

Remote sensing of bacterial response to degrading phytoplankton in the Arabian Sea

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Abstract A remote sensing technique has been developed to detect physiological condition of phytoplankton using in situ and moderate imaging spectroradiometer (MODIS)-Aqua data. The recurring massive mixed algal bloom of diatom and *Noctiluca scintillans* in the Northern Arabian Sea during winter-spring was used as test bed to study formation, growth and degradation of phytoplankton. The ratio of chlorophyll (chl) to particulate organic carbon (POC) was considered as an indicator of phytoplankton physiological condition and used for the approach development. Algal blooms represent the areas of new production, and therefore, knowledge of their degradation is important to the study microbial loop and export carbon flux. Relation of chl/POC ratio with bacterial abundance revealed Gaussian distribution. Bacteria were strongly correlated with POC, and hence, the latter which is available from satellite data could be used as a proxy for remote assessment of bacteria. Thresholds for active and degrading phytoplankton were determined using the ratio computed from the satellite data. The criteria were implemented on MODIS data to generate an image representing

distribution of degrading algal bloom. Bacteria abundance data from two validation cruises during dinoflagellate and cyanobacteria bloom confirmed well match up of phytoplankton degradation information from the satellite. Comparison of environmental parameters during decay phase of dinoflagellate (*N. scintillans* bloom (winter) and *Trichodesmium* bloom (summer) revealed that degradation after active *Trichodesmium* bloom was more severe as compared to the *N. scintillans*. The present study also highlights the prediction capability of phytoplankton degradation using a time series of satellite retrieved chlorophyll/POC images.

Keywords Algal bloom · Degradation · Remote sensing · Arabian Sea

Introduction

Ocean colour data from the remote sensors promote estimation of phytoplankton in a comprehensive manner. Phytoplankton serves as an index of biological activity and forms the base of marine food web. Phytoplankton physiological condition reflects overall health of the ecosystem. The tropical seas experience massive algal blooms attributed to availability of nutrients driven by the physical forces (Prasanna et al. 2012; Kumar et al. 2001; McCreary et al. 2001; Sergey and Nikolay 2012). Efforts have been made to identify and monitor the algal blooms at species level using remote sensing techniques (Ryan et al. 2002; Cannizzaro et al. 2008; Tomlinson et al. 2009; Simon and Shanmugam 2012;

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Dwivedi et al. 2015). However, a technique to assess physiological condition of phytoplankton at synoptic scale especially during massive algal bloom events using remote sensing data still remains a gray area and requires attention.

One of the most productive tropical waters, the Northern Arabian Sea (NAS), encounters extensive bloom of diatom and *Noctiluca scintillans* covering a large area of the basin between west coast of India and Oman during winter-spring (Dwivedi et al. 2015). Diatom is found to precede *N. scintillans*. This massive event is followed by *Trichodesmium* bloom, which occurs all over the coastal and off shore waters of west coast of India during summer. During such large scale and persistent algal blooms, intense degradation of phytoplankton occurs and causes accumulation of bacteria and other heterotrophs. Hence, the information on degradation of the algal blooms can be utilized in studying the response of microbes, carnivorous zooplankton and higher level marine resources to the degrading bloom. It can also serve as an initial step in the study of microbial food chain. Moreover, algal blooms are known to contribute towards new (export) production due to their tight coupling with nutrient entrainment from subsurface or from atmosphere nitrogen fixation. *Trichodesmium* is reported as fixing 40% of all nitrogen fixation occurring

in the ocean (Karl et al. 2002). Therefore, information on development and degradation of the algal blooms facilitates the study of carbon and nitrogen cycle in the marine environment. Degradation of bloom causes bacterial aggregation, which subsequently supports higher level pelagic/benthic organisms in the food chain. Thus, the process of degradation has an intense ecological impact in the area.

In the present study, approach of detecting physiological status of phytoplankton was carried out using remote sensing data based on the concept of microbial loop. The ratio of chlorophyll to particulate organic carbon (POC) retrieved from MODIS data was used as an indicator of phytoplankton degradation.

Materials and methods

Study area

Shipboard in situ data on chlorophyll, bacteria abundance and nutrients from US Joint Global Ocean Flux Study (US-JGOFS) cruises were analysed for developing an approach for detection of the areas of degradation during NAS winter algal bloom. The study area as shown in Fig. 1a covers bloom influenced eutrophic

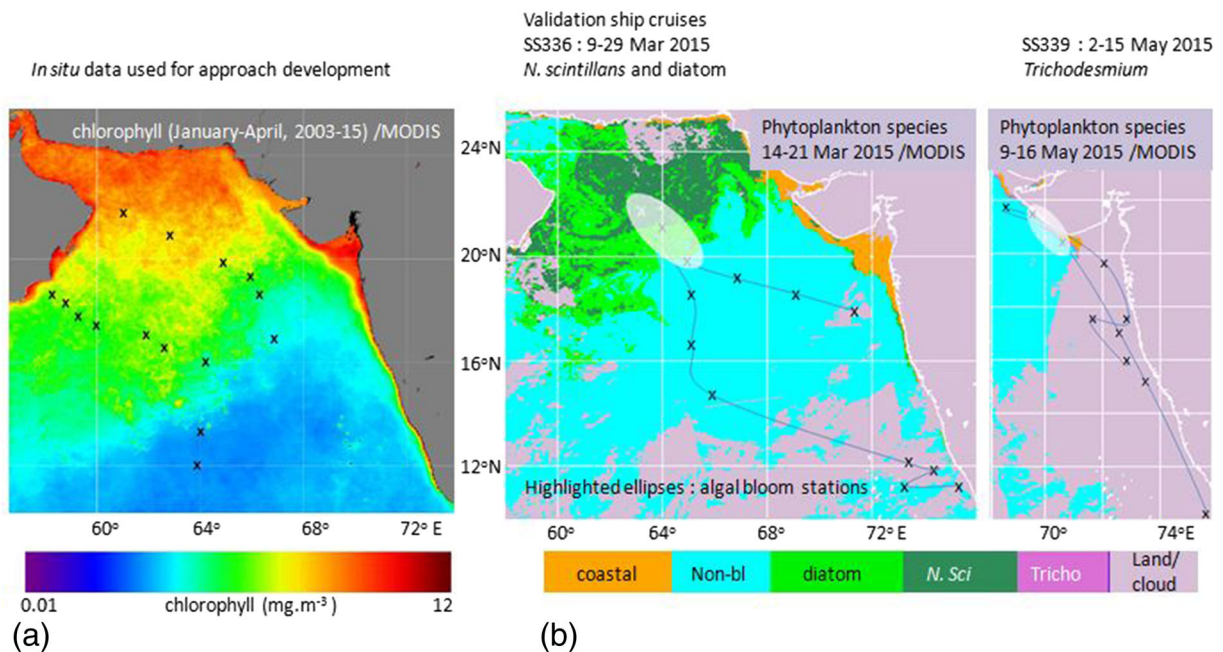


Fig. 1 **a** Locations of in situ measurements in the western and central Arabian Sea during US-JGOFS process cruises. **b** Ship tracks for validation cruises in the central, Northeastern Arabian Sea and coastal waters of west coast of India

waters as well as non-bloom oligotrophic waters of the northern and central basin of the Arabian Sea.

