

Enhanced chlorophyll *a* and primary production in the northern Arabian Sea during the spring intermonsoon due to green *Noctiluca (N. scintillans)* bloom

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Abstract

The surface waters of the northeastern Arabian Sea sustained relatively high chlorophyll *a* (av. $0.81 \pm 0.80 \text{ mgm}^{-3}$) and primary production (av. $29.5 \pm 23.6 \text{ mgC m}^{-3}\text{d}^{-1}$) during the early spring intermonsoon 2000. This was caused primarily by a thick patch of algal bloom spread over a vast area between 17° to 21°N and 66 to 70°E . Satellite images showed exceptionally high concentration of chlorophyll *a* in the bloom areas, representing the annually occurring 'spring blooms' during February-March. The causative organism of the bloom was the dinoflagellate, *Noctiluca scintillans* Macartney (synonym *Noctiluca miliaris* Suriray, Dinophyceae: Noctilucidea), symbiotically associated with an autotrophic prasinophyte *Pedinomonas noctilucae*. The symbiosis between *N. scintillans* and *P. noctilucae* is likely responsible for their explosive growth (av. 3 million cells L^{-1}) over an extensive area making the northeastern Arabian Sea highly productive (av. $607 \pm 338 \text{ mg Cm}^{-3}\text{d}^{-1}$) even during an oligotrophic period such as spring intermonsoon.

Key words: - Chlorophyll *a*; Algal bloom; *Noctiluca scintillans*, *Pedinomonas noctilucae*; Spring intermonsoon

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Introduction

The Arabian Sea (AS hereafter) is one of the most productive regions in the Indian Ocean (Madhupratap et al., 1996), exhibiting a bimodal temperature cycles annually, with lows during winter (northeast monsoon - NEM) and summer (southwest monsoon - SWM) seasons. The reversing winds and changing temperature are accompanied by appreciable alteration of mixed layer depths (MLDs), which stimulate the phytoplankton production in the surface layers. The primary production of the eastern AS generally exhibits two peaks, one during SWM (due to coastal upwelling) in the southeastern AS (Bhattathiri et al., 1996; Madhu, 2004) and another during NEM (due to winter convective mixing) in the northeastern AS (Madhupratap et al., 1996; Prasanna Kumar et al., 1996). Hence, these two physical processes are very critical and play a major role in the biogeochemistry of the eastern AS (Wiggert et al., 2005).

The entrainment of nutrients in the AS surface waters facilitates massive phytoplankton blooms that occur annually in the coastal as well as in the open ocean waters (Banse & McClain, 1986). Studies using satellite images of chlorophyll *a* have revealed the frequent occurrence of algal blooms in the northern AS (Sarangi et al., 2005; Dwivedi et al., 2006) during the beginning of spring intermonsoon (SIM hereafter). The causative organism for this particular bloom was found to be *Noctiluca scintillans* Macartney, a large (~500 -1000 μm diameter) and conspicuous heterotrophic dinoflagellate (Elbrachter & Qi, 1998), that is known to periodically harbor algal endosymbionts and function as a mixotroph (Hansen et al., 2004). In the Indian waters, blooms of *N. scintillans* are very common following the enhanced phytoplankton production due to coastal upwelling (Naqvi et al., 1998; Satish et al., 2005., Padmakumar et al., 2010) and winter convective mixing (Banse, 1986; McCreary et al., 1996; Gomes et al., 2008). Generally, there are two strains of *Noctiluca* have been reported worldwide, the green and the red. The green *Noctiluca* is autotrophic and that contains photosynthetic green flagellate *Pedinomonas noctilucae* as an endosymbiont, whereas the *Noctiluca* without endosymbiont is called red *Noctiluca*, which is heterotrophic and imparts pink or red colour to the bloom (Elbrachter & Qi, 1998).

The OCM (Ocean Colour Monitor) images retrieved from IRS-P4 could substantiate the increased chlorophyll *a* in the northern AS towards the end of March (Sarangi et al., 2005; Dwivedi et al., 2006). Even though the satellite sensors are widely used to study the distribution of chlorophyll *a*, the *in-situ* primary production data and related physico-chemical parameters in the northern AS are still lacking. In this paper, we use the sea-truth data on physico-chemical as well as biological variables collected during the early SIM period and explain the impact of *N. scintillans* bloom on the productivity pattern of the northeastern AS.

