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Remote sensing of evolution and coupling of green *Noctiluca* and diatom blooms in the northern Arabian Sea using value-added time-series products

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Original Article

Abstract

Bloom of the dinoflagellate, *Noctiluca scintillans*, appears in the form of a green tide in the Northern Arabian Sea covers a large area of the basin between west coast of India and Oman. It is known to occur during winter-spring and is reasonably persistent on time scale (January-March). Moreover, it is found that the bloom is not mono-species one and more exactly is concurrent with diatom. These blooms have been sampled at various stages by the Indian research vessels from 2003 onwards. *Noctiluca scintillans* can be identified by SeaWiFS or MODIS chlorophyll images due to high chlorophyll pattern associated with it. However, generalized algorithm for chlorophyll retrieval breaks down in presence of the algal bloom and provides unrealistic estimates of chlorophyll. Besides this, the chlorophyll images do not reveal phytoplankton species/group level information. To enable this, an approach was developed and validated for detection of the bloom forming algae *Noctiluca scintillans* and its discrimination from diatom in a mixed species environment using ocean colour data of MODIS-AQUA. Spectral shapes of the reflectance spectra were used for the species identification. This paper highlights detection of onset (evolution) of the bloom and study of its spatial and temporal variations at species/group level using remote sensing. Capability of optical detection of the species from space has been used in generating a time-series images for this purpose. Green *Noctiluca* was found associated with extremely high levels of phytoplankton, which influenced its abundance. In addition, observations from the time-series also pointed towards feeding behaviour of *Noctiluca scintillans* and its coupling with diatom. The two were found to be out of phase and revealed a time lag, *Noctiluca scintillans* being successor of diatom.

Keywords*: Remote sensing, Northern Arabian Sea, N.scintillans diatom coupling, Inter annual variability.*

Introduction

Ever since the launch of Indian satellites Oceansat 1 and 2 that carried Ocean Colour Monitor (OCM), time series chlorophyll images were generated for fishery application. OC-2, an empirical algorithm (O'Reilly *et al.*, 1998) was used to estimate chlorophyll from Oceansat /OCM data. The algorithm uses a third degree polynomial of 490:555 nm band ratio of remote sensing reflectance to retrieve chlorophyll. Temporal pattern of chlorophyll retrieved from OCM data of February-March, 2000 revealed unusually high concentration of chlorophyll in the Northern Arabian Sea (NAS) along 19°-22° N latitude belt. This area represents oceanic waters in the central part of the NAS at depths typically greater than 2500 m. The phenomenon of increased productivity in the NAS has been described as winter bloom and it develops as a result of convection of water masses in a column (Banse and McClain, 1986; Banse, 1987 and Prasanna Kumar *et al.*, 2000). Though generalized algorithm for chlorophyll retrieval (like OC-2) breaks down in presence of the algal bloom it was possible to infer presence of the bloom with signature of elevated chlorophyll level from the satellite images. Subsequently, a ship cruise was conducted in March 2003 to confirm the inference drawn from satellite observations about presence of the bloom. Phytoplankton analysis of water samples indicated presence of green tide of dinoflagellate, *Noctiluca scintillans* (*N. scintillans* (is the scientific form) or *Noctiluca miliaris*), in the oceanic waters (Matondkar *et al.*, 2004). *N. scintillans* is characterized by the presence of the symbiotic Pedimonas *Noctiluca*e. This organism shows a predominantly green discoloration due to the presence of high chlorophyll b along with chlorophyll a. Multi date chlorophyll images revealed that the bloom persists for significantly long period, initiating by January and lasting till middle of March. It was also realized that north-easterly trade winds accelerate cooling of surface waters through evaporation, which gives rise to convective motion of the water mass. It causes vertical transport of nutrient rich bottom waters to euphotic zone (Dwivedi *et al.*, 2008). The bloom was sampled at various physiological stages with the help of Indian research vessels, FORV *Sagar Sampada* and ORV *Sagar Kanya*, from 2003 onwards. Ship observations indicated that the bloom detected from satellite chlorophyll images was not mono-species in nature and the two dominating species were *N. scintillans* and diatom. Though this bloom could be easily identified from satellite chlorophyll images due to prominent chlorophyll pattern associated with it, they did not provide species level information and also discrimination between *N. scintillans* and diatom was not possible. In view of this, an approach was developed for detection of the bloom forming algae *N. scintillans* and its discrimination from diatom in a mixed species environment using MODIS-AQUA data (Dwivedi *et al.*, 2015). It makes use of species-specific response of phytoplankton from remote sensing reflectance spectra obtained with Satlantic™ under water profiling radiometer. It was realized that spectral shape, *i.e.* the optical response was different for bloom waters as compared to the same in non-bloom waters. Subsequently, the identification criteria were developed and implemented on MODIS-Aqua data. Scatter of points representing different phytoplankton classes on a derivative plots revealed four diverse clusters, *viz. N. scintillans*, diatom, non-bloom oceanic and non-bloom coastal waters. Validation of the approach of recognizing species from satellite data was performed using phytoplankton classes identified from water samples collected during a ship cruise in March 2013. Time-series phytoplankton species images were generated from MODIS data using the technique developed for the value-added product. This paper discusses the results obtained from the interpretation of satellite species images. A set of such images provides knowledge of spatial distribution of diatom and *N. scintillans* across the season. Capability of species identification also facilitated detection of onset (*i.e.* first appearance of the signature) of diatom as well as *N. scintillans* from the satellite images. Subsequently, the study was extended to understand coupling between diatom and *N. scintillans*. It was found that diatom develops initially in the northern basin with arrival of nutrient-rich waters in euphotic zone from deeper depths due to convection. When diatom concentration is increased sufficiently; it supports *N. scintillans*. Details including time lag between the two species have been presented in the sections to follow.

Material and methods

Ship cruises were conducted during January-March 2001-2012 in the study area as shown in Fig. 1A. Spectral upwelling radiance and down welling irradiance were recorded using profiling under-water radiometer in 350-800 nm calibrated range. Remote sensing reflectance was computed using these two parameters and Pro Soft software. The profiling radiometer was deployed at all stations during the noon period near synchronous to MODIS over pass. Water samples were collected corresponding to optical measurements in the bloom as well as non-bloom waters and were analyzed to measure phytoplankton concentration ($mg.m^{-3}$), cell density ($cells.l^{-1}$) and species identification (*N. scintillans* and diatom).

