Journal of Coastal Research	28	1A	105–113	West Palm Beach, Florida	January 2012

Remotely Sensed Chlorophyll: A Putative Trophic Link for Explaining Variability in Indian Oil Sardine Stocks

Grinson George[†], Bharathiamma Meenakumari[‡], Mini Raman[§], Srinivasa Kumar[††], P. Vethamony[†], M.T. Babu[†], and Xivanand Verlecar[†]

[†]National Institute of Oceanography
Dona Paula
Goa 403 004, India
grinsongeorge@yahoo.co.in

[‡]Central Institute of Fisheries Technology
Matsyapuri P.O.
Kochi 682 029, India

[§]Space Applications Centre
Ambawadi Vistar P.O.
Ahmedabad 380015, India

[††]Indian National Centre for Ocean Information Services
Hyderabad 500 055, India

www.cerf-jcr.org

www.JCRonline.org

ABSTRACT

GEORGE, G.; MEENAKUMARI, B.; RAMAN, M.; KUMAR, S.; VETHAMONY, P.; BABU, M.T., and VERLECAR, X. 2012. Remotely sensed chlorophyll: a putative trophic link for explaining variability in Indian oil sardine stocks. *Journal of Coastal Research,* 28(1A), 105–113. West Palm Beach (Florida), ISSN 0749-0208.

The landing of Indian oil sardines, *Sardinella longiceps* Valenciennes, 1847, along the southwest coast of India is highly variable. A few physical parameters and processes correlated with sardine landing could not establish a flawless connection and explain the phenomena of interannual variability. Earlier research has indicated that the probable appearance and disappearance of sardines is an active movement in search of food and favourable conditions. But no specific study has been carried out to explain the variability of sardine catch based on chlorophyll availability on a synoptic scale. An attempt is made in this study to correlate variability in chlorophyll *a* with sardine landings along the waters of the southwest coast of India. We have estimated monthly averaged surface phytoplankton biomass along the waters of the southwest coast of India from the shoreline up to the 200-m isobath for 10 years from *SeaWiFS* ocean-colour data. This estimation is compared with the biological calendar of Indian oil sardines. The average chlorophyll *a* for the bloom initiation month (1998–2006) matches very well with oil sardine landings. The results imply that the concentration of chlorophyll during the bloom initiation month can be used to assess the quantity of fish that recruit into the population. Finer scale spatial variations in the chlorophyll along the coastal waters help in deciphering the migratory pattern of sardines during their active breeding phase. This study shows that 39% of interannual variability in fish landings is related to availability of chlorophyll *a* during the bloom initiation month.

ADDITIONAL INDEX WORDS: *Upwelling, fisheries, ocean colour, phytoplankton, southwest coast of India.*

INTRODUCTION

The interannual variability in the landings of Indian oil sardines, *Sardinella longiceps* Valenciennes, 1847 (hereafter called sardines), has been explained as an outcome of seasonal variability in the marine environment (Hornell, 1910a). Based on the physical parameters and processes such as sea surface temperature, rainfall, sea level, and upwelling, indices relating to total sardine catch with environmental factors are formulated (Longhurst and Wooster, 1990). These indices, formulated based on a correlation between sardine catch and rainfall, wind stress, and sea level, failed with time as a result of large variability in landings and correlated factors (Madhupratap, Shetye, and Nair, 1994). Failed correlations should not be dismissed summarily on the assumption that data were faulty, the criteria for comparison were ill founded, or the relation spurious; rather, the cause and effect should be explored in detail to explain the phenomena (Skud, 1983). There are several interrelated factors that are responsible for the recruitment of fishes and their abundance. The estimation of all environmental variables responsible for this is perhaps a difficult task. Surplus models, recruitment models, and similar time series models globally were having limited success. Changes in physical factors affecting marine food-web based studies gained more relevance because of this. The concept of fish stock assessment rather concentrates now on predicting the expectant biomass based on ambient environment changes that have a trophic link (ICES, 2000; NRC, 1999).

Biological studies suggest an extended spawning period from May to September for sardines (Antony Raja, 1969; Hornell, 1910a; Hornell and Nayadu, 1924; Prabhu and Dhulked, 1970). After occlusion from the egg, larval development is rapid in sardines, with yolk sac absorption taking place in 3 days (Nair, 1960). These larvae will undergo their critical first feeding period almost immediately after yolk absorption (Hunter, 1981; Lasker, 1975; Lasker, 1981). The earliest spawned surviving individuals will be recruited to the fishery by the end of the spawning period, which in turn determines the yearly landings. Thus, larval ecology decides the later abundance of recruits to the fishery. Collating various information cited on young, juvenile, and adult sardines and their feed during spawning period (Devanesan, 1943; Hornell, 1910a; Hornell and Nayadu, 1924; John and Menon, 1942; Van der Lingen, 2002), we can confirm that the larvae are predominantly

DOI: 10.2112/JCOASTRES-D-10-00070.1 received 10 May 2010; accepted in revision 17 August 2010.
© Coastal Education & Research Foundation 2012

surface and column feeders, with phytoplankton forming a major group, dominated by diatoms like *Fragillaria oceanica*, *Pleurosigma* sp., and *Coscinodiscus* sp. (Kuthalingam, 1960; Nair, 1959).

Sardines feature a fine-meshed filtering apparatus in their gill rakers (Van der Lingen, 2002), with more than 130 gill rakers on the lower part of the gill arch. They are able to filter smaller particles. Therefore, they thrive on very tiny particles that may occur in the coastal waters through which they continually migrate and these tiny particles (phytoplankton), predominated by diatoms occur throughout their range of distribution (Bakun and Broad, 2003). Moreover, sardines are serial batch spawners (as are anchovies, sprats, tunas, *etc.*). They spawn for several days during extended spawning seasons. The fact that sardines employ a combination of migrating capabilities, ability to feed on very small particles, and serial spawning habits, underlines the importance of studying sardines along with their feed availability during the spawning season.

The Hjort-Cushing hypothesis (Cushing, 1974; Cushing 1990; Hjort, 1914) refers to the critical first feeding period and the timing of the spring phytoplankton bloom. In the case of sardine larvae, the bloom that decides its biology is an upwelling-induced bloom, the bloom initiation time and intensity is the only variation that could account for changes in the food supply to sardine larvae. These variations in food supply between different years will be reflected in the larval development and further recruitment of sardines into the fishery. This aspect was not examined in the earlier studies on sardine landing variability.

Sardines perform a normal migration from offshore to coastal waters and *vice versa* coinciding with the customary wind conditions (Hornell, 1910b). A gradual increase in temperature within the range of 26 to 28°C is favourable for the inshore migration of the juveniles, and with increasing temperatures (above 29°C) during March to May they disappear to deeper waters (Chidambaram, 1950). The specific gravity of water, which is above 1.023 during March to May, also promotes the disappearance of the shoals. The shoreward migration of spawners during monsoon months and their outward migration to deeper waters during postmonsoon months is for feeding (Nair 1959) on the luxuriant growth of phytoplankton that blooms up during the onset of monsoon (Chidambaram, 1950; Hornell, 1910b; Hornell and Nayudu, 1924; Nair, 1953). The longitudinal migration either way is an excursion from offshore to inshore waters and *vice versa* due to availability of food and favourable hydrographic conditions (Devanesan, 1943).

