

## Distribution and Ecology of the *Trichodesmium* spp. in the Arabian Sea: Ship and Satellite studies

SUSHMA G PARAB<sup>1</sup>, S.G PRABHU MATONDKAR<sup>1\*</sup>, MINI RAMAN<sup>2</sup>, and R.M. DWIVEDI<sup>2</sup>

**Abstract--***Trichodesmium* is a filamentous cyanobacteria which forms dense blooms along the west coast of India. These are high biomass blooms which are mostly surface floating. The chlorophyll *a* content of water crossed  $>100 \mu\text{g l}^{-1}$  during active bloom and hence was ideal for the detection by space. Besides the Arabian Sea, the Lakshadweep Sea, the Andaman Sea and the Bay of Bengal are also well known sites for the *Trichodesmium* bloom. During our special cruises to the Arabian Sea we collected data to help us to understand the seasonality of *Trichodesmium* spp. *Trichodesmium* starts appearing just after the SW monsoon in the offshore waters of the Arabian Sea. We have noticed massive blooms of *Trichodesmium thiebautii* when water temperatures were low ( $26^{\circ}\text{C}$ ). *T. thiebautii* was also found to be distributed throughout the water column. It was also observed in the coastal waters during March and in the Lakshadweep waters during April. The OCM images taken during these observations have been used to map and estimate the concentration of *T. thiebautii*. Low temperatures and calm condition are required for *Trichodesmium thiebautii* to bloom. According to our study, November-December appears to be the time during which this bloom flourishes in offshore waters of the Arabian Sea.

*T. erythraeum* blooms were noticed in the coastal waters during the March to May and in the offshore waters during the April-May period. During the months from March-April a mixed bloom of *Trichodesmium* with *Noctiluca miliaris* was also observed. We have generated a series of OCM imageries from January to March in order to locate the appearance of these blooms in different regions of the Arabian Sea. However in a typical *Trichodesmium* bloom chlorophyll *a* values are in the range of  $2\text{-}5.905 \mu\text{g l}^{-1}$ . We have recorded upto 99.49% of *Trichodesmium* in the phytoplankton population. The *Trichodesmium* filaments varied from 74 to 516400 filaments $\text{l}^{-1}$ . Goa was found to be one of the most prominent site for *Trichodesmium* occurrence and the chlorophyll *a* level during our study varied from 187.2 to 2080  $\mu\text{g l}^{-1}$  which is extremely high. From our data collected on various cruises it appears that the depletion of nitrate by the diatoms supplied by the upwelling during the SW monsoon triggered the *T. thiebautii* bloom in the offshore waters of the Arabian Sea. Similar conditions developed in the coastal waters during March-April-May period, which witnessed with higher water temperatures causing the *T. erythraeum* grow in bloom. Meanwhile offshore waters are conducive for *Trichodesmium* after April as they support mixed blooms of the *Trichodesmium* spp. in the offshore region. These events have been depicted by satellite images and discussed.

**Keywords:** *Trichodesmium*; Monsoon; Chlorophyll *a*; Phytoplankton; Remote Sensing; Arabian Sea.

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\*Corresponding author, 1-NIO, Goa and, 2-SAC, Gujarat

## INTRODUCTION

*Trichodesmium* is the ecologically most successful organism distributed in tropical and temperate regions (Capone et al., 1997; Mulholland and Capone 2009; Subramaniam and Carpenter, 1994). Arabian sea is one of the prominent site for the *Trichodesmium* forming dense blooms all along the coastal waters of Arabian Sea (Ramamurthy et al., 1972; Devassy et al., 1978; Capone et al., 1998; Lugomela et al., 2002; Desa et al., 2005; Parab et al., 2006; Basu et al., 2011, Lakshadweep Sea (Qasim, 1970 ), Andaman (Jyothibabu et al., 2003) and Bay of Bengal Bengal (Jyothibabu et al., 2003; Hegde et al., 2008). The blooms formed are dense and is floating type giving greenish/brown colouration to the sea surface. *Trichodesmium* is also important since it can fix carbon and nitrogen. Since *Trichodesmium* mainly grow in nitrate poor water and is important in the Arabian Sea since primary productivity is nitrogen limited most of the time of the year (Capone, et al., 1997). It has been estimated that N<sub>2</sub>-fixed in ocean by *Trichodesmium* spp. globally is ~ 80 TgN (Capone et al., 1997). However little is known about the contribution by *Trichodesmium* in the Arabian Sea. Attempt is made here to study *Trichodesmium* distribution in the Arabian Sea in space and time. Distribution of *Trichodesmium* spp. is also supported by Chl *a* estimated using survey and OCM images as indicator of larger aggregation of *Trichodesmium* in the Arabian Sea. The development of these blooms depend upon calm sea condition (low wind), high temperature favours the development of *Trichodesmium*. The nitrogen fixed by these organisms enters in marine food chain through exudation, grazing, sinking and decomposition. Characteristics of *Trichodesmium* that appear to contribute to its distribution in the oligotrophic open ocean include its capability to fix N<sub>2</sub> and natural buoyancy that positions it in the upper water column. Further, it is also noticed that the process of photosynthesis of *Trichodesmium* is well adapted to a high-light intensity, coupled with a lack of grazers that allows it to maintain relatively in the form of high biomass (Carpenter 1983).

Pigment composition of *Trichodesmium* indicates that the photosystem is adapted for both maximum efficiency and photoprotection at high light intensity (Carpenter, 1983). Among trace elements, Fe is believed to play a decisive role in the growth of *Trichodesmium*. Field and laboratory studies (Karl, et al., 1992) suggest that Fe is a key factor limiting *Trichodesmium* growth and distribution in the marine environment. Moreover, Fe enters the open ocean primarily through atmospheric deposition, and location of these organisms in the upper waters column may be advantageous with respect of availability of Fe in surface layers.

Although physical processes most often dominate oceanic plankton distribution, large surface accumulations of *Trichodesmium* may affect the bulk physical and chemical properties of surface waters. Meso-scale sea-surface features of the extent and intensity characteristics of *Trichodesmium* blooms are likely to modify light penetration and the quality of the in situ light field (Oliver and Ganf, 1988) and gas transfer across the ocean-atmosphere interface (Siegel, et al., 1995). Organic and inorganic nutrients accumulated during blooms can influence phytoplankton succession and hence productivity (Devassy, et al., 1978). *Trichodesmium* affects the structure and function of the oligotrophic ocean through its contribution to productivity and tropho-dynamics, by providing a unique pelagic habitat. Thus, the nitrogen and carbon fixed by *Trichodesmium* enters the food web. A specialized group of harpacticoid copepods is reported to be adapted and are capable of directly grazing *Trichodesmium* (O'Neil and Roman, 1994), although their quantitative role in the consumption of *Trichodesmium* is not clear. In natural populations of *Trichodesmium*, a large proportion of recently fixed N is released as organic N (Capone, et al., 1994) important source for microbes inhabiting the *Trichodesmium* colonies (Paerl, et al., 1989) In a culture experiment on *Trichodesmium*, Mullholland, et al. (2001) have shown that the organic and inorganic compound released, which are utilized by the other phytoplankton or bacterial flora.

## Methodology

The data presented here was collected on board two research vessels the ORV Sagar Kanya (SK) and FORV Sagar Sampada (FORV). This collection of data was done in the months spanning from November to May. While planning the cruises, special emphasis was given to study the distribution of *Trichodesmium* in the Arabian Sea covering 12-22°N and 65-74°E (Fig. 1) and seasons (November –fall inter-monsoon (fall IntM); December to February –NE monsoon (NE MoN) and March to May – spring inter-monsoon (spring IntM) so as to include samples from coastal and offshore as well as regions where physical processes such as upwelling and winter cooling, were known to occur. Different cruises during same seasons have been referred as the early NE monsoon - December, mid NE monsoon -January, late NE monsoon-February; early spring intermonsoon-March and late spring intermonsoon-April and May.

