Seasonal and interannual variations of oceanographic conditions off Mangalore coast (Karnataka, India) in the Malabar upwelling system during 1995–2004 and their influences on the pelagic fishery

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ABSTRACT

Mangalore coast is well known for its multi-species and multi-gear fisheries and the fishery and oceanographic features of this region is a true representation of the Malabar upwelling system. Ten years of study (1995–2004) of oceanographic parameters has been carried out from the inshore waters off Mangalore to understand their seasonal and interannual variations and influences on the pelagic fishery of the region. Attempt has been also made to understand the influence of local and global environmental conditions on the alternating patterns of abundance between the Indian mackerel and oil sardine from the area. Field- and satellite-derived oceanographic data have shown that coastal upwelling occurs during July–September with a peak in August resulting in high nutrient concentrations and biological productivity along the coast. Nearly 70% of the pelagic fish catch, dominated by oil sardine and mackerel, was obtained during September–December, during or immediately after the upwelling season. Catches of scombroid fishes were significantly related to cold Sea Surface Temperature, while such relationships were not observed for sardines and anchovies. Significant positive correlations were observed between the ENSO events (MEI) and seawater temperature from the study area. The extreme oceanographic events associated with the cold La Niña, which preceded the exceptional 1997–98 El Niño event, were responsible for the collapse of the pelagic fishery, especially the mackerel fishery along the southwest coast of India (Malabar upwelling system). Coinciding with the collapse of the mackerel fishery, oil sardine populations revived during 1999–2000 all along the southwest coast of India. Tolerance of oil sardine to El Niño/La Niña events and the low predatory pressure experienced by their eggs and larvae due to the collapse of mackerel population might have resulted in its population revival.

Key words: fishery, mackerel, Mangalore, oceanography, sardine, upwelling

INTRODUCTION

Studies on the characteristics of the marine environment are important in fisheries research, as the conditions in the sea play a major role in the availability of fish. The fluctuations in the physical, chemical and biological oceanographic conditions have a profound influence on the periodic and seasonal migration of fishes in the sea (Kawasaki *et al.*, 1991). Long-term natural variability in climate, oceanography and marine ecosystems leads to fluctuations in the abundance of exploited fish populations (Francis and Hare, 1994). Information on the physical, chemical and biological oceanographic parameters is important in predicting, locating and exploiting marine fishery resources.

The Malabar coast (southwest coast of India) is one of the major upwelling systems of the world (Bakun *et al.*, 1998). It was established that upwelling takes place along this coast during the summer monsoon months from May to September and the ensuing productivity sustains a fishery for a number of commercially important fishes (Ramamirtham and Patil, 1965). The Malabar coast of India is rich in primary (660 mg C m^{-2} day^{-1}) and secondary (10–57 mg C m^{-2} day^{-1}) production and contributes nearly 50% of the total Indian marine fish landings (Vivekanandan *et al.*, 2003; Smith and Madhupratap, 2005).This coast is characterized by the abundance of oil sardine (*Sardinella longiceps*) and Indian mackerel (*Rastrelliger*

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kanagurta) which support the western Indian Ocean's largest coastal pelagic fishery (Vivekanandan *et al.*, 2005). There have been few attempts from Indian waters to relate pelagic fish catch to seawater temperature, salinity, rainfall, upwelling, chlorophyll distribution and so on, and with very limited success (Banse, 1959; FAO, 1980; Johannessen *et al.*, 1981; Longhurst and Wooster, 1990; Madhuprathap *et al.*, 1994; Yohannan and Abdulrahiman, 1998; Jayaprakash, 2002).

The Mangalore coast is well known for its multi-species and multi-gear fisheries and the fishery and oceanographic features of this region are a true representation of the Malabar upwelling system. The popular gears of the region at present are trawl net, purse seine, ring seine and gill net. The mechanized units contribute 95% to the annual catch and the rest is by artisanal gears, which operate mostly during southwest monsoon period. The important resource groups are mackerel, oil sardine, carangids, whitebaits, threadfin breams, penaeid prawns, stomatopods and cephalopods (Mohamed *et al.*, 1998). This coast is historically known as 'mackerel coast' due to the predominance of mackerel fishing by the now defunct *rampani* nets. By sheer volume, oil sardine and mackerel have traditionally been the mainstay of the marine fisheries of this region (Prathibha and Bhat, 2003; Prathibha and Gupta, 2004). The changing pattern in the fishery over the years has resulted in the variation in the contribution of these species to the total landings (Mohamed *et al.*, 1998).

Several oceanographic parameters have been previously studied from the southwest coast of India (Ramamirtham and Patil, 1965; Sharma, 1968; Madhuprathap *et al.*, 1994; Madhupratap *et al.*, 1996; Bakun *et al.*, 1998; Pillai *et al.*, 2000; Prasannakumar *et al.*, 2000; JGOFS, 2002; Smith and Madhupratap, 2005) and from the coastal waters off Mangalore (Reddy *et al.*, 1979; Pai and Reddy, 1981; Gupta *et al.*, 1998; Krishnakumar *et al.*, 2006). However, long-term studies on oceanographic parameters and their influence on pelagic fishery have not been reported from the Malabar coast and particularly from the Mangalore coast. The purpose of this study is to understand the seasonal and interannual variations in the oceanographic parameters and temporal pattern in upwelling off the Mangalore coast and their influences on the pelagic fishery, especially oil sardine and Indian mackerel, based on 10-yr data (1995–2004) collected from the inshore waters. An attempt also has been made to understand the influence of local and global environmental conditions on the alternating patterns of abundance observed between the Indian mackerel and oil sardine from the area.

METHODS

Fishery data

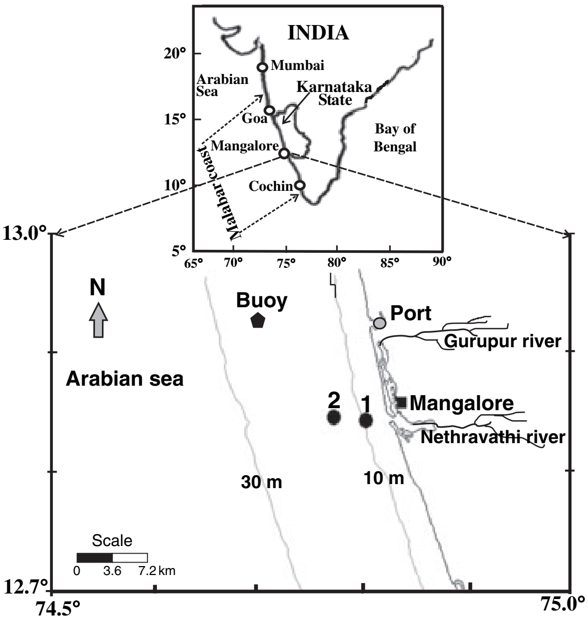
The Central Marine Fisheries Research Institute (CMFRI) estimates the marine fish landing in India by employing the stratified multistage random sampling design (Srinath, 2003) and maintains a database of the results. The monthly estimated pelagic fish landings (1995–2004) at Mangalore by boats (indigenous gears, purse seine and drift gill net) operating in the inshore waters off Mangalore were taken from the CMFRI database. Landings of major groups such as oil sardine (*Sardinella longiceps*), sardines other than *S. longiceps*, Indian mackerel (*Rastrelliger kanagurta*), anchovies (Genera *Stolephorus* and *Encrasicholina*), seerfishes (Genus *Scomberomorus*), tunas, carangids (scads, horse mackerel etc.), thryssa (Genus *Thryssa*), ribbonfishes (Family *Trichiuridae*), pomfrets (black and white pomfrets) and cephalopods (squids and cuttlefishes) were used to study the relationship with oceanographic conditions.

