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Phytoplankton bloom monitoring in the offshore water of northern Arabian Sea using IRS-P4 OCM satellite data

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IRS-P4 Ocean Color Monitor (OCM) satellite data were analyzed to generate chlorophyll-*a* images during the winter monsoon period to understand the high productivity and algal bloom patches as observed in the chlorophyll images. The winter bloom in the northern Arabian Sea is the most intense because of the nutrient build-up prior to its onset is so large and the mixed layer detrains earlier than in the other regions, which in turn triggers the surface productivity. A few bloom forming features are identified in the OCM derived chlorophyll images in nine days of overpasses (February, 15 to March 4, 2000) of the late winter monsoon period and their movement mechanism on temporal scale has been studied. Very high chlorophyll concentration in the range of 2.0 to 5.0 mg/m^3 have been observed around the bloom forming waters in satellite images. The peak chlorophyll concentration observed in the center of patches reduces towards their peripheral water. The curly bloom forming features initiates with moderate chlorophyll concentration (0.6-1.0 mg/m^3), grows to high concentration (1.0-2.0 mg/m^3) and diminishes with low concentration (<0.6 mg/m^3) ranges, lasting for about two-three weeks duration.

Ocean colour remote sensing is a widely recognized tool for monitoring the optically active biogeochemical parameters like phytoplankton pigments (e.g. chlorophyll), suspended particulate matter and yellow substance. Measurements of ocean colour and the fate of light in the ocean are extremely useful for describing biological dynamics in surface waters[1-3], thus the oceanographic community has made their commitment to remote sensing of ocean colour from space[4,5]. The central Arabian Sea was found to be more productive than sub-tropical gyre elsewhere, and the area north of 20°N to be richer than the central Arabian Sea[6]. The results from an Indian Joint Global Ocean Flux Studies (JGOFS) cruise, during February – March 1995, also revealed the evidence of high productivity in the northern Arabian Sea compared with inter-monsoon period[7].

Occasionally phytoplankton grows very fast or “blooms” and accumulates into dense, visible patches near the surface water. Knowledge of presence, absence and timing of elevated plant concentrations is a pre-requisite for successful planning of studies of plant productivity, the investigation of suspension feeding zooplankton and the seasonality of particle fluxes to the deep sea[8]. High levels of primary production and phytoplankton biomass reflect a favorable environment in terms of light and the supply of inorganic nutrients. However, it has been recognized that the most important factor controlling phytoplankton is turbulence and advection[9], because they determine the duration of how long the plankton stays in the euphotic zone or close to favorable conditions.

The blooms can form rapidly and it is often difficult to assess their development and extent from traditional sampling methods using a boat or a fixed-site monitoring station. Remote sensing technique offers a practical tool in overcoming these problems[10,11]. Large areas can be covered rapidly to determine the spatial extent of a bloom in near real time, providing quick and effective means to detect and monitor bloom formation.

The ocean colour monitor (OCM) of the Indian Remote Sensing Satellite IRS-P4 is optimally designed for the estimation of chlorophyll in coastal and oceanic waters, detection and monitoring of phytoplankton blooms, studying the suspended sediment dynamics and the characterization of the atmospheric aerosols. The technical specifications of the OCM sensor are given in Table 1. In the present study, the phytoplankton blooming has been monitored in the chlorophyll images derived from the IRS-P4 OCM data for the offshore waters of the

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Table 1—Technical characteristics of IRS P4 OCM payload

Spectral Range	404-882 nm
No. of channels	8
Wavelengths range (nm) and Signal to noise ratio (SNR)	Channel 1:404-423 (340.5)
	Channel 2:431-451 (440.7)
	Channel 3:475-495 (427.6)
	Channel 4:501-520 (408.8)
	Channel 5:547-565 (412.2)
	Channel 6:660-677 (345.6)
	Channel 7:749-787 (393.7)
	Channel 8:847-882 (253.6)
Satellite altitude (km)	720
Spatial resolution (m)	360×236
Swath (km)	1420
Repeativity	2 days
Quantisation	12 bits
Equatorial crossing time	12 noon
Along track steering (to avoid sunglint)	20°

