

Inter-annual variability of phytoplankton blooms in the northern Arabian Sea during winter monsoon period (February-March) using IRS-P4 OCM data

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Phytoplankton bloom has been observed and interpreted utilizing Indian Remote Sensing Satellite (IRS-P4), Ocean Colour Monitor (OCM) sensor retrieved chlorophyll images for the northern Arabian Sea for three years period (2000-2002). The overall mean chlorophyll concentration was found higher in year 2001, when compared to years 2000 and 2002 in the selected bloom waters north of 15° N latitude. The algal blooms were most intense during the year 2001. The monthly sea surface temperature (SST) and its anomaly data retrieved from NOAA-NCEP archive have been correlated with the phytoplankton blooming conditions in the study area during February-March, 2000-2002. The SST maps of January and February show similar trend in the bloom (~26°C) and non-bloom (~29°C) water, but in March month the SST has been raised by about 3°C in both the bloom and non-bloom waters for the three years. The SST anomaly has been observed to be of higher range (-3° to +4°C) in February and March 2001 and the gradient is having significant link with the algal bloom period. The phytoplankton bloom and the hike in chlorophyll concentration during the winter monsoon season has been linked with winter cooling and the detrainment phenomenon and its relationship with SST and SST anomaly has been discussed.

[Key words: Phytoplankton bloom, northern Arabian Sea, winter monsoon, IRS-P4 OCM, NOAA-NCEP SST]

Introduction

The phytoplankton are critical to all life on earth because of their great contribution to food webs and their generation of large amounts of atmospheric oxygen through photosynthesis. Because of coastal upwelling and land run-off, nutrient levels are highest near the continents. Plankton are most abundant there, and productivity is highest. In large basin seas like the Arabian Sea, the spatial and temporal distributions of non-conservative oceanographic properties, e.g. concentrations of phytoplankton, are difficult to study rigorously with ships. For a single ship survey, it is difficult to observe a larger area in the ocean on temporal and spatial scale. In contrast, satellites can provide wide-ranging, often repeated coverage of some properties, like the chlorophyll content of the upper parts of the euphotic zone¹. Remote sensing of ocean colour yields information on the constituents of seawater, such as the concentration of phytoplankton pigments, suspended sediments and yellow substances. The methods of detecting and mapping seawater constituents from aircraft and from space-borne platform have been successfully developed during the past three decades².

To get the access for significant temporal and spatial variability in phytoplankton biomass, the remote sensing of near-surface pigment concentrations provides the only practical means of obtaining large scale observations of phytoplankton distributions over appropriate time-scales. The present availability of satellite ocean colour data offers an unprecedented opportunity to force biogeochemical models to estimate the pigment distributions. Satellite measurements have been applied successfully to the measurement and mapping of surface pigment concentrations^{3,4}. Satellite observations of ocean colour provide large-scale, repeat coverage sampling of global ocean chlorophyll that are necessary to help understand the role of phytoplankton on biogeochemical cycling, climate change and fisheries⁵. Data on ocean colour, obtained from aircraft or satellite, are now used in a routine manner to map the concentration of phytoplankton in near surface waters at very large scale^{6,7}. Measurements of ocean color and the fate of light in the ocean are extremely useful for describing biological dynamics in surface⁸, thus the oceanographic community has made a substantial commitment to remote sensing of ocean colour from space^{9,10}.

The Arabian Sea lies on the northwest side of the Indian Ocean (Fig. 1) is unique among low-latitude sea by terminating at a latitude of 25° N and being under marked continental influence. It is the region of monsoon and biological production is affected by the physical processes altering the vertical flux of nutrients in the mixed layer¹¹. Satellite based observations on ocean color provides a tool to monitor the biological productivity in term of phytoplankton concentration. 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 prerequisite for successful planning of studies of plant productivity, the investigation of suspension feeding zooplankton and the seasonality of particle fluxes to the deep sea. 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.

The ocean colour monitor (OCM) of the Indian Remote Sensing satellite IRS-P4 (IRS-P4 OCM) is optimally designed for the estimation of chlorophyll in coastal and oceanic waters^{12,13}, detection and monitoring of phytoplankton blooms¹⁴, studying the suspended sediment dynamics¹⁵ etc. 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 northern Arabian Sea and the movement mechanism of blooming features (algal filaments) are discussed. The present study is an extension to our previous work carried out on phytoplankton bloom monitoring in northeastern part of the Arabian Sea for duration of about two weeks using IRS-P4 OCM satellite derived chlorophyll images. In this paper we present the estimates of chlorophyll concentrations by the IRS-P4 OCM satellite data in the north-eastern part of the Arabian Sea to assess the phases of winter bloom in three consecutive years during the period February-March, 2000-2002 as the blooms have been evidenced particularly during these months from our observation. The variability in chlorophyll concentration during the winter monsoon season has been linked with winter cooling and the detrainment phenomenon and it's relationship with SST and SST anomaly has been studied.

