Satellite Remote Sensing of Chlorophyll-a Distribution in the Northeast Arabian Sea

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Abstract-The present paper discuss on spatial and temporal distribution of chlorophyll-a (Chl-*a*) in the coastal and offshore waters of northeastern Arabian Sea, using Advanced Earth Observation Satellite OCTS data. The Chl-*a* concentration found high all along the western Indian coastal waters, with significant variations at Gulf of Cambay and Gulf of Kutch regions, ranging from 0.05 to 4.0 mg m^{-3}. Several intermittent eddies with a duration of 3 days to 4 weeks were observed in this season as a result of wind speed and circulation patterns with maximum Chl-*a* (4.0 mg m^{-3}) at their centers. The coastal chlorophyll is observed to transfer in pole-ward direction coupled with eastern boundary current or West Indian Coastal current (WICC) and, the clockwise tendency of Coriolis effect apart from wind direction. Possible interactions between Chl-*a* measurements, eddies, Sea Surface Temperature (SST), wind speed and river water discharge are discussed.

Keywords: Chl-*a*, OCTS, winter/northeast monsoon, Arabian Sea, eddy, West Indian Coastal Current

1. Introduction

In northern Arabian Sea, the rate of phytoplankton cell division is controlled by nutrient availability rather than light, while light inhibition of photosynthesis near the surface is negligible (*Tang et al*., 2002). The boundary and open ocean processes of Arabian Sea is influenced by upwelling during summer and cooling in winter that brings in high amount of nutrients into the upper ocean enhancing primary productivity, and ultimately the fisheries (*Madhupratap et al*., 2001). Along with productivity, the cold eddies are also known for occurrence in the Arabian Sea at some stages in winter monsoon (*Bohm et al*., 1999). In general, eddies appear to have appreciable deep vertical extension (*Qasim*, 1982) and the eddy circulation is attributed to the influence of bottom topography, that is marked by depressions and rises (*Das et al*., 1980). The physical response of northern Arabian Sea to the atmospheric jet and eddy fields are well explained by *Flagg and Kim* (1998) and *Lee et al*. (2000). The present paper is aimed to focus on Chl-*a* distribution in the northeast Arabian Sea with available OCTS data.

2. Material and methods

2.1. Study area

The Study area is extended between Latitude, N: 8^0-24^0 and Longitude, E: 65^0-76^0 on the surface waters of northeast Arabian Sea with a depth ranging from 200 to 4000m between coastal and offshore waters.

2.2. Satellite Chl-a data

We have analyzed Ocean Color and Temperature Sensor (OCTS) data onboard of Advanced Earth Observation Satellite (ADEOS-1).

2.3. Sea Surface Temperature

The AVHRR (Advanced Very-High Resolution Radiometer) pathfinder SST data (*http://podaac.jpl.nasa.gov/sst*) with a spatial resolution of 4 km/day (daytime) has been considered to study the correlation between Chl-*a* and SST measurements.

2.4. Surface wind speed

The weekly mean wind speed data was acquired from French Research Institute for Exploitation of the Sea (IFREMER) (*http://www.ifremer.fr*), corresponding with the dates of present analysis.

3. Results

3.1. Spatial distribution of Chl-a

Fig 1 shows distribution of Chl-*a* in the range of 0.05-4.0 mg m^{-3} (arbitrary scale) during the onset of winter monsoonal period (November, 1996). Higher concentrations are evidently seen all along the west coast and wide spread areas at the margins of Gulf of Cambay and Gulf of Kutch localities. Small synoptic/anticyclone eddies are also clearly seen over the sea at depth ranges from 200-3000m. The white circles in each image represents high chlorophyll patch and eddies while, black color indicates either land or no data. An anticyclone eddy (circle-A) with a diameter of 300km (N: 14^0-17^0 and E: 70^0-72^0) occurred along with a high patch of chlorophyll on its northern portion (20^{0}N, 69^{0}E), close to Gujarat state on the west coast of India (both areas are shown with white circles on 3 November image, Fig. 1). On next day (4 November), the intensity of eddy found reduced and moved further