Approach development

Co-variance between bacterial abundance (cells mL^{-1}) and POC ($\mu\text{M } \Gamma^{-1}$) was observed from the in situ data from US-JGOFS cruises in the Northwestern Arabian Sea (NWAS). Subsequently, the correlation between the two parameters was verified considering POC from MODIS-Aqua data. POC images were downloaded from 8-day composite, 4-km level-3 MODIS data available at OceanColor web (<http://oceancolor.gsfc.nasa.gov>). In view of the fact that turnover time of carbon biomass is of the order of 1–2 weeks, 8-day composite was considered adequate to ensure no data gap. The final product uses power function fit to POC versus remote sensing reflectance blue to green ratios at 443 and 555 nm (Stramski et al. 2008) and estimates surface concentration of POC. POC retrieval algorithm of Stramski et al. (2008) emphasizes applicability of the algorithm in oligotrophic as well as eutrophic coastal upwelling waters with normalized root mean square error of about 20%. This was followed for investigation of response of bacteria as an indicator of degradation. The data required for the present study were obtained from US-JGOFS cruises in the Arabian Sea, which included parameters like bacterial abundance (cells Γ^{-1}) and POC ($\mu\text{mol } \Gamma^{-1}$) from water samples collected during late northeast monsoon and spring inter monsoon seasons. The period of data collection covered initial, active and decay phases of the algal bloom. Subsequently, bacteria were replaced by POC. It was found that the distribution was Gaussian in both the cases. A threshold for chl/POC ratio was determined corresponding to the values of bacterial concentration lying within the standard deviation on either side of the mean value. This threshold represented a range of chl/POC ratio for which the bacteria can be expected in abundance.

Implementation and validation

As a part of implementation of the approach, chl/POC ratio images were generated from the MODIS data and the set threshold was used to detect the degrading phytoplankton. Level 3 chlorophyll products were also downloaded from the OceanColor web. MODIS data were processed to generate time series of chl/POC ratio images to study temporal variability in the degradation

process during the total duration of winter algal bloom in the Arabian Sea. Two cruises were conducted during 11–21 March 2015 and 2–15 May 2015 in the oceanic waters of Northeastern Arabian Sea (NEAS) and in the coastal waters of the west coast of India to validate the approach. Discrete water samples were collected to analyse bacterial abundance and associated chemical and biological and optical parameters.

Bacterial abundance

Samples for enumeration of bacterial abundance were collected along 23 stations (Fig. 1b). The water samples (50 ml aliquots) were collected from the surface using a bucket, were fixed in 0.2- μm prefilter and 25% glutaraldehyde and were stored in dark at 4 °C. Microscopic slides were prepared onboard within 3 days of sampling.

Acridine orange direct counts (AODC) were made following Parsons et al. (1984). Sample volumes of 2–3 ml were stained with acridine orange (final concentration 0.01%) for 3 min, filtered (0.22- μm black Nucleopore filters) and mounted on glass slides using immersion oil and observed immediately under 100 $\times$ objective of an epifluorescence microscope (Olympus BH2, Japan). Total bacterial abundance was calculated using the methodology detailed in Parsons et al. (1984).

Determination of oxygen minimum zone

Determination of oxygen minimum zone (OMZ) was done from dissolved oxygen (DO) profiles of modular CTD profiler (Sea-Bird Inc.). The column where oxygen value was less than 0.5 $\mu\text{l } \Gamma^{-1}$ was considered as OMZ (Wyrski 1962; Helly and Levin 2004). Depth of occurrence of the minimum oxygen concentration was considered for analyzing station wise variation in OMZ.

Results and discussion

Rationale

Algal blooms being the areas of high productivity develops chain of living organisms followed by formation of detritus. NAS experiences massive, multi-species blooms of *N. scintillans* and diatom during winter-spring and *Trichodesmium* during summer (Matondkar et al. 2004; Matondkar et al. 2006; Capone et al. 1998). Detritus production starts as a consequence sink to deep

waters. Bacteria aggregate at the sites of sinking POC and break down complex organic compounds for their heterotrophic growth. Thus, the two parameters, bacteria and POC should be correlated. Therefore, POC, which is available from the satellite data, can be used to determine bacterial distribution, in other words, degradation process. Earlier, Bird and Kalff (1984) and Cole et al. (1988) also had reported correlation between bacterial abundance and phytoplankton as well as POC concentrations both in fresh and marine waters. However, POC can also increase due to increase in live phytoplankton during active phase of the bloom. Bacteria do not respond to live POC, and therefore, POC alone cannot be taken as a reliable indication of degradation. In general, chlorophyll follows a decreasing trend during degradation process. However, chlorophyll can also decrease due to predation by other organisms. Therefore, temporal decay of chlorophyll also cannot be taken as a signal of degradation. In a nutshell, neither POC nor chlorophyll individually provides indication of the degradation process. Therefore, the two parameters need to be used synergistically to extract the information on the physiological condition of phytoplankton. Increase in POC is associated with decrease in chlorophyll when degradation occurs, and therefore, the ratio is a reliable indicator of degradation.

Assumption

POC includes live and biogenic detrital particles in the oceanic waters. POC either from in situ measurements or from satellite contains both of these particles. However, bacteria respond mainly to detritus for remineralization. Total live carbon concentration (total zooplankton, diatom, dinoflagellate, other phytoplankton and copepod-nauplii) was calculated from the NWS across the algal bloom season (January–March) using US-JGOFS data. The column mean value of total live carbon concentration was observed as $8.03 \mu\text{g C l}^{-1}$, which is 25% of the total POC in the NAS. It indicated dominance of detrital organic carbon in the measured as well as satellite-retrieved POC. In general, the detrital organic carbon represents main fraction of the total organic carbon (Ribes et al. 1999). In view of dominance of detritus in total POC, the same was linked with degradation process as an alternative to bacteria as an approximation. A threshold of chl/POC ratio representing degradation

was determined by generating 260 data points for different types of waters including bloom and non-bloom stations. The threshold, which is a range of chl/POC ratios indicating degradation, is believed to absorb uncertainties due to live POC as well as errors in estimations of chlorophyll and POC from the satellite data.