Satellite data processing

MODIS-Aqua Level-3 HDF data (derived geophysical variables; sea surface temperature (SST) chlorophyll and R_{rs} (remote sensing reflectance)) in the form of 3 days, 8 days and monthly time averaged composite binned to 4 km were downloaded for the bloom period (January-March) through NASA Internet server: Ocean Colour Web (http://oceancolor.gsfc.nasa.gov/). The atmospherically corrected at-surface remote sensing reflectance (Rrs) band data were processed to generate time-series of phytoplankton species images using ERDAS / Modeler for January-March 2001-2015 period. The download data from the ocean colour site were in HDF format and were converted into band sequential image files using "import" function of ERDAS. Chlorophyll images were generated using Sea DAS image processing software. A time-series of phytoplankton species images was generated for the subset image using Rrs derivatives at 443, 488 nm and 531 nm and species-specific threshold. The technique of species identification classifies the marine waters in four categories, *viz. N. scintillans*, diatom, oceanic non-bloom and coastal non-bloom waters (Dwivedi *et al.*, 2015). A typical phytoplankton specie image is presented in Fig. 1B. Chlorophyll image for the corresponding date was downloaded from ocean color site and color coded using SeaDAS image processing package (Fig. 1A). Monthly scale species images were generated for the fifteen years satellite

