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Study of spatial-temporal variations in the green *Noctiluca scintillans* and diatom blooms in the Arabian Sea using MODIS data

by

R. Dwivedi, Aneesh Lotlikar, T. Srinivasa Kumar and S.S.C. Shenoi

Indian National Centre for Ocean Information Services (INCOIS)
Earth System Science Organization (ESSO)
Ministry of Earth Sciences (MoES)
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Author(s) [Last name, First name]: R. Dwivedi, Aneesh Lotlikar, T. Srinivasa Kumar and S.S.C. Shenoi

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Abstract (100 words)

Phytoplankton blooms of green *Noctiluca scintillans* (a dinoflagellate) and diatom, which appear in the Northern and Central Arabian Sea during winter are far-reaching and persistent. Generation of phytoplankton species images revealed a massive winter bloom with huge spatial extent in 2015. In contrast to this, the classified species images for 2013 indicated relatively weaker bloom with respect to its spread. A plot of total number of pixels classified as diatom and *Noctiluca scintillans* for different years revealed a cyclic pattern of the spread. The report deals with an approach to forecast the bloom / productivity of the oceanic waters in the Northern-Central Arabian Sea in a qualitative way making use of the systematic pattern of its distribution across the years.

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ABSTRACT

Phytoplankton bloom of *Noctiluca scintillans* (a dinoflagellate), which appears in the form of a green tide in the Northern Arabian Sea covers a large area of the basin between the west coast of India and Oman coast. A recent study has indicated that the high productivity waters develop in the Central Arabian Sea also and even beyond. This far-reaching bloom occurs during winter-spring and is reasonably persistent on time scale (January-March). Moreover, it is observed that the high productivity event is not a mono-species bloom and more exactly *Noctiluca scintillans* is concurrent with diatom. These blooms were sampled at various stages by the Indian research vessels from 2003 onwards. The ship data spread over ten years were used to develop an approach for species identification of the bloom using satellite data. The approach identifies the bloom forming algae *Noctiluca scintillans* and discriminates it from diatom in a mixed species environment using 445, 488 and 531nm bands of MODIS-AQUA. Generation of multi-year phytoplankton species images revealed a massive winter bloom with huge spatial extent in 2015. In contrast to this, the classified species images for 2013 indicated relatively weaker bloom with respect to its spread. Subsequently, a time-series of species images was generated for 2013 and 2015 to study spatial and temporal variations of the bloom at species/group level using ocean colour data from MODIS. Further to this, 2013-15 time series was extended for all the available MODIS data from 2003 to 2015. Capability of optical detection of the species from space was applied for quantifying spatial extent of the bloom. A plot of total number of pixels classified as diatom and *Noctiluca scintillans* for different years revealed a cyclic pattern of the spread. The report deals with an approach to forecast the bloom / productivity of the oceanic waters in the Northern-Central Arabian Sea in a qualitative way during winter making use of the systematic pattern of its distribution across the years.

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^o-22^o 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. A ship cruise, first in the series, 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* (here after *N. sci* (is the scientific form) or *Noctiluca miliaris*), in the oceanic waters (Matondkar et al., 2004). Green *Noctiluca* holds autotrophic symbiont *Pedinomonas noctilucae* (prasinophyte) to meet its food requirement. 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 a 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. sci* and diatom. Diatom being the preferred food for *N. sci*, it is often seen succeeding the bloom of diatom (Harrison et al. 2011). These algal blooms cover an extensive area of the basin between west coast of India and Oman. In recent times, it has been noticed that development of these blooms is not confined only to the Northern Arabian Sea but also takes place in the Central Arabian Sea (Dwivedi et al. 2016). 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. sci* and diatom was not possible. In view of this, an approach was developed for detection of the bloom forming algae *N. sci* 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^{TM} 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. sci*, 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. Generation of multi-year phytoplankton species from quarterly averaged remote sensing reflectance band data revealed a cyclic pattern of abundance of algal bloom with reference to the spatial extent. This study puts forward possibility of forecasting this bloom making use of its peculiar pattern of inters annual variance. MODIS-derived species images reflected an acute bloom of *N. sci* and diatom in 2015 covering a large area extending from extreme north of the basin up to at least 15 degree north cross latitudes. A comparison of this magnitude of spread with previous years indicated a contrasting pattern. In 2013, spatial extent of the waters under influence of bloom was limited to small scattered patches indicating a weak bloom year. Going back in time, looking at MODIS data of 2012 revealed yet another massive bloom appearing like the one found during 2015. Signature of these strong blooms (2012, 2015) and weak bloom (2013) can be seen in the species images in Figure 1.