Materials and Methods

The observations were made onboard *FORV Sagar Sampada* (cruise No.182) in the NEAS (Fig.1) from 12th to 28th March 2000, as a part of the studies of the project 'Marine Research - Living

Resources in the EEZ of India'. The weekly mean winds were obtained from ERS-2, at a spatial resolution of $1^{\circ} \times 1^{\circ}$ (<http://poet.jpl.nasa.gov>). Temperature and salinity profiles were recorded using a Sea-Bird Electronics CTD (Conductivity-Temperature-Depth, Model: SBE-911 plus, USA) profiles and the sea surface temperature (SST) was measured using a bucket-thermometer. The mixed layer depth (MLD) was determined from the temperature profile as depth at which the temperature was 1°C less than the surface value. Water samples were collected from 7 depths (ie, 0, 10, 20, 50, 75, 100 & 120 meters), using 5-litre Niskin samplers attached to the CTD and analyzed for major nutrients using an onboard auto-analyser (SKALAR, Model SA - 1050) following standard procedure (Grasshoff, 1988). Biological parameters such as chlorophyll *a* (Strickland and Parsons, 1972) and primary production (^{14}C - assimilation method; UNESCO, 1994) were also estimated from the above mentioned depths. The incubation for primary productivity experiments were extended up to 12 hours (06.00 to 18.00hrs). Sea-viewing Wide Field-of-view Sensor's (SeaWiFS) monthly mean images of chlorophyll *a* (9-km resolution data products) were taken from the Ocean Biology Processing Group (OBPG) generated by NASA's Giovanni (<http://reason.gsfc.nasa.gov/Giovanni/>). Phytoplankton ($>5\mu$) identification (only from surface waters) was done under a stereoscope binocular inverted microscope (Olympus CK 30, magnification 100x - 400x) in a Sedgewick-Rafter counting cell (Subrahmanyam, 1959; Tomas, 1997).

Results

3a. Physico-chemical characteristics

The region experienced relatively weak winds ($<3 \text{ ms}^{-1}$) of predominantly northwesterly direction during the period of observation (Fig. 1). The SST showed a decreasing trend towards north and reached the lowest (24.9°C) at inshore waters of 21°N (Fig. 2a). Sea surface salinity (SSS) showed relatively low values ($<36 \text{ psu}$) along 17°N (except 68°E) as compared to other two transects (Fig. 2b). The MLD was deeper ($\sim 60 \text{ m}$) in the open waters of 17°N and in the coastal waters of 19° and 21°N (Fig. 2c). The isolines of $1 \mu\text{M}$ nitrate (NO_3) showed an upsloping towards the coast along 19°N and 21°N , while it was towards the offshore along 17°N (Fig. 2d). The Arabian Sea high saline water (ASHSW) mass, which originated in the northern AS (commonly seen at 20 - 100 m depth, having the potential temperature of $26 \pm 2^{\circ}\text{C}$, salinity and density ranges of 35.3 to 36.7 psu and 22.8 to 24 Kg m^{-3} , respectively) was evidenced in the upper 50 m at all the three transects and was more pronounced along 21°N (Figs. 3d, e & f). Vertical section of sigma-*t* in the three transects showed a downsloping towards the coast, while in the surface an increase towards north was seen (Figs. 3g, h & i).

3b. Chlorophyll *a* and primary production

Chlorophyll *a* (Figure 2e & f) and primary production (Table 1) showed wide variations, both in the surface (av. $0.81 \pm 0.80 \text{ mgm}^{-3}$ & av. $29.5 \pm 23.6 \text{ mgC m}^{-3}\text{d}^{-1}$) and integrated column (up to 120 m) waters (av. $28.2 \pm 21.4 \text{ mgm}^{-2}$ & av. $607 \pm 338 \text{ mgC m}^{-2}\text{d}^{-1}$). Surface chlorophyll *a* was fairly

high (1.25 - 2.54 mgm⁻³) at stations where the bloom occurred, but in other regions it was low (<0.8 mgm⁻³). Primary production in the surface was exceeded 50 mg Cm⁻³d⁻¹ in the bloom waters and <20 mgC m⁻³d⁻¹ in the non-bloom waters (Table 1). The integrated column primary production showed a mean value of 814 mgCm⁻²d⁻¹ during the time of bloom (reached maximum primary production of 1192 mgCm⁻²d⁻¹ at 17°N, 68°E) whereas it was low (av. 513 mg Cm⁻²d⁻¹) in the non-bloom period (Table 1).