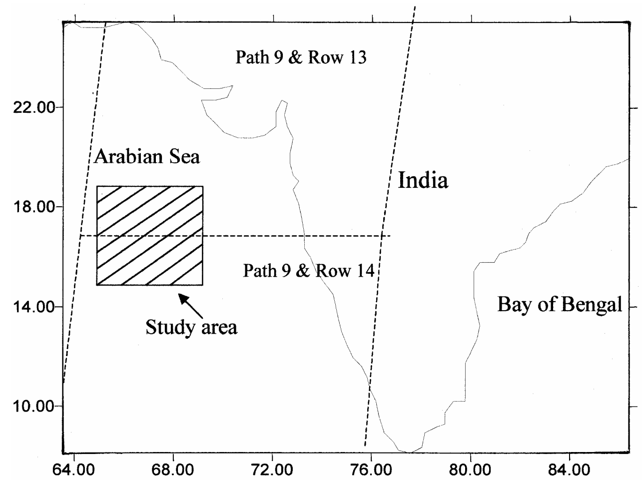

Fig. 1—Location map of bloom area, viewed by Path 9 and Row (13,14) of IRS-P4 OCM satellite overpasses, covering the Arabian Sea.

northern Arabian Sea and the movement mechanism of blooming features (algal filaments) are discussed.

Materials and Methods

The retrieval of ocean colour parameter such as phytoplankton pigment (chlorophyll-*a*) in oceanic waters, involves two major steps, the atmospheric correction of visible channels to obtain normalized water leaving radiances in shorter wavelengths and application of the bio-optical algorithm for retrieval of phytoplankton pigment concentrations.

Atmospheric correction of the IRS-P4 OCM imagery

In remote sensing of the ocean, the signal received at the satellite altitude is dominated by radiance contributions through atmospheric scattering processes and only 8-10% signal corresponds to oceanic reflectance[12]. Therefore, it has been mandatory to correct the atmospheric effect to retrieve any quantitative parameter from space. An algorithm has been developed at Space Applications Centre (ISRO), Ahmedabad, to correct OCM data for atmospheric contamination[13]. The OCM scenes were corrected for atmospheric effects of Rayleigh and aerosol scattering using an approach called long wavelength atmospheric correction method. The approach[12] used the two near-infrared channels at 765 and 865 nm to correct for the contribution of molecular and aerosol scattering in visible wavelengths at 412, 443, 490, 510, and 555 nm. The water leaving radiances derived after atmospheric correction is converted to remote sensing reflectance (R_{rs}) using the following formula and were used to compute chlorophyll-*a* pigment concentration:

$$R_{rs} = \pi L_w / F_{0,}$$

where L_w is the water leaving radiance and F_0 is the extra-terrestrial solar flux[12].

Chlorophyll algorithm

A number of bio-optical algorithm for retrieval of chlorophyll have been developed to relate measurements of water leaving radiance to the *in situ* concentrations of phytoplankton pigments. An empirical algorithm (also known as Ocean Chlorophyll 2 or OC2) is being operated for SeaWiFS ocean colour data[14]. This algorithm captures the inherent sigmoid relationship between the log transformed band ratio (R_{rs}490/R_{rs}555) and chlorophyll concentration C, where R_{rs} is the remote sensing reflectance at 490 and 555 nm bands respectively. The algorithm was shown to retrieve low as well as high chlorophyll concentration which means a better retrieval even in case 2 waters[14]. The algorithm operates with five coefficients and has the following mathematical form.

$$C=-0.040+10^{[0.341-3.001*X+2.811*X2-2.041*X3]}$$

where C is chlorophyll concentration in mg/m^3 and $X = \log_{10}[R_{rs}490/R_{rs}555]$.

While comparing all available algorithms for Indian waters, it was observed that this algorithm provided best results for chlorophyll retrieval[15]. This algorithm has been presently used for generating the chlorophyll maps, using IRS-P4 OCM derived water leaving radiances.

Dataset used

The chlorophyll images were generated using the above mentioned procedure for nine consecutive passes of IRS-P4 OCM on 15, 17, 19, 23, 25, 27 and 29 February and on 2 and 4 March 2000 over the north-east part of Arabian Sea (Path 9 and Row 13-14) (Fig. 1). The chlorophyll images were geometrically corrected and gridded with 2° latitude and longitude intervals. The two passes' images were mosaiced for each day and a subset was taken for the Arabian Sea coverage. The analysis of these chlorophyll images revealed the presence of high-chlorophyll filament-like structures in deep oceanic regions (around 14°-20° N latitude and 65.5° - 68° E longitude) (Fig. 2). A transect is drawn on the bloom forming areas in the image of February 15 (Fig. 3), the data points on the transect were extracted from 9 images covering 9 days and were plotted to study the phytoplankton dynamics. Subset images were also retrieved around the transect to study the dynamics pattern during the algal bloom in detail.