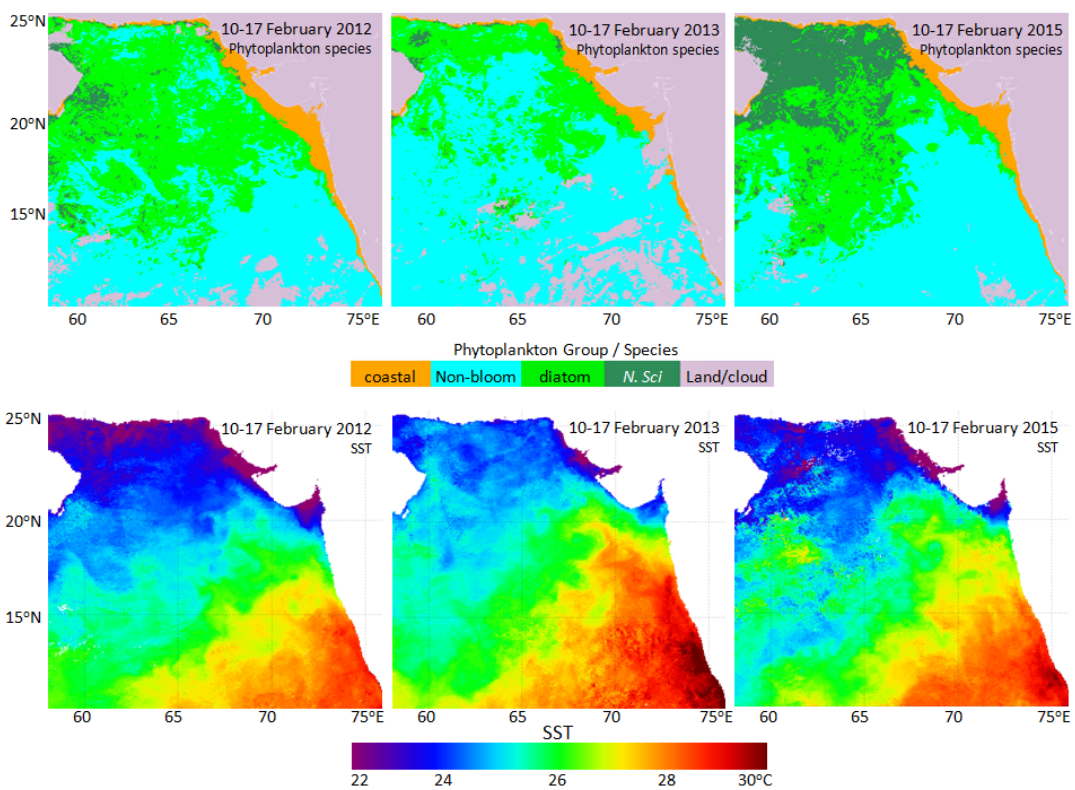

Figure 1. Inter-comparison of spatial extent of the winter bloom and SST for 2012, 2013 and 2015

SST images corresponding to the species images in the figure display a pattern of overall cooler waters during strong bloom years as opposed by relatively warm waters in patchy bloom condition.

Data analysis and methods

In situ measurements

Ship cruises were conducted using research vessels of the Ministry of Earth Sciences during November-April 2001–2012 in the oceanic and coastal waters of the Northeastern Arabian Sea. Spectral upwelling radiance and down welling irradiance were recorded using Satlantic profiling under-water radiometer in 350-800 nm calibrated range. Remote sensing reflectance was computed using these two parameters and the ProSoft software. The profiling radiometer was deployed at all stations up to euphotic depth during the noon period near synchronous (1100 – 1300 hours) 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 for species identification (*N. sci* and diatom).

Satellite data processing

MODIS-Aqua Level- 2 and 3 HDF/NC data (derived geophysical variables; sea surface temperature (SST) 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 (R_{rs}) band data were processed to generate time-series of phytoplankton species images using ERDAS / Modeler for January-March 2001-2015 period. The downloaded data from the ocean colour site were in HDF/NC format and were converted into band sequential image files using “import” function of ERDAS. SST images were generated using SeaDAS image processing software. A time-series of phytoplankton species images was generated for the subset image using R_{rs} 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. sci*, diatom, oceanic non-bloom and coastal non-bloom waters (Dwivedi et al., 2015). 8-days and 3-months averaged species images were generated for the fifteen years satellite data to study the inter-annual variability of diatom bloom in the study area. Day time SST images were downloaded from the ocean colour site, which makes use of long-wave thermal radiation (11-12 μm) of MODIS.

