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Phytoplankton response to the contrasting physical regimes in the eastern Arabian Sea during north east monsoon

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ABSTRACT

Phytoplankton abundance and composition in two contrasting physical regimes - convective mixing in the northeastern Arabian Sea (NEAS) and Arabian Sea mini warm pool (ASMWP) in the southeastern Arabian Sea (SEAS) - were investigated during the northeast monsoon (NEM) of 2015 and 2017. Observations in 2015 were carried out late during the season, and only one station in the north (at 21°N latitude) fell within the zone of convective mixing where microplankton was dominated by diatoms. In 2017, convective mixing occurred even at 16°N latitude, but the microplankton contribution was low, presumably due to low Si/N ratios. Within the convective mixing regime of the NEAS, chlorophyll (Chl) *a* concentrations were higher in 2015 (maximum 1080 ng L^{-1}; average 493 ng L^{-1}) than in 2017 (maximum 673 ng L^{-1}; average 263 ng L^{-1}). In contrast, picophytoplankton were dominant in the ASMWP of the SEAS with peak abundance associated with the subsurface chlorophyll maximum. A warm core eddy was present in 2015 in the SEAS where four times higher *Prochlorococcus* counts were found within the core of the eddy than at its periphery. This study provides the first description of the phytoplankton community in the ASMWP. Our results clearly demonstrate phytoplankton response to the contrasting physical conditions, highlighting the role of bio-physical coupling in the productivity of the Arabian Sea.

1. Introduction

The northern Indian Ocean is bounded by the Eurasian landmass at low latitudes (~25°N), which makes its oceanographic processes including biogeochemistry quite different from those in other ocean basins. For example, unlike the Atlantic and the Pacific Oceans, the most intense upwelling in the Indian Ocean occurs in its northwestern part - the Arabian Sea - in summer, when the winds blow from the southwest to the northeast. In winter, when the atmospheric and surface oceanic circulations are reversed, the northern Arabian Sea experiences moderate convective mixing due to cooling of surface waters. Together, these phenomena make the Arabian Sea one of the most productive regions of the world oceans (Madhupratap et al., 1996; Naqvi et al., 2006). High biological productivity along with restricted oxygen supply also result in the development of an intense oxygen minimum zone at intermediate depths (150–1200 m) (Wyrtki, 1971) providing suitable conditions for large scale nitrogen loss, mostly through denitrification (Sen Gupta and Naqvi, 1984; Naqvi, 1987, 1991; Ward et al., 2009). In contrast to the eastern Pacific Ocean, the denitrification zone is geographically separated from the high productive upwelling centres in the Arabian Sea (Naqvi, 1991).

The Arabian Sea has been extensively studied under two major international programmes – the International Indian Ocean Expedition (IIOE) in the 1960s and the Joint Global Ocean Flux Study (JGOFS) three decades later (Naqvi et al., 2003). Unfortunately, security concerns due to piracy constrained research in the region for about a decade but another major international project – IIOE-2 – has just been launched in recognition of the unique oceanography of this region and its sensitivity to human activities.

Among the best known features of the Arabian Sea is the response of the phytoplankton community to seasonal reversals of winds during the summer or southwest monsoon (SWM) and the winter or northeast monsoon (NEM) seasons (*e.g.* Sawant and Madhupratap, 1996; Madhupratap et al., 1996; Garrison et al., 1998, 2000; Tarran et al., 1999; Wood, 1999). These studies revealed that nutrient enrichment in euphotic zone arising from upwelling and convective mixing leads to extensive phytoplankton blooms contributing to the fishery potential of the region, not only in the open waters (~100 million tons of

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myctophids in OMZ; Madhupratap et al., 2001) but also to the coastal fishery (~2.3 million tons along the west coast of India; http://eprints.cmfri.org.in/11964/1/CMFRI%20Annual%20Report%202016-17.pdf). During winter, the cool dry continental air brought to the northern Arabian Sea by the trade winds promotes evaporation and cooling of surface waters. This drives convective mixing leading to the deepening of the mixed layer and entrainment of nutrients from the thermocline into the surface layer thereby supporting widespread winter blooms that are mostly dominated by diatoms (Madhupratap et al., 1996; Prasanna Kumar and Prasad, 1996; Prasanna Kumar et al., 2001). However, a recent study has reported a dramatic shift in the phytoplankton community over the past decade or so with the diatoms having been replaced by dinoflagellate *Noctiluca scintillans* (Gomes et al., 2014). This shift has been attributed to large-scale development of hypoxic conditions in the euphotic zone thereby favoring the growth of *N. scintillans* because the endosymbiont of this organism (*Pedinomonas noctilucae*) can fix carbon efficiently under hypoxic conditions. Such an ecosystem shift is expected to have huge impact on fisheries as the major consumers of *N. scintillans* are salps and jellyfish, both minor components of fish diet (Gomes et al., 2014). However, subsequent work by Prakash et al. (2017), employing *in situ* measurements and Argo floats data collected in winter, did not find any indication of the reported incursion of hypoxic waters into the surface layer in the NEAS.