Approach development

Bacteria aggregate in the marine waters to decompose dead particulate organic matter acts as a source of food and energy. Therefore, its abundance reflects the degradation process. However, this parameter cannot be detected from satellite directly. In view of the fact that bacteria are linked with detritus, an attempt was made to investigate if detritus (POC) could be used as an indirect tracer of bacteria and, hence, the degradation process. POC and bacteria were pulled from US-JGOFS data (January and March–April) for the Arabian Sea (Fig. 1a). The plot in Fig. 2a shows that the two parameters co-vary. Plots of bacteria versus in situ POC (Fig. 2b) and satellite POC (Fig. 2c) also depict the strong correlation between the two parameters. In short, Fig. 2a–c suggested that POC, which is retrievable from the satellite data, can be used as a substitute to bacteria. However, as explained above in the rationale, chl/POC ratio appears to be an indicator of phytoplankton degradation process and the same was examined subsequently. Bacterial counts were plotted as a function of chl/POC ratio and the scatter of points can be seen in Fig. 2d. The scatter reveals a definite pattern that looks similar to Gaussian or polynomial. Subsequently, bacteria were replaced by POC (Fig. 2e), and the scatter was still observed with similar pattern as shown in Fig. 2d.

Both the variables presented in Fig. 2e used in situ data, and the same were replaced by satellite-derived inputs to have an approach that is operationally implementable. The data points ($N = 240$, third degree polynomial fit, $R^2 = 0.77$) represent oligotrophic case 1 waters as well as eutrophic waters influenced by active and degrading algal blooms (Fig. 3). Gaussian fit was also attempted to this data set and was found to yield a similar result. Corresponding to maximum POC (447.5) on y-axis in Fig. 3, there was a specific value of chl/

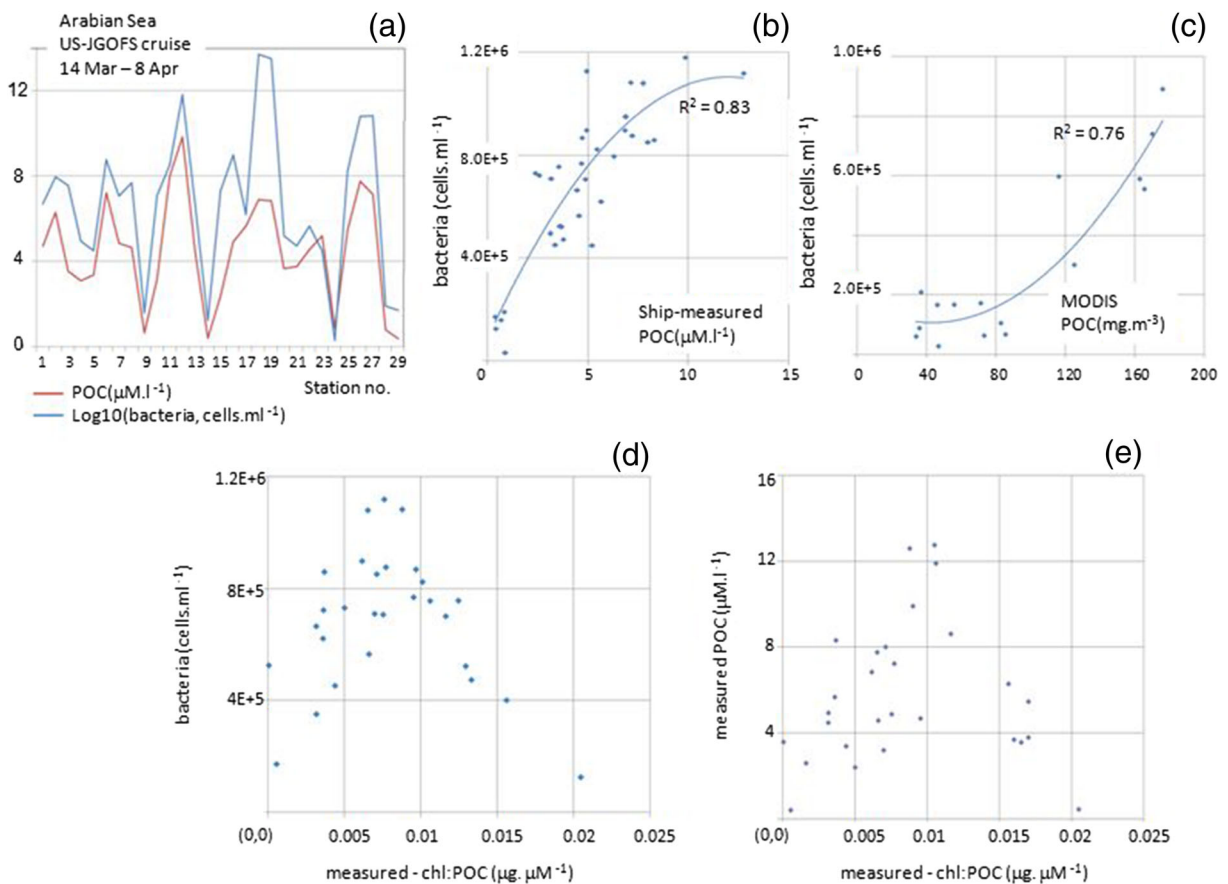


Fig. 2 **a** In situ POC and bacteria at different stations in the NAS during winter bloom. **b** Plot of bacteria versus in situ POC. **c** Plot of bacteria versus satellite-derived POC. **d** Plot of bacteria versus

measured chl/POC ratio. **e** Plot of POC versus measured chl/POC ratio (all in situ data from US-JGOFS cruise)

POC (0.019) which represented a situation of maximum degradation because this scenario also represents maximum bacterial abundance. POC/bacteria on either side with reference to this point was expected to decrease and, hence, the severity of degradation also. Mean (μ) and standard deviation (σ) were computed for POC data. The degradation criterion was developed which considers all the points in the plot located above $\mu + \sigma$ Line (solid line in blue colour) as degradation scenario. This line intersects the curve at two points and their projection on x -axis provides minimum and maximum value of chl/POC and it forms a threshold (range) for deciding degrading pixels. The criterion was extended to generate other classes like moderate and low degradation. If POC for a given pixel is located between μ and $\mu + \sigma$, the corresponding chl/POC values form a range for moderate

degradation (Fig. 3). POC value in this case is more than μ and less than $\mu + \sigma$, which indicates that bacteria accumulation is moderate. Some pixels with POC's having values less than $\mu + \sigma$ can be seen located on extreme right of x -axis in the figure, and these pixels were classified as post active bloom-low degradation condition. When the bloom is in decay stage, no new POC (live or dead) results and the existing POC as well as associated bacteria become prey for the co-existing higher level organisms like protozoa, carnivorous zooplankton, etc. This resulted in a very high chl/POC ratio. Also, phytoplankton was active prior to the decay phase; hence, oxygen was consumed in respiration and bacteria were comparatively less in this environment. No significant degradation occurred in this case, and it became high chlorophyll, moderate bacteria/POC, and low degradation