Results and discussion

Spatio temporal variations in abundance of *N. sci* and diatom during 2013 and 2015

Two contrasting years were selected for the study when the spread of the bloom was large (in 2015) and comparatively less (in 2013). This can be seen in Figure 2. On the left, there are the species images generated from quarterly MODIS data for January-March 2012 and 2015. The difference between the spread of the bloom in these two years is visible. On the right, there are two time series for phytoplankton species images for 2013 and 2015 generated from the 8-days averaged MODIS data. The sequential images at a glance reveal that spread of the bloom is more in 2015 as compared to that in 2013 in general.

Diatom is seen emerging before *N. Sci* in sequence. This is because diatom is autotroph and thrive when nutrient and light in the upper mixed layer are favorable due to prevailing convective mixing. In comparison to this, *N. Sci* is heterotroph (non-photosynthetic) and require abundant phytoplankton including diatom.

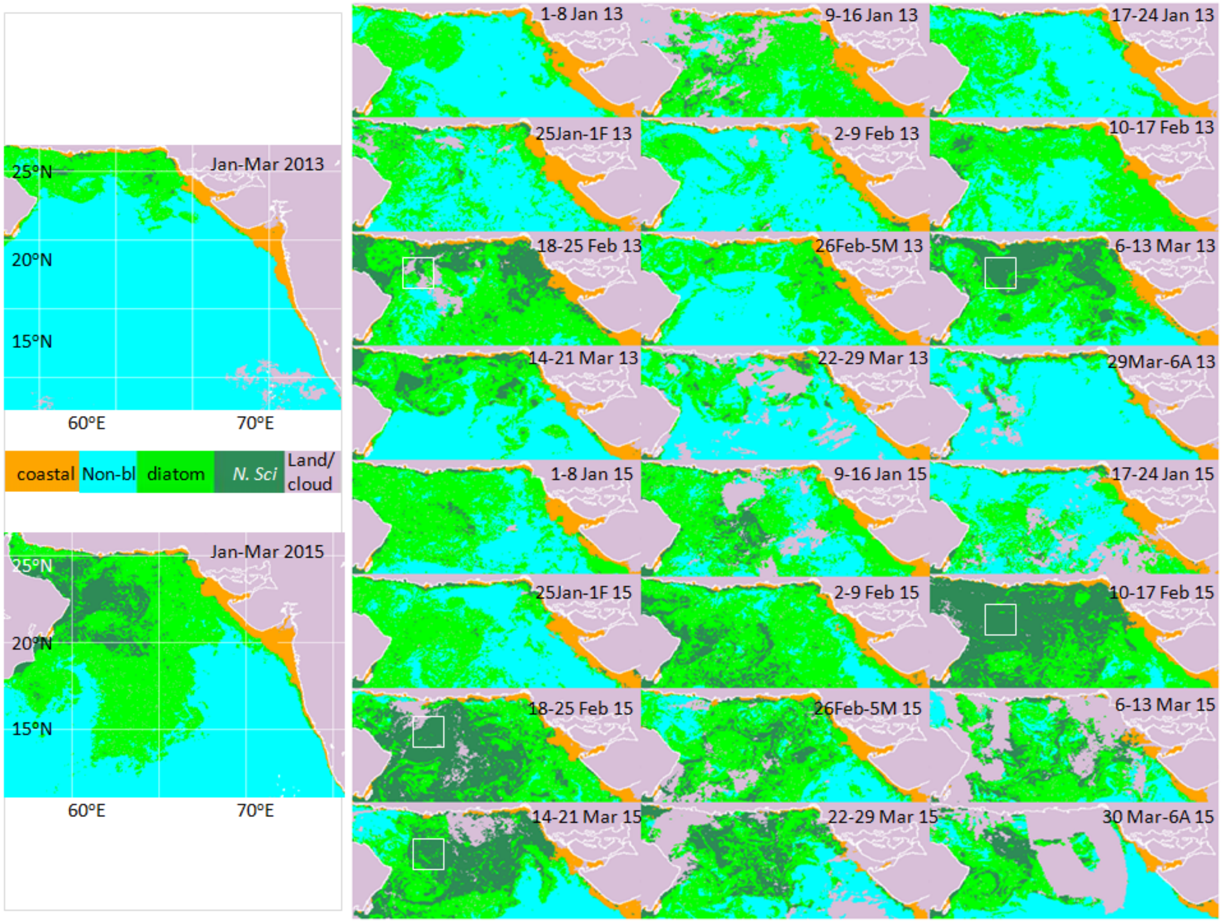

Figure 2. Quarterly (left) and 8-days (right) averaged phytoplankton species images for 2013 and 2015

