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Species identification of mixed algal bloom in the Northern Arabian Sea using remote sensing techniques

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Abstract Oceanic waters of the Northern Arabian Sea experience massive algal blooms during winter–spring (mid Feb–end Mar), which prevail for at least for 3 months covering the entire northern half of the basin from east to west. Ship cruises were conducted during winter–spring of 2001–2012 covering different stages of the bloom to study the biogeochemistry of the region. Phytoplankton analysis indicated the presence of green tides of dinoflagellate, *Noctiluca scintillans* (= *N. miliaris*), in the oceanic waters. Our observations indicated that diatoms are coupled and often co-exist with *N. scintillans*, making it a mixed-species ecosystem. In this paper, we describe an approach for detection of bloom-forming algae *N. scintillans* and its discrimination from diatoms using Moderate Resolution Imaging Spectroradiometer (MODIS)-Aqua data in a mixed-species environment. In situ remote sensing reflectance spectra were generated using Satlantic™ hyperspectral radiometer for the bloom and non-bloom waters. Spectral shapes of the reflectance spectra for different water

types were distinct, and the same were used for species identification. Scatter of points representing different phytoplankton classes on a derivative plot revealed four diverse clusters, viz. *N. scintillans*, diatoms, non-bloom oceanic, and non-bloom coastal waters. The criteria developed for species discrimination were implemented on MODIS data and validated using inputs from a recent ship cruise conducted in March 2013.

Keywords Remote sensing · Algal bloom · Species identification · Arabian Sea

Introduction

Winter–spring ocean color images for the Northern Arabian Sea (NAS) generated from Moderate Resolution Imaging Spectroradiometer (MODIS) data revealed a pattern of consistently high chlorophyll concentrations during the period between January and March. Microscopic observations of water samples indicated that the observed high production in the oceanic waters of NAS was due to prevailing bloom-forming species (Matondkar et al. 2004; Gomes et al. 2010; Gomes et al. 2014), *Noctiluca scintillans* (*N. scintillans* (is the scientific form) or *Noctiluca miliaris*). During our cruises, the color of the waters even in areas where bottom depths exceeded 2000 m was often found to be remarkably dark green. Banse and McClain (1986) had earlier reported unusual large-scale phytoplankton growth during winter across deep waters of the NAS (north of 15° N, 60° E–70° E), using ship observations

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and chlorophyll images generated from Nimbus-7 Coastal Zone Color Scanner (CZCS) data. Also, sequential chlorophyll images generated from Oceansat I/OCM data for this area had revealed a similar pattern of a large-scale increase in abundance of phytoplankton during February–March 2000 and in the subsequent years (Dwivedi et al. 2006). It can be seen from Fig. 1 that spatial extent of the bloom is large and includes waters from Oman (North Western Arabian Sea, NWAS) to Gujarat (North Eastern Arabian Sea, NEAS) and from the extreme north of the basin up to 15° N across latitudes. This offshore bloom is large and widespread and can persist for 1.5 months from February to middle of March. It is believed to be the result of a continuous process of winter cooling and convective mixing which helps recharge the 100–120-m water column with nutrients from the deep. Cold dry continental air from the northeast causes an increase in density in the upper layer due to evaporative cooling, which leads to convective mixing and nutrient enrichment, thereby increasing the biological production (Prasanna and Prasad, 1996; Madhupratap et al. 1996; Dwivedi et al. 2008). In situ measurements were taken using two research vessels *FORV Sagar Sampada* and *ORV Sagar Kanya* during the period 2001–2012 to study the phases like pre-bloom, initial, active, and post-bloom. A set of data collected included optical, biological, chemical, hydrographic, and atmospheric parameters besides water samples for phytoplankton analysis and primary productivity measurements.

One would expect massive bloom like this to lead to high production, affording it a crucial role in understanding the carbon cycle and carbon export to the deep oceans. Besides, this bloom is found to be eco-friendly and supports fishery in the NEAS (Dwivedi et al. 2012). High hooking rates of tunas were reported in NEAS as a result of strongly developed food chain supported by the algal bloom. No significant increase in ammonium or decrease in dissolved oxygen was observed in the surface waters during degrading stage of the bloom in NEAS waters. Thus, the event may be exploited for profitable fishing in these. Increase in biological production as shown by Gomes et al. (2010) and spreading and intensification of column oxygen minimum zone (OMZ) associated with these ecosystem (Stramma et al. 2008; Gomes et al. 2014) also indicate the need for a regular monitoring of the bloom to study its dynamics.