Materials and Methods

The retrieval of ocean colour parameter such as phytoplankton pigment (chlorophyll-*a*) in oceanic

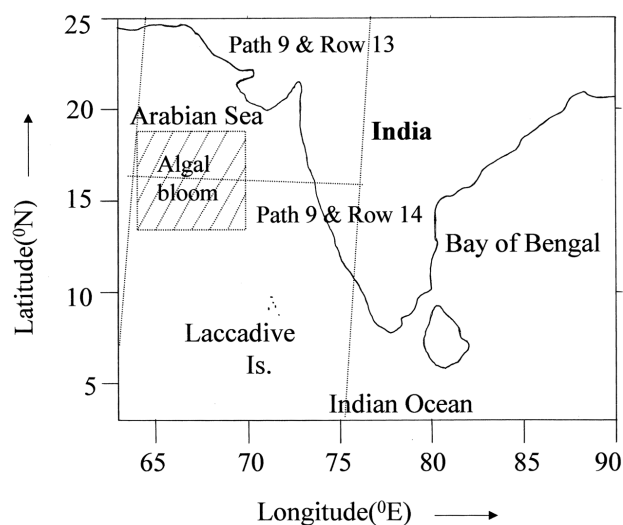


Fig. 1—Location map of bloom area, viewed by Path 9 and Row (13,14) of IRS-P4 OCM satellite overpasses, covering the Arabian Sea off Indian west coast

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 reflectance¹⁶. Therefore it has been mandatory to correct the atmospheric effect to retrieve any quantitative parameter from space. An algorithm has been developed at the Space Applications Centre (ISRO), Ahmedabad, to correct OCM data for atmospheric contamination¹⁷. The OCM scenes were corrected for atmospheric effects of Rayleigh and aerosol scattering using an approach called long wavelength atmospheric correction method. The approach 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.

Chlorophyll algorithm

A number of bio-optical algorithms 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 data¹⁸. This algorithm captures the inherent sigmoid relationship between the log transformed band ratio (R_{rs490}/R_{rs555}) 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. The algorithm operates with five coefficients and has the following mathematical form.

$$C = 10^{[0.319 - 2.336 * X + 0.879 * X^2 - 0.135 * X^3]} - 0.071$$

where, C is chlorophyll concentration (in mg/m^3) and $X = \log_{10}[R_{rs490}/R_{rs555}]$.

While comparing all available algorithms for Indian waters, it was observed that this algorithm provided best results for chlorophyll retrieval¹⁹. 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 fifteen consecutive passes of IRS-P4 OCM path 9 and row 13, 14 during February-March, 2000-2002 over the north-eastern part of the Arabian Sea (Fig. 1). The chlorophyll images were geometrically corrected and gridded with 3° 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° - 70° E longitude indicating the occurrence of phytoplankton bloom (Figs. 2-4). The monthly Sea Surface Temperature (SST) and its anomaly data has been retrieved from NOAA-NCEP website²⁰ for the period January-March 2000-2002 and has been compared with chlorophyll maps.

Results and Discussion

The present study is an extension to our previous work carried out on phytoplankton bloom monitoring in northeastern part of the Arabian Sea for duration of about two weeks using nine dates IRS-P4 OCM satellite derived chlorophyll images¹⁴. To study the detailed phenomenon of phytoplankton bloom in the year 2000 (February-March), few more dates satellite derived chlorophyll images, pre and post to the previous analysis period have been taken up. For the

year 2000 and the corresponding years 2001 and 2002, IRS-P4 OCM data has been analyzed for a month's period (between February to March) and the chlorophyll images have been displayed for the three years (Figs. 2-4). The mean values for all the data of corresponding 3 years have been plotted year-wise with respect to all satellite overpass dates for the study area (Fig. 5).

During the year 2000, the bloom has appeared to initiate from 11th February 2000 and observed to be retained like eddies for the 3 consecutive passes up to 17th February 2000 (Fig.2). In the image of 19th February, the bloom forming high chlorophyll concentration ($\sim 1.00 \text{ mg}/\text{m}^3$) patches appear to be scattered around longitude 66 - 69° E and latitude 14 - 18° N. The process continues in the next pass on 21st February 2000. The area around bloom patches appears to be accumulated in eddy like structures. The coastal waters off Gulf of Kachchh and Khambhat show higher chlorophyll concentration water in the next passes during 29th Feb-4th March 2000. Chlorophyll patches were maximum during this period 29th Feb-2nd March (Fig. 2). The bloom patches again reappeared in 4th March 2000 in curly and spiral stripe shapes and disappeared in corresponding passes on 6th and 10th March 2000.