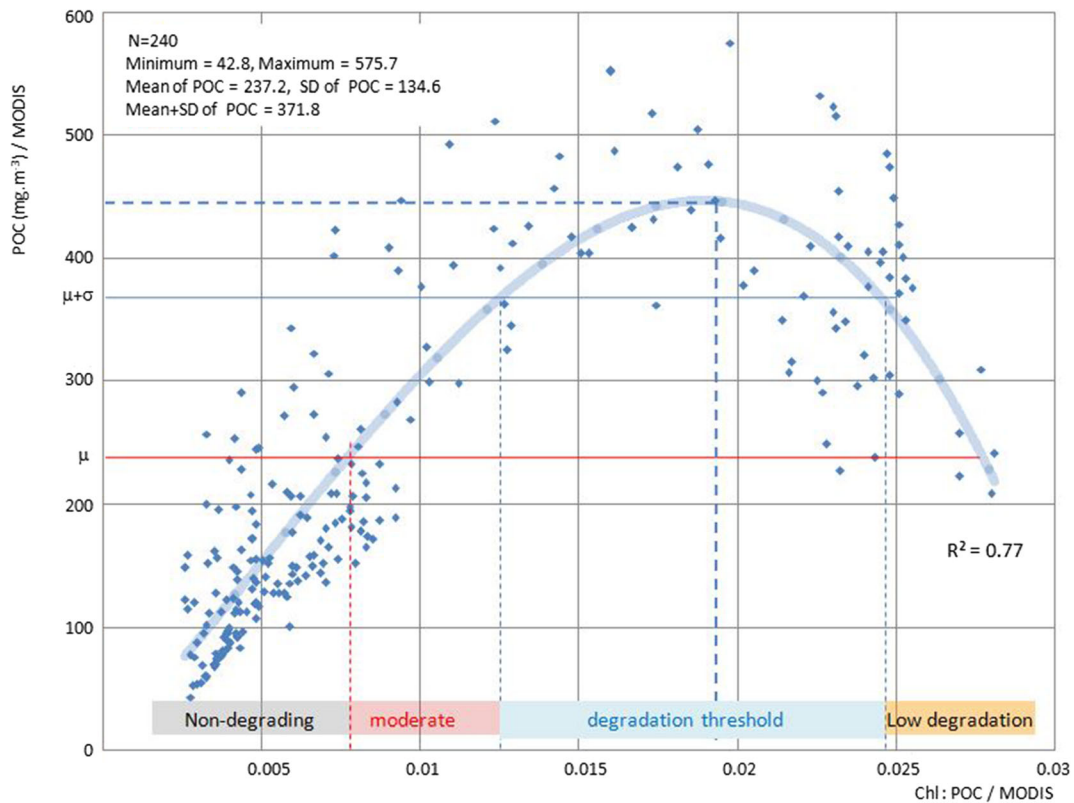


Fig. 3 Plot of POC versus chl/POC estimated from MODIS data from the NAS and CAS

conditions. High chl/POC ratio also reflects initial bloom-low degradation situation when chlorophyll has increasing trend but there is no sufficient POC produced as degradation is weak in initial stage.

In cases when POC less than mean, bacteria concentration is expected to be very low, and correspondingly, chl/POC ratio is also low. This is classified as non-degrading and can be seen in Fig. 3 on extreme left of the ratio axis. Chl/POC ratio images were generated from MODIS data and were compared with the chlorophyll species images of corresponding dates. It was found that the pixels with very low chl/POC ratio were located in the areas of low chlorophyll concentration representing oligotrophic, non-bloom, oceanic waters. This class is shown as non-degrading water in Fig. 3.

Bacteria, chl/POC ratio and surface nitrate (ship data—US JGOFS) for various bloom as well as non-bloom stations have been presented in Fig. 4. Station numbers 1 to 15 (shaded in light blue on the left hand side) of the figure represent initial phase of the bloom (January–February) in the first part. The second part is represented by stations 16

to 30 (shaded in dark blue on the right hand side), and this is the decay phase of the bloom (late March–April). Overall, the chl/POC ratio and surface nitrate were relatively higher, and bacterial concentration was lower in the first part (initial phase) and it is in compliance with active bloom-low degradation class presented in Fig. 3. The observed higher concentration of nitrate was due to winter convection that prevails in this period. The second part of the plot represents decay phase of the bloom. It can be seen from the figure that concentration of bacteria was higher overall, and it can be seen increasing noticeably from station nos. 25 to 28. This is an indication of degradation of prevailing winter bloom in the northern basin. Low nitrate concentration at stations 16–30 as observed from the figure substantiates termination of convection and degradation of the bloom. Corresponding to these stations, chl/POC ratio was also relatively lower and fluctuates in a narrow specific range as shown with a rectangular box in pink colour. This range matches with the same, which was shown in Fig. 3 using MODIS data. Low chl/POC ratio

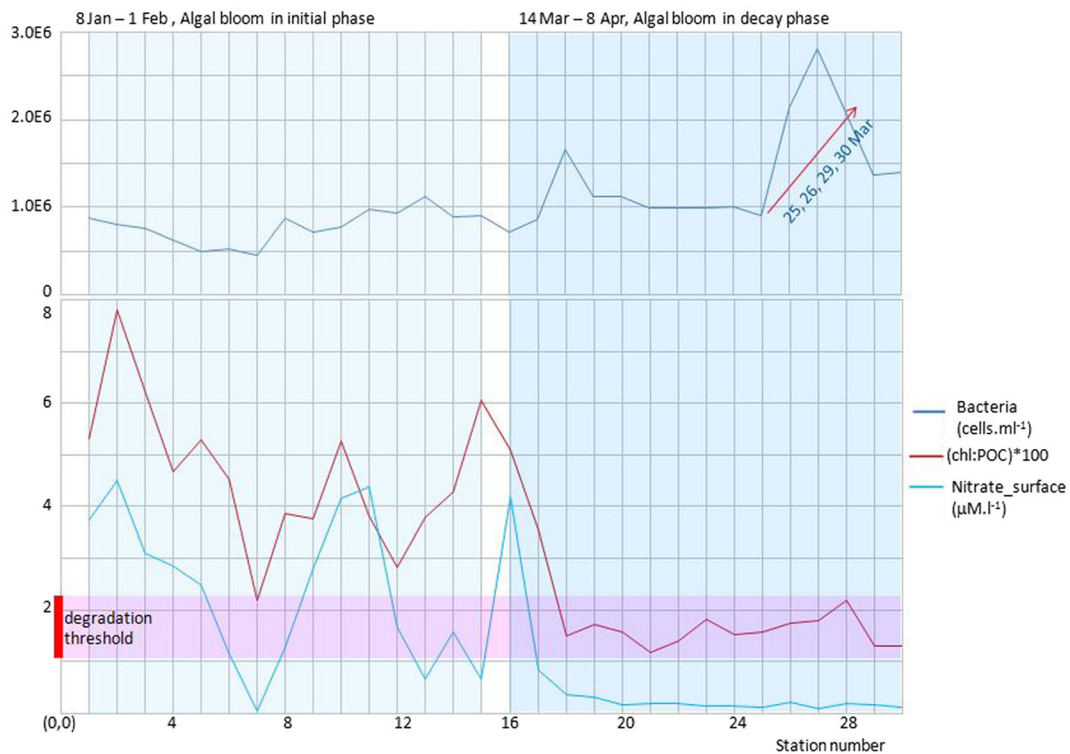


Fig. 4 Bacteria, chl/POC ratio and nitrate for various bloom as well as non-bloom stations of US-JGOFS cruise

during degradation (late March–April) as can be seen from the figure is expected because chlorophyll was on decline phase and POC in increasing phase.