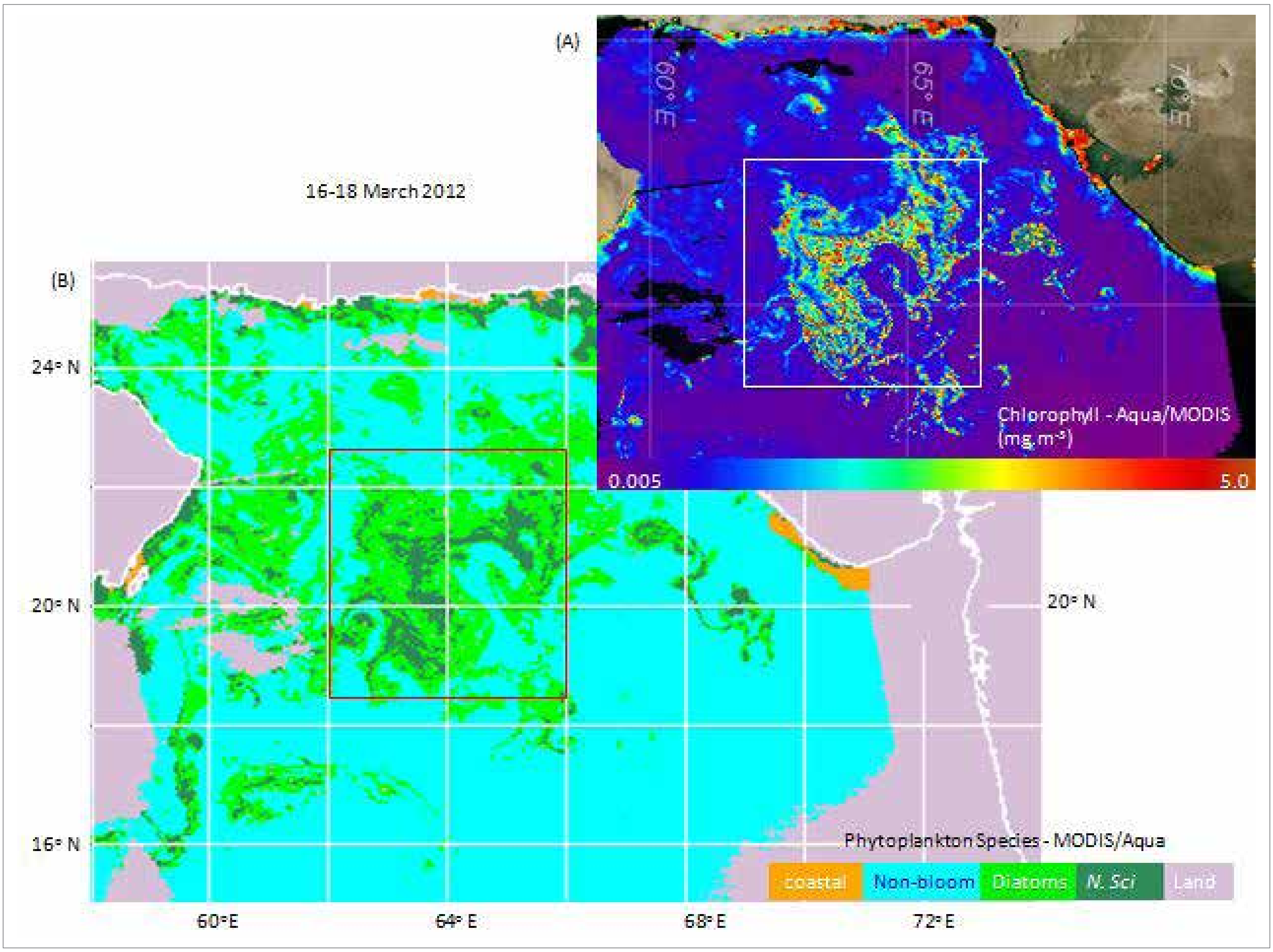


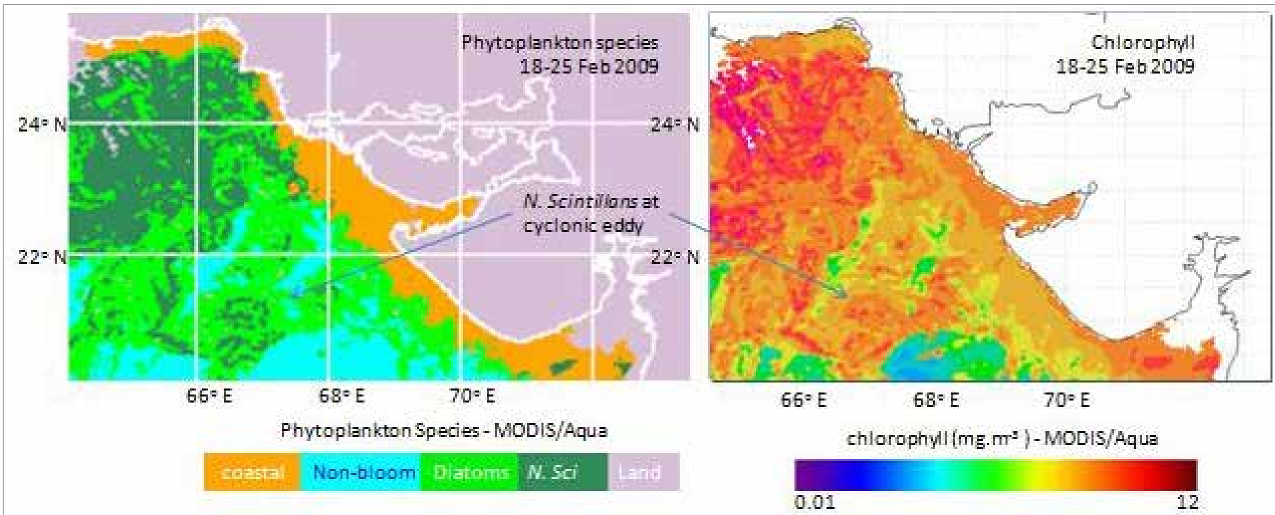
Fig.1. A typical chlorophyll image (16-18 March 2012) generated from MODIS data showing high chlorophyll patch, (B) corresponding phytoplankton species image

data to study the inter-annual variability of diatom bloom in the study area. February being active bloom period was selected for this purpose. Day time SST images were downloaded from the ocean colour site, which makes use of long-wave (11-12 μm) thermal radiation of MODIS.

Results and discussion

i. *N. scintillans* - diatoms - chlorophyll correspondence

Spatial distribution of *N. scintillans* and diatom in the Arabian Sea can be seen in Figure 1B, a typical active bloom illustration. This image was generated using spectral derivatives computed using 3-days composite MODIS-AQUA data of 16-18 March 2012. Dark green patches of *N. scintillans* can be seen in vicinity of diatom (light green) surrounded by non-bloom oceanic waters (cyan). Signature of *N. scintillans* within a marked box is associated with relatively higher levels of chlorophyll (Fig. 1A). A similar pattern of *N. scintillans* corresponding to high chlorophyll can be seen in Fig. 2. Formation of *N. scintillans* bloom due to cyclonic eddy is revealed with the arrows in this figure. A ship cruise with ORV *Sagar Kanya* SK-256 was conducted during this period (February 2009). Water sample analysis confirmed *N. scintillans* bloom at the eddy location (21° 05´ N, 66° 45´ E) with high cell density (19600 cells.l^{-1}) and relatively lower density of diatom (860 cells.l^{-1}). *In situ* chlorophyll measured high (27.7 mg.m^{-3}) here. Resembling observation of development of *N. scintillans* in the cyclonic eddy was made during another cruise *Sagar Sampada* SS-314 in March 2013 also. This observation, "*N. scintillans*-high chlorophyll", from Figures 1 and 2 provides an indication that *N. scintillans* might prefer high chlorophyll. In order to confirm this, an exercise was conducted to determine chlorophyll ranges for *N. scintillans* and diatom. Ship data of 85 stations from 12 years' ship cruises (January-March, 2001-2012) in the oceanic waters of Northeastern Arabian Sea (NEAS) were pulled together to investigate whether the correspondence as described above did exist. It was noticed from the *In situ* data that chlorophyll measured at various *Noctiluca* stations was in a range 2.4 - 27.7 mg.m^{-3}, for diatom this was 0.4 - 2.9 mg.m^{-3}. Preference of *N. scintillans* for high chlorophyll levels can be explained with respect to its



Ship cruise (18F 09) Bloom station at 21° 05' N, 66° 45' E	Phyto species image reveals *N. sci.* (dark green) (*N. scintillans* : 19600 cells.l⁻¹, diatom: 860 cells.l⁻¹)	Chl / MODIS reveals cyclonic eddy (chl at the center = 27.7 mg.m⁻³)

N = 85	chl (min) mg.m⁻³	chl (max) mg.m⁻³	Ship data from NEAS, off shore waters within the Indian EEZ for Jan – March period
Diatoms	0.4	2.9	
N. Scintillans	2.4	27.7	
non-bloom oceanic	0.15	0.9	

Fig. 2. A set of chlorophyll and phytoplankton species images (18-25 February 2009) generated from MODIS data

feeding behaviour. Diatoms are autotrophs and flourish when conditions (nutrients and light) in the upper mixed layer are favourable. Relatively higher rates of primary production were observed in the NEAS during winter (January-March), which are supported by the process of convection-induced nutrient enrichment (Dwivedi *et al.*, 2008). Thus, diatoms do not require high concentration of chlorophyll to flourish. Unlike diatom, *N. scintillans* is a heterotroph (non-photosynthetic) and voraciously feeds on phytoplankton. Barbara Van Mol *et al.* (2007) have mentioned that *N. scintillans* feeds on particles, mainly diatoms, and its growth requires large amount of food suggesting that its nature may be limited by food availability. Some more studies have also shown that *Noctiluca* requires a relatively high quantity of its phytoplankton prey to support optimal growth (Lee and Hirayama, 1992; Kiorboe and Titelman, 1998; Kiørboe, 2003 and Miyaguchi *et al.*, 2006). Reference of Luciana de Souza Cardoso (2012) also can be traced, which mentions about need for a rich food supply for *Noctiluca* to reproduce massively. Also, laboratory studies have reported high growth rates of *N. scintillans* on pure diets of diatom (Buskey, 1995). In this study, we have realized the association of *N. scintillans* and diatom to specific ranges of chlorophyll with the help of ship data collected over twelve years in the NEAS. It means that chlorophyll images can be used as a proxy to species product to infer the species as a first-cut approximation. However, it should be kept in mind that the species-specific chlorophyll ranges were obtained from *In situ* measurements and are not applicable to satellite derived chlorophyll. Generalized algorithms for chlorophyll retrieval use reflectance band ratios are developed for Case1 waters where phytoplankton (chlorophyll-a) is a dominating constituent, usually <1 mg.m^{-3}. They break down in optically complex waters (David *et al.*, 2014, Shen *et al.*, 2012). Pigment compositions, shape and size for different phytoplankton types are different (IOCCG, 2000), which alter its inherent optical property, especially absorption co efficient. This affects retrieval of phytoplankton from satellite data. Also the band-ratio algorithms are empirical in nature and hence, region specific (Sathyendranath *et al.*, 2001; Dierssen and Smith, 2000). Morel (1997) has mentioned that dominance of cyanobacteria within an algal assemblage can modify the optical properties of an oceanic water.

