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Article

Blooms of *Trichodesmium erythraeum* in the South Eastern Arabian Sea during the onset of 2009 Summer Monsoon

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Abstract – This study presents *in situ* evidence for the blooms of *Trichodesmium erythraeum* observed in the shelf waters of the South Eastern Arabian Sea (SEAS) during the onset of the southwest monsoon in June 2009. Evidence showed that water surface discoloration was caused by the accumulation of *T. erythraeum*, and that the water column contained a colony of *T. thiebautii*. The surface water color in the bloom region varied from pale brown to pinkish red. Pale brown indicated healthy algae at the peak of its photosynthetic activity, while pinkish red indicated the presence of photosynthetically less active filaments. Zooplankton abundance, especially copepodites, in the bloom area substantiated the theory that *Trichodesmium* filaments are excellent epiphytes to which the copepodites cling. The bloom area was very fertile with copious quantities of dissolved oxygen (6.85 ml L^{-1}), PO_4-P (0.108 μmol L^{-1}) and SiO_4 (1.29 μmol L^{-1}). Lower NO_3-N (0.028 μmol L^{-}1) values in the bloom area did not appear to affect *Trichodesmium* growth from molecular nitrogen fixation. However, lower NO_3-N values altered the normal phytoplankton composition of this area.

Key words – *Trichodesmium* bloom, *Trichodesmium erythraeum*, *Trichodesmium thiebautii*, South Eastern Arabian Sea, summer monsoon

1. Introduction

Trichodesmium is a common non-heterocystous colonial marine diazotroph found in oligotrophic tropical and subtropical oceans. Several authors have reported its importance in nitrogen fixation (Capone and Carpenter 1982; Zehr et al. 2001; Lugomela et al. 2002; Capone et al. 2005). With daily fixation rates of approximately 30 mg^{-1} N m^{-2} d^{-1}, nitrogen fixation by *Trichodesmium* cells represents an important input of new nitrogen into the euphotic zone (Carpenter and Romans 1991). Red tide phenomena by *Trichodesmium* blooms have been reported during the pre-monsoon months (March to May) in the exclusive economic zone (EEZ) of India by a number of researchers (Devassy et al. 1978; Adhikary and Sahu 1991; Santhanam et al. 1994; Satpathy et al. 1996; Jyothibabu et al. 2003). Generally, the bloom of this filamentous algae occurs during hot weather with brilliant sunlight and stable high salinity (Sellner 1997; Suvapepant 1992). Occurrence of this bloom is quite unusual during the onset phase of summer monsoon in the SEAS, where the key factor driving productivity is coastal upwelling. This paper reports an unusual occurrence of *Trichodesmium erythraeum* blooms along the shelf waters of the SEAS during the onset phase of the monsoon and associated coastal upwelling of 2009.

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2. Materials and Methods

From 29 May to 11 June 2009, blooms of *Trichodesmium erythraeum* were observed in three locations (Figures 1 and 2) during a *FORV Sagar Sampada* cruise 267 along the SEAS. The first bloom observed off Kollam (Bloom-1, 08°59.492 N, 75°59.334 E), with a pale brown surface water discoloration, spread over an area of approximately 10 km^2 on 3 June 2009. The brown color of the *Trichodesmium* bloom showed the healthy nature of the bloom. The second bloom observed off Kochi (Bloom-2, 09°56.183 N, 75°54.948