The shoals start disappearing from the northern region first, and then from the southern Malabar area. From April to September, the shoals of spawners and juveniles migrate from offshore to inshore all along the west coast following the onset of bloom (Antony Raja, 1972). This observation suggests a northward migration of sardines steadily during southwest monsoon period and retrogression from north to south in the northeast monsoon phase (Figure 1). Lack of continuous seasonal information to characterize synoptic scale variability in chlorophyll concentration of the region was an impediment to verifying the food availability between different years to explain the interannual variability in sardine landings. Also, it

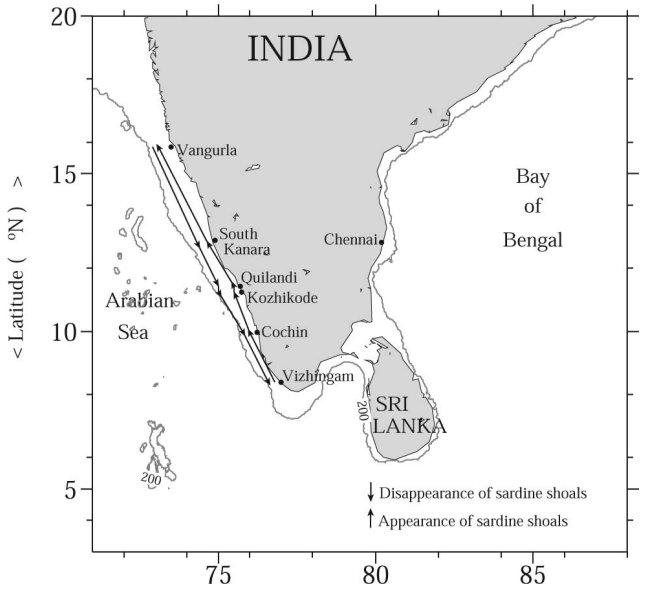

Figure 1. Schematic representation of progression of sardine shoals from Vizhingam to Vangurla (Chidambaram, 1950; Hornell, 1910b) and their departure in the reverse direction (Panikkar, 1952).

was not feasible to study the spatial and temporal variations in chlorophyll concentration in these areas because of nonavailability of *in situ* data. With the advent of remote sensing, however, this was possible with ocean-colour data. Platt, Yaco, and Frank (2003) applied remotely sensed ocean-colour data as direct evidence for a putative trophic link and suggested it as an important link in future analyses of dwindling fish stocks. Time series phytoplankton cycle information derived from satellite data can be used to construct a variety of ecological indicators of the pelagic system useful in ecosystem-based management (Platt *et al.,* 2009).

Remotely sensed sea surface temperature (SST) and ocean-colour images reveal eddies and fronts. These features frequently coincide with areas where fish species aggregate as a result of enhanced phytoplankton biomass and primary production, which in turn is linked with changes in nutrient supply or mixed-layer depth. Since higher plant biomass is associated with zooplankton, one might expect to add supplementary information on fish stock distribution from ocean-colour pigment fields. Colour patterns were useful in differentiating the relevance of food over other environmental factors like temperature in fish aggregation, offering better information regarding the location of Albacore tuna (Laurs, Fiedler, and Montgomery, 1984). It was originally assumed that tuna prefer to reside within certain limited temperature ranges, which explains their tendency to aggregate at a temperature front. In instances where colour and SST fronts were spatially separated, they found that tuna actually tend to aggregate on the clear side of a colour front.

Ocean-colour pigments are relevant in detecting a bloom. Fragmented observations in the waters of the southwest coast of India hypothesized two seasonal blooms: (i) upwelling blooms, coinciding with the arrival of prespawning adults

during May–June, and (ii) winter blooms, in September–October, coinciding with the main fishery for juveniles (Bensam, 1964). For sardines, a filter feeder, the amount of food ingested depends on chlorophyll concentration as well as copepods present in the ambient waters; better availability of food is expected in chlorophyll-rich waters. In the present study, variability in chlorophyll along the waters of the southwest coast of India had been quantified from satellite data and related to annual variability in the sardine landings. The synoptic scale spatial and temporal changes in chlorophyll *a* were useful in explaining the appearance and disappearance of sardine shoals along the coastal waters.

STUDY AREA

The entire sardine fishing ground off the southwest coast of India, extending from 5°N to 15°N, was considered for the study. The seaward limit of the study area extends up to the outward edge of the continental shelf (200-m isobaths) (Figure 2). Figure 1 explains the schematic representation of sardine movement, but the actual dwelling area of sardines is segregated in the satellite image by following the depth contour as shown in Figure 2. The spatial extent of the study area was determined in concurrence with earlier observations (Longhurst and Wooster, 1990). The coastal zone current characteristics and environmental setting described in an earlier study (Dinesh Kumar and Srinivas, 2007) also defines this study area as a narrow continental shelf domain with strong upwelling and downwelling signatures.

METHODS AND MATERIALS

We used data on marine fish landings in India for the period 1985–2006 published by the Central Marine Fisheries Research Institute (Srinath *et al.,* 2006). We collected 316 samples of sardines from the major sardine landing centre at Cochin for length and weight measurements during the study period. Sardine catch is dominated by 0-year class individuals, *viz.,* measuring ≤14 cm total length (Dayaratne and Gjøsaeter, 1986), spawned during the earlier spawning period starting from May (Table 1). The entire breeding activity of sardines is confined to coastal waters with an active artisanal fishery (ring seines, purse seines, and shore seines), which responds with vital fishing efforts depending on fish availability. Mechanized trawlers in the coastal waters are restricted to a period of 45 days starting from 15 June. The artisanal sardine fishery comprised of motorized and nonmotorized country crafts is active during this period also. Decrease in sardine fishery within the study area did not result in heavy landings elsewhere, thus ruling out the possibility of migration of sardines from the study area. Hence, it is assumed that the sardine landings within the study area are representative of stock abundance (Longhurst and Wooster, 1990). This assumption holds good since the present study is restricted to a time period when there was relatively little change in the composition of fishing crafts and gears.

Monthly averaged chlorophyll maps at 9-km spatial resolution derived from *sea-viewing wide field of view sensor* (*SeaWiFS*) satellite data for the period January 1998–December 2006 was downloaded from the website http://oceancolor.gsfc.nasa.gov/cgi/l3 (NASA, 2002). The optically sensitive constituents such as suspended solids and yellow substance in CASE 2 waters in this region (Menon, Lotliker, and Nayak, 2005; Menon *et al.,* 2006) were tackled during extraction of chlorophyll *a* from the composite image using an algorithm for masking turbid waters (Bricaud and Morel, 1987). A trend between sardine landing and chlorophyll *a* during the study period was found using the polynomial trend line, which gave the best fit. Coefficient of determinant was worked out for quantifying the variability in sardine landings and chlorophyll *a* during the bloom initiation month.

