



The bloom of the dinoflagellate (*Noctiluca miliaris*) in the North Eastern Arabian Sea: Ship and Satellite study

S. G. Prabhu Matondkar^{1*}, S. Basu¹, Sushma G. Parab¹, Suraksha Pednekar¹, R. M. Dwivedi², Mini Raman², J. I. Goes³ and H. Gomes³

¹National Institute of Oceanography, Dona Paula, Goa

²Space Application Centre, Ahmedabad

³Lamont Doherty and Earth Observatory, Columbia University, New York, USA

Abstract

The bloom of *Noctiluca miliaris* (a dinoflagellate) which appears in the form of a green tide was studied from 2003-2011. This bloom covered a large area of the Arabian Sea from the west coast of India to the coast of Oman. The bloom was easily identified by OCM I and OCM II images (as well as SeaWiFs images) and had been sampled by Indian research vessels like the Sagar Kanya and the Sagar Sampada. The bloom persisted for almost 4 months (January-April) and its peak levels were seen from 15th January -15th February.

N. miliaris is characterized by the presence of the symbiont *Pedimonas noctilucae*. This organism shows a predominantly green colouration due to the presence of high chlorophyll *b* along with chlorophyll *a*. Time series of OCM I and OCM II images were used to establish the onset and demise of this bloom. Simultaneously samples were taken during cruises and these were analyzed for pigments and other associated biological parameters.

The bloom period corresponded with the NE monsoon of the region. During this time it was seen that winter cooling was predominant. The water temperature of the bloom area was $25.14 \pm 0.42^{\circ}\text{C}$ while the non-bloom area was $26.04 \pm 1.85^{\circ}\text{C}$ during the month of the February. The declining of the bloom during March is related seen to be related to elevation of temperature in the bloom area. This rise in temperature is about $26.04 \pm 0.78^{\circ}\text{C}$. Nitrate levels were high during February 0.88 ± 0.49 (bloom stations) as compared to 0.59 ± 0.56 in the non-bloom area. Similarly high wind speed was also an important ($>5 \text{ ms}^{-1}$) factor for the blooms to

appearance and persistence as a high biomass bloom. In general it was observed by means of a ship and OCM images that the bloom initiates during January and declines during April.

The cells of *N. miliaris* varied from 2-9600 cells l^{-1} and dominated the phytoplankton population during the active phase of the bloom. Similarly chlorophyll *a* varied from 0.53-27.969 $\mu g l^{-1}$ during the *N. miliaris* bloom. C-DOM A_{c325} values during the active bloom were 0.2 to 0.6 m^{-1} compared to non-bloom conditions of 0.05 to 0.1 m^{-1} . Weekly images of OCM-I were used to establish the growth and demise of the *N. miliaris*. The data collected along the same lines prior to the *N. miliaris* bloom as well as in post bloom conditions will be presented and discussed. A total of eight cruises were undertaken during the years from 2003-2011 in the Arabian Sea and both OCM I and OCM II data has been used.

Keywords: HPLC, phytoplankton, ocean colour monitor, Arabian Sea, chlorophyll.

1. INTRODUCTION

The reversal of monsoon winds brings about changes in circulation pattern of the Arabian Sea (Wytki 1973; Banse 1984 and 1987) have shown that this reversal winds can induce seasonality in the abundance of phytoplankton in the Arabian Sea and winter blooms (Dwivedi et al., 2006). The seasonality of phytoplankton is also connected to coastal processes related to monsoons (Shetye et al., 1987; Shetye 19990). During southwest monsoon (June-September), west coast of India experience upwelling of nutrient rich water. During this period there is a southwardly movement of surface currents and shallowing of isotherms along the coast. Towards the end of the SW monsoon offshore component of wind stress recedes so is upwelling. During NE monsoon (November-March), the surface currents reverse their direction and move northwards along the coast carrying warm, low saline, low nutrient waters from equatorial region. During this time thermoclines are located in deeper part of water column. In the region north of $15^{\circ}N$ this northward flowing current turns westwards off the coast of Saurashtra. These environmental changes decide the phytoplankton seasonality in the Arabian Sea along the west coast of India. Since the early 1940s the method of choice for studying phytoplankton diversity has been microscopy (John and Menon 1942; Subrahmanyam and Varma 1961 and 1967; Devassy et al., 1978 and 1979; Devassy and Goes, 1988; Sawant and Madhupratap 1996). Although the data

sets obtained have provided valuable insights into the diversity of phytoplankton, such information has been limited to regions very close to the coast.

In addition to microscopy, photosynthetic and non-photosynthetic pigment distributions was used to identify the presence of different algal groups (Wright et al., 1991; Jeffrey 1997; Bidigare and Charles 2002). Accessory pigments can provide class-specific differentiation, allowing for the recognition of major taxonomic groups of marine phytoplankton (Wright et al., 1991). Over the last twenty years, the development of high performance liquid chromatography (HPLC) has greatly advanced our understanding of phytoplankton pigment composition and functionality in response to ecosystem changes (Wright et al., 1991; Barlow et al., 1999). In the western and central Arabian Sea for example, HPLC-analyzed pigments helped provide new information as well as a better understanding of changes in phytoplankton populations associated with the seasonal cycle of the monsoons (Latasa and Bidigare 1998; Goericke 2002; Brown et al., 2002).

During this study a wide and varied sampling strategy offshore as well as close to the coast ensured a comprehensive investigation on the seasonality of phytoplankton during the SW monsoon (June-August) when upwelling occurs along the west coast of India⁵, during the NE monsoon (November – February) when winter cooling takes place (Banse et al., 1993; Banse and English 2000; Madhupratap et al., 1996; Kumar et al., 2001) and during the inter-monsoon (March-May) when the water column becomes highly stratified and devoid of nutrients (Desouza et al., 1996). Chlorophyll and primary productivity studies are also conducted during this study.

2. METHODOLOGY

The data presented here was collected on board two vessels (Table 1; Fig. 1), the ORV Sagar Kanya (SK) and the FORV Sagar Sampada (FORV) this collection of data was done in the months spanning from November to April. A wide range of geographical areas (Fig. 2a and 2b) and seasons (November – fall inter-monsoon; December to February – NE monsoon and March to April – spring inter-monsoon) were covered so as to include samples from regions where physical processes such as upwelling and winter cooling, were known to occur.

2.1 Physico-chemical study: Temperature and salinity data was collected by using CTD. Nutrients like PO₄-P and NO₃-N are analysed by using standard methods (Grasshoff et al., 1983).

2.2 Biological studies: Water was collected within the euphotic zone with 5L Niskin sampling bottles mounted onto a Sea Bird Electronics[®] CTD Rosette and processes in ship laboratory for pigments, primary productivity and taxonomy of the phytoplankton. The depth of the euphotic zone was established using a Secchi Disc.

2.2.1 Pigments 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). Prior to the HPLC analysis, the filters were immersed in 90 % acetone, extracted under cold and dark conditions overnight, sonicated and finally filtered through 0.2 µm, 13 mm PTFE filters to free the sample from any particulate debris. Aliquots of 1 ml of the pigment extract were then mixed with 0.3 ml of distilled water in a 2 ml amber vial and allowed to equilibrate for 5 minutes prior to its injection into an HPLC (Agilent[®] 1100 series) equipped with a diode array detector. 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).

2.2.2 Phytoplankton Taxonomy

For identification and enumeration of phytoplankton, 1000 ml of seawater samples was fixed with 3 % Lugol's iodine (Thronsdon 1978) and then stored in dark and cool conditions until the time of analysis. Prior to microscopic analysis, samples were concentrated to 5 - 10 ml by carefully siphoning the top layer with a tube covered with a 10 µm Nynetex filter on one end. Replicates of 1ml sample concentrates were transferred to a Sedgwick-Rafter and counted using an Olympus Inverted microscope (Model IX 50) at 200 X magnification. Identifications were based on standard taxonomic keys (Tomas 1997). The results are expressed as numbers of cells except for *Trichodesmium* which are expressed as number of trichomes.

2.3 Satellite data

2.3.1 Estimation of chlorophyll from Ocean Colour data

As a part of processing of OCM data to generate chlorophyll images water leaving radiances were retrieved through removal of atmospheric effects from the satellite radiance values in the first step (Gordon and Wang 1994). The atmospheric correction scheme makes use of long wavelengths for estimating aerosol optical thickness. Subsequently, bio-optical algorithm was applied to the corrected water leaving radiance data (Chauhan et al., 2001; Reilly et al., 1998). O'Reilly's OC-2 algorithm was used for generating chlorophyll images from OCM data.

Sea-WiFS and MODIS-Aqua 8-day composite 4km resolution Chlorophyll a data and lat-long averaged plots during 2003-2011 were obtained from the Giovanni online data system, developed and maintained by the NASA, GES DISC (Acker and Leptoukh, 2007) in order to study the seasonal genesis, growth and subsequent decline of the winter-bloom in the Arabian Sea.

3. RESULTS AND DISCUSSION

IRS-P4-1 (OCM-1) generated the first image of the high Chl a in the N-E Arabian Sea (Fig. 3) and type of organisms causing bloom were not known. Subsequently, we have planned cruises in the N-E Arabian Sea during Feb-Mar 2003 (Cruise FORV SS212) in order to examine the nature and extent of the bloom noticed in the OCM-I image. Bloom was intense and stretched all over the Arabian Sea basin (Fig. 3). The bloom was composed of *Noctiluca miliaris* cells giving green coloration to the waters (Fig. 4). Chl a estimated was 0.2 - 1.65 $\mu\text{g L}^{-1}$. OCM images also depicted presence of intense bloom during 11th Feb 2003- 11th Mar 2003 (Fig. 5). Subsequently, every year *N. miliaris* bloom appeared during Feb-Mar period. The bloom is also detected by other sensors like MODIS-Aqua (Fig. 6a and 6b) and Sea-WiFS (Fig. 7) depicted by time-series images. Chl a during these years varied from \sim 1-6 $\mu\text{g L}^{-1}$ during various stages of the bloom (Table 3). Data was collected upto 2011 Mar in order to understand dynamics of the *N. miliaris* bloom in the Arabian Sea.

Gulf of Thailand (Sriwoon et al. 2008) and Arabian Sea (Subramaniam 1954) are two prominent site for the appearance of the blooms of the green *N. miliaris*. In the gulf of Thailand

N. miliaris appears during SW monsoon (Sriwoon et al. 2008) and happens to be in the coastal waters. However, *N. miliaris* appears in coastal waters (Subramaniam 1954; Devassy 1987) as well as in the open-ocean (Gomes et al., 2008). In the coastal waters along the West-coast of India bloom is recorded during SW monsoon(September) and in the open-ocean it is recorded during N-E monsoon (Feb-Mar period). The green *Noctiluca* started appearing in N-E Arabian Sea (open-ocean) in the large scale during 2000 year which was recorded during OCM-1 image (Fig. 3) and in the coastal waters of Pakistan (Chaghtai and Saifullah 2006). Although, *N. miliaris* appears only during the N-E monsoon the sequence of events starts much earlier in the Arabian Sea.

Arabian Sea environment is greatly influenced by SW monsoon and NE monsoon systems. During SW monsoon water-masses are enriched with nutrients brought up by monsoon upwelling during June-September (Figs. 8 and 9). At the end of September diatom blooms are triggered (Banse and McClain, 1986). These blooms support rich fishery of the region. During December, nutrients (specially Nitrate) is depleted and dinoflagellate blooms appear. The blooms of cyanobacteria follow upto N-E monsoon where *N. miliaris* is appearing since 1998.

Fall Intermonsoon season (November)

During November high Chl *a* at surface (0.726 mgm^{-3}) and column (43.812 mgm^{-2}) is due to *Trichodesmium thiebautii* bloom. The bloom of *T. thiebautii* during November was also seen under ocean colour image of November. The productivity of area was comparatively low at surface ($8.46 \text{ mgCm}^{-3} \text{d}^{-1}$) as well as column ($21.139 \text{ mgCm}^{-3} \text{d}^{-1}$) and is mainly due to shortage of nitrogen nutrients as indicated by *Trichodesmium* growth in the environment. The presence of *Trichodesmium* was also noticed in the pigment analysis. During November zeaxanthin and β -carotene level in particulate matter is high. The environmental conditions during November favoured the *Trichodesmium* growth. NE Arabian Sea, wind was low and PAR was high. This combined with low nitrate level was responsible for growth of the *Trichodesmium* during November (fall intermonsoon) in the Arabian Sea.

NE Monsoon (December to February)

The NE monsoon season is responsible for the churning of the water column through nutrients (Table 2a and 2b) like NO_3 and PO_4 level was high during NE monsoon, instability of

water column was responsible for maintaining Chl *a* to moderately high level (Figs. 10a and 10b). Chl *a* during December was 0.34mgm⁻³, January 0.723 mgm⁻³ and February 0.344 mgm⁻³. During January increase in Chl *a* was due to high counts of dinoflagellates in water column. This peak in dinoflagellates has helped to promote growth of the *Noctiluca miliaris* during January and February. Similar trend of the Chl *a* was also observed by OCM images (Fig. 11). The column Chl *a* values were maximum during January (44.524 mgm⁻²) compared to December and February (Table 3). The *Noctiluca miliaris* is the heterotrophic dinoflagellates and same productivity recorded was due to symbiotic algae (prasinophytes) inside *Noctiluca miliaris* cells (Table 4).

Spring Intermonsoon (March to April)

The hike in Chl *a* (surface and column) was recorded during March-April, due to blooms of the *T. erythraeum*. This has increased primary productivity at surface as well as in column. During this period (spring intermonsoon) water temperature was high, nutrients were low which help to develop *T. erythraeum* bloom in the NE Arabian Sea (Table 5). The chemotaxonomic studies during January revealed the presence of peridinin indicating the growth of dinoflagellates prior to *Noctiluca*. During *Noctiluca* bloom Chl *b* at high level so was prasinoxanthin due to symbiotic prasinophytes. During spring intermonsoon the high levels of the zeaxanthin and β -carotene was indicative of the *Trichodesmium* in the NE Arabian Sea specially during April. In the May, zeaxanthin was 11.77 %, β -carotene was 8 % due to extensive bloom of the *Trichodesmium* in the Arabian Sea specially in coastal region (Fig. 12).

Diversity Change

During JGOFS programme of various countries including India, Salp was the important component of the ecosystem which is replaced by *Noctiluca* around 1998. Although Salp can feed on bacteria, phytoplankton, zooplankton, green *Noctiluca* can photosynthesize food due to the presence of the symbionts *Pedinomonas noctilucae* (Fig. 4). *Noctiluca* is further grazed by Zooplankton (Fig. 13).

Phytoplankton biomass during bloom

Noctiluca bloom is prominent in the surface layer as seen by high Chl *a* and phytoplankton counts. Phytoplankton population was mainly composed of *N miliaris* cells (Fig. 14). The bloom form during 'active' phase in surface layer (during February) became inactive during March and cells start sinking (Fig. 15). During 'active' bloom of the *N miliaris* contribution by other phytoplankton is negligible (Fig. 14). This is more clearly seen when plotted *N miliaris* cells as the function of the total Phytoplankton counts (Fig. 16) and also function of the Chl *a* (Fig. 17). Similarly, relationship in the *N miliaris* cells and satellite derived Chl *a* is also recorded (Fig. 18). The bloom in the deeper layer of the euphotic zone also reflected in the estimation of the accessory pigments, specially Chl *b* (Fig. 12).