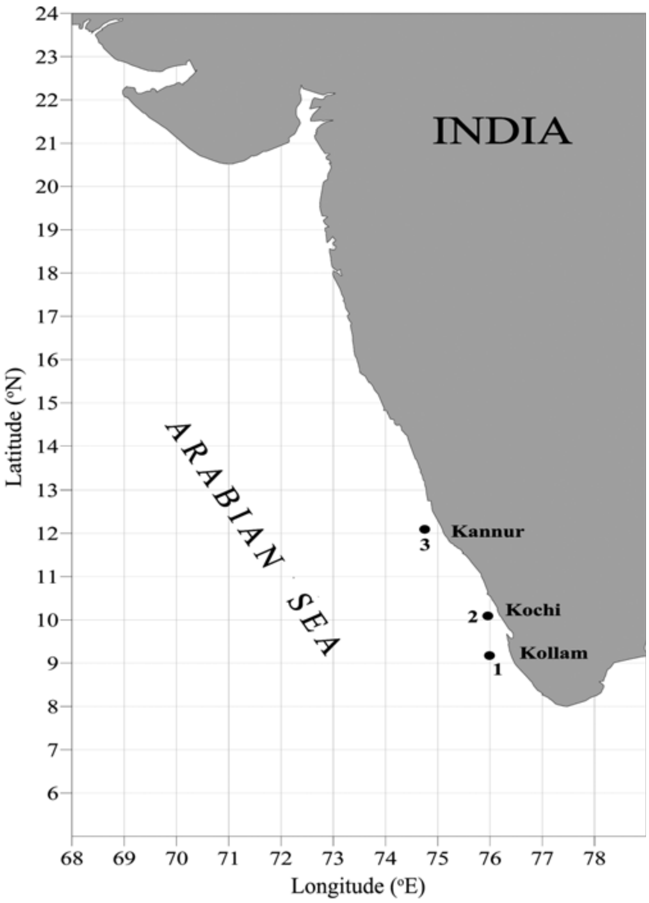

Fig. 1. Location map of the *Trichodesmium* blooms

E), and the third one off Kannur (Bloom-3, 11°59.891 N, 74°35.153 E), extended over an area of more than 20 km^2 in a thick, sawdust-like layer with pink reddish discoloration on 4 and 10 June 2009, respectively. The red or pink discoloration was due to a water soluble accessory pigment called phycoerythrin, an extracellular leachate. After the leaching of accessory pigments, chlorophyll *a* becomes visible in cells and *Trichodesmium* filaments appear light green. Accessory pigment leaching indicates the initial decay phase of a bloom.

To understand the bloom area environment, continuous recordings of weather data, such as wind speed, direction, and rainfall were studied onboard using Automated Weather Station (AWS). Hull-mounted Acoustic Doppler Current Profiler (ADCP-BB 75 KHz) was used to record vertical current profiles in 4 m bin using the bottom track facility. The system was run via VMDAS (Vessel Mounted Data Acquisition Software), and data were post-processed using WinADCP during the entire cruise. Vertical profiling of parameters, such as temperature, salinity, and density, was also done using Conductivity-Temperature-Depth profiler (CTD Seabird 911 plus) attached sensors for understanding oceanic processes. Sea Surface Temperature (SST) of bloom regions was measured by a bucket thermometer. A rosette system, equipped with 10 liter Niskin bottles, attached to the CTD profiler was used for the collection of water samples for *Trichodesmium* counts from various depths in the upper water column. Accumulations of *Trichodesmium* at the surface were also sampled using a plastic bucket and ~10 liters filtered through 60 μ bolting silk and the filtrates were preserved in 1-3% neutralized formaldehyde solution. The *Trichodesmium* filaments were counted using Sedgewick Rafter counting cell under a Nikon Eclipse microscope. Onboard, nitrite, nitrate, phosphate and silicate were analyzed using a segmented flow Auto Analyzer (SKALAR) by following standard procedures. Ammonium concentrations were determined manually by colorimetric methods. Photosynthetic pigments, such as chlorophyll *a* and phaeophytin, were measured spectrophotometrically using a double beam UV-Visible spectrophotometer (Parsons et al. 1984). Mesozooplankton samples were collected by Multiple Plankton Nets (MPN) and Bongo nets.