Environmental data

Time series (1995–2004) of monthly mean satellite-derived Sea Surface Temperature (Der SST) available for nearest coastal (Lat 13°N and Long 74°E) and offshore (Lat 13°N and Long 73°E) stations falling within the study area was extracted from the original 1° grid (latitude × longitude) from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) website (http://dss.ucar.edu). The assumption made was that during certain months, SST in the coastal station will be lower than the offshore stations due to coastal upwelling. The monthly mean coastal upwelling index (CUI) was downloaded from the Global Upwelling Index data group of NOAA's PFEG Live Access Server (http://las.pfeg.noaa.gov) for the Mangalore coast (Lat 12.5–13.5°N; Long 74.5°E), having 158° coast angle. Multivariate ENSO Index (MEI) data were obtained from the NOAA-CIRES Climate Diagnostics Center (http://www.cdc.noaa.gov/people/klaus.wolter/MEI). The MEI is the weighted average of the main ENSO features of six variables such as sea-level pressure, the east-west and north-south components of the surface wind, SST, surface air temperature, and total amount of cloudiness (Wolter and Timlin, 1998). The positive MEI values indicate warm (El Niño) and negative values indicate cold (La Niña) water conditions.

The SST data (1999–2004) were taken from the moored data buoy maintained at 3 m depth off Mangalore (Lat 12.933°N; Long 74.716°E) by the National

Figure 1. Map showing the sampling stations 1 and 2 and location of the moored data buoy off Mangalore, southwest coast of India.



Institute of Ocean Technology, Chennai, India (Fig. 1). Fortnightly sampling was made from two stations, one at 10 m depth area (Lat 12.841°N; Long 74.802°E) and another at 20 m depth area (Lat 12.844°N; Long 74.771°E) in the inshore waters off Mangalore (Fig. 1) during 1995–2004. Due to inclement weather conditions, sampling could not be carried out in the peak southwest monsoon season (June–August) during most of the years. However whenever possible, samples were collected in the monsoon season during some years. Fishing activities are also restricted during June–August due to a fishing ban imposed on mechanized boats by the state government (Mohamed *et al.*, 1998). Water samples in duplicate were collected in the morning hours. A clean plastic bucket was used for collection of surface water samples while bottom samples were collected using a Nansen reversing bottle (HydroBios, Kiel-Holtenau, Germany). Upon collection, samples were transferred to clean polythene bottles and stored in an ice box for transportation for analysis in the laboratory. SST was measured *in situ* with a centigrade thermometer of 0.5° accuracy. Sea bottom temperature (SBT) was taken from the reversing thermometer attached to the water sampler. Water transparency or sun light penetration was measured using the conventional Secchi disc of 30-cm diameter and light attenuation coefficient (LAC) was calculated using the formula, LAC = 1.7/D, where D denotes Secchi disc reading (Poole and Atkins, 1929). The hydrogen ion concentration (pH) of the water samples was measured using a Jenway model–350 pH meter (Jenway, Dunmow, UK). Salinity was estimated by using a conductivity meter (WTW LF 320, Weilheim, Germany). Standard procedures were adopted for estimating dissolved oxygen (DO) and inorganic nutrients (Strickland and Parsons, 1968; Parsons *et al.*, 1984). The seawater density (sigma t) was computed from temperature and salinity (chlorinity) data as per Knudsen's method. Samples for plant pigments were filtered using *Whatman* GF/D glass fibre filters (Whatman, Mumbai, India) and pigments extracted in 90% acetone were estimated using a spectrophotometer (Strickland and Parsons, 1968). Zooplankton samples were collected using a 0.5-m diameter conical plankton net of 0.33-mm mesh size, and zooplankton biomass (ZB) was expressed as mL m^{-3}.

Data analysis

Statistical analyses such as Pearson correlation and multiple regression were carried out using SPSS 12 software (SPSS, Bangalore, India). Multiple stepwise regression analyses (linear fit) were performed to identify the oceanographic parameters that were significantly correlated with pelagic fish catch.

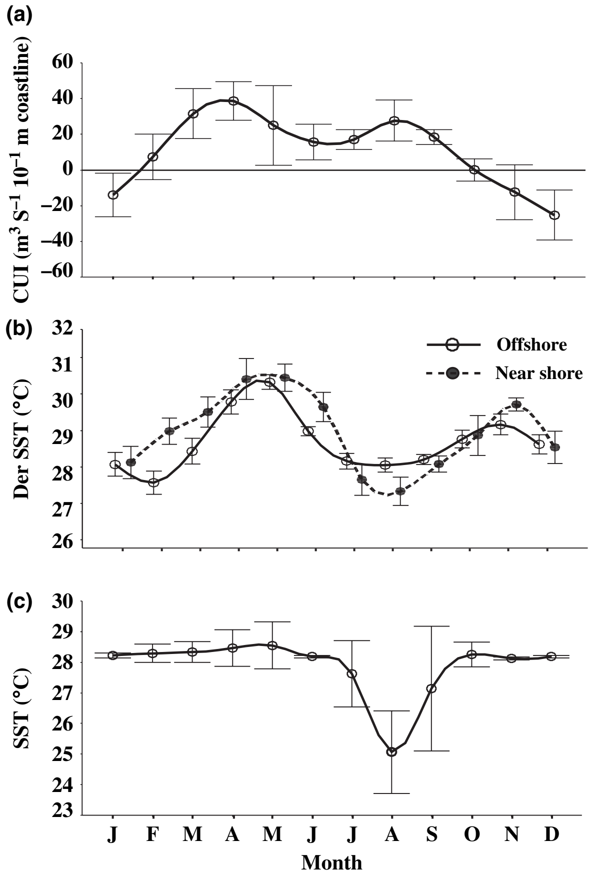
RESULTS

Physical parameters

Mean monthly variations in CUI, Der SST for near shore and offshore stations and mean monthly variations in SST recorded by the moored data buoy are shown in Fig. 2. Peak upwelling was observed in April followed by August (Fig. 2a). Low SST was observed during July–September with a lowest peak in August in the near shore station (Fig. 2b). The lowest SST was recorded during August followed by September by the moored data buoy at 3 m below the surface (Fig. 2c). A year-wise statistical summary of seawater temperature, salinity, sigma t, pH, DO, nutrients, chlorophyll a (chl a), LAC and ZB averaged from two stations off Mangalore is shown in Table 1. Statistically significant differences ($P < 0.001$) were not observed in the physicochemical parameters between the two stations. Statistically significant differences ($P < 0.001$) were also not observed in pH, nitrate, nitrite and chl a content between the surface and bottom.

The monthly variations in the oceanographic parameters during 1995–2004 are shown in Figs 3 and 4. The SST varied from 25 to 32.8°C (mean

Figure 2. (a) Average monthly coastal upwelling index (CUI) for the Mangalore coast taken from the NOAA's PEEL Live Access Server. (b) Average monthly satellite-derived ICOADS sea surface temperature (Der SST) for a near shore station compared to offshore station off Mangalore. (c) Average monthly SST recorded by the moored data buoy maintained at 3 m depth off Mangalore. Vertical lines: SDs.



29.18), while the SBT varied from 21.5 to 32.0°C (mean 28.3). Surface salinity varied from 11.6 to 35.7 (mean 32.3), while bottom salinity varied from 32.43 to 35.88 (mean 34.47). Surface sigma t varied from 5.01 to 22.81 (mean 20.02), while bottom values varied from 20.03 to 24.48 (mean 21.9). Surface DO varied from 3.13 to 5.65 mL/L (mean 4.33), while bottom values varied from 0.13 to 5.56 mL/L (mean 3.6). The LAC varied from 0.12 to 4.25 (mean 0.95) and low LAC was observed during September–October. The observed values for water temperature and DO were significantly higher ($P < 0.001$) in the surface waters compared to the bottom (Table 1). Salinity and sigma t values were significantly lower in the surface compared to the bottom as expected ($P < 0.001$).