First appearance of *N. sci* in 2013: occurred during 18-25 February in the Northwestern Arabian Sea

(NWAS). The window shown in the image defines area within 22.5^o-24.5^{o}N, 60^o-62^{o}E. Average water temperature was 23.9^{o}C, which is considered favorable for *N. sci* growth and surface density was high, 24.76, an indicator of convection process.

Second appearance of NS in 2013: can be seen in 6-13 March image. Diatom was found in abundance at this time (8700 pixels in the window) besides favorable SST. *N. sci* feeds voraciously on phytoplankton and diatom and increased diatom population also accelerates *N. sci* growth.

Appearance of *N. sci* in 2015: Large homogeneous patches of *N. Sci* can be seen in10-25 February and 14-21 March images. All the three factors as discussed above, viz. SST near 24°C, density greater than 24.5 and abundance of diatom (food), are found conducive in these cases.

A comparative study of intensity of the winter bloom between the years 2013 and 2015 was extended to 2016 also. This can be seen in the species images in Figure 3(A).

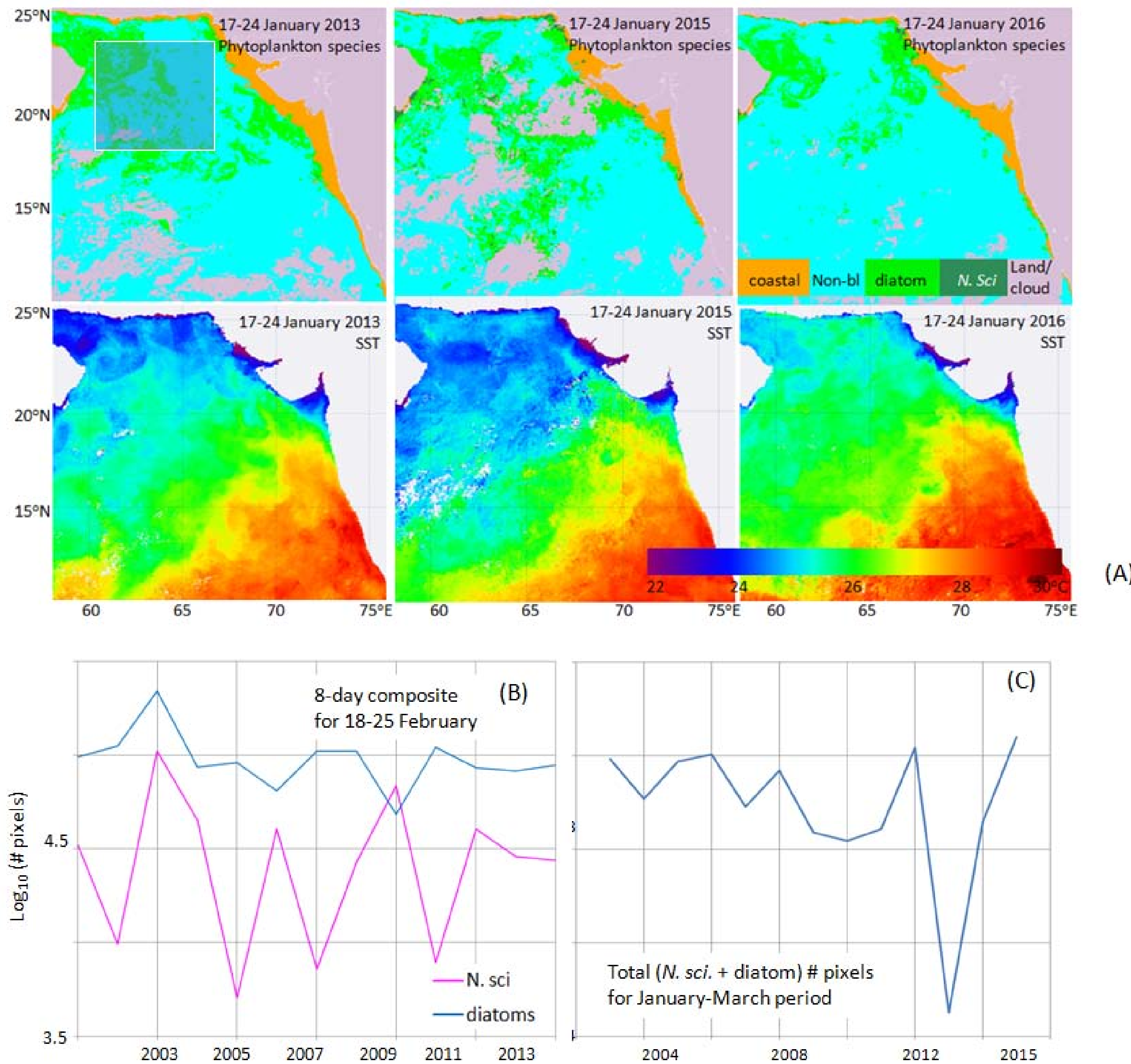

Figure 3. (A) Phytoplankton species and SST images for 17-24 January 2013, 2015 and 2016. (B) Plot of number of N. sci and diatom pixels and (C) Total number of bloom pixels for different years.

Relatively cool water can be seen prevailing over a large area during 2015 as compared to the same in 2013 as well as 2016. This is an indication of stronger convection in 2015. A window shown in the figure represents the area considered for computing diatom, *N. sci* and total bloom pixels as an index of spread of the bloom. Number of diatom and *N. sci* pixels haven been plotted for 18-25 February slot in different years as seen in Figure 3(B). This 8-days period forms a part of active phase of the bloom. It can be seen that spread of the bloom oscillates between maximum and minimum at a near to regular interval of one to two years. Quarterly