3. Results and Discussion

Qualitative and quantitative analyses of bloom samples revealed that, in all three bloom areas, *Trichodesmium erythraeum* contributed 90% of the surface phytoplankton population. The remaining 10% was predominantly composed of diatoms and dinoflagellates. Bloom sample analysis

Fig. 2. *Trichodesmium* bloom off Kochi

revealed that elongated rafts of *T. erythraeum,* called "tufts", cause water discoloration. Cell density was 1.14× 10^6 filaments L^{-1}, 1.968×10^6 filaments L^{-1} and 1.51×10^6 filaments L^{-1} at bloom sites off Kollam, Kochi and Kannur, respectively. However, column phytoplankton analysis depicted the presence of spiky balls, called "puffs", of *T. thiebautii* as a major constituent. The colony consisted of 10-30 trichomes in *T. erythraeum* and 30-50 trichomes in *T. thiebautii*. Positive buoyancy of *Trichodesmium* is well known; *T. erythraeum* is more buoyant than *T. thiebautii*. *T. erythraeum* has copious numbers of gas vacuoles and, hence, was found in abundance in the surface waters (Carpenter 1983; Capone et al. 1997; Lugomela et al. 2002).

The 2009 monsoon set in over Kerala on 23 May. This occurred one week earlier than its normal date of 1 June. During 8-20 June, there was a prolonged hiatus in the advance of the monsoon along the region (IMD end of-season report 2009). In all three transects where blooms were recorded, the wind pattern was westerly to northerly and moderate with an average magnitude of 5 m/s (Figure 3). Whereas, off Kollam (9°N) and further south, wind was north-northwesterly and so induce offshore transport causing upwelling. Orientation of the coast line may also have a positive influence in the triggering of upwelling in the region (Smitha et al. 2008). Though upward lifting of subsurface isotherms starts from March (Shenoi et al. 2005), chemical and biological indications of the process are evident only with the commencement of the summer monsoon. With onset in late May, weak to moderate upwelling occurs off of the Kanyakumari coast (8°N lat). The upwelling spreads northwards along the coast as the monsoon advances, reaching up to the Goa coast (15.5°N lat) during the peak monsoon. Upwelling in the surface waters was observed in the southern area (Figure 4) up to Kollam (9°N), but it was confined to the coast, particularly around a depth of 50 m (34 km off shore) off Kollam. Whereas inter spring characteristics prevailed in the offshore surface waters of the transect, surface waters off Kochi and Kannur showed higher SST (>28.5 °C) and stratified waters due to abundant sunlight and weak wind. Vertical temperature profiles (Figure 5) from CTD showed an upward shifting of isolines (26 °C) towards the coast in the subsurface layers in