Seawater temperature showed a primary peak during April–May and a secondary peak during October–November. Surface salinity was low during June–September coinciding with southwest monsoon. The DO values in the bottom were low during September–October. The lowest seawater temperature (21.5°C) was recorded at 20 m bottom from station 2 in September 2000, while the highest temperature (32.8°C) was recorded at the surface from station 1 in May 2001. Lowest DO (0.13 mL/L) was recorded at 10 m bottom from station 1 in September 1996, while the highest DO (5.65 mL/L) was recorded at the surface from station 1 in May 1999.

Chemical and biological parameters

Surface pH varied from 7.45 to 8.42 (mean 8.08), while pH at the bottom varied from 7.24 to 8.58 (mean 8.04). Surface phosphate concentrations varied from 0.01 to 0.90 mM (mean 0.21), while bottom concentrations varied from below the detection limit (bdl) to 1.17 mM (mean 0.29) (Fig. 3). Surface nitrate concentrations varied from bdl to 3.32 mM (mean 0.25), while bottom concentrations varied from bdl to 2.87 mM (mean 0.29). Surface nitrite values varied from bdl to 0.89 mM (mean 0.08), while bottom values varied from bdl to 0.91 mM (mean 0.13). Surface silicate concentrations varied from bdl to 50.2 mM (mean 5.78), while bottom concentrations varied from bdl to 15.8 mM (mean 3.26) (Fig. 4). Phosphate, nitrate and nitrite concentrations were high during September and October in seawater (Figs 3 and 4). Surface chl a content varied from bdl to 18.59 mg m^{-3} (mean 3.71), while bottom concentrations varied from bdl to 20.8 mg m^{-3} (mean 4.47). The ZB in the study area varied from 0.07 to 233.8 mL m^{-3} with a mean value of 16.3 mL m^{-3} (Fig. 4). The chl a content was high in March and September while, ZB was high in October (Fig. 4).

Fish catch

The total pelagic fish catch landed by purse seiners (PS), drift gill netters (DGN) and indigenous gears (IG) at Mangalore harbour varied from 15 673 t in 1995 to 10 239 t in 2004 (Table 2), while the total catch per unit effort (CPUE) varied from 1.53 t/boat in 1995 to 1.56 t/boat in 2004 (only in PS and DGN). The lowest catch of 7611 t was obtained in 2003 and the highest catch of 19 357 t was obtained in 1998. Out of the total pelagic fish catch nearly 80% was contributed by PS, 13% by single day trawlers, 4% by IG and 3% by DGN. Nearly 47% of the annual pelagic fish catch was recorded during September–October and 72% was recorded during September–December

Table 1. Year-wise summary of the oceanographic parameters recorded at the surface and bottom from the inshore waters (station 1 and 2 combined) off Mangalore during 1995–2004.

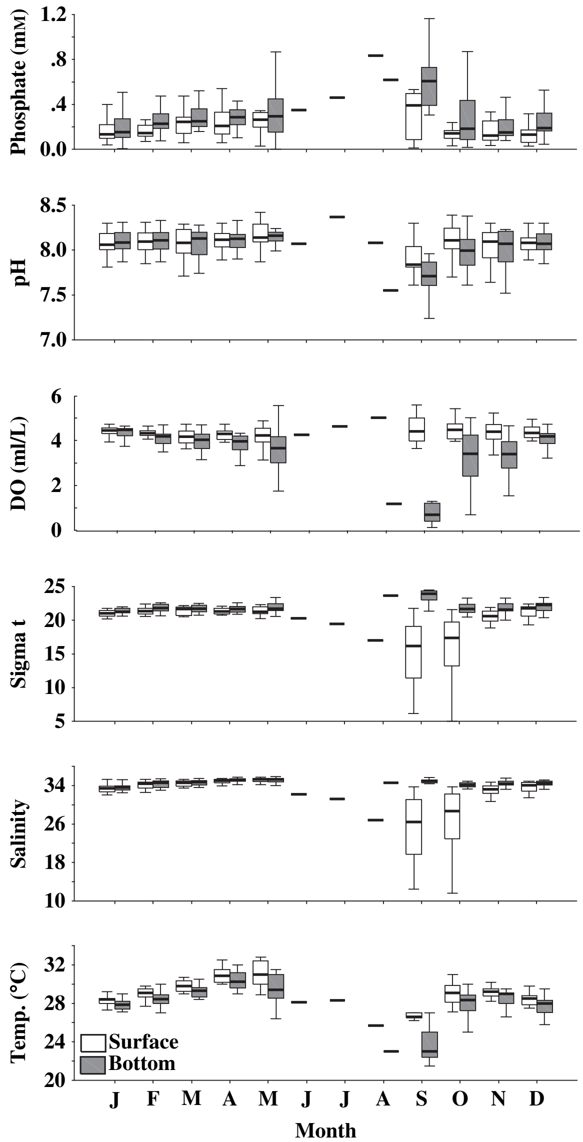
Year	Water temperature (°C)		Salinity		Sigma t		Dissolved oxygen (mL/L)		pH		Nitrate (mM)		Nitrite (mM)		Phosphate (mM)		Silicate (mM)		Chlorophyll a (mg m^{-3})		Zooplankton biomass (mL m^{-3})	Light attenuation coefficient
	Sur	Bot	Sur	Bot	Sur	Bot	Sur	Bot	Sur	Bot	Sur	Bot	Sur	Bot	Sur	Bot	Sur	Bot	Sur	Bot		
1995																						
Mean	28.4	28.1	33.2	35.1	20.9	22.5	4.29	3.95	8.04	8.05	0.16	0.18	0.03	0.04	0.20	0.22	5.81	3.95			15.7	
Minimum	27.0	23.0	19.7	34.4	11.3	21.6	3.35	0.40	7.45	7.50	0.05	0.05	bdl	0.01	0.09	0.11	2.22	2.58			3.0	
Maximum	30.4	31.4	35.5	35.7	22.8	24.5	4.86	5.56	8.20	8.21	0.41	0.50	0.06	0.13	0.39	0.39	31.76	9.60			46.8	
1996																						
Mean	28.6	27.7	30.7	34.3	19.0	22.0	4.41	3.25	8.18	8.18	0.16	0.16	0.04	0.07	0.12	0.23	6.69	4.17	1.88	2.00	18.1	
Minimum	26.2	22.0	12.5	32.5	6.1	20.7	3.48	0.13	7.61	7.66	bdl	0.04	bdl	bdl	0.03	0.05	1.11	1.78	bdl	0.66	0.1	
Maximum	30.2	30.5	35.4	35.6	22.3	24.4	5.42	4.62	8.31	8.58	0.38	0.54	0.22	0.24	0.34	0.70	31.02	8.12	5.31	3.39	72.5	
1997																						
Mean	29.6	28.8	33.2	34.1	20.5	21.5	4.50	3.68	8.20	8.12	0.10	0.25	0.05	0.14	0.20	0.21	5.65	2.56	4.81	6.00	1.5	1.53
Minimum	28.2	26.0	29.0	32.4	17.3	20.0	3.93	0.86	8.10	7.24	bdl	0.07	0.01	0.02	0.03	0.02	0.40	1.00	0.87	0.36	0.1	0.64
Maximum	31.2	30.0	35.7	35.9	22.1	22.6	5.00	4.66	8.30	8.28	0.25	0.68	0.14	0.75	0.60	0.51	50.22	3.92	13.71	20.78	5.7	2.94
1998																						
Mean	29.6	28.7	32.8	34.8	20.2	22.0	4.26	3.56	8.09	8.06	0.15	0.31	0.09	0.18	0.23	0.33	5.16	2.70	2.59	2.18	15.7	1.41
Minimum	27.1	25.0	20.3	33.7	11.7	21.2	3.98	0.89	7.74	7.62	bdl	0.01	0.01	0.02	0.05	0.13	0.13	bdl	1.02	0.87	0.2	0.34
Maximum	32.5	31.6	35.5	35.5	21.9	23.3	4.59	4.66	8.29	8.28	0.75	1.38	0.33	0.52	0.59	0.85	18.52	7.81	5.02	4.21	109.0	4.05
1999																						
Mean	28.7	27.0	29.4	34.4	18.0	22.3	4.38	3.04	7.91	7.82	0.44	0.35	0.10	0.19	0.23	0.41	9.02	3.71	2.90	4.75	34.4	1.26
Minimum	25.0	22.0	11.6	33.0	5.0	21.0	3.29	0.41	7.64	7.41	bdl	bdl	bdl	bdl	0.07	0.07	0.09	bdl	bdl	bdl	4.5	0.26
Maximum	31.2	29.7	35.3	35.3	22.1	24.2	5.65	5.45	8.17	8.12	2.27	1.24	0.26	0.82	0.86	1.16	33.64	10.05	7.05	11.17	233.8	4.25
2000																						
Mean	28.9	27.4	33.1	34.8	20.7	22.5	4.31	3.23	7.97	7.90	0.11	0.74	0.05	0.26	0.26	0.42	5.04	4.29	4.05	7.18	29.0	0.78
Minimum	26.5	21.5	24.6	33.2	14.3	21.1	3.13	0.60	7.81	7.70	bdl	bdl	0.01	0.01	0.10	0.13	1.70	1.34	1.31	1.54	0.2	0.41
Maximum	31.2	30.8	35.6	35.6	22.2	24.5	5.23	4.70	8.19	8.02	0.26	2.87	0.16	0.91	0.90	0.87	14.38	8.91	13.23	17.26	116.8	1.62
2001																						
Mean	29.8	28.7	33.3	34.4	20.6	21.7	4.32	3.60	8.12	8.12	0.24	0.30	0.09	0.12	0.22	0.34	3.04	2.74	3.55	3.31	8.8	0.66
Minimum	27.8	27.0	26.6	33.2	16.2	20.9	3.44	2.31	7.90	7.90	0.02	0.04	bdl	bdl	0.05	0.08	0.72	0.76	0.90	1.13	0.9	0.22
Maximum	32.8	31.3	35.3	35.4	22.0	22.5	4.74	4.53	8.42	8.33	1.02	1.17	0.39	0.58	0.47	0.52	11.93	5.32	13.98	6.61	48.0	1.88
2002																						
Mean	29.3	28.7	31.5	34.1	19.3	21.5	4.27	3.93	8.01	8.03	0.41	0.17	0.13	0.07	0.17	0.26	7.42	3.55	3.51	4.89	3.4	0.76
Minimum	26.5	23.0	19.7	33.2	11.4	20.6	3.42	1.13	7.72	7.70	0.01	bdl	bdl	bdl	0.03	bdl	1.67	0.30	0.43	0.44	0.3	0.12
Maximum	31.8	31.3	34.5	34.7	21.4	23.6	5.59	5.02	8.42	8.37	3.31	0.71	0.89	0.24	0.46	0.87	32.21	15.77	10.80	20.13	17.0	2.74