**Physicochemical measurements:** The QUickSCAT images were downloaded from the SSM/I website at [http://www.remss.com/qscat/qscat\\_browse.html](http://www.remss.com/qscat/qscat_browse.html). Temperature and salinity data was taken from CTD. Nutrients, whenever estimated, were analyzed in an Auto-analyzer using standardized techniques for nutrient analysis in seawater (UNESCO, 1994).

**Chlorophyll a by HPLC method:** For pigment estimations, samples between 1 and 2.5 litre were filtered through GF/F filters, frozen in liquid nitrogen at sea and then transported to the shore lab for analysis by HPLC (Wright et al., 1991; Bidigare and Charles, 2002). Pigments were separated in a C-18 reverse-phase column using the eluent gradient program of Wright, et al. (1991) as adapted by Bidigare and Charles (2002) as detailed in Parab, et al. (2006).

**Phytoplankton cells:** Water samples were collected by CTD rosette, preserved using lugol's iodine. Settled material is counted for phytoplankton using Inverted microscope (Olympus XI 50). Phytoplankton samples were identified using standard reference material (Tomas, 1997).

**Satellite data:** The Chlorophyll *a* images were generated using OC-2 algorithm; ERDAS Imagine 2.5 software was used for image processing (O'Reilly et al., 1998).

## Results and Discussion

### Fall Intermonsoon

#### *Wind, temperature, salinity and nutrients*

During the fall inter-monsoon the wind was blowing from the northeast towards the offshore region of the Arabian Sea and wind speed was found to be 5-6 ms<sup>-1</sup> (Fig. 2a). These calm conditions supported the dense bloom of the *Trichodesmium thiebautii* at 17°N 70°E and 17°N 69°E. In this area the water temperature was 28°C while mixed layer depth was 5m (coastal) to 70 m (offshore) region (Fig. 3a).

The area of *Trichodesmium thiebautii* was marked by nitrate and nitrite at non detectable level (Fig. 4). The phosphate and silicate level at these areas was also low, registering at ~ 0.2 µM and ~ 0.5 µM respectively. Other areas (15°N 73°E and 18°N 69°E) showed high level of nutrients with high percentage of diatoms but absence of *Trichodesmium* spp.

#### *Chlorophyll a and Trichodesmium distribution*

Chl *a* content was high (0.1733 to 5.344 mgm<sup>-3</sup>; Fig. 6a) at most of the locations during the fall IntM. The surface Chl *a* maxima observed (Fig. 6a) at areas like 18°N 70°E (0.75 mgm<sup>-3</sup>) and 20°N 71°E (5.344 mgm<sup>-3</sup>) was on account of the blooms of *Trichodesmium thiebautii* in the offshore region. Similarly at 17°N 69°E and 18°N 70°E up to a depth of 30 m, *Trichodesmium* bloom was noticed. Out of the 23 stations sampled 10 stations showed the presence of *Trichodesmium thiebautii*. Similarly the highest phytoplankton counts were observed at 18°N 70°E (15.831 cell nos. x 10<sup>4</sup>L<sup>-1</sup>) where *Trichodesmium* constituted a major portion. The average

total cells counts of phytoplankton was  $1.590 \pm 3.546 \times 10^4 \text{L}^{-1}$  at the surface and  $43.226 \pm 95.189 \times 10^6 \text{m}^{-2}$  in the euphotic zone (Fig. 6b). The number of *Trichodesmium* filaments across transect varied from 0 to 10.9570 filaments  $\times 10^4 \text{L}^{-1}$ . The average filament distribution was  $6.9993 \pm 3.025 \times 10^4 \text{L}^{-1}$  at the surface and  $9.686 \pm 30.720 \times 10^6 \text{m}^{-2}$  in the euphotic zone (Fig. 6c). At some areas like,  $16^\circ\text{N } 71^\circ\text{E}$ ,  $19^\circ\text{N } 69^\circ\text{E}$  and  $20^\circ\text{N } 70^\circ\text{E}$  N the diatom counts were higher side. However, the *Trichodesmium* stations were invariably marked by low percentages of diatoms and dinoflagellates.

## **NE Monsoon**

### ***Wind, temperature and salinity***

During the NE Monsoon the wind was blowing from the northwest and moving along the eastern coast of India (Fig. 2b). The wind speed during this period was found to be  $< 5 \text{ms}^{-1}$ . During this season offshore water was showing the effects of winter cooling and the growth of the *Trichodesmium thiebautii* continued. The temperature data collected from the NE Arabian Sea is presented in Fig. 3b. The observations indicate that the offshore water was largely influenced by the winter cooling lowering the temperatures (Fig. 3b). During this season, *Trichodesmium thiebautii* began to appear in the shelf region also. By the end of the NE MoN it was found that *Trichodesmium erythraeum* had replaced *T. thiebautii* in the NE Arabian Sea.

Nutrients concentrations recorded during this season was low (Figs. 4 & 5). However, *Trichodesmium erythraeum* and *Trichodesmium thiebautii* appeared as mixed bloom in the shelf region. The prevailing calm weather during this period was particularly useful for the growth of *Trichodesmium* at the sub-surface. During this period phosphate varied from 0 to  $0.35 \mu\text{M}$  which was low most of the time. The nitrate values ranged from 0 to  $0.75 \mu\text{M}$  and the silicate content recorded was  $11.08 \mu\text{M}$  which was high at the bottom of the euphotic zone, as compared to the surface which was  $2.30 \mu\text{M}$  ( Fig. 4).

### ***Chlorophyll a and Trichodesmium distribution***

Phytoplankton biomass in terms of the Chl *a* and total cell counts was reasonably high during this season (Fig. 6a). Average Chl *a* was  $0.526 \pm 0.453 \text{mgm}^{-3}$  at surface and  $32.588 \pm 46.851 \text{mgm}^{-2}$  in euphotic zone (Fig. 6a). Highest Chl *a* was recorded at  $21^\circ\text{N } 69^\circ\text{E}$  and lowest at  $12^\circ\text{N } 72^\circ\text{E}$ . Similarly average cell density at the surface was  $0.112 \pm 0.129 \text{nos.} \times 10^4 \text{L}^{-1}$  (Fig. 6b). The highest cell counts ( $0.606 \text{nos.} \times 10^4 \text{L}^{-1}$ ) were recorded at  $12^\circ\text{N } 74^\circ\text{E}$  and lowest ( $0.002 \text{nos.} \times 10^4 \text{L}^{-1}$ ) at  $21^\circ\text{N } 68^\circ\text{E}$ . Filament counts of *Trichodesmium* spp. varied from 0 to  $0.616 \text{filaments nos.} \times 10^4 \text{L}^{-1}$  and average  $0.039 \pm 0.119 \text{filaments nos.} \times 10^4 \text{L}^{-1}$  at the surface and  $0.214 \pm 0.272 \times 10^6 \text{m}^{-2}$  at the euphotic zone (Fig. 6c).