In the case of 2001 chlorophyll image analysis study, less number of patches of chlorophyll have been observed during the initial dates on 9th and 11th February 2001, which retains the chlorophyll concentration around $0.8 \text{ mg}/\text{m}^3$ (Fig.3). But, in the 13th February 2001 image, the chlorophyll patches appear like algal bloom patches of higher concentration $>1.00 \text{ mg}/\text{m}^3$, which appears to be pushed off towards northern and eastern side of the image around the coastal waters off Gulf of Kachchh and Khambhat (Cambay). The bloom patches have appeared in corresponding days up to 9th March 2001. The bloom patches are conspicuous in the chlorophyll images of February and March 2001. But, these are wide spread like those of previous year and no major oceanographic features like eddies have been seen in the period of study during 2001 and the chlorophyll concentration appears to be higher and it was around $2.00 \text{ mg}/\text{m}^3$, whereas in 2000 images the chlorophyll concentration was about $1.00 \text{ mg}/\text{m}^3$.

During 3rd year 10th February-10th March 2002 high chlorophyll patches has been observed in the form of many eddies and currents (Fig. 4). Several eddies appeared consistently till 20th February 2000

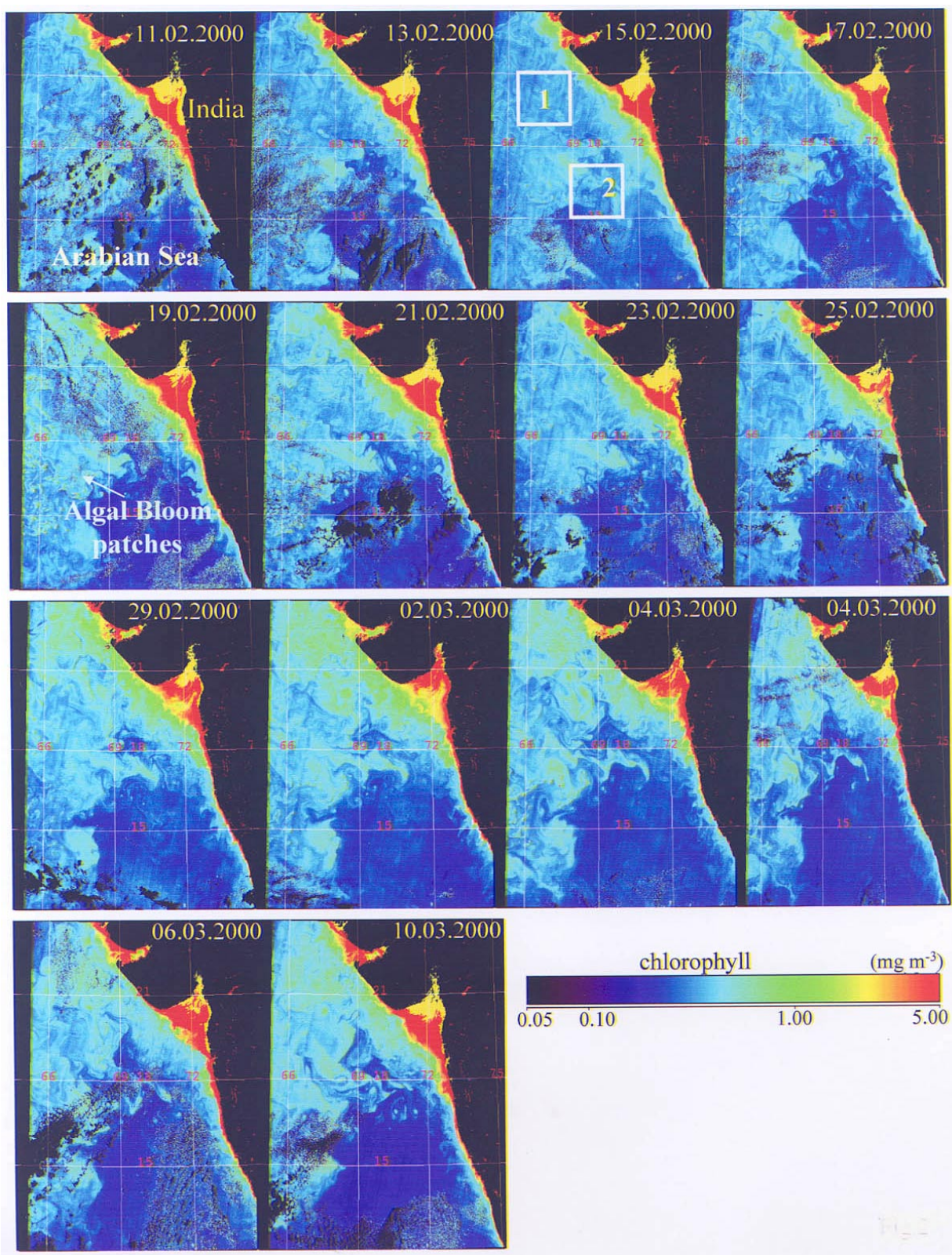


Fig. 2—IRS-P4 OCM derived chlorophyll images for February-March 2000 showing the algal bloom stages in north-eastern part of the Arabian Sea