Satellite chlorophyll pattern can be used to infer the species as preliminary level information only if chlorophylls are retrieved using species specific algorithm.

ii. Detection of evolution (appearance) and decay (disappearance) of *N. scintillans* bloom using a time-series phytoplankton species images

It can be seen from the species time-series in Fig. 3 that diatom had developed by December end (18-25 Dec 2012) in the

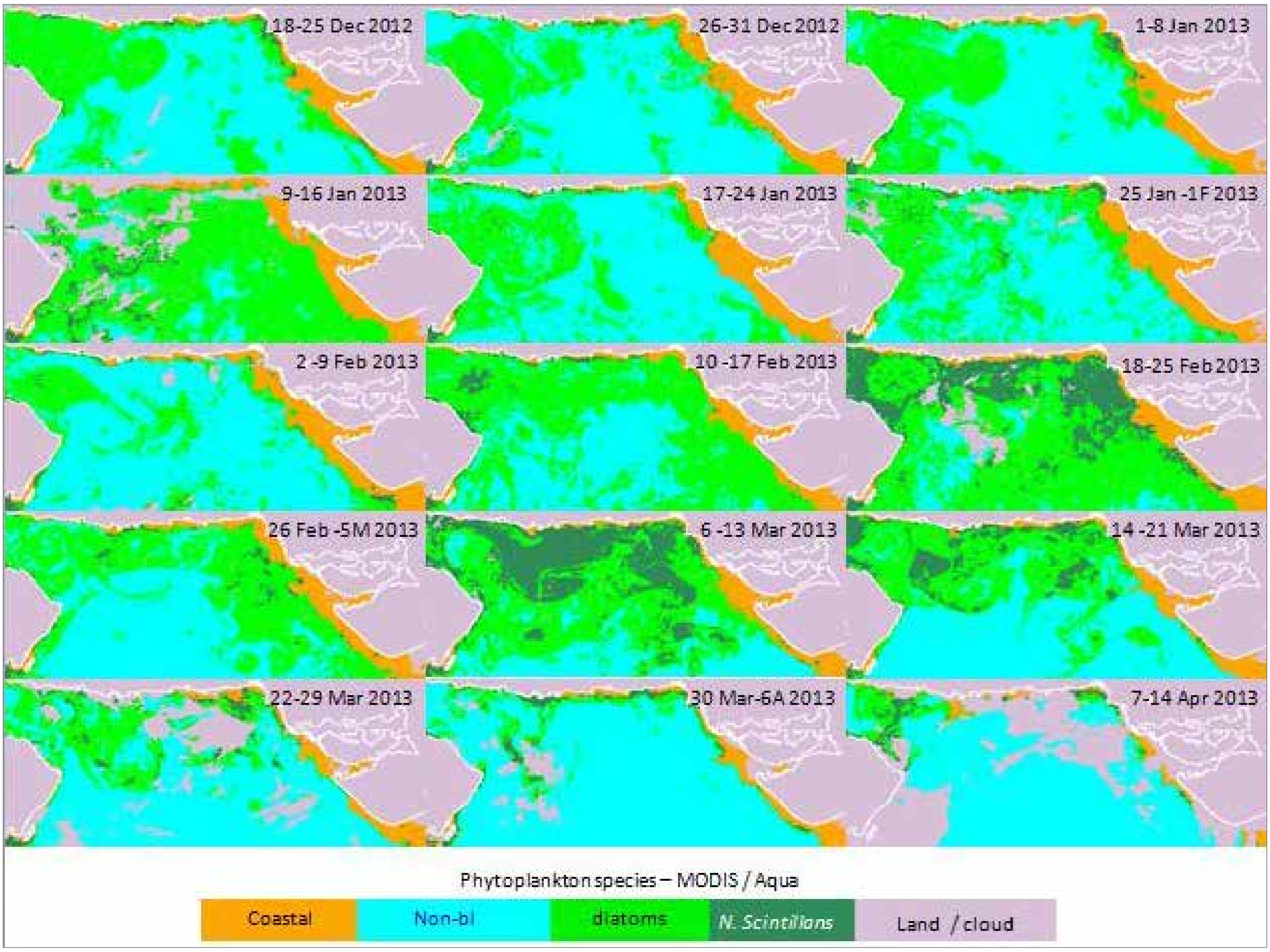


Fig. 3. Time-series phytoplankton species (December 2012 - April 2013)

Northwestern Arabian Sea (NWAS). This is seen as light green colour in the top left corner of the figure. No signature of diatom is seen in NEAS at this time. The diatom is seen dispersed in the next image (26-31 Dec 2012) and it developed again in first week of January (1-8 Jan 2013). Signature of *N. scintillans* can be seen (dark green colour) first time in the NWAS in the second week of January (9-16 Jan 2013). NEAS waters still reveal non-bloom class (cyan colour) in this image. Thus, surfacing of *N. scintillans* bloom occurs earlier in the NWAS as compared to the same in the NEAS.

Subsequent to development of *N. scintillans*, diatom is seen broken up in the next two images (17-24 Jan and 25jan-1Feb). It may be probably due to predation of diatoms by *N. scintillans* (confirmed later in this paper). Decrease in diatom spread due to depletion of nutrient can be ruled out as this is the season of active convection. Evolution of *N. scintillans* is seen again in the NWAS in second week of February (10-17 Feb 2013). The next image (18-25 Feb 2013) shows development of *N. scintillans* on both the sides (NEAS and NWAS) with increase of diatom. Development of *N. scintillans* reduces diatom spread (26 Feb - 5 Mar 2013) and ultimately *N. scintillans* also collapses. Diatom is seen to have picked up again in the next week (6-13 Mar 2013) and *N. scintillans* appears third time in the NWAS and second time in the NEAS. This is followed by decrease in extent of *N. scintillans* as well diatom on both the sides (14-21 Mar 2013 and time onwards).