Product generation

Phytoplankton chl/POC ratio images were generated using MODIS data and classified according to the scheme presented in Fig. 3. Phytoplankton species images were generated (Dwivedi et al. 2015) using remote sensing reflectance bands of MODIS at 443, 488 and 588 nm for active (10–17 February) and decay stages (14–2 March) of the bloom (Fig. 5a). Classified images showing physiological status of phytoplankton for these dates can be seen in Fig. 5b. Corresponding to non-bloom pixels (cyan colour) in Fig. 5a, there are pixels classified as non-degrading (cyan colour) (Fig. 5b). NAS winter bloom is active in first half of February and accordingly; signature of degradation can be seen spread over a larger area in 10–17 February 2015 (Fig. 5b) as compared to the same in an adjacent image of 14–21 March 2015, which represents

decay phase of the bloom. It can be seen that low degradation signature (dark blue colour) in March image is widespread relative to the adjacent image on left. Thus, detection of degradation classes is consistent with the conventional knowledge of active and decay phases of the bloom.

Product validation

In situ bacterial concentration collected from validation cruises (SS336—March 2015 and SS339—May 2015) were studied with relation to chl/POC ratios computed from MODIS data (Fig. 6a). Scatter of the points appeared to follow Gaussian/polynomial trend and is similar to Fig. 1d prepared using US-JGOFS data. DO was relatively higher at the bloom station near surface and at shallow depths (Fig. 6b). This might be due to the process of photosynthesis where phytoplankton releases oxygen in the euphotic zone. As a result of their degradation, more POC was generated that ultimately sinks to deeper waters in the form of detritus. While sinking, decomposition occurs by the microbes and oxygen is consumed for their

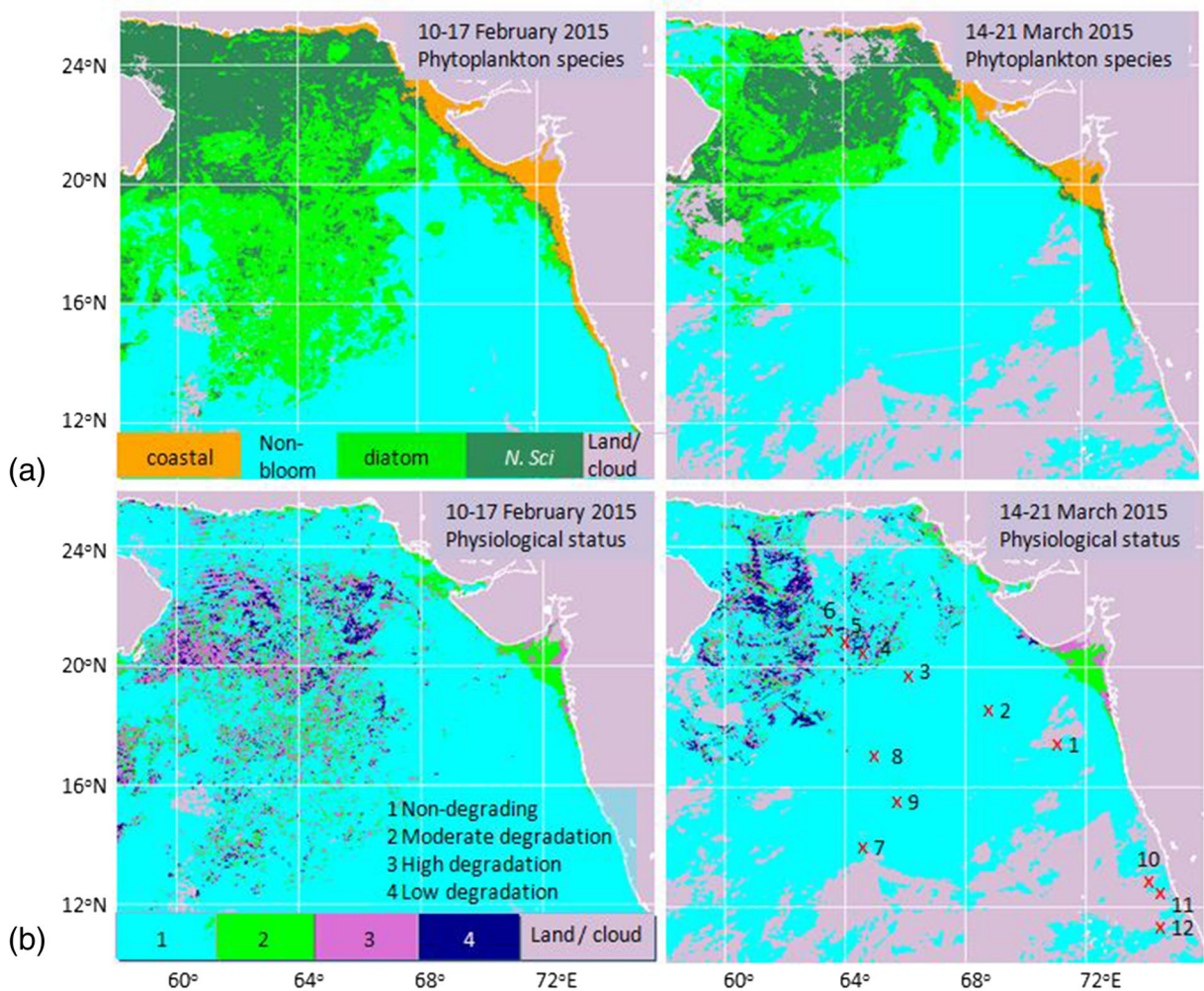


Fig. 5 **a** Typical products to reveal distribution of phytoplankton species and **b** physiological status generated from MODIS data

respiration (Morrison et al. 1999). It can be seen that DO is lower for the bloom station beyond 800 m indicating the process of degradation.

Chl/POC ratios were plotted for different stations of the validation cruises and are presented in Fig. 6c. The threshold for degradation is highlighted with a rectangle in blue colour. The threshold detects station numbers 4, 5, 6, 11 and 13 as degrading waters. It can be seen from Fig. 1b that these stations represent *N. scintillans*/diatom (4, 5 and 6) and *Trichodesmium* (11, 13) blooms according to the species classification scheme (Dwivedi et al. 2015). Further, the same was confirmed by water sample analysis for cruises of March and

May 2015. These stations were highlighted with ellipses in white colour in the Fig. 1b.