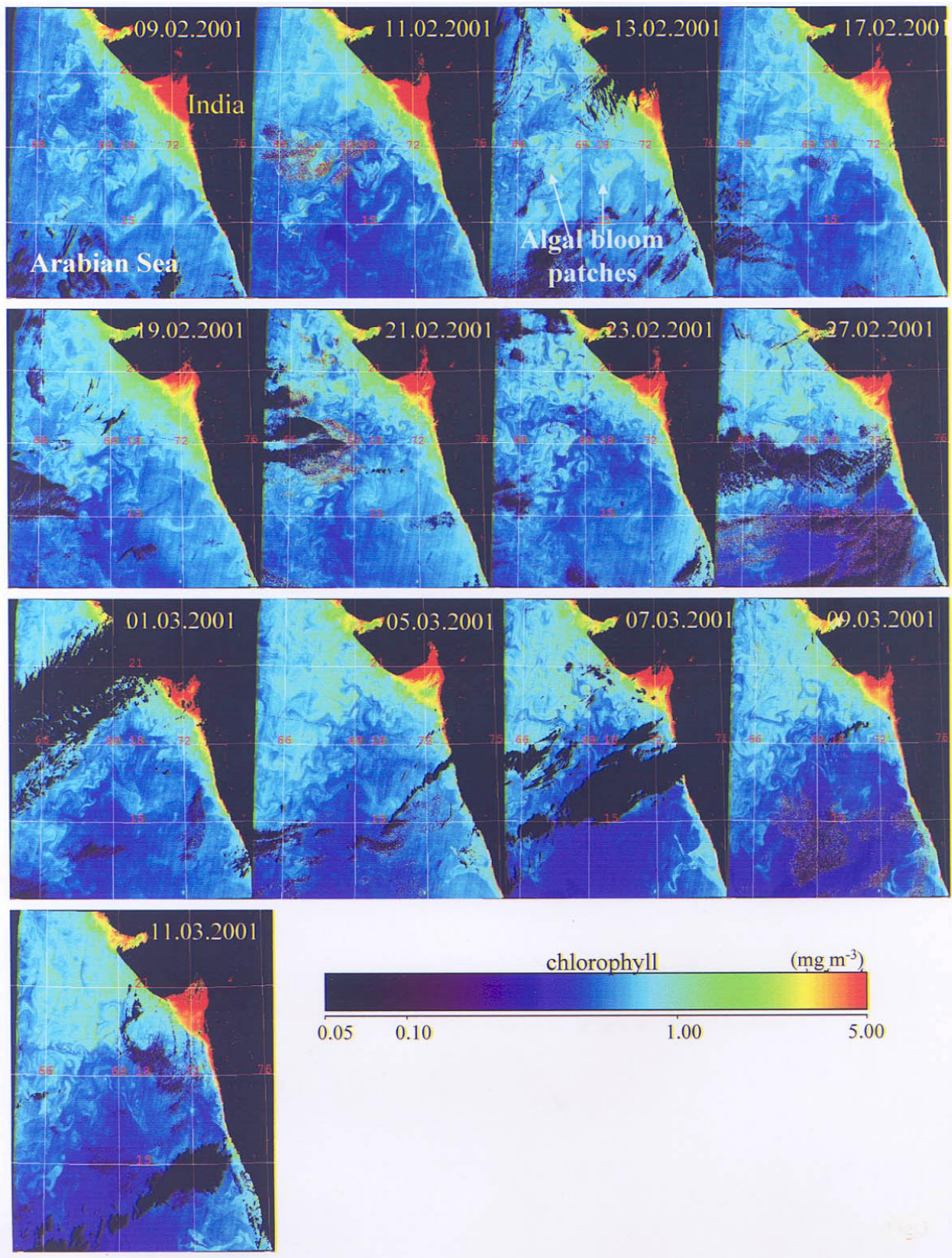


Fig. 3—IRS-P4 OCM derived chlorophyll images for February-March 2001 showing the algal bloom stages in north-eastern part of the Arabian Sea