Contrasting with the cooling of surface waters in the NEAS, the warm sea surface temperatures over the southeastern Arabian Sea (SEAS) are important for the onset of the SWM over western India during February–May (Vinayachandran et al., 2007). This warm region in the SEAS was defined as a "mini warm pool" (Rao and Sivakumar, 1999) or SST high (Shenoi et al., 1999). Later, Vinayachandran et al. (2007) called it the Arabian Sea mini warm pool (ASMWP). Warming of surface waters in this region begins in February and continues up to April–May. During this period, circulation in the SEAS consists of a quasi-permanent anti-cyclonic eddy (warm-core eddy) associated with a high sea level – the Lakshadweep High (Schott and McCreary, 2001). The eddies propagate westward and affect the hydrography of the region. Several studies (*e.g.* Fryxell et al. (1985) and Gould and Fryxell (1988) in the Gulf Stream; and Stramma et al. (2013) in the Pacific Ocean) found distinct phytoplankton communities associated with warm core eddies. Huang et al. (2010) observed the dominance of prochlorophyceae as well as haptophyceae in two different warm core eddies in South China Sea. The phytoplankton community structure within the warm core eddies of the Arabian Sea has not been investigated in detail so far.

In the present study, we highlight the response of phytoplankton to the contrasting physical regimes in the eastern Arabian Sea during NEM – the convective mixing that entrains nutrients from below the thermocline in the north, and stratification within the ASMWP that creates oligotrophic conditions in the south. Both processes lead to deepening of the mixed layer, but are expected to have different impacts. We employ HPLC based pigment analysis along with flow cytometry data to understand the phytoplankton community structure in the region, a tool found useful in several other recent studies (Mitbavkar et al., 2015; Rajaneesh et al., 2015; Roy et al., 2015; Ahmed et al., 2016). Based on the *in situ* measurements of physical and biological data, we explore the bio-physical coupling in the eastern Arabian Sea during the NEM season in 2015 and 2017.

2. Materials and methods

2.1. Sampling

Water samples for phytoplankton pigments and picophytoplankton counts were collected during the 79th cruise of R.V. *Sindhu Sankalp* (SSK-079; 7th to 15th March 2015) and 33rd cruise of R.V. *Sindhu Sadhana* (SSD-033; 5th to 15th February 2017). Samples were collected from nine stations in 2015 (Fig. 1a) and 13 stations (at every degree interval) in 2017 (Fig. 1b) from 21°N (II-14) to 9°N (II-2) along 68°E. Samples were taken from discrete depths using Niskin bottles mounted on a rosette frame fitted with a Sea-Bird Electronics conductivity-temperature-depth profiler (CTD). Temperature was measured using a pre-calibrated sensor attached to the CTD. Dissolved oxygen was measured onboard following the Winkler procedure using an autotitrator. Samples for nutrients were preserved at −20 °C and later analyzed using an Autoanalyzer (Skalar) following standard procedures (Grasshoff et al., 1983).

2.2. Pigment analyses

Samples for phytoplankton pigments were immediately filtered on glass fiber filter papers (GF/F, 0.7 μm pore size, 25 mm diameter) under dark and cold condition and preserved at −80 °C until analysis. The frozen filters were extracted with 100% methanol and analyzed using HPLC (Agilent HPLC 1200 Series) as detailed in Kurian et al. (2012). The calibration of the HPLC was performed using pigment standards procured from DHI Inc. Denmark. Since there was no standard available for divinyl chlorophyll *b* (divChl *b*), it was quantified using the response factor of chlorophyll *b*.

2.3. Picophytoplankton cell counts

Picophytoplankton samples fixed with glutaraldehyde (0.2% final concentration), were frozen in liquid nitrogen and stored at −80 °C until analysis. The analysis was carried out using a BD FACS Calibur Flow cytometer equipped with blue (488 nm) and red (633 nm) lasers, and absolute counts were obtained following Marie et al. (1997).

2.4. Satellite data

Sea surface temperature data were downloaded from http://apdrc.soest.hawaii.edu:80/dods/public_data/satellite_product/AMSR/AMSR-2/3dayIs with a spatial resolution of 0.25 × 0.25°. The daily mean sea level anomaly (MSLA) data were acquired from http://www.aviso.altimetry.fr/ with the same spatial resolution.

2.5. Statistical analysis

Prior to the statistical analysis, phytoplankton marker pigments (DP) were normalized and square root transformed. Spatial distribution of pigments was assessed through the non-metric-multidimensional scaling (nMDS) analysis based on Bray-Curtis index (Bray and Curtis, 1957). Moreover, the spatial association of maker pigments was explained by the distance-based redundancy (dbRDA) plot where the strength and direction of effect of the variable on the ordination plot can be clearly seen (Anderson et al., 2008). All the statistical analyses were performed in the module PRIMER V6 software.

3. Description of study area

Based on the SST distribution, the NEAS (SST $<$ 26.5 °C) and the SEAS (SST $>$ 28 °C) represented two distinct physical domains. While only the northernmost station (II-14; 21°N) experienced winter cooling in 2015 (Fig. 1a), six stations (II-14 to II-9; 21–14°N) were located within the zone of seasonal cooling in 2017 (Fig. 1b). The 28 °C isotherm has been used to identify the ASMWP in the SEAS. Vinayachandran et al. (2007) pointed out that ASMWP has the combination of some unique features such as warm SST ($>$ 28 °C; Fig. 1a & b) and presence of warm core (anti-cyclonic) eddy known as the Lakshadweep High (LH). In March 2015, stations II-2 to II-6 were within the ASMWP (Fig. 2a), while only three stations (II-2 to II-4) fell within this feature in 2017 (Fig. 2b). Note that the satellite SST was averaged over 10 days (5–15 February 2017) in Fig. 1b; whereas stations II-2 to II-4 were sampled within three days (5–7 February), resulting in a slight