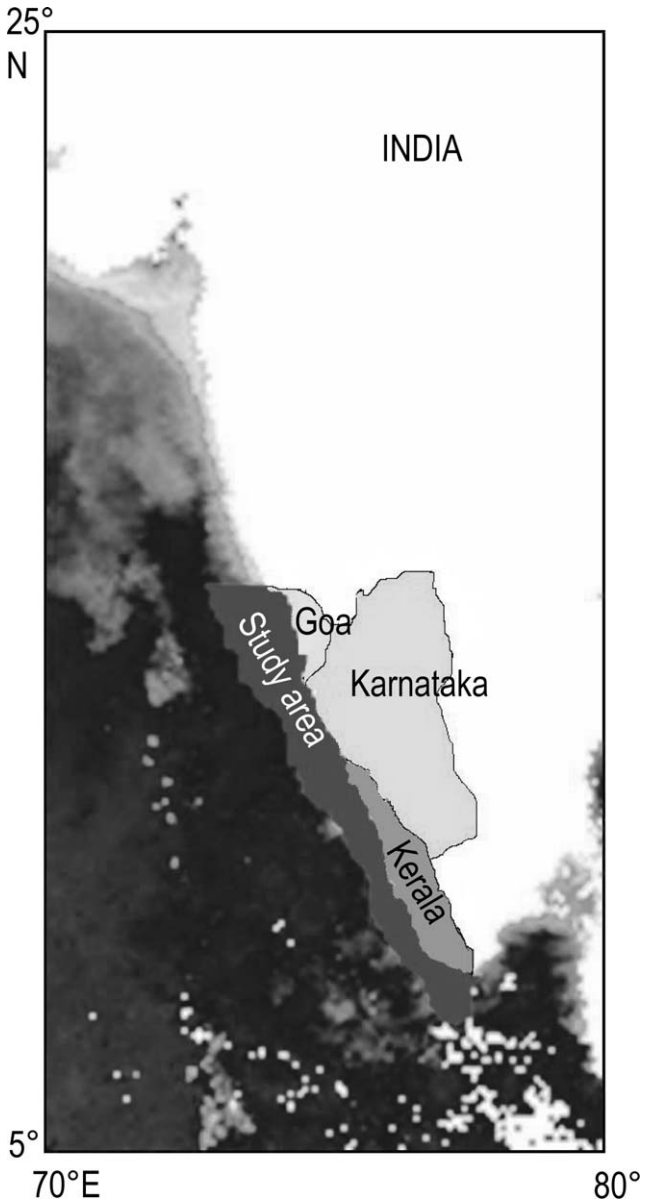

Figure 2. Study area and three major sardine landing maritime states displayed in the satellite image from *SeaWiFS*.

Table 1. *Average length and weight measurements of 316 random sardine samples from a major landing centre.*

Total Length (cm)	Fork Length (cm)	Std Length (cm)	Gill Girth (cm)	Max Girth (cm)	Mouth Diameter (cm)	Weight (g)
11.64±2.57	10.24±2.28	9.64±2.15	1.77±0.49	1.90±0.52	0.88±0.39	12.58±10.96

RESULTS

The variability in sardine landings, chlorophyll variability, and chlorophyll during upwelling bloom initiation were examined for explaining the interannual sardine variability and sardine migration in the coastal waters.

Sardine Landing Variability

Sardine landing data reveal interannual variability since 1925 with an increasing trend during the study period (Figure 3). Sardine landings showed a drastic decline in 1985 and 1994, which alternated with very high landings of Indian mackerel during these two years. Marine fisheries of the southwest coastal waters are characterized by the predominance of pelagic fish resources dominated by sardines and Indian mackerel (*Rastrelliger kanagurta*), which supports the western Indian Ocean's largest coastal pelagic fishery. Alternating patterns of abundance between these species could have been the reason for these two major falls.

The landing pattern of these two species (Figure 4) along this coast could be compared with the alternating patterns of abundance between sardines and anchovies observed in other upwelling areas of the world. The study period (1998–2006) was a sardine dominant period (period of high sardine and low mackerel). Figure 4 shows a sardine revival phase, and the period reflects an ideal phase for the study of sardines without interference from the mackerel fishery.

Chlorophyll Variability in the Study Area

Observed chlorophyll in the study area during 1984–2006 ranged from 0 to 6.25 mg/m^3 with a mean value of 0.32 mg/m^3 and a standard deviation of 0.59 mg/m^3, indicating that the chlorophyll available in the coastal waters was highly variable. *SeaWiFS* chlorophyll values in the study area remain within the maximum–minimum limits of *in situ* chlorophyll (Figure 5) except for the month of August 2002 (6.557 mg/m^3), which may be due to an unusually high upwelling bloom.

The chlorophyll *a* concentration remained high from May to October, but the peaks varied from year to year. Periods of higher chlorophyll *a* concentration match with the active breeding period of sardines (Figure 6). The biological calendar of sardines (Figure 6) commences with the entry of spawners in May, followed by fresh juveniles during July–August. During September to December, the adults occur in reduced numbers, and the adult population is replaced by large shoals of juveniles. They, however, get numerically reduced in January–February and subsequently disappear, reappearing during May–July. With the onset of premonsoon showers or southwest monsoon rains, they move toward the inshore waters with the gonads in various stages of ripening. The spent and resting adults, on the other hand, appear in small quantities along with their juveniles during January–February, disappear in the following months along with the juveniles, and reenter for their second spawning along with the virgin spawners. For numerically representing the average chlorophyll, which determines the active breeding phase, chlorophyll

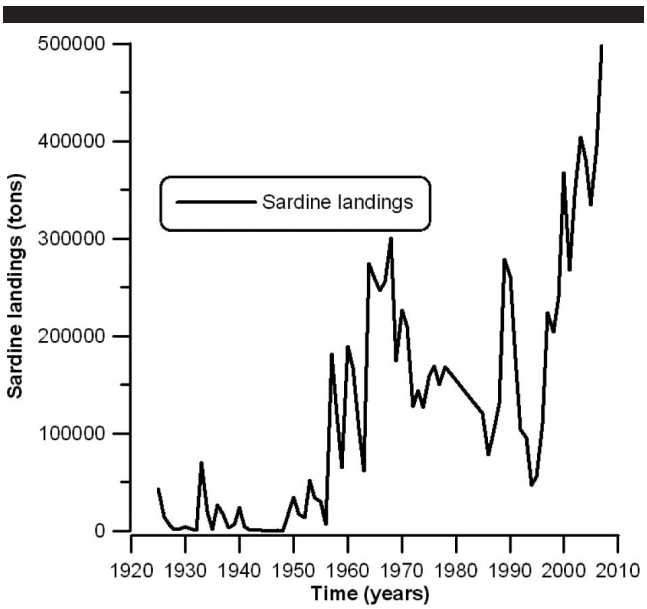

Figure 3. Interannual variability in sardine landing since 1925.

