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A persistent eddy in the central Arabian Sea: Potential trophic significance

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Arabian Sea is an area of strong currents, complicated flow patterns with several eddies and semi annually reversing monsoon winds. This paper deals with a cold eddy highly rich in phytoplankton in the Central Arabian Sea, centered around: 14° 25’ N and 69° 20’ E during January – March 1998. The eddy was about 100 km in diameter with a depth of about 4000 m and maximum chlorophyll-*a* concentration was 1 mg m^{-3} compared with 0.2 mg m^{-3} in the surrounding areas. Average optical depth of the area was 12 m. The occurrence of the eddy and the related oceanographic variables were inferred from SeaWiFS derived chlorophyll-*a* (Chl-*a*), NOAA Pathfinder AVHRR derived sea surface temperature, sea surface height from TOPEX altimeter and collateral information. The cold eddy formation is probably due to longshore density variation in the ocean. Due to negative sea level anomalies, associated surface divergence and upwelling process, the region of cold eddy is known to be highly productive. The cold eddy in the same location was observed during January 2000. The persistence of the eddy for more then a month indicates that this area is a rich forage ground for tuna fishery.

[**Key words**: Arabian Sea, chlorophyll, cold eddy, SST, OCM, SeaWiFS, tuna, fishery]

Introduction

Arabian Sea experiences unique features and events compared with other world oceans. The semi-annual reversal of monsoon winds blowing from northeast during December-February (Northeast monsoon) and from southwest during June-September (Southwest monsoon) drive strong currents, produce complex eddy fields, deepen the mixed layer and induce both coastal and open ocean upwelling[1,2]. These physical changes directly affect primary production processes besides influencing the abundance, distribution and diversity of fishery resources. The surface winds are consistent in their direction during the monsoon. Besides, the Arabian Sea is strongly forced by solar heating being in the sub tropics. Evaporation and precipitation are intense, particularly during the southwest monsoon period[1,3]. The Arabian Sea is connected to the warm, highly saline waters of the Persian Gulf and the Red Sea. Spatial and temporal variations in temperature, salinity, currents, and the associated circulation, contribute to increased productivity.

Various studies based on experiments and *in situ* observations have shown close association of fish larvae and eddy. High abundance of fish larvae often exist in eddies, this may be because eddies generally tend to remain nearly stationary for period of weeks causing limited dispersion[4,5]. Some eddies have unique chemical properties[6], which may aid prey production and survival of larvae in the eddy[7]. Bailey & Macklin[8] suggest how larval survival may be related to an integration of wind-mixing, stratification within an eddy.

The Average annual production of tuna from Indian waters is about 24,000 tonnes[9], whereas the annual potential exploitable yield is 240, 000 tonnes[10]. Cold eddies are pockets of cold water surrounded by warmer water and are deepest and coldest at the centers. During winter months (December-February), a jet of wind from the northwest of India blowing across the open Arabian Sea to Africa generates wind stress curl ensuing phytoplankton production. In general during the northeast monsoon (December-February), wind speeds average 6 m s^{-1}. The mixed layer depth is deeper (~110 m) than the summer mixed layer depth (~80 m), primarily because of surface cooling and convection[11]. This paper deals with the occurrence of a persistent cold eddy associated with high chlorophyll *a* biomass in the central Arabian Sea, during winter/post winter monsoon. And an attempt has been made to study physical and biological oceanographic conditions associated with the eddy and its possible significance with tuna fishery in the Arabian Sea, which is grossly underexploited by the Indian fishing community.

Materials and Methods

Data from various sources have been used for this study. Chlorophyll, K_d and optical depth images were generated using SeaWiFS data and primary productivity images have been procured from the NASA web site. Chlorophyll (January 4-30, 2000) generated from IRS P4-OCM was also used. Besides this, NOAA-AVHRR derived sea surface temperature (February-March, 1998) and sea surface height anomalies (June 1997 – May 1998) from TOPEX altimeter were also used. Historical data on tuna from published literature were used to understand the distribution and migratory patterns of tuna in the Indian Ocean. This study also used *in situ* data collected by *ORV Sagar Kanya* over the central Arabian Sea (Fig. 1).

Generation of chlorophyll images

SeaWiFS level 2 product has been analysed using the SeaDAS software. While processing it uses the header information contained in the SeaWiFS data itself, such as the radiances at 765 and 865 nm, which are used for atmospheric correction. Besides this, meteorological and atmospheric ozone data are also used. The atmospheric influence is removed for each pixel, and the radiances are converted to normalized water-leaving radiances (nLw). After the nLw values are calculated, chlorophyll concentration (mg m^{-3}) is retrieved using SeaWiFS Ocean Chlorophyll 4 (OC4v1) algorithm. Similarly chlorophyll *a* images were generated over central Arabian Sea from IRS-P4 OCM data using OC2 algorithm. This algorithm has been fine tuned for chlorophyll-*a* concentration retrieval in the Arabian Sea using *in situ* data collected over the same region[12].