In view of the above, it is important to have knowledge on distribution and abundance of the bloom for scientific as well as commercial applications. However,

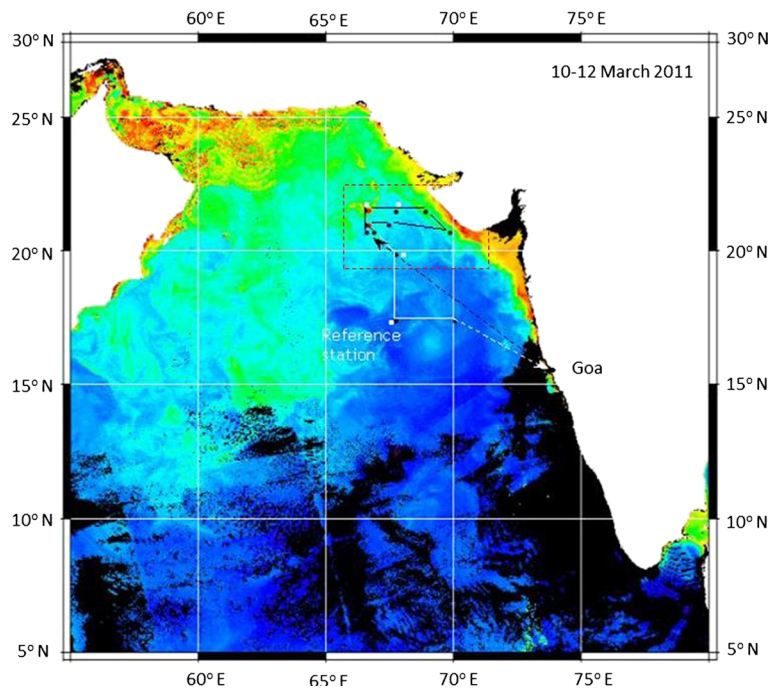
satellite images of this region reveal a patchy distribution of high productivity areas pertaining to this bloom on the northeastern side (offshore waters of northwest coast of India). This requires developing an approach to detect the presence of the bloom and species identification from satellite data. Also, this capability of species identification in near real time can help in planning field campaigns for guiding the ship to an appropriate location for in situ measurements. Siswanto et al. (2013) have used differences of normalized water-leaving radiance (referred to as slope) from MODIS data to classify HAB-forming algae *Karenia mikimotoi* in the coastal region of the western part of Seto Inland Sea, Japan. Cannizzaro and others have used particulate backscattering derived from satellite data for algal bloom detection (Cannizzaro et al. 2008). Balch and Haxo (1984) developed an approach for detecting *N. miliaris* Suriray based on coastal zone color scanner. Stumpf et al. (2003) have suggested the use of chlorophyll rolling anomaly product from SeaWiFS data to locate *Karenia brevis* bloom. Another ocean color remote sensing approach is based on detecting changes in spectral shape of normalized water-leaving radiance spectra and has been used to detect *K. brevis* bloom along the west coast of Florida and applied to SeaWiFS and MODIS data (Tomlinson et al. 2009). However, these approaches were not considered in the present study because NAS/winter are not mono-species environment and the two species *Noctiluca* and diatoms co-exist. Furthermore, it is known that chlorophyll anomaly method fails when high chlorophyll persists for a longer duration. The NAS bloom dealt here persists for almost 3 months starting from January.

The present analysis has been carried out by utilizing species-specific response of phytoplankton from remote sensing reflectance spectra obtained with a Satlantic™ underwater 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 implemented on MODIS-Aqua data. Validation of the approach of recognizing species from satellite data was performed using phytoplankton classes identified from Sagar Sampada cruise samples collected during March 2013.

Materials and methods

The data sets supporting this study were derived through ship cruises (FORV Sagar Sampada and ORV Sagar

Fig. 1 Site for intensive in situ measurements (*dashed rectangle in red*) in the NEAS waters during bloom season and ship tracks



Kanya) during January–March 2001–2012. The study area and repetitive ship track are presented in Fig. 1.