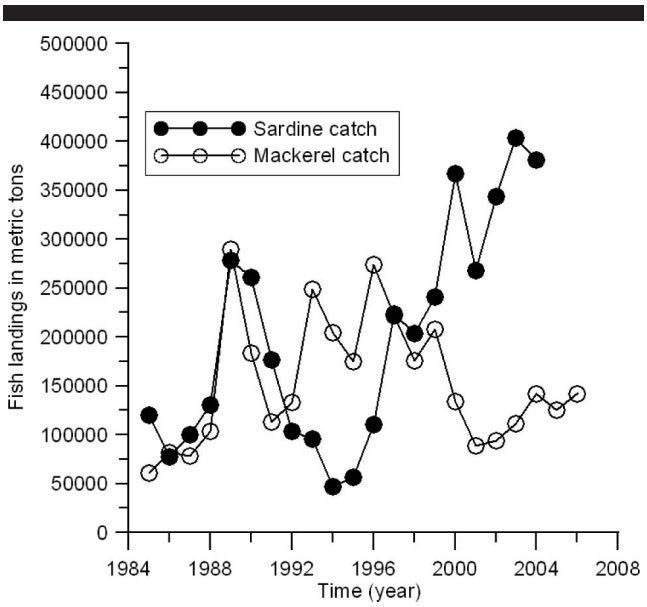

Figure 4. Comparison between sardine and mackerel landings (1985–2006).

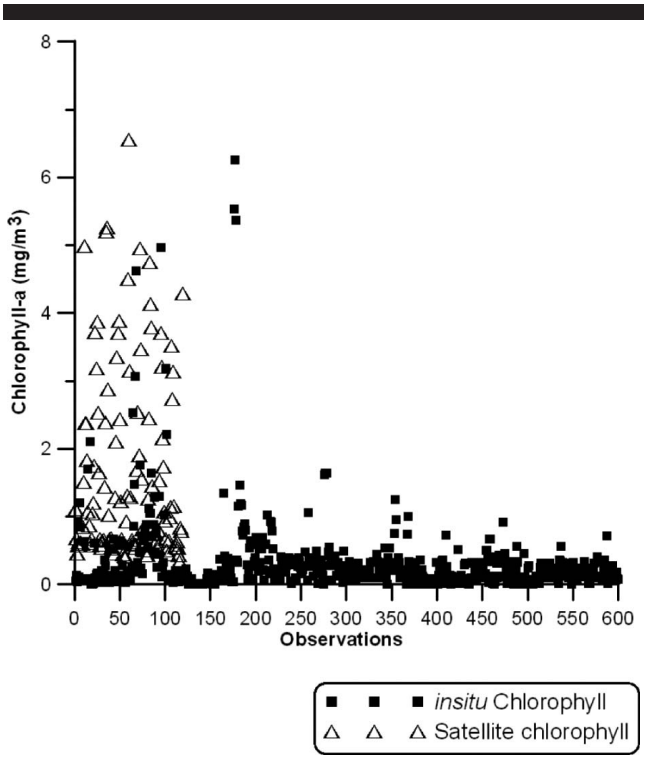

Figure 5. Observed chlorophyll during 1984–2006 for a comparison with monthly *SeaWiFS* chlorophyll values retrieved for the study area (data source: Indian Oceanographic Data Centre, NIO, Goa).

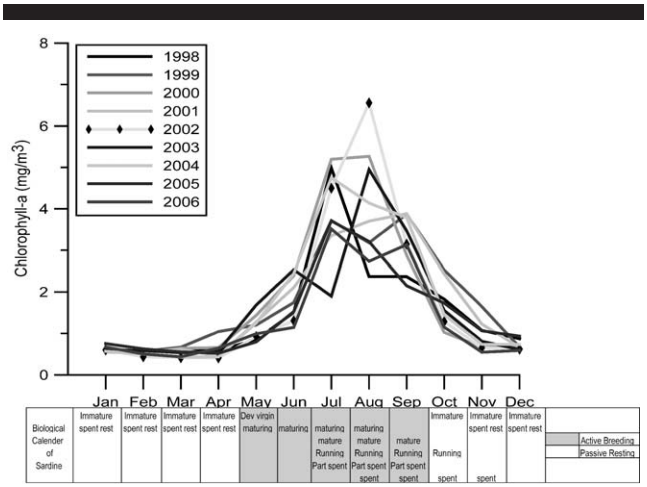

Figure 6. Monthly satellite chlorophyll concentration for the period 1998–2006 in relation to the biological calendar of sardines. Grey coloured columns in the table show the active breeding phase, and remaining columns show the passive resting phase.

concentrations ≥1 mg/m^3 can be a threshold mark as calculated for the entire study period (Table 2). The average monthly chlorophyll *a* values in May reach a threshold level of above 1 mg/m^3 (Table 2). We have examined the suggestion (Madhupratap *et al.,* 1994) that a mismatch *viz.* an early spawning and a time lag in development of food (through a break in monsoon or upwelling) would be detrimental to recruitment.

Sardine Landings *vis-à-vis* Chlorophyll during Bloom Initiation

We tested the null hypothesis that the variability in sardine landings was independent of fluctuations in average chlorophyll concentration during bloom initiation month. We could confirm that 39% variability in sardine landings was related to average chlorophyll *a* concentration during the bloom initiation month. Figure 7 clearly depicts an increase in chlorophyll *a*, which is associated with high landings (match), and a decrease with reduced landings (mismatch), except for the year 2002. Since chlorophyll availability cannot be the only factor affecting the sardine biomass, there are other factors also affecting sardine biomass. But the availability of chlorophyll-rich water in the bloom initiation month will result in better survival of sardine larvae. Early food availability provided by an upwelling bloom, indicated as higher chlorophyll *a* in the chart, is reflected in increased sardine landings, since many of the total larvae recruited were able to survive because of surplus food. Even though *SeaWiFS* data are short, the data do indicate a definite link between chlorophyll *a* and sardine landings. Early initiation of phytoplankton bloom may not be sufficient to ensure a higher survival of sardine larvae in the same year, but it is definitely a necessary condition as envisaged in the study. This was reflected in the sardine landings, since the fishery was dominated by 0-year class fishes (Table 1). An unprecedented blooming was observed in 2002 when chlorophyll *a* values were the highest during the study period. Thus, the year 2002 was exceptional to have a low chlorophyll in May followed by an unanticipated high chlorophyll period (Figure 6). Since the spawning period of sardines is protracted, high survival of later spawned larvae in the years when bloom development delayed could make up for poor survival of early spawned larvae.

Gut analysis shows that, being filter feeders, sardines ingest the particulate phytoplankton and zooplankton available in its ambient waters. The phytoplankton bloom (mostly diatoms and dinoflagellates) results in better productivity enhancing the microzooplankton and zooplankton in the Arabian Sea (Madhupratap *et al.,* 2001). This is evident in this study, since zooplankton biomass observations in the study area also show several peak values during the months (September–December) following increased chlorophyll *a* (Figure 8).