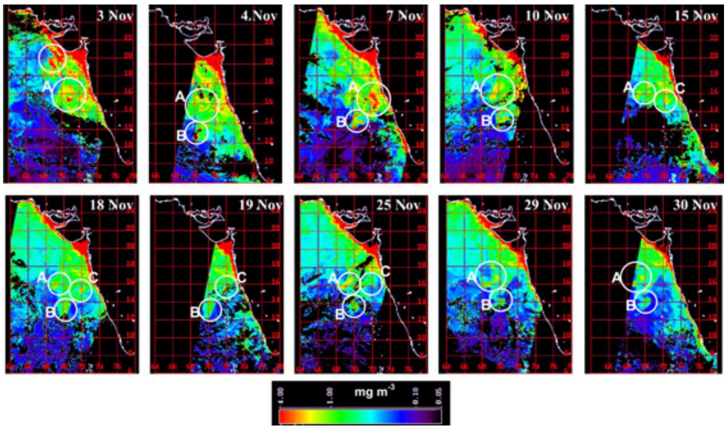

Fig. 1. Chl-*a* in the northeastern Arabian Sea during November 1996 (white circle with alphabets: eddies; white circle: high Chl-*a* patch; black color: no data/land)

east (towards the west coast of India) and, trapped the coastal Chl-*a* (7 November). On 10 November, the eddy slightly shifted westwards (16^0N, 69^0E) with lowering Chl-*a* (~2.0-3.0 mg m^{-3}) and continued to persist until end of the month. On 4 November, another eddy (circle-B) on its southern side (N: 12^0-14^0 and E: 70^0-72^0) at a depth ~3000m appeared for almost the same period like other with a slow pole-ward movement and less Chl-*a* concentration (~0.5-1.0 mg m^{-3}). Aggregation of costal Chl-*a* was observed (*vide* 10 November) on the left side (15^0N, 72^0E) of anticyclone eddy (circle-A) and, turned finally into a small synoptic eddy (circle-C) on 15 November that appeared for about 10 days.

3.2. Ocean environmental variables

3.2.1. SST (^{0}C)

Fig. 2 shows SST variations in the range, 20^0C-31^0C. During November, 1996, the coastal waters located on north to the Gulf of Kutch showed a gradual decrease in SST (white oval representing ~22^0C-23^0C) up to 20^0C by the month of December. Such low SST zone (around 20^0C) extended to the northern boarder of the Arabian Sea (25^0 N and 65^0 E) and occurred till the end of monsoon. However, a significant increase in SST (up to 30^0C) was observed in the southern side (15 November), and appeared slowly extended in upward (pole-ward) direction. While, most of the northeastern Arabian Sea region shows SST within the range 24^0C-25^0C for the first week of November (7 November), but enhanced temperatures covering utmost of study area witnessed during the third week of December.

3.2.2. Sea surface wind (m/s)

The average wind speed in the study area for the season is varied between 2 and 8 m/s. A steady increase in wind speed was observed from November onwards as the monsoon progresses until mid of January. Later on, the sea found calm at most parts with less intensity of wind speed.

4. Discussion

4.1. High Chl-a and eddies

The present results have clearly highlighted the incidence of high Chl-*a* concentration as a prime source of productivity in the coastal and offshore waters of northeast Arabian Sea. The winter convection (overturning) process which brings nutrient rich subsurface waters to the photic zone found responsible for this enhanced biological production. *Wiggert et al.* (2000) reported significant nitrate flux in surface waters (upper 100m) following the effect of convection, with increased nitrate concentrations (4µM). Also, the SeaWiFS (Sea-viewing Wide Field-of-view Sensor) data analysis (*Wiggert et al.*, 2001), revealed a consistent seasonal behavior that starts with a notable increase of Chl-*a* between mid-November and mid-