A district seasonality was recorded during various cruises covering different months (SK-214, SK-186, FORV-212 and FORV-222) undertaken. During the early NE MoN (SK-214), the concentration of Chl *a* was from  $0.187 - 0.507 \text{mgm}^{-3}$ . High concentration of Chl *a* was recorded at  $17^\circ\text{N } 69^\circ\text{E}$  while low concentration of Chl *a* was found at  $15^\circ\text{N } 71^\circ\text{E}$ . The sub-surface Chl *a* maxima was found at a depth of 40 m depth at  $17^\circ\text{N } 69^\circ\text{E}$ ,  $18^\circ\text{N } 67^\circ\text{E}$ ,  $20^\circ\text{N } 66^\circ\text{E}$ ,  $21^\circ\text{N } 69^\circ\text{E}$  and  $21^\circ\text{N } 65^\circ\text{E}$ . Out of the 14 stations sampled, 10 samples showed the presence of *Trichodesmium* in the sub-surface waters while others showed its presence at deeper depths (~ 60 m). The total phytoplankton cell counts varied from 0.032 to  $0.4352 \text{cell nos} \times 10^4 \text{L}^{-1}$  at the surface. At two locations ( $15^\circ\text{N } 73^\circ\text{E}$  and  $18^\circ\text{N } 70^\circ\text{E}$ ) *Trichodesmium erythraeum* and *Trichodesmium thiebautii* were found at the depth of 5 and 60 m respectively. The highest counts of *Trichodesmium* filaments were found at  $22^\circ\text{N } 67^\circ\text{E}$  ( $0.0216 \text{filaments} \times 10^4 \text{L}^{-1}$ ) and lowest at  $20^\circ\text{N } 66^\circ\text{E}$  ( $0.0022 \text{filaments} \times 10^4 \text{L}^{-1}$ ). During this season diatoms were also recorded in large numbers at  $15^\circ\text{N } 73^\circ\text{E}$ ,  $15^\circ\text{N } 71^\circ\text{E}$  and  $18^\circ\text{N } 67^\circ\text{E}$ . The *Trichodesmium* percentages in total phytoplankton counts ranged from 0.78 to 35.71 %. The other dominant phytoplankton throughout this season were *Rhizosolenia setigera*, *Nitzschia longissima*, *Thalassiothrix longissima*, *Pyrophaccus horologium* and *Protoperidinium sternii* (Table 1).

The Chl *a* during the mid NE MoN (SK-186) was higher at most of stations, compared to early NE MoN. It ranged from 0.173 to 2.6mgm<sup>-3</sup>. Higher concentrations of chl *a* were found at 21°N 69°E where diatoms were dominant (93.94 %) followed by dinoflagellates (4.55 %) and other algae like (1.52 %). Sub-surface Chl *a* maxima was observed at locations like 17°N 72°E, 17°N 70°E, 17°N 67°E, 19°N 66°E, 20°N 66°E, 20°N 66°E, and 17°N 68°E during this season. The total phytoplankton cell counts ranged from 0.002 to 0.459 cell nos x 10<sup>4</sup>L<sup>-1</sup>. Higher counts were found at 17°N 70°E where, diatoms made up 94.44 % and dinoflagellates formed 5.56% of the total phytoplankton population. The presence of *Trichodesmium* (25 to 28.57 %) was found in the 5 out of the 25 stations sampled at the surface. *Trichodesmium erythraeum* was found to be more dominant than *Trichodesmium thiebautii*. The *Trichodesmium* filaments was more (760 filaments L<sup>-1</sup>) at 18°N 69°E. The other species that were observed during this period were *Thalassiothrix longissima*, *Chaetoceros dichatea*, *Thalassiosira subtilis*, *Coscinodiscus nitidus*, *Navicula* spp., *Nitzschia seriata*, *Nitzschia closterium*, *Rhizosolenia setigera* and *Chaetoceros lorenzianus* (Table 1).

During late the NE MoN (part of FORV-212 and FORV-222) it was found that values for Chl *a* varied from 0.132 – 0.960 mgm<sup>-3</sup> with high values at 17°N 69°E due to the presence of the *Trichodesmium erythraeum* bloom. The sub-surface Chl *a* maxima was found at a depth of ~ 40-60 m specially at 16°N 72°E, 10°N 74°E, 12°N 72°E and 14°N 73°E. The presence of *Trichodesmium* was observed in 7 out of the 10 stations sampled in this month. The total phytoplankton counts ranged from 0.0078 to 0.2508 cell nosx10<sup>4</sup>L<sup>-1</sup>. Higher phytoplankton cell counts were found at 17°N 69°E due to the presence of the *Trichodesmium erythraeum* bloom. The *Trichodesmium* filaments ranged from 0 to 0.6160 filaments x 10<sup>4</sup>L<sup>-1</sup>. During this period bloom of the *Noctiluca* was also recorded with the *Trichodesmium* bloom at 10°N 64°E and 17°N 69°E. It appears that the *Noctiluca* bloom may have followed the *Trichodesmium* bloom in the Arabian Sea, an idea which provides us with new insights in the study of phytoplankton in the Arabian Sea. A full growth of *Noctiluca miliaris* bloom was stuck at 17°N 70°E.

## **Spring Intermonsoon**

### ***Wind, Temperature and Salinity***

During this season the wind was blowing from the northeast and moving along the East Coast of India (Fig. 2c), the wind speed during this period was found to be <5ms<sup>-1</sup>. This period is the transitional period during which *Trichodesmium* spp. and *Noctiluca miliaris* co-existed. These blooms were related to the deepening of the thermocline in this area (Fig. 3c). During this season, the nitrogenous nutrients were low at the surface which varied from 0.0 to 0.39 μM (Figs. 4 & 5). During this time, high (1.66 – 3.38 μM) silicate content was recorded (Fig. 4), which suggests an inadequate uptake and coincides with the low density of diatom.

### ***Chlorophyll a and Trichodesmium distribution***

During the spring IntM the Chl *a* ranged from 0.074 -5.905 mgm<sup>-3</sup>. The average Chl *a* was 0.759±1.025 mgm<sup>-3</sup> at the surface and 14.749±13.828 mgm<sup>-2</sup> in the euphotic zone (Fig. 6a). At the surface high Chl *a* was found at 20°N 70°E and low at 15°28.76N. The total phytoplankton cell counts ranged from 0.025-41.992 cell nos. x 10<sup>4</sup>L<sup>-1</sup>. The average cell counts were 2.033±7.302 cell nos. x 10<sup>4</sup>L<sup>-1</sup> at the surface and 16.929±26.176 cell nos. x 10<sup>6</sup>m<sup>-2</sup> (Fig. 6b) Similarly *Trichodesmium* filaments were also high at the same position as the total cell counts. The filaments varied from 0-40.074 nos. x 10<sup>4</sup>L<sup>-1</sup> at the surface and 0.021-100.301 nos. x 10<sup>6</sup>m<sup>-2</sup>. The average *Trichodesmium* filaments were 2.381±8.313 at surface and 6.115±20.737 at the column (Fig. 6c).

In the early springIntM the concentration of Chl *a* varied from 0.169 – 2.741 mgm<sup>-3</sup>. The high Chl *a* was found at 19°N 66°E (2.741 mgm<sup>-3</sup>) can be attributed to the bloom of *Noctiluca*

*miliaris*. The phytoplankton counts ranged from 0.0252 to 1.1164 cell nos.  $\times 10^4 L^{-1}$ . The high cell count found at 19°N 66°E was also due to the *Noctiluca miliaris* bloom. During this month a total of 13 stations were studied out of which only 4 stations showed the presence of *Trichodesmium*. The observations indicate that part of the NE Arabian Sea, where the winter cooling affect (low temperature and high nutrients), supports *Noctiluca* and the other part of the Sea, where the nutrient concentration was low and high temperatures prevail, is for *Trichodesmium* area (Table 1).