Seasonal Appearance of Sardines and Chlorophyll

The present study clearly reveals the synoptic scale temporal changes (1998–2006) with respect to chlorophyll availability in the three prominent sardine landing maritime states (Figure 9) of India—Kerala, Karnataka, and Goa. Figure 9 illustrates how chlorophyll-rich waters appear earlier in the south (Kerala coastal waters) and move gradually northward, and the pattern reverses during the retrieval of monsoon. The changing intensities of chlorophyll in the coastal waters (area under the graph for each year in Figure 9) of the states describe

Table 2. *Estimation of monthly average chlorophyll during the study period indicating a higher value above the threshold during the active breeding season.*

Month	Average Chlorophyll (mg/m³) during 1998–2006	Life Stage of Sardines
January	0.618333	immature, spent resting
February	0.540444	immature, spent resting
March	0.546444	immature, spent resting
April	0.593778	immature, spent resting
May	1.158222	maturing, developing virgins
June	1.858333	maturing
July	3.957667	maturing, mature, running, partially spent
August	4.011889	maturing, mature, running, partially spent, spent
September	3.187778	mature, running, partially spent, spent
October	1.666556	immature, running, spent
November	0.937333	immature, spent resting, spent
December	0.708	immature, spent resting

the possible appearance and disappearance of sardine shoals during the active breeding phase.

The variation in quarterly sardine landing in each maritime state (Figure 10) is proportional to the changing intensities of chlorophyll in the respective coastal waters. This shows an aggregation response of sardine larvae to chlorophyll concentrations.

DISCUSSION

There was very little change in the fishing effort during the study period, with 238,772 fishing crafts in 2005 (CMFRI, 2005) in comparison with 239,000 crafts in 1997 (Sathiadhas, 2006). Thus, the increase in sardine landings during the study period, despite steady fishing effort, indicates a direct trophic link as a reason for the revival of the fishery. Sardines possess a fine branchial apparatus and feed predominantly by filter feeding on phytoplankton and zooplankton in ambient waters. Chlorophyll *a* in a given area, as an index of phytoplankton biomass, is capable of assessing the food availability for sardines.

Summer chlorophyll *a* concentration estimates from the study area are reported to be 0.1 to 5 mg/m³ for a normal distribution and can be very high, from 5 to 10 mg/m³, during bloom period (Raghavan *et al.,* 2006). Heavy blooms of *F. oceanica* were observed in 1949 and 1953 during the rebuilding of sardine stock after the population crash of the 1940s (Nair, 1953; Nair and Subrahmanyan, 1955), suggesting and strengthening the view that the advantage of an early bloom is that more larvae will survive which otherwise would have perished due to lack of food.

The life cycle of sardines depicted a clear picture of an active breeding season from May to September. This coincides with

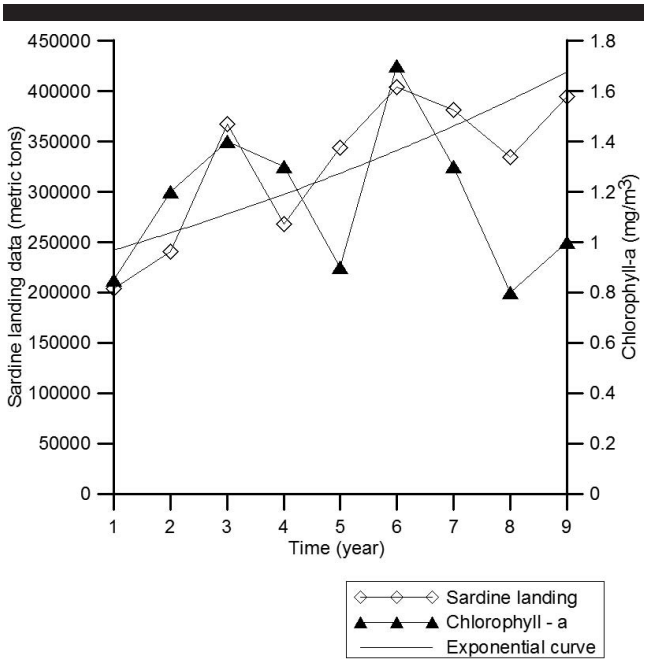

Figure 7. Comparison between chlorophyll *a* concentration during bloom initiation month and sardine landing.

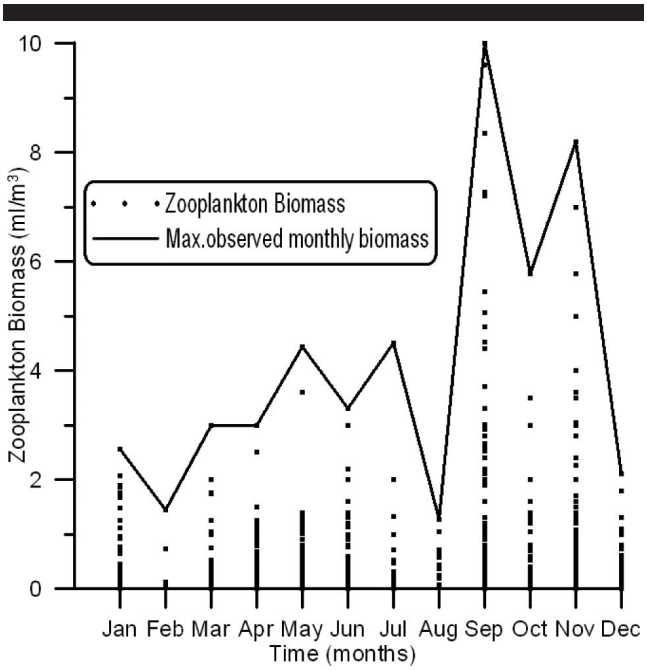

Figure 8. Monthly observed zooplankton biomass during 1984–1996 (data source: Indian Oceanographic Data Centre, NIO, Goa).

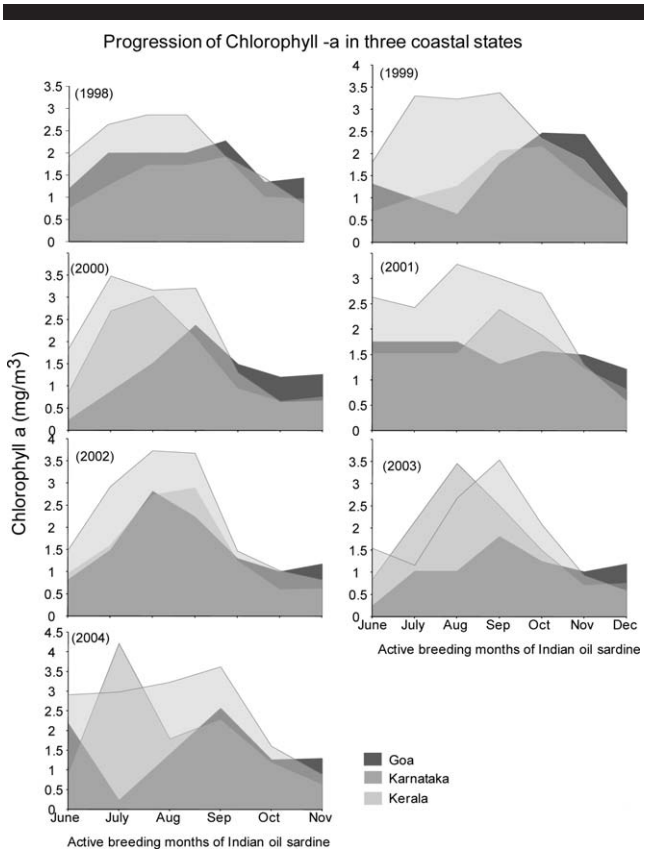

Figure 9. Progression of remotely sensed chlorophyll in the three maritime states during the active breeding season of sardines.