3c. Characteristics of algal bloom

The thick yellowish-green algal bloom was spread extensively in the open waters of northern AS (Figure 4a). Initially (12th March, 2000) it was observed in the open waters of 17°N (68°E) over a large area extending up to 21°N (open as well as coastal waters). Most of the time, the bloom appeared like a yellowish-green mat over the surface (Figure. 4b). Microscopic examination revealed that the species that caused the bloom was *Noctiluca scintillans* (Fig. 4c), belonging to the group Dinoflagellata (Pyrrophyceae). This particular bloom was characterized by a mono-specific proliferation (av. 3 million cells L⁻¹) of *N. scintillans* (>90%) with less number (av. 24000 cells L⁻¹) of diatoms (dominant genera - *Rhizosolenia*, *Thalassionema* and *Chaetoceros*). In the non-bloom waters, diatoms constituted the dominant group (av. 42,000 cells L⁻¹). *Chaetoceros* sp., *Thalassionema nitzschioides*, *Thalassiosira* sp., *Pseudo-nitzschia* sp., *Nitzschia seriata*, *Rhizosolenia setigera*, *Pleurosigma* sp., *Navicula* sp., *Thalassiosira subtilis*, *T. oceanica*, *Fragilaria* sp., *Fragilariopsis pseudonana* and *Coscinodiscus* sp., were the dominant diatom species. Dinoflagellates such as *Ceratium* sp., *Protoperdinium* sp., *Gonyaulax* sp., *Gymnodinium* sp., *Ornithocercus* sp., and *Coccolithophores* such as *Florisphaera* sp., *Umbellosphaera* sp., *Papposphaera* sp. were identified in less numbers (av. <3000 cells L⁻¹) in the non-bloom waters.

4. Discussion

Relatively low SST (<27°C) and deep MLDs (>60 m) towards the coast of 19°N & 21°N indicate that the inshore waters of the northeastern AS are still under the influence of winter cooling. However, weak winds (<3 ms⁻¹) and shallow MLDs (<40 m) in the open waters of these latitudes showed weak signatures of convective mixing as compared to the coastal waters. The vertical distribution of temperature, salinity and sigma-*t* along 17°N, point out the presence of a mesoscale cold core eddy around 68°E (Figs. 3a, d & g) resulting in deep MLD (~60 m) at this location. Generally, in the northern AS, the oceanic waters stabilize much faster than coastal waters through a process known as detrainment, which is a successor of entrainment (prevalent during the winter cooling period), that reduces the MLD (McCreary et al, 1996). It was established that the detrainment in the upper layers of the northern AS was due to the decrease in wind speed and increase in SST and as a consequence of the prevailing weak winds and warm SST, the MLD detrains to become shallow (<35 m) everywhere in the basin during the end of February (McCreary et al., 1996). Our results also show shallow MLD (<40 m) in the open waters off 19° & 21°N as reported earlier. Within the northern AS, blooms begin during the first week of February and last

until the end of March (Sarangi et al 2001, Dwivedi et al, 2006) and hence these are known as *spring blooms* or *detrainment blooms*. These blooms are intense in the northern AS as they utilize the rich nutrients available in the surface waters brought up due to the entrainment by winter convective mixing (McCreary et al., 1996).