Table 1. Continued

Year	Water temperature (°C) Sur	Bot	Salinity Sur	Bot	Sigma t Sur	Bot	Dissolved oxygen (mL/L) Sur	Bot	pH Sur	Bot	Nitrate (mM) Sur	Bot	Nitrite (mM) Sur	Bot	Phosphate (mM) Sur	Bot	Silicate (mM) Sur	Bot	Chlorophyll a (mg m^{-3}) Sur	Bot	Zooplankton biomass (mL m^{-3})	Light attenuation coefficient
2003																						
Mean	29.9	29.6	33.1	34.5	20.3	21.5	4.43	4.04	8.06	8.03	0.32	0.18	0.05	0.07	0.19	0.19	5.60	2.55	3.67	3.50	22.4	0.66
Minimum	27.5	26.3	19.9	33.3	10.2	20.5	3.95	3.28	7.71	7.74	bdl	bdl	0.01	bdl	0.03	bdl	1.55	1.50	0.87	1.13	0.8	0.37
Maximum	32.5	32.0	35.0	35.1	22.1	22.3	5.23	4.64	8.33	8.24	1.79	1.45	0.32	0.27	0.54	0.34	28.53	4.18	6.73	7.16	212.3	1.26
2004																						
Mean	28.9	28.6	33.3	34.4	20.9	21.7	4.18	3.88	8.18	8.18	0.32	0.21	0.14	0.09	0.24	0.28	4.30	2.30	4.71	4.24	15.5	0.76
Minimum	25.7	24.7	26.8	33.5	17.0	21.0	3.35	3.21	7.97	8.00	bdl	bdl	bdl	bdl	0.01	0.03	bdl	0.25	bdl	bdl	0.8	0.32
Maximum	30.8	30.5	35.1	35.0	22.4	23.4	5.01	4.51	8.39	8.38	1.21	0.79	0.65	0.33	0.84	0.84	18.80	7.50	18.59	18.59	62.3	1.55
Total 10 yrs																						
Mean	29.2	28.3	32.3	34.5	20.0	21.9	4.33	3.60	8.08	8.04	0.25	0.29	0.08	0.13	0.21	0.29	5.78	3.26	3.71	4.47	16.3	0.95
Minimum	25.0	21.5	11.6	32.4	5.0	20.3	3.13	0.13	7.45	7.24	bdl	bdl	bdl	bdl	0.01	bdl	bdl	bdl	bdl	bdl	0.01	0.12
Maximum	32.8	32.0	35.7	35.9	22.8	24.5	5.65	5.56	8.42	8.58	3.31	2.87	0.89	0.91	0.90	1.16	50.22	15.77	18.59	20.78	233.8	4.25

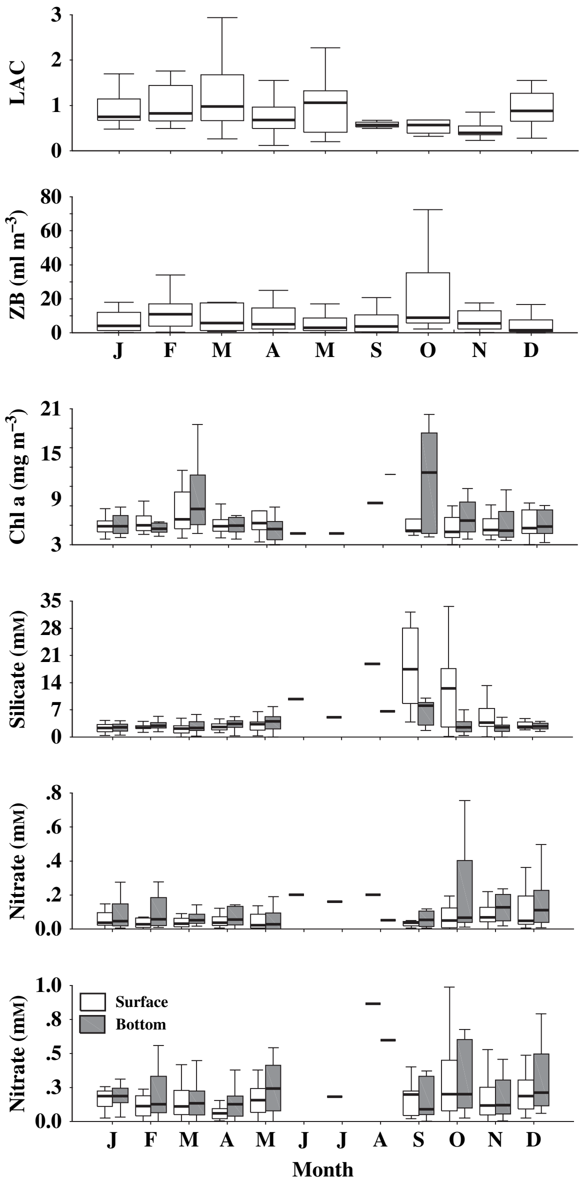
Sur, surface; Bot, bottom; bdl, below the detection limit.