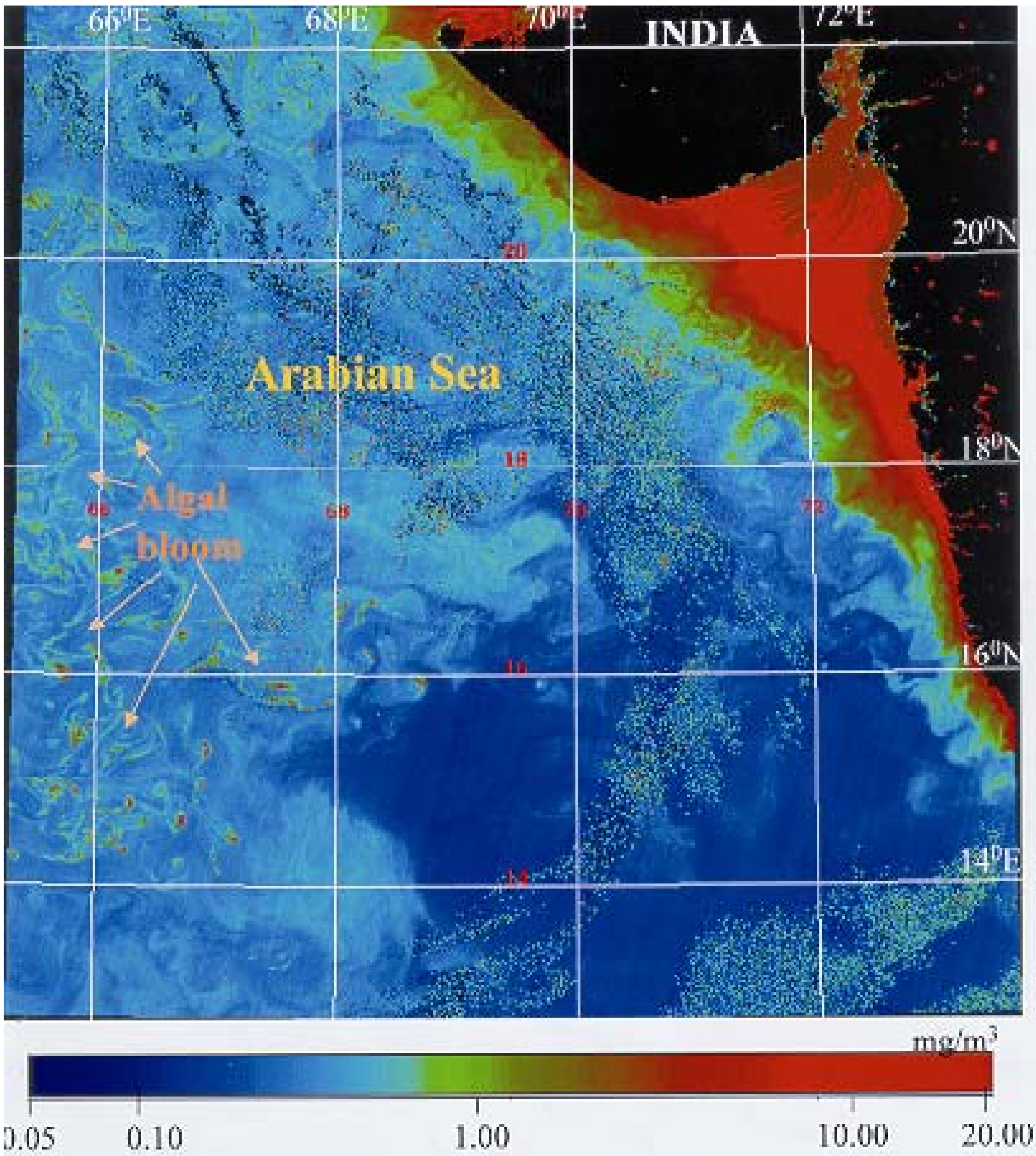

Fig. 2—IRS-P4 OCM derived chlorophyll image, showing phytoplankton blooms and other oceanic features for the date 19th February 2000.