During late spring IntM concentration of Chl *a* varied from 0.074 to 5.905  $\mu g L^{-1}$  with the highest values recorded at 20°N 70°E and the lowest values recorded at 15°N 70°E. Phytoplankton cell counts ranged from 0.033 to 41.991 cell nos.  $\times 10^4 L^{-1}$ . The phytoplankton cell density showed peak values in coastal waters (21°N 69°E, 20°N 70°E and 15°N 73°E) mostly north of 20°N. *Trichodesmium* was the major component of the phytoplankton averaging  $3.8063 \pm 10.3463$  filaments  $\times 10^4 L^{-1}$  (n=29) with high concentrations (40.0737 filaments  $\times 10^4 L^{-1}$ ) at 20°N 70°E in the coastal waters off Gujarat (Fig. 6c). In general, diatoms and dinoflagellates were less numerous, averaging 0.2936 and 0.0630 cells  $L^{-1}$  respectively during this period. However at some locations, like 20°N 70°E to 20°N 72°E the domination of diatoms was noticed. The dominant diatom, *Nitzschia* sp. (2.3025 cells  $\times 10^4 L^{-1}$ ) was found at 20°N 70°E. Dinoflagellates reached a maximum of 1.1666 cells  $\times 10^4 L^{-1}$  at 20°N 70°E, which was adjacent to the diatom dominated stations indicating succession of phytoplankton groups. The area between 16-18°N in coastal waters was characterized by domination of dinoflagellates. For example, at areas like 16°N 73°E, 18°N 72°E and 17°N 72°E dinoflagellates like *Ceratium* spp., *Peridinium* spp., and *Prorocentrum* spp. were dominant organisms. At the edge of the shelf, a mixed community of diatoms, dinoflagellates and *Trichodesmium* dominated the flora specially at 21°N 69°E, 20°N 70°E, 15°N 73°E which was in coastal as well as offshore waters (Fig. 6c). The other areas like 21°N 69°E, 18°N 72°E and 17°N 72°E also supported high counts of *Trichodesmium erythraeum*. The *Trichodesmium erythraeum* was well distributed during this time of year and mostly in succession to the dinoflagellates (south of 18°S) and the diatoms (north of 18°N). Diatoms were the second most important group of organisms that were encountered during the present study, they were also the most diverse in nature.

## Discussion

The Arabian Sea experiences hydrographic changes, which are related to the monsoon system (Shetye, et al., 1990; Brock and McClain, 1992; Banse and English, 1993, 2000; Madhupratap, et al., 1996). The region of study undertaken fall under the influence of both the NE and the SW monsoon. During the onset of the SW monsoon season, i.e. June, the west coast of India experiences intense upwelling, which is first visible off the southern tip of India. During this period, continental slope waters begin to shoal upward into the shelf region causing substantial cooling, which is observed in the satellite sea surface temperature imagery (Sreejith and Shenoi, 2002; Vinayachandran et al., 2004). As the season advances the upwelling signatures migrate northward, covering the entire coast of India by late July (Shetye, et al., 1990). This process is responsible for bringing in the much needed new nutrients (DeSouza, et al., 1996) that help to trigger large phytoplankton blooms by early August (Goes, et al., 1992) and continue upto October.

The NE monsoon, marks a period wherein the offshore region receives a substantial amount of new nutrients (Kumar et al., 2009). Satellite derived measurements of Chl *a* concentrations in the region of the NE Arabian Sea start to increase by December and tend to reach peak values by February (Banse and English, 2000). The data collected during early NE MoN showed that, the nitrate concentrations were undetectable at 18°05.98, 18°10.47N and 21°17.81N where as low ( $<0.97 \mu M$ ) at most of the NE Arabian Sea, presumably because a significant fraction of nutrients had already been used by phytoplankton (Parab, et al., 2006),

whereas other nutrients such as phosphate and silicate were present. Considering the nutrients enrichment during NE MoN the phytoplankton growth in the water column appears to be reduced by an active grazing by zooplankton (Landry, et al., 1998; Caron and Dennet, 1999) a notion that is reinforced by the elevated level of ammonium concentration found in the water column during early NE MoN estimated at the order of 0.57-6.13  $\mu\text{M}$  of ammonia.

In our study, we found that during low wind speeds ( $< 5 \text{ ms}^{-1}$ ), thick blooms of *Trichodesmium* spp. were observed (Fig. 2). However wind speed  $>6$  knot resulted in disappearance of the *Trichodesmium* bloom. Earlier studies (Chang et al., 2000) have reported that besides wind and water temperature, low nutrients were also factors that favoured growth of the *Trichodesmium*. In the Arabian Sea, during the non monsoonal period, the upper layers of the water were devoid of nutrients. In such a situation, *Trichodesmium* had an advantage over other phytoplankton, as it could fix nitrogen and it could make use of phosphate from subsurface layers. The stratification of the water column during low wind conditions (as seen during mid and late NE MoN and early spring IntM) was also an important factor for the *Trichodesmium* blooms to develop and persist in the Arabian Sea. Associations between abundance of *Trichodesmium* and vertical stratification have been reported in the North Pacific sub-tropical gyre (Capone, 1983). The average mixed layer depth during our study was 10-40m, during *Trichodesmium* bloom.

The bloom of *Trichodesmium thiebautii* observed during the fall intermonsoon continued during the early NE MoN where out of the 15 stations sampled 13 showed the presence of a *Trichodesmium thiebautii* bloom. The filaments were distributed throughout the water column in the euphotic zone. Deep Chl *a* maxima was noticed at a *Trichodesmium thiebautii* concentrations were also observed during mid NE MoN. Out of the 18 stations sampled, 7 stations showed the presence of a mixed population of *Trichodesmium erythraeum* and *Trichodesmium thiebautii*. Surface Chl *a* maxima was observed at  $15^{\circ}14.21\text{N}$  and was largely attributed to *Trichodesmium thiebautii* and *Trichodesmium erythraeum*.

During late NE MoN and early spring IntM, mixed populations of *Trichodesmium erythraeum* and *Trichodesmium thiebautii* were noticed at  $20^{\circ}29.1\text{N}$ ,  $19^{\circ}3.7\text{N}$  and  $15^{\circ}8.57\text{N}$ . However, in the late spring IntM, 29 stations out of the 35 stations sampled supported *Trichodesmium erythraeum* blooms.

Thus our present study illustrates the seasonal distribution of *Trichodesmium* in the Arabian Sea. A large part of the Arabian Sea tends to become oligotrophic during a major part of the year (6-7 months). During the present study, a total of 143 stations were sampled in the NE Arabian Sea in order to study the *Trichodesmium* bloom. Majority of these stations (93 stations) showed the presence of *Trichodesmium* i.e. 65 % of the total stations were represented by *Trichodesmium*. A significant finding of the present study was the occurrence of *T. thiebautii* in the offshore part of the Arabian Sea, just after the SW monsoon, as early as November (Fig. 7). This was largely attributed to the low temperatures ( $22\text{-}27^{\circ}\text{C}$ ) and low nitrate levels in the euphotic zone; *Trichodesmium erythraeum* began appearing in February in the coastal water and spread to offshore water during the months of April and May, when temperatures generally high and nitrate concentrations are low and so *Trichodesmium erythraeum* thrives in this environment.

Another important feature observed during the NE MoN was that *Trichodesmium thiebautii* occurred as deep as 70 – 80 m in the water column. Phosphate availability may be an important factor for *Trichodesmium* to appear (Karl, et al., 1992). In the NE Arabian Sea, the contribution of *Trichodesmium* to total phytoplankton counts varied from 1% to 95 %, with the highest counts being observed in the spring IntM. The dominant phytoplankton species in the *Trichodesmium* bloom were *Trichodesmium erythraeum*, *Trichodesmium thiebautii*, *Navicula* spp., *Nitzschia closterium*, *Nitzschia seriata*, *Rhizosolenia setigera*, *Rhizosolenia shrubsolei*, *Chaetoceros curvisetus*, *Noctiluca miliaris*, *Melosira moniliformis*, *Chaetoceros decipiens*, *Rhizosolenia hebetata* and *Thalassiothrix frauenfeldii*.