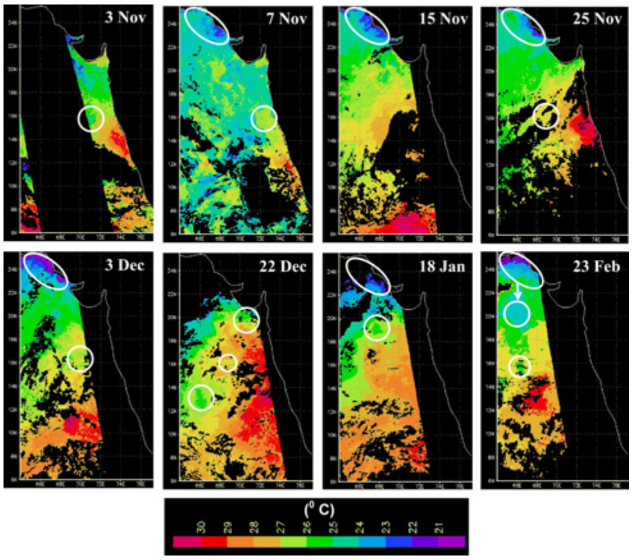

Fig. 2. SST variations in the study area: November 1996 – February 1997 (white circle: area of eddies/high Chl-*a* patch; black color: no data/land; white oval: low SST; down arrow: path of lower SST gradient)

December, followed with no appreciable change over the following months. However, the productivity of coastal waters found higher than open sea during winter monsoon, well in conformity with the observations made by *Dey and Singh* (2003). The winter monsoon (begins by November every year) supplies about 20% of Indian rainfall in most of the states on the west coast of India, where the two rivers, Narmada and Tapti are the major input sources of nutrients from up stream locations into northeast Arabian Sea. Based on available long-term river discharge database (1949-1979) (*GRDC*, 2004), the mean annual discharge of these two rivers are estimated as 1216 and 489 m^3/sec while, an average of November and December period is found to be 255.2 and 132.80 m^3/sec respectively. Nevertheless, from March onwards the chlorophyll concentration in the Arabian Sea is likely to decrease with the approach of spring-winter monsoon (March-May), when ocean water becomes warm and highly stratified, under the influence of peak insolation together with lighter winds that inhibits vertical mixing and upwelling of subsurface nutrients (*Kumar et al*., 2000). The tendency of deceasing Chl-*a* was observed from the foremost northern boarder of Arabian Sea to the south, attributed to the movement of cold water from upper layer to the lower.

Large and persistent eddies carrying upwelled water and the included biological populations from the coastal area into the interior of the Arabian Sea was reported by *Brink et al*. (1998) and *Lee et al.* (2000). In addition, *Flagg and Kim* (1998) mentioned that northern Arabian Sea currents are dominated by these features (spatial scale of ~300 km) due to coastal current systems and their instabilities as a source. *Kim et al.* (2001) reported the spatial scale of these eddies ranges between 200 and 500 km in the nearshore region and decrease to 100-200 km offshore. In the present study, altogether 14 eddies were observed for the period of winter season, of which two are anticyclonic in nature lasting for maximum time (3-4 weeks) while, rest are small from 3 days to 3 weeks. Eddies formed close to the west coast of India persisted for longer periods compared to offshore ones, which could be due to the trapping of coastal water around these eddies thus creating a high productivity region. At each of these eddies, the circular movement of water enfolded the plankton in near water and brings it to their center recording maximum Chl-*a* of 4.0 mg m^{-3}. Eddies with longer duration have also shown a gradual movement in pole-ward direction following the current of coastal water.