Noctiluca blooms imparting a red colour to seawater are occasionally developed along the southwest coast of India soon after the withdrawal of upwelling (Naqvi et al., 1998; Sahayak et al., 2005; Padmakumar et al., 2010). Despite the fact that this *N. scintillans* is typically heterotrophic, the bloom that was observed in the present study was yellowish-green in colour and contained exceptionally high chlorophyll *a* (1.25 - 2.54 mgm⁻³). We found the bloom of *N.scintillans* contained an endosymbiotic prasinophyte, a mixotrophic phenomenon that is not unusual in tropical seas (Furuya et al., 2006). Subrahmanyam (1954 & 1959) has observed that *N. scintillans* at times, exhibit a symbiotic association with an autotrophic euglenoid namely '*Protoeuglena noctiluca*', which is green in colour. Later, Sweeney (1978), identified it as a prasinophyte '*Pedinomonas noctilucae*', measuring 5 to 9.5 µm in length and 4.4 to 7.8 µm in breadth. The symbiotic association of this particular prasinophyte inside the *Noctiluca* cells imparts green colour to the algal bloom and also enhance chlorophyll *a* content (Figure 2e & f) and primary production (Table 1). Culture experiments by Hansen et al, (2004) have proved that green *Noctiluca* is photosynthetically active and can grow up to 2 weeks in the laboratory without the ingestion of food. Three decades back, Sweeney, (1971) demonstrated that *N. scintillans* incorporates *P. noctilucae* into small vacuoles in the cytoplasm and utilizes their photosynthetic products in the form of exudates as nutrition. The pigment studies (by HPLC method) conducted by Parab et al, (2006), quantified the accessory pigments such as peridinin (indicator pigment of dinoflagellates), chlorophyll *b*, and prasinoxanthin (indicator pigments of prasinophytes) in northwest coast of India during the February-March months, where green *N. scintillans* bloom occurred. Reports of episodic occurrence of green *Noctiluca* bloom along the west coast of India during February-March are available (Subrahmanyam, 1954; Devassy & Nair, 1987). High concentrations of chlorophyll *a* in association with green *Noctiluca* blooms were reported in the near shore waters off Goa (16.7 mg m⁻³; Devassy & Nair, 1987), Manila Bay (0.6-522 mg m⁻³; Furuya et al., 2006) and Port Blair Bay (17.6 mg m⁻³; Eashwar et al., 2001). However, the bloom of red *Noctiluca* observed in the southwest coast of India recorded relatively less chlorophyll *a* (<1 mg m⁻³), even though the cell density exceeds millions per litre (Sahayak et al., 2005; Padmakumar et al., 2010). This indicates that *Noctiluca* cells contained *Pedinomans noctilucae* as an endosymbiont, have the photosynthetic capacity and ultimately it leads to enhanced chlorophyll concentration when it become a bloom.

The time series images of chlorophyll derived from the IRS-P4/OCM (Sarangi et al., 2001) has shown large scale increase in phytoplankton biomass (>1 mg m⁻³) in the open waters of northeastern AS during February-March 2000, due to the formation of *N. scintillans* blooms. Satellite observations (Sarangi et al., 2005) have identified the occurrence of algal blooms along 66

- 68°E, 17-18.5°N between 22nd February and 8th March 2000 and it appeared like an eddy (having a diameter of 150 km), containing high chlorophyll *a* (1 mg m⁻³). Incidentally, our observation was between 12th and 28th March 2000, and we could capture this particular bloom from the same location (Fig. 4a). Despite the fact that the green *N. scintillans* regularly forms massive blooms in the northern AS during early SIM (Sarangi et al., 2005; Gomes et al., 2008), the reason for its proliferation and association with *P. noctilucae* need further study.

5. Summary and Conclusion

The spring (March to May) and fall intermonsoon (October) seasons are considered as oligotrophic periods in the AS because of the nutrient depletion, due to thermal stratification (Morrison et al., 1998). However, during the early SIM, detrainment of the upper layers triggers algal blooms (so called spring blooms) in the northern AS. The monthly images generated from IRS-P4 data (Dwivedi et al., 2006) revealed high concentration of chlorophyll *a* in the northeastern AS during February-March months for three consecutive years of 2003 to 2005. Hence, it can be assumed that the detrainment blooms are annual features which enhance the chlorophyll *a* and primary production in the northeastern AS during the early SIM period. Although we propose that the detrainment in the upper layers of northeastern AS as a potential cause for the *N. scintillans* bloom during the early SIM, more intense (time series) observations would be needed to unravel the mysteries behind the annual formation of green *N. scintillans* bloom as well as its symbiotic association with *P. noctilucae* over the vast area of the northern AS.

