

## Pigment patterns in the Arabian Sea: Spatio-temporal variability as observed by ADEOS

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### Abstract

The spatial and temporal variations of the near-surface concentration of phytoplankton pigment observed by ADEOS during November 1996 - May 1997 are studied in relation to SST and winds. Monthly composite images from OCTS depict spatial and temporal variation of phytoplankton pigment concentration in the Arabian Sea. Appreciable regional differences in levels and timing of changes of pigment concentration was found, with a large bloom north of 20°N in February 1997. Pigment concentration at 20°N, 10°N and equator ranged from 0.3–3.0, 0.01–0.3 and 0.01–1.0 mg m<sup>-3</sup> respectively during the NEM (October-January) period and between 0.01–0.3, 0.01–0.3 and 0.01–0.03 mg m<sup>-3</sup> respectively during the TR (February-May) period. Monthly means of SST and winds are related to monthly averaged pigment concentrations in order to explain the observed changes in pigment concentration. Low SST and high pigment concentration in the northern Arabian Sea during northeast monsoon may be due to the winter cooling as reported earlier. Chlorophyll concentrations remained relatively high from November to February when winds reversed direction. The results indicate that the OCTS images along with the wind field obtained from NSCAT are useful for understanding the distribution of pigment concentration in the Arabian Sea.

### 1. Introduction

Phytoplankton pigments, principally chlorophyll *a*, are of intrinsic interest as an estimate of phytoplankton biomass in regional and seasonal contexts. Pigment concentrations can also be used for estimating photosynthesis (e.g., Platt *et al.*, 1991; Berthot and Morel, 1992) or the role of light absorption in heating of the upper layers of oceans (Sathyendranath *et al.*, 1991). The analysis of the images of the ocean colour collected with the help of remote sensing seems to be a good method for estimation of the general patterns of spatial and temporal variations of phytoplankton pigment concentrations in surface layer of sea water. Although there are discrepancies in the remote measurement of pigment as compared to the *in situ* methods (Chavez, 1995), these observations are rather regular and numerous; thus, they are important for assessing the variations of the phytoplankton pigment in the Arabian Sea.

The goal of this paper is twofold. First, we describe the observed spatial and temporal variability of the surface chl *a* over the Arabian Sea as observed by ADEOS during November 1996 – May 1997. Second, we see if there is any relation between the observed spatio-temporal variability of chl *a* in the Arabian Sea with the upper ocean physical parameters like SST and surface winds.

### 2. Data and Methods

#### 2.1. Data

Our analyses are based on data sets from diverse sources. The mission characteristics of (Ocean Colour and Temperature Sensor) OCTS are given in Table 1 whereas Table 2 gives the major parameters of OCTS. Kawamura *et al.*, 1998 have given an overview of the OCTS mission. The OCTS data was obtained from NASDA. For the present study monthly, Chl *a* (Ver. 4.0) and SST (Ver. 4.1) from 01-11-96 – 31-05-97 were used. The data set has a resolution of 9 km. NASA's Scatterometer (NSCAT), a microwave radar scatterometer had measured near-surface wind *vectors* (both speed and direction) over the global oceans. The NSCAT acquired data in two, 600 km swaths separated by a 329 km gap at nadir. Earlier research work published in Journal of Geophysical Research, 1999 104(C5), has discussed the accuracy and other aspects of this radar. Wind data obtained from NSCAT was obtained from <http://www.eorc.nasda.go.jp>.

#### 2.2. The study area

For the present study, we have covered the Arabian Sea from equator to 25°N and 60°–80°E (fig. 1). Three regions have been defined and are as follows:

- (i) 00° - 10°N (A),
- (ii) 10° - 20°N (B),
- (iii) above 20°N (C).

Table 1. OCTS mission characteristics.

Orbit type	Sun synchronous
Altitude	~ 800 km
Inclination	98.6°
Orbital Period	101 min
Repetivity	3 days
Swath width	1400 km
Tilt angle	± 20°
Digitization	10 bits
IFOV	700 m at nadir
Scan Angle	± 40°

Table 2. Major parameters of OCTS.