4.2. Environmental impact

The consequences of SST and phytoplankton blooms are recently studied in detail by *Tang et al*. (2002) for the northern Arabian Sea region. Water temperature and nutrients are the two important factors affecting the growth of phytoplankton (*Tang et al*., 2003). The presence of high phytoplankton biomass might raise SST values on as it could intercept the short wave radiation in blue (*Chaturvedi et al*., 1998). In contrast, a gradual decrease of temperature (~24-25^{0}C to 20^{0}C) was observed together with the movement of Chl-*a* concentration in pole-ward direction (Fig. 1). In other words, it could be also expressed as Chl-*a* moved in pole-ward direction with the approach of warm waters down from southern side, where its concentration has become less than 1.0 mg m^{-3}. Similar pattern of temperature variation has been reported by *Wiggert et al.* (2001) for central Arabian Sea and, *Tang et al*. (2002) at the Gulf of Oman (northwestern Arabian Sea) regions for the same season. In the present analysis, low temperature with a variation of 1^{0}C in SST (~25-26^{0}C and 26-27^{0}C) encountered near the places of eddies and high Chl-*a* (Fig. 2). This may be likely due to the wind stress curl related to vertical pumping velocity associated with cyclonic eddies. These blooming areas are supplied with nutrient enriched subsurface cold waters to the surface layer, accountable for decreasing temperatures as shown with white circles on Fig. 2.

When surface wind speed is taken into consideration, a clear-cut correlation was observed between eddies and the wind speed. The places of eddies and high Chl-*a* are representing an average wind speed of 6.5-7.5 m/s. The places with high wind and low temperatures are likely to represent the vertical mixing of waters that bring subsurface cold waters above. *Gardner et al*. (1999) suggested that two monsoonal regimes (winter and summer) separated by spring and fall intermonsoon periods in Arabian Sea, characterized by a reduction of wind stress over the ocean surface and consequential diminishing of the upper mixed-layer depth. The high winds with a maximum speed of 8 m/s are observed only during November and December as wind velocity decreased from January onwards with increased SST, establishing an inverse relationship. The surface currents in Arabian Sea are directed against to the monsoonal winds, in contrast with historical ship-drift data indicating currents following the wind (*Flagg and Kim,* 1998). Finally, wind appeared to be the driving factor and dominated over other environmental parameters in the distribution and transformation of materials during the winter monsoon period. However, less influence of wind irrespective of pronounced Chlorophyll blooming adjacent to the west coast of India, must be associated with upstream discharges that bring nutrients to the sea.

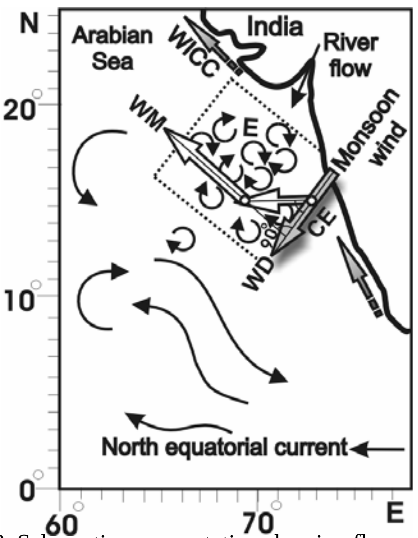

Fig. 3. Schematic representation showing flow pattern and eddies in the northeast Arabian Sea during winter monsoon.

Finally, Chl-*a* concentration is significantly high due to winter convective mixing and slowly transferred in pole-ward direction where, the transfer of material was primarily because of West Indian Coastal Current (WICC) (Fig. 3). In this case, the movement of water along the coast is also influenced by the rightward tendency of Coriolis effect and the gravity-powered movement of water down the pressure gradient. Apart from wind direction, the water movement has taken its initial direction with about 30^0-45^0 from the coast and finally turned up to 90^0 right parallel to the coast. A direct relationship between Chlorophyll and wind parameters was established, while SST-wind and SST-Chlorophyll are inversely proportional.

ACKNOWLEDGEMENTS

The present research was carried out with the help of partial support of Chinese Academy of Sciences Research Fund (KZCX3-SW-227) and 'One Hundred Talents Program' of Chinese Academy of Sciences.

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