Vertical profiles of in-water upwelling spectral radiance (L_w) and downwelling irradiance (E_d) were measured using a Satlantic™ hyperspectral free-fall optical profiler in 350–800-nm calibrated range. The radiometric sensor measures these spectral parameters simultaneously at 1-nm interval. In-air surface irradiance (E_s) was measured using a deck reference sensor, SMSR (SeaWiFS Multi-channel Surface Reference—“reference”). The reference sensor was mounted at a clear site avoiding any ship shadow and at height above 4 m from the deck. The profiling radiometer was deployed at all stations during the noon period when the solar zenith angle was low.

Remote sensing reflectance, which is essentially the ratio of water-leaving radiance to downwelling irradiance just above the surface (sr^{-1}), was derived from the following:

$$R_{rs}(\lambda) = \frac{L_w(0^+, \lambda)}{E_d(0^+, \lambda)}$$

$L_w(0^+, \lambda)$ upwelling spectral radiance propagated through the surface

$E_d(0^+, \lambda)$ downwelling spectral irradiance extrapolated through the surface

L_w describes the apparent optical property of the water and it is the signal that contains information about water constituents. In the first step, water-leaving radiance (radiance emerging from water) was computed from

$$L_w(\lambda) = L_u(0^-, \lambda) \frac{1 - r(\lambda, \theta)}{n_w^2(\lambda)}$$

$r(\lambda, \theta)$ Fresnel reflectance index of seawater

$n_w(\lambda)$ index of refraction of water (≈ 1.34)

$L_u(0^-, \lambda)$ upwelling spectral radiance immediately below sea surface

$E_d(0^+, \lambda)$ was extrapolated through the surface using $E_d(0^+, \lambda) = \frac{E_d(0^-, \lambda)}{1 - \alpha}$.

α is Fresnel's reflection albedo for irradiance from the sun and sky.

ProSoft software developed for processing the in situ data collected with the Satlantic™ radiometer was used to compute $R_{rs}(\lambda, sr^{-1})$. The derived R_{rs} was used to generate derivative spectra for different water types. Water samples were collected from bloom as well as non-bloom waters and analyzed to identify phytoplankton species, concentration

(mg m^{-3}), and cell density (cells L^{-1}) for *N. scintillans* and diatoms.

Satellite data processing

MODIS-Aqua Level-3 HDF data were downloaded for the bloom period (January–March) through NASA Internet server Ocean Color Web. The data were processed to retrieve remote sensing reflectance using SeaDAS for multi-dates during January–March 2009–2012. SeaDAS makes use of atmospheric correction scheme based on clear water radiance (Briyan et al. 2013). It considers computation of aerosol optical depth based on radiative transfer that uses near-infrared correction scheme with assumptions of zero water-leaving radiance at long wavelengths (748 and 869 nm) of MODIS (Gordon and Wang 1994). No serious problems were anticipated in retrievals of R_{rs} with this approach, as the area of interest (winter bloom) lies in the open ocean (case 1 waters) where aerosols are purely of marine origin and assumption of dark pixel at near-infrared wavelengths is found holding good even in the presence of bloom. Hooker et al. (1992) have reported uncertainty in retrieval of water-leaving radiance within 5 % with this atmospheric correction scheme for case 1 waters. Chlorophyll images were generated using SeaDAS image processing software. It uses a standard operational OC3 algorithm based on logic of maximum of $R_{rs}(443)/R_{rs}(550)$ and $R_{rs}(488)/R_{rs}(550)$ for MODIS data.

Appropriate thresholds (range) were determined for R_{rs} derivatives at 488 nm corresponding to four distinct classes, viz. *N. scintillans* diatoms, oceanic non-bloom, and coastal non-bloom waters. Level 3 R_{rs} images, output from SeaDAS, were imported in ERDAS Imagine image processing software to have HDF file converted into band sequential image file. Subsequently, ERDAS Modeler was used to mask land/cloud, and in the following step, class allocation was performed through checking the derivative value for each class on pixel by pixel basis. Five separate class images were generated corresponding to each scene. These were composited to a single classified image indicating distribution of the bloom species and non-bloom oceanic and coastal waters.