averaged species images were generated for different years and total number of bloom pixels was computed for the window as shown in Figure 3(A). This is plotted for different years (2003-2015) in Figure 3(C). Inter annual variability in spread of the bloom is cyclic and is similar to the species-specific pattern shown in Figure 3(B). Association of environmental variables like SST, chlorophyll, density, wind speed and sea surface height anomaly with the bloom was studied and is presented in Figure 4.

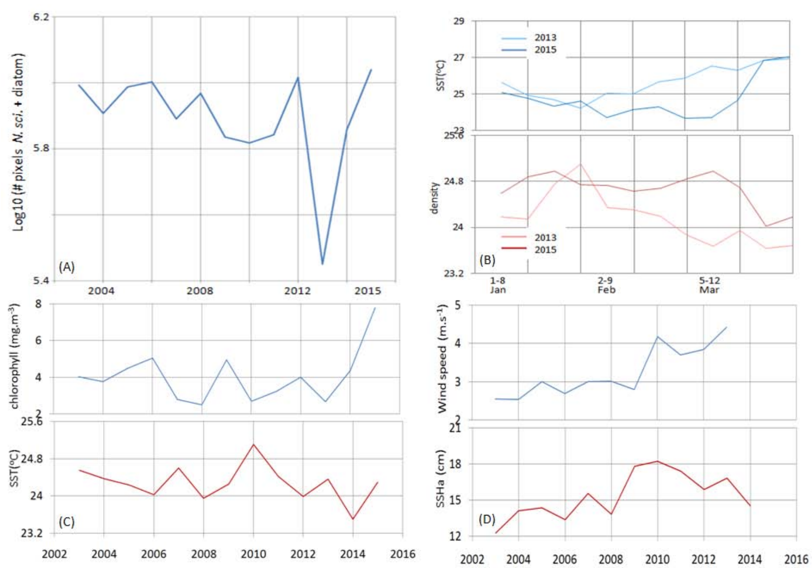

Figure 4. Inter-annual variance in number of bloom pixels in context with the related environmental parameters

Total number of bloom pixels (spread) was considered to describe abundance of the bloom in this study. A pattern of inter-annual variance in the spread of *N. sci* and diatom from 13-years time-series showed a cyclic nature of variations as can be seen in Figure 4(A). This figure is a plot representing spread of the bloom (Logarithm of number of bloom pixels, *N. sci.* as well as diatom averaged over a window 18.5-24.5^{o}N, 60-66^{o}E) for different years. A prominent maximum can be seen during 2015 and minimum in 2013. The interval between the two consecutive maxima is found to be varying from 1 to 2 years. Huang and Qi, 1997 had observed annual oscillations in population abundance of *Noctiluca* in coastal waters of the south China Sea. Before this, Uhlig and Sahling, 1990 had also reported annual cycle in the abundance of *N. sci* at three-year intervals with mention of a year with relatively high abundance followed by low for the next two years. These observations of periodic behavior of the bloom involved continuous monitoring of the bloom for several years and water sample collection to measure the cell counts to assess for *N. sci* abundance at marked stations. In our study, we have studied periodicity of the bloom using remote sensing data and by calculating bloom pixels.