Figure 3. The box and whisker plots showing median (centre value), lower and upper quartiles and the smallest and largest values of seawater temperature (Temp.), salinity, sigma t, dissolved oxygen (DO), pH and phosphate recorded from the surface (clear box) and bottom (shaded box) off Mangalore (stations 1 and 2 combined) during 1995–2004.



(Fig. 5). The mean annual catches of total pelagic fishes, oil sardine and mackerel from Mangalore coast and from the west coast of India (Malabar upwelling system) are shown in Fig. 6. From 1995 to 1999, mackerels were dominant in the fishery and from 2000 oil sardine became dominant (Fig. 6a). Along the southwest coast of India, a similar inverse pattern in abundance of oil sardine and mackerel was observed from 1999 (Fig. 6b).

Figure 4. The box and whisker plots showing median (centre value), lower and upper quartiles and the smallest and largest values of nitrate, nitrite silicate, chlorophyll a (Chl a), zooplankton biomass (ZB) and light attenuation coefficient (LAC) recorded from the surface (clear box) and bottom (shaded box) off Mangalore (stations 1 and 2 combined) during 1995–2004.



Statistical analysis

The correlation (Pearson) between physical and biological parameters and with pelagic fish catch is shown in Tables 3 and 4. SST showed significant positive correlations with SBT, surface salinity, surface sigma t, pH, bottom DO, MEI, CUI and Der SST. Bottom sigma t showed significant positive correlations with phosphate, silicate and Chl a. CUI showed significant positive correlations with phosphate, bottom salinity and Der SST (Table 3). Total pelagic fish catch in PS and DGN, and catches of fishes such as thryssa, carangids, mackerels, seerfishes and tunas showed significant positive correlations with bottom sigma t and significant negative correlations with bottom DO (Table 4). CUI showed significant negative correlations with DGN, oil sardine, other sardines and seerfishes.

Results of stepwise multiple linear regression analysis between fish catch and oceanographic parameters are shown in Table 5. The r^2 obtained for total purse seine catch and drift gill net catch indicates that 48.7% and 56% of the variations respectively in the catch can be explained by the significant variables (salinity, DO, CUI etc.) in the model (Table 5). Generally, surface and bottom DO (indicator of upwelling) explain 72.8% of the catch variations of Scombroid fishes (mackerels, seerfishes and tunas) and surface salinity explains 47% of catch variations of sardines. The r^2 values obtained in the multiple regression analysis for carangids and thryssa were very low (<30%).

DISCUSSION

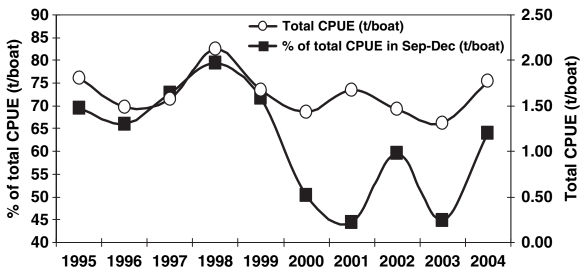
Seasonal and interannual variations

Upwelling and variations in SST influence the nutrients level and productivity in the coastal waters. Significant positive correlations were observed for the satellite-derived SST (ICOADS) with the SST (r^2, 0.57) and SBT (r^2, 0.50) recorded from the inshore waters off Mangalore, indicating that inshore data are reflecting the general trends in the oceanographic conditions of the area (Table 3). Significant correlations were observed for SST and SBT values (Table 3) with MEI indicating a remote connection between the oceanographic conditions of the area with ENSO events in the equatorial region of the Pacific. Study of oceanographic conditions off Mangalore for 10 yrs (1995–2004) shows definite seasonal variations with some deviations in certain years (Figs. 3 and 4). The major reason for these fluctuations was the onset of southwest monsoon in the beginning of June every year and the related upwelling as reported by earlier workers (Banse, 1959; Ramamirtham and Rao, 1973; Johannessen *et al*., 1981; Muraleedharan and Prasannakumar, 1996). After the onset of the southwest monsoon, upwelling is generated from 8°N to at least 15°N, by the large scale, wind driven, clockwise circulation, causing a south flowing current along the west coast of India (Banse, 1959; Ramamirtham and

Table 2. The total pelagic fish catch (t) and CPUE – t/boat (shown in brackets) obtained by purse seines, drift gill net and indigenous gears at Mangalore harbour during 1995–2004.

Year	Purse seine	Drift gill net	Indigenous gears	Total pelagic
1995	14 448 (1.45)	439 (0.10)	767	15 673 (1.53)
1996	11 975 (1.16)	385 (0.09)	509	12 848 (1.21)
1997	13 515 (1.27)	209 (0.09)	140	13 926 (1.33)
1998	18 571 (1.81)	400 (0.11)	376	19 357 (1.89)
1999	9240 (1.28)	493 (0.09)	375	10 137 (1.33)
2000	8964 (1.09)	395 (0.07)	546	9961 (1.15)
2001	11 458 (1.37)	446 (0.10)	445	12 401 (1.42)
2002	7863 (1.16)	305 (0.07)	142	8326 (1.21)
2003	6622 (1.02)	623 (0.09)	416	7611 (1.08)
2004	9045 (1.51)	391 (0.08)	937	10 239 (1.56)

Figure 5. The annual catch per unit effort (CPUE – t/boat) of total pelagic fishes (t) landed by all gears (purse seines and drift gill nets) and % of total CPUE recorded only during September–December.



Rao, 1973; Johannessen *et al.*, 1981). Vertical time series sections of both temperature and oxygen were used by earlier workers as the major indicators of the upwelling process (Banse, 1959; Ramamirtham and Rao, 1973; Johannessen *et al.*, 1981). In certain years during August–September, seawater with very low temperature (~21.5°C), low oxygen (~0.13 mL/L) and high density (sigma t > 23) was observed near the bottom indicating strong upwelling (Table 1). However, the signature of upwelling near the surface was less visible from both the sampling stations as they are located close to the discharge zone of Nethravathi and Gurupur Rivers (Fig. 1). In the upwelling season,

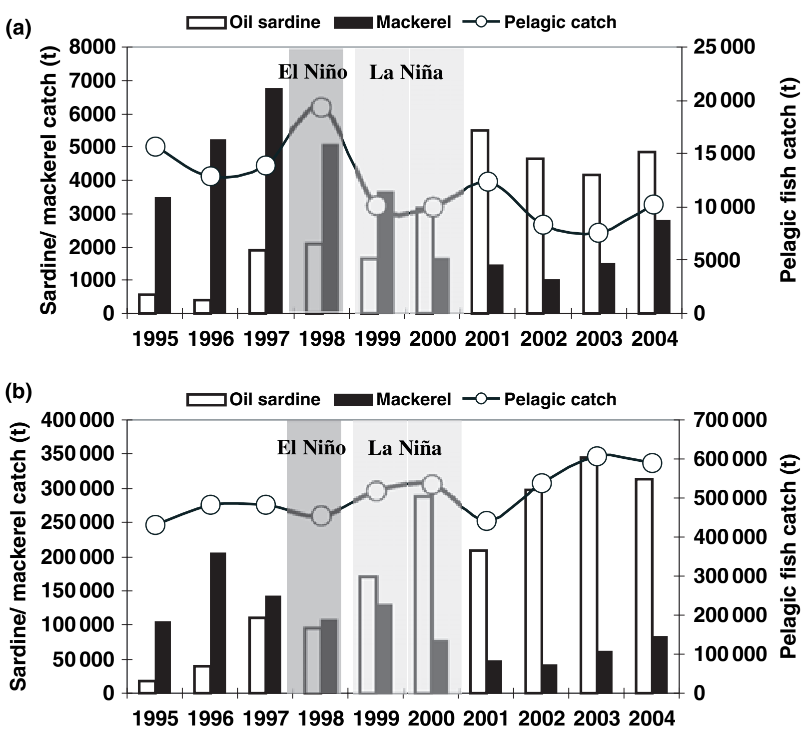


Figure 6. (a) Annual catches (t) of total pelagic fishes, Indian oil sardine (*Sardinella longiceps*) and Indian mackerel (*Rastrelliger kanagurta*) from Mangalore coast. (b) Annual catches (t) of total pelagic fishes, oil sardine and Indian mackerel from the southwest coast of India (Malabar upwelling system).