Results and discussion

Adequacy of R_{rs} retrieval using SeaDAS software

Normalized water-leaving radiance standardizes measured water-leaving radiance with respect to surface illumination (considering sun at zenith) and at the mean earth–sun distance, making it independent of measurement conditions. It enables comparison between the radiance values corresponding to bloom and non-bloom pixels from two different locations in vicinity.

Normalized water-leaving radiance was derived at long wavelengths (748 and 800 nm) from the radiometer profiles for an intense bloom station. This is indicated in Table 1. The corresponding radiance values were compared for non-bloom waters at the station that was not too far from the bloom station with respect to distance and time (Table 1). It can be seen from the table that the two normalized water-leaving radiance are comparable and are near to zero for bloom as well as non-bloom locations. This can be seen from Fig. 2 as well. It means that the assumption of negligible water-leaving radiance at long wavelengths holds good even for bloom waters, and hence, the approach of clear water radiance as used in SeaDAS atmospheric correction algorithm does not constrain its application. Moreover, for taking derivative, difference in R_{rs} between the two bands is considered, and therefore, one can expect that any uncertainty in retrieval of R_{rs} would be partially eliminated.

Rationale for species discrimination

Different phytoplankton types (algal blooms) react to incoming electromagnetic radiation in a unique way in terms of reflectance, i.e., the shape of the reflectance spectra is different for different phytoplankton classes. This information was inverted to detect the bloom as well as to identify its species from reflectance pattern obtained from satellite data. Spectral characteristics of the two phytoplankton types (*N. scintillans* and diatoms) and non-bloom waters in the NEAS during winter can be seen from Fig. 3. For each class spectra, an average of remote sensing reflectance was calculated from the last 12-year Satlantic™ radiometer data of bloom season. It can be seen that the shapes of all the three spectra are different because of unique reflectance properties specific to phytoplankton. However, there is a reflectance minimum in the vicinity of 450 nm (blue 450–495 nm) common in all the three plots, which mainly represents well-known primary

Table 1 Comparison between normalized water-leaving radiance (in situ) from bloom and non-bloom waters at long wavelengths (radiometer deployment between 1100 and 1300 hours)

Water type	Date	Latitude (° N)	Longitude (° E)	nL_w (Satlantic/ProSoft) ($\mu\text{W cm}^{-2} \text{ nm}^{-1} \text{ sr}^{-1}$)		Chlorophyll (mg m^{-3})	Cell density (cells L^{-1})
				748 nm	800 nm		
Intense bloom oceanic water	14 March 2013	20.95	66.17	0.007828	0.011106	27.7	Diatoms (130880), <i>N. scintillans</i> (5800000)
Non-bloom oceanic water	17 March 2013	21.76	65.38	0.010067	0.014121	1.09	Diatoms (284), <i>N. scintillans</i> (220)

absorption feature of phytoplankton. Reflectance minimum at 675 nm (secondary absorption peak) is not distinct; however, relatively lower reflectance at this wavelength can be seen and it is followed by fluorescence reflectance peak in the immediate vicinity at 680 nm. The magnitude of fluorescence peak is relatively more in the case of *Noctiluca* as compared to non-bloom waters.

Further, remote sensing reflectance can be seen increasing from 440 to 550 nm in the case of *N. scintillans* in Fig. 3. None of the other two phytoplankton types reveal this pattern. *N. scintillans* is a bioluminescent organism and emits light from 420 to 580 nm with a maximum at 470 nm (blue). A further increase in reflectance that peaks near 550 nm (green) could be due to endosymbiont of green color. Balch and Haxo (1984) have studied the variation in spectral attenuation in single-celled absorption spectra of the red variety of

N. scintillans. Observation of the difference in spectral shape between total and exclusive *Noctiluca* spectra (absorbance decreasing from 480 to 540 nm) is similar to our observations. In the case of diatoms, spectral response is relatively flat in this slot (440–550 nm, Fig. 3), and the plot for non-bloom oceanic waters reveals a decreasing trend of reflectance in this region. Reflectance is found increasing from 440 to 550 nm in the case of *N. scintillans*. This trend is different from the other classes and was utilized to identify *N. scintillans*. Overall high reflectance beyond 550 nm as compared to the same in the case of the other two classes is another feature specific to *N. scintillans*.

One more prominent feature is the secondary absorption peak, which can be seen as weak reflectance minimum at 665 nm. This is followed by a chlorophyll fluorescence peak near 680 nm.