C-DOM produced during *N miliaris* is extremely high ~600% more than normal value. These dissolved organic compounds will be quickly utilized by micro-flora, enriching environment. Besides this *Noctiluca* cells are showing absorption which is important for further remote-sensing monitoring of the bloom (Fig. 20). The excellent relationship of absorption properties and total Chl *a* is also indicative (Fig. 21). This will form basis of the future detection of *N miliaris* bloom by Ocean-color sensor and monitoring. Presently, satellite derived Chl *a* is used for such studies. The match-up analysis of the in-situ Chl *a* and OCM-I derived Chl *a* ($R^2=0.9$) is mainly associated with the off-shore nature (case-1) of the environment under study. Similar, results are also obtained during OCM-II comparisons where $R^2=0.852$ as high as OCM-I data. This has helped us to use OCM derived Chl *a* to monitor *Noctiluca* bloom .

As seen by OCM-I data during 2003 (Fig. 11), bloom was active from 11th February to 11th March (almost 1 month). Similarly, February 10th - March 13th (one month) bloom is recorded by MODIS-Aqua sensor, which is also confirmed by the Sea-WiFS OCM-2 data (Fig. 22-23). During 2011 our cruise has sampled only later part of the bloom during March 2011 (Fig. 24) by OCM-II images. The seasonality is particularly seen during imaging of the weekly Modis-Aqua level-3 and Sea-WiFS Chl *a* images for various years (Fig. 23).

In the coastal waters of the tropical environment, eutrophication and low-temperature are identified as the important factors for the development of *N miliaris* blooms (Harrison et al., 2011). From, the historical data of the Arabian Sea it appears that low oxygen during SW monsoon is also a factor to be considered (Subramaniam, 1954). In the open-ocean nutrients supplemented by winter-cooling (low temp and high nitrate) acts as a trigger for the *N miliaris* in

the Arabian Sea. The food availability for *N. miliaris* is also a factor to be looked into. *N. miliaris* (red and green) is phagotrophic and can feed on everything possible. In addition to this green form can photosynthesize due to symbiont *Pedinomonas noctilucae*, a prasinophyte in the cell.

During our cruise in Jan (SK186) we have come across blooms of the flagellates followed by *Noctiluca* bloom during Feb (Fig. 11). From our observations it appears that environmental conditions prevailed during Feb-Mar months are favorable for flagellates type of organisms promoting growth of *Pedinomonus noctiluca* in the *Noctiluca* cell. The region is also known for high counts of the prasinophytes studied by Russian expeditions prior to IIOE expeditions. Mystery is to be resolved what made *N. miliaris* to dominate Ocean life from 1998 onwards and how come it became an annual Arabian Sea bloom? One of the possibility is that seeding of the organism may have done by the ballast waters on route to Oman which triggered bloom around 1998. Second option is expansion of perennial low oxygen zone due to climatic changes in the region as envisaged by Goes et al. 2005. Last but may be equally important is absorption of light by *Noctiluca* cell will change heat-budget of region further triggering changes in the Ocean environment which needs to be monitored. March up analysis based upon *insitu* Chl *a* and OCM-2 derived Chl *a* indicated robust relationship (Figs. 24-25). Based on OCM I and OCM-2 data 15th February to 15th March appears to be season for *Noctiluca miliaris* bloom. Effect of other parameters like wind also need to be accounted in future monitoring programme.

Acknowledgment:

We appreciate the encouragement and support of Director, NIO Dr. S. R. Shetye for conducting this work. This study was carried out under the Ocean Colour Project with financial assistance from Space Application Centre (SAC), Ahmedabad. A DST Fellowship to S. Parab and SAC fellowship to S. Pednekar is gratefully acknowledged.

REFERENCES

1. Banse, K. 1987. "Seasonality of phytoplankton chlorophyll in the central and northern Arabian Sea". *Deep-Sea Res.*, 34, 713-723.

2. Banse, K., English, D. C., 1993. Revision of satellite-based phytoplankton pigment data from the Arabian Sea during the northeast monsoon”, *Marine Research I (Pakistan)*, 2, 83 – 101.
3. Banse, K., English, D. C., 2000. Geographical differences in seasonality of CZCS-derived phytoplankton pigment in the Arabian Sea for 1978 – 1986. *Deep-Sea Research II*, 47, 1623 – 1677.
4. Banse, K., McClain, C.R., 1986. Winter blooms of phytoplankton in the Arabian Sea as observed by the Coastal Zone Color Scanner. *Marine Ecology Progress Series* 34, 201–211.
5. Banse, K., 1984. “Overview of the hydrography and associated biological phenomena in the Arabian Sea, Off Pakistan”, *Marine geology and oceanography of Arabian Sea and coastal Pakistan*. B. H. Haq and J. D. Milliman, 217-303.
6. Acker, J. G. and Leptoukh, G., 2007. Online Analysis Enhances Use of NASA Earth Science Data, *Eos, Trans. AGU* 88(2), 14-17.
7. Barlow, R. G., Mantoura, R. F. C., Cummings, D. G., 1999. Monsoonal influence on the distribution of phytoplankton pigments in the Arabian Sea. *Deep-Sea Research II*, 46, 677-699.
8. Bidigare, R. G., Charles, C. T., 2002. HPLC phytoplankton pigments: sampling, laboratory methods and quality assurance procedures. In: Fargion, G. S., Mueller, J. L (Eds.), *Protocols For Satellite Ocean Colour Validation Revision*. NASA, Goddard Space Flight Centre, Greenbelt, Maryland 20771, 154-160.
9. Brown, S. L., Landry, M. R., Christensen, S. D., Garrison, M. M. Gowing, R. R. Bidigare, Campbell L., 2002. Microbial community dynamics and taxon-specific phytoplankton production in the Arabian Sea during the 1995 monsoon seasons. *Deep-Sea Research II*, 49, 2345 – 2376.
10. Chaghtai F, Saifullah S M. 2006. On the occurrence of green *Noctiluca scintillans* blooms in coastal waters of Pakistan, North Arabian Sea. *Pak. J. Bot.*, 38(3), 893-898.
11. Chauhan, P., Mohan, M., Nayak, S., 2001. Retrieval of Ocean constituents by IRS-P4 OCM. *Proceedings 4th Berlin Workshop on Remote Sensing '5 Years of MOS-IRS*, DLR, Berlin.
12. DeSouza, S. N., Kumar, M. D., Sardesai, S. V., Sarma, V. S., Shirodkar, P. V., 1996. Seasonal variability in oxygen and nutrients in the central and eastern Arabian Sea. *Current Science* 71, 857-862.
13. Devassy, V. P., Goes, J. I., 1988. Phytoplankton community structure and succession in a tropical estuarine complex (Central west coast of India)”, *Estuarine Coastal and Shelf Science*, 27, 671-685.
14. Devassy, V. P. Bhattathiri, P. M. A, Qasim, S. Z., 1978. *Trichodesmium* phenomenon. *Indian Journal of Marine Sciences*, 7, 168-186.
15. Devassy, V. P. Bhattathiri, P. M. A, Qasim, S. Z., 1979. Succession of organisms following *Trichodesmium* phenomenon”, *Indian Journal Marine Science*, 8, 89-93, 1979.
16. Devassy, V.P., 1987. *Trichodesmium* red tides in the Arabian Sea. In: Rao, T.S.S., Natrajan, R., Desai, B.N., Narayana Swamy, G., Bhat, S.R. (Eds.), *Contributions in Marine Sciences, Sastyabdapurti Felicitation Volume*. National Institute of Oceanography, Dona Paula, Goa, India, pp. 61–66.

17. Dwivedi, R. M., Raman, M., Parab, S., Matondkar, G. P., Nayak, S., 2006. Influence of northerly trade winds on intensity of winter bloom in the northern Arabian Sea. *Current Sci.*, 90, 1397-1406.
18. Goericke, R., 2002. Top-down control of phytoplankton biomass and community structure in the monsoonal Arabian Sea. *Limnology and Oceanography*, 47, 1307-1323.
19. Goes, J.I., Prasad, T.G., Gomes, H.do.R., Fasullo, J.T., 2005. Warming of the Eurasian landmass is making the Arabian Sea more productive. *Science* 308, 545–547.
20. Gomes, H.do.R., Goes, J. I., Matondkar S. G. P., Parab, S. G., Al-Azri, A. R. N., Thoppil, P. G., 2008. Blooms of *Noctiluca miliaris* in the Arabian Sea-An *in situ* and satellite study. *Deep- Sea Research I* 55, 751-765.
21. Gordon, H. R., Wang M., 1994. Retrieval of water leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: A preliminary algorithm, *J. App. Optics*, 33, 443-452.
22. Grasshoff, K., Ehrhardt, M., Kremling, K., 1983. *Methods of seawater analysis*, 419, Verlag Chemie, New York, NY.
23. Harrison, P. J., Furuya, K., Glibert, P. M., Xu, J., Liu, H. B., Yin, K., Lee, L. H. W., Anderson, D. M., Gowen, R., Al-Azri, A., Ho, A. Y. T., 2011. Geographical distribution of red and green *Noctiluca scintillans*. *Chinese Journal of Oceanology and Limnology* 29, 807-831.
24. Jeffrey, S. W., 1997. Application of pigment methods to oceanography, *Phytoplankton pigments in oceanography guidelines to modern methods*, S. W. Jeffrey, S.W. Wright, , United Nations Educational, Scientific and Cultural Organization, Paris, 127-166.
25. John, C. C. and Menon, M. A. S., 1972. Food and feeding habits of the oil sardine and mackerel. *Current Science*, 11, 243-244.
26. Kumar, Prasanna, S.P., Ramaiah, N., Gauns, M., Sarma, V.V.V.S., Muraleedharan, P.M., Raghukumar, S., Dileep-Kumar, M., Madhupratap, M., 2001. Physical forcing of biological productivity in the Northern Arabian Sea during the Northeast Monsoon. *Deep-Sea Research* 48, 1115–1126.
27. Latasa, M. Bidigare, R., 1998. A comparison of phytoplankton populations of the Arabian Sea during the Spring Intermonsoon and Southwest Monsoon of 1995 as described by HPLC-analyzed pigments, *Deep-Sea Research II* 45, 2133 – 2170.
28. Madhupratap, M., Kumar, S.P., Bhattathiri, P.M.A., Kumar, M.D., Raghukumar, S., Nair, K.K.C., Ramaiah, N., 1996. Mechanism of the biological response to winter cooling in the north-eastern Arabian Sea. *Nature* 384, 549–552.
29. O'Reilly, J. E. Maritonena, S., Mitchell, B. G., Siegal, D. A., Carder, K. L., Graver, S. Kahru, A. M., McClain, C. R., 1998. Ocean color chlorophyll algorithms for SeaWiFS. *Journal of Geophysics Research*, 103, 24937-24963.
30. Parab, S. G., Prabhu Matondkar, S. G., Gomes, H.do. R., Goes, J. I., 2006. Monsoon driven changes in phytoplankton population in the Eastern Arabian Sea as revealed by microscopy and HPLC pigment analysis. *Continental Shelf Research* 26, 2538-2558.
31. Sawant, S., Madhupratap, M., 1996. Seasonality and composition of phytoplankton in the Arabian Sea. *Current Science*, 17, 869 – 873, 1996.

32. Shetye, S. R., 1999. Propagation of tides in the Mandovi and Zuari estuaries. *Sadhana*, 24, 5 – 16, 1
33. Shetye, S. R., Gouveia, A. D., Shenoi, S. S. C., Soundar D., Michael, G. S., Almeida, A. M., Santanam, K., 1990. Hydrography and circulation off the west coast of India during the Southwest Monsoon 1987. *Journal of Marine Research* 48, 359-378.
34. Sriwoon R, Pholpunthin P, Lirdwitayaprasit T, Kishino M, Furuya K. 2008. Population dynamics of green *Noctiluca scintillans* (Dinophyceae) associated with the monsoon cycle in the upper Gulf of Thailand. *J. Phycol.*, 44, 605-615.
35. Subrahmanyam R. 1954. A new member of Euglenineae, *Protoeuglena noctilucae* gen. et. Sp. n., occurring in *Noctiluca miliaris* Suriray causing green discoloration off the Sea of Calicut. *Proc. Ind. Acad. Sci.*, 39, 120-127.
36. Subrahmanyam, R. 1959. Studies on the phytoplankton of the west coast of India” *I. Quantitative and qualitative fluctuation of the total phytoplankton crop, the zooplankton crop and their relationship, with remarks on the magnitude of the standing crop and production of matter and their relationship to fish landings*, B50 , 113-187, Proceedings Indian Academy of Sciences (Biological Science).
37. Subrahmanyam, R., Sarma, A. H. V., 1961. Studies on the phytoplankton of the west coast of India Part III seasonal variation of the phytoplankton and environmental factors. *Indian Journal of Fisheries*, 7, 307 – 336.
38. Subrahmanyam, R., Sarma, A. H. V., 1967. Studies on the phytoplankton of the west coast of India Part IV, magnitude of the standing crop for 1955–1962, with observations on nanoplankton and its significance to fisheries. *Journal of the Marine Biological Association of India*, 7, 406 – 419.
39. Throndsen, J. 1997. Preservation and storage. *Phytoplankton manual*, A. A. Sournia, 69-74, United Nations Educational, Scientific and Cultural Organization, Paris.
40. Tomas, C. R., 1997. Identifying Marine Phytoplankton. Academic Press, New York, USA, pp. 858.
41. UNESCO, (1994). Protocols for the Joint Global Ocean Flux Study (JGOFS) core measurements, Manual and guides 29, Scientific Committee on Oceanic Research, pp. 170.
42. Wright, S.W. Jeffrey, S. W. R. Mantoura, Llewellyn, G. C. C. A., Bjornland D. R., Welschmeyer, 1991. Improved HPLC method for the analysis of chlorophylls and carotenoids from marine phytoplankton. *Marine Ecology Progress Series*, 77, 183-196.
43. Wyrtki, K., 1973. Physical Oceanography of the Indian Ocean, *The Biology of the Indian Ocean*. B. Zietzschel and Geralache, 18-36.

List of Tables

1. Cruise sampling dates.
- 2a. Nutrients during February.
- 2b. Nutrients during March.
3. Chlorophyll *a* at surface and column.
4. *Noctiluca miliaris* (cells L⁻¹) in the Arabian Sea.
5. Dominant phytoplankton species in the NE Arabian Sea.