Table 3. Correlation coefficient (Pearson) between different environmental parameters from the inshore waters (stations 1 and 2 combined) off Mangalore (*$P < 0.05$; ** $P < 0.001$).

	Sea surface temperature	Sea bottom temperature	Surface salinity	Bottom salinity	Surface sigma t	Bottom sigma t	Surface dissolved oxygen	Bottom dissolved oxygen	pH	Phosphate	Nitrate	Nitrite	Silicate	Chlorophyll a	Zooplankton biomass	Rainfall	Multivariate ENSO index	Coastal upwelling index	Derived sea surface temperature
Sea surface temperature	1	0.879(**)	0.525(**)	0.109	0.402(**)	−0.562(**)	−0.18	0.286(**)	0.363(**)	−0.186	−0.096	−0.174	−0.462(**)	−0.159	−0.107	−0.171	0.277(**)	0.242(*)	0.569(**)
Sea bottom temperature		1	0.632(**)	−0.036	0.540(**)	−0.754(**)	−0.082	0.613(**)	0.585(**)	−0.451(**)	−0.176	−0.108	−0.543(**)	−0.246(*)	−0.047	−0.271(*)	0.319(**)	0.178	0.504(**)
Surface salinity			1	0.1	0.990(**)	−0.379(**)	−0.085	0.565(**)	0.478(**)	−0.228(*)	−0.205	0.005	−0.846(**)	0.019	−0.069	−0.422(**)	0.175	0.021	0.276(*)
Bottom salinity				1	0.089	0.683(**)	−0.181	−0.255(*)	−0.246(*)	0.379(**)	0.074	0.064	0.046	0.284(*)	0.107	0.017	−0.007	0.433(**)	0.319(*)
Surface sigma t					1	−0.320(**)	−0.062	0.563(**)	0.456(**)	−0.218(*)	−0.204	0.034	−0.836(**)	0.05	−0.057	−0.426(**)	0.142	−0.018	0.211
Bottom sigma t						1	−0.064	−0.607(**)	−0.586(**)	0.571(**)	0.181	0.126	0.419(**)	0.376(**)	0.112	0.204	−0.243(*)	0.148	−0.145
Surface dissolved oxygen							1	0.284(**)	0.241(*)	−0.195	−0.279(**)	−0.209	0.039	0.023	−0.017	0.15	0.085	−0.042	−0.250(*)
Bottom dissolved oxygen								1	0.599(**)	−0.636(**)	−0.377(**)	−0.21	−0.554(**)	−0.219	−0.016	−0.343(**)	0.153	−0.171	0.095
pH									1	−0.493(**)	−0.348(**)	−0.16	−0.391(**)	−0.159	−0.307(**)	−0.292(**)	0.345(**)	−0.049	0.167
Phosphate										1	0.410(**)	0.145	0.380(**)	0.230(*)	−0.059	0.350(**)	−0.107	0.268(*)	−0.092
Nitrate											1	0.418(**)	0.336(**)	0.053	0.125	0.378(**)	−0.121	0.032	0.003
Nitrite												1	0.088	0.137	0.007	−0.024	−0.07	−0.07	0.078
Silicate													1	0.073	0.013	0.506(**)	−0.031	0.107	−0.202
Chlorophyll a														1	0.081	0.043	−0.135	0.208	−0.138
Zooplankton biomass															1	−0.072	−0.325(**)	0.072	−0.023
Rainfall																1	0.088	0.118	−0.173
Multivariate ENSO Index																	1	0.048	0.156
Coastal Upwelling Index																		1	0.238(*)
Derived sea surface temperature																			1

Table 4. Correlation coefficient (Pearson) between environmental parameters (stations 1 and 2 combined) and catches of different pelagic fish groups from the inshore waters off Mangalore (*$P < 0.05$; **$P < 0.001$).

	Oil Sardine	Other Sardines	Anchovies	Thyrssa	Ribbonfishes	Carangids	Pomprets	Indian Mackerel	Seerfishes	Tunas	Cephalopods	Purse seine catch	Drift gill net catch	Total pelagic catch
Sea surface temperature	−0.177	−0.129	−0.042	−0.246(*)	−0.03	−0.278(**)	−0.244(*)	−0.298(**)	−0.343(**)	−0.260(*)	0.129	−0.391(**)	−0.380(**)	0.171
Sea bottom temperature	−0.219(*)	−0.064	0.038	−0.148	−0.099	−0.372(**)	−0.244(*)	−0.417(**)	−0.367(**)	−0.423(**)	−0.014	−0.440(**)	−0.434(**)	0.1
Surface salinity	−0.214(*)	−0.076	−0.015	−0.13	−0.352(**)	−0.456(**)	−0.410(**)	−0.512(**)	−0.272(**)	−0.457(**)	−0.006	−0.547(**)	−0.507(**)	−0.018
Bottom salinity	−0.115	−0.03	−0.058	0.165	−0.008	0.104	−0.021	−0.033	0.032	0.106	0.165	−0.042	0.006	−0.228(*)
Surface sigma t	−0.202	−0.061	−0.008	−0.101	−0.373(**)	−0.446(**)	−0.401(**)	−0.503(**)	−0.237(*)	−0.449(**)	−0.027	−0.525(**)	−0.484(**)	−0.047
Bottom sigma t	0.085	0.032	−0.059	0.215(*)	0.067	0.339(**)	0.164	0.277(*)	0.288(**)	0.377(**)	0.121	0.294(**)	0.322(**)	−0.223(*)
Surface dissolved oxygen	0.095	−0.047	0.015	0.193	0.192	0.116	0.058	0.052	0.122	0.074	−0.02	0.095	0.196	0.037
Bottom dissolved oxygen	−0.143	0.036	0.178	−0.133	−0.242(*)	−0.426(**)	−0.179	−0.569(**)	−0.265(*)	−0.485(**)	−0.211	−0.431(**)	−0.399(**)	−0.049
pH	−0.052	−0.124	−0.034	−0.008	0	−0.201	−0.239(*)	−0.262(*)	−0.108	−0.299(**)	−0.063	−0.283(**)	−0.271(**)	0.156
Phosphate	0.059	−0.11	−0.153	0.384(**)	0.05	0.037	0.007	0.076	0.095	0.260(*)	0.127	0.002	0.132	−0.07
Nitrate	0.093	0.026	0.091	0.189	0.320(**)	−0.057	0.094	−0.012	0.183	0.193	0.061	0.064	0.114	0.09
Nitrite	0.191	0.027	0.092	−0.039	0.17	−0.014	0.022	0.199	0.177	0.075	−0.062	0.212(*)	0.074	0.031
Silicate	0.186	0.003	0.048	0.331(**)	0.297(**)	0.378(**)	0.294(**)	0.393(**)	0.202	0.374(**)	0.017	0.430(**)	0.351(**)	−0.012
Chlorophyll a	0.199	−0.178	−0.245(*)	0.172	0.136	−0.044	−0.093	−0.001	−0.077	0.096	0.079	−0.062	−0.066	−0.047
Zooplankton biomass	0.024	0.177	0.189	0.034	0.016	0.152	0.023	−0.026	−0.016	−0.018	−0.066	0.146	0.06	0.001
Rainfall	−0.231(*)	−0.156	−0.311(**)	0.168	−0.074	−0.142	−0.074	−0.069	−0.345(**)	−0.001	−0.328(**)	0.11	0.126	−0.064
Multivariate ENSO Index	−0.014	−0.198(*)	−0.087	−0.015	−0.02	−0.117	−0.059	0.048	−0.13	−0.144	0.164	−0.045	−0.138	−0.048
Coastal Upwelling Index	−0.225(*)	−0.193(*)	−0.087	0.329(**)	−0.01	−0.064	−0.038	−0.014	−0.374(**)	−0.002	0.131	−0.125	−0.247(*)	0.1
Derived sea surface temperature	−0.051	−0.022	0.098	−0.230(*)	0.15	−0.162	−0.143	−0.135	−0.021	−0.025	0.187	−0.218	−0.175	0.17

Table 5. Stepwise multiple linear regression analysis between fish catch and oceanographic parameters (stations 1 and 2 combined) recorded from the coastal waters off Mangalore.

