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Arabian Sea oceanography and fisheries of the west coast of India

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The physical and chemical forcing, which drives the Arabian Sea production is now fairly understood. The main attributes which contribute to the productivity are (1) the boundary and open ocean processes, which manifest as upwelling during summer monsoon and (2) cooling in the northern Arabian Sea during winter. These bring in higher amount of nutrients into the upper ocean, which enhance primary productivity and we examine how these might contribute to the fisheries along the west coast of India. The highest catches are between October and March. From an oceanographic point, this region can be divided into two areas: south of 15°N and north of this latitude. Although the fish catches from these two areas are fairly equal, there is considerable difference in the composition. In the south, planktonivorous fishes dominate, whereas in the north carnivores are more abundant. This appears to be a puzzle, and not reported hitherto. Based on the lower food-web, which appears to be similar in the two regions, we seem to be unable to explain this difference.

ESTIMATES of potential fishery resources from the Exclusive Economic Zone of India (EEZ) are about 3.5 to 4.7 mt (million tonnes)[1–4]. The recent estimates on annual marine landings from the Indian coast show that they fluctuate between 2.2 and 2.8 mt[5]. Of this, about 73% of the catches originate from the west coast of India. But a close look at the catch statistics[5] shows that the composition of marine landings significantly changes, not only between the east and west coasts, but also within the latter.

This and other observations, which also encompass different trophic levels, bring us to some unresolved puzzles mainly on the composition and feeding habits of the fishes, which show changes over space. Under the studies conducted during the Joint Global Ocean Flux Studies (JGOFS) programme (1992–1997), we have come to some new understanding on the physics, chemistry and basic biology of the Arabian Sea, which could be a part of the fishery biology, although interpretations of these in relation to fisheries would require a further concerted effort from all concerned. This paper is an attempt (1) to address the seasonal and spatial variability of the processes controlling the physics, chemistry and biology of the waters of the west coast of India, (2) their influence on fish composition, (3) changes in feeding habits between south and north, and (4) to speculate on the productivity and its relation to fisheries in the Arabian Sea.

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Table 1. Average values of biological measurements (data from JGOFS–India observations, 1992–1997, see text) for different seasons and areas from the eastern Arabian Sea (integrated for the upper 120 m). Primary production is ^{14}C-based (m mol C m^{-2} d^{-1}), while others are standing stocks (m mol C m^{-2})

Parameter	Primary production		Chlorophyll *a*		Bacteria		Microzooplankton		Mesozooplankton	
Season	Coastal	Oceanic	Coastal	Oceanic	Coastal	Oceanic	Coastal	Oceanic	Coastal	Oceanic
Inter-monsoon	21	14	44	47	11	11	379	235	143	106
Winter	42	44	92	81	1	2	269	100	108	84
Summer	92	81	77	174	6	8	139	168	97	96

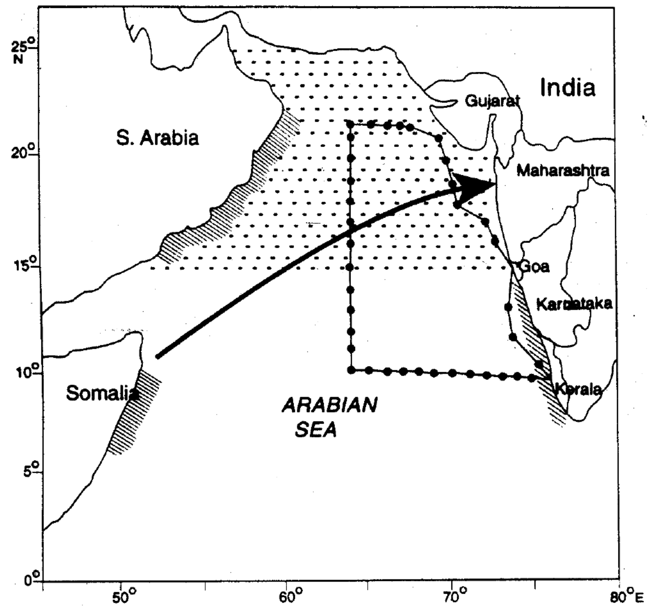

Figure 1. Cruise track in central and eastern Arabian Sea for JGOFS-India. Hatched area shows regions of coastal upwelling along Somalia, Arabia and south-west coast of India during summer, while the stippled area comes under cooling effects during winter. Arrow shows the axis of the Findlater jet, active during summer monsoon, north of which open ocean upwelling takes place.