Variations in spatial extent of the blooms correlate with environmental factors

Environmental parameters like SST, surface density, chlorophyll, wind speed and sea surface height anomaly were plotted for different seasons and years as shown in Figure 4(B-D). These parameters are known to play a role in causing variability in the bloom. Their temporal patterns were compared with the pattern of spatial extent of the bloom as shown in Figure 4(A). Chlorophyll maxima and minima (Figure 4(C)) are almost matching with the variations in spread of the bloom (Figure 4(A)). It indicates a direct relation between the two in the Arabian Sea. SST (Figure 4(C)) and # bloom pixels in Figure 4(A) are seen out of phase. Low SST corresponds to high spread. It can be seen that SST corresponding to maximum spread is 24^{o}C or less and these are the most favorable temperatures causing the green *Noctiluca* bloom. This correspondence between cool waters and green *Noctiluca* supports the hypothesis of convection being responsible for triggering the recurring bloom in the Arabian Sea (Wiggert, 2001, Dwivedi et al. 2008). Weak bloom years as manifested by minima in Figure 4(A) correspond to temperatures greater than 24.5 ^{o}C. *N. sci* do not prefer warm waters and also, the high temperature condition cannot sustain convection; resulting in weaker bloom. Gomes et al. (2008) concluded that green *Noctiluca* clearly appeared to be associated with colder waters in the north and was rarely seen in warmer water >26°C off the southwest coast of India where *Trichodesmium* bloomed, especially during May to Sept. While a plot of wind speed (Figure 4(D)) did not show any direct agreement with pattern of the abundance (Figure 4(A)), sea surface height anomaly did indicate a link; low positive SSHa was found matching with the peaks in Figure 4(A). SSHa of lower magnitude reflects better stability of the water mass and it is a favorable condition for *Noctiluca* growth. Temporal profiles (8 days interval) of SST and density can be seen in Figure 4(B) for strong bloom (2015) and weak bloom (2013) case. It can be seen from the SST profile that temperatures remained in a preferred range (23.7-24.3^{o}C) for a long period of 40 days during 2015 when the bloom was relatively strong. In comparison to this in 2013, suitable temperatures for *N. Sci* were short-lived and a pattern of continuous increase can be seen right from February and beyond. A similar pattern of high surface density persisting for a long time in 2015 can be seen from the figure and it is an indication of dominating convection. Huang and Qi (1997) have explained accumulation *N. sci* cells in the surface layers considering factors like high wind velocity followed by calm surface layers and lower rainfall residuals. Miyaguchi et al. (2006) have also mentioned the same factors responsible for high abundance of *N. sci*. Harrison et al (2011) considered heavy rainfall responsible for causing sharp decrease in

N. sci. population. Thus, Not only are the relationship between *N. sci* and hydrographic and biological factors are significant, but also meteorological factors influencing accumulation of the cells are crucial in the bloom formation.

Forecasting algal bloom through extrapolation of oscillating nature of *N. sci*

Though variations in abundance of the bloom are periodic, the periodicity is not strictly consistent (Figure (4A)). It is noticed that switching over between the extreme phases occurs at the interval of one or two years. This partial consistency in the trend can create an ambiguity in exploiting cyclic nature of the variability to forecast abundance of the bloom through extrapolation. The problem of mixed pattern of variance was solved by combining the past trend with current pattern of development. Having observed a peak at 2015 point in Figure 4(A), one is not sure whether the minimum would be encountered after one year or two years. Species images for the initial stage, 2nd week of January, were generated for the current year (2016) and compared with 2015 as shown in Figure 5.