It is noticed that *N. scintillans* occurs intermittently two to three times in the entire season depending on availability/ non-availability of prey (diatom). An early evolution of *N. scintillans* and diatom blooms in the NWAS (December-January) can be explained with reference to the temporal profile for SST generated from MODIS data as shown in Fig. 4. Every point on the plot represents average SST for the windows in NEAS and NWAS waters as shown in the figure. It can be seen that waters of the NWAS are cooler all the time during winter as compared to the same on eastern side. Cooling (SST $< 25°C$) starts by early January in NWAS and also prevails longer (till middle of March). Secondly, rate of decrease of SST with time is higher in the NWAS (active convection) and the waters below 25°C persist longer on NWAS. Moreover, ASHSW (Arabian Sea

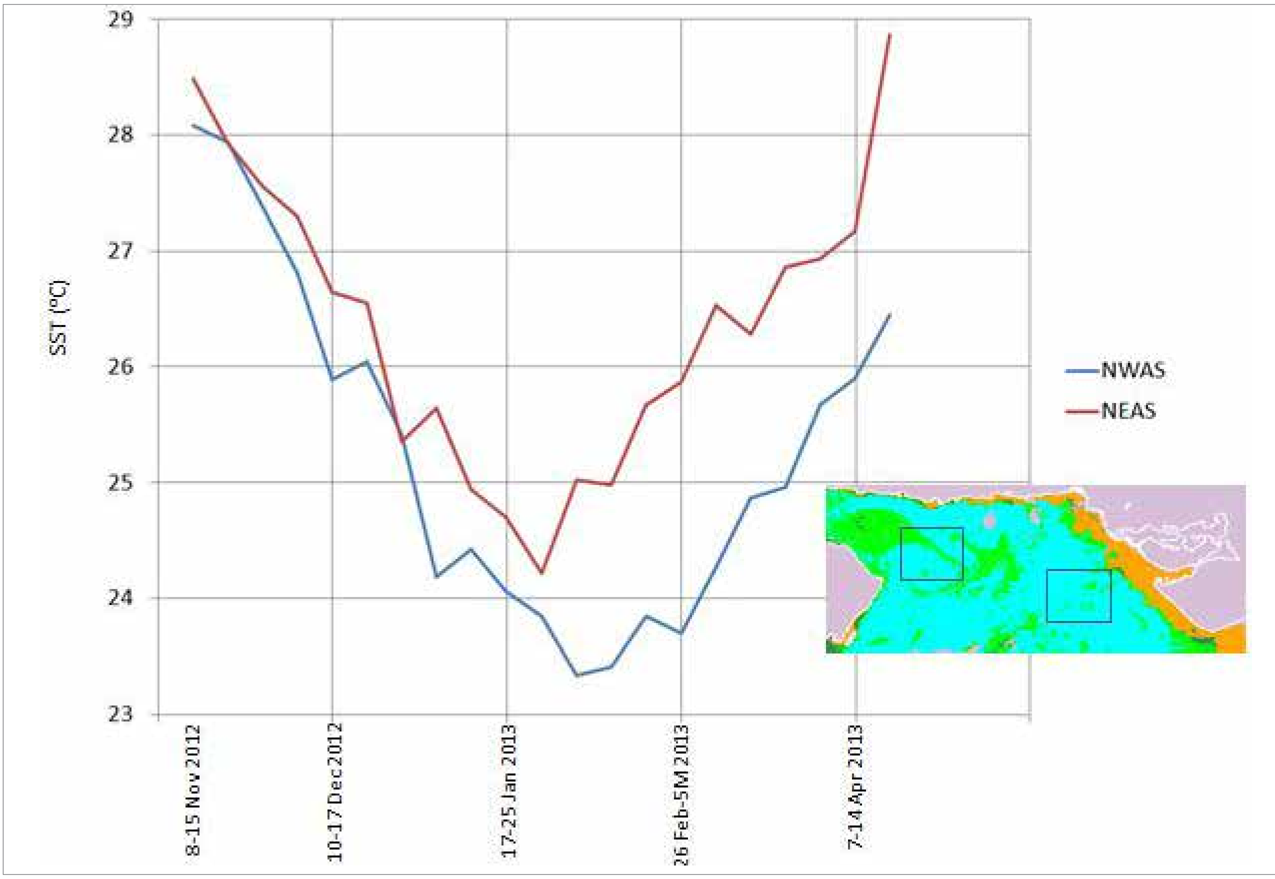


Fig. 4. Temporal variations in SST in NEAS and NWAS using MODIS data

high salinity water) forms in the Northwestern Arabian Sea during winter (Prasanna Kumar and Prasad, 1999). Extreme SST and salinity values prevail in the NWAS resulting in an increased density of the surface layer and correspondingly stronger convection.

Overall, the variations in species distribution across the season displays a pattern of appearance and disappearance of *N. scintillans* and diatom blooms in a sequential manner indicating predator-prey relation between the two.

iii. *N. scintillans* - diatom coupling

Graphical representation of a time-series presented in Fig.3 can be seen in Fig. 5. Logarithm of number of pixels under *N. scintillans* and diatom were computed from MODIS derived 8-days composite images. This has been plotted on time-scale from 3 Oct -7 Nov 2012 to 7-14 April 2013. It covers a span of entire winter bloom period. A window in top right corner of Figure 5 represents the area for which the number of bloom pixels was computed.

It can be seen from the figure that diatoms dominate over *N. scintillans* with respect to its spatial extent at any stage of the bloom. Initially, in the early season (November-December) diatoms develop due to onset of convection triggered by northeasterly monsoon winds and seasonal cooling (Dwivedi *et al.*, 2008). Abundance of diatom (number of cells in the window) is seen increasing continuously with arrival of nutrients in the euphotic zone due to prevailing convection. Also, increasing pattern of diatom can be attributed to lack of predation in absence of *N. scintillans*. This is shown by an area highlighted with blue colour in the figure. Number of pixels under *N. scintillans* is seen increasing from 1-8 Jan 2013 with availability of diatom in abundance and reaches to peak by 9-16 Jan 2013. As the *N. scintillans* peak develops, spatial extent of diatoms is seen decreasing sharply (till 2-9 February 2013). The cycle of increase in diatom leading to increase in *N. scintillans* and then collapse of both the species continues. In this context, Harrison *et al.* (2011) have mentioned that once *Noctiluca* becomes dominant, its active grazing is expected to prevent population growth of co-existing phytoplankton. This hypothesis of decreasing diatom abundance with increase in *N. scintillans* was verified by Zakaria and Mesaad (2007) in NWAS waters. They have mentioned about microscopic examination of live cells from