Table 1 Cruise sampling dates

Cruises	Date	Months	Year
SK-252	29-14	March-April	2000
SK-171	2-18	November	2001
SK-186	2-20	January	2003
SS-212	27-2	February-March	2003
SS-222	22-10	February-March	2004
SK-214	3-18	December	2004
SS-244	15-29	April	2006
SS-253	28-19	February-March	2007
SK-256	9-23	February	2009
SS-263	29-14	February-March	2009
SK-258	17-1	April-May	2009
SS-273	6-10	March	2010
SS-286	7-19	March	2011

Table 2a Nutrients during February

Nutrients	Bloom (n=6)	Non-Bloom (n=4)
Nitrate (μM)	0.48-1.80 (0.88 \pm 0.49)	0.23-1.42 (0.59 \pm 0.56)
Nitrite (μM)	0.19-1.10 (0.68 \pm 0.32)	0.22-1.57 (0.60 \pm 0.65)
Phosphate (μM)	0.70-5.23 (1.64 \pm 1.77)	0.54-1.08 (0.72 \pm 0.25)
Silicate (μM)	9.64-20.87 (15.09 \pm 4.35)	9.07-62.28 (31.04 \pm 22.48)

Table 2b Nutrients during March

Nutrients	Bloom (n=7)	Non-Bloom (n=9)
Nitrate (μM)	0-0.39 (0.07 \pm 0.14)	0-0.40 (0.09 \pm 0.12)
Nitrite (μM)	0.03-0.11 (0.06 \pm 0.03)	0.03-0.52 (0.11 \pm 0.16)
Phosphate (μM)	0.05-0.39 (0.18 \pm 0.15)	0-0.99 (0.45 \pm 0.38)
Silicate (μM)	0.87-3.38 (2.13 \pm 0.90)	0.73-3.16 (1.74 \pm 0.82)

Table 3 Chlorophyll *a* at surface and column

Months	Surface Chl <i>a</i> (mgm⁻³)			Column Chl <i>a</i> (mgm⁻²)		
	Min	Max	Aver	Min	Max	Aver
Nov (n=13)	0.173	5.344	0.726	8.621	146.426	43.812
Dec (n=14)	0.190	0.510	0.340	18.39	27.24	22.140
Jan (n=25)	0.173	2.6	0.723	1.743	322.525	44.529
Feb (n=10)	0.132	0.960	0.344	3.292	49.383	17.366
March (n=13)	0.169	2.741	0.963	1.605	338.975	62.842
April (n=35)	0.074	5.905	0.665	3.337	64.126	14.001

Table 4 *Noctiluca miliaris* (cells L⁻¹) in the Arabian Sea

Years	Bloom
27 th Feb-5 th March 2003	64-4128 (179±162)
22 nd Feb-8 th March 2004	60-2494 (745±827)
7 th -15 th March 2007	48-7200 (1844±2800)
9 th -23 rd Feb 2009	8-9600 (1645±3897)
29 th Feb-14 th March 2009	2-80 (26±37)

Table 5 Dominant phytoplankton species in the NE Arabian Sea

Months	Dominant phytoplankton species					
	Surface			Column		
Nov	<i>Trichodesmium thiebautii</i>	<i>Nitzschia closterium</i>	<i>Ampphora hyalina</i>	<i>Chaetoceros socilalis</i>	<i>Melosira moniliformis</i>	<i>Chaetoceros danicus</i>
Dec	<i>Gymnodinium gracile</i>	<i>Prorocentrum minimus</i>	<i>Rhizosolenia alata</i>	<i>Trichodesmium thiebautii</i>	<i>Nitzschia longissima</i>	<i>Actinoptychus senarius</i>
Jan	<i>Gymnodinium breve</i>	<i>Gonyaulax schilleri</i>	<i>Amphidinium carteare</i>	<i>Amphidinium carteare</i>	<i>Coscinodiscus radiatus</i>	<i>Gyrodinium spirale</i>
Feb	<i>Noctiluca miliaris</i>	<i>Navicula sp. I</i>	<i>Nitzschia closterium</i>	<i>Noctiluca miliaris</i>	<i>Rhizosolenia shrubsolei</i>	<i>Coscinodiscus oculus</i>
March	<i>Trichodesmium erythraeum</i>	<i>Noctiluca miliaris</i>	<i>Hemiaulus sinensis</i>	<i>Rhizosolenia shrubsolei</i>	<i>Pyrophacus horologium</i>	<i>Cocconeis scutellum</i>
April	<i>Trichodesmium erythraeum</i>	<i>Coscinodiscus marginatus</i>	<i>Peridinium elegans</i>	<i>Navicula delicatula</i>	<i>Trichodesmium erythraeum</i>	<i>Rhizosolenia stolterfothii</i>

List of Figures

1. Research vessels used for sampling
- 2a. Sampling locations for cruise 29th Feb-14th March 2009 superimposed on 8-day composition of Sea-Viewing Wide Field-of-View Sensor and Aqua-moderate Resolution Imaging Spectroradiometer level-3 merged satellite images of chlorophyll *a* (Chl *a*) corresponding to the sampling period.
- 2b. Map showing sampling locations and their *insitu* surface Chl *a* during the study period.
3. Ship cruise track and time evolution of the bloom observed from chlorophyll *a* images generated from OCM-I data.
4. Active and declining phases of *Noctiluca miliaris* bloom in the Northern Arabian Sea: (a) Active-phase bloom of Feb-09 (b) Green *N miliaris* cells morphology (c) Symbiotic prasinophytes of *Noctiluca miliaris* (d) DAPI stained prasinophytes showing bi-flagellates(100X) (e) Declining phase bloom of Mar-09 (f & g) lysis of *Noctiluca* cells releasing prasinophytes (h) Grazing observed in lysed biomass of *Noctiluca miliaris* bloom.
5. Detection of *Noctiluca* bloom by Ocean Sat-I during Feb-March 2003
- 6a. day mean Chl *a* acquired from MODIS-Aqua (4km resolution) showing winter-bloom during 2008-2009.
- 6b. Average Chl *a* distribution in the Arabian Sea during 18th -25th February for past 15year period (1998-2012) showing intensification of winter bloom phase. 8-day composite Chl *a* images of Sea-WiFS and MODIS-Aqua were obtained from the *Giovanni* online system maintained by NASA GES DISC.
7. Sea-WiFS images showing Chl *a* distribution during Feb-Mar winter bloom of 2009.
8. Nitrate in the Arabian Sea.
9. Nitrate in the Arabian Sea during September 1997-2002.
- 10a. Temperature and Salinity A & B *Noctiluca miliaris* bloom and non- bloom during February 2009.
- 10b. Temperature and Salinity A & B -*Noctiluca miliaris* bloom and C non- bloom during March 2009.
11. Chlorophyll *a* from OCM I in the Arabian Sea during different months.
12. Distribution of pigments during different months. Chl *a* – chlorophyll *a*; Chl *b* – chlorophyll *b*; Chl *c*- chlorophyll *c*; fuco – fucoxanthin ; β -caro- β -carotene; per-peridinin.

13. Photo-micrographs showing grazing activities during the *Noctiluca miliaris* bloom:
(a) Diatoms shells located in *Noctiluca miliaris* cells (20X) (b) Amphipods ambushing *Noctiluca miliaris* cells (c & d) Ostracods grazing on *Noctiluca miliaris* (e & f) Jelly-fish and Salps feeding on *Noctiluca miliaris* cells.
14. Dominant phytoplankton species during *Noctiluca miliaris* bloom.
15. Distribution of *Noctiluca miliaris* during the winter-bloom of 2009 in the Northern Arabian Sea.
16. Linear regression between Total phytoplankton cells and *Noctiluca miliaris* cells.
17. Linear relation between *Noctiluca miliaris* cells and Chl *a*.
18. (a) Scatter plots of *N. miliaris* cell counts (L_1) versus SeaWiFS and Aqua-MODIS Level-3 merged chl *a* (m_{gm_3}) for CRUISE-4-MAR-2004.
19. CDOM characteristics in water-column of: (a) Active bloom of *Noctiluca miliaris* in Feb -09 bloom (b) Declining bloom of *Noctiluca miliaris* in Mar-09 and (c) Coastal non-bloom waters off Veraval, Gujrat in the Northern Arabian Sea during Feb-09.
20. Measured particulate (a_p), Detritus (a_{nap}) and phytoplankton absorption spectra (a_ϕ) at *Noctiluca* bloom station ($20^0 53.98'N$ and $66^0 10.18'E$).
21. Correlation between $a_\phi(675)$ and TChl *a* concentration at *Noctiluca* bloom station $20^0 53.98'N$ and $66^0 10.18'E$.
22. Detection of *Noctiluca miliaris* bloom area in NAS using OCM-II images in the NAS during receding phase of Mar-2011.
23. (a–h) Weekly SeaWiFS and MODIS-Aqua Level-3 merged satellite chl *a* images from 2003–2006 . The color bar denotes chl *a* in log scale.
24. Match-up analysis of in-situ Chl *a* from bloom area with OCM-I derived Chl*a* from the dinoflagellate green *Noctiluca miliaris* bloom of the Northern Arabian Sea during Feb-March
25. Match-up analysis of in-situ Chl *a* from bloom area with OCM-II derived Chl *a* from the dinoflagellate green *Noctiluca miliaris* bloom of the Northern Arabian Sea during 2010-2011



Fig. 1 Research vessels used for sampling

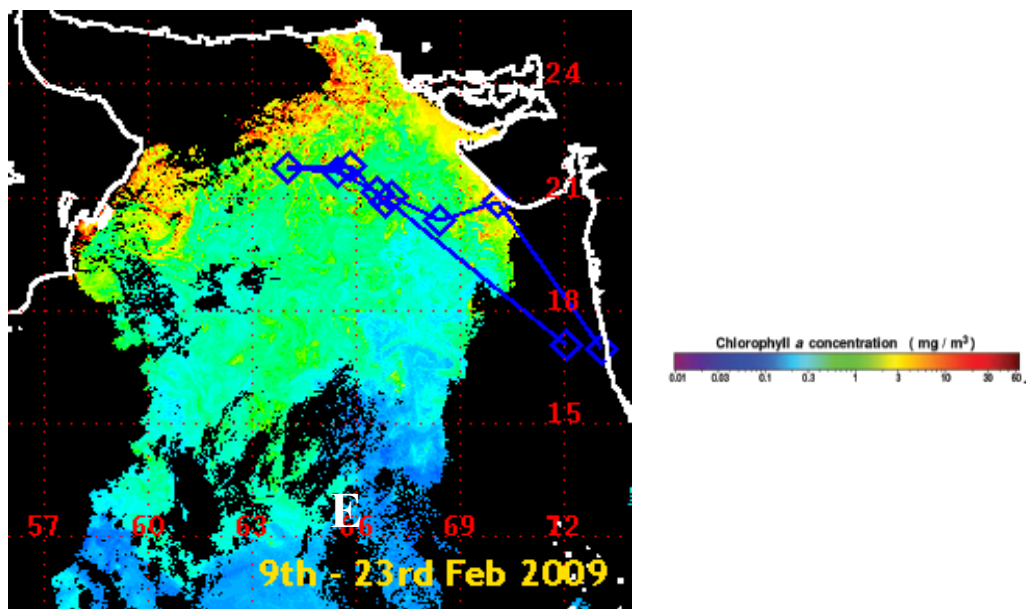


Fig. 2a Sampling locations for cruise 29th Feb-14th March 2009 superimposed on 8-day composition of Sea-Viewing Wide Field-of-View Sensor and Aqua-moderate Resolution Imaging Spectroradiometer level-3 merged satellite images of chlorophyll *a* (Chl *a*) corresponding to the sampling period.

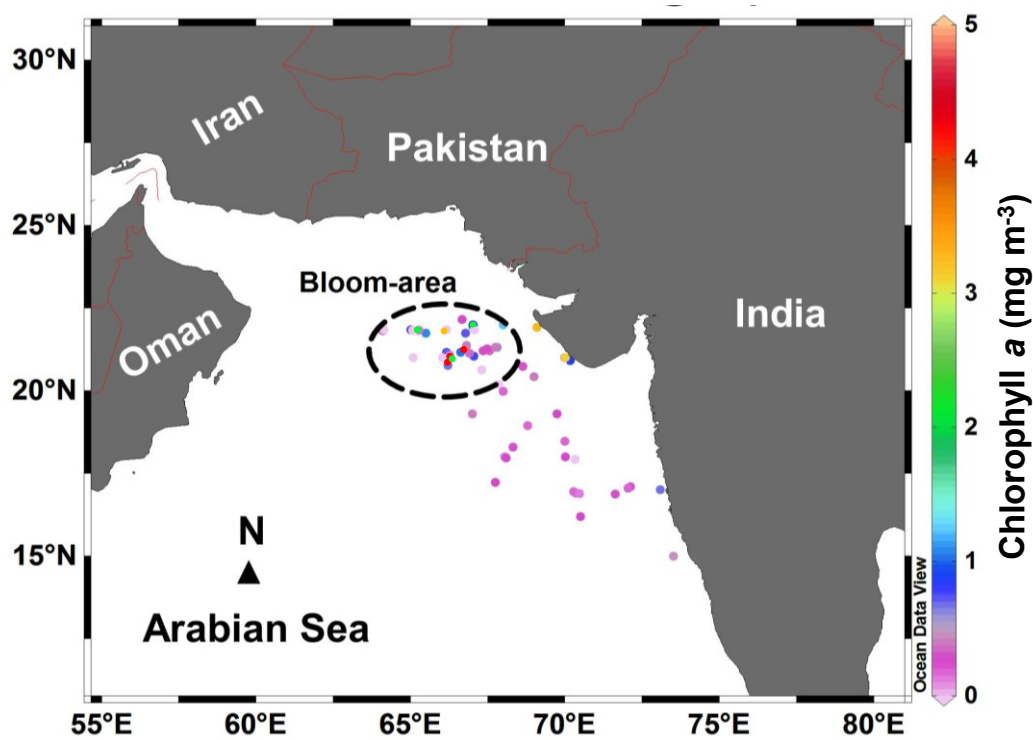


Fig. 2b Map showing sampling locations and their *insitu* surface Chl *a* during the study period.

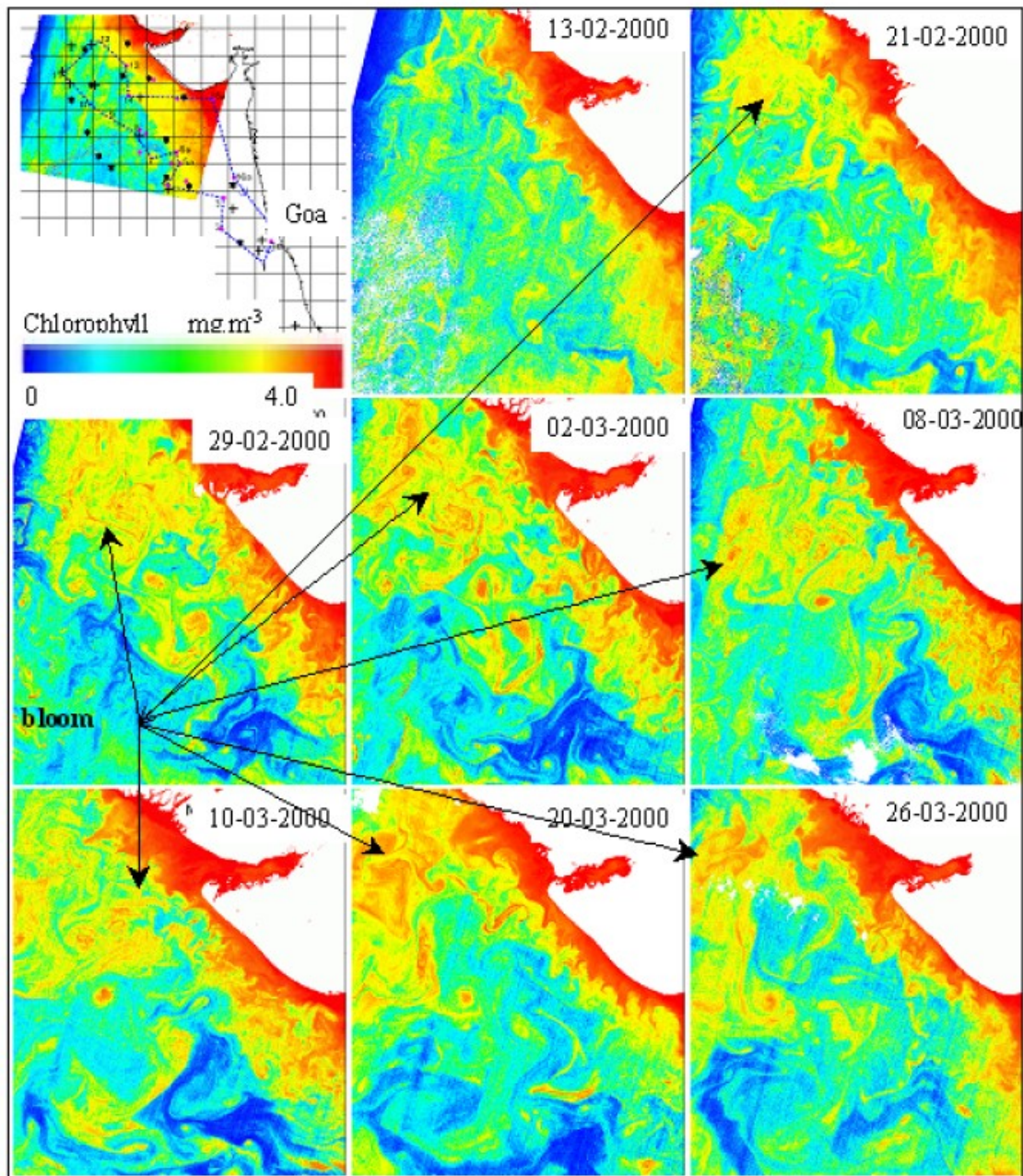


Fig. 3 Ship cruise track and time evolution of the bloom observed from chlorophyll *a* images generated from OCM-I data