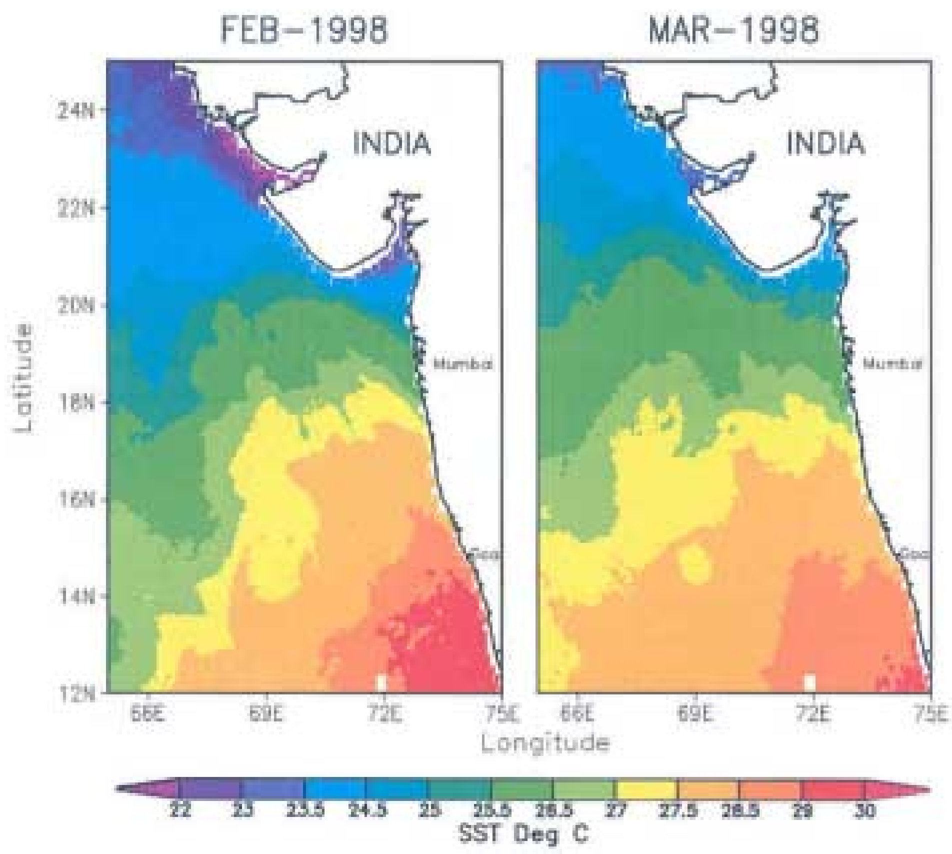

Fig. 1—Sea surface temperature images derived from NOAA-AVHRR showing a cold eddy in the Central Arabian Sea

Generation of diffuse attenuation coefficient (K_d) images

Maps of K_d were generated using the bio-optical model developed by Morel[13], which allows the determination of $K_d(\lambda)$ if C (chlorophyll) is measured. The model is given below:

$$K_d(\lambda) = K_{dw}(\lambda) + \chi(\lambda)\, C^{\, e(\lambda)}$$

where $K_{dw}(\lambda)$ is the diffuse attenuation for pure seawater and $\chi(\lambda)$ and $e(\lambda)$ are statistically derived functions that convert the chlorophyll concentration (C mg m^{-3}) into K_d values (in m^{-1}). This model is applicable to case 1 waters with $C \leq 30$ mg m^{-3}.

Sea surface height anomaly maps

Sea Surface Height Anomaly (SSHA) Product of TOPEX altimeter, produced and distributed by the Jet Propulsion Laboratory, (JPL PO.DAAC) have been used to study the SSHA in the eddy location. The SSHA represents the difference between the estimate of the sea surface height at a particular time and a mean sea surface. The formulae for calculating the SSHA parameter, from TOPEX altimeter data are described by Benada[14]. The values of the mean sea surface height used in this product to calculate SSHA are from the GSFC00.1 model and data[15].

Sea surface temperature maps

The thermal infrared channel 4 and 5 (10.5 - 11.3 µm and 11.5 - 12.5 µm) of NOAA-AVHRR has been used for deriving the SST images for the daytime pass. This region is highly sensitive to thermal variation of earth/ocean. SST is computed using McClain's[16] MCSST (multi-channel sea surface temperature) approach, which essentially accounts for signal loss in atmosphere due to absorption by water vapor and further relates brightness temperature with sea surface temperature.

Results and Discussion

The eddy environment

Oceanic eddies are tornado-like structures created as a result of the major ocean currents. Eddies are distinct, closed cyclonic or anticyclonic circulations. This paper deals with a persistent cold core eddy located around 13° 45' - 15° 10' N and 68° 35' - 69° 55' E, where the water temperature increases as one moves outward from the center, with the coldest temperature at the center (Fig. 1). This area in the central Arabian Sea is bio-optically classified as the oligotrophic ocean based on the Undulating Oceanographic Recorder (UOR) measurements, characterised by a deep mixed layer (50-60 m), low surface chlorophyll concentrations (0.05-0.10 mg m^{-3}), deep chlorophyll maximum (~ 1 mg m^{-3}) and surface blue waters[17]. The diffuse attenuation coefficient for this location has been observed for the surface water as K_{445}=0.051, K_{490}=0.038 and K_{550}=0.073 m^{-1}. However, SeaWiFS derived chlorophyll *a* and primary productivity images reveal persistently high concentration of chlorophyll *a* (average value of 0.9 mg m^{-3}) and monthly primary productivity (28 mg C m^{-2}) respectively, lasting for about 3 months (January – March 1998).