Another noteworthy observation made during the present investigation was the occurrence of mixed blooms of *Trichodesmium erythraeum* and *Noctiluca miliaris* during late NE MoN and early spring IntM in the shelf region, whereas, in the offshore region, *Noctiluca* dominated the bloom, this coincided with a reduction in the density of the *Trichodesmium* filaments. Further, unique occurrence of patches of decomposed *Trichodesmium* filaments in combination with *Noctiluca* at a few stations coupled with elevated levels of nutrient suggests that, the *Trichodesmium* bloom triggers the *Noctiluca miliaris* bloom in the Arabian Sea. It is a well known fact that the Arabian Sea becomes productive during the late NE MoN, which supports the occurrence of a *Noctiluca miliaris* (Gomes et al., 2008; 2009). Winter convection (February-March) that brings high nutrients to surface water in the NE Arabian Sea triggers blooms of the *Noctiluca miliaris*. Subsequently, in the Arabian Sea *Noctiluca* and *Trichodesmium* blooms coexist also with high counts of *Navicula* sp., *Nitzschia closterium*, *Nitzschia seriata* and *Thalassiosira subtilis*, driving ecosystem. Thus the presence of *Trichodesmium* spp. recorded from November to May in the Arabian Sea (Fig. 7) is an important factor responsible for maintaining the ecosystem of the Arabian Sea during oligotrophic conditions.

## Conclusion

The nutrient cycle and carbon cycle are driven by few key species in the Arabian Sea where *Trichodesmium* spp. is found important. The blooms of the diatom/dinoflagellates (SW monsoon), *Trichodesmium*/cyanobacteria (Intermonsoon), flagellates and *Noctiluca* (winter monsoon) connected both monsoons (SW and NE monsoon) and hence important to monitor climate change in the Arabian Sea.

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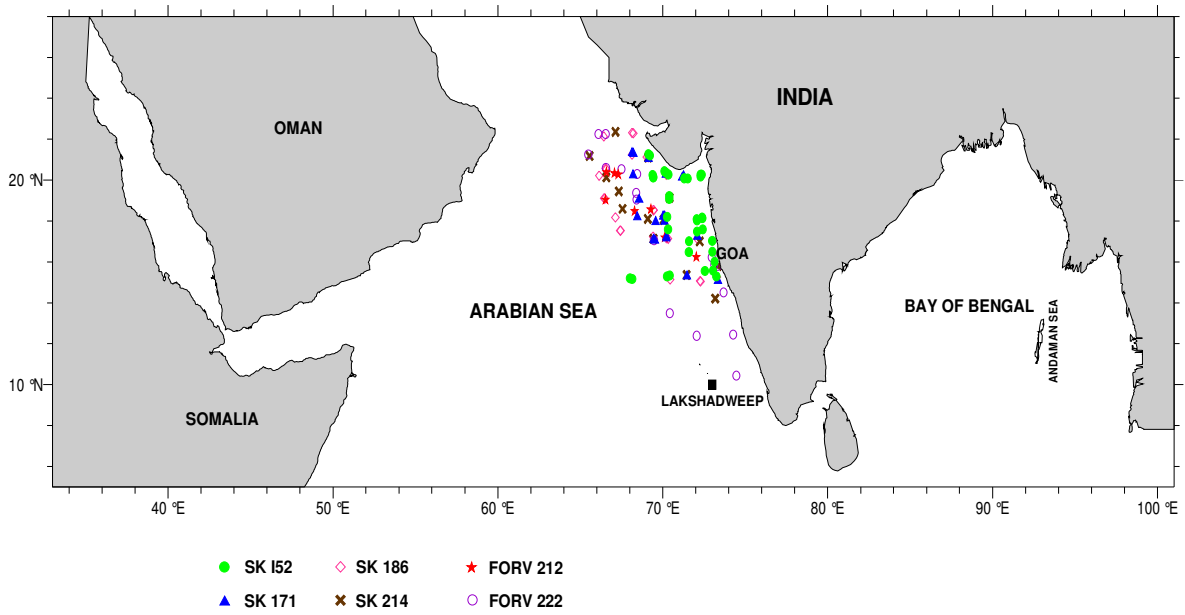
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**Table 1** Dominant phytoplankton in the Arabian Sea

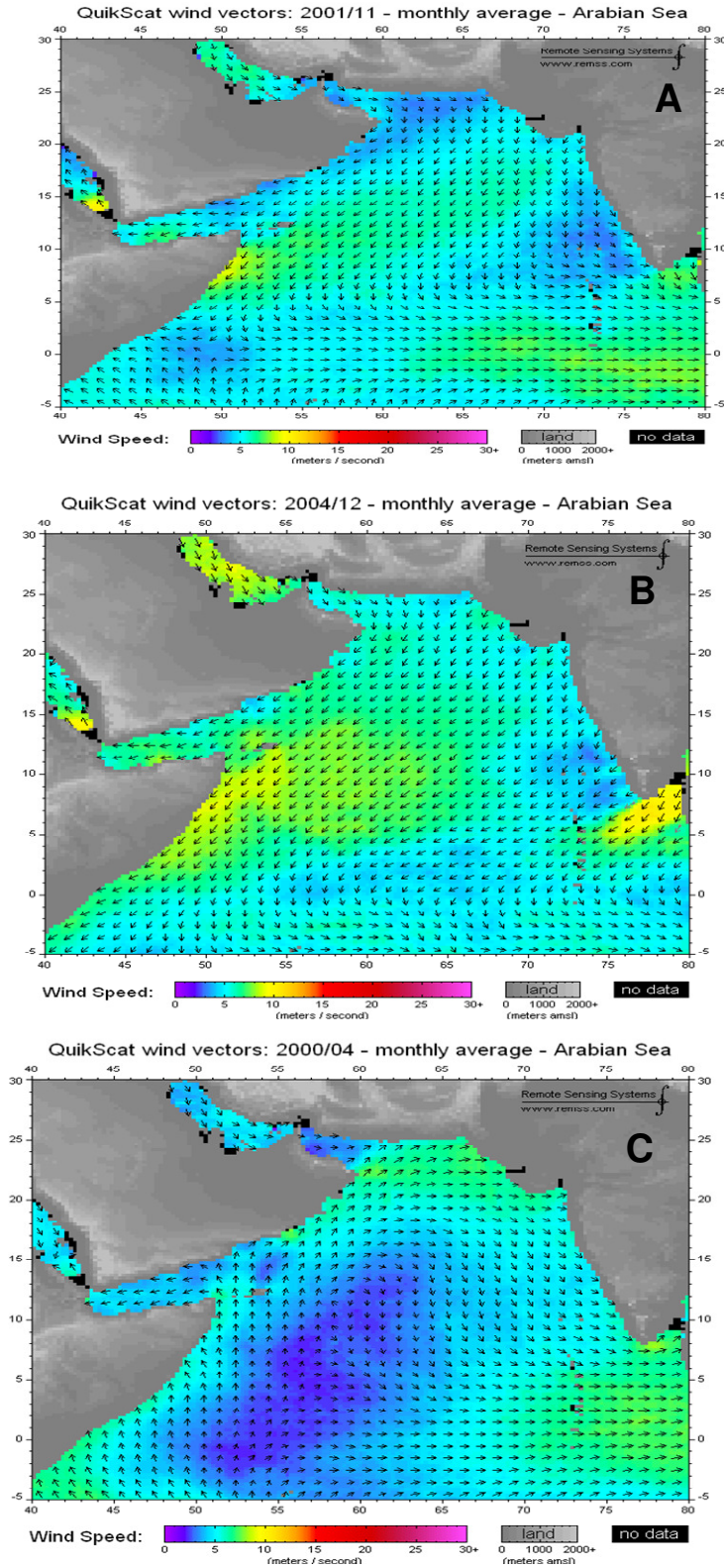
	Surface			Column		
<b>Nov</b>	<i>Trichodesmium thiebautii</i>	<i>Nitzschia Closterium</i>	<i>Amphora Hyaline</i>	<i>Chaetoceros socialis</i>	<i>Melosira moniliformis</i>	<i>Chaetoceros Danicus</i>
<b>Dec</b>	<i>Gymnodinium gracile</i>	<i>Prorocentrum minimus</i>	<i>Rhizosolenia alata</i>	<i>Trichodesmium thiebautii</i>	<i>Nitzschia longissima</i>	<i>Actinopterychus Senarius</i>
<b>Jan</b>	<i>Gymnodinium breve</i>	<i>Gonyaulax schilleri</i>	<i>Amphidinium carteare</i>	<i>Amphidinium carteare</i>	<i>Coscinodiscus radiatus</i>	<i>Gymnodinium spirale</i>
<b>Feb</b>	<i>Noctiluca miliaris</i>	<i>Navicula sp.I</i>	<i>Nitschia closterium</i>	<i>Noctiluca miliaris</i>	<i>Rhizosolenia shrubsolei</i>	<i>Coscinodiscus oculus</i>
<b>March</b>	<i>Trichodesmium Erythraeum</i>	<i>Noctiluca milaris</i>	<i>Hemiaulus sinensis</i>	<i>Rhizosolenia shrubsolei</i>	<i>Pyrophacus horologium</i>	<i>Cocconeis Scutellum</i>
<b>April</b>	<i>Trichodesmium erythraeum</i>	<i>Coscinodiscus marginatus</i>	<i>Peridinium elegans</i>	<i>Navicula delicatula</i>	<i>Trichodesmium erythraeum</i>	<i>Rhizosolenia stolterfothii</i>