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Table.1 - Primary production of northeastern Arabian Sea during March 2000 (S. PP - Surface primary production, C. PP - Column primary production, '*' stations observed *N. scintillans* bloom)

Lat (°N)	Long (°E)	S. PP (mgC m ⁻³ d ⁻¹)	C. PP (mgC m ⁻² d ⁻¹)
17	68	*63.2	*1192
17	70	5.1	540
17	73	22.7	535
19	72	5.5	162
19	70	5.1	572
19	67	*42.9	*866
21	66	*48.7	*952
21	68	15.1	402
21	70	*56.8	*243
Mean (SD)		29.5 ± (23.6)	607 ± (338)

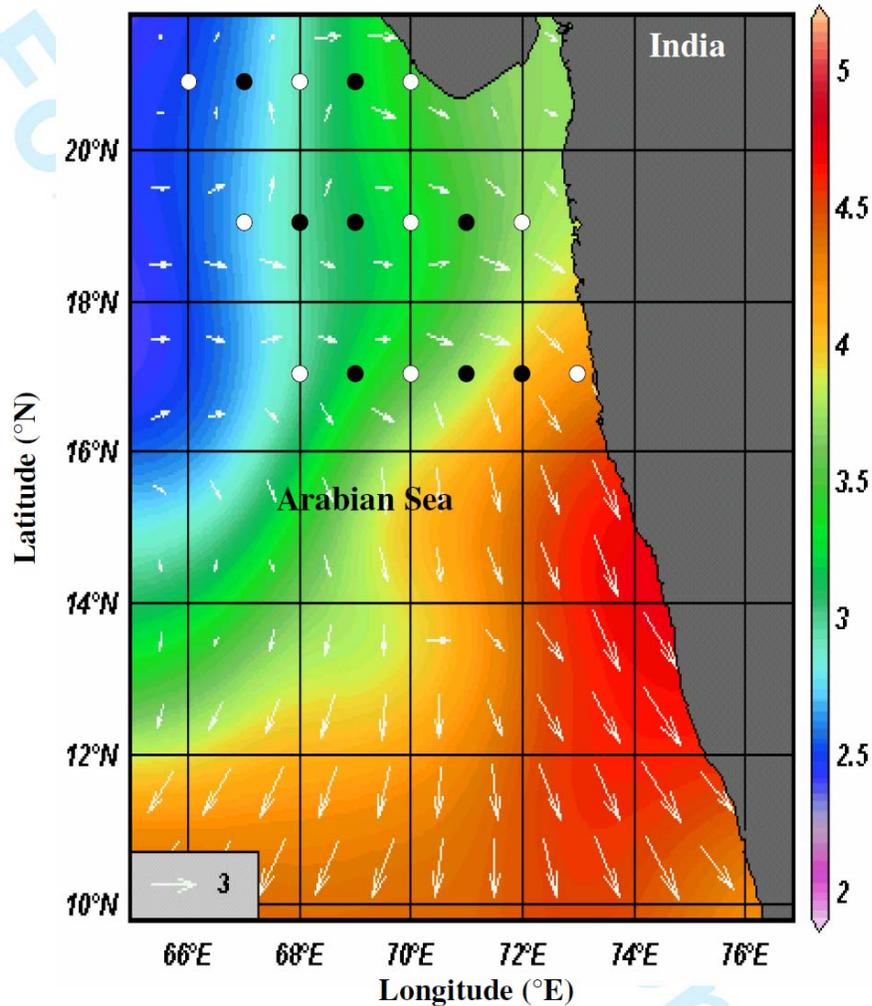


Figure 1. Station locations (circles) and wind speed (ms^{-1}) with northwesterly direction (weekly mean, ERS-1) in the northeastern Arabian Sea during the 2nd week of March 2000