The eddy formation and nutrient enrichment: Probable cause

In the ocean, submesoscale (0.5-10 km) and mesoscale (10-200 km) spatial structures are results of dynamic balance between local and regional generation processes[18]. The cause of the cold eddy formation in the central Arabian Sea in 1998 is probably due to longshore density variation in the ocean. Studies conducted in the central Arabian Sea during winter monsoon depict the possibility of advection of cold water over warm saline water[19]. This is because of the northward intrusion of the waters of Bay of Bengal during winter. The salinity shows a well marked increase (33 ppt) because of the excess of evaporation in the central Arabian Sea. The magnitude of the thermohaline-driven surface flow is a function of the longshore density gradient. Temperature inversion takes place at a depth of about 30–50 meters with a horizontal extent of roughly 400 km having vertically well-mixed water[19].

The consequent sinking and convection result in the deepening of the mixed layer and an upward transport of nutrients into the surface layers from the base of the mixed layer (80-100 m). As a result of these changes biological productivity increases. The highest productivity measured in winter (807 mg $Cm^{-2}d^{-1}$) although less than that reported from active upwelling areas (2.5 g $Cm^{-2}d^{-1}$) in the northwestern Arabian Sea during summer monsoon[17]. Studies conducted using Joint Global Ocean Flux Studies (JGOFS) data suggests that the phytoplankton cell numbers were very high during winter months of 1996 in the eddy location. Besides, Picoplankton abundance was also very high associated with increased nutrients[20].

Oceanographic and optical characteristics of cold-core eddy in 1998

Fortnightly composite chlorophyll images generated using SeaWiFS data (Fig. 2) show high concentration of chl *a* in the north and northeastern Arabian Sea and a circular patch of high chl *a* (bloom like) concentration is prominent in the central Arabian Sea centered around: 14° 25’ N and 69° 20’ E, persisting for a period of 3 months starting from January 16, 1998 to April 15, 1998. A subset of 1°×1° image within the region of interest shows an average chlorophyll value 0.9 mg m^{-3} and the surrounding areas show only 0.2 mg m^{-3}. This results in the presence of a strong colour front in the region.

To understand the water types in the eddy and the surrounding areas, Jerlov’s[21] scheme was followed. Based on that classification scheme, the water mass within the eddy corresponds to Jerlov water type II with an average optical depth of about 12 m in the eddy region and the surrounding areas show more than 25 m indicating a moderately rich phytoplankton zone (Fig. 3). In addition to the above characteristics, monthly sea surface height anomaly (SSHA) was also studied for the eddy region from June 1997 to May 1998 (Fig. 4). The SSHA during the said period

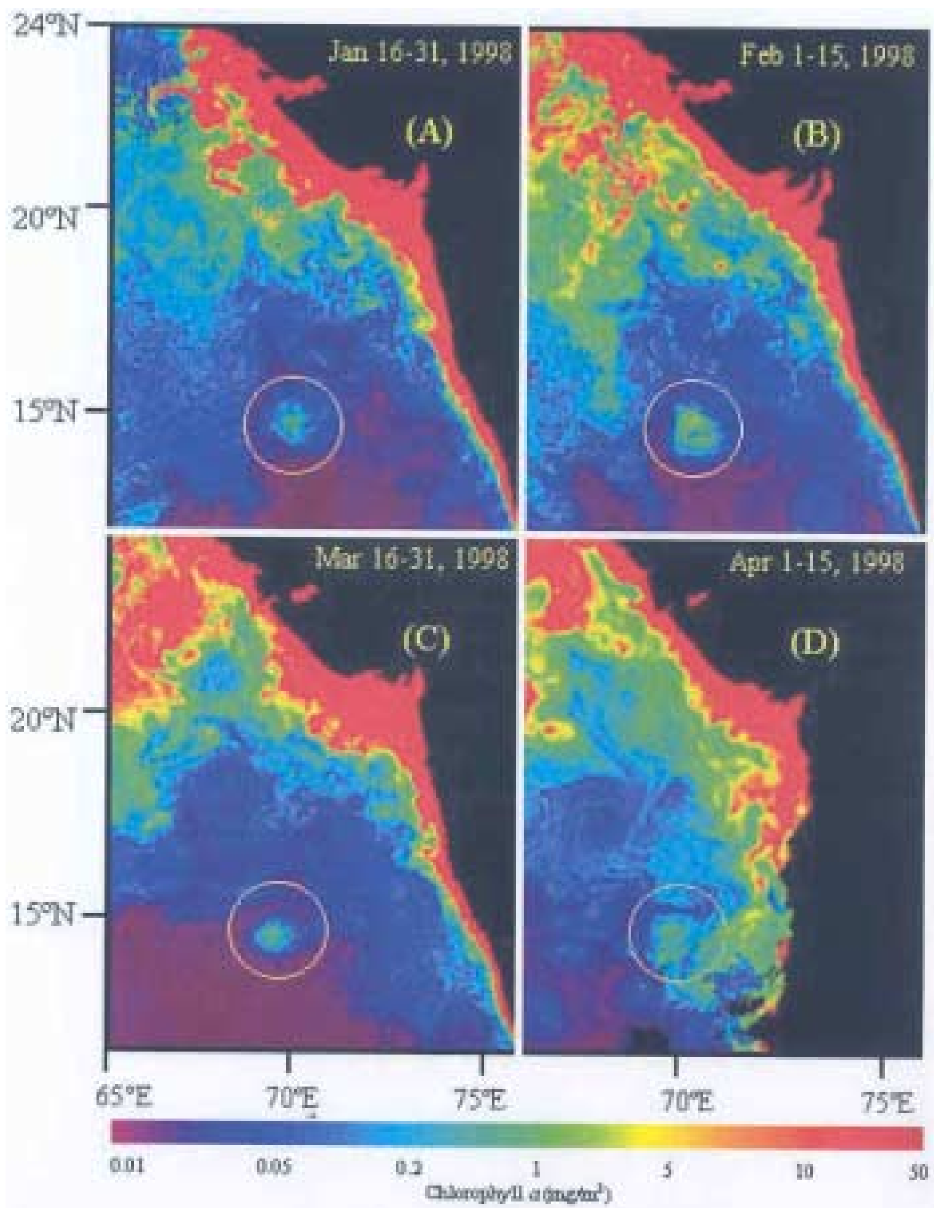

Fig. 2—SeaWiFS fortnightly composite images showing chlorophyll a as tracer of an eddy in the Central Arabian Sea