Water samples were analysed to measure bacteria concentration, and it can be seen from the adjacent plot (Fig. 6d) that their concentrations were relatively higher for the bloom stations confirming that the degradation process was active. It is interesting to notice from the OMZ plot (Fig. 6c) that low oxygen column intensified at the stations where the algal blooms were degrading.

DO at surface, 20, 50, 100 and 120 m were also plotted for the different stations as shown in Fig. 6d. It can be seen that DO increased at surface and 20 m at bloom stations 4, 5 and 6 (diatom and

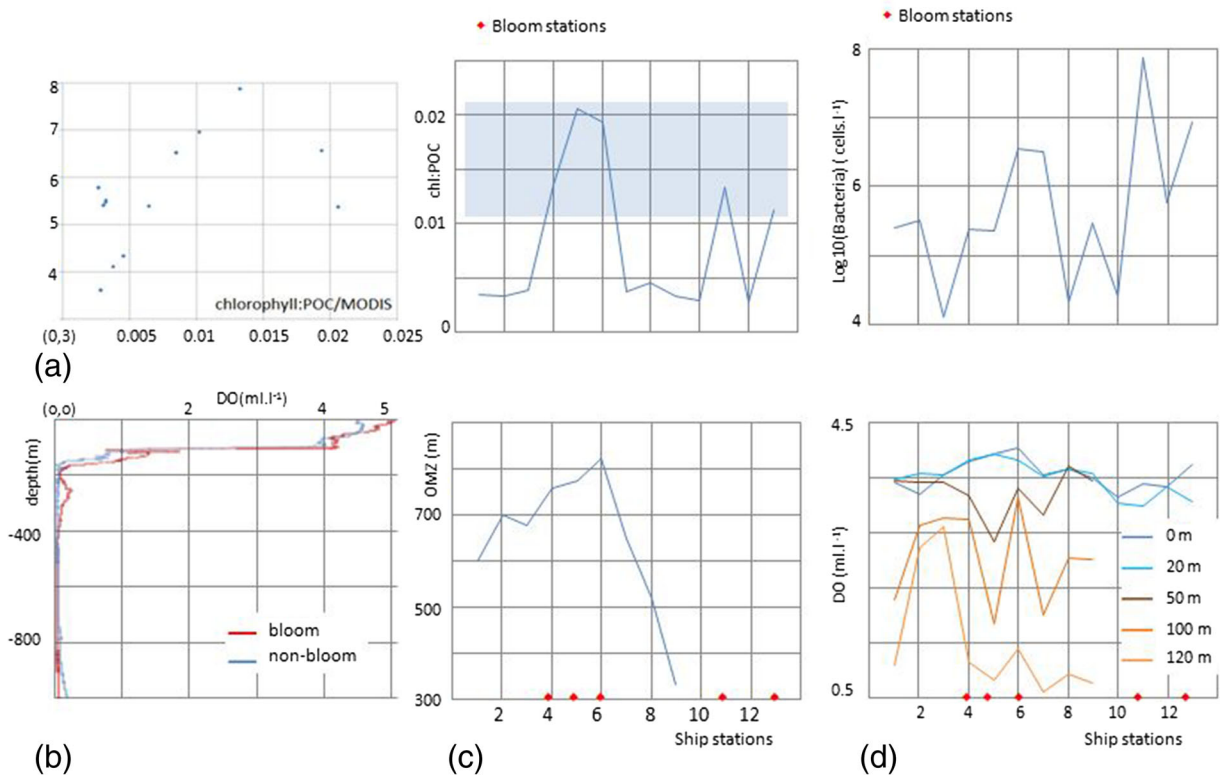


Fig. 6 Plots from validation cruises SS-336 and SS-339. **a** Log-bacteria versus chl/POC ratio. **b** Dissolved oxygen profile for bloom and non-bloom stations. **c** chl/POC ratio and OMZ for all stations. **d** Log-bacteria and DO for all stations

N. scintillans). Growth and decay of phytoplankton occurs simultaneously and higher levels of oxygen in shallow waters reflect photosynthetic growth. POC formed as a consequence sinks to deeper waters as detritus where the organic matter is degraded by aerobic bacteria and oxygen is consumed in the process. This gets reflected as a pattern of declined oxygen at 50, 100 and 120 m in case of stations 4, 5 and 6. Stations 11 and 13 are from May 2015 cruise, which was executed when *Trichodesmium* had just terminated. The bloom had completely decayed, and a few traces of broken trichoms were found in the water samples. Corresponding to this, a decreasing pattern of low oxygen can be seen even at the surface and 20 m.

Figure 6d also revealed that bacteria concentration was more in case of degrading *Trichodesmium* (stations 11, 13) as compared to the same for degrading *N. scintillans* (stations 4, 5 and 6). Similarly, decrease in oxygen was more for

Trichodesmium at these stations. It indicated that degradation process after active *Trichodesmium* was extremely vigorous. In situ bacterial counts was in a range 0.24×10^6 – 0.37×10^7 cells l⁻¹ in case of degrading *N. scintillans*, whereas the same was within 0.91×10^7 – 0.75×10^8 cells l⁻¹ for *Trichodesmium*. Capone et al. (1997) have mentioned that *Trichodesmium* blooms have been found to contain a microcosm including bacteria, other cyanobacteria, protozoa, fungi, hydrozoans and copepods and provide a source of carbon to them and these organisms are the primary predators (O'Neil and Roman 1992).

Status of algal bloom and its degradation can be perceived from a series of images (January–April 2015) (Fig. 7). First and third rows in the figure represent the species, and second and fourth indicate its degradation status. As per the early ship-board observations; the winter bloom in this basin is in initial stage in January, peaks during February,