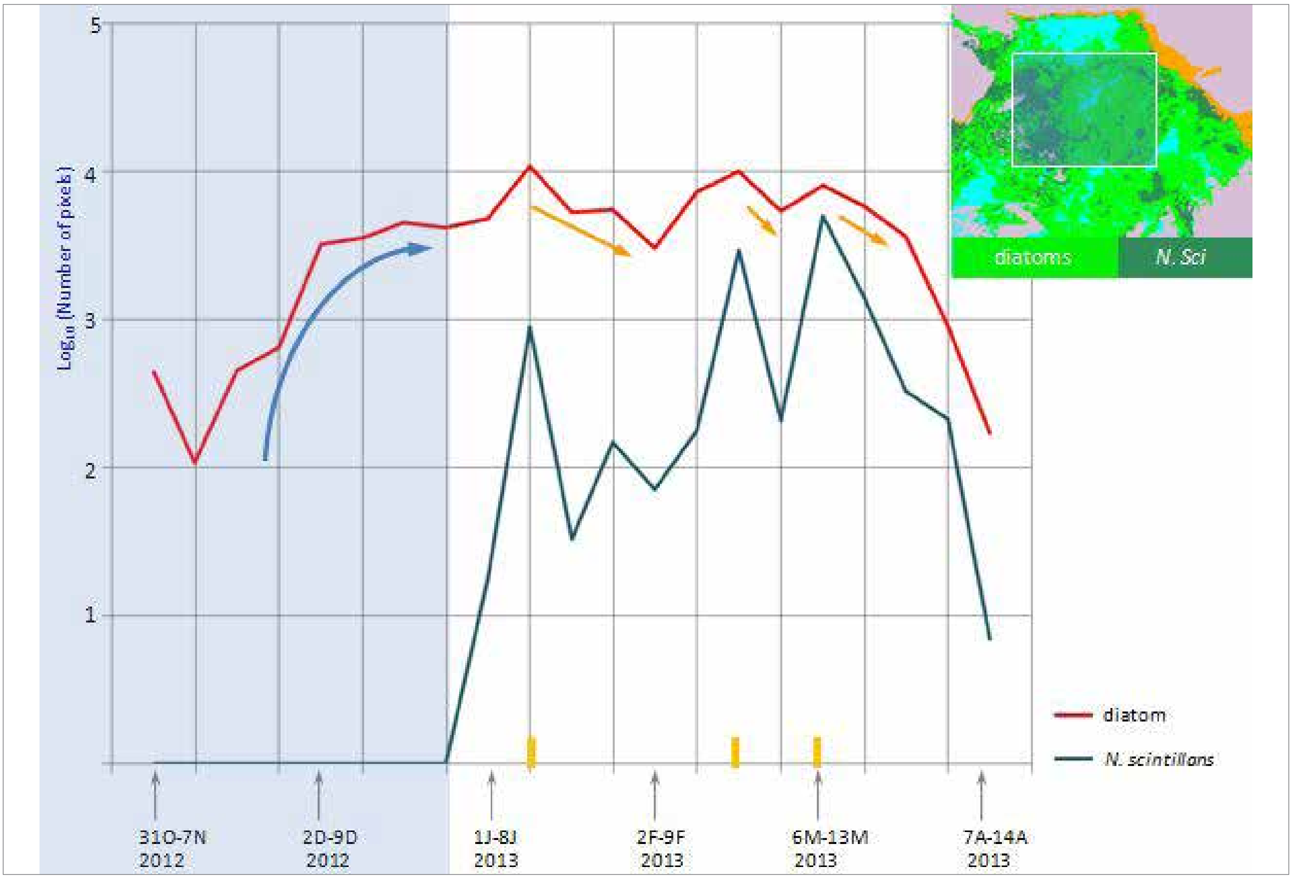


Fig. 5. Temporal variations in distribution of *N. scintillans* and diatom using 8 days composite MODIS data