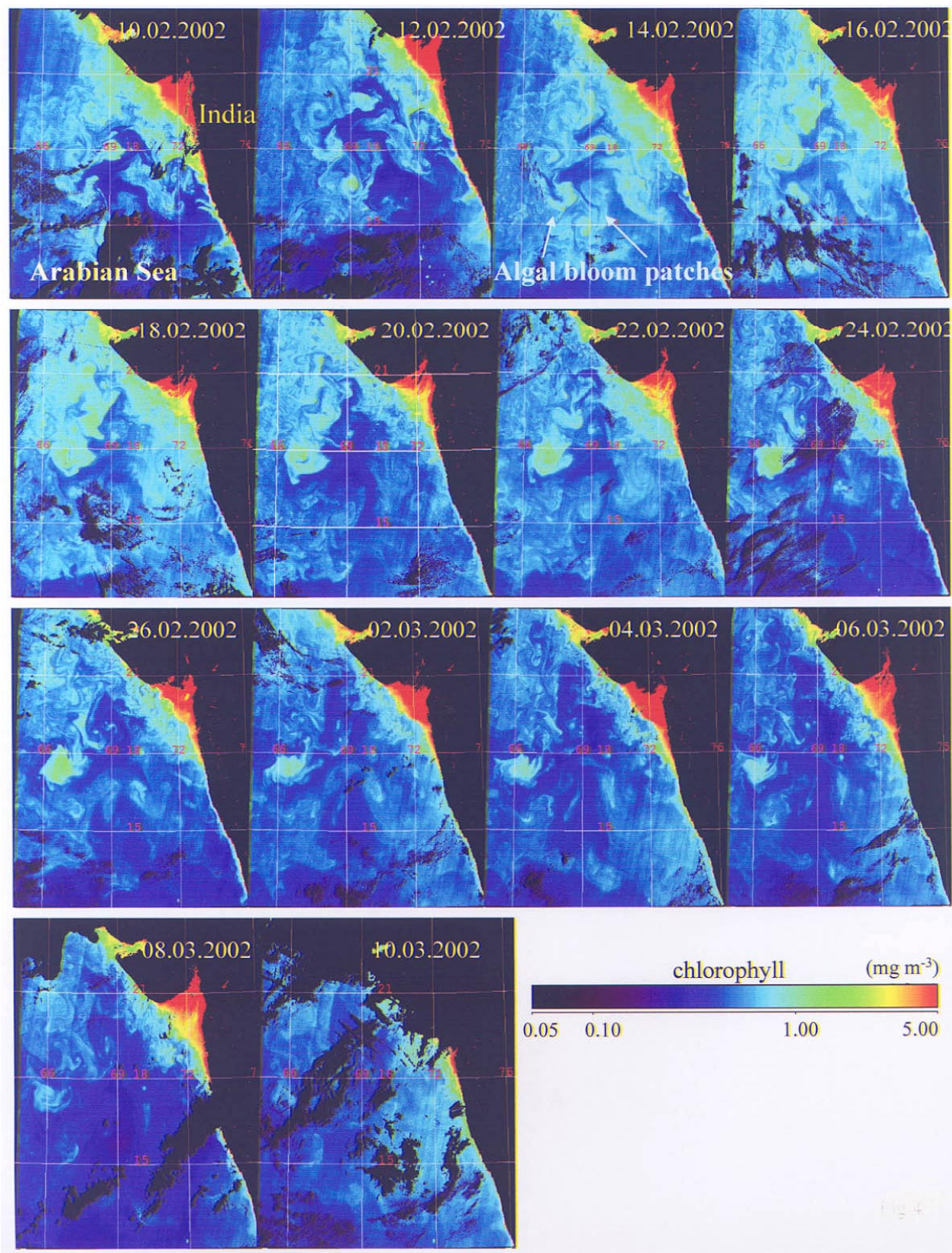


Fig. 4—IRS-P4 OCM derived chlorophyll images for February-March 2002 showing the algal bloom stages in north-eastern part of the Arabian Sea

with high chlorophyll concentration ($>1.00 \text{ mg/m}^3$) in their center. It shows that there was heavy churning of water in the study area and the phytoplankton has been aggregated by the eddies and has been reflected in the chlorophyll images in our study. Finally number of eddies have been dissipated, so the high concentration bloom patches along with those eddies have disappeared. A major eddy started to retain in the 22nd February 2000 image around longitude $66-68^\circ\text{E}$ and latitude $17-18.5^\circ\text{N}$, about a diameter of 150 km, with higher chlorophyll concentration around 1 mg/m^3 (Fig. 4). The surrounding water shows moderate chlorophyll concentration around 0.8 mg/m^3 . The eddy has been retained till 8th March 2000 and which disappears then and with a marking in 10th March 2000 image. Hence, during the year 2002, the bloom was not so intense like 2001 and 2000. The most intense bloom observed was during February-March 2001 period with massive algal bloom patches with higher chlorophyll concentration even $>2.00 \text{ mg/m}^3$. The chlorophyll images of year 2000 show wide spread distribution of bloom patches of less chlorophyll concentration than the year 2001. Finally, the 2002 images showed very less number of algal bloom patches, few eddies and later a major eddy accumulating phytoplankton.