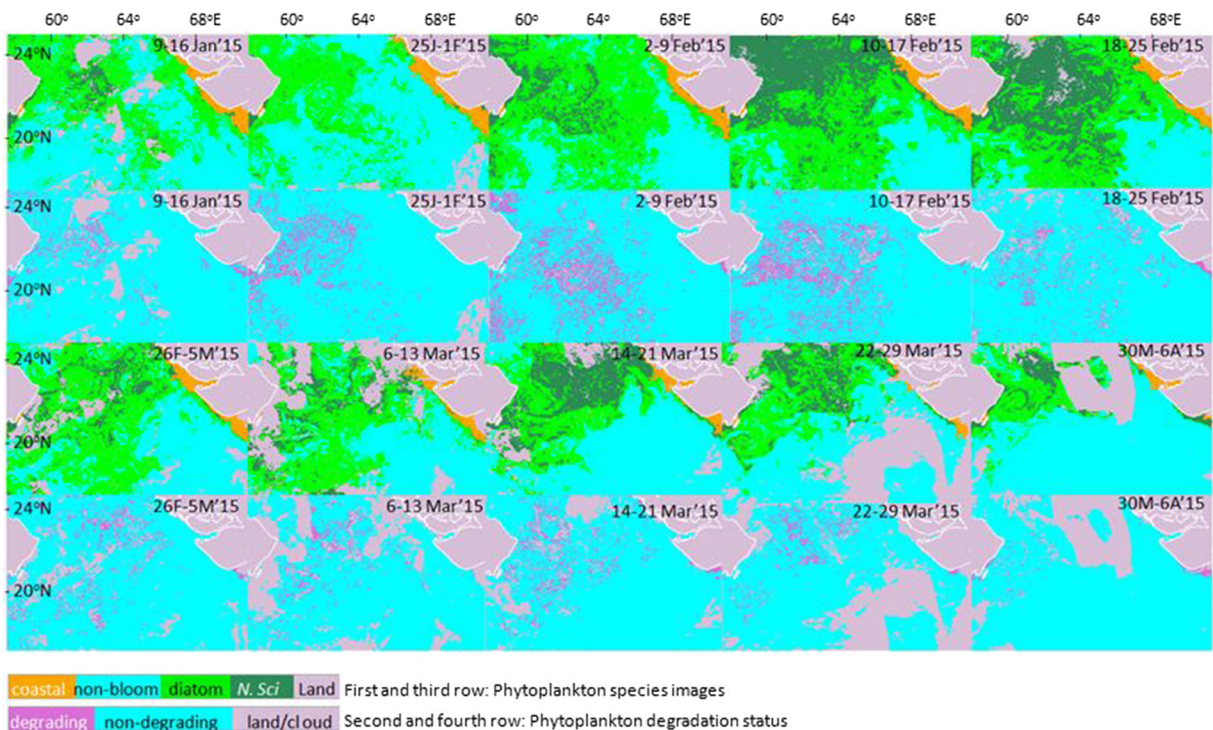


Fig. 7 Time series of phytoplankton species and physiology for January–April 2015 using MODIS data

decays towards March and ends in April. Patterns of distribution of both these parameters in the figure are according to the expected trend. Maximum spread of diatoms and *N. scintillans* can be seen during February (peak phase), and it declined on either side on time scale. When the bloom withdraws and terminates by March-end and April, there was very little degradation. This could be due to the reason that when active phase of the bloom stops after February; there was increasing trend of water temperature and it was unfavourable for the bloom, causing termination of the new phytoplankton growth. The existing detritus/bacteria could be consumed by the predators. Thus, degradation dominates during February when the bloom was active and not in March-end at the time of termination.

Secondly, degradation was more when diatom dominated (2–9 February and 10–17 February) and less when *N. scintillans* (18–25 February and 14–21 March) dominated (Fig. 7). Unlike diatom, the *N. scintillans* is gelatinous and hardly contains carbon in it. Accordingly, the detritus formation is

less on its degradation. Another possibility is that when *N. scintillans* is in growth stage, they voraciously feed on diatom and thereby causing low degradation due to decline of diatom. Gomes et al. (2014) have mentioned that *N. scintillans* blooms were associated with large population of salps during all the cruises in the NAS during the bloom season. They observed from the grazing experiments that high concentrations of salps could rapidly consume dense aggregations of *N. scintillans*.

During the validation cruise, waters at station no. 6 (21.2° N 63.5° E, 16 March 2015) were identified as degrading *N. scintillans* and the remote sensing approach also confirmed the same. Temporal profiles of satellite chlorophyll and POC for this location can be seen in Fig. 8a, b. The points on time axis represent pre-bloom period (November), initial bloom (January), peak (February) and decay phase (March-end/April). It can be seen that both these parameters increased slowly with time till January and then rapidly from

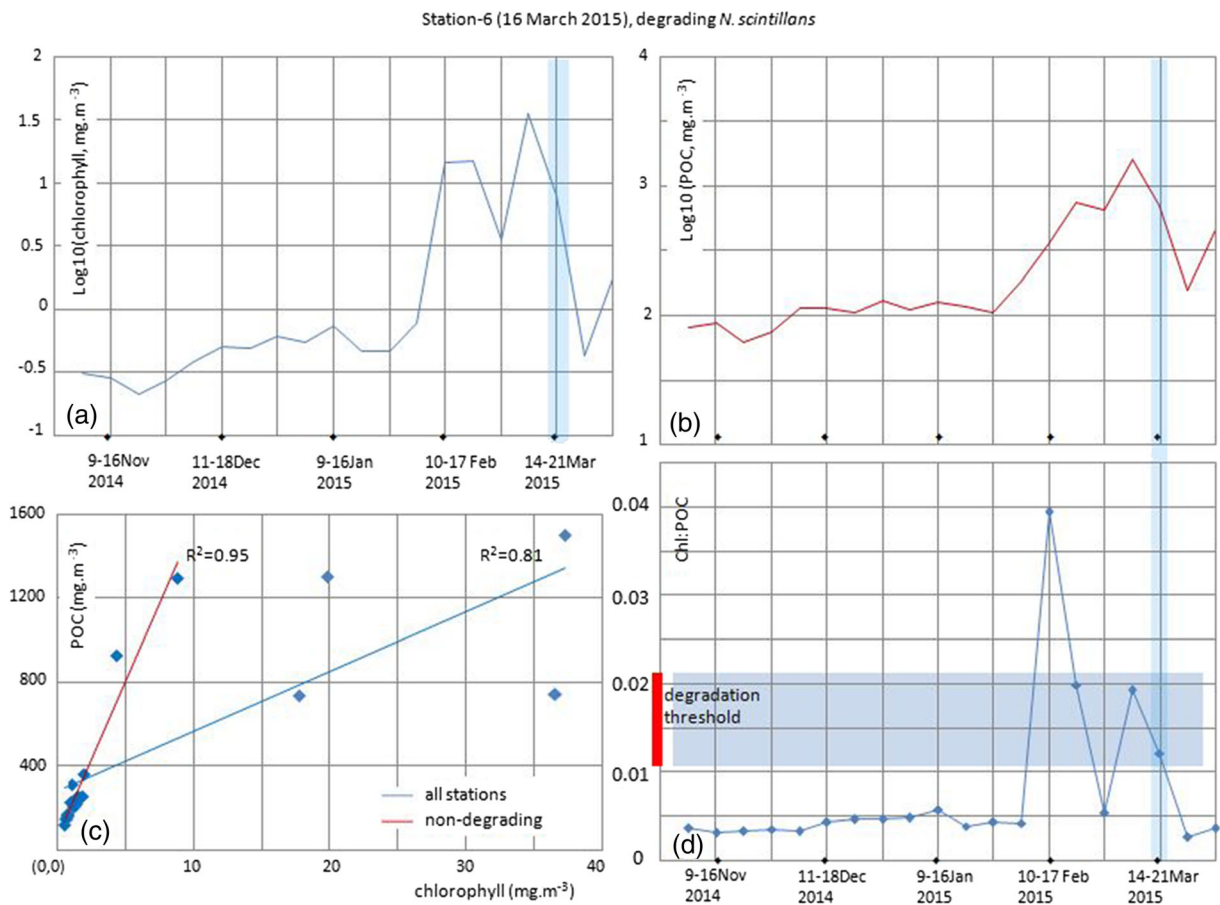


Fig. 8 Temporal variations in **a** chlorophyll, **b** POC, **c** plots of chlorophyll versus POC estimated from MODIS data for the stations of validation cruise and **d** chl/POC ratio from November 2014 to April 2015 using MODIS data