	Band	Band Range (µm)	Central Wavelength (µm)
Visible and NIR Bands	B1	0.402 - 0.422	0.412
	B2	0.433 - 0.453	0.443
	B3	0.480 - 0.500	0.490
	B4	0.510 - 0.530	0.520
	B5	0.555 - 0.575	0.565
	B6	0.655 - 0.675	0.670
	B7	0.745 - 0.785	0.765
	B8	0.845 - 0.885	0.865
TIR Bands	B9	3.55 - 3.88	
	B10	8.25 - 8.80	
	B11	10.3 - 11.4	
	B12	11.4 - 12.5	

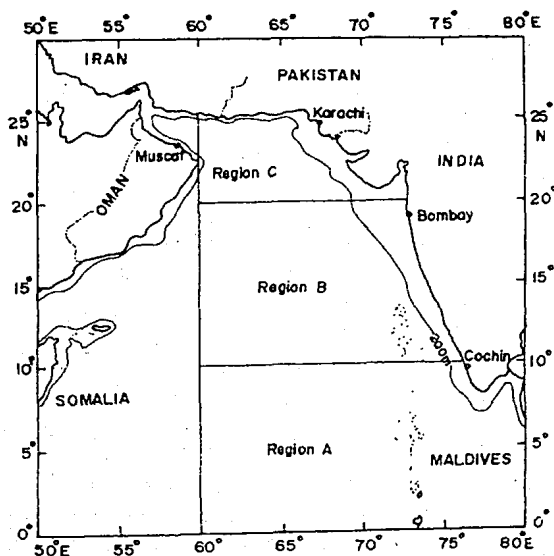


Fig. 1. Study Area.

Each region is further sub-divided into coastal and open ocean waters. Region A covers only the peninsular tip and is thus, more oceanic. The 200 m depth contour is taken as the boundary for the coastal and open ocean waters. *In situ* chl *a* measurements obtained from the recently published Indian Ocean Atlas (Bhargava, 1999). These have been used in our study for comparison with the satellite data to arrive at more complete descriptions. The data in the atlas has been compiled from 1959–96, grouped into three seasons – Northeast Monsoon (NEM), Transition (TR) and Southwest Monsoon (SWM) as mentioned earlier but the seasons are named as post-monsoon, pre-monsoon and monsoon, respectively. The results and discussions section proceeds in an approximate south-to-north sequence i.e., from an oceanic to the most influenced by land, treating region A (00° – 10°N) first and region C (above 20°N) last.

### 3. Results and Discussion

#### 3.1 Spatial and temporal ocean colour variability in the Arabian Sea

##### 3.1.1. NEM Period (November 1996 – January 1997)

A general trend of low chl *a* concentration in south (region A) and high chl *a* concentration in the north (above 10°N) was observed. In region A, chl *a* concentration ranged from 0.01–1.0 mg m<sup>-3</sup> in open ocean waters and 0.3–1.0 mg m<sup>-3</sup> in coastal waters. In region B, chl *a* concentration ranged from 0.3–1.0 mg m<sup>-3</sup> in open ocean waters. During this period, the coastal water concentration ranged from 0.3–10.0 mg m<sup>-3</sup> but <30.0 mg m<sup>-3</sup>. Patches of high concentration of chl *a* (upto 2.0 mg m<sup>-3</sup>) were observed between 10°–20°N and 70°–80°E. Coastal waters showed high chl *a* concentration as compared to the open ocean waters (Table 3). Chl *a* concentrations had steadily increased from November to January. In the central Arabian Sea, chl *a* concentration ranged from 0.3–1.0 mg m<sup>-3</sup> during this period.

##### 3.1.2. TR Period (February 1997 – May 1997)

From March to May most parts of the Arabian Sea resembled an oligotrophic ocean with chl *a* concentration ranging from 0.01–0.1 mg m<sup>-3</sup>. Small patches of high chl *a* concentration (0.3–1.0 mg m<sup>-3</sup>) were observed during March in region A, which completely disappeared in April. Coastal waters showed high chl *a* concentration as compared to the open ocean waters, Table 4. Chl *a* concentration ranging from 0.1–1.0 mg m<sup>-3</sup> were observed around the peninsula in May. Similar trends of chl *a*

Table 3. Monthly Chl *a* (mg m<sup>-3</sup>), SST (°C) and wind speed (m/s) in the Arabian Sea during the NEM period.