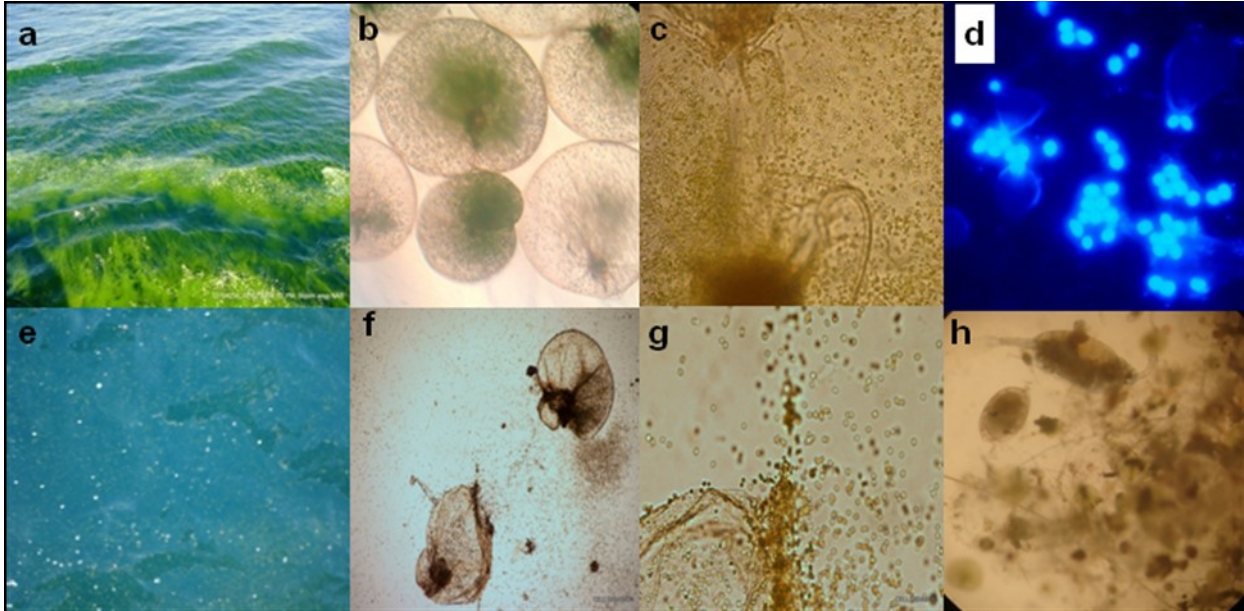


Fig. 4 Active and declining phases of *Noctiluca miliaris* bloom in the Northern Arabian Sea: (a) Active-phase bloom of Feb-09 (b) Green *N. miliaris* cells morphology (c) Symbiotic prasinophytes of *Noctiluca miliaris* (d) DAPI stained prasinophytes showing bi-flagellates(100X) (e) Declining phase bloom of Mar-09 (f & g) lysis of *Noctiluca* cells releasing prasinophytes (h) Grazing observed in lysed biomass of *Noctiluca miliaris* bloom

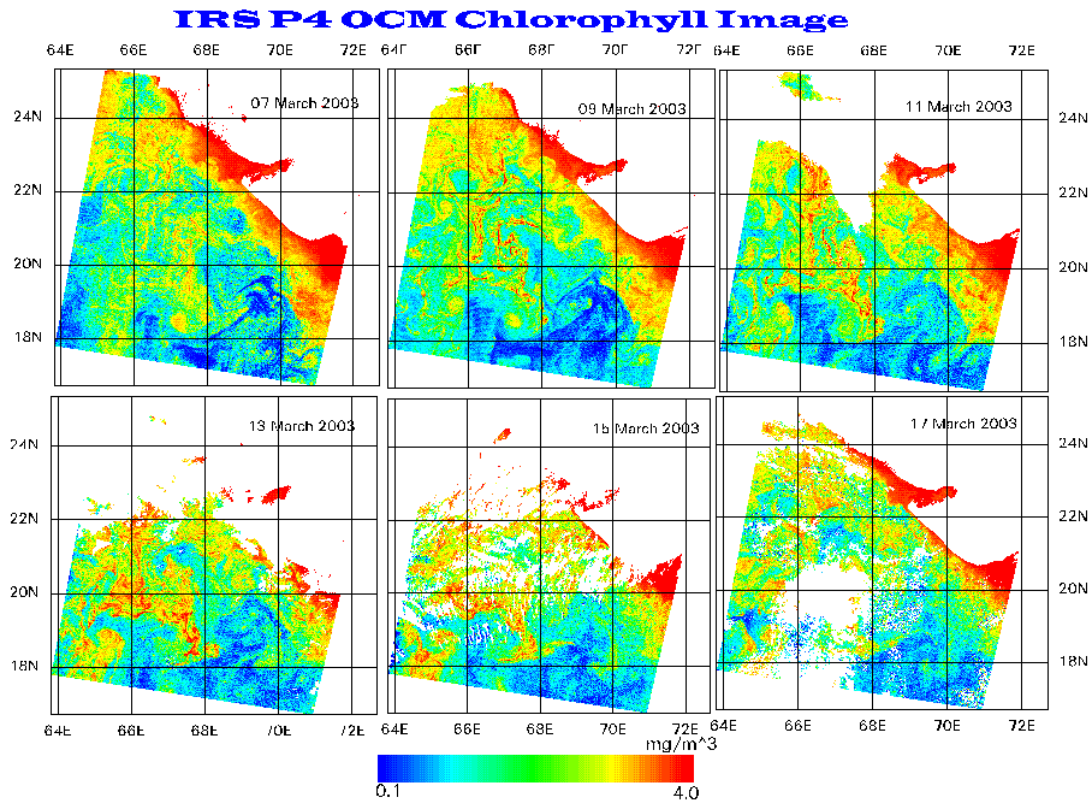
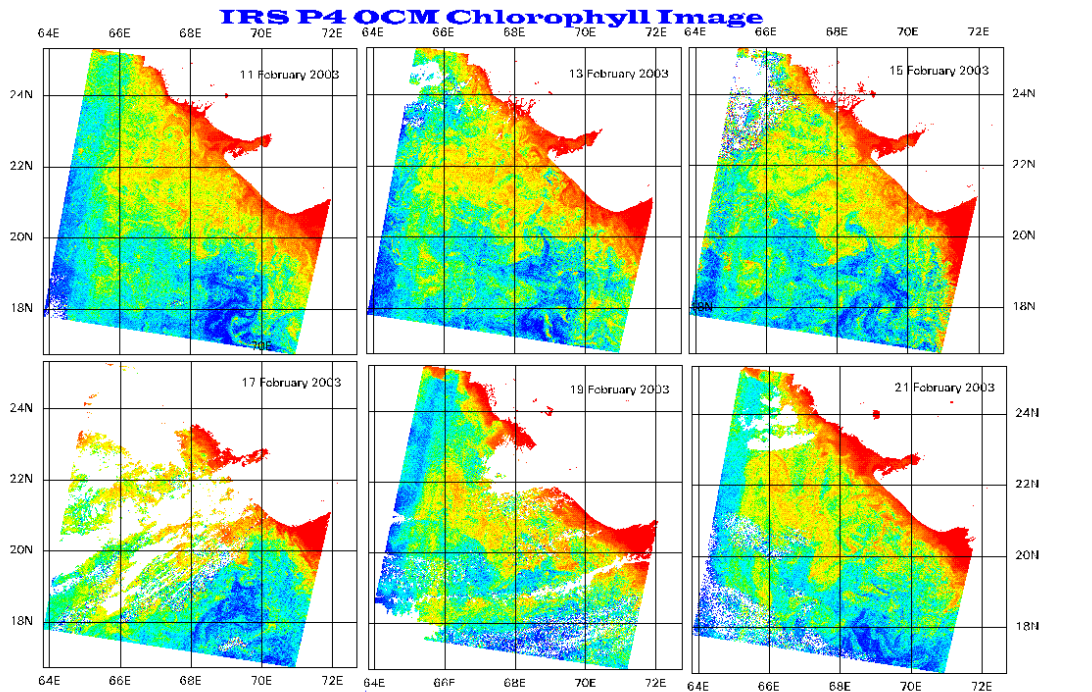


Fig. 5 Detection of *Noctiluca* bloom by Ocean Sat-I during Feb-March 2003

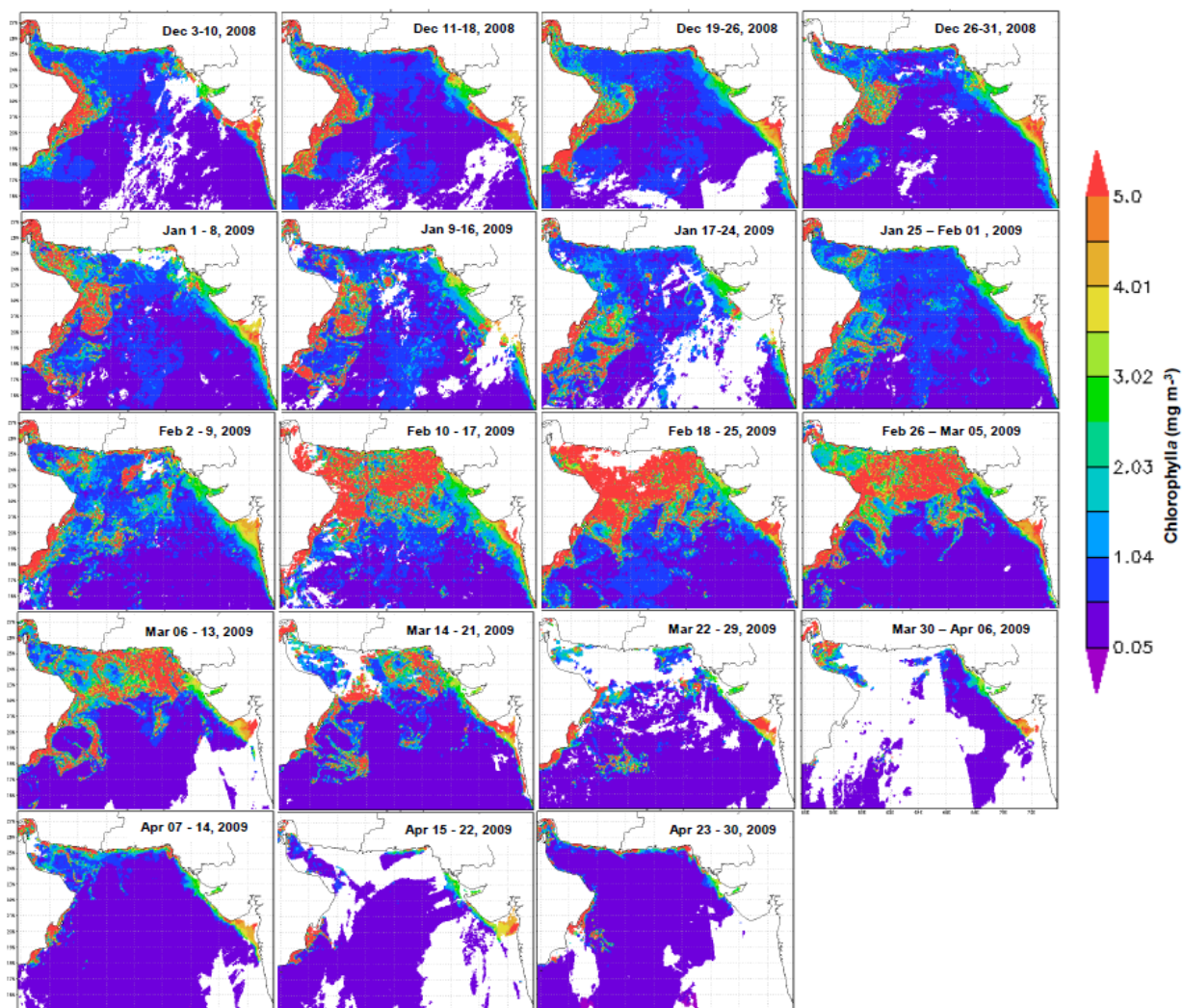


Fig. 6a day mean Chl *a* acquired from MODIS-Aqua (4km resolution) showing winter-bloom during 2008-2009.

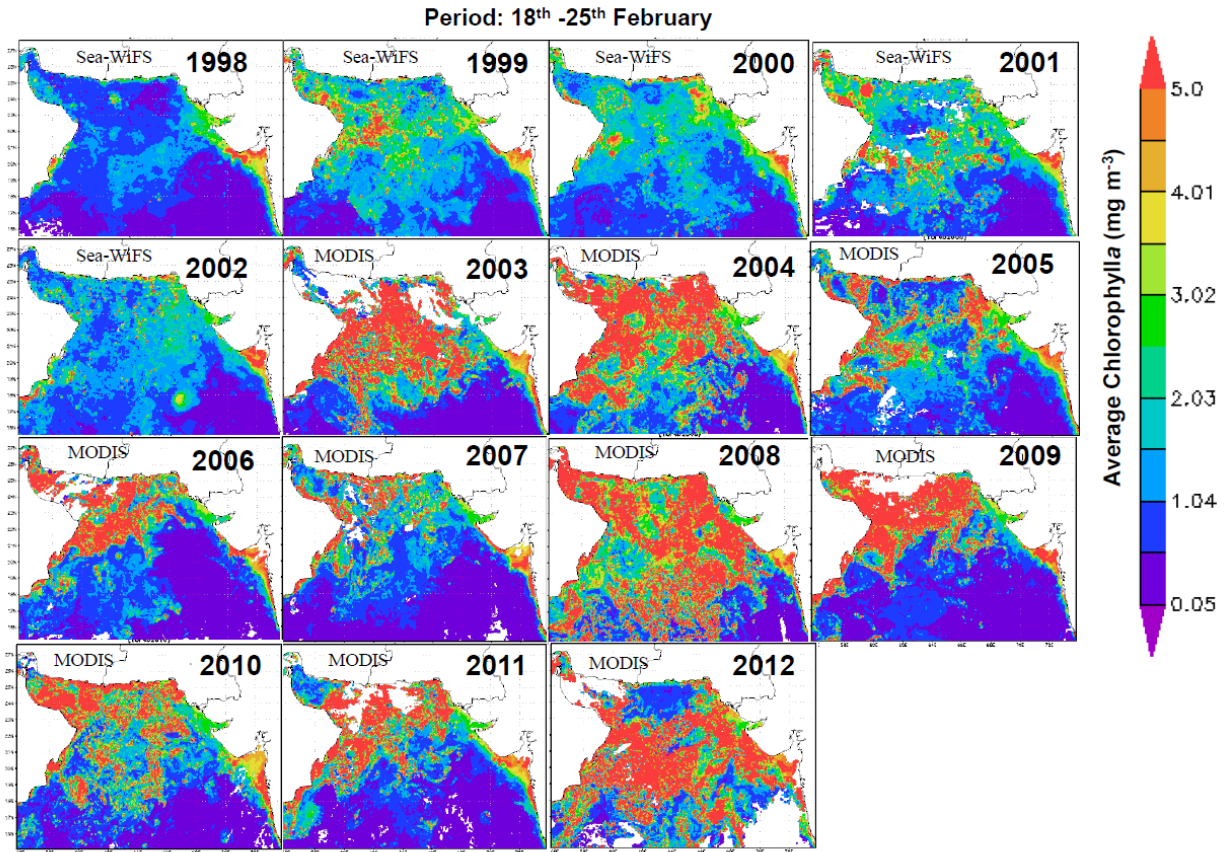


Fig. 6b Average Chl *a* distribution in the Arabian Sea during 18th -25th February for past 15 year period (1998-2012) showing intensification of winter bloom phase. 8-day composite Chl *a* images of Sea-WiFS and MODIS-Aqua were obtained from the *Giovanni* online system maintained by NASA GES DISC.