Dependent variable	Independent variable	Coefficient	SE	*F*	*N*	r^2 (%)	*P*-value
Total purse seine catch	Retained				48	48.7	0.001
	Constant	1.62×10^7	4.73×10^6				
	Sur. Salinity	-7.62×10^4	3.12×10^4	22.3			0.001
	Bot. DO	-4.32×10^5	1.19×10^5	17.3			0.001
	Bot. Salinity	-3.24×10^5	1.43×10^5	14.3			0.001
Total drift gillnet catch	Retained				48	56.0	0.001
	Constant	1.41×10^5	7.03×10^4				
	Sur. Salinity	-3.95×10^3	1.39×10^3	23.1			0.001
	Bot. DO	-2.40×10^4	5.94×10^3	15.9			0.001
	CUI	−39.86	14.33	15.7			0.001
	Sur. DO	2.83×10^4	1.29×10^4	14.0			0.001
Scombroids (mackerel, seerfishes and tunas)	Retained				45	72.8	0.001
	Constant	-6.65×10^5	6.81×10^5				
	Bot. DO	-4.23×10^5	6.28×10^4	28.9			0.001
	Sur. DO	5.69×10^5	1.63×10^5	24.3			0.001
Sardines (oil sardines and other sardines)	Retained				45	47.0	0.001
	Constant	2.35×10^6	5.42×10^5				
	Sur. Salinity	-5.83×10^4	1.65×10^4	12.5			0.001
Ribbonfishes	Retained				48	44.6	0.001
	Constant	4.23×10^4	1.35×10^5				
	Sur. Sigma t	-1.41×10^4	2.51×10^3	30.03			0.001
	Der. SST	9.15×10^3	4.24×10^3	18.50			0.001
Pomfrets	Retained				48	36.0	0.001
	Constant	5.51×10^5	1.74×10^5				
	Bot. DO	-1.86×10^4	4.01×10^3	16.12			0.001
	Bot. Salinity	-1.36×10^4	4.96×10^3	12.91			0.001
Thryssa	Retained				48	30.0	0.001
	Constant	-9.87×10^3	7.53×10^3				
	CUI	10.47	2.89	12.57			0.001
	Sur. Sigma t	8.93×10^2	3.68×10^2	9.88			0.001
Carangids	Retained				48	11.5	0.02
	Constant	7.07×10^5	2.47×10^5				
	Sur. Sigma t	-2.98×10^4	1.21×10^4	6.09			0.02

Sur, surface; Bot, bottom; Der, satellite derived.

earlier workers also failed to observe low temperature and low oxygen water in the surface along the west coast of India, because of heavy monsoon rains and large influx of fresh water from the rivers (Ramamirtham and Rao, 1973; Johannessen *et al.*, 1981).

In August, earlier workers observed the occurrence of intense upwelling off Kasaragod, located approximately 40 km south of the present sampling station (FAO, 1980; Johannessen *et al.*, 1981). Extracted CUI shows the occurrence of peak upwelling in April followed by August (Fig. 2a) from the study area. Based on the computation from ICOADS data, Bakun *et al.* (1998) reported the existence of a moderate offshore Ekman transport along the Malabar coast throughout the year. However, low Der SST in the near shore station compared to offshore station was observed during July–September with the lowest peak in August as an indication of coastal upwelling (Fig. 2b). The SST data taken from the moored buoy also clearly indicate the occurrence of peak coastal upwelling in August (Fig. 2c). These observations clearly indicate that coastal upwelling along the Mangalore coast occurs during July–September with a peak in August (Fig. 2). The signature of a peak coastal upwelling in April as observed in the extracted CUI data (Fig. 2a) was not visible in the field data collected from the inshore waters off Mangalore (Fig. 2 c). The onset of southwest monsoon generates the Somali current resulting in a general clockwise circulation in the Arabian Sea which in turn develops into a relatively strong southerly current at the surface levels along the west coast of India (FAO, 1980; Johannessen *et al.*, 1981). Upwelling along the Mangalore coast during July–September is mainly caused by this strong southerly current, with perhaps some support from local wind.

The above physical changes were reflected in the concentrations of nutrients (nitrate, phosphate and silicate), bottom chl a and zooplankton biomass during the same period (Table 1). Coinciding with upwelling a general increase in nutrient concentrations and chl a content was observed during August–October from the inshore waters off Mangalore (Figs 3 and 4). These observations were in agreement with the earlier studies reported from the west coast of India (Banse, 1959; Ramamirtham and Rao, 1973; Johannessen *et al.*, 1981; Rao *et al.*, 1992; Muraleedharan and Prasannakumar, 1996; Marra and Barber, 2005; Smith and Madhupratap, 2005). Earlier workers reported high nutrient concentrations and primary production from the inshore waters off Mangalore during August–September (Bhargava *et al.*, 1978; de Souza *et al.*, 1996; Lierheimer and Banse, 2002). During September–November low LAC was observed as compared with all other months, indicating high turbidity mainly due to phytoplankton growth (Fig. 4) as reported by Marra and Barber (2005). Relatively higher zooplankton biomass was observed in the present study in October immediately after the upwelling period (Fig. 4). High zooplankton count from the coastal stations off Mangalore was also reported by earlier workers as a result of coastal upwelling (Smith and Madhupratap, 2005). Results of the present study indicate that coastal upwelling occurs during July–September along Mangalore coast, which results in high biological productivity (Figs 3 and 4). The general pattern of the changing oceanographic parameters is repeated year after year with varying intensities (Table 1).

Upwelling and pelagic fish catch

The importance of upwelling is the associated availability of large concentrations of commercially important pelagic fishes such as oil sardine, mackerel and whitebaits (anchovies) in the inshore waters (Rao *et al.*, 1992). During upwelling, the phytoplankton bloom is followed by increased zooplankton abundance attracting commercially important fishes. Normally, record fish catch was reported during upwelling and the subsequent periods from the west coast of India (Devaraj and Vivekanandan, 1999). Correlations observed between bottom sigma t and bottom DO (indicators of upwelling) with fish catch indicate that coastal upwelling during July–September support a very good pelagic fishery (Table 4). Nearly 70% of the pelagic fish catch from Mangalore was obtained during September–December, during or immediately after the upwelling season (Fig. 5). Usually, the peak pelagic fish production from the Malabar coast is recorded during August–December, during or immediately after the upwelling season (Banse, 1959; FAO, 1980; Johannessen *et al.*, 1981; Yohannan and Abdulrahiman, 1998; Prathibha and Bhat, 2003; Prathibha and Gupta, 2004). Stepwise multiple linear regression analysis of pelagic fish catch and catches of scombroid fishes (mackerel, seerfishes and tunas), sardines, ribbonfishes, pomfrets and thryssa with oceanographic parameters also indicates that variations in the catches are influenced by salinity, sigma t and DO (Table 5), which are directly related to the time, duration and intensity of upwelling. Catches of scombroid fishes were significantly related to cold SST, while such relationships were not observed for sardines and anchovies (Table 4).