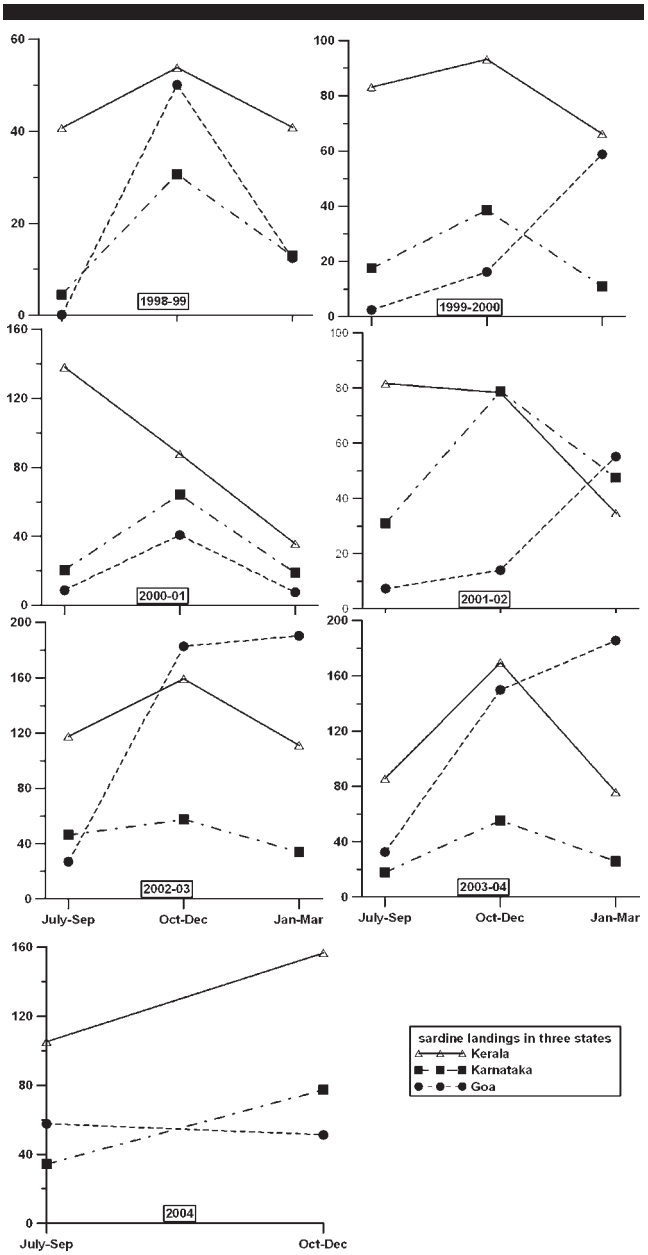

Figure 10. Quarterly sardine landing/km of coastline in the three maritime states.

the high chlorophyll concentration seen during May to October every year. Thus, there is a seamless connection of life history and biology of sardines to phytoplankton bloom dynamics. This supports the finding that the fish itself times its appearance to exploit the productive southwest monsoon period (Madhupratap *et al.,* 1994). The upwelling bloom can be characterized with respect to its peak amplitude, timing of peak, timing of initiation, and duration. In the present study, magnitude of the bloom at initiation is considered for characterization of bloom, which naturally falls in the month of May every year. May is the most critical month for sardines because both bloom initiation and the beginning of sardines' active breeding phase occur during May.

A delay in the initiation of bloom in the area results in hampering the congenial conditions for survival of sardine larvae. In the prevailing rough conditions when fishing activity is slackened, there may be an apparent paucity of sardines. But, as we find in the published reports (Antony Raja, 1969; Longhurst and Wooster, 1990), when there was fishing during July–August, it was noticed that the spawners entered the coastal waters due to increase in food production and migrated beyond the usual fishing belt (30-m depth) for spawning. The spawners again made a reentry to compete with the juveniles for feeding during September to December. The juveniles entered the coastal waters gradually for feeding during January–March and steadily migrated to deeper waters with reduced food. Their disappearance initiates first from the northern limits of sardine fishing ground and ends up in the southern areas later.

Recent works on the survival and early life history of fishes elucidates various factors including predation, drift pathways, and changing environmental conditions in addition to variation in food (Bakun and Broad, 2003; Cury *et al.,* 2000; Houde, 1987; Legget and Deblois, 1994; Miller *et al.,* 1988). Upwelling in the waters of the southwest coast of India is restricted to 5 to 15°N, and the variability in physical parameters is manifested in the chlorophyll intensity (Smitha *et al.,* 2008). A correlation

between available environmental datasets (SST, sea bottom temperature, surface salinity, surface dissolved oxygen, bottom dissolved oxygen, pH, nutrients, chlorophyll, zooplankton, rainfall, multivariate *El Nino* Southern Oscillation index, coastal upwelling index, and derived SST) and sardine catch from the study area vividly segregate the significance of chlorophyll from other environmental factors in explaining the sardine catch from the Malabar upwelling area (Krishnakumar and Bhat, 2008). A similar analysis of data sets is redundant in the context of this investigation. Hence, this investigation focused on food alone, the lone implicated factor chlorophyll *a* (as an index of phytoplankton biomass), and explored various avenues of this factor in explaining sardine variability.

A finer scale spatial and temporal pattern of egg and larval stages of sardines in relation to chlorophyll concentration could have yielded a proper model describing the presence or absence of sardines in coastal waters with a definite chlorophyll range. There are sparse reports of sardine eggs from Quilandy (Devanesan, 1943) and Kozhikode (Nair, 1953) and also descriptions of the larval and postlarval stages of sardines in these regions (Nair, 1959). But lack of information on distribution of eggs and larvae emphasizes the need for sampling of early life history stages of sardines over many years for determining the annual condition of larval and juvenile sardines in relation to chlorophyll concentrations.