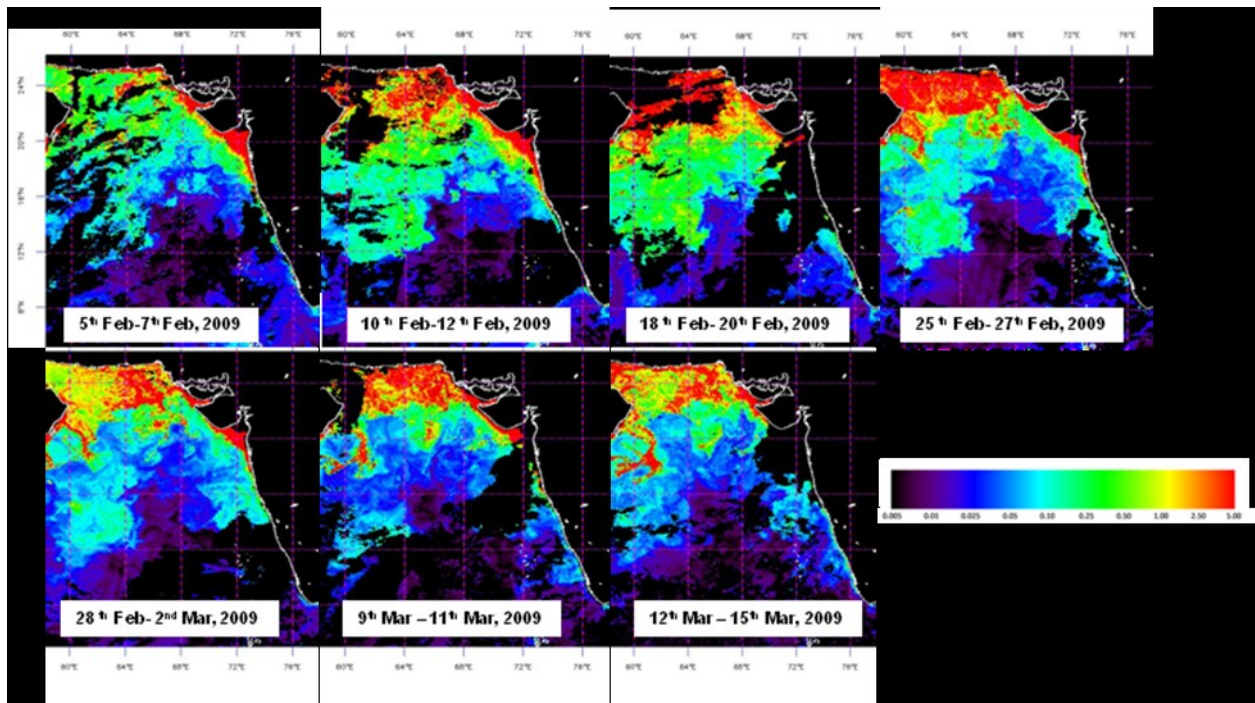


Fig. 7 Sea-WIFS images showing Chl *a* distribution during Feb-Mar winter bloom of 2009.

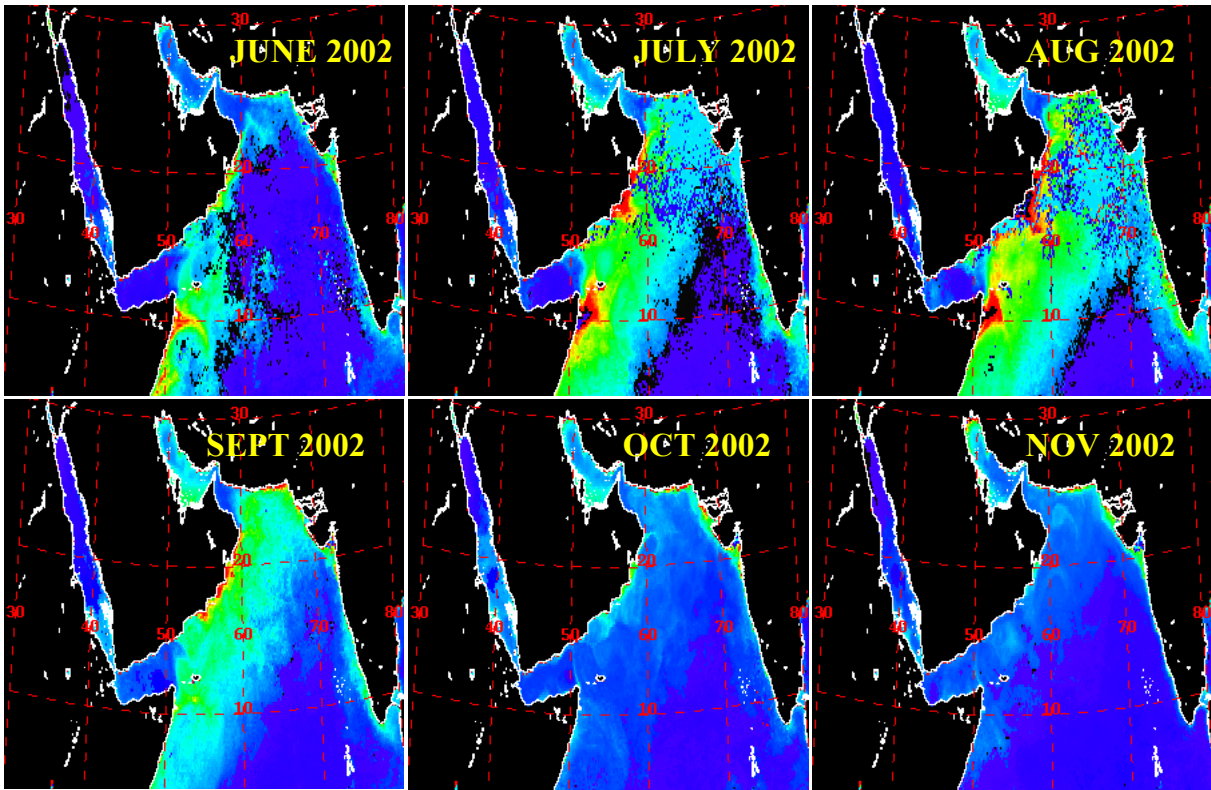


Fig. 8 Nitrate in the Arabian Sea

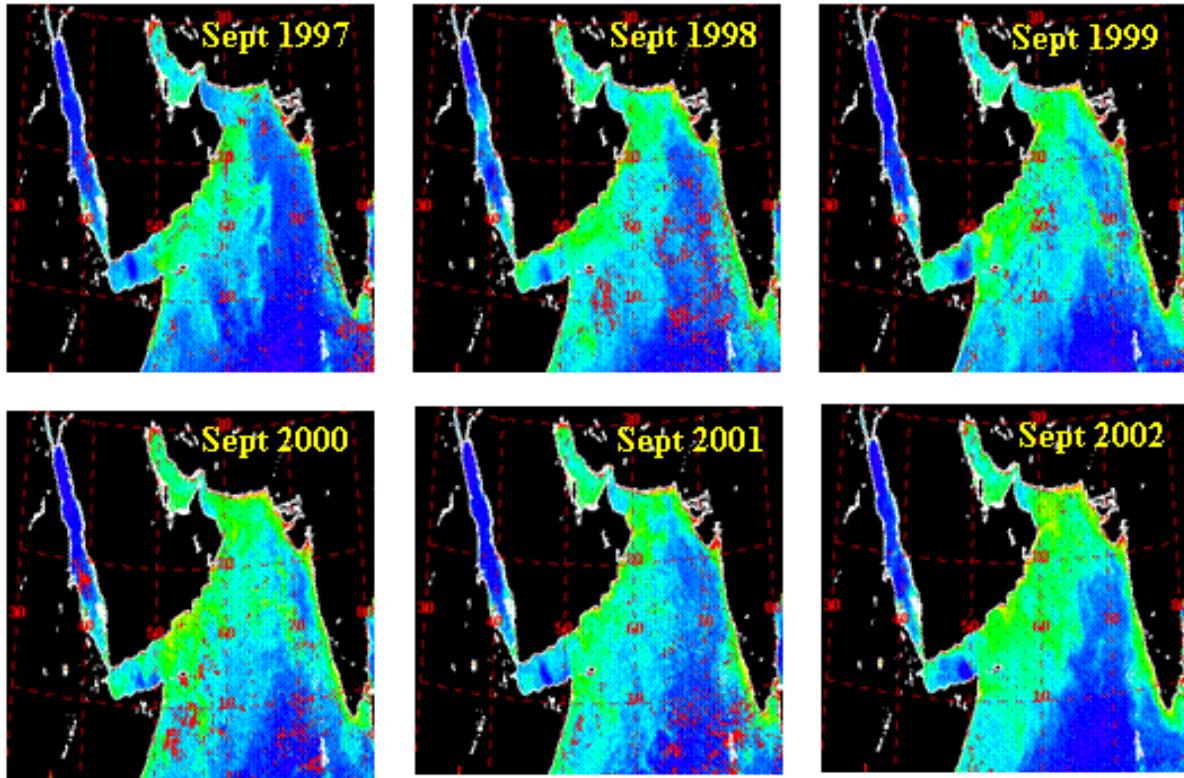


Fig. 9 Nitrate in the Arabian Sea during September 1997-2002.

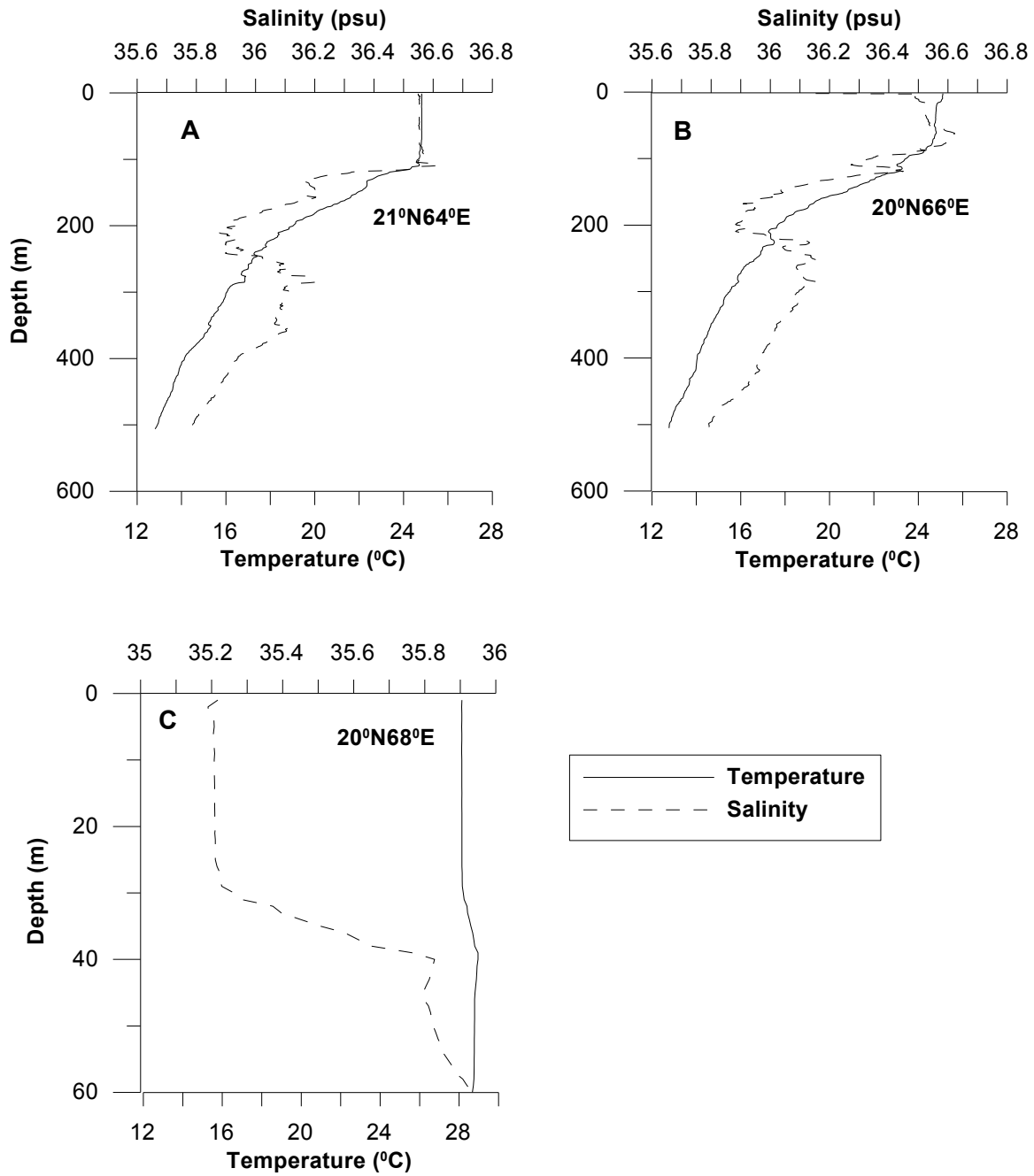


Fig. 10a Temperature and Salinity A & B *Noctiluca miliaris* bloom and non- bloom during February 2009.