Further, studying in detail about their bloom features and ultimately the chlorophyll concentration, the mean has been computed for each dates for the two selected bloom waters (Box. 1 and 2, marked in white ink in Fig. 2 of 15-02-2000) images for the above 3 years data and displayed in Fig. 5. For the year 2000, the mean chlorophyll concentration ranged between $0.29-0.37 \text{ mg/m}^3$; for 2001, mean was between $0.34-0.68 \text{ mg/m}^3$ and finally for 2002, mean was between $0.45-0.70 \text{ mg/m}^3$. So, the wider chlorophyll concentration range has been found to be varying in Box 1 during the winter monsoon period. Similarly for the 2nd bloom water (Box 2), the mean for the selected bloom area for a year, different dates during February-March found in the following range; in the year 2000, the range was $0.16-0.23$, in 2001 the range was $0.19-0.60$ and in the year 2002, the range was between $0.32-0.54$. The plots in Fig. 5 reveal that the chlorophyll mean trend in 2001 was at peak followed by 2002 and 2000 and maintains consistency in the two bloom waters. So, it gives clarity that the intensity of bloom in 2001 was the maximum.

The classical explanation for the winter bloom has been given as follows with the following two

evidences. Firstly, the winter cooling phenomenon in the northern Arabian Sea occurs with effect of dry cool continental air brought by the north-east monsoon winds²¹. Further it enhances evaporation, leading to surface cooling of northern Arabian Sea water²². The decrease in solar insolation also plays a major role in winter cooling during January and February²² finally, which increases depth of mixed layer in northern Arabian Sea²³. 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. So, we observe the high chlorophyll concentration in different blooming phases in Arabian Sea water. Secondly, the winter bloom in the Northern Arabian Sea is most intense because the nutrient build up prior to its onset is large²¹. Off northwest India, the bloom occurs towards the beginning of the February because there the mixed layer detrains earlier than in the other region²⁴. This occurs when the mixed layer detrains after a period of entrainment, during which the layer

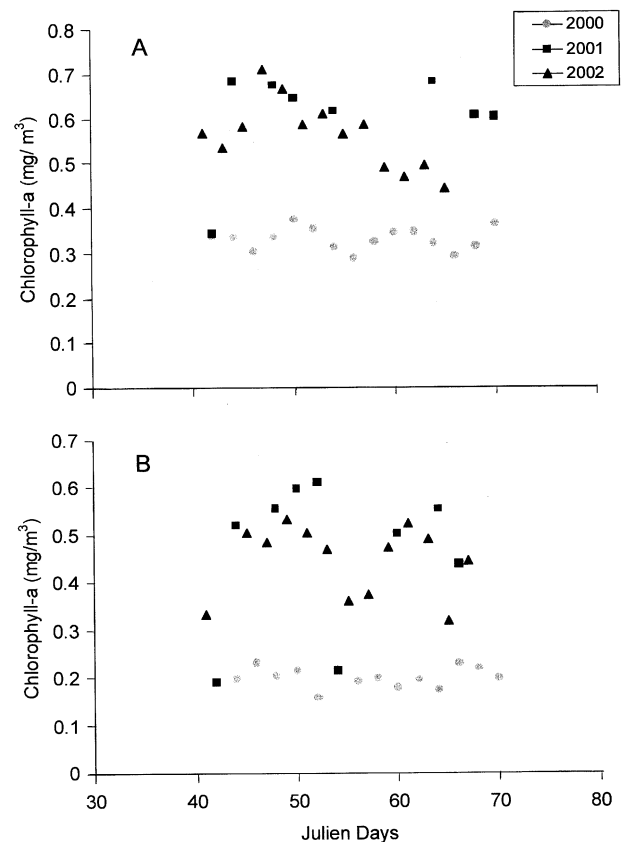


Fig. 5—Mean chlorophyll concentration derived from IRS-P4 OCM data during phytoplankton bloom in the Arabian Sea for (a) Box 1 and (b) Box 2.

