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Trichodesmium blooms and warm-core ocean surface features in the Arabian Sea and the Bay of Bengal

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ABSTRACT

Trichodesmium is a bloom-forming, diazotrophic, non-heterocystous cyanobacteria widely distributed in the warmer oceans, and their bloom is considered a 'biological indication' of stratification and nitrogen limitation in the ocean surface layer. In the first part of this paper, based on the retrospective analyses of the ocean surface mesoscale features associated with 59 *Trichodesmium* bloom incidences recorded in the past, 32 from the Arabian Sea and the Bay of Bengal, and 27 from the rest of the world, we have showed that warm-core features have an inducing effect on bloom formation. In the second part, we have considered the environmental preferences of *Trichodesmium* bloom based on laboratory and field studies across the globe, and proposed a view about how warm-core features could provide an inducing pre-requisite condition for the bloom formation in the Arabian Sea and the Bay of Bengal. Proposed that the subsurface waters of warm-core features maintain more likely chances for the conducive nutrient and light conditions required for the triggering of the blooms.

1. Introduction

The marine cyanobacteria, *Trichodesmium,* are well-known for their sporadic and abrupt blooms in the surface waters of warm oceans during conducive conditions and their thick, yellowish-brown, mat-like bloom biomass that floats on the sea surface is referred to as 'Sea Sawdust' (Qasim, 1972; Capone et al., 1997; Jyothibabu et al., 2003). These blooms are expected to channel large amounts of molecular nitrogen into the photic zone of the ocean through new production and, therefore, believed to play a substantial role in ocean nitrogen cycle (Carpenter and Capone, 1992; Capone et al., 1997; Gandhi et al., 2011; Parab and Matondkar, 2012). Also, it has been believed since the last few decades that *Trichodesmium* blooms represent biological indications of prolonged ocean surface layer stratification and nitrogen limitation (Carpenter and Roenneberg, 1995; Matondkar et al., 2006). Although the formation mechanism of *Trichodesmium* blooms continues to be an enigma across the globe, several concerted field surveys and laboratory experiments in the recent decades world over have helped in significantly improving our understanding on the environmental preferences for the *Trichodesmium* bloom formation (Ohki et al., 1986; Ohki and Fujita, 1988; Carpenter and Capone, 1992; Capone et al., 1998; Chen et al., 1996; Subramaniam et al., 1999, 2001; Jyothibabu et al., 2003; Bell et al., 2005; Matondkar et al., 2006; Parab and Matondkar, 2012). It is also pertinent to remember that ocean colour satellite remote sensing has contributed significantly in synoptically tracking thick blooms of *Trichodesmium* in ocean surface layers (Subramaniam et al., 2001; Hegde et al., 2008; Gower et al., 2014; McKinna, 2015 and references therein).

The bloom formation of *Trichodesmium* (both *Trichodesmium erythraeum* and *T. thiebautii*) in the northern Indian Ocean and their possible linkages to the ocean surface mesoscale processes are the focus points of this study. To make the evaluation in the northern Indian Ocean more reliable, certain bloom incidences from other parts of the world were also considered in this paper. Literature confirms that *Trichodesmium* population inhabits the Arabian Sea and the Bay of Bengal throughout the year, albeit their contribution to the native phytoplankton community remains insignificant except at conducive times when they proliferate (Ramamurthy, 1972; Jyothibabu et al., 2003; Hegde et al., 2008; Ashadevi et al., 2010; Mohanty et al., 2010; Parab and Matondkar, 2012). The predominant conducive season of *Trichodesmium* blooms in the northern Indian Ocean is the pre-southwest monsoon (March–May), when the region is exposed to the seasonal highest solar heating and has thermally stratified and nitrogen limited ocean surface waters (Qasim, 1972, Devassy et al., 1978, Capone et al., 1997; Subramaniam et al., 1999; Jyothibabu et al., 2003, Matondkar et al., 2006; D'Silva et al., 2012 and references therein). However, it is a reality that the usual *Trichodesmium* blooms that occur in the Arabian Sea and the Bay of Bengal have only sporadic appearance

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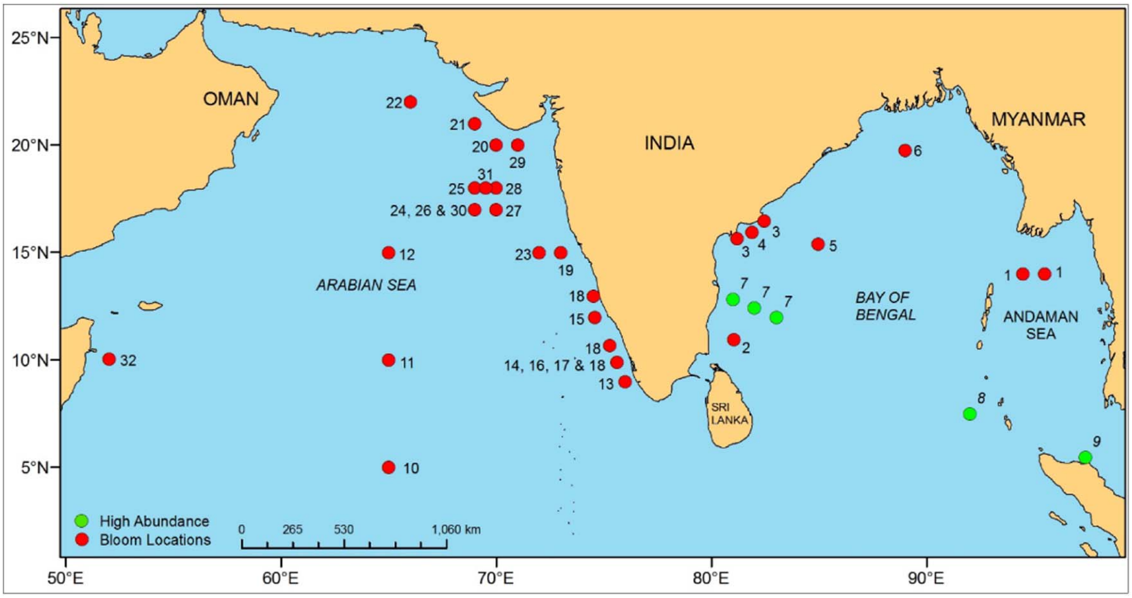