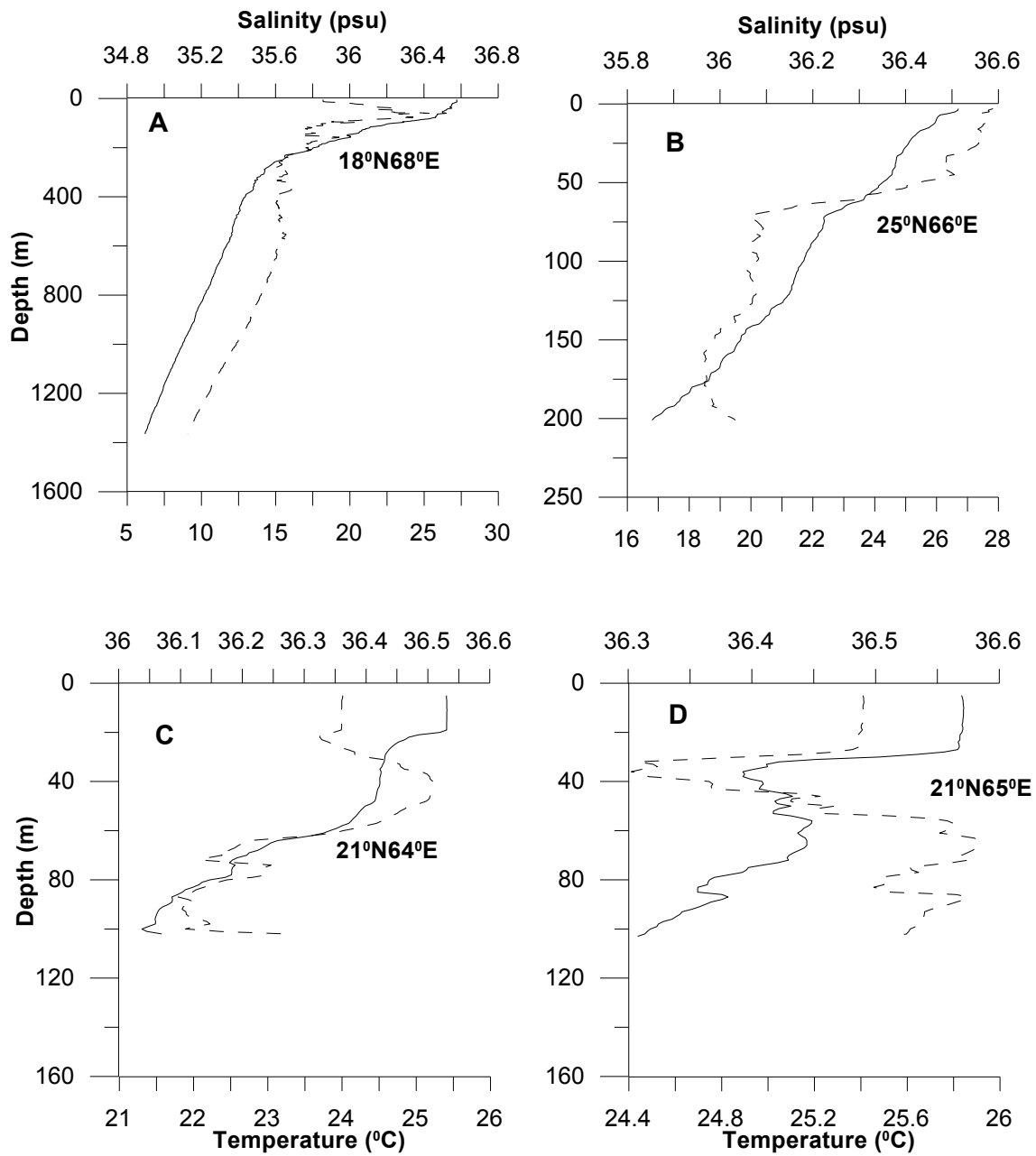


Fig. 10b Temperature and Salinity A & B -*Noctiluca miliaris* bloom and C non- bloom during March 2009.

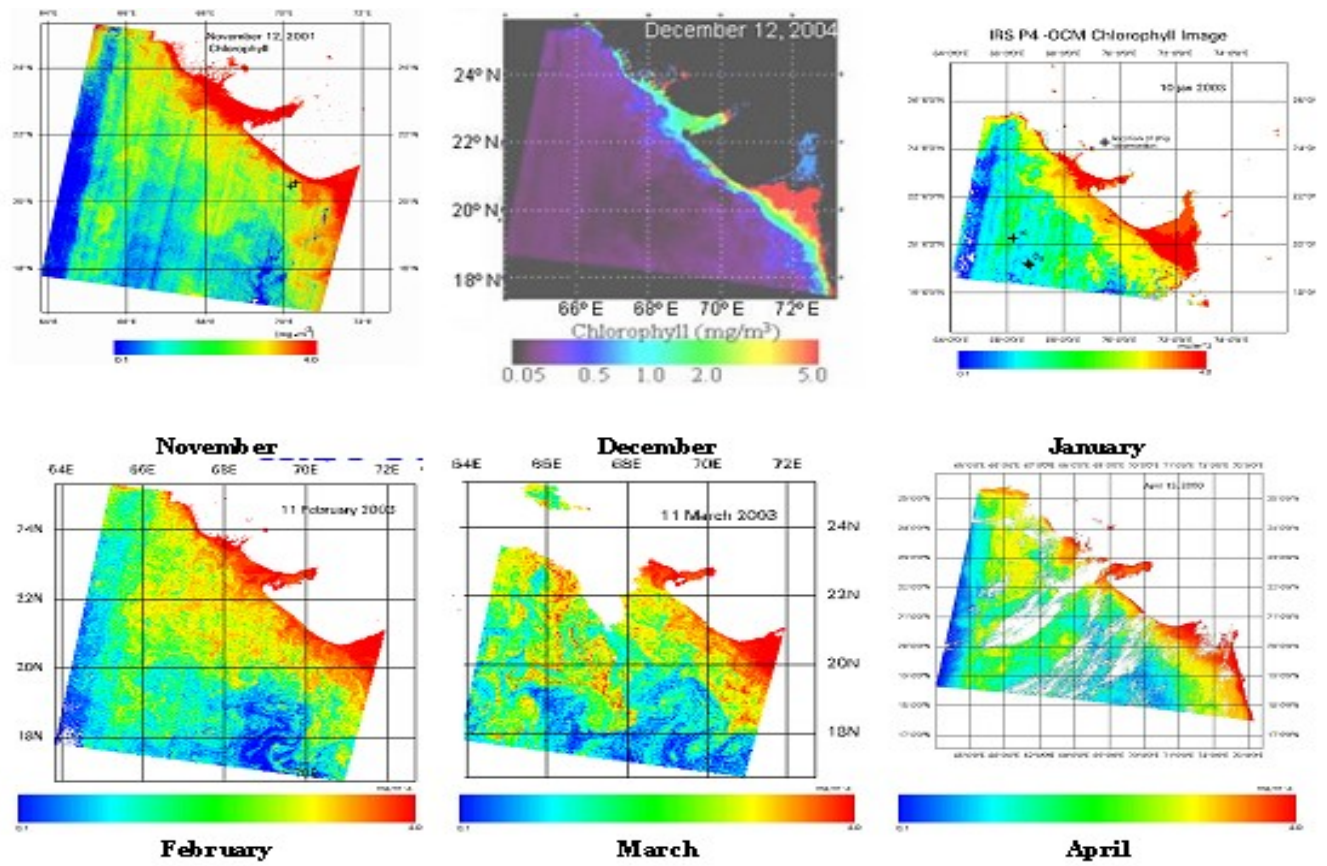


Fig. 11 Chlorophyll *a* from OCM I in the Arabian Sea during different months.

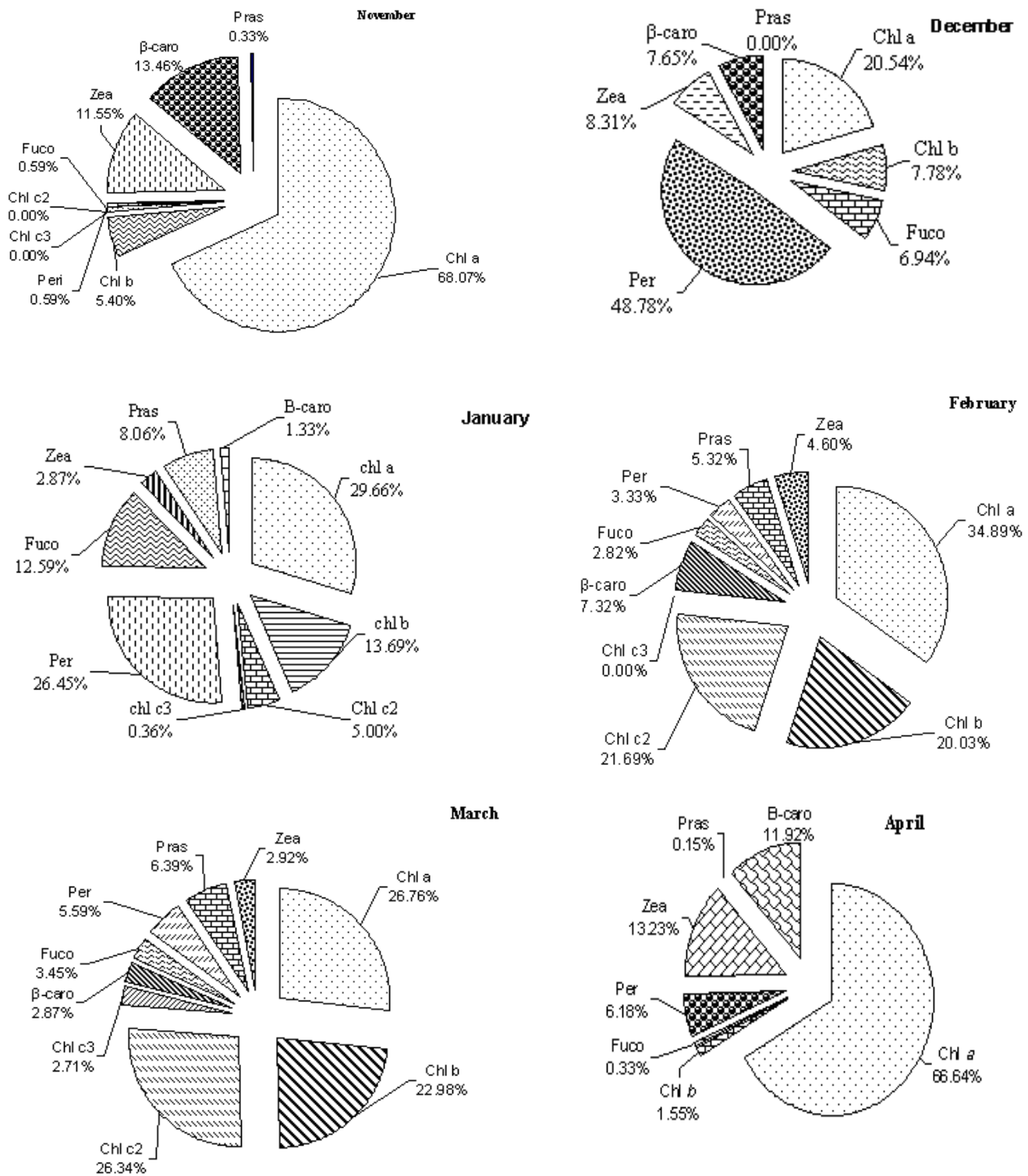


Fig 12 Distribution of pigments during different months. Chl *a* – chlorophyll *a*; Chl *b* – chlorophyll *b*; Chl *c*- chlorophyll *c*; fuco – fucoxanthin ; β -caro- β -carotene; per-peridinin.

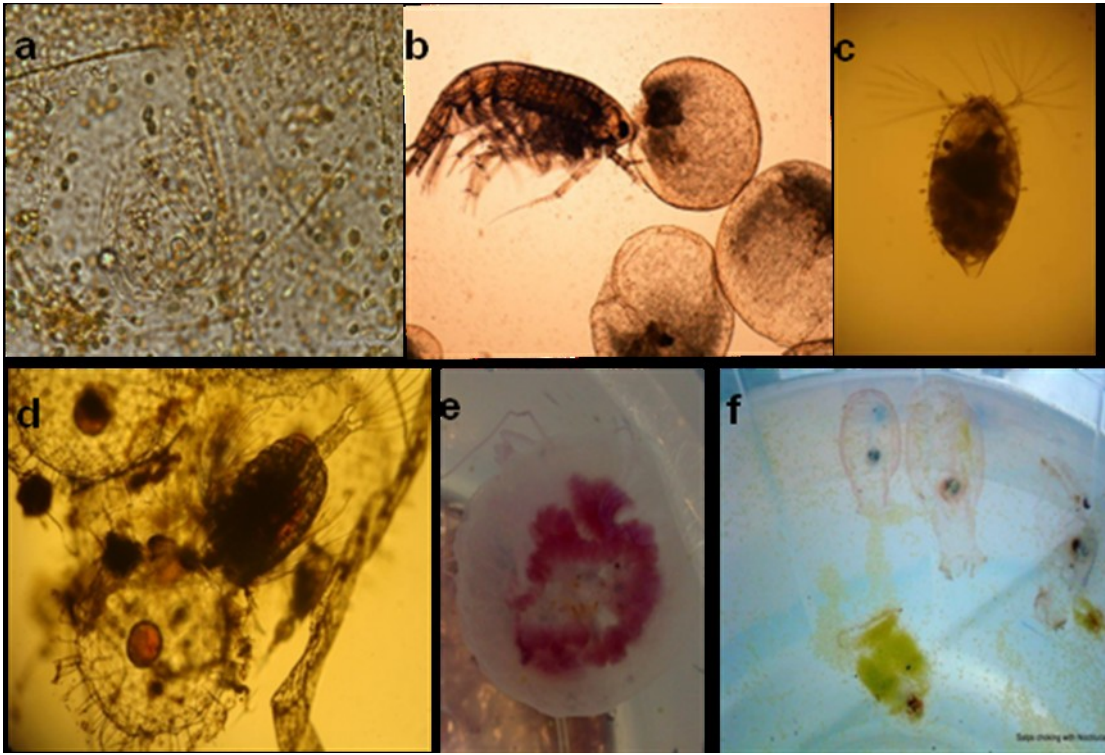


Fig.13 Photo-micrographs showing grazing activities during the *Noctiluca miliaris* bloom: (a) Diatoms shells located in *Noctiluca miliaris* cells (20X) (b) Amphipods ambushing *Noctiluca miliaris* cells (c & d) Ostracods grazing on *Noctiluca miliaris* (e & f) Jelly-fish and Salps feeding on *Noctiluca miliaris* cells.

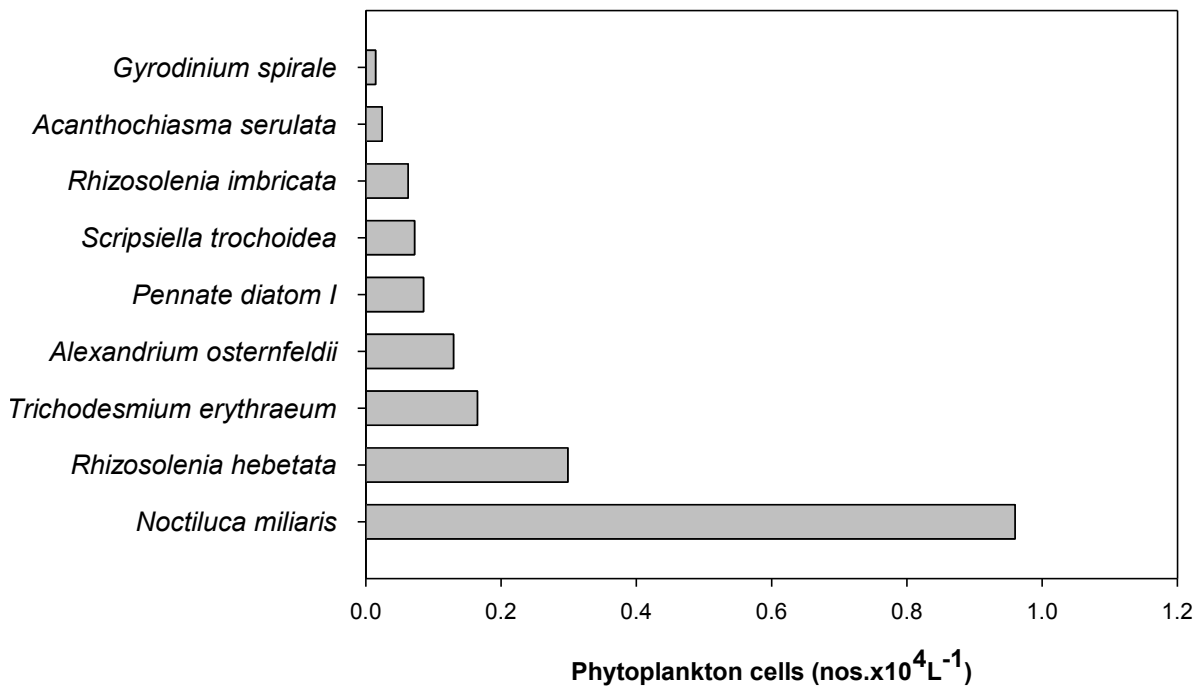


Fig. 14 Dominant phytoplankton species during *Noctiluca miliaris* bloom.