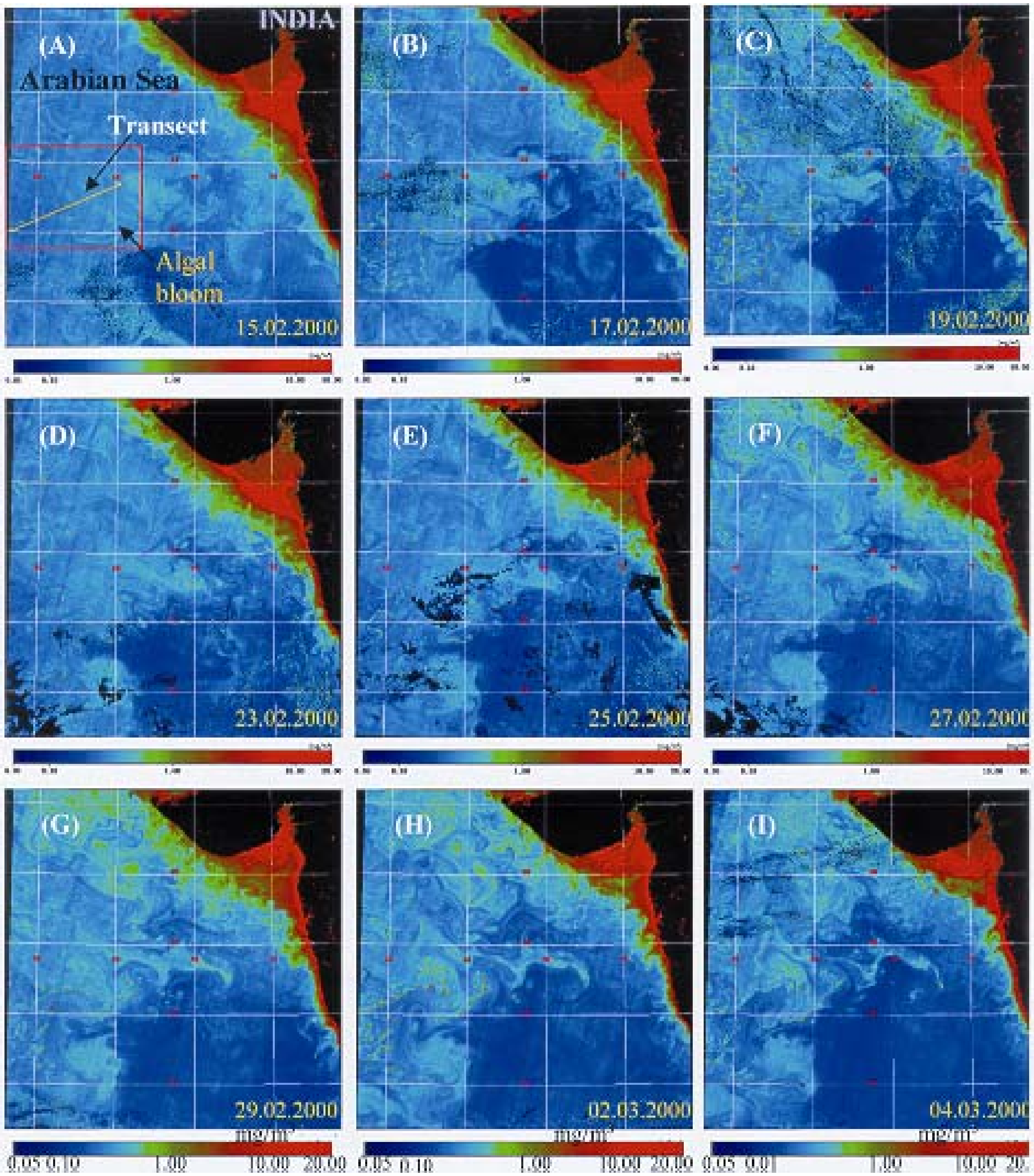

Fig. 3—IRS-P4 OCM derived chlorophyll images of northeast part of the Arabian Sea, featuring the phytoplankton blooming stages.