Month	Region	Coastal			Open Ocean Waters		
		Chl <i>a</i>	SST	Wind speed	Chl <i>a</i>	SST	Wind speed
November 1996	A	0.3 – 1.0	30	5 – 7	0.01 – 1.0	30	6 – 7
	B	0.3 – 10.0	25 – 30	5 – 7	0.1 – 1.0 *	25 – 30	6 – 7
	C	3.0 – 10.0	25	5 – 7	0.3 – 1.0*	25	4 – 6
December 1996	A	0.3 – 1.0	30	5 – 7	0.01 – 1.0	25 – 30	4 – 6
	B	0.3 – 1.0	30	5 – 7	0.01 – 1.0	25 – 30	5 – 6
	C	> 3.0 < 10.0	20 – 25	5 – 7	0.3 – 1.0	20 – 25	3 – 6
January 1997	A	0.3 – 1.0	30	8	0.01 – 1.0	28	6 – 7
	B	0.3 – >3.0	25 – 30	5 – 7	0.01 – 1.0	25 – 28	5 – 7
	C	> 3.0 < 10.0	20	5 – 7	0.3 – 1.0	20	5 – 7

\* Patches of 2.0 mg m<sup>-3</sup> observed.Table 4. Monthly Chl *a* (mg m<sup>-3</sup>), SST (°C) and wind speed (m/s) in the Arabian Sea during the TR period.

Month	Region	Coastal			Open Ocean Waters		
		Chl <i>a</i>	SST	Wind speed	Chl <i>a</i>	SST	Wind speed
February 1997	A	0.01 – 0.3	> 25 < 30	2 – 4	0.01 – 0.1	> 25	4 – 7
	B	0.3 – 10.0	25	5 – 7	0.01 – 3.0	20 – 25	5 – 6
	C	10.0 – 30.0	20	4 – 6	10.0 – 30.0	20	2 – 4
March 1997	A	0.01 – 0.03	> 25 < 30	2 – 4	0.01 – 0.3	25	2 – 6
	B	0.1 – 1.0	> 25 < 30	2 – 5	0.01 – 1.0	25 – 30	2 – 6
	C	> 3.0 < 10.0	20 – 25	4 – 7	0.3 – 10.0	20 – 25	4 – 6
April 1997	A	0.01 – 0.3	30	2 – 4	0.1 – 0.1	> 25 < 30	5 – 6
	B	0.01 – 0.3	> 25 < 30	5 – 6	0.01 – 0.1	> 25 < 30	2 – 6
	C	0.03 – 1.0	25	5 – 6	0.01 – 1.0	25	3 – 6
May 1997	A	0.1 – 1.0	30	6 – 8	0.01 – 0.3	30	5 – 8
	B	0.1 – 1.0	30	6 – 7	0.01 – 0.3	30	2 – 6
	C	0.3	30	6 – 7	0.01 – 0.1	30	5 – 7

distribution have been reported earlier by Sastry and Gopinathan (1985). Chl *a* concentration had decreased from February to May. In the central Arabian Sea, *i.e.*, region B, the chl *a* values ranged from 0.01–0.3 mg m<sup>-3</sup> during this period. High chl *a* concentration were observed in the north (region C) where a large bloom was observed during February.

### 3.1.3. Bloom

A bloom covering almost the entire region C was observed during February (Fig. 2). The chl *a* concentration in this region ranged from 0.3–1.0 mg m<sup>-3</sup> around 60°N and >10.0 but < 30.0 mg m<sup>-3</sup> beyond 65°N in the open ocean waters and was 10.0–30.0 mg m<sup>-3</sup> in coastal waters. The bloom started to retreat northward in March and disappeared by April. This bloom was deduced to be due to addition of nutrients in the surface layers convective overturn (Prasanna Kumar and Prasad, 1996, Madhupratap *et al.*, 1996).