Fig. 1. Past incidences of *Trichodesmium* (red and green filled circles) in the northern Indian Ocean analysed in the present study. A total of 32 incidences from the northern Indian Ocean are presented in which 9 are from Bay of Bengal and 23 from the Arabian Sea. The bloom incidences considered from the rest of the world (other than the Indian Ocean) are not represented here. Red filled circles represent sighting of the surface blooms whereas, green filled circles indicate the presence of high abundance of *Trichodesmium*. Serial numbers of the bloom incidences here are the same in Table 1, wherein, more details of each bloom incidence are given. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with much lesser geographical extent and duration compared to the ocean surface layer stratification and nitrogen limitation, which are actually basin-scale seasonal features during the pre-southwest monsoon period. In other words, even during the stratified and nitrogen-limited pre-southwest monsoon ocean surface conditions that prevail in the entire northern Indian Ocean, *Trichodesmium* surface blooms occur sporadically and abruptly, and mostly on a micro-scale (a few km) to meso-scale (10s to100s of km) spatial extent.

The scientific reasoning presented above and our field experience in the seas around India during the last two decades have motivated us to investigate the role of ocean mesoscale features in facilitating the optimum conducive conditions for *Trichodesmium* blooms. The other motivation behind this paper is the interesting research paper published by Davis and McGillicuddy (2006), who showed that waters in the north Atlantic with warm core (anti-cyclonic) mesoscale features harbour high abundance of *Trichodesmium* filaments. This observation was based on Video Plankton Recorder (VPR) tows across the north Atlantic during the spring season. More recently, another study from the same geographical area showed that cold core (cyclonic) eddies also harbour abundant *Trichodesmium* filaments, but during the fall season (Olson et al., 2015). The common message in these studies is the potential of the mesoscale features (both anti-cyclonic and cyclonic) to provide conducive condition for the prevalence of *Trichodesmium* populations. Nevertheless, it is relevant to recall here that the above studies from the north Atlantic neither dealt with *Trichodesmium* bloom incidences nor the possible mechanism that favour the bloom formation in the region.

Earlier studies on *Trichodesmium* blooms from the northern Indian Ocean have mainly dealt with the environmental characteristics that existed either during or just after the sighting of the surface blooms (Devassy et al., 1978; D'Silva et al., 2012 and the references therein). Therefore, they failed to capture the mechanisms that triggered/favoured the formation of the bloom, which has greatest scientific importance while considering that *Trichodesmium* population with its slow growth rate requires more than a week's time to form mat-like surface blooms (Ohki and Fujita, 1988; Chen et al., 1996; Bell et al., 2005). This indicates that the conditioning of the favourable environment that triggers *Trichodesmium* blooming begins a few weeks prior to the actual sighting of the floating bloom biomass on the ocean surface. This agrees very well with earlier observations that the floating bloom biomass on the sea surface mostly represents the collapsing/dead phase of the bloom biomass and, therefore, consists of fewer viable individuals (Ramamurthy, 1972; Ohki and Fujita, 1988; Chen et al., 1996; Bell et al., 2005). Therefore, naturally, the environmental features recorded during the surface bloom sightings might have essentially represented the post-bloom disintegration phase rather than the actual environmental conditioning that favours the bloom formation. All the above points indicate the relevance of focussed time - series studies that begin at least a fortnight prior to the sighting of the bloom biomass on the ocean surface, to understand the environmental conditioning triggering the bloom. However, a progressive time series study to track *Trichodesmium* bloom formation in a marine environment has large uncertainties as we never know exactly when and where the bloom occurs, even when stratification and nitrogen limitation exist over an extensive geographical area. Time series data from environmental data buoys with biochemical sensors could be a promising tool in this regard, but research in this line in the northern Indian Ocean is still in the beginning phase. Therefore, in this paper we addressed the following (a) investigated the linkage between meso-scale features and the *Trichodesmium* bloom incidences in the northern Indian Ocean (b) analysed a few *Trichodesmium* bloom cases and mesoscale processes from the rest of the world ocean and (c) attempted to explain the possible mechanism behind the observed biophysical linkage.

2. Methods

Although ocean-colour sensors have been used for direct synoptic-scale detection of *Trichodesmium*, a majority of such methods are non-quantitative and developed for mapping dense surface aggregations; therefore, they are unsuitable for tracking low background (cases < 3200 trichomes L^{-1}) bloom concentrations (McKinna, 2015). The approach is different in this paper, wherein, a retrospective analysis of the mesoscale ocean surface features have been carried out based on relevant satellite remote sensing data associated with *Trichodesmium* bloom incidences recorded in many literature. The geographical co-ordinates of the bloom incidences given in the literature are used to scientifically assess the proximity/linkage of these blooms

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