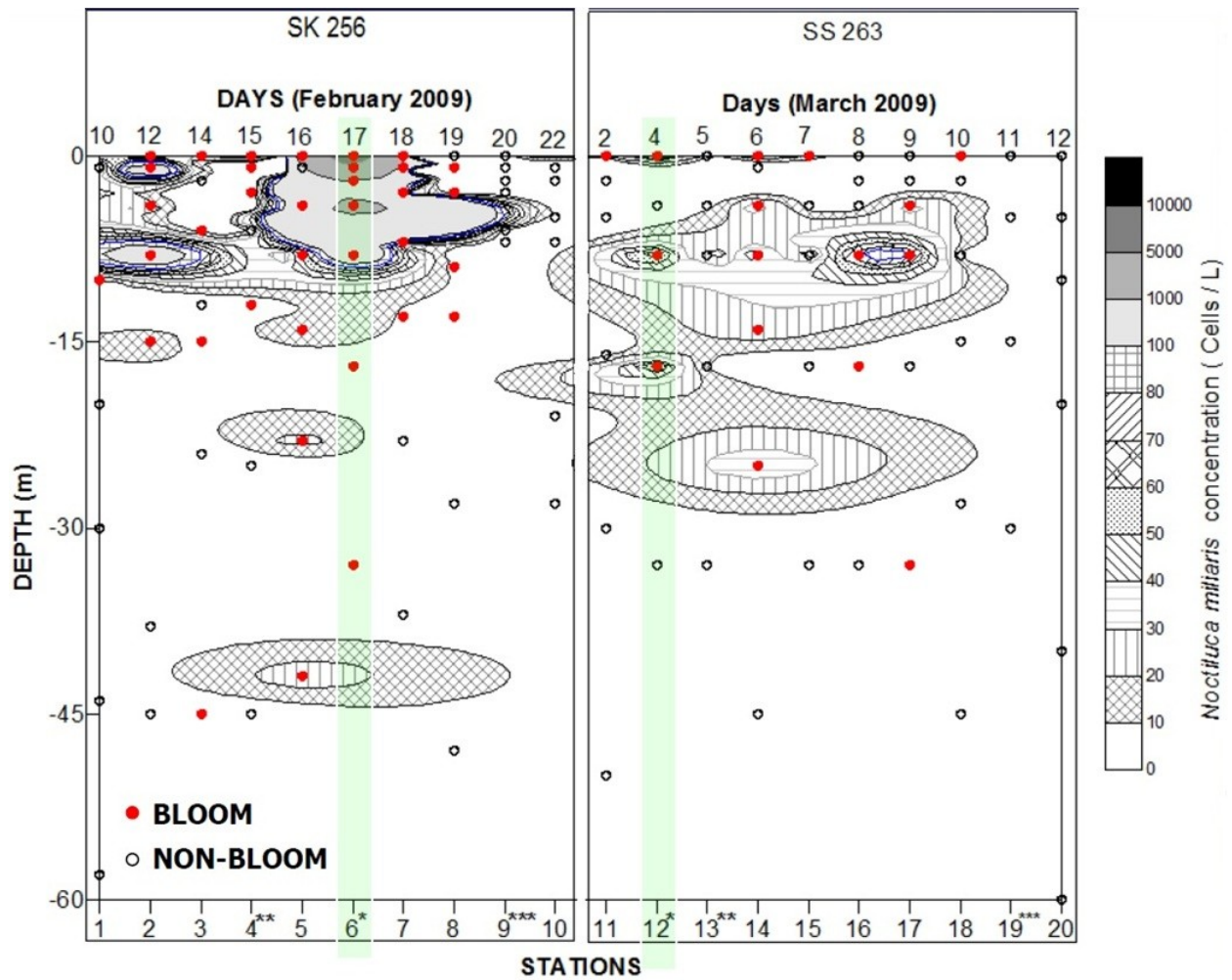


Fig. 15 Distribution of *Noctiluca miliaris* during the winter-bloom of 2009 in the Northern Arabian Sea

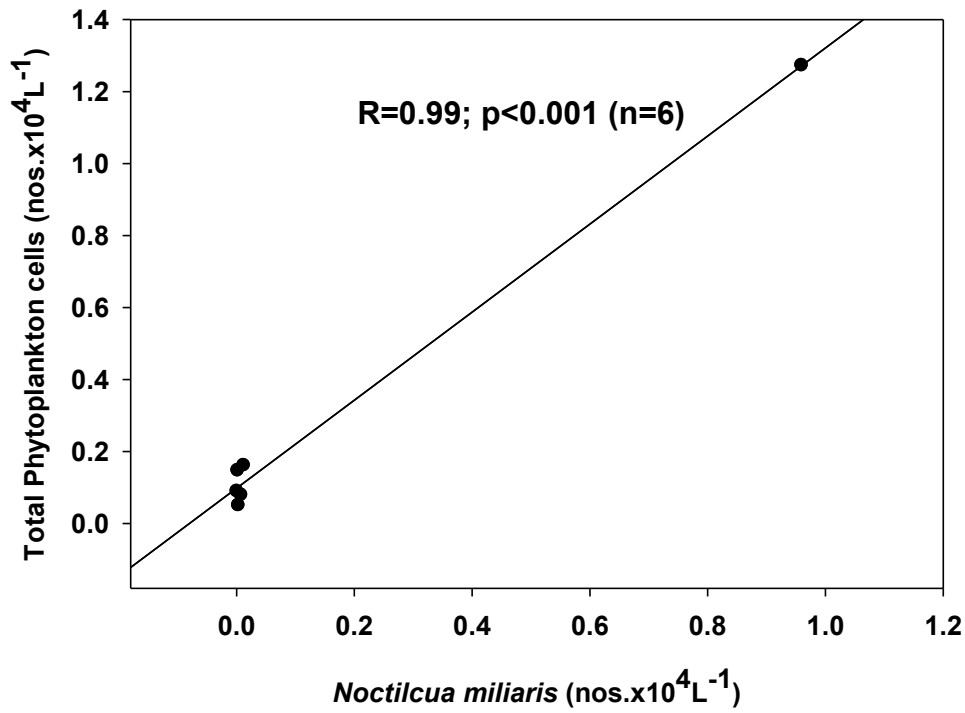


Fig. 16 Linear regression between Total phytoplankton cells and *Noctiluca miliaris* cells

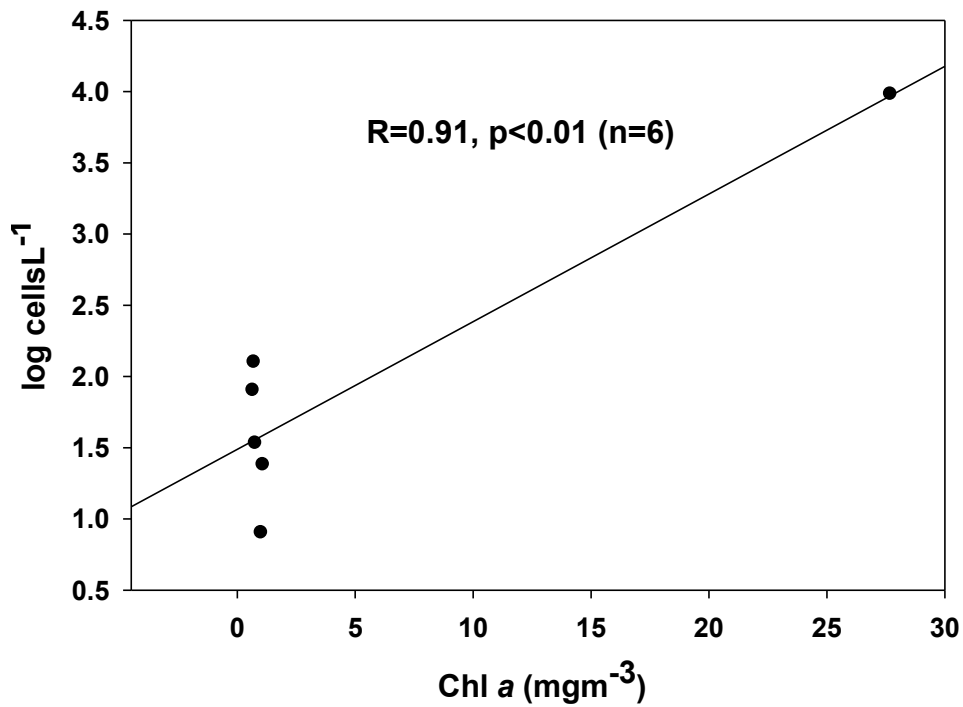


Fig. 17 Linear relation between *Noctiluca miliaris* cells and Chl a

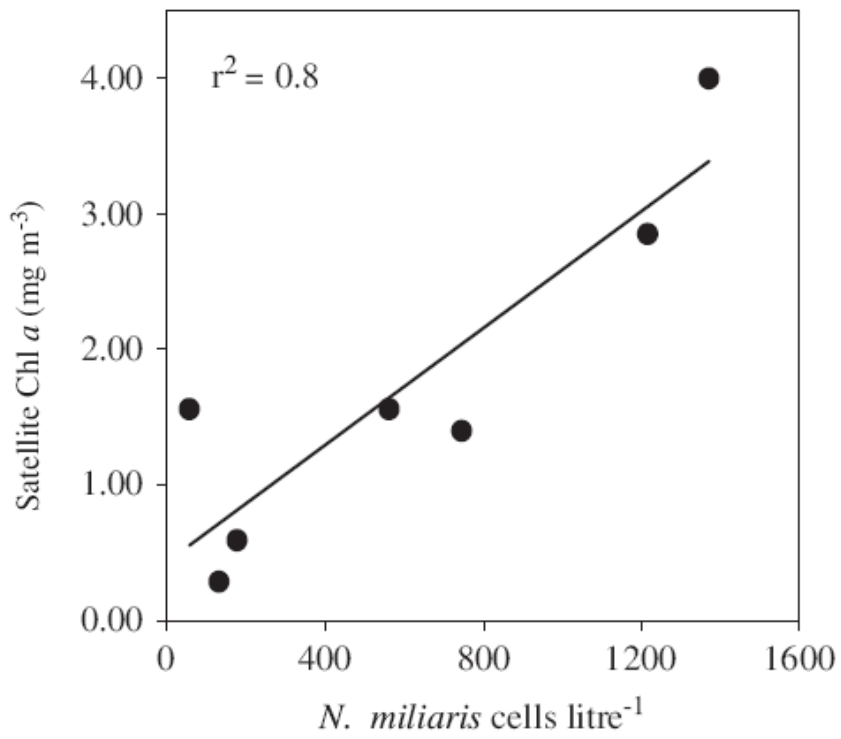


Fig. 18 (a) Scatter plots of *N. miliaris* cell counts (L_1) versus SeaWiFS and Aqua-MODIS Level-3 merged chl *a* (mgm_3) for CRUISE-4-MAR-2004.

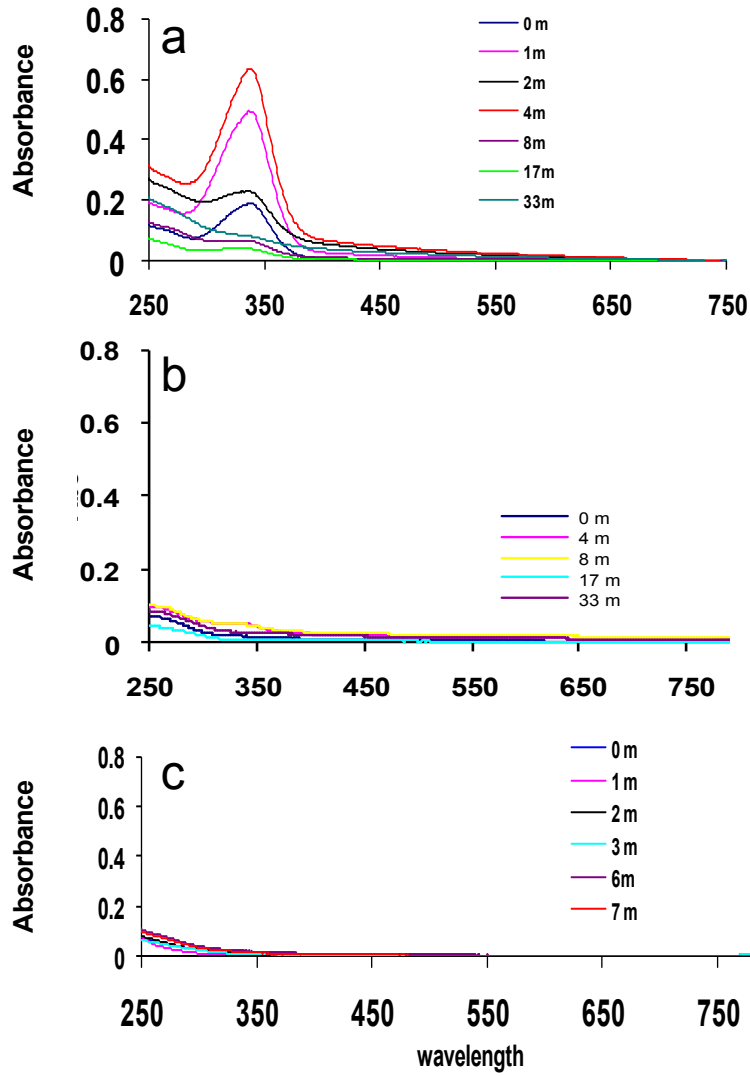


Fig. 19 CDOM characteristics in water-column of: (a) Active bloom of *Noctiluca miliaris* in Feb-09 bloom (b) Declining bloom of *Noctiluca miliaris* in Mar-09 and (c) Coastal non-bloom waters off Veraval, Gujrat in the Northern Arabian Sea during Feb-09.