Data set

The major data set on Arabian Sea oceanography (physics, chemistry, primary production, chlorophyll *a*, and abundance of bacteria, micro and mesozooplankton) is based on a series of observations made between 1992 and 1997 on-board *ORV Sagar Kanya*. These observations were made in seven cruises along the eastern and central Arabian Sea (Figure 1) during inter-monsoons (March–May; September–October), summer (south-west) monsoon (June–August) and winter (north-east) monsoon (November–February). The protocols of the measurements and results are detailed in the literature[6–12]. The data on marine landings and general composition are from the statistics given by the Central Marine Fisheries Research Institute (CMFRI)[5] for the period 1985–1993.

General oceanography and the lower food chain

Based on the atmospheric forcing, the seasonality in the Arabian Sea could be clearly defined and divided into four seasons as given earlier, albeit with some interannual variability. This is also reflected in the spatial–temporal variations in productivity.

During the spring inter-monsoon period (March–May), a transition period from winter to summer, the entire Arabian Sea has on an average very low primary production (14 to 21 m mol C m^{-2} d^{-1}) and chlorophyll (ca. 45 m mol C m^{-2}, Table 1). During this period, the Arabian Sea attains the Typical Tropical Structure (TTS)[13]. A more or less similar scenario prevails during September–October, the transition of summer to winter monsoon (not presented). These periods have higher sea surface temperature (SST, about 28°C), shallow mixed layer depths (MLDs, around 20–30 m) and strong stratification. Nutrients, especially nitrate, the main limiting factor in primary production in these waters (Figure 2 *a*) are at undetectable levels in the surface waters during this period.

With the onset of the summer monsoon (June–September), the situation changes considerably. Under the influence of the south-westerly winds along the west coast, the surface waters move away from the coast and are replaced by colder, nutrient-rich and often oxygen-depleted waters from the subsurface (Ekman pumping/transport). This leads to phytoplankton blooms (mostly diatoms and dinoflagellates) and increased productivity. For example, observations in 1995 showed that off Mangalore (12°N) the 24°C isotherm surfaced, nitrate was about 2 μM near the coast (Figure 2 *b* and *d*) and primary production and chlorophyll exceeded 142 m mol C m^{-2} d^{-1} and 250 m mol C m^{-2}, respectively at this station (Table 1 shows averages for the entire west coast). The upwelling starts at the southern tip of the west coast by end May/early June and propagates northwards with time. Some recent observations[14] show that apart from winds, remote forcing may be a major cause to the upwelling. Surprisingly, no major upwelling occurs north of Goa[15], ca. 16°N. This condition prevails until the end of August/early September and then the coastal upwelling subsides. Notwithstanding the fact