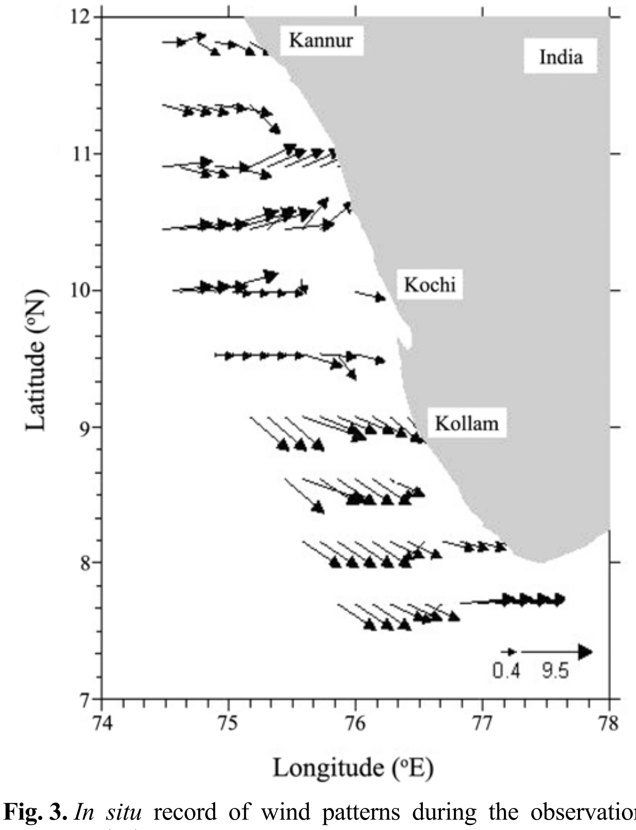

Fig. 3. *In situ* record of wind patterns during the observation period

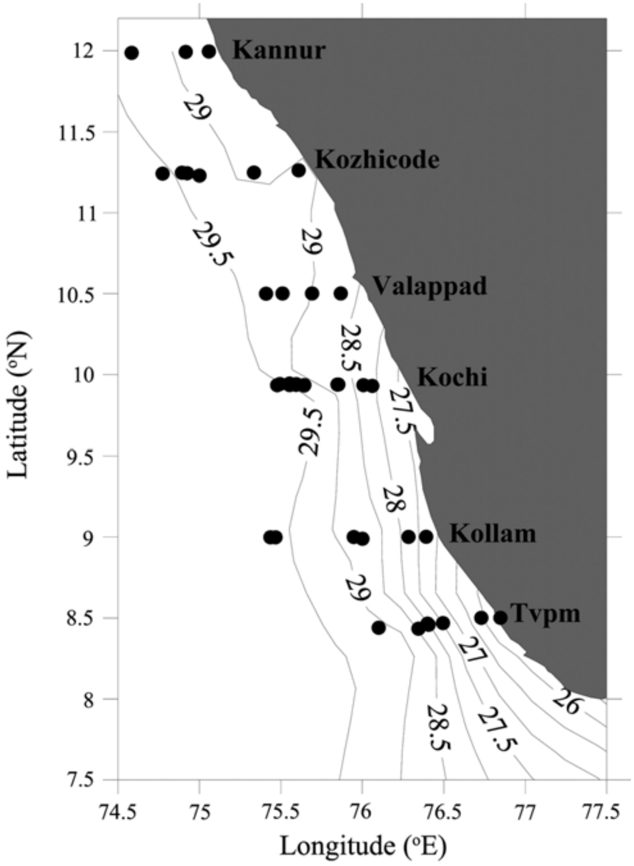

Fig. 4. SST distribution during the onset phase of upwelling

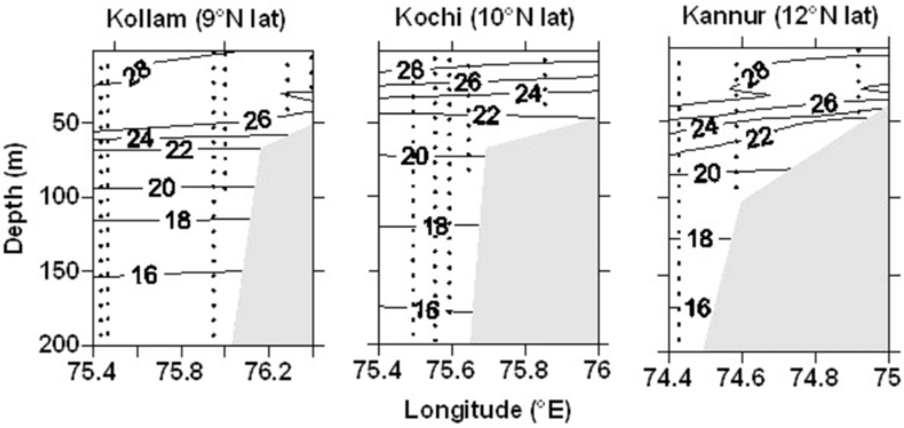

Fig. 5. Vertical section of temperature along the bloom transects. (....) indicate the sampling points

Table 1. Met-ocean parameters of the three bloom areas

Parameters	off Kollam	off Kochi	off Kannur
Water color	Pale brown	Straw yellow	Pink reddish
Wind speed (m/sec)	4.6	4.9	5.1
Wind direction (°)	299	270	282.2
Air Temperature (°C)	29.7	31.5	28.4
Humidity (%)	82.2	79.3	83.1
Pressure (mbar)	1010	1006.8	1007.5
Solar radiation (mw/sq. cm)	79.2	76.2	7.8
SST (°C)	28.7 °C	29.48	29.03
Salinity (psu)	35.13 psu	35.17	35.47
Mixed Layer Depth- MLD (m)	10	10	16
Isothermal Layer Depth-ILD (m)	17	12	20
Rainfall	Moderate rain	Nil	Nil
Weather	Calm	Calm	Calm

these two transects. Table 1 shows the met-ocean parameters of the three bloom areas.