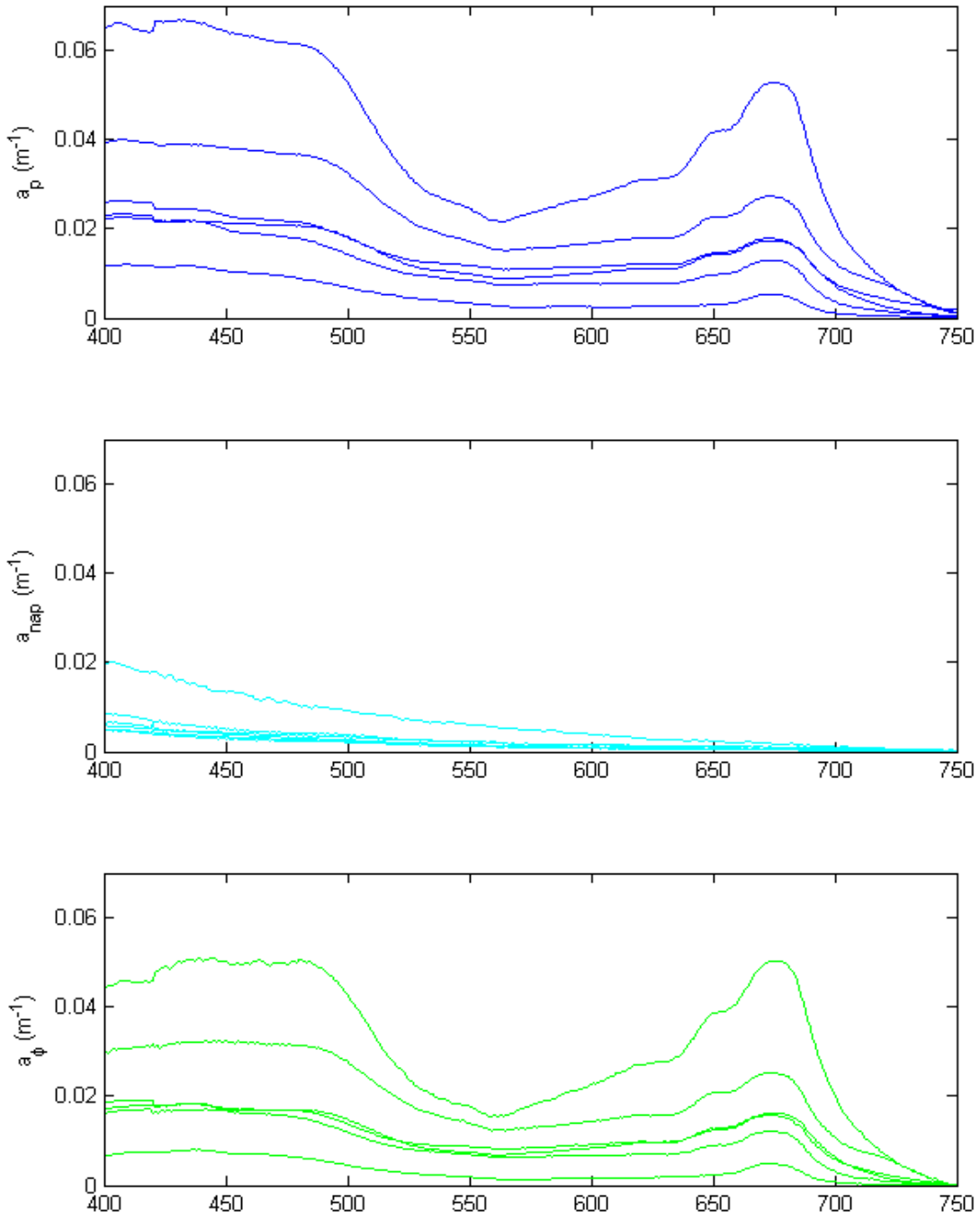


Fig. 20 Measured particulate (a_p), Detritus (a_{nap}) and phytoplankton absorption spectra (a_ϕ) at *Noctiluca* bloom station ($20^{\circ} 53.98'N$ and $66^{\circ} 10.18'E$) **F**

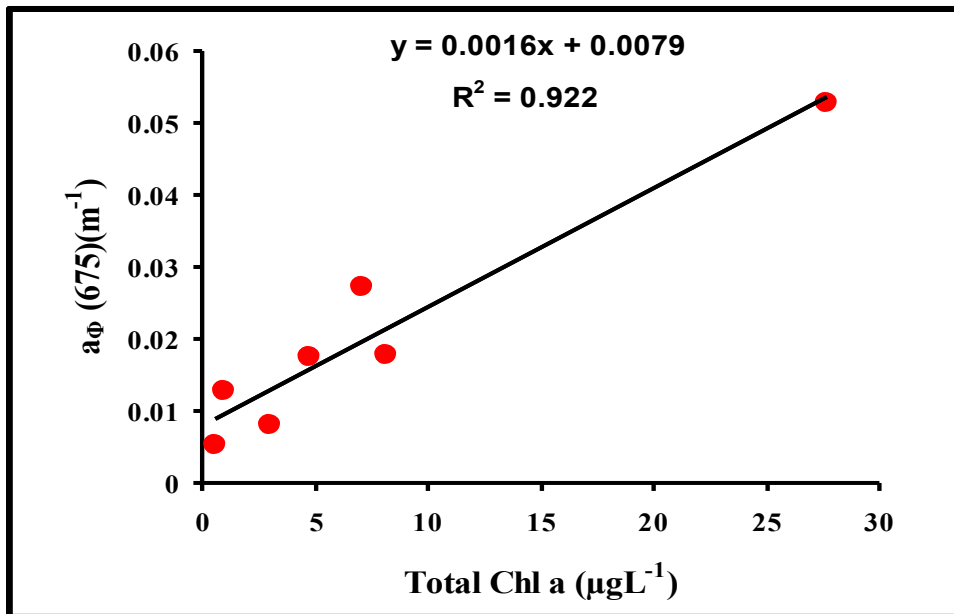


Fig. 21 Correlation between a_{ϕ} (675) and TChl a concentration at *Noctiluca* bloom station 20⁰ 53.98'N and 66⁰ 10.18'E.

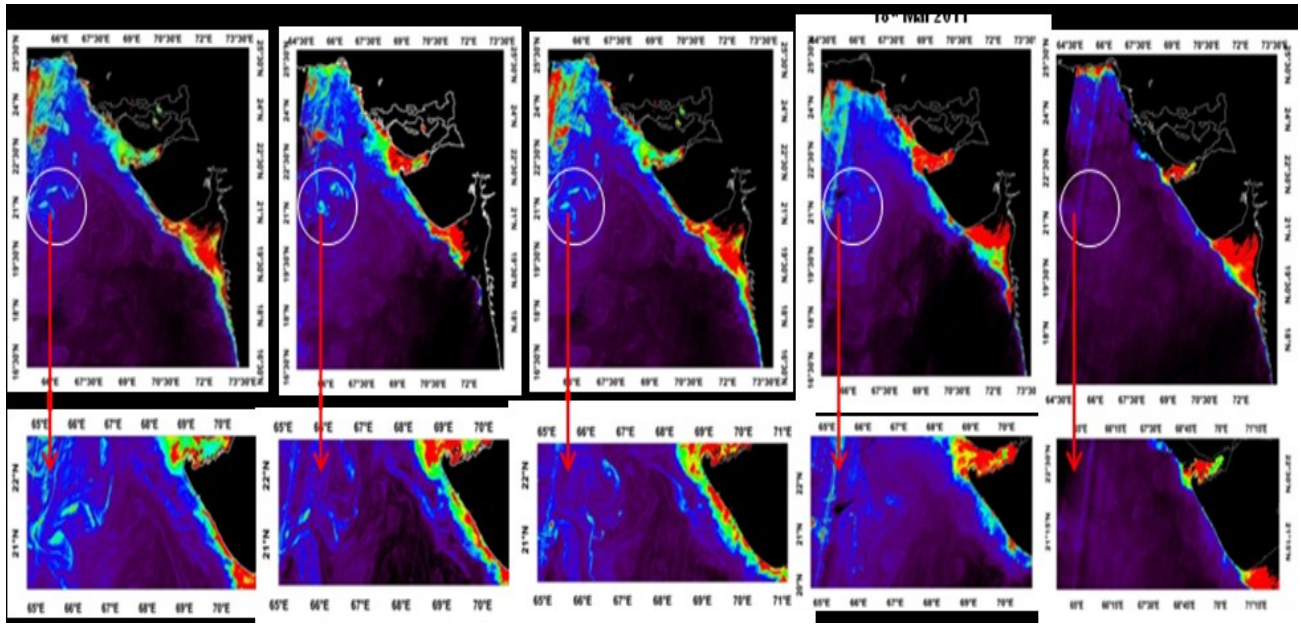


Fig. 22 Detection of *Noctiluca miliaris* bloom area in NAS using OCM-II images in the NAS during receding phase of Mar-2011.

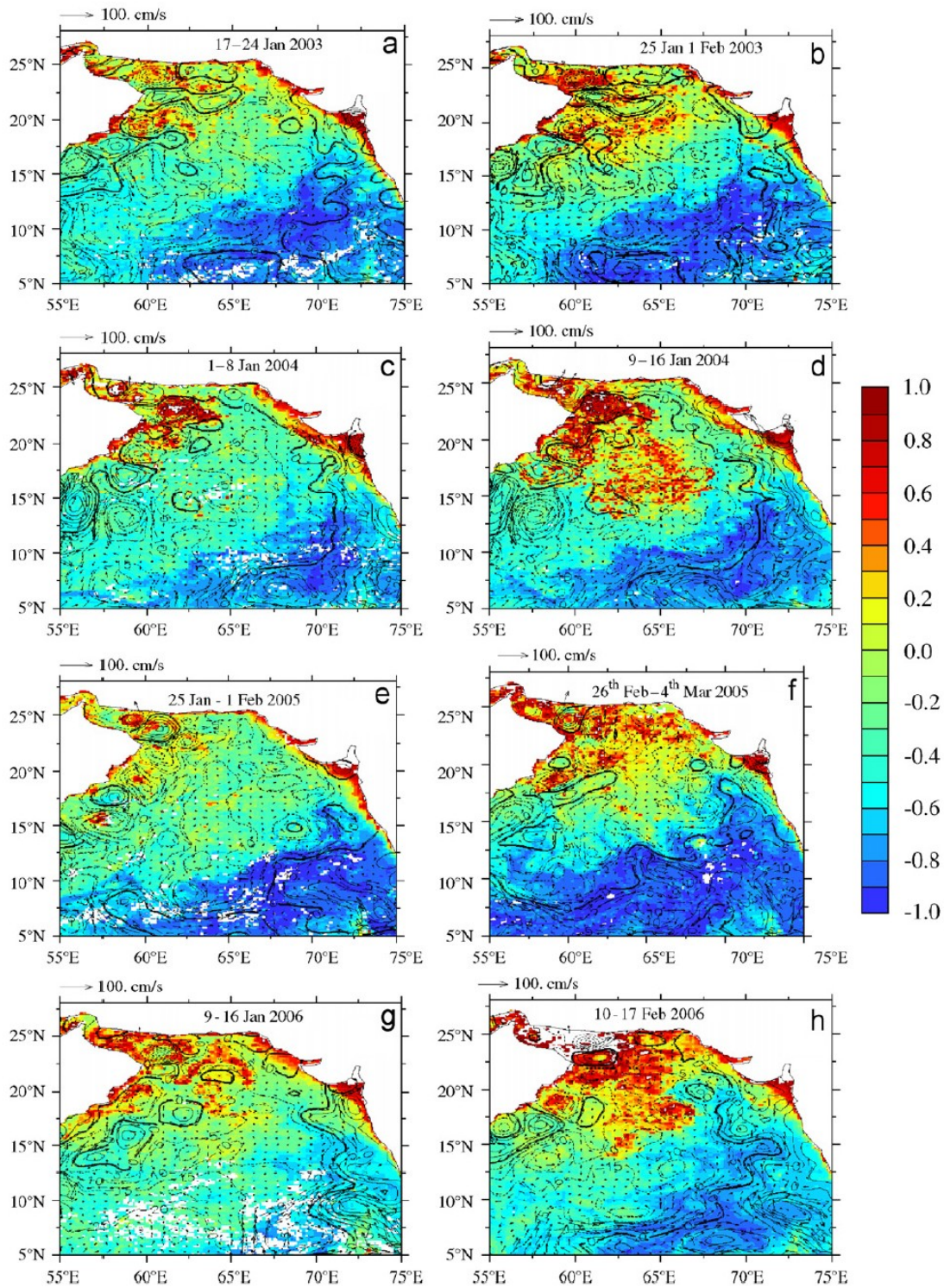


Fig. 23 (a–h) Weekly SeaWiFS and MODIS-Aqua Level-3 merged satellite chl *a* images from 2003–2006. The color bar denotes chl *a* in log scale.

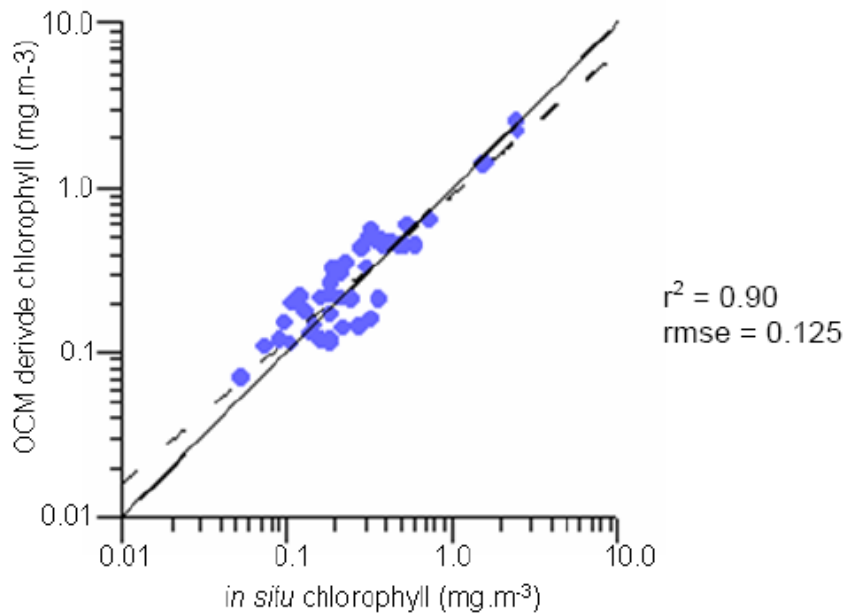


Fig. 24 Match-up analysis of in-situ Chl *a* from bloom area with OCM-I derived Chl *a* from the dinoflagellate green *Noctiluca miliaris* bloom of the Northern Arabian Sea during Feb-March

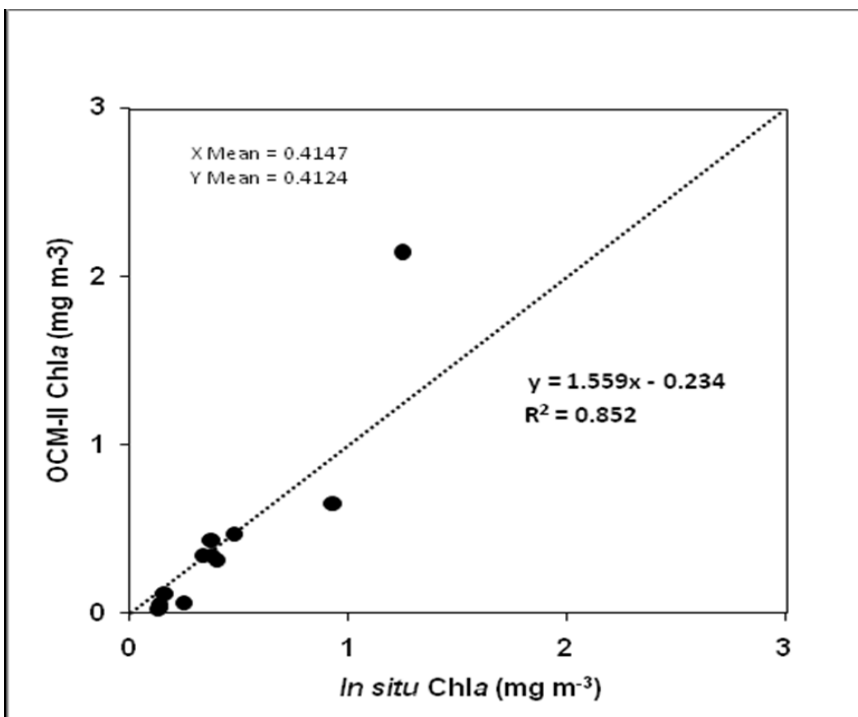


Fig. 25 Match-up analysis of in-situ Chl *a* from bloom area with OCM-II derived Chl *a* from the dinoflagellate green *Noctiluca miliaris* bloom of the Northern Arabian Sea during 2010-2011.