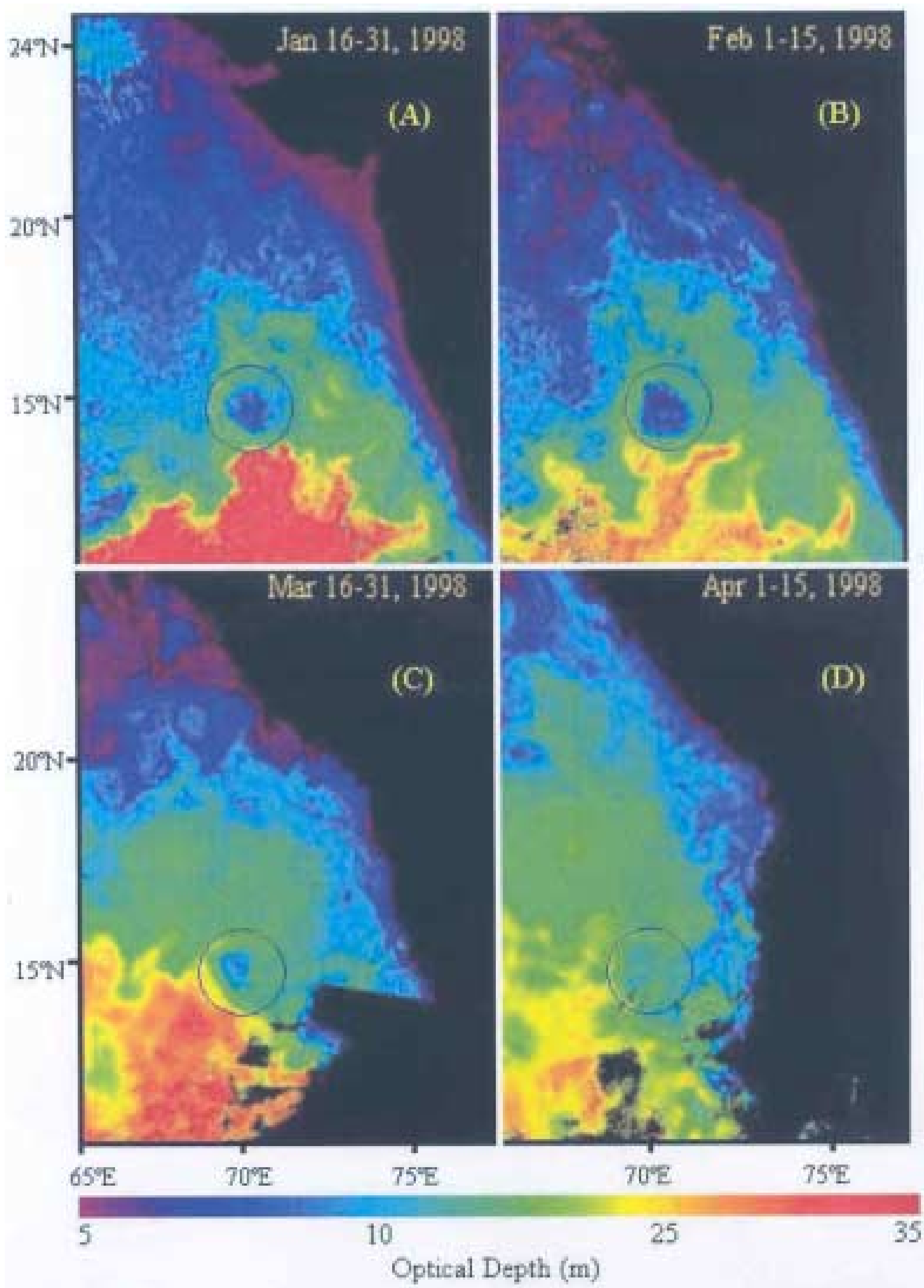

Fig. 3—Fortnightly composite Seawifs images showing optical depth

ranges from about 0.12 m to - 0.04 m with the lowest SSH observed during January 1998 coinciding with the eddy. As mentioned in the earlier section, the eddy observed is of cold core (cyclonic) type. Cold eddies are regions of negative sea level anomalies (lows) and are associated with surface divergence. In such regions, upwelling from the deeper layer occurs to compensate for the surface water loss and the thermocline moves up. With this upwelling, nutrients and phytoplankton are brought to the surface where they are exposed to solar radiation. This activates

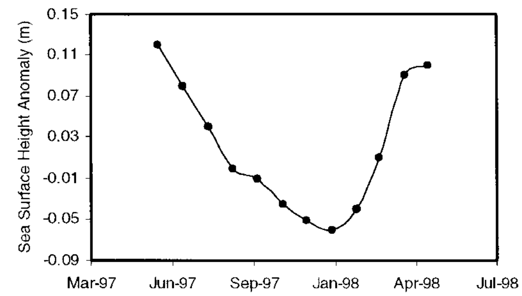

Fig. 4—Sea surface height anomalies derived from TOPEX altimeter for a period of 12 months showing negative anomalies during the winter months