## Figure captions

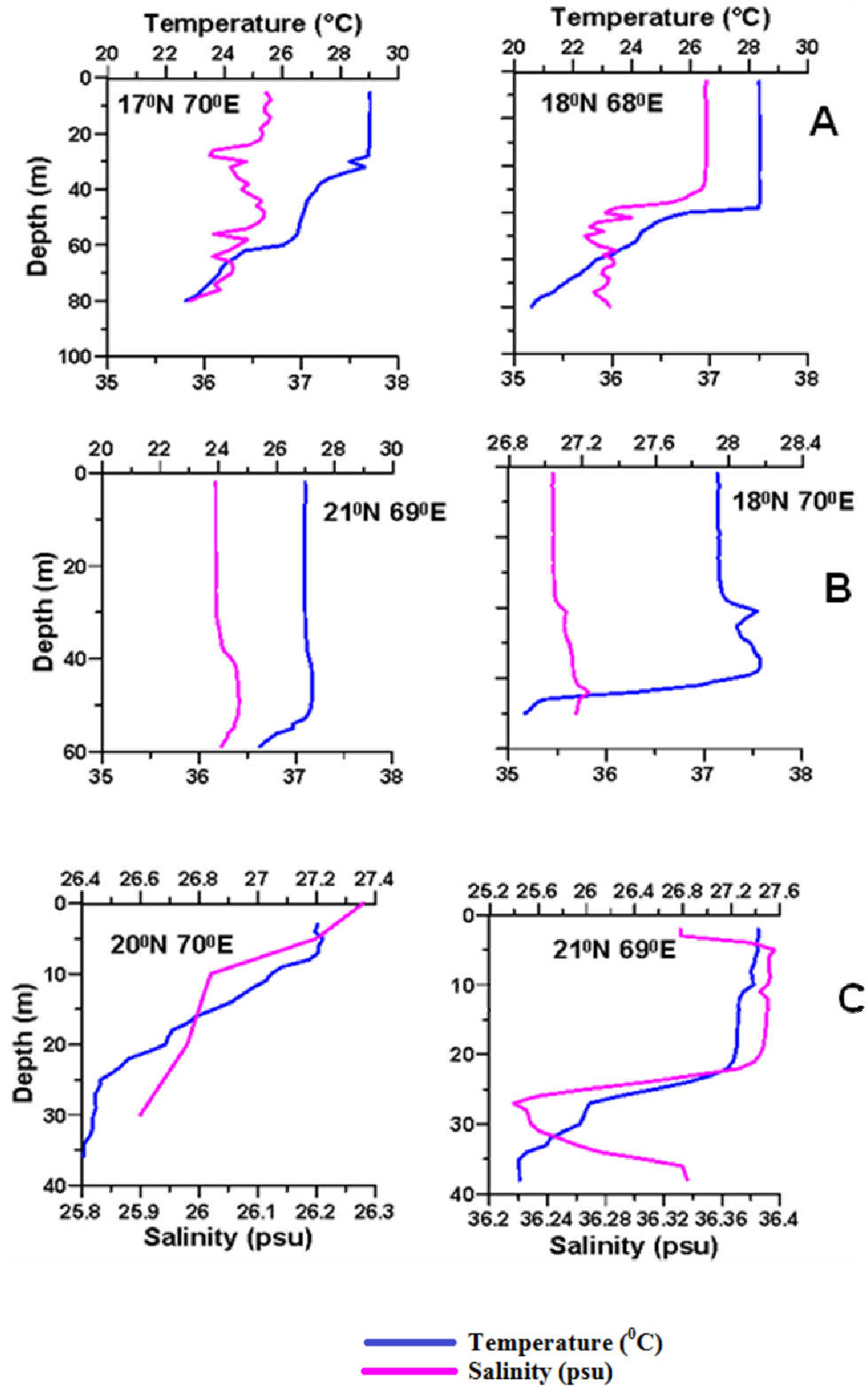
1. Study area showing sampling positions.
2. The pattern of wind direction during (a) fall intermonsoon (b) NE monsoon and (c) Spring intermonsoon.
3. Variations in water temperature ( $^{\circ}\text{C}$ ) and salinity (psu) during (a) fall intermonsoon (b) NE monsoon and (c) Spring intermonsoon.
4. Vertical profiles of nutrients during (a) fall intermonsoon (b) NE monsoon and (c) Spring intermonsoon.
5. Nitrate cycle estimated by MODIS data especially during NE and SW monsoon.
6. Seasonal distribution of (a) Chlorophyll *a* (b) Phytoplankton cell density and (c) *Trichodesmium* filaments. The sets of panels at the left side are surface and right side are column.
7. Chlorophyll *a* from OCM in the Arabian Sea during different months.



