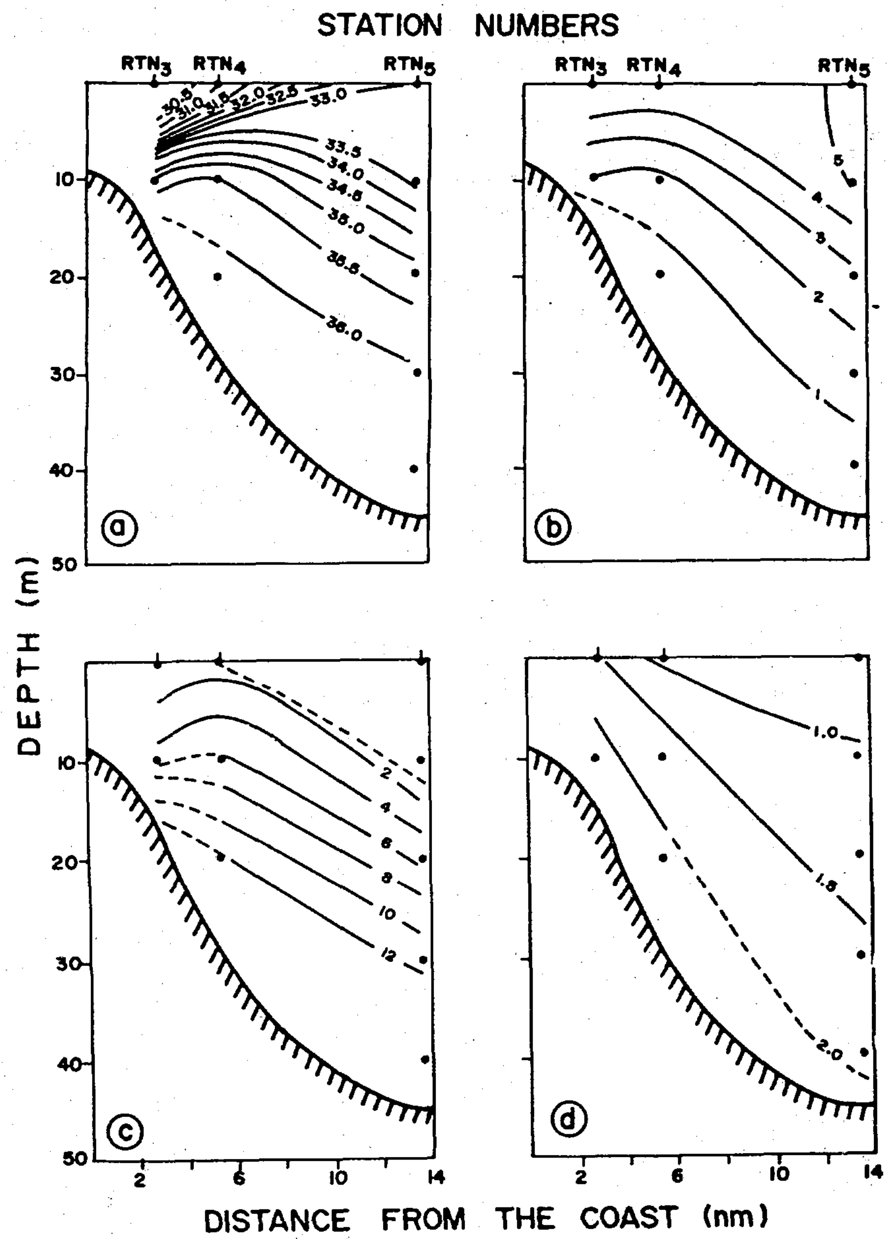

Fig. 2—Vertical profiles of: a) salinity × 10^{-3}, b) oxygen ($ml.l^{-1}$), c) nitrate ($\mu mol.l^{-1}$) and d) phosphate ($\mu mol.l^{-1}$) along the Ratnagiri transect

and low nutrient concentrations. On the contrary, the surface salinity at the Karwar section was comparatively higher nearshore ($>33.5 \times 10^{-3}$) and decreased offshore. The concentration of nutrients was also higher in the nearshore regions off Karwar, associated with relatively lower oxygen content. Similar distribution of surface properties was observed at Mormugao section while Malvan and Mangalore sections showed a distribution similar to the Ratnagiri section (Table 1).

This is a case of two opposing mechanisms operating in this area during monsoon. While coastal upwelling (as discussed below) brings up to the surface relatively more saline deep waters, rich in nutrients, as observed near Karwar and Mormugao where surface water is more saline and richer in nutrients near the coast than offshore. At some locations, however, the high salinity nutrient rich

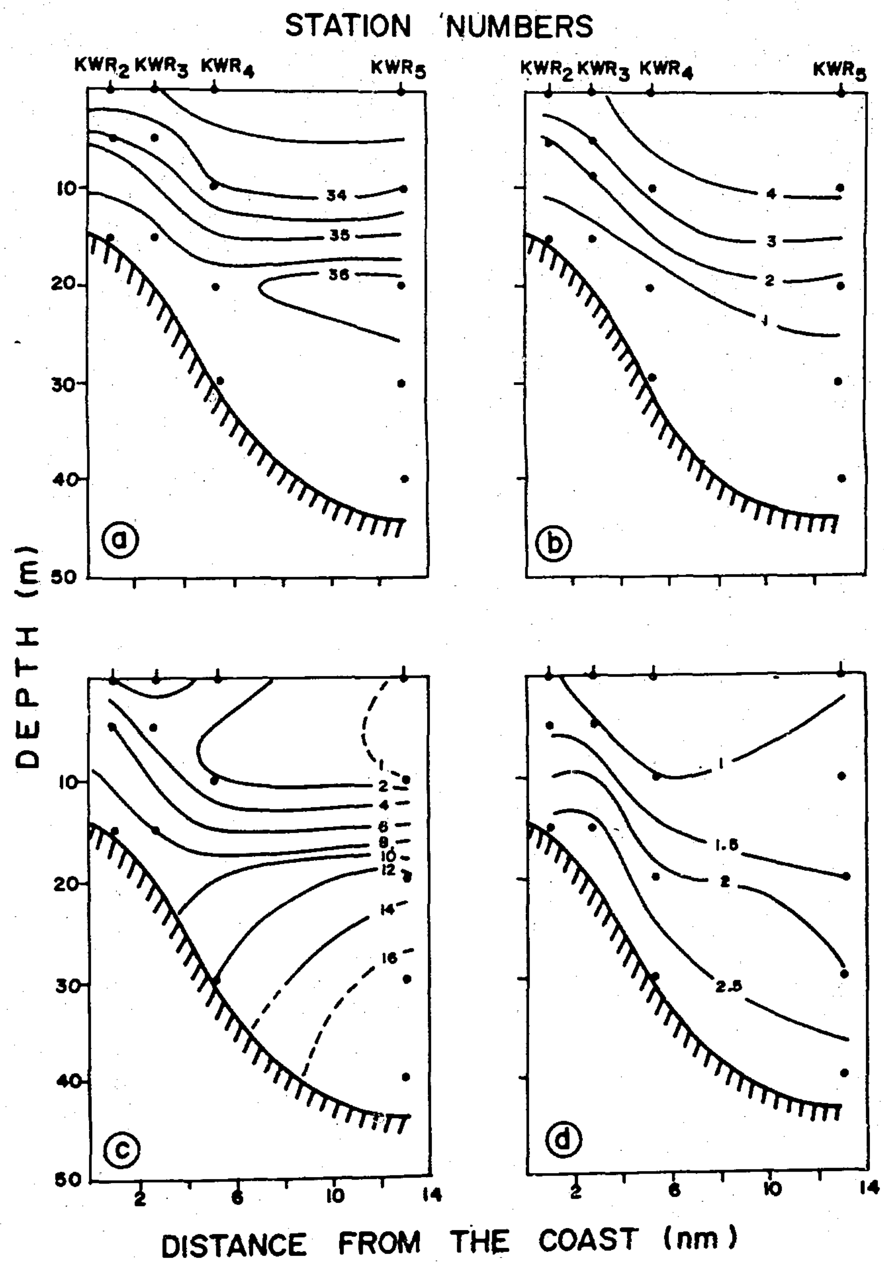

Fig. 3—Vertical profiles of: a) salinity × 10^{-3}, b) oxygen ($ml.l^{-1}$), c) nitrate ($\mu l.l^{-1}$) and d) phosphate ($\mu mol.l^{-1}$) along Karwsar transect

upwelled waters are diluted to varying degrees by freshwater coastal runoff, thereby reducing the surface salinity and nutrient content, as seen near Ratnagiri and Mangalore. Similar phenomenon of suppression of upwelling by freshwater river flow has been reported elsewhere in India[5-7]. Other factors which can have masking effect on coastal upwelling are the short term effects of tide and wind. While it is difficult to discuss the effect of tide in the present study as no tidal rhythm was followed during sampling, the winds which are north-northwesterly during this season[8] may have an opposing effect on the surface distribution of properties. Winds blowing towards the coast push the nutrient poor offshore surface waters towards the coast and may restrict the offshore spreading of upwelled water. In the present case, however, judging from the distribution of salinity, the effect of coastal runoff appears to be the predominant one.

Table 1—Distribution of salinity ($\times 10^{-3}$), dissolved oxygen ($ml.l^{-1}$), nitrate ($\mu mol.l^{-1}$) and phosphate ($\mu mol.l^{-1}$) against depth (m) at various stations during monsoon of 1991

Depth	Sal.	D.O.	NO_3^-	PO_4^{3-}	Depth	Sal.	D.O.	NO_3^-	PO_4^{3-}
RTN_5					G_5				
1	33.04	5.04	0.11	0.71	1	32.44	4.51	0.34	0.74
10	33.47	5.04	0.04	1.05	10	33.09	4.33	1.32	0.89
20	35.29	2.58	5.96	1.32	20	35.62	3.40	8.84	1.24
30	36.12	1.57	11.86	1.57	30	36.40	2.43	15.91	1.98
40	36.05	0.56	13.68	1.72	40	36.03	1.34	14.54	1.95
RTN_4					50	36.03	0.76	16.23	2.06
1	31.25	4.70	0.72	0.96	KWR_3				
10	35.72	1.68	6.49	1.54	1	33.49	3.90	1.01	0.64
20	36.14	0.56	12.34	2.10	5	34.27	3.02	3.83	1.07
RTN_3					15	35.83	0.45	7.93	2.64
1	26.20	5.04	0.15	1.54	KWR_2				
10	35.17	1.79	4.97	2.32	1	33.31	3.92	1.16	1.15
MLV_5					5	34.94	2.02	6.89	1.38
1	31.69	4.37	0.21	0.49	15	35.77	0.34	9.09	2.72
10	35.86	2.35	2.07	1.40	KWR_5				
20	35.96	0.56	8.79	1.48	1	33.01	4.48	0.84	0.91
30	36.23	0.89	11.44	1.42	10	33.95	4.26	1.01	1.24
40	36.14	0.56	11.63	1.91	20	36.21	1.79	13.06	1.49
50	36.16	0.34	10.42	2.25	30	35.83	0.22	17.40	2.07
MLV_4					40	35.81	0.23	17.65	2.72
1	31.27	4.37	0.49	0.65	KWR_4				
10	35.75	2.13	5.26	1.18	1	33.21	4.48	2.51	0.81
20	36.38	1.23	11.82	1.48	10	33.95	3.70	1.97	1.00
30	35.99	0.67	12.60	2.53	20	35.92	0.56	10.32	2.25
MLV_3					30	35.92	0.34	12.05	2.81
1	27.95	4.82	1.37	0.93	MGL_5				
5	35.90	0.90	10.53	1.79	1	31.58	4.14	1.27	0.78
15	36.19	0.78	10.99	2.03	10	32.63	3.81	2.30	0.89
G_2					20	35.07	0.34	18.83	1.98
1	31.49	4.14	5.40	0.67	30	35.11	0.45	19.24	1.81
10	36.23	0.22	10.72	1.82	40	35.04	0.57	19.81	1.90
G_3					MGL_4				
1	32.04	4.14	—	0.84	1	31.25	4.48	2.70	1.03
5	32.55	3.47	—	1.11	10	35.02	0.45	11.86	1.92
15	36.12	0.34	—	2.10	15	35.22	0.25	15.39	2.04
					25	35.13	0.45	16.83	2.13
G_4					MGL_3				
1	32.26	4.37	—	0.72	1	29.44	4.70	1.39	0.75
10	32.26	4.26	—	0.74	5	34.96	0.56	10.17	1.81
20	35.99	0.34	—	2.70	15	35.22	0.25	11.01	1.94

Below the surface layer all the contours dipped downward offshore in all sections (Figs 2, 3) indicating upwelling of bottom waters. Table 1 shows presence of saltier (sal. $35.75-36.4\times 10^{-3}$), oxygen depleted (DO 0.2-3.4 $ml.l^{-1}$) waters at relatively shallower depths of 10 to 20 m during monsoon. These waters have high concentrations of nutrients (NO_3^- 1.3-12 $\mu mol.l^{-1}$ and PO_4^{3-} 1-2.3 $\mu mol.l^{-1}$). During postmonsoon, waters having these characteristics were found at deeper layers (50-75 m) and away from the coast De Sousa (unpublished data). The above observations indicate the occurrence of coastal upwelling during monsoon. The effect of this upwelling on the surface distribution of properties is, however, suppressed by the opposing mechanisms as discussed above. Nevertheless, the upwelled water does reach the surface at some locations as seen above.

Upwelling along this coast during monsoon has been reported earlier[9-15]. Shetye[16] studied the mechanism of this upwelling and suggested it to be Ekman-type coastal upwelling driven by the southeasterly coastal current prevailing during this season. According to Kumar *et al.*[8] the wind system during this season is north-northwesterly which leads to the formation of the southeasterly coastal current.

Some major rivers originating in the western Ghats discharge in this region (Fig. 1). During the southwest monsoon all these rivers discharge large volumes of freshwater into the sea, thus reducing the salinities over the shelf near the river mouths and leading to longshore variation of surface salinity. As such, under the action of continental shelf current and variable rainfall, patches of nutrient-rich upwelled water may be expected to migrate along the coast in response to the net equatorward flow, thus giving the region a patchy distribution of properties. However, the effect of river flow is mostly confined to the top layer of the water column which may extend from surface up to 10 m depth (Figs 2, 3) and is a perturbation on the broad continental shelf scale of the process of upwelling.

Several workers have previously reported high biological production in these waters during and after the upwelling season. For example, Devassy[17] had reported high primary and secondary production in this area during September-October 1980 while Madhupratap *et al.*[18] observed increased zooplankton biomass during the same period. Similarly, Harkantra & Parulekar[19] reported high benthic production in this area during the late postmonsoon. Fish catch, both pelagic and demersal, was also maximum during the period October-December[20,21]. During the period 1975-84 approximately 43 to 65% of the total annual fish landed in the three bordering states of Kerala, Karnataka and Goa occurred during the period October-December[20,21]. One of the important factors contributing to the increased fish production is the availability of food, and this is available in plenty during monsoon as a consequence of coastal upwelling. Thus, it is concluded that coastal upwelling of nutrients occurring during the southwest monsoon is supporting the rich fisheries in this region during the following postmonsoon season.

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