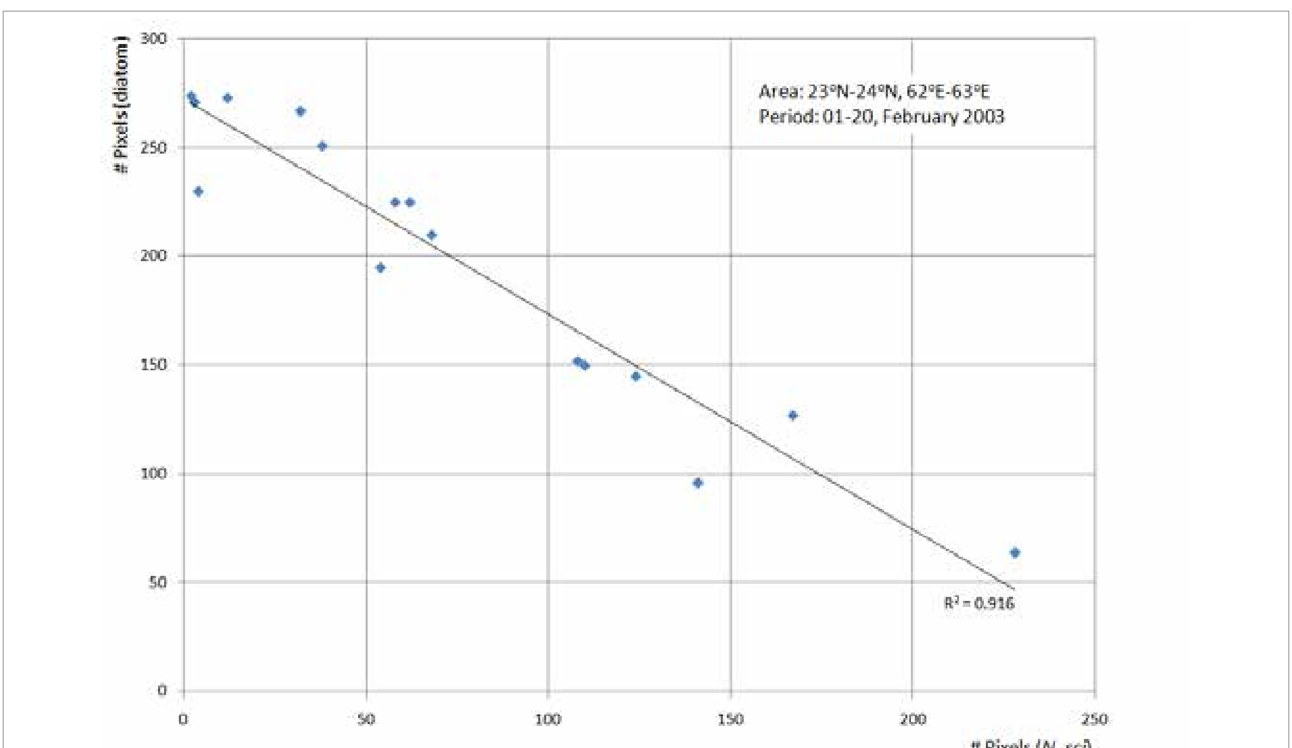


Fig. 6. Trend showing distribution of diatom and *N. scintillans* pixels

Noctiluca blooms, which showed presence of some species of diatoms and dinoflagellates within the *Noctiluca* body and it confirmed grazing of *N. scintillans* on these microalgae. In view of these references and the satellite observations, it is concluded that the abundance of *N. scintillans* is correlated negatively with all densities of diatoms. To further substantiate this, MODIS-Aqua data were processed to identify diatom and *N. scintillans* for the period 1-20 February 2003 at three days interval. Number of pixels for diatom and *N. scintillans* were plotted and an inverse correlation can be seen in Fig.6.

It also emerges from these observations that the two species under discussion are coupled and they occur in sequence in nature, diatom precedes *N. scintillans*. Kiorboe *et al.* (1998), Tiselius and Kiorboe (1998) and Dela-Cruz *et al.* (2003) have also reported that *N. scintillans* blooms were found to occur after diatom blooms. In our study, we have used a time-series species images generated from ocean color data to demonstrate this coupling.

iv. *N. scintillans* - diatom time lag

While Fig. 5 indicates coupling between *N. scintillans* and diatom and succession of *N. scintillans* to diatom, it does not provide information on time lag between the two species. It appears from the figure that rise and fall of *N. scintillans* and diatom occurs simultaneously. This plot was prepared using a time-series species images with 8 days composite (averaged) MODIS data and the details of actual evolution of each species could be lost. A new time-series for species was generated using 3 days composite MODIS data for the active bloom period (February) and the temporal profile representing the species abundance is shown in Fig. 7. A window shown at top right corner of the figure represents the active bloom area for which bloom pixels were counted for all the dates. It is obvious from the figure that *N. scintillans* and diatom are out of phase (as *N. scintillans* increases diatom decreases) indicating that diatom should be prey for *N. scintillans*. Dharani *et al.* (2004) have also reported a negative relationship between *Noctiluca* and other phytoplankton in the Indian coastal waters. A time lag between *N. scintillans* and diatom can be seen in Fig.7 and it seems to be about 3-4 days.

v. Inference of feeding behaviour of *N. scintillans* using remote sensing

Phytoplankton species images were generated using three

Fig. 7. Temporal variations in distribution of *N. scintillans* and diatom during active bloom period using 3 days composite MODIS data

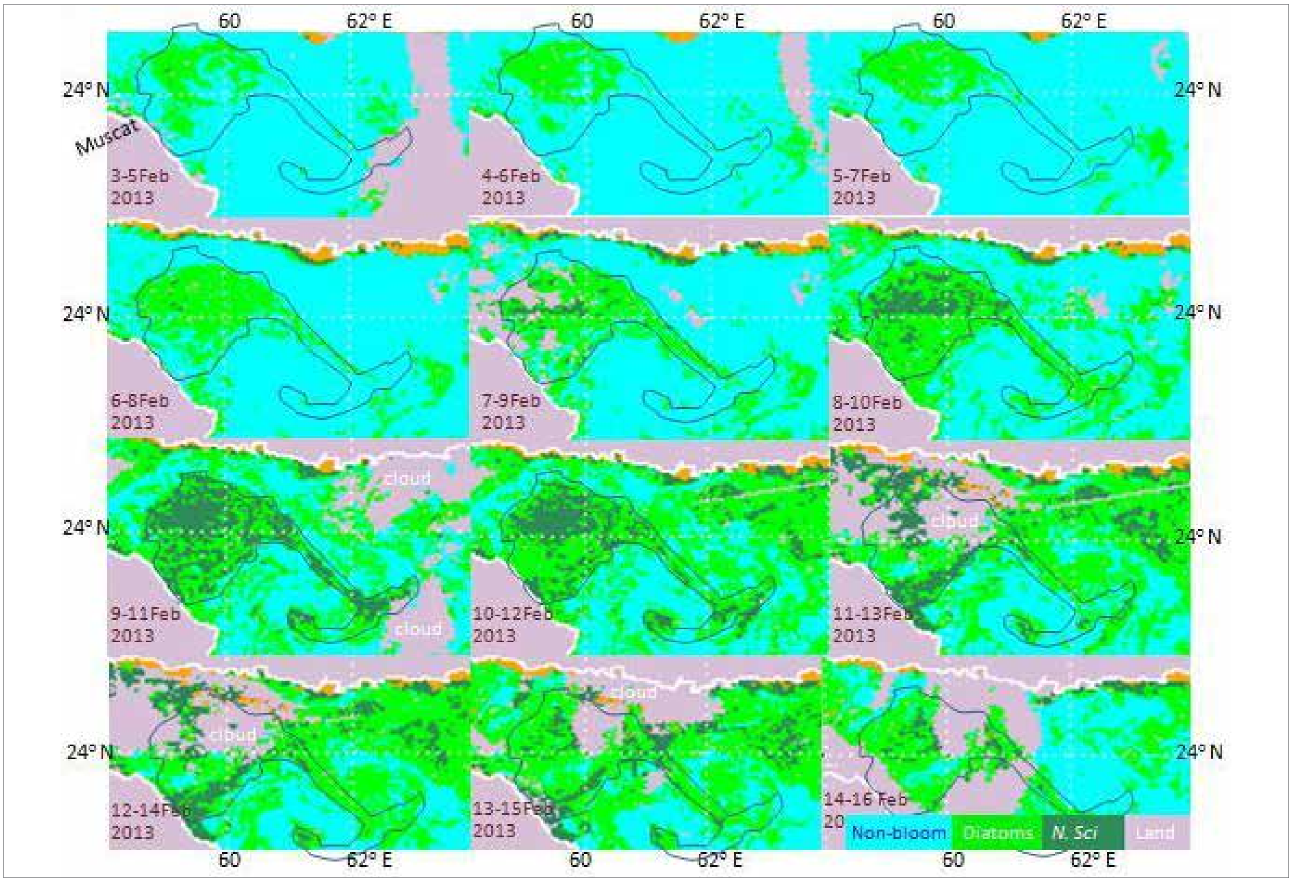


Fig. 8. Time-series of phytoplankton species images for NWAS at 1 day interval using MODIS data