February when the bloom attained peak phase. When the bloom was active, growth and degradation occurred simultaneously. Also, predation of chlorophyll as well as live and dead POC occurred by the living biota in vicinity. This disturbed both the parameters and fluctuations in their profiles were observed. This difference in the pattern during initial and peak phase is explained by a plot of chlorophyll versus POC in Fig. 8c. The plot reveals a strong correlation in case of non-degrading waters (red line) suggesting that chlorophyll and POC co-vary and the ratio (chl/POC) should be constant. Nearly constant ratio can be seen in Fig. 8d in the beginning and till January. Also, its magnitude was small and less than lower limit of the degradation threshold. Following this,

phytoplankton growth increased in February (peak phase of the bloom) and new POC was produced. Sudden increase in the ratio can be seen in Fig. 8d at '10–17 February 2015' point crossing the degradation threshold indicating the growth dominated waters. The ratio fluctuates from high to low after this point depending on dominance of growth or decay. It can be noticed from the Fig. 8d that the ratio satisfied the degradation criterion at three instances after the 10–17 February 2015 point. In summary, the constant ratio indicated non-degrading/normal phytoplankton, and if chl/POC ratio is monitored from the satellite data and picks up its stepping up, it is the signal that degradation may occur after 1 or 2 weeks. Thus, detection of increasing pattern of the ratio through its

monitoring on timescale can be considered as predictor of the degradation process.

Total number of algal bloom pixels and corresponding POC was averaged over the window in NWS (Fig. 9a, b). Maxima of number bloom pixels (spread) can be seen at four vertical highlighted bars. First two maxima represent proliferating bloom, and correspondingly, increase in POC was insignificant in the early stage. Third and fourth maxima represented active phase when growth and decay were simultaneous. It can be seen that significant increase in POC occurs with time lag of 8 days after the maxima of bloom pixels. As POC and bacteria are strongly correlated, this increase in POC represented abundance of bacteria and, hence, the degradation. In view of the time lag between maximum spread and degradation, the former can also be used to predict the degradation besides the chl/POC ratio as discussed above.

Conclusion

Technique for detection of algal bloom from remote sensing data has been developed and validated for the Arabian Sea. Chl/POC can serve as a useful indicator for deriving information on degradation of marine phytoplankton. *Trichodesmium* causes relatively stronger degradation as compared to *N. scintillans*. Time series of degradation and species images revealed that degradation is more with diatom dominance and relatively less with *N. scintillans* prevalence. The information of bloom degradation is very important for the estimation of export carbon and study of microbial loop. Further, the time series analysis of chl/POC images could be used to predict the degradation process. The output of this study could help to identify the sites for deploying sediment trap to measure sinking (export) carbon as a part of study of carbon cycle.

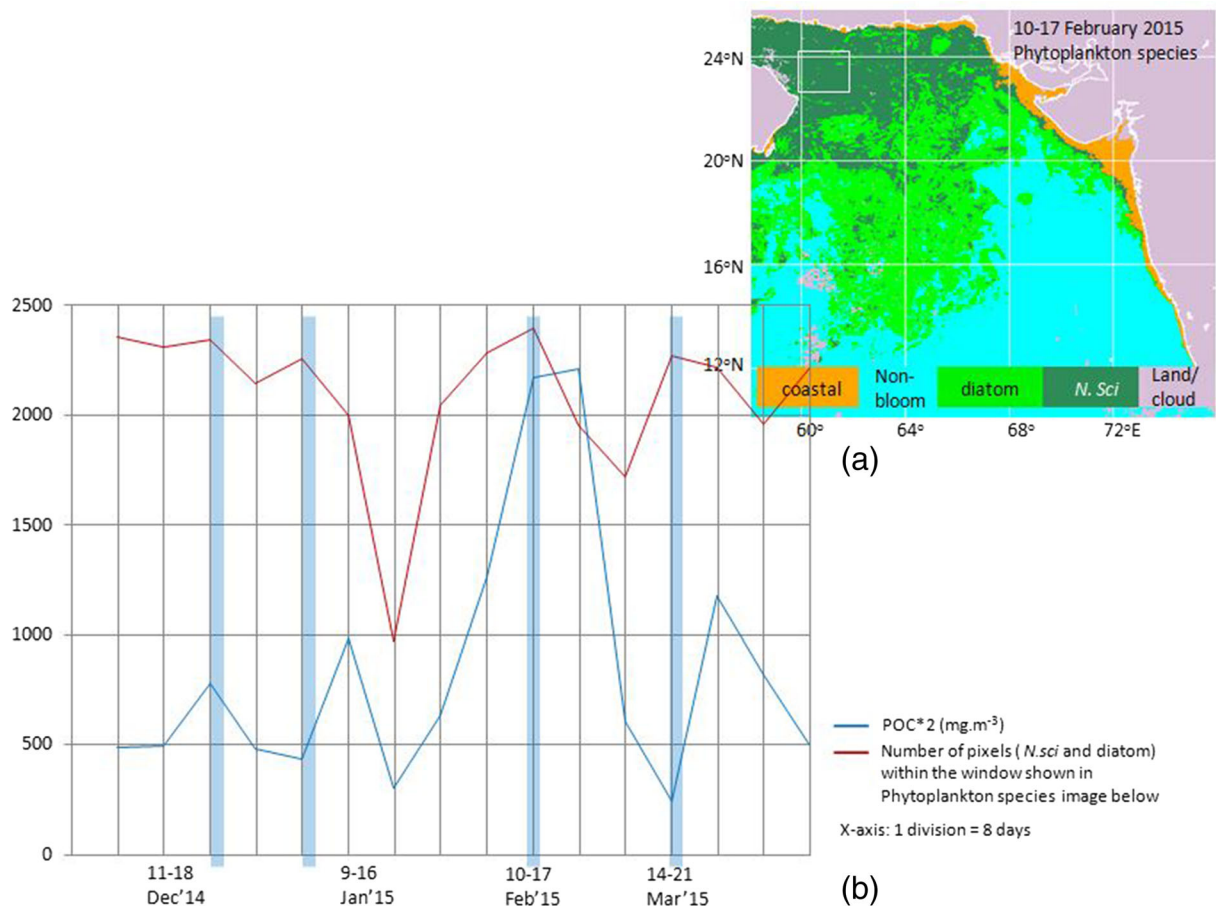


Fig. 9 **a** Phytoplankton species image showing the window considered for the average. **b** Temporal variations in average POC and number of bloom pixels in the NWS

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