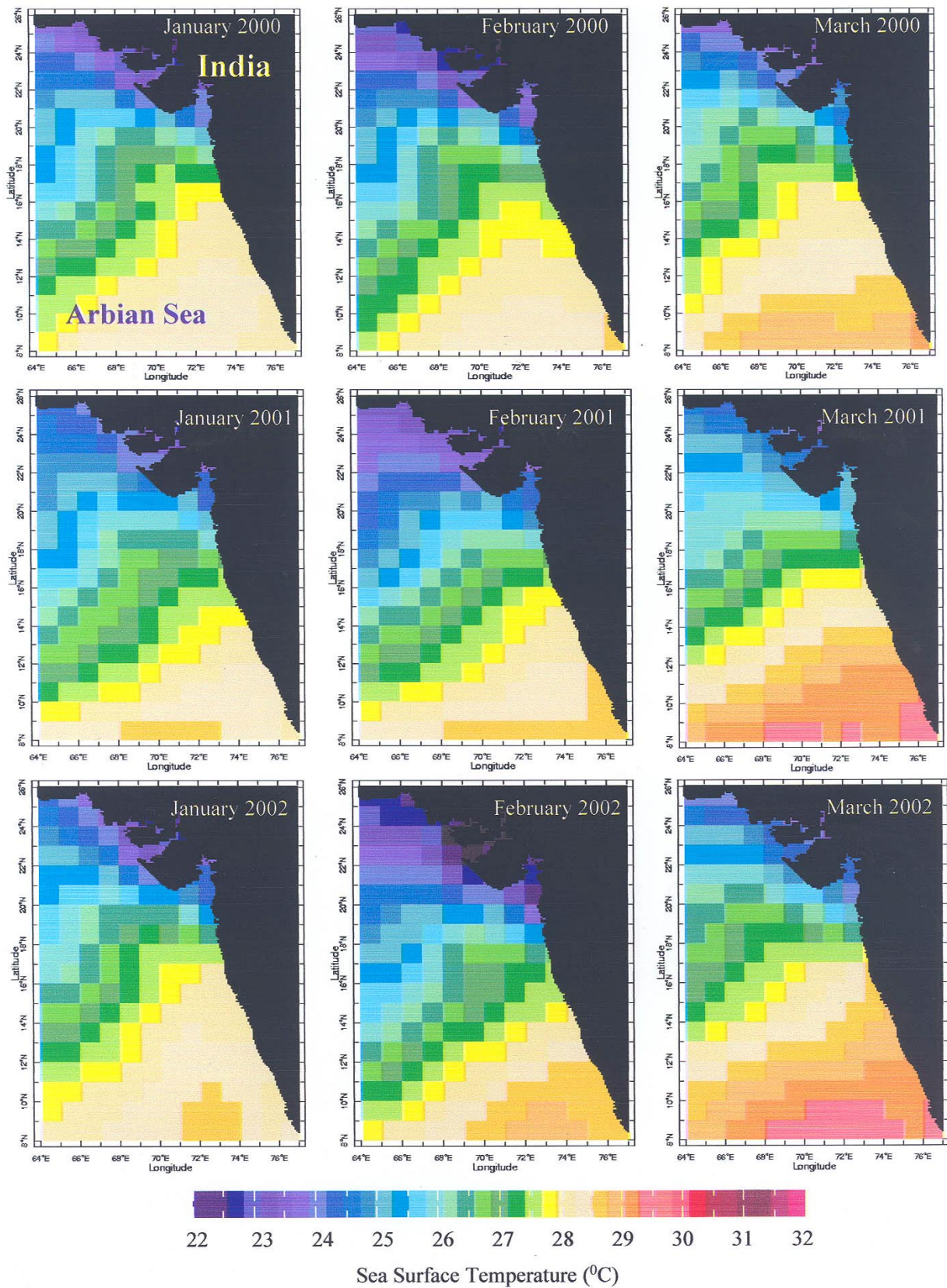


Fig. 6—Monthly averaged Sea Surface Temperature maps during January-March, 2000-2002 retrieved from NOAA-NCEP archive