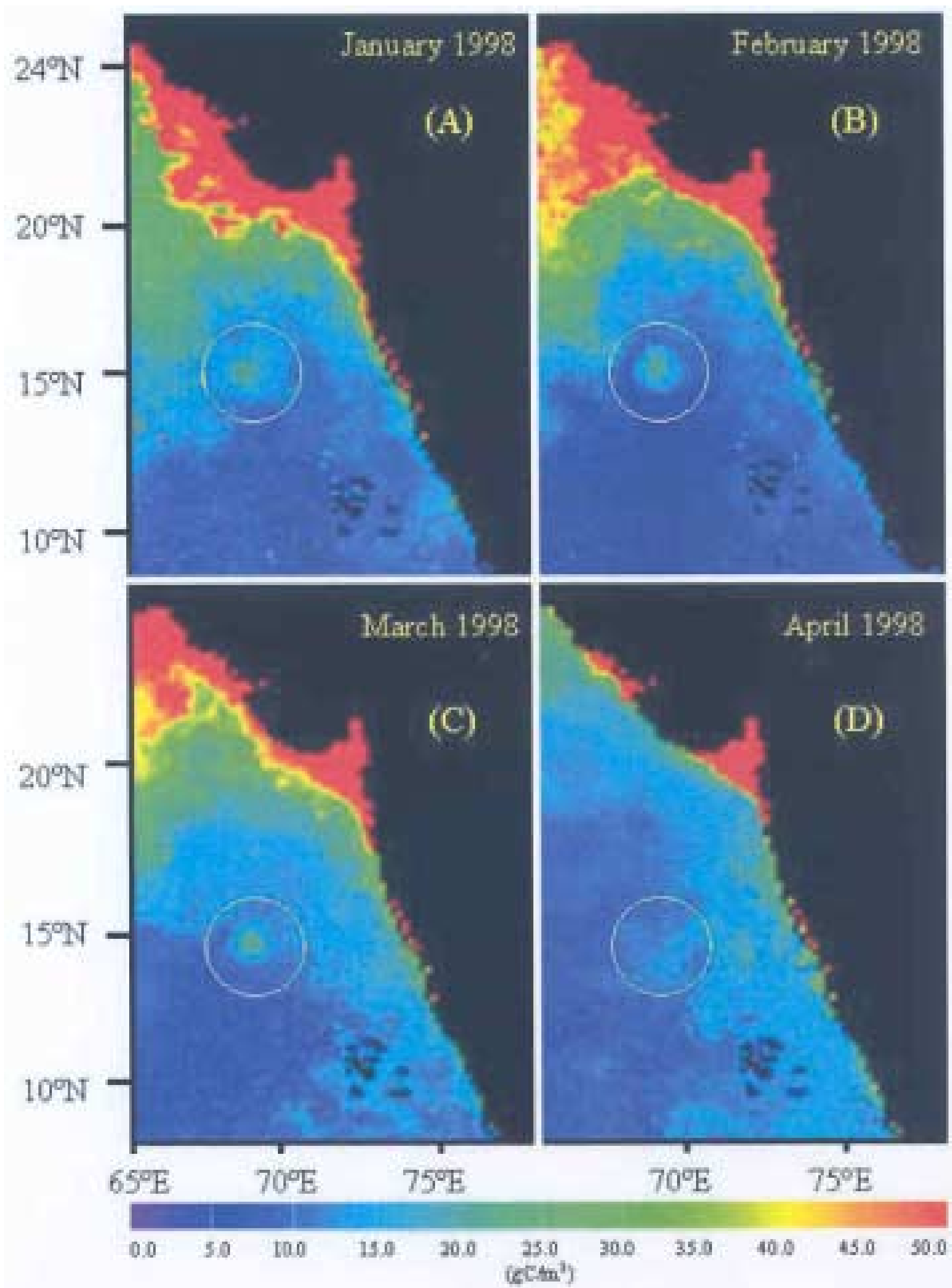

Fig. 5—Monthly composite Seawifs images showing primary productivity

photosynthesis, which in turn induces primary production. SeaWiFS derived monthly primary productivity images (Fig. 5) show high primary production of about 28 g C m^{-2} in the eddy location, which clearly demonstrates that cold eddies are favorable locations for increased primary production.

Latitudinal variation of mixed layer depth, sea surface temperature and wind speed along the eddy location have been studied based on *in situ* observations. The mixed layer depth observed was about 70 m and the wind speed along the eddy location was recorded as 5-6 m.s^{-1} and the SST shows substantial variation from 24.5°C to 26.5°C as moved from the centre of the eddy to outside (Fig. 6).

Interannual variations

The occurrence of a cold core eddy, rich in phytoplankton in the central Arabian Sea during January – March 1998 was discussed in detail in the previous section. Chlorophyll *a* images derived from the IRS P4-OCM indicate chlorophyll rich zones in the central Arabian Sea in January 2000 in the same location (Fig. 7). This observation is of biological significance because the conventional understanding is that the central Arabian Sea is oligotrophic in nature. This study indicates that during winter monsoon there is high probability of the occurrence of cold eddy leading to high productivity areas in the central Arabian Sea.