The vector plot of surface ADCP currents (Figure 6) shows an overview of the prevalent conditions from 29 May to 13 June 2009. The near surface current pattern (24 m level) shows the presence of a well-established WICC (West India Coastal Current) flowing south along the coast. The current is weaker (<100 mm/s) in the north, but strengthens up to 700 mm/s through the middle and southern parts of the study area. The slight offshore deflection seen in the pattern at 9°N, and at the southern latitudes, coincides with the upwelling areas showing offshore transport and mixing of water with the coastal current.

Generally, the bloom of this filamentous algae occurs during hot weather with brilliant sunlight and stable high salinity (Suvapepant 1992; Sellner 1997). Carpenter (1983) also pointed out that *Trichodesmium* growth is not stimulated in classical upwelling areas.

Trichodesmium bloom occurrence during a monsoon in an upwelling area can therefore be considered quite unusual. Observations showed that upwelling was at its initial/onset phase, and was evident only at the southern part of the region up to Kollam (9ºN). The offshore extent of the process off Kollam was only limited to 50 m depth station (34 km from coast). The first bloom observed off Kollam was in and around an area where the station depth was approximately 100 m (64 km from coast). It is noted that SST at these two locations, separated by a distance of 30 km, differed by 1.457 °C. No signature of upwelling was noticed in the surface, and water characteristics were more or less those of hot weather due to the break in monsoon during the period off Kochi (10°N) and Kannur (12°N). During the observation, SST fell in the range of 28.52 to 29.22 °C and salinity ranged from 34.55 to 35.47 psu in bloom regions. Warm sea

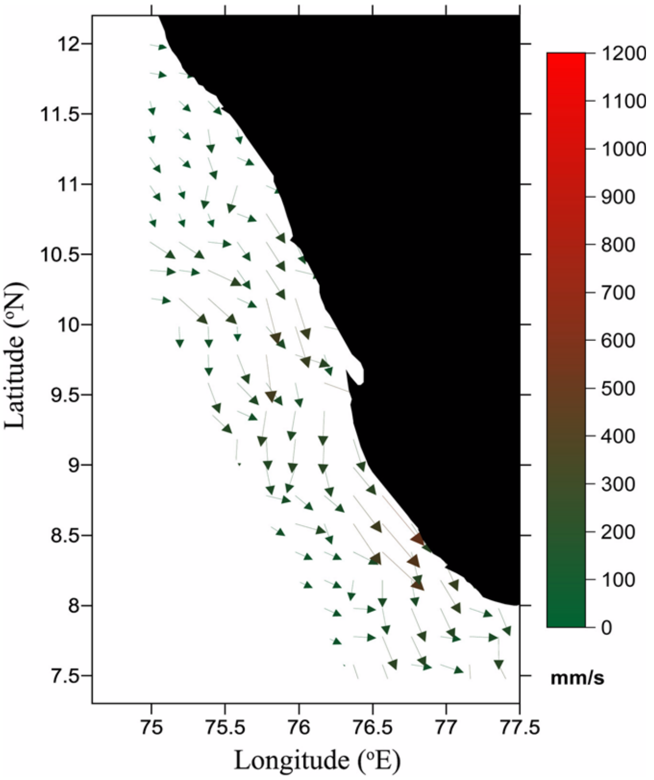

Fig. 6. Near surface (24 m) current pattern from ADCP during the onset phase of upwelling

surfaces with moderate salinity and sunlight were not subject to much change during this observation and, like the pre-monsoon months, were typical of the upper few meters of tropical ocean waters. Since *Trichodesmium* is a stenohaline form, stable salinity conditions with 32 psu or above support species growth and abundance. Salinity remained almost constant in the three bloom areas and there was no evidence of sea water dilution, due to the irregularity in the onset phase of the southwest monsoon, from fresh water influence or rainfall. This irregularity and the associated delay in the occurrence of coastal upwelling might have helped the persistence of pre-monsoon conditions in the area, which sustained the *Trichodesmium* blooms that developed during the pre-monsoon months.