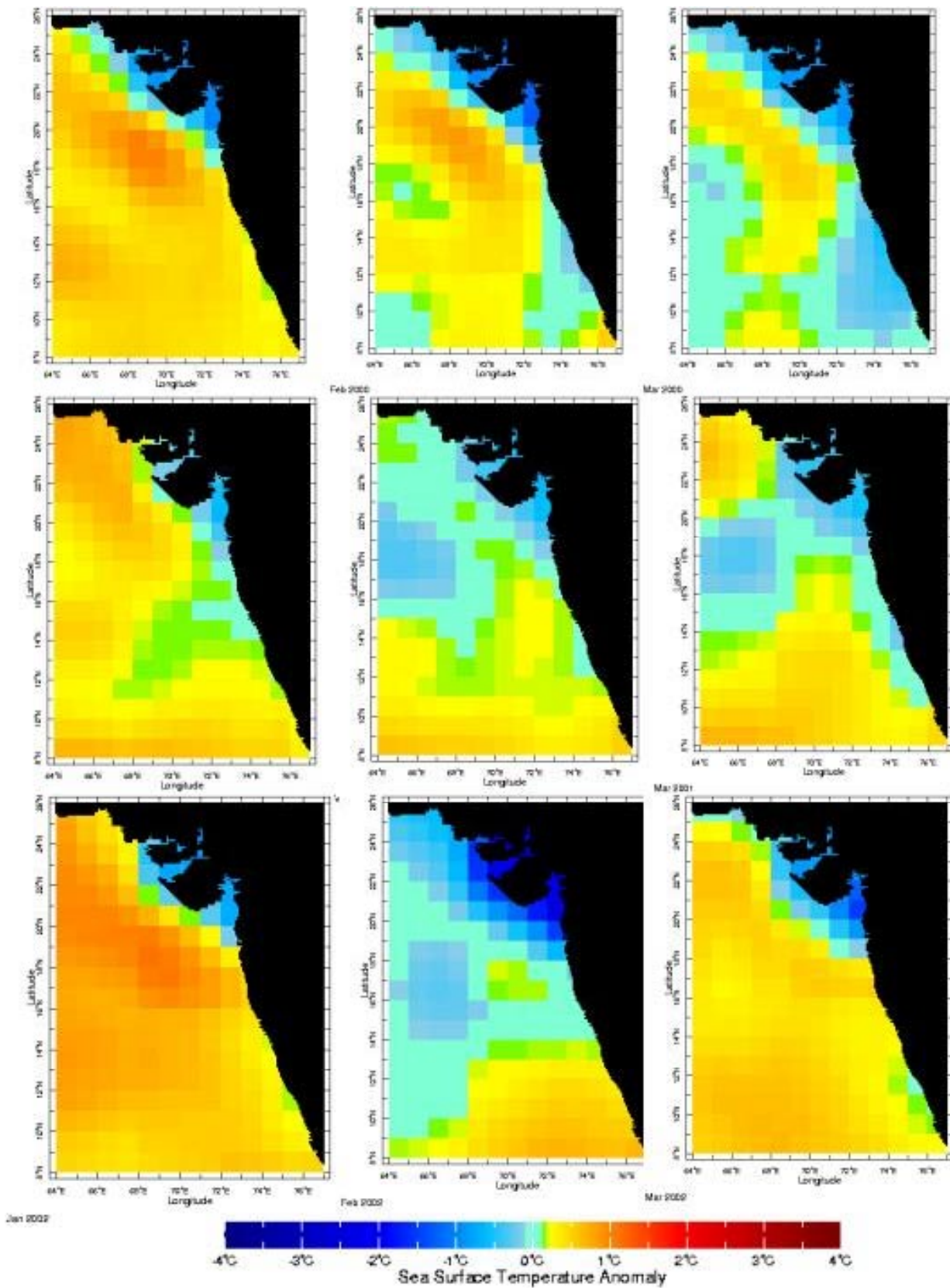


Fig. 7—Monthly averaged Sea Surface Temperature anomaly maps during January-March, 2000-2002 retrieved from NOAA-NCEP archive

is thick enough to inhibit phytoplankton growth. 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 growth²³. However the phytoplankton 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 peak²⁴.

To study the link between chlorophyll variability with climatological SST, monthly SST maps for January-March, 2000-2002 have been retrieved from NOAA-NCEP archive for our study area (Fig. 6). The bloom was found to be more intense in the last 2 weeks of February month as evidenced from chlorophyll image of 3 years period, which has also been reflected in the January-February month's SST images and these appear similar. But in March month's SST maps, warm water having higher SST around 3.0°C intrudes northward and the decrease in chlorophyll concentration has been correlated with the seasonal warming during March.

The SST anomaly maps have also been retrieved for the study area for the months January-March, 2000-2002 from the NOAA-NCEP archive (Fig. 7). Interpreting the SST anomaly maps having range (-4°C to +4°C), it has been observed that anomaly was negative (-3° to +4°C) with higher gradient, around central part of the study area for February 2001 and 2002, also in the bloom region, where bloom was intense in 2001 and 2002, where a major eddy was observed. Hence, the decrease in SST anomaly is more relevant to our observation of algal blooming. During other months of three years also show positive anomaly, showing increasing trend and less gradient in temperature anomaly (+1 to +4°C), where any prominent chlorophyll variability has not been observed.

Earlier, the occurrence of higher pigment concentration algal bloom north of 20°N has been deduced using Coastal Zone Colour Scanner data during February-March 1979-1980 in Arabian Sea water²⁵. High concentrations of pigment 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^{12,14}.

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 bloom²⁶, 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 show high concentration patches like phytoplankton blooms in the north-eastern 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. For ocean applications, primary productivity is the net rate of carbon fixation by phytoplankton through the process of photosynthesis. Ocean primary productivity rates reflect the fact that phytoplankton biomass, as estimated by chlorophyll concentration can experience up to several doublings per day. So, the phytoplankton concentration and their biomass structure is important in the algal blooming conditions, which enhances the productivity to higher extent.

The bloom forming features of the phytoplankton, observed in the present study are in good agreement with the few works carried out previously as well as with our own study. This is due to the winter cooling phenomenon induced by high evaporation, mixing and convection processes leading to the nutrient injection to the surface layers and other way the detrainment of the mixed layer causing surface water nutrient rich and more productive. The inter-annual phytoplankton bloom has been studied and it was most intense during the year 2001 from the point of view of consistent higher chlorophyll concentration around 1 mg/m³ in the bloom water. The bloom conditions has been significantly linked with the change in the physical condition of water, the sea surface temperature gradient, which was about 3°C rise in SST in the bloom and non-bloom condition in March. Its anomaly was also observed to be of higher range (-3 to 4°C) in February and March 2001. These bloom phenomena are also of special interest from the point of biodiversity of the phytoplankton and their seasonal growth, distribution and assemblage as the type of bloom and species specific spectral analysis and interpretation with remote sensing satellite data will be of more significance.

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