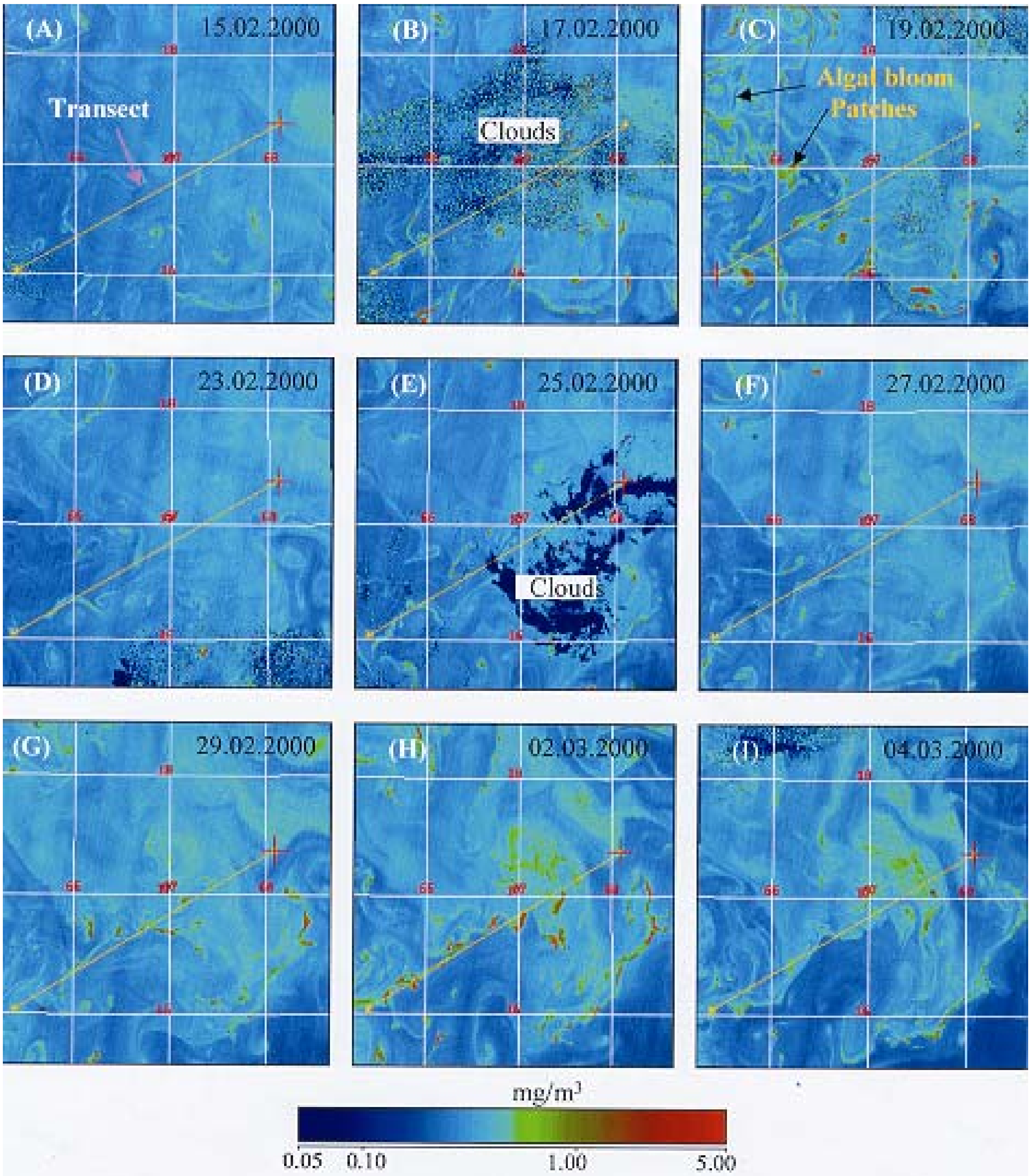

Fig. 4—IRS-P4 OCM derived chlorophyll-*a* sub-images for the observed bloom area along with the transect (box marked in Fig. 3).

Results and Discussion

For identifying the period of bloom in the study area, the chlorophyll images generated from the IRS-P4 OCM data were reviewed for the period January – March 2000. The bloom (high chlorophyll concentration patches) period is identified between 15th February to 4th March 2000 (Fig. 3) with different phases for the selected area (Fig. 4). During the bloom period, the chlorophyll concentration ranged between 0.01 – 5.0 mg/m^3 as observed in the subset images in Fig. 4. In the 1st image of the present study for the date 15th February 2000 (Fig.3A), smaller patches of higher chlorophyll concentration are seen in the range of 0.50 – 2.0 mg/m^3, which gives information about the initiation phase of the algal bloom. From here onwards the growth phase is observed in images of 17, 19 February 2000 (Fig. 3 B, C). The patches have changed their position with high chlorophyll concentration (> 2.0 mg/m^3) at around 14°-22°N latitude and 65°-69°E longitude (Figs 3, 4). Each