Blooms occurring during same period have been reported earlier by Banse and English (1993). No seatruth data was available for comparative studies. However, the bloom was also observed earlier by the CZCS (Fig. 3). Thus, as reported earlier, the northern Arabian Sea continues to sustain fairly high biological production after the upwelling season and during much of the NEM (Banse and McClain, 1986) probably due to the winter cooling effect (Madhupratap *et al.*, 1996). Chl *a* concentrations of 0.3–1.0 mg m<sup>-3</sup> were seen in a small area north of 20°N in April.

### 3.2 IME

In order to explain the Island Mass Effect (IME) we describe chl *a* as observed from the OCTS in the vicinity of the Laccadive and the Maldiv Islands. The IME is an important contributor to the productivity of the region and therefore, potentially important for fisheries in the area. We have compared the satellite

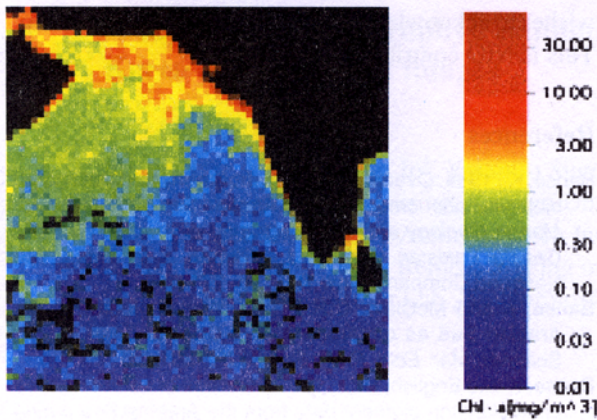


Fig. 2. Bloom during February 1997 from OCTS.

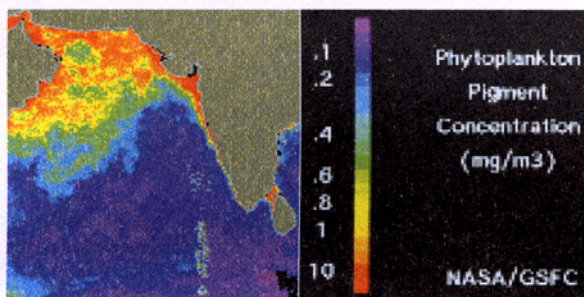


Fig. 3. Bloom during February 1982 from CZCS.

observed values of chl *a* with the *in situ* data obtained from the Indian Ocean Atlas.

High surface chl *a* concentration (0.3–1.0 mg m<sup>-3</sup>) in the vicinity of the Laccadive and Maldivé Islands were observed during the entire period of observation, except February (due to lack of data). Surrounding region had low chl *a* ranging from 0.01–0.1 mg m<sup>-3</sup>. *In situ* surface values range from 0.05–0.1 mg m<sup>-3</sup> in the NEM and from 0.1–0.2 mg m<sup>-3</sup> in TR period around the Laccadive Islands. Around the Maldivé Islands, they range from 0.05–0.1 mg m<sup>-3</sup> in the NEM and from 0.05–0.2 mg m<sup>-3</sup> in TR period. The enhancement and persistence of high concentration of chl *a* around the islands can be attributed to the IME. The effect consists of a combination of turbulent mixing and enrichment of surrounding water from land drainage, the former being more appropriate since land drainage (around Laccadive Islands) is very negligible. The high concentrations of chl *a* around these islands were also observed by the CZCS (Lierheimer, 1997). Further studies covering a longer period is required to throw more light on this aspect.

### 3.3 Relationships between satellite derived chl *a* and SST and wind field

It is presumed that processes responsible for lowering of SST or increase of surface winds would enhance

vertical movement and, the supply of nutrient to the upper layers and thus affect the timing of the phytoplankton abundance and bloom formation.