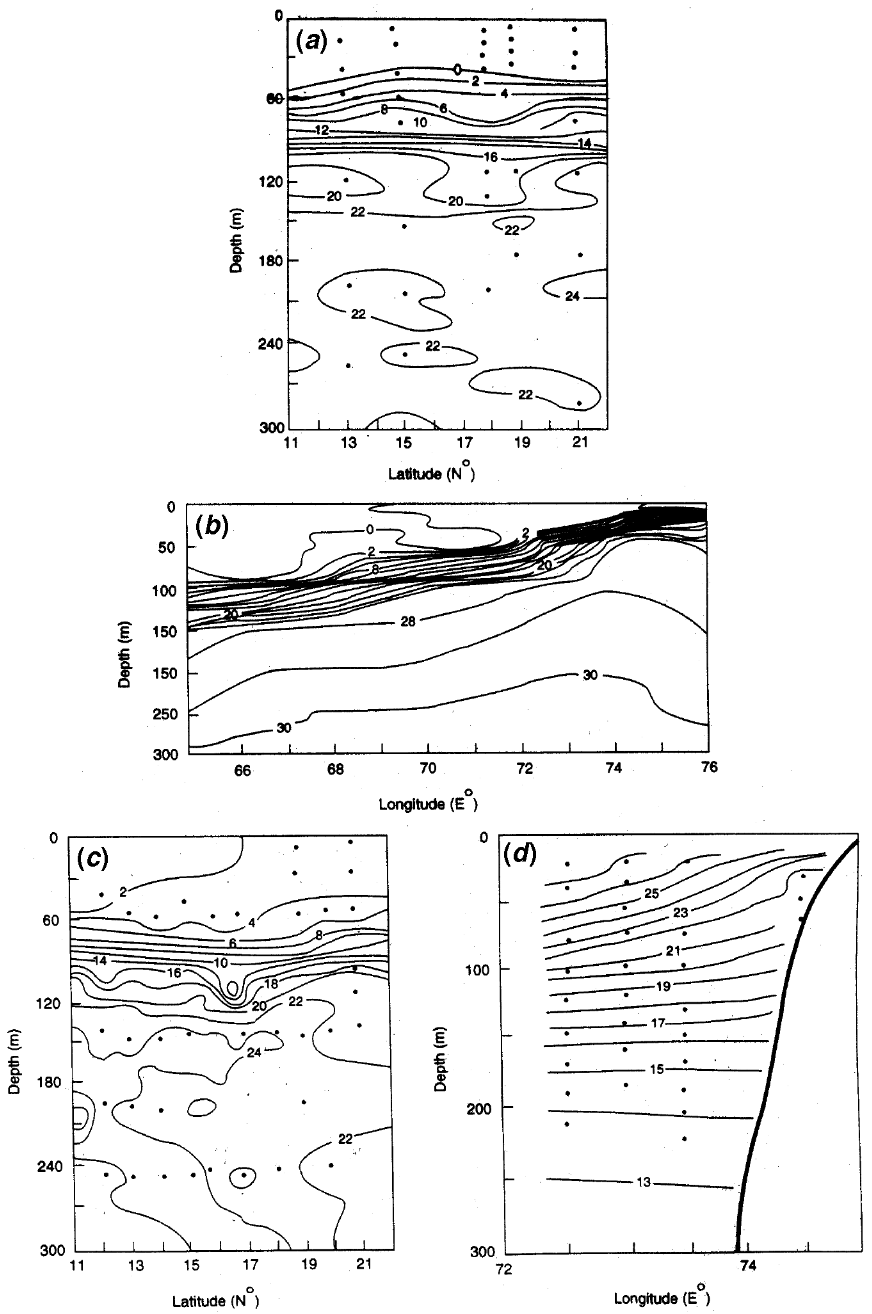

Figure 2. Distribution of nitrate (μM) from 11 to 21°N along 64°E during (***a***), intermonsoon 1994 and (***c***), winter 1995, (***b***), Nitrate distribution (μM) in a coastal section off Mangalore in July 1995 (summer); and (***d***), shoaling of isotherms in the same section in summer, indicating upwelling.

that upwelling does not occur, the coastal waters of the north also have fairly high abundance of phytoplankton and zooplankton in this season[6,16], probably as a result of land/river run-off (Table 1). During this period, a low level jet[17] flows across the Arabian Sea, from the horn of Africa to northern India (Figure 1). Open ocean upwelling occurs in this season in the northern region as a result of positive wind stress curl, north of the Findlater jet, leading to shallower MLDs and higher productivity and biomass (80 m mol C m^{-2} d^{-1}, 170 m mol C m^{-2}).

Another feature which emerged from these cruises is the winter cooling effects in the northern (ca. north of 15°N) Arabian Sea[10]. During winter (November–February), the cold, dry continental air blowing into the northern Arabian Sea causes cooling (SST ca. 24°C), densification of surface waters and sinking. This in turn, leads to deep MLDs (exceeding 100 m) despite weaker winds, the latter, as opposite to summer[9,10] and a convective mixing, injecting nutrients into the surface layers (2–4 μM, Figure 2*c*) generating higher production (ca. 40 m mol C m^{-2} d^{-1} or more)[9,10].