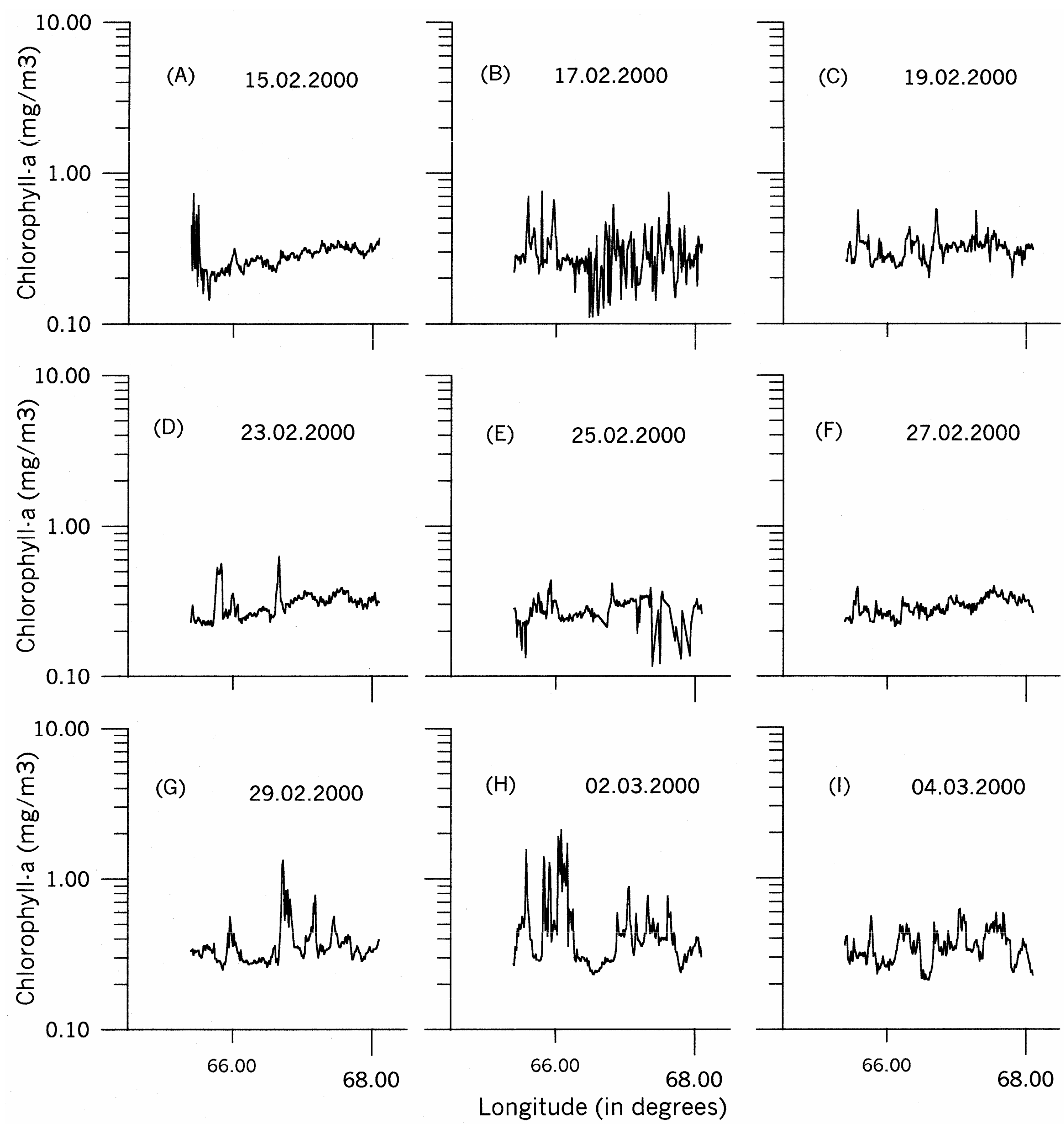

Fig. 5—Plots showing the variation of chlorophyll-*a* concentration along the transect (see Fig. 3) and the same transect coordinates from respective dates images, derived from IRS-P4 OCM satellite data. (The plot for the date 17.02.2000 shows lot of fluctuation due to the presence of cloud as seen in the images (Figs 3 and 4), which contaminates the adjacent pixel).