**Fig. 1** Study area showing sampling positions.

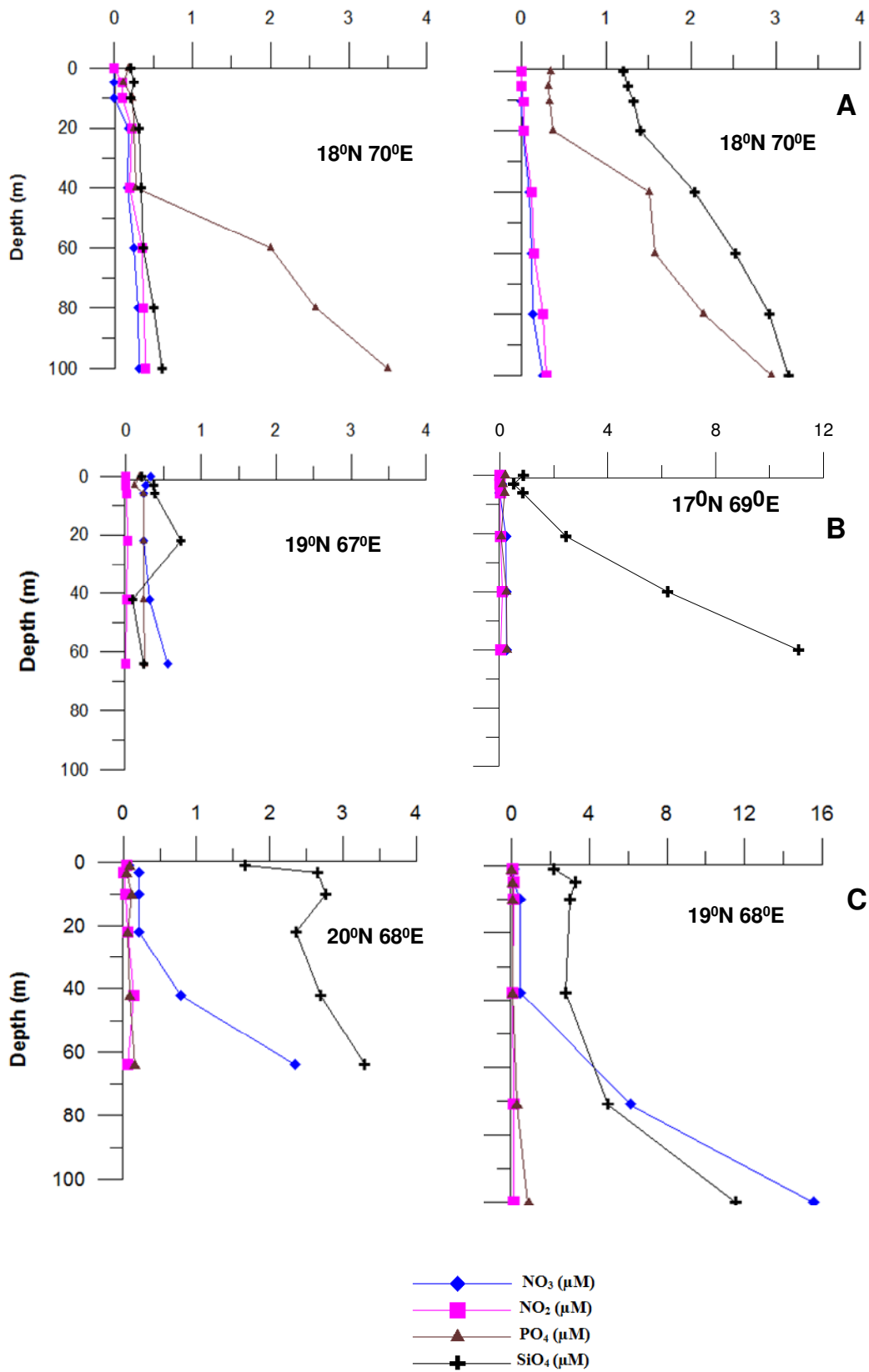


**Fig. 2** The pattern of wind direction during (a) fall intermonsoon (b) NE monsoon and (c) Spring intermonsoon.

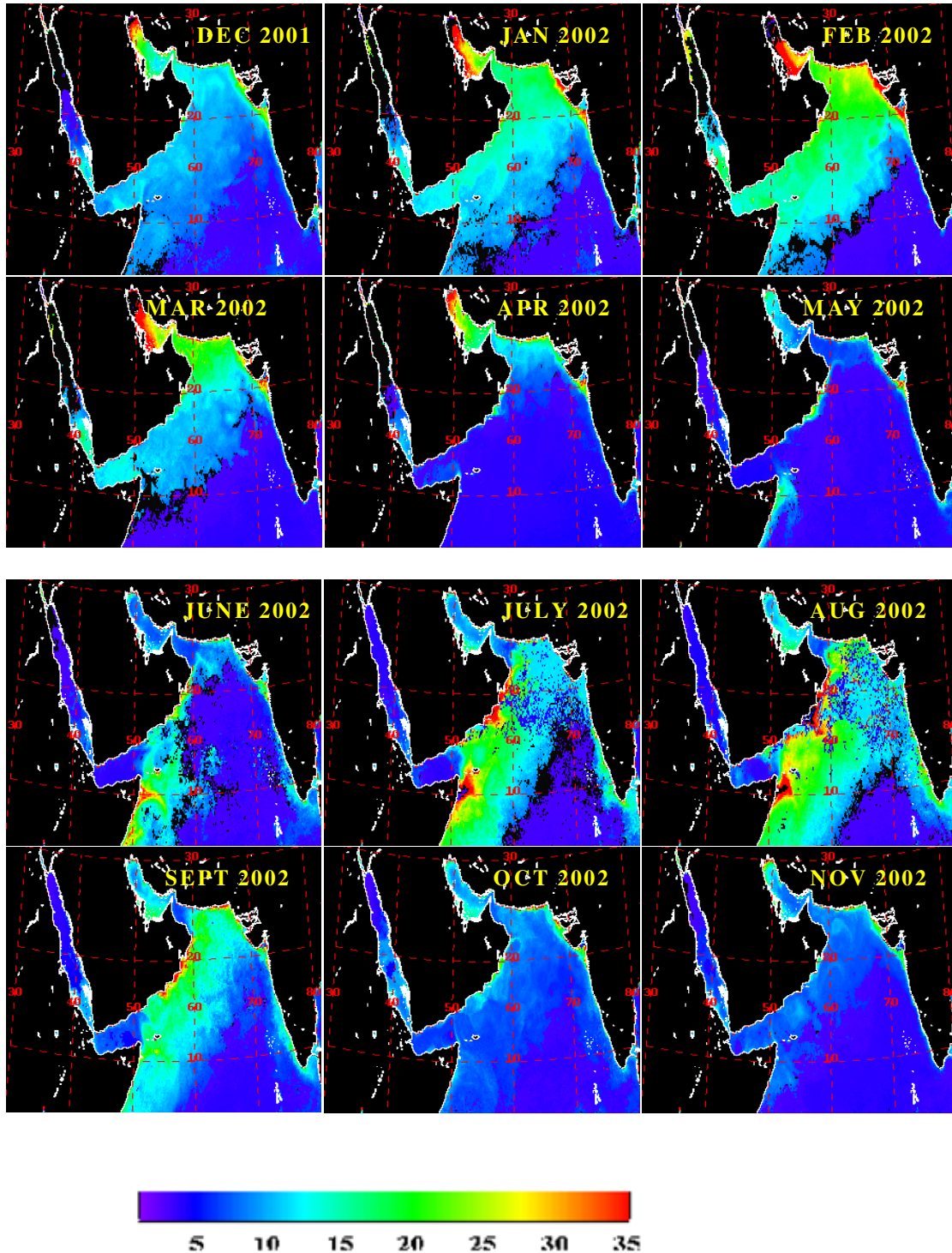


**Fig. 3** Variations in water temperature ( $^{\circ}\text{C}$ ) and salinity (psu) during (a) fall intermonsoon (b) NE monsoon and (c) Spring intermonsoon.