Bacterial and microzooplankton production, in contrast, is highest during the intermonsoon seasons, when productivity is low[8,12] (Table 1). The latter happens through bacteria and the dissolved organic carbon (DOC) pool that build up as the winter and summer blooms senescense[12,18,19]. Microzooplankton (mainly consisting of ciliates), which mostly feed on bacteria in this season (these are facultative feeders on bacteria or phytoplankton) increase and often has the highest standing stocks (Table 1).

The results from the cruise also showed some new findings about the mesozooplankton biomass in the upper layers of the Arabian Sea. It remains relatively unchanged over seasons, in spite of variations in phytoplankton production and abundance[6,11,16,20] (Table 1). Apparently, the mesozooplankton of the Arabian Sea, mostly small in size (< 2 mm) and dominated by the copepod crustaceans, is able to make a switch in their feeding habits. They feed on the abundant microzooplankton[8] during periods of low phytoplankton production such as the inter-monsoons and thus a microbial loop[21] becomes active during this period. Recent findings from the east coast (Godhantaraman, pers. commun.) show that microzooplankton directly form about 48.3 and 31.5% of food for secondary and tertiary consumers during this time.

In short, the seasonal higher productivity in the eastern Arabian Sea is mainly through upwelling during summer and cooling during winter. The former occurs up to about 15°N along the southern coast, whereas the latter is restricted to ca. north of 15°N. During intermonsoons, when the productivity is low, the microbial loop could be important and mesozooplankton abundances are high in all seasons. With this background, we shall try to analyse the fisheries along the west coast of India.

Fisheries

The source of analysis of the capture-fisheries is from the marine landings along the west coast[5] for the years 1985–1993. The values presented are average percentages for these years (Table 2). Based on oceanographic features presented above, we have clubbed the landings from south as those from Kerala, Karnataka and Goa (ca. south of 15°N; Figure 1) and north as those observed along Maharashtra and Gujarat. The main considerations for this cut-off are oceanographic features like coastal upwelling, which occurs only south of ca. Goa and winter cooling, a dominant feature north of it. The split-up is also logical, since the length of the coastline of each state is different and each half represents approximately 8° (7–15°N; 15–23°N).

Table 2. Average percentage catch of each major group of fish from north (lat. > 15°N) and south (1985–1993) along the west coast of India (data from ref. 5)

	Percentage (north of 15°)	Percentage (south of 15°)
Elasmobranchs	78.5	21.5
Eels	99.3	0.70
Catfishes	71.2	28.8
Clupeids	22.3	77.7
Bombay duck	99.99	0.01
Lizard fishes	25.7	74.3
Half beaks and full beaks	11.2	88.8
Flying fishes	10.3	89.7
Perches	28.4	71.6
Goatfishes	25.4	74.5
Bream	96.3	3.70
Croakers	81.1	18.9
Ribbon fishes	75.1	24.9
Carangids	15.6	84.4
Silverbellies	16.0	84.0
Big-jawed jumper	67.8	32.2
Pomfrets	83.4	16.6
Mackerels	15.2	84.8
Seer fishes	58.2	41.8
Tunnies	23.3	76.7
Bill fishes	64.0	36.0
Barracudas	22.7	77.3
Mullets	91.9	8.1
Bregmaceros	99.7	0.3
Flat fishes	31.7	68.3
Crustaceans	58.8	41.2
Cephalopods	51.7	48.3
Others	57.3	42.7
Total average tonnage	59,63,951 ± 32,013	64,58,635 ± 17,30817
Total average catch (%)	48.0	52.0

The total quantity or percentage of yearly landings from these two areas is more or less equal (52% and 48% in south and north, respectively; Table 2), although there was a traditional belief that catches are more from the south. A few groups dominate the total composition along the entire coast: clupeids, 21%; carangids, 7%; Bombay duck, 7%; mackerels, 5%; ribbon fishes, 4% and seer fishes, 2.1% are the major pelagic components whereas crustaceans, 20%; croakers, 6%; perches, 5%; cephalopods, 4%; cat fishes, 2% and pomfrets, 2% are the common demersal groups. The crustaceans mostly consisting of prawns and the carnivorous cephalopods are excluded in further analysis, although it is important to notice that their catches are slightly more from the north compared to south. Among the crustaceans, this is mainly due to higher harvest of the small epipelagic crustacean *Acetes,* and 99.6% of this is from northern states of Maharashtra and Gujarat. However, more important as well as interesting is to have a look at the composition of landings from each half and further analyse them on a seasonal basis.