Trophic significance of the eddy

This section highlights the potential influence of high phytoplankton biomass, high productivity levels, SST variations and other characteristics of a persistent eddy on tuna aggregation. Tuna are highly mobile, economically exploitable resources because of their tendency to aggregate into schools and the school's tendency to aggregate at specific oceanographic features such as eddies and temperature fronts, which are known to be areas of increased productivity and relatively high prey abundance[22-23]. Numerous investigators have tried to determine the effect of environmental conditions on depth distribution, migratory speed, residency time, tendency to aggregate and eventually the vulnerability to specific fishing gears over time and space[24-25]. The horizontal movements and vertical distribution of various tuna species and their catch efficiency of various fishing gears are influenced by oceanographic conditions[26].

Food is an important factor influencing the growth, migration and abundance of fish stocks in time and space. By identifying the feeding ground and feeding habit, exploitation strategy can be refined and improved upon. Several authors have reported on the food and feeding habits of yellowfin tunas from different Oceans as well as from the Indian waters. Various studies have indicated observations on the feeding habits of yellowfin tunas caught on longline gears in the Indian waters[27-28]. All these studies suggest that plankton rich areas are suitable ground for tuna forage.

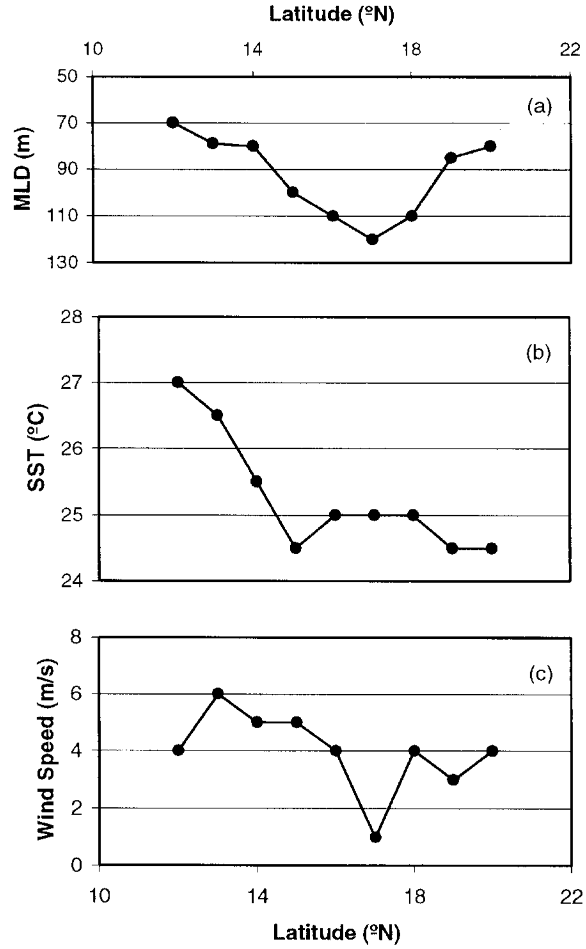

Fig. 6—Latitudinal variation of mixed layer depth (a), sea surface temperature (b), and wind speed (c) along the eddy location based on *in situ* observation

Young *et al.*[29] have observed the highest catch in 1996 (~75%) from an eddy location, concluding that the presence of the eddy has provided a localised but productive area to which the yellowfin were attracted. Pelagic Fisheries Research Program (University of Hawaii) has been studying the role of oceanographic features and phenomena on yellowfin tuna aggregation and vulnerability to fishing[30]. This study exploits the combined oceanographic information acquired from satellites (altimetry, temperature, ocean