Average nutrient data of SEAS for June 2008 was NO_3-N 0.093 µmol L^{-1}, PO_4-P 0.061 µmol L^{-1} and SiO_4 0.972 µmol L^{-1}. However, higher values of PO_4-P, SiO_4 (0.108 µmol L^{-1} and 1.29 µmol L^{-1}) and low values of NO_3-N (0.028 µmol L^{-1}) were recorded in 2009 where the blooms occurred. It is possible that the elevated phosphate concentration was due to the microbial decomposition of organic matter and that the silicate concentration could be associated with underutilization by the cyanobacteria bloom. Prolonged growth of phytoplankton in the stratified photic zone of the west coast during the pre-monsoon period seems to be the cardinal reason for the reduction of NO_3-N. In such situations where the growth of phytoplankton that require NO_3-N seems to be restricted, *Trichodesmium* flourishes in the area due to its ability to fix molecular nitrogen. Ammonium concentration of the bloom water (0.843 µmol L^{-1}) was slightly higher than that of non bloom areas (BDL). This could be ascribed to the diazotrophic nature of *Trichodesmium* (Chang et al. 2000) and the decomposition of ungrazed *Trichodesmium* bloom (Nair et al. 1992).

Dissolved oxygen was higher (6.85 ml L^{-1}) in the bloom areas, possibly due to photosynthetic release of O_2 by the highly dense algal biomass. A similar increase in DO was also reported by (Capone et al. 1997). Higher values of chlorophyll *a* and phaeophytin were observed in bloom areas (chlorophyll *a* 14.66 µg L^{-1} and phaeophytin 2.21 µg L^{-1}) compared to non-bloom areas (chlorophyll *a* 0.273 µg L^{-1} and phaeophytin 0.134 µg L^{-1}). High phaeophytin suggests that the peak of the bloom had finished at the time of collection.

Zooplankton samples, collected from the bloom area using Bongo nets, contained large quantities of *Trichodesmium.* In all three bloom areas, zooplankton biomass was high (11.59 ml m^{-3}) compared to non bloom areas (2.39 ml m^{-3}). Copepods showed maximum numerical abundance and percentage composition among zooplankton followed by chaetognaths, jellyfish, amphipods, lucifer, gastropods, cladocerans, fish eggs, and larvae. Among copepods, the harpacticoid copepod *Macrosetella gracilis* was dominant. Microscopic analysis showed adult and larval *Macrosetella gracilis* attached to *Trichodesmium* filaments. The creeping larvae of this copepod require substrate for development while adults graze on *Trichodesmium* filaments. Larvae, copepodites and adults have specialized hooks for attachment. This observation supports a previous laboratory observation that this algae serves as a substrate for copepod development (Bjornberg 1965). Among the fish eggs and larvae in the zooplankton samples, eggs were more abundant. The presence of fish eggs and larvae in association with the blooms indicate congregations of spawning fish in the bloom area. Hence, the occurrence of fish eggs and larvae in association with the *Trichodesmium* blooms appear to be a species adaptation to provide food and protection for the developing eggs and larvae.

Harmful effects associated with blooms may vary from negligible to severe mortality of marine fauna. Fish mortality numbers by *Trichodesmium* blooms have been reported earlier by workers from Indian waters (Chacko 1942; Devanesen 1942). However, no fish mortality was observed during the 2009 bloom in any of the three areas. Fish landing information, gathered from different fishing harbors at Kollam, Kochi and Kannur, shows that *Sardinella gibbosa*, *S. longiceps*, *Rastrelliger kanagurta* and *R. neglectus* form the major constituency of the fishery in the area. Gut content analysis of these species showed that *Trichodesmium* forms 55-65% of the total stomach contents. Many reports have reported that *Trichodesmium* provides the food for marine copepods and fishes (Bryceson and Bay 1980; Carpenter 1983). This observation on the bloom, associated environment, and productivity pattern does not indicate any direct inhibitory influence on the fishery in the bloom region. In conclusion, it is apparent that *Trichodesmium* blooms are ecologically significant to the productivity patterns of SEAS.

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