CONCLUSIONS

Variation in sardine abundance could be attributed to variability in physical forces such as upwelling, sea level, temperature, wind stress, rainfall, and monsoon conditions (Krishnakumar and Bhat, 2008; Longhurst and Wooster, 1990). However, such an indicator was not a direct trophic link to sardines. The important factors responsible for the offshore–inshore migration appear to be the strength, duration of upwelling bloom, and changes it brings about in physicochemical and biological conditions in the coastal waters. But a lag phase between upwelling and intense production is notable in earlier studies in this region (Vimal Kumar *et al.*, 2008). Hence, chlorophyll concentration in coastal waters is the most important factor for establishing a trophic link that summarizes the above physical and chemical process. An early spawning and a time lag in development of food (through a break in monsoon or upwelling) would be detrimental to sardine recruitment. Consequently, chlorophyll concentration during the bloom initiation month substantially explains the interannual variability in sardine landings. The spatial and temporal variations in the intensity of chlorophyll in the coastal waters were reflected in the sardine abundance.

Application of remotely sensed chlorophyll provided a putative trophic link for explaining variation in sardine catches along the waters of the southwest coast of India. Remote sensing from satellites offers some solution for the requirement of an entire range of information needed to assess the "changing ocean." But this information has to be coupled with other appropriate biological data for forecasting fish distribution. Thus, satellite chlorophyll in its present state alone cannot be an alternative to *in situ* chlorophyll. The absolute chlorophyll present in CASE 2 waters often gets challenged by the turbidity contributed by other optical constituents. It is the judicious application of both satellite and observed data that will help in deducing the correct picture. There are many recent developments in building of trophic models of aquatic ecosystems (Hall and Mainprize, 2004). There is potential for satellite phytoplankton data to serve in future as a surrogate for sardine biomass. Usually, investigations in fisheries biology lack time series environmental or other biological data sets (Longhurst and Wooster, 1990; Madhupratap *et al.,* 1994). The combination of satellite data sets with fisheries data can lead to robust conclusions. Longer time series will be required to confirm and determine the large-scale fluctuation in abundance, population crashes, and subsequent revival of this major pelagic fishery in the southwest coast of India.

ACKNOWLEDGMENTS

We acknowledge the director of the National Institute of Oceanography, Goa; the Council of Scientific and Industrial Research, New Delhi; the Nippon Foundation (NF) and Partnership on Ocean Global Observation (POGO) for providing funds and facilities to carry out this work. The support received from NF-POGO team members at National Institute of Oceanography (NIO) Regional Centre, Kochi, is also acknowledged. *SeaWiFS* data were downloaded from the NASA site http://oceancolor.gsfc.nasa.gov/cgi/l3. This article is NIO contribution 4825.

LITERATURE CITED

Antony Raja, B.T., 1969. *The Indian Oil Sardine*. Mandapam, India: Central Marine Fisheries Research Institute, 128p.

Antony Raja, B.T., 1972. Possible explanation for the fluctuation in abundance of the Indian oil sardine *Sardinella longiceps* Valenciennes. *Proceedings of Indo-Pacific Fisheries Council* (Wellington, New Zealand, FAO regional office for Asia and Far East), pp. 241–252.

Bakun, A. and Broad, K., 2003. Environmental loopholes and fish population dynamics: comparative pattern recognition with focus on *El Nino* effects in the pacific. *Fisheries Oceanography,* 12, 458–473.

Bensam, P., 1964. Growth variation in oil sardine. *Indian Journal of Fisheries,* 11, 699–708.

Bricaud, A. and Morel, A., 1987. Atmospheric corrections and interpretation of marine radiances in CZCS imagery: use of a reflectance model. *Oceanologica Acta,* 7, 33–50.

Chidambaram, K., 1950. Studies on the length frequency of oil sardine, *Sardinella longiceps* Cuv. & Val. and on certain factors influencing their appearance on the Calicut coast of the Madras Presidency. *Proceedings of Indian Academy of Sciences,* 31, 252–286.

CMFRI (Central Marine Fisheries Research Institute), 2005. *Marine fisheries census 2005*. Cochin, India: Central Marine Fisheries Research Institute, Part I, 104p.

Cury, P.; Bakun, A.; Crawford, R.J.M.; Jarre, A.; Quinones, R.A.; Shannon, L.J., and Verheye, H.M., 2000. Small pelagic in upwelling systems: patterns of interaction and structural changes in 'wasp-waist' ecosystems. *ICES Journal of Marine Science,* 57, 603–618.

Cushing, D.H., 1974. The natural regulation of fish populations. *In:* Harden Jones, F.R. (ed.), *Sea Fisheries Research*, London: Elek Science, pp. 399–412.

Cushing, D.H., 1990. Plankton production and year-class strength in fish populations: an update of the match-mismatch hypothesis. *Advances in Marine Biology,* 26, 249–294.

Dayaratne, P. and Gjøsaeter, J., 1986. Age and growth of four *Sardinella* species from Sri Lanka. *Fisheries Research,* 4(1), 1–33.

Devanesan, D.W., 1943. A brief investigation into the causes of the fluctuation of the annual fishery of the oil sardine of Malabar, *Sardinella longiceps* Cuv. & Val., determination of its age and an account of the discovery of its eggs and spawning grounds. *Madras Fisheries Bulletin,* 28(1), 1–38.

Dinesh Kumar, P.K. and Srinivas, K., 2007. Variability in measured current structure on the southwest continental shelf of India. *Journal of Coastal Research,* 23(3), 647–657.

Hall, S.J. and Mainprize, B., 2004. Towards ecosystem-based fisheries management. *Fish and Fisheries,* 5(1), 1–20.

Hjort, J., 1914. Fluctuations in the great fisheries of Northern Europe viewed in the light of biological research. *Rapports et Procès-Verbaux des Réunions du Conseil Permanent International pour l'Exploration de la Mer* 20, 228p.

Hornell, J., 1910a. Report on the feasibility of operating deep-sea fishing boats on the coasts of the Madras Presidency with special reference to the selection of fishing centres and harbours of refuge. *Madras Fisheries Bulletin,* 4(3), 33–70.

Hornell, J., 1910b. Report on the results of a fishery cruise alone the Malabar Coast and to the Laccadive Islands in 1908. *Madras Fisheries Bulletin,* 4(4), 71–126.

Hornell, J. and Nayadu, M.R., 1924. A contribution to the life history of the Indian oil sardine with notes on the plankton of the Malabar Coast. *Madras Fisheries Bulletin,* 17, 129–127.

Houde, E.D., 1987. Fish early dynamics and recruitment variability. *American Fisheries Society Symposium,* 2, 17–29.

Hunter, J.R., 1981. Feeding ecology and predation in marine fish larvae. *In:* Lasker, R. (ed.), *Marine fish larvae*. Seattle: University of Washington Press, pp. 34–59.

ICES (International Council for the Exploration of the Sea), 2000. Ecosystem effects of fishing. *In:* ICES Marine Science Symposium. 210, *ICES Journal of Marine Sciences,* 57, 791.

John, C.C. and Menon, M.A.S., 1942. Food and feeding habits of the oil sardine and mackerel. *Current Science,* 11, 243–244.