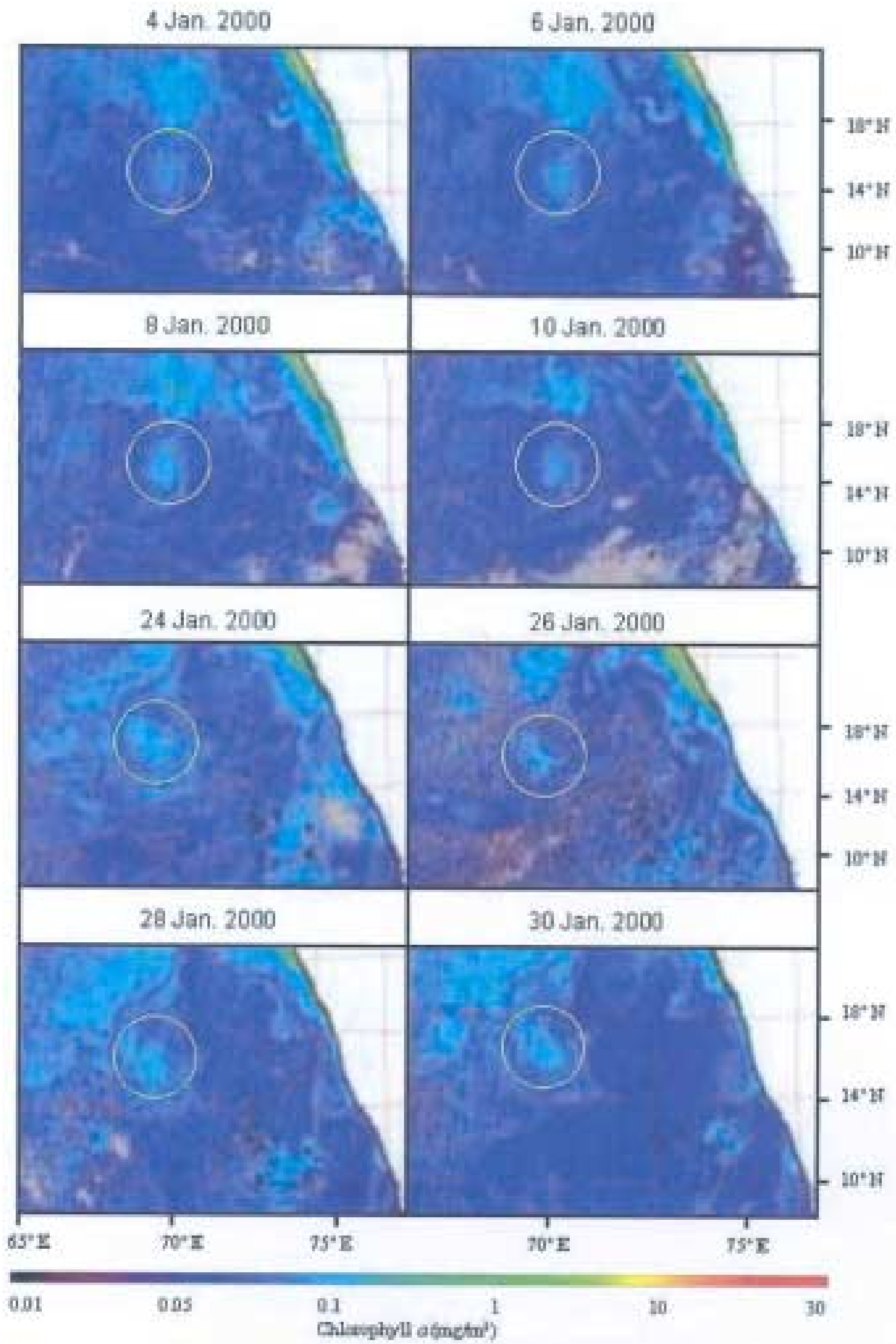

Fig. 7—IRS P4 OCM derived chlorophyll a image showing high chlorophyll patch in the central Arabian Sea during January 2000

color), moored arrays, and shipboard platforms together with commercial and research fishery data for the assessment. Surface thermal gradients measured both by satellite and *in situ* measurements have shown stronger gradients in the eddy. As the eddy becomes older, substantial increase in chlorophyll at the surface and within the subsurface chlorophyll maximum was measured making it a suitable ground for tuna aggregation.

Tunas are visual predators, hence live mostly in clear waters surrounding the eddy so as to locate their prey visually at close range and then occasionally visit the colder enriched upwelling areas to feed. The optimum transparency for tuna is at 20-30 m depth because locating the prey becomes difficult below this range. Water transparency is also an indicator of availability of tuna forage. The diffuse attenuation coefficient $K_d(\lambda)$ is strongly correlated with chlorophyll concentration, thus provide a linkage between biology and optics. Tunas are known to be in abundance in the frontal region of highs and lows (i.e. between positive and negative sea level anomalies). While migrating, tuna follow a path where the food resources are high and the environment is conducive to their physiology and behaviour. Therefore it is believed that such areas are indicative of tuna aggregation.

Conclusion

Using SeaWiFS and OCM derived chl *a* images, NOAA-AVHRR derived sea surface temperature images we observed a cold core eddy associated with high chlorophyll *a* biomass in the central Arabian Sea during January - March 1998. The negative sea surface height anomalies derived from TOPEX altimeter has authenticated the presence of a cold eddy in the region. This observation is of immense importance because the central Arabian Sea is conventionally understood to be an oligotrophic region. This is a rare observation of phytoplankton rich zone coinciding with a cold eddy in the central Arabian Sea.

Since most of the tuna species tend to remain in the water masses where prey abundance is high and the surrounding water mass is clear enough for them to be effective visual predators, the eddy location discussed in this paper is a potential zone for tuna aggregation. This study demonstrates the use of satellite ocean colour and SST images to monitor seasonal and interannual variability of phytoplankton distribution and other dynamical ocean features and highlights the potential application of this information to detect the highly migratory tuna fishery in the Arabian Sea which is underexploited by the Indian fishing community.