It is apparent that the fisheries in the two regions differ very much. Among some of the major groups mentioned earlier, almost 100% of Bombay duck, 81% of croakers and 75% of ribbon fishes are caught from the northern half (Table 2). On the other hand, 78% of clupeids, 72% of perches, 85% of carangids and 84% of mackerels are obtained from landings from the southern area. Within some of the latter groups mainly caught from the south, species like *Sardinella longiceps* (oil sardine), *Rastrelliger kanagurta* (Indian mackeral) and *Stolephorus* (anchovies) rarely occur in the north[5]. Further, majority of the catches of some lesser groups like elasmobranchs, eels, catfishes, threadfins and pomfrets are from the north, while lizard fishes, flying fishes, silverbellies, tunnies, barracudas and flat fishes are from the south.

Thus, it is interesting to note that most of the major pelagic fisheries in the north are based on carnivorous forms like Bombay duck, horse mackerel and ribbon fishes. Apart from this, other carnivorous groups of fishes which form a smaller percentage of catch, elasmobranchs, eels and cat fishes are mainly caught in the north. But the dominant forms in the south like sardines, mackerels and anchovies are planktonivorous (which feed on both phytoplankton and smaller zooplankton). Thus, there is a clear tendency of carnivorous fishes dominating the northern coast and planktonivorus forms being more abundant in the south. It might be interesting to analyse the landings seasonally (Tables 3 and 4), although the data on quarterly landings available overlap the seasons described earlier from the oceanographic/climatological viewpoint.

Food web

We will have to try to address these questions based on both oceanography and biology of the fishes. Understanding these is a difficult task at the moment, and would require looking into the feeding, breeding, and behavioural habits of fishes and relate them to other parameters[22]. We seem to know the feeding habits of most fishes which are the base of this analysis. The present data available on the food web at a lower level show that diatoms dominate the phytoplankton composition all along the coast in all seasons, except some blooms of the dinoflagellate *Noctiluca*, the premnesiophyte *Phaeocystis* and blue green alga *Trichodesmium*, during summer or winter[20,23,24]. The zooplankton community is virtually unchanged over seasons in the upper 100 m or so, dominated by copepods composing both herbivorous calanoids and carnivorous poeciliostomatids and cyclopoids – more or less small forms, below 2 mm size class (e.g. dominant forms belong to Paracalanidae, Calanidae and Clausocalanidae–herbivores; Onceaidae and Oithonidae–carnivores)[25]. A major difference may be that ostracods (again a small crustacean) and salps are often more common in the north compared to southern areas. The bacteria and microzooplankton do not directly enter the fish food, except at larval stages of the fishes.

Table 3. Average quarterly percentage of catches (based on total yearly catches from 1985 to 1993)[5] from the west coast of India

I QR (January–March)	II QR (April–June)	III QR (July–September)	IV QR (October–December)
23	17	18	42

Table 4. Quarterly percentage catch of major fishes from the west coast

	I QR (January–March)	II QR (April–June)	III QR (July–September)	IV QR (October–December)
Oil sardines	28	12	24	36
Anchovies	14	21	27	38
Bombay duck	17	13	12	58
Perches	26	17	38	19
Croackers	27	19	12	42
Carangids	12	12	34	42
Mackerels	8	10	34	48

The averages (Table 3) show that the total catch along the west coast peaks in the last quarter (42%, October–December) followed by the first quarter (24%, January–March) and is lower (about 17% each) during mid-year. The trend is same for the major fisheries also (Table 4). The poorest catch in the second quarter (April–June) could be related to poor primary production and general higher SSTs during the season. Most of the common pelagic fishes disappear during this season[22]. They should be migrating elsewhere (deep?), but we do not know of this. The highest catches in the north in the first and last quarters (Bombay duck, croakers) may be indirect effects of winter cooling, when larvae and juveniles could become abundant. But the fairly high percentages in the catches comprising some fishes, including juveniles during summer monsoon (third quarter) from the southern coast (those of oil sardine, anchovies, perches, carangids and mackerels) show that they indeed proliferate (and also spawn) in the area during this season. They take advantage of the upwelling and higher primary productivity during this season[22] and it should be noted that landings are not truly fully representative, since fishing is either prohibited or comparatively less during peak monsoon.