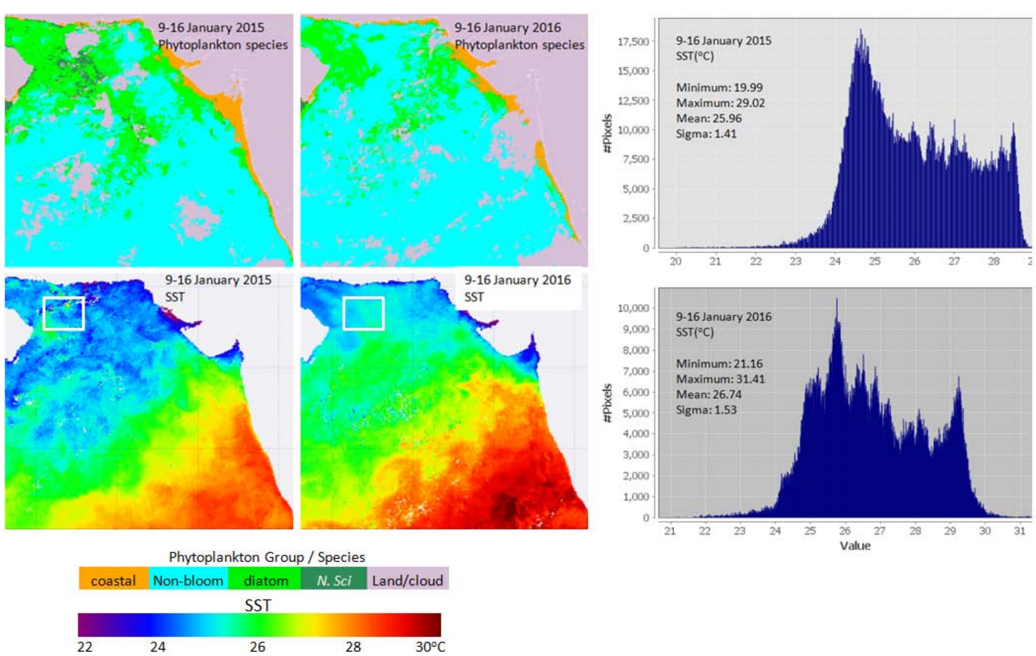

Figure 5. Comparison of distribution of bloom pixels and SST at initial stage in 2015 and 2016

Overall cooling of water mass is less in 2016 relative to the same in 2015. Histograms for SST presented in Figure 5 correspond to the windows shown in the adjacent species images. It can be noticed that mean temperature in the window is more with relatively high standard deviation in 2016 in comparison with the same in previous year. In view of this, one can expect a weaker convection in 2016. Corresponding to this, the species images reveal development of the bloom in small patches (9-16 January 2016 species image in the figure). This ensures that a point of minimum abundance would reach this year in 2016.

The Forecast

With this logic, a relatively weak bloom is forecasted for the remaining ten weeks period of the current season (2016) that is till March end.

Validation

It can be seen from Figure 6 that spatial extent of *N. sci* and diatom is significantly less in this year as compared to the same during last year.

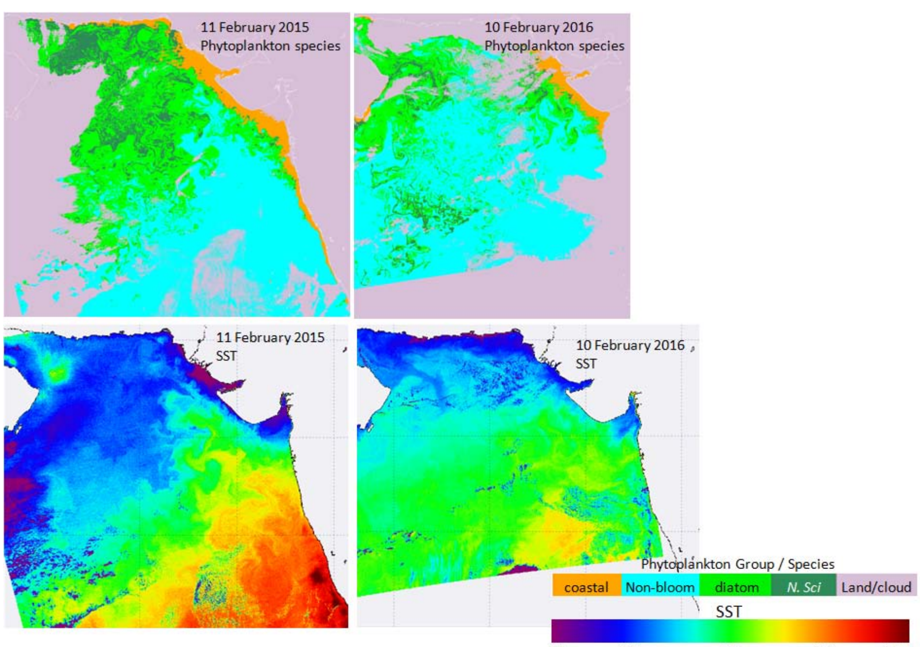

Figure 6. Spatial extent of the bloom is less in 2016 as compared to the same in 2016