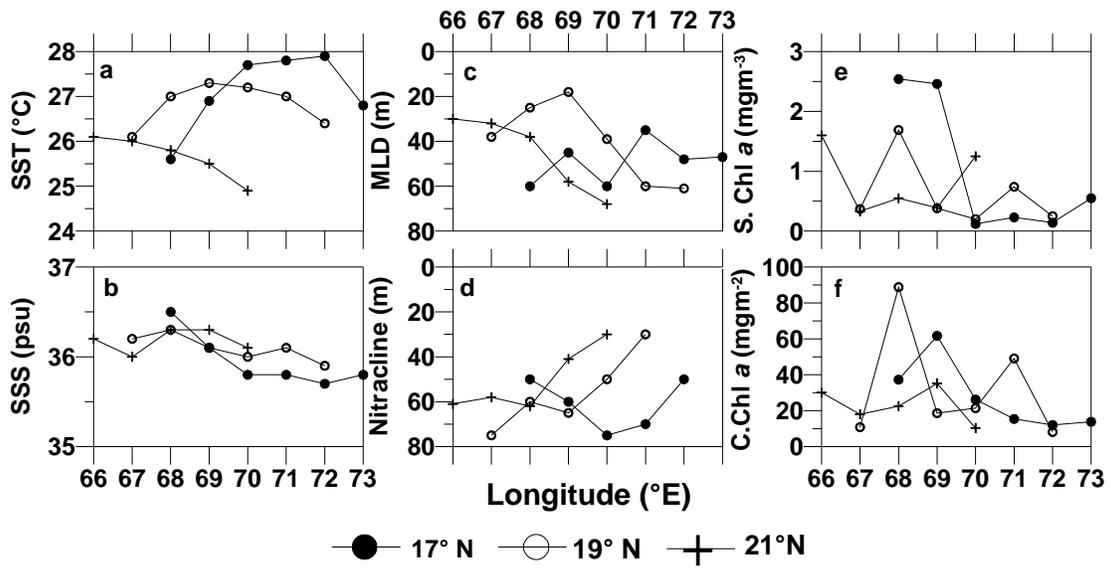


Figure 2 - Distribution of SST (°C), SSS (psu), MLD (m), Nitracline (m) and chlorophyll *a* (surface and column) along 17°, 19° & 21°N