days composite MODIS data at one day's interval from 3-5 February to 14-16 February 2013. This can be seen in Fig.8. High productivity water mass dominated by diatom (off Muscat, Gulf of Oman) can be seen bifurcating and forming eddy. This is a common structure in the time-series and is delineated to facilitate observation of change detection. The structure can be seen fully developed with diatoms cells in 6-8 February 2013 image. *N. scintillans* is noticed replacing diatom in the next two images and the diatom is almost fully overtaken by *N. scintillans* in 9-11 February 2013 image. A matching pattern of diatom and *N. scintillans* is observed with time delay of three days. It shows that *N. scintillans* grows efficiently where diatoms are there because the prey is available, then, it is logical to think that *N. scintillans* feeds on diatom. This has been demonstrated using remote sensing data and without gut content analysis of *Noctiluca* cell. The time-series in the figure also brings to notice that diatom emerges first and population of *N. scintillans* succeeds the bloom of diatom.

vi. Inter-annual variability

Noctiluca and diatom pixels were computed for active period of the bloom (18-25 February) for different years as shown in Fig.9(A). A window shown in the corresponding species image adjacent to this plot represents the area considered for counting number of bloom pixels. It is evident that diatom dominate over *N. scintillans* over all. Also, diatom and *N. scintillans* are out of phase. Total number of bloom pixels (sum of *N. scintillans* and diatom) for the entire season, January to March, is plotted for different years in Fig.9 (B) and adjacent image is monthly averaged species distribution for February 2015. It can be seen from both the plots Fig.9 (A) and (B) that there is no increasing trend of the bloom with respect to its spread (areal extent) over a period more than a decade. The bloom expands and shrinks across the years and the variations are cyclic in nature.

Coupling between diatom and *N. scintillans*, *N. scintillans* succeeds diatom and time lag between the two have been substantiated using remote sensing. A negative correlation between *N. scintillans* and diatom pixels was observed using the satellite species images. Time-series of species images revealed two to three cycles of increasing and decreasing *N. scintillans* and diatom across the season. And hence, it is anticipated that the technique developed for species identification using

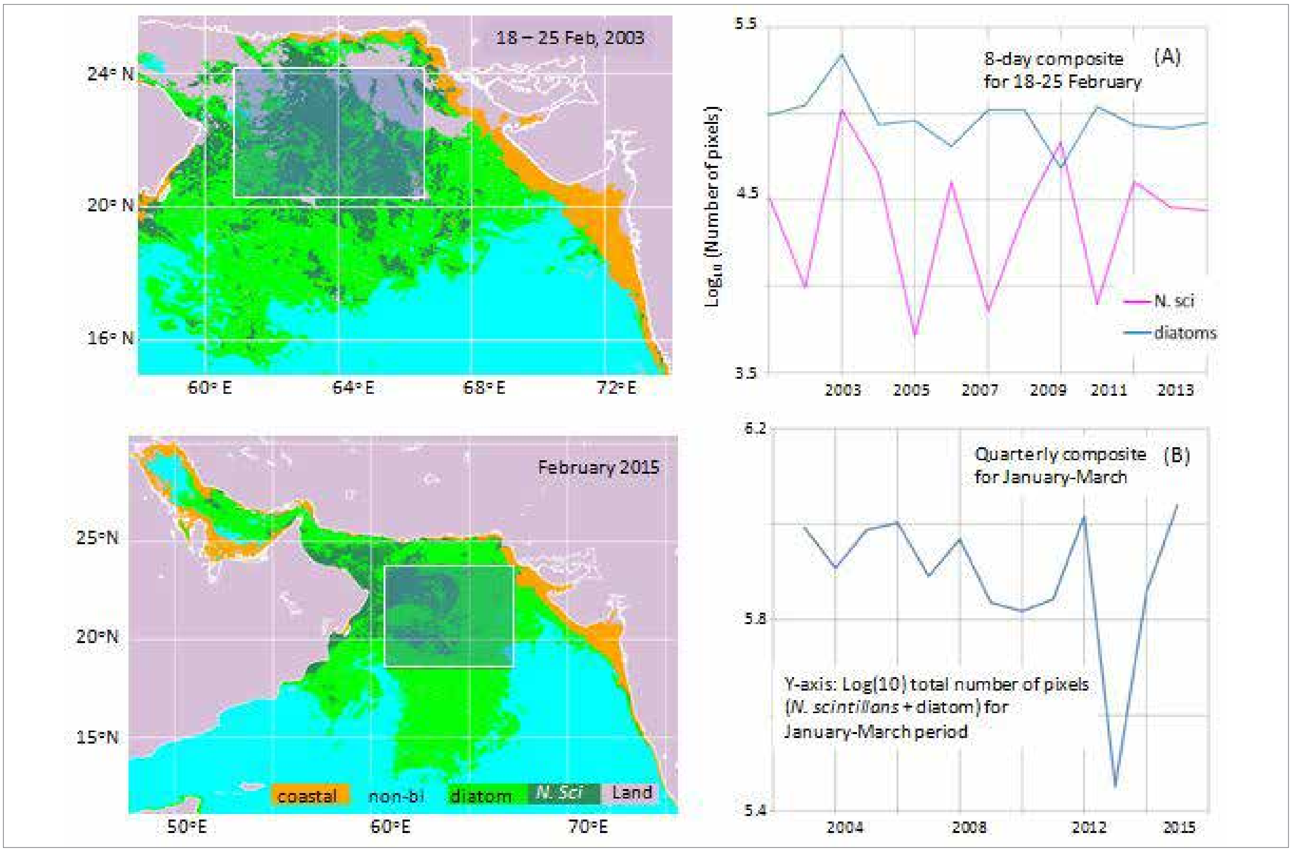


Fig. 9. (A) Inter-annual variability in *N. scintillans* and diatom for active bloom period (18-25 February) (B) Over all inter-annual variability in *N. scintillans* and diatom for January-March period

MODIS data has potential for its use in monitoring the NAS/ winter bloom at operational level.

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