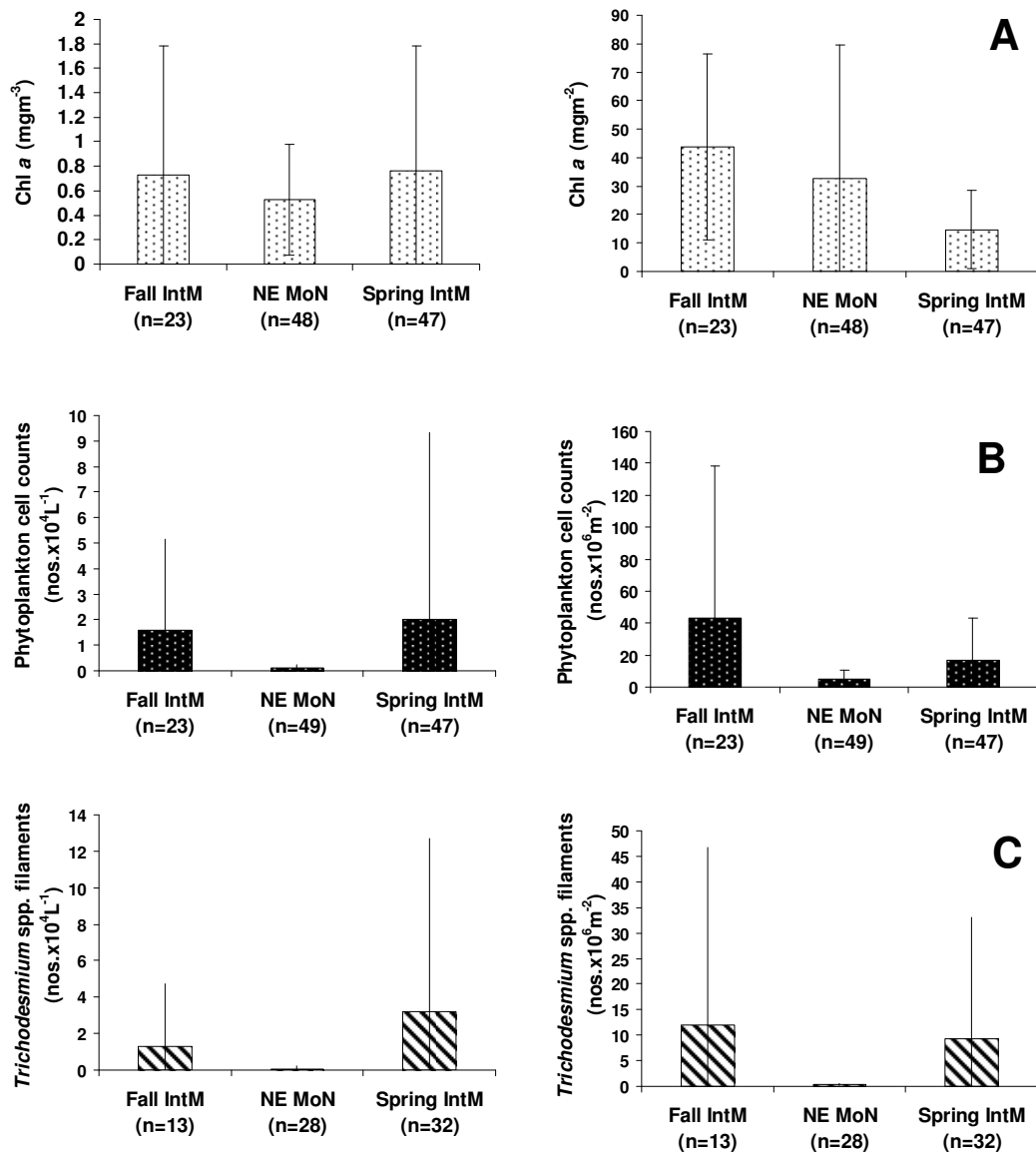
**Fig. 4** Vertical profiles of nutrients during (a) fall intermonsoon (b) NE monsoon and (c) Spring intermonsoon.



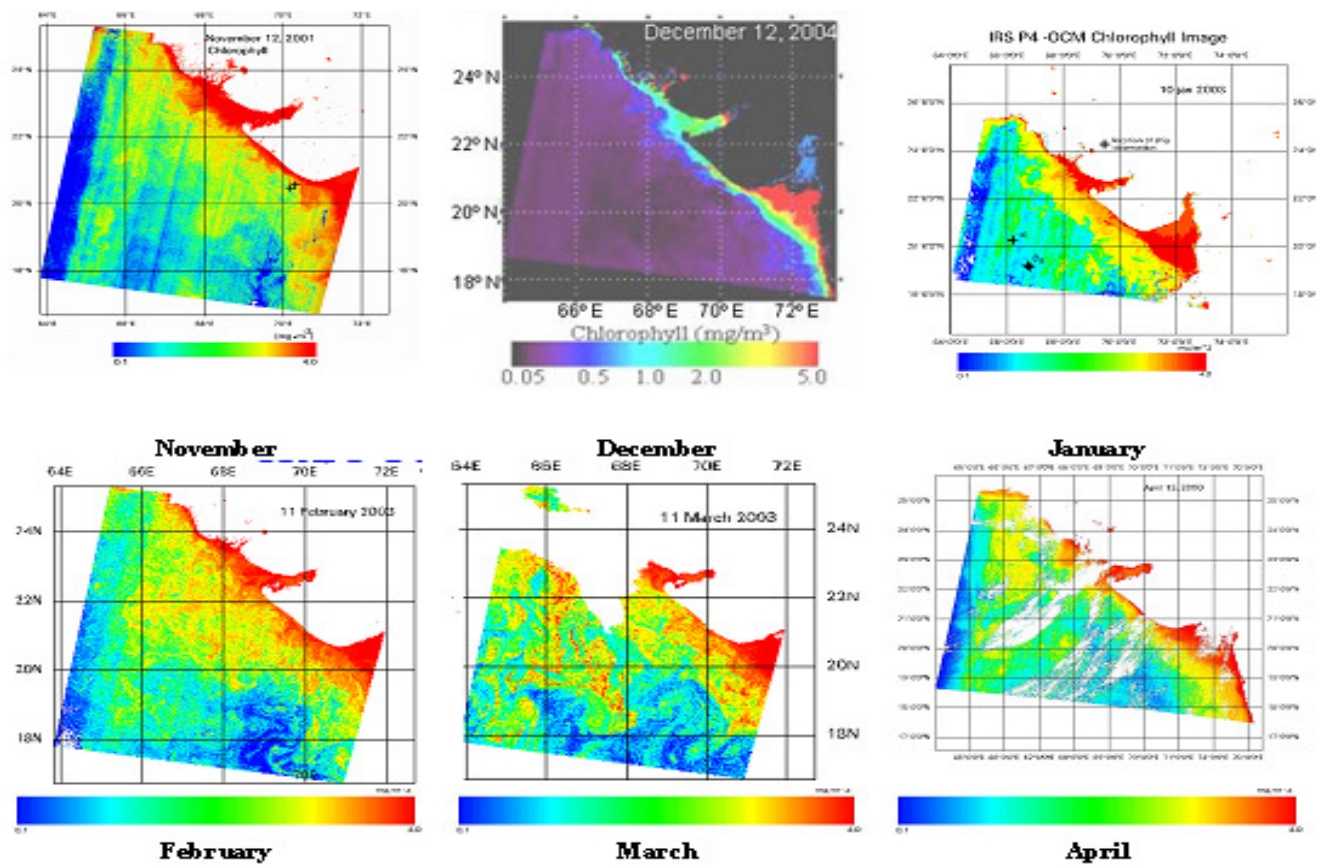
Nitrate ( $\mu\text{M}$ )

Goes, et al., 2006

**Fig. 5** Nitrate cycle estimated by MODIS data especially during NE and SW monsoon (Goes et al., 2004).



**Fig. 6** Seasonal distribution of (a) Chlorophyll *a* (b) Phytoplankton cell density and (c) *Trichodesmium* filaments. The sets of panels at the left side are surface and right side are column.



**Fig.7** Chl *a* from OCM in the Arabian Sea during different months