SST has a bimodal cycle with lower temperature during the wet SWM and the dry and cool NEM periods. Surface temperature ranges from 22.5–28.5°C, increasing from north to south (Qasim, 1982). It has been recognized for some time that the distribution of phytoplankton chlorophyll in the Arabian Sea is influenced by seasonal changes in atmospheric winds (Banse, 1984; Nair *et al.*, 1989; Smith, 1984; Smith and Codispoti, 1980). In response to the winds the direction of ocean circulation changes *i.e.*, the Somali Current flows towards the southwest during the NEM and towards the northeast during the SWM.

#### 3.3.1. NEM Period (November 1996 – January 1997)

The increase in chl *a* concentration during November–December is concomitant with decreasing SST, from 25–30 °C. The surface winds during November–December were predominantly north/north easterlies (Table 3). Wind speeds of 2–3 m/s were observed near Laccadive Islands. Similar observations were also reported by Luis and Kawamura (2000). During January, wind speed upto 8 m/s was observed along the coast around the peninsular tip of India. Luis and Kawamura (2000) reported 7.5 m/s around the peninsular tip of India and have contributed this to the characteristic topography of South India and Sri Lanka and their orientation to the direction of the air flow. During November, the observed wind speed along the coast varied between 5 and 7 m/s most of the time. In the open ocean, the wind speed showed a gradual increase from about 4–7 m/s towards south. During December, the wind speed ranged from 3–6 m/s from north to south. In the open ocean, wind speeds were high north of 10°N reaching up to 8 m/s between 10°–20°N and 60°–70°E. With decrease of SST from south to north, chl *a* concentration decreased. During January, SST was as low as 20°C, in region C and the surface winds were predominantly northerly and ranging from 5–7 m/s. Wind speed of <5 m/s was reported earlier by Prasanna Kumar and Prasad (1996).

#### 3.3.2 TR Period (February 1997 – May 1997)

The surface winds during February–March, were weak (2–6 m/s) and were predominantly north/north easterly. In region B, SST was around 25 °C (Table 4). However, south of this region, conditions were warm (SST was high around 30 °C). Similar values have been reported earlier by Prasanna Kumar and Prasad (1996). Along the coast, the observed wind speed varied between

4–7 m/s, except in March in region A where it was 2 m/s. SST ranged from 20–30°C from north to south. During April, the surface wind speed ranged from 3–6 m/s. A large area with low wind speed ( $\cong 2$  m/s) was observed in region B (between 10–20°N and 60–70°E). Above and below this area, wind speed ranged from 4–7 m/s. SST ranged from 25–30°C and chl *a* concentration from 1.0–0.03 mg m<sup>-3</sup> from north to south. During the period of bloom (i.e., high in chl *a* concentration), SST in region C was 20°C. Along the northern coast, the wind speeds were between 4–7 m/s. During May, westerlies with speed of 8 m/s were observed. The sea was warm (SST  $\cong 30^\circ\text{C}$ ) and chl *a* concentration was low (0.01 mg m<sup>-3</sup>) for almost the entire Arabian Sea. During May, the Arabian Sea resembles an oligotrophic ocean. Lower values of chl *a* observed during this period may also be due to low nutrient concentration. An inverse relationship between chlorophyll concentration and SST (as observed) may be due to negative correlation between temperature and nutrients (Kamykowski, 1987), which ultimately affects phytoplankton growth occurrence.

The above analysis brings out the interesting changes from the NEM to the TR period as well the predominant south-north variations.

#### 4. Conclusion

The overall spatial and temporal patterns of pigment distribution in the upper region of the euphotic zone described in the present study, support the findings from earlier studies. Pigment concentrations increase from south to north in general and region C is richer than region B. The winter bloom of the northern Arabian Sea, in region C, is the principal biological difference from the remaining parts of the Arabian Sea. While it is possible to infer that chl *a* and SST are inversely related, no relationship between chl *a* and winds could be found. We suggest that extensive work on this aspect needs to be carried out with larger datasets from the present day satellite sensors such as SeaWiFS, OCM, AVHRR, ASTR, MSMR and SCAT sensors for a better understanding of the effect of SST and winds on the pigment distribution. High pigment concentration around the islands of Laccadives and Maldives can be attributed to the island mass effect.

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