patch has the peak chlorophyll value in its central position within the range of 2.0 - 5.0 mg/m^3 and the peripheral waters show unusual high values of chlorophyll of around 1.0 mg/m^3, which in normal conditions does not appear in the deep oceanic water (Fig. 3 B,C and Fig. 4 B,C). The chlorophyll images on 23 and 25 February, show lower chlorophyll concentration (about 0.8 mg/m^3) strips than the previous days images along the northern Arabian Sea. The higher concentration patches might have shifted their position and do not appear in subset images of 23-27 February (Fig. 4 D,E,F). The patches again reappear in images of 29th February and 2nd March with peak chlorophyll concentration of around 2.0 – 5.0 mg/m^3 (Figs 3 G,H and 4 G,H). The 4th March image shows the faint red colour patches with low chlorophyll concentration (< 1.0 mg/m^3), gives information about degradation phase (Figs 3 I and 4 I). The congregation of phytoplankton and their blooming are also being reflected in the plots for the same transect at different dates (Fig. 5). The peak chlorophyll-*a* values along the transect have been observed on 17th, 29th February and 2nd March 2000, which is greater than 1.0 mg/m^3.

The winter cooling phenomenon in the northern Arabian Sea occurs with effect of dry cool continental air brought by the north-east monsoon winds[16,17]. Further it enhances evaporation, leading to surface cooling of northern Arabian Sea water[18]. The decrease in solar insolation also plays a major role in winter cooling during January and February[18], finally which increases depth of mixed layer in northern Arabian Sea[19]. Hence, due to the effect of winter cooling, the northern Arabian Sea experiences cooling and densification, leading to sinking and convective mixing, which injects nutrients into surface layers from thermocline region.

The classical explanation for the winter bloom was given as follows with the following evidence also[20]. The winter bloom in the northern Arabian Sea is the most intense because the nutrient build-up prior to it's onset is large. Off India, the bloom occurs towards the beginning of the February because there the mixed layer detrains earlier than in the other region. This occurs when the mixed layer detrains after a period of entrainment, during which the layer is thick enough to inhabit phytoplankton growth. Detrainment occurs when there is a decrease in turbulent mixing (when the wind weakens or there is surface heating). Again the deeper mixed layer attenuates after winter time cooling. As fluid detrains from the mixed layer, a temporary inner layer is created that thickens in time. Detrainment blooms tend to be highly productive because detrainment results in a thin mixed layer, which intensifies the depth-averaged light intensity and favors phytoplankton growth[20]. However they also tend to be short-living because detrainment does not inject nutrients into the mixed layer and so they can persist only until the initial nutrient supply is depleted. Nutrient limitation is also the reason for the demise of detrainment blooms, but grazing and self-shading cause the rapid decay of the initial peak. Grazing is always an essential process in limiting the amplitude of phytoplankton concentrations during both bloom and oligotrophic conditions.

On the basis of the Coastal Zone Colour Scanner data[21], scientists deduced the occurrence of highest pigment concentrations north of 20°N during February - March 1979-1980. High concentration of pigments have been observed from the IRS-P4 OCM satellite derived chlorophyll images for the northern Arabian Sea water around 20°N latitude and 65°E longitude[22]. Chlorophyll patches forming blooms are also seen for about 2 –3 weeks duration. The winter convection in the northeastern Arabian Sea leads to elevated pigment values, as does even modest mixing during southwest (summer) monsoon. Satellite observations also showed winter blooms[23] also during 1978 – 79 and 1979 – 80. This portraits the previous evidence of blooms in the late winter season in the northern part of the Arabian Sea water. The chlorophyll images for the late winter period shows high concentration patches like phytoplankton blooms in the northeastern part of the Arabian Sea water. In particular, winter mixing in the northern part of Arabian Sea is related to a number of biological observations suggesting enhanced algal production.

The bloom forming features of the phytoplankton, observed in the present study are in good agreement with the previous work carried out by several researchers in the same regions along the northern Arabian Sea during the winter monsoon period[15,20]. This is due to winter cooling due to high evaporation, mixing and convection processes leading to the nutrient injection to the surface layer. These bloom like phenomenon are of special interest from the point of biodiversity of the phytoplankton and their seasonal growth, distribution and assemblage. *In situ* data and field monitoring of this region and the seasonal phytoplankton blooms and their causes are needed to study in detail.

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