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References

1 Shetye S R, Gouveia A D & Shenoi S S C, Circulation and water masses of the Arabian Sea, *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 103 (1994)107-123.
2 Pal P K and Ali M M, Arabian Sea eddies simulated by an ocean model with thermodynamics, *Indian J. Mar. Sci*., 27 (1998) 72-75.
3 Brock J C, McClain C R & Hay W W, A southwest monsoon hydrography climatology for the northwestern Arabian Sea, *J. Geopphys. Res*., 97 (1992) 9455 – 9465.
4 Schumacher J D, Stabeno P J & Bograd S J, Characteristics of an eddy over a continental shelf: Shelikof Strait, Alaska, *J. Geophys. Res.,* 98 (1993) 8395-8404.
5 Schumacher J D & Stabeno P J, Ubiquitous eddies of the Eastern Bering Sea and their coincidence with concentrations of larval pollock, *Fish. Oceanogr.*, 3 (1994) 182-190.
6 Incze L S, Kendall A W, Schumacher J D Jr & Reed R K, Interactions of a mesoscale patch of larval fish (*Theragra chalcogramma*) with the Alaska coastal current, *Cont. Shelf Res.*, 9 (1989) 269-284.
7 Schumacher J D & A W Kendall Jr, Some interactions between young walleye pollock and their environment in the western Gulf of Alaska, *CalCOFI Rep.,* 32 (1991) 22-40.
8 Bailey K M & Macklin S A, Analysis of patterns in larval walleye pollock *Theragra chalcogramma* survival and wind mixing events in Shelikof Strait, Gulf of Alaska, *Mar. Ecol. Prog. Ser.,* 113 (1994) 1-12.
9 Sudarsan D, Sivaprakasam T E, Somvanshi V S, John M E, Nair K N V & Antony Joseph, An appraisal of the marine fishery resources of the Indian Exclusive Economic Zone, *Bull. Fish. Surv. India,* 18 (1988) 61-74.
10 Somvanshi V S & John M E, The oceanic tuna fishery in India - An update, *IPTP*, 9 (1996) pp. 1-5.
11 Rao R R, Molinari R L & Festa J F, Evolution of the climatological near-surface thermal structure of the tropical Indian Ocean. Part-I: Description of mean monthly mixed-layer depth and sea-surface temperature, surface current and surface meteorological fields, *J. Geophys. Res*., 94 (1989) 10801 – 10815.
12 Prakash C, Mohan M, Sarangi R K, Kumari B & Nayak S, Surface chlorophyll a estimation in the Arabian Sea using IRS-P4 Ocean Colour Monitor (OCM) satellite data, *Int. J. Remote Sensing*, 23 (2002) 1663-1676.
13 Morel A, Optical modeling of the upper ocean in relation to its biogenous matter content (case 1 waters), *J. Geophys. Res.,* 93 (1998) 10749-10759.
14 Benada J R, PO.DAAC Merged GDR (TOPEX/POSEIDON) Generation B User's Handbook, (1997) Web page: http://podaac.jpl.nasa.gov/.
15 Picot N, Case K, Desai S & Vincent P, AVISO and PODAAC User Handbook. IGDR and GDR Jason Products, SMM-MU-M5-OP-13184-CN (AVISO), JPL D-21352 (PODAAC) (2003) web page: http://podaac.jpl.nasa.gov/jason/documents/Handbook_Jason.pdf.
16 McClain E P, Pichel W G & Walten C C, Comparative performance of AVHRR based multichannel sea surface temperature, *J. Geophys. Res.*, 90 (1985) 11587-11601.

17 Owens N J P, Burkill P H, Mantoura R F C, Woodward E M S, Bellan I E, Aiken J, Howland R J M & Llewellyn, Size-fractioned primary production and nitrogen assimilation in the northwestern Indian Ocean, *Deep-Sea Res.,* II, 40 (1993) 697-709.

18 McCreary J P, Shetye S R & Kundu P K, Thermohaline forcing of eastern boundary currents: With application to the circulation off the west coast of Australia, *J. Mar. Res*., 44 (1986) 71–92.

19 Thadathil P & Gosh A K, Surface layer temperature inversion in the Arabian Sea during winter, *J Oceanogr.*, 48 (1992) 293 -304.

20 Madhupratap M, Gopalakrishnan T C, Haridas P, Nair K K C, Aravindakshan P N, Padmavati G & Paul S, Lack of seasonal and geographic variation in mesozooplankton biomass in the Arabian Sea nd its structure in the mixed layer, *Curr. Sci*., 71 (1996) 863-868**.**

21 Jerlov N G, *Marine optics*, (Elsevier, Amsterdam) 1976, pp. 132-137.

22 Beena Kumari, Mini Raman, Narain A & Sivaprakasam T E, Location of tuna resources in Indian waters using NOAA AVHRR data, *Int. J. remote Sensing*, 14 (1993) 3305-3309.

23 Holland K N & Grubbs R D, The trophic ecology of tuna aggregations: rationale, experimental design and early results, *52nd Annual Tuna Conference*, Lake Arrowhead, California. May 2001.

24 Grudinin V B, On the ecology of yellowfin tuna (*Thunnus albacares*) and big eye tuna (*Thunnus obesus*), *J. Ichthyol.*, 29 (1989) 22-29.

25 Dagorn L, Bach P & Josse E, Movement patterns of large big eye tuna (*Thunnus obesus*) in the open ocean determined using ultrasonic telemetry, *Mar. Biol.*, 136 (2000) 361-371.

26 Brill R W, A review of temperature and oxygen tolerance studies of tunas pertinent to fisheries oceanography, movement models and stock assessments, *Fish. Oceanogr.*, 3 (1994) 204-216.

27 Vijayakumar K, Parasuraman P S, Rajakumar S A & Nagarajan G, A study on the food and feeding habits of Yellowfin tuna (*Thunnus albacares*) caught in Andaman waters of Indian EEZ by tuna long lining, *Bull. Fish. Surv. India,* 24 (1992) 40-44.

28 Govindraj, John M E, Premchand, Unnikrishnan N, Jacob Thomas & Somvanshi V S, Oceanic tuna resources in the north west region of India EEZ, *Bull. Fish. Surv. India*, 27 (2000) 20-24.

29 Young J W, Bradford R, Lamb T D, Clementson L A, Kloser R & H. Galea H, Yellowfin tuna (*Thunnus albacares*) aggregations along the shelf break off south-eastern Australia: links between inshore and offshore processes, *Mar. Freshwater Res.*, 52 (1999) 463 – 474.

30 Brill R W, Block B A, Boggs, C H, Bigelow, K A, Freund E V & Marcinek D J, Horizontal movements and depth distribution of large adult yellowfin tuna (*Thunnus albacares*) near the Hawaiian Islands, recorded using ultrasonic telemetry: implications for the physiological ecology of pelagic fishes, *Mar. Biol.,* 133 (1999) 395-408.