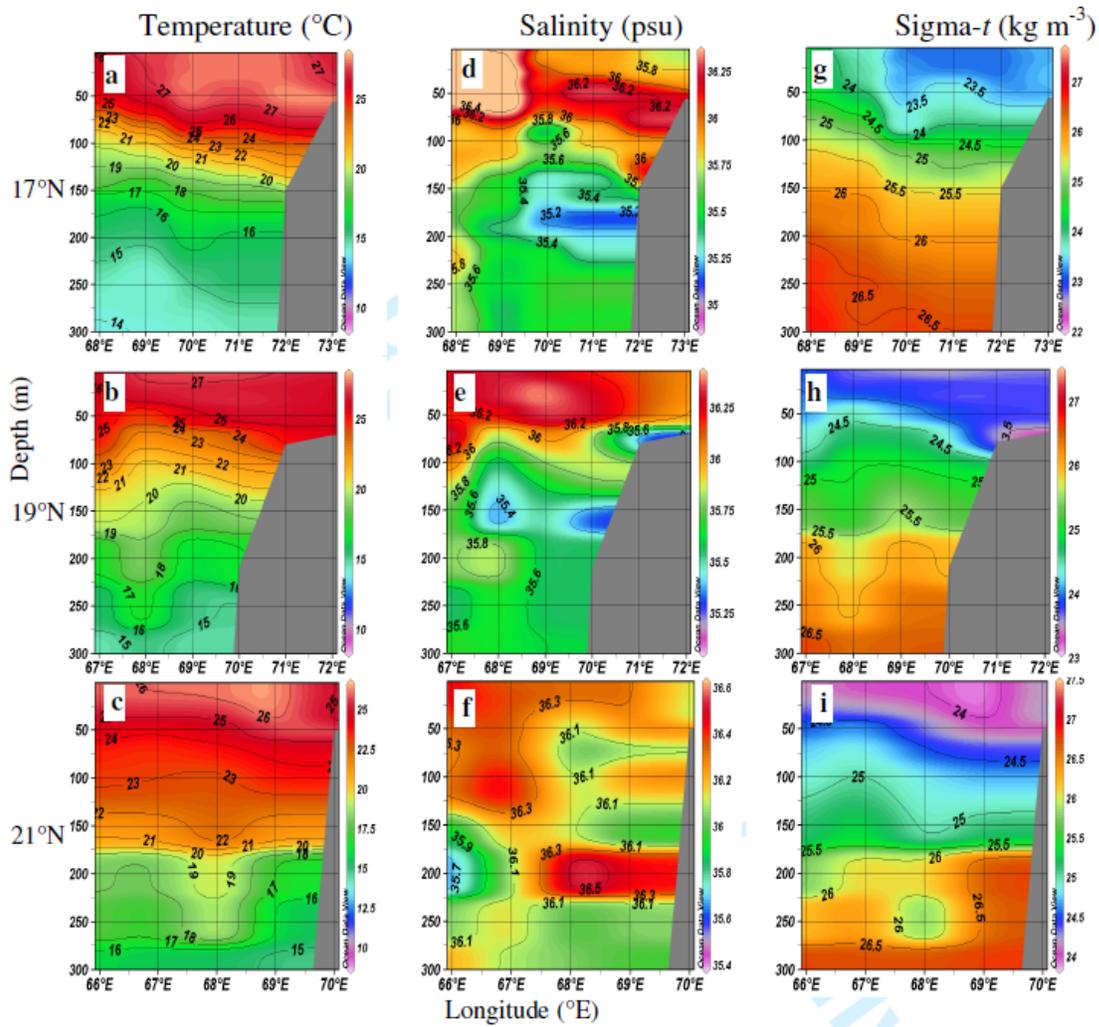


Figure 3 - Vertical distribution of temperature, salinity & sigma- t along 17°, 19° & 21°N

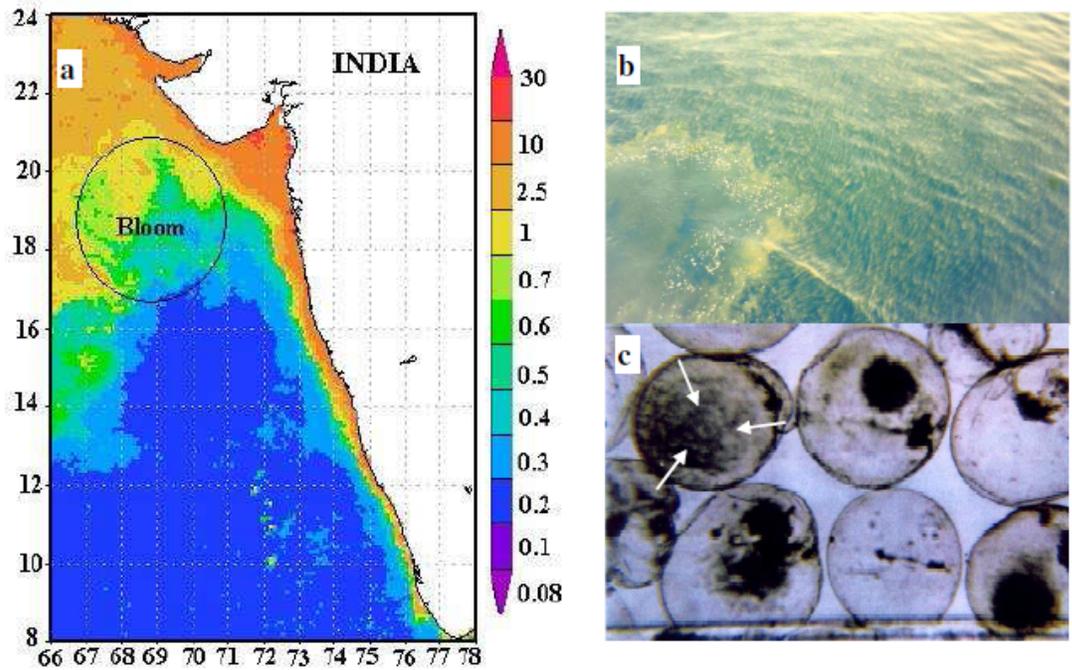


Figure 4. Distribution chlorophyll *a* (mgm^{-3} ; SeaWiFS monthly mean global 9-km products) in the northern Arabian Sea (a) during March 2000, generated by NASA Giovanni (Circle shows the area of occurrence of *Noctiluca scintillans* bloom). b) *Noctiluca scintillans* bloom observed in the northern Arabian Sea at 17°N, 68°E on 12th March 2000, c) Microscopic view of *Noctiluca scintillans* (100x magnification) and the white arrows show the abundance of *P. noctilucae* inside *N. scintillans* (dark green shades)