Species images in this figure represent February period, which is supposed to be the peak phase of the bloom. Still, coverage of the bloom is significantly less compared to 2015 images of similar dates. The weak bloom of 2016 can be seen associated with relatively warm water over all in the basin. This confirms the forecast of weaker bloom in the current year made using the past trend. A time-series of bloom species images (8-days) generated for the active bloom phase for 2015 and 2016 can be seen in Figure 7.

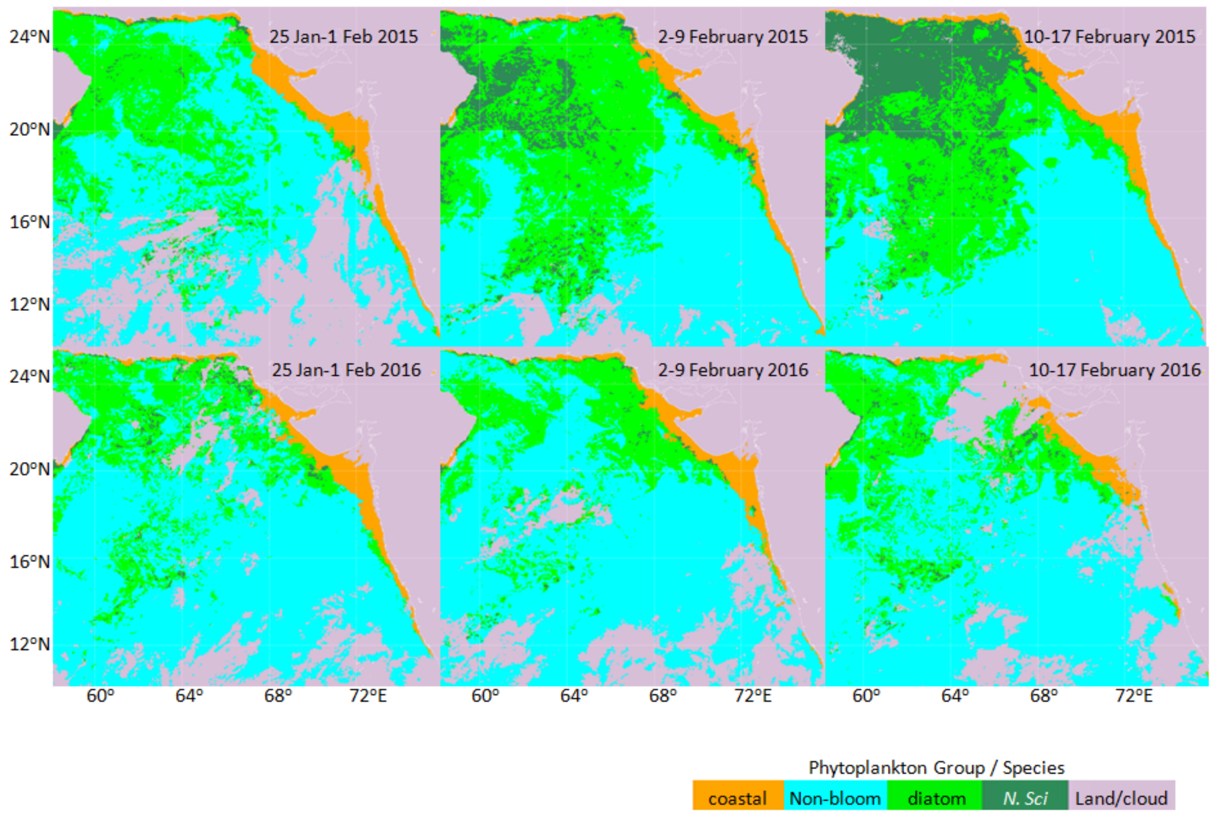

Figure 7. Eight-days time-series species images for 2015 and 2016.

It can be seen from the figure that anticipated development of weak bloom in 2016 is consistent during active bloom period.

Conclusion

Knowledge of the oscillating pattern of abundance of the bloom when combined with current species images of initial bloom period facilitates the forecast for the remaining season.

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