The present study shows that upwelling triggers some favourable changes in the physical, chemical and biological conditions in the inshore waters which attract pelagic fishes in large numbers for feeding and spawning (Table 5). During upwelling, some fish populations move into the shallow surface waters while the others move offshore, away from the centre of strong upwelling to avoid cool and low oxygen zone (Banse, 1959). Mortality of demersal fishes has been reported even from the Mumbai coast (northwest coast of India) coinciding with intense upwelling due to very low DO content in seawater (Carruthers *et al.*, 1959; Singh, 2005). Even the disappearance of demersal fishes from a rather broad belt parallel to the southwest coast of India has been reported as a result of upwelling (Banse, 1959). Pelagic fishes like mackerel, oil sardine and whitebaits temporarily avoid the areas of intense upwelling (oxygen poor water) and tend to concentrate into dense schools close to the surface along the inshore waters, affording good catches. With the progress of upwelling along the southwest coast of India, pelagic shoals spawn intensely during June–September when there is maximum availability of food for larvae (Devaraj and Vivekanandan, 1999; Prathibha and Bhat, 2003; Prathibha and Gupta, 2004). Hence, during upwelling the abundance of pelagic fishes in the inshore waters increases as they congregate in large numbers for feeding and/or spawning. Californian sardine and Peruvian anchoveta reportedly spawn right in the coastal upwelling zones (Wooster and Reid, 1963; Forsbergh and Joseph, 1964). Fishing activities by mechanized boats along the Karnataka coast during the peak monsoon season (June–August), which also coincide with the peak upwelling (August), are banned by the state government mainly to protect the spawning stock.

Physical processes and fluctuations in the pelagic fishery

Oil sardine and mackerel have traditionally been the mainstay of the marine fisheries of Malabar upwelling region, and the peak production period for the two major pelagic species from the Mangalore coast is during August–October coinciding with or immediately after upwelling (Prathibha and Bhat, 2003; Prathibha and Gupta, 2004). Like many other tropical pelagic fishes, these two fishes have shown population crashes and sudden recoveries, and a strong inverse relationship (Devaraj and Vivekanandan, 1999). A general increase in mackerel catch was observed from Mangalore in 1997, and by 1998–99 it showed a declining trend (Fig.6a). By 1999–2000, the mackerel fishery was totally collapsed and the oil sardine fishery showed a revival, and a more or less similar trend was observed from the entire Malabar upwelling system (Fig. 6b). In 1999 very low pelagic fish landings were observed at Mangalore resulting in *fish famine* (Muthiah *et al.*, 2000).

The El Niño Southern Oscillation (ENSO) is now recognized as a climatic event of global significance and this periodic variation in oceanic and climatic conditions influences the abundance and distribution of several marine organisms (Bakun and Broad, 2003). The strongest El Niño of the 20th century occurred in 1997–98, closely followed by a strong La Niña in 1998–2000. We have observed significant positive correlations between the ENSO events (MEI) and seawater temperature from the study area (Table 3). The Indian Ocean response to ENSO is well known to be a basin-scale surface warming/cooling with a lag of about a season, whereas the subsurface response appears to be simultaneous, forced by ENSO-related wind anomalies (Yu and Lau, 2005).

The closely occurring El Niño and La Niña events (or vice versa) with very short intervals between them (1–2 months) may be acting as triggering mechanisms for regime shifts in the marine ecosystem (Krishnakumar *et al.*, 2006). During the peak of the El Niño event in 1998 and during the transition period towards the La Niña event in 1999, a general increase in SST and weakening of coastal upwelling was observed along the coast (Table 1). Extreme oceanographic events such as strong and sustained warming followed by enhanced cooling were also recorded in the Southern Benguela during the 1999–2000 summer season (Roy *et al.*, 2001). The sudden fluctuations in SST, sea-level pressure and scalar wind associated with these extreme climate transitions resulted in a regime shift in the Malabar upwelling system during 1997–98 (Krishnakumar *et al.*, 2006).

Scombroid fishes like mackerel are very temperature sensitive as they maintain higher body temperature than the ambient temperature (Yohannan and Abdulrahiman, 1998; Kitagawa *et al.*, 2006). Hence, the extreme oceanographic events of 1998–99 might have adversely affected the spawning and recruitment of most of the scombroid fishes (tunas, mackerel and seerfishes) which ultimately resulted in the failure of pelagic fishery along the Mangalore coast in 1999–2000 (Figs 5 and 6a). In Peru, high squid catch rates of early 1990s declined during the cold La Niña event which preceded the exceptional 1997–98 El Niño event (Yamashiro *et al.*, 1998). During 1995–1999 mackerels were the dominant group in the fishery compared to oil sardine and subsequently during 2000–2004 the reverse order was observed (Fig. 6). Alternating patterns of abundance between one species of sardine (or sardinella) and one species of anchovy have been observed in most upwelling ecosystems during recent decades (Cury *et al.*, 2000). The collapse of mackerel fishery in 1999–2000 due to extreme oceanographic events of 1998–99 might have helped the successful recruitment and recovery of oil sardine fishery along the entire southwest coast of India (Fig. 6). Sardines have often experienced improved reproductive success during El Niño years when compared to other species (Arntz and Fahrbach, 1996). Skud (1982) observed that dominant species respond to environmental factors, and subordinate species respond to the abundance of the dominant one. Based on two-species competition models, Ferrie‘re and Cazelles (1999) showed that phases of extremely low abundance followed by short peaks in abundance could arise in a simple community model as a result of competitive interactions within and between species. The Malabar upwelling system was generally dominated by oil sardine or mackerel, and most often only one of the two is dominant at any particular time. Alternating patterns of abundance between these species have been observed in the past (Devaraj and Vivekanandan, 1999) as reported from other upwelling systems of the world (Crawford *et al.*, 1987). The peak spawning and recruitment of both oil sardine and mackerel occur during June–August (Prathibha and Bhat, 2003; Prathibha and Gupta, 2004) and they share almost similar habitat in the Malabar upwelling system. Increased mortality rate of eggs and larvae of oil sardine owing to predation by adult mackerel can be considered a likely cause of a severe reduction in sardine biomass during certain years along the coast when mackerels were the dominant species.

In conclusion, the coastal upwelling along the Mangalore coast occurs during July–September with a peak in August every year with varying intensity. The seasonal upwelling supports coastal productivity, zooplankton production and multi-species and multigear pelagic fishery dominated by oil sardine and mackerel. Significant correlations were observed between the SST measured from the inshore waters and satellite-derived SST values indicating that inshore data are reflecting the general trends in the oceanographic conditions of the area. Total pelagic fish catch in purse seine and drift gill net, and catches of fishes such as thryssa, carangids, mackerels, seerfishes and tunas showed significant positive correlations with bottom sigma t and significant negative correlations with bottom DO (upwelling indicators). Significant positive correlations were observed between the ENSO events (MEI) and seawater temperature from the study area. The extreme oceanographic events associated with the strong cold La Niña event which preceded the 1997–98 El Niño event, one of the strongest of the 20th century, were responsible for the collapse of the pelagic fishery, especially the mackerel fishery along the southwest coast of India. Coinciding with the collapse of the mackerel fishery, oil sardine populations have revived during 1999–2000 all along the coast. Tolerance of oil sardines to El Niño/La Niña events and the low predatory pressure experienced by its eggs and larvae due to the collapse of the mackerel population might have resulted in the oil sardine population revival. Alternating patterns of abundance observed between these two species is comparable with the pattern observed in the abundance of pelagic fishes such as sardine, horse mackerel, bonito, anchovy and chub mackerel from other major upwelling ecosystems of the world.

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