Krishnakumar, P.K. and Bhat, G.S., 2008. Seasonal and interannual variations of oceanographic conditions off Mangalore coast (Karnataka, India) during 1995–2004 and their influences on pelagic fishery. *Fisheries Oceanography,* 17, 45–60.

Kuthalingam, M.D.K., 1960. Observations on the life history and feeding habits of the Indian sardine *Sardinella longiceps* (Cuv. & Val.), *Treubia,* 25, 202.

Lasker, R., 1975. Field criteria for survival of anchovy larvae: the relationship between inshore chlorophyll maximum layers and successful first feeding. *U.S. Fisheries Bulletin,* 73, 453–462.

Lasker, R., 1981. The role of a stable ocean in larval fish survival and subsequent recruitment. *In:* Lasker, R. (ed.), *Marine fish larvae*. Seattle: University of Washington Press, pp. 80–85.

Laurs, R.M.; Fiedler, P.C., and Montgomery, D.R., 1984. Albacore tuna catch distributions relative to environmental features observed from satellites. *Deep-Sea Research,* 31, 1085–1099.

Leggett, W.C. and Deblois, E., 1994. Recruitment in marine fishes: is it regulated by starvation and predation in the egg and larval stages? *Netherlands Journal of Sea Research,* 32, 119–134.

Longhurst, A.R. and Wooster, W.S., 1990. Abundance of oil Sardine (*Sardinella longiceps*) and upwelling on the southwest coast of India. *Canadian Journal of Fisheries and Aquatic Sciences,* 47, 2407–2419.

Madhupratap, M.; Nair, K.N.V.; Gopalakrishnan, T.C.; Haridas, P.; Nair, K.K.C.; Venugopal, P., and Mangesh Gauns, 2001. Arabian Sea oceanography and fisheries of the west coast of India. *Current Science,* 81, 355–361.

Madhupratap, M.; Shetye, S.R.; Nair, K.N.V., and Sreekumaran Nair, S.R., 1994. Oil sardine and Indian mackerel: their fishery, problems and coastal oceanography. *Current Science,* 66, 340–348.

Menon, H.B.; Lotliker, A.A.; Krishnamurthy, K., and Nayak, S.R., 2006. Variability of remote sensing reflectance and implications for optical remote sensing—A study along the eastern and north eastern waters of Arabian Sea. *Geophysical Research Letters,* 33, L15602.

Menon, H.B.; Lotliker, A., and Nayak, S.R., 2005. Pre-monsoon bio-optical properties in estuarine, coastal and Lakshadweep waters. *Estuarine, Coastal and Shelf Science,* 63, 211–223.

Miller, T.J.; Crowder, L.B.; Rice, J.A., and Marschall, E.A., 1988. Larval size and recruitment mechanisms in fishes: towards a conceptual framework. *Canadian Journal of Fisheries and Aquatic Sciences,* 45, 1657–1670.

Nair, R.V., 1953. Studies on the revival of the Indian oil sardine fishery. *Proceedings of Indo-Pacific Fisheries Council* (Quezon City, Republic of Philippines), pp.115–129.

Nair, R.V., 1959. Notes on the spawning habits and early life history of the oil sardine, *Sardinella longiceps* Cuv & Val. *Indian Journal of Fisheries,* 6, 342–359.

Nair, R.V., 1960. Synopsis on the biology and fishery of the Indian sardines. *Proceedings of world scientific meeting on the biology of sardines and related species* (Rome, Italy), pp. 329–359.

Nair, R.V. and Subrahmanyan, R., 1955. The diatom, *Fragillaria oceanica* Cleve, an indicator of abundance of the Indian oil sardine, *Sardinella longiceps* Cuv. & val. *Current Science,* 24, 41–42.

National Aeronautic and Space Administration, Inc. 2002. http://oceancolor.gsfc.nasa.gov/cgi/l3 (accessed July 19, 2009).

NRC (National Research Council), 1999. *Sustaining Marine Fisheries*. Washington, D.C.: National Research Council, National Academy Press, 164p.

Panikkar, N.K., 1952. Fisheries research in India. Part I—marine fisheries. *Journal of Bombay Natural History Society,* 50, 741–765.

Platt, T.; Sathyendranath, S.; White, G.N. III; Fuentes-Yaco, C.; Zhai, L.; Devred, E., and Tang, C., 2009. Diagnostic properties of phytoplankton time series from remote sensing. *Estuaries and Coasts,* doi: 10.1007/s12237-009-9161-0.

Platt, T.; Yaco, C.F., and Frank, K.T., 2003. Spring algal bloom and larval fish survival. *Nature,* 423, 398–399.

Prabhu, M.S. and Dhulked, M.H., 1970. The oil sardine fishery in the Mangalore zone during the seasons of 1963–64 and 1967–68. *Indian Journal of Fisheries,* 17, 57–75.

Raghavan, B.R.; Mini Raman; Chauhan, P.; Sunil Kumar, B.; Shylini, S.K.; Mahendra, R.S., and Nayak, S.R., 2006. Summer chlorophyll-a distribution in eastern Arabian Sea off Karnataka-Goa coast from satellite and *in-situ* observations. *In:* Frouin, R.J.; Agarwal, V.K.; Kawamura, H.; Nayak, S., and Pan, D. (eds.), *Proceedings of SPIE volume 6406, Remote sensing of the marine environment*. Goa, India: 64060W.

Sathiadhas, R., 2006. Socio-economic scenario of marine fisheries in India—an overview. *In:* Kurup, B.M. and Ravindran, K., (eds.) *Sustain Fish*, School of Industrial Fisheries, Cochin, India: Paico Press, pp. 84–101.

Skud, B.E., 1983. Interactions of pelagic fishes and the relation between environmental factors and abundance. *In:* Sharp, G.D. and Csirke Y.J. (eds.), *Proceedings of the Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Resources*. San Jose, Costa Rica: FAO, Rome, 291(3), 1133–1140.

Smitha, B.R.; Sanjeevan, V.N.; Vimal Kumar, K.G., and Revichandran, C., 2008. On the upwelling off the southern tip and along the west coast of India. *Journal of Coastal Research,* 24, 95–102.

Srinath, M.; Kuriakose, S.; Ammini, P.L.; Prasad, C.J.; Ramani, K., and Beena, M.R., 2006. *Marine Fish Landings in India 1985–2004 Estimates and Trends*. Cochin, India: Central Marine Fisheries Research Institute, 161p.

Van der Lingen, C.D., 2002. Diet of sardine *Sardinops sagax* in the southern Benguela upwelling ecosystem. *South African Journal of Marine Science,* 24, 301–316.

Vimal Kumar, K.G.; Dinesh Kumar, P.K.; Smitha, B.R.; Habeeb Rahman, H.; Josia, J.; Muraleedharan, K.R.; Sanjeevan, V.N., and Achuthankutty, C.T., 2008. Hydrographic characterization of southeast Arabian Sea during the wane of southwest monsoon and spring intermonsoon. *Environmental Monitoring and Assessment,* 140, 231–247.