Thus, we point out that the better landings in the first and last quarters is mainly due to fair weather and the prevailing oceanographic conditions. But the fact remains that we do not know how the carnivore vs planktonivore food chains have developed between the north and south. Is the wide shelf area of north compared to south a reason for this? However, the distribution of macrozoobenthos[26] does not show much difference from south to north. It is obvious that we have to pay critical attention to the feeding and breeding habits of the fishes, to understand their response to oceanographic conditions.

Or, have these differences developed out of some past geological events? Although the Tethys Sea evolved into the Indian and the Pacific oceans sometime between the Triassic and the Cretaceous (70–180 m.y. BP) and the Atlantic just started attaining its present configuration around this period, the history of modern fishes goes beyond these time periods[27,28]. Thus it is difficult to conceive that these difference arose based on allopatric speciations. On the other hand, the monsoons and upwelling in the Arabian Sea did not start until ca. 8 m.y. ago[29]. Did the latter lead to a change in the feeding habits in the Quaternary? In order to speculate on this, we need to analyse the fisheries, distribution and habits of allied species as well, on a global tropical scale, which does not come under the scope of the present paper.

Finally, we also briefly analyse the landings trend between the Arabian Sea and Bay of Bengal. The oceanographic conditions between these two seas differ considerably. In the northern Bay, heavy discharge of freshwater reduces the surface salinity and leads to stratification. In the Bay also, carnivorous fishes like Bombay duck and croackers are predominantly caught from the northern areas (data not presented). Lesser sardines are more important in the southern Bay. However, there is an increasing trend in catches of Indian mackerel and oil sardine from the south-east coast over the last few years, for reasons yet unknown.

Potential fish production

Earlier annual estimates of potential fish production from the Indian Ocean have a wide range between 8 and 16 mt[30–33]. But these estimates include presumably less-productive areas like the Bay of Bengal and southern areas up to 40°S. However, Cushing[34] puts it at as high as 3.3×10^8 tonnes. The total catch from the Indian Ocean is about 7.9 mt[35] (western – 4.1 mt and eastern – 3.8 mt). However, coming back to the Arabian Sea, the primary production values (recalculated by us) given by Qasim[32] (470 mg C m^{-2} d^{-1}) are more comparable to our average for the year (600 mg C m^{-2} d^{-1}) and that by Bhargava[2] from the west coast (ca. 619 mg C m^{-2} d^{-1}).

The returns from the EEZ of India are less certain. Potentials are estimated to be between 3 and 5 mt, including the coastal waters of the Bay of Bengal, Andamans and Lakshadweep (total area ~ 2.02 million km^2) out of which, on the average 2.5 mt is realized. However, we think that the latter estimates of total tertiary production might be below potential, since these do not take into account the high average zooplankton standing stock (1400 mg C m^{-2} or 5.5 ml/m^3) compared to Goswami's[3] estimates of 0.8 ml/m^3, nor the (high seasonal) bacterial and microzooplankton biomass. We recalculated the secondary production rates of zooplankton in relation to temperature (t°C) based on growth rate (g) (eqs (1) and (2)) and the latter was averaged, based on both equations.

$$g = 0.018 \exp(0.12t) \text{ (Uye, unpublished)} \quad (1)$$

$$g = 71.71t^{-1.22} \text{ (Cushing}^{34}\text{)} \quad (2)$$

Production (P) = Biomass (B) × Growth rate (g).

Our findings show that tertiary production based on primary productivity, microzooplankton and mesozooplankton could be about 108 mt from the Arabian Sea alone. At present, the landings from the west coast of India is only about 1.2 mt (ref. 5). If so, the region is underexploited and the main reason for this could be the unexploited mesopelagic myctophid population which apparently has a turnover of about 100 mt per year (still unconfirmed, but see refs 36 and 37 for more details). They migrate to the surface at night[37] and feed exclusively on zooplankton. The paradox of mesozooplankton[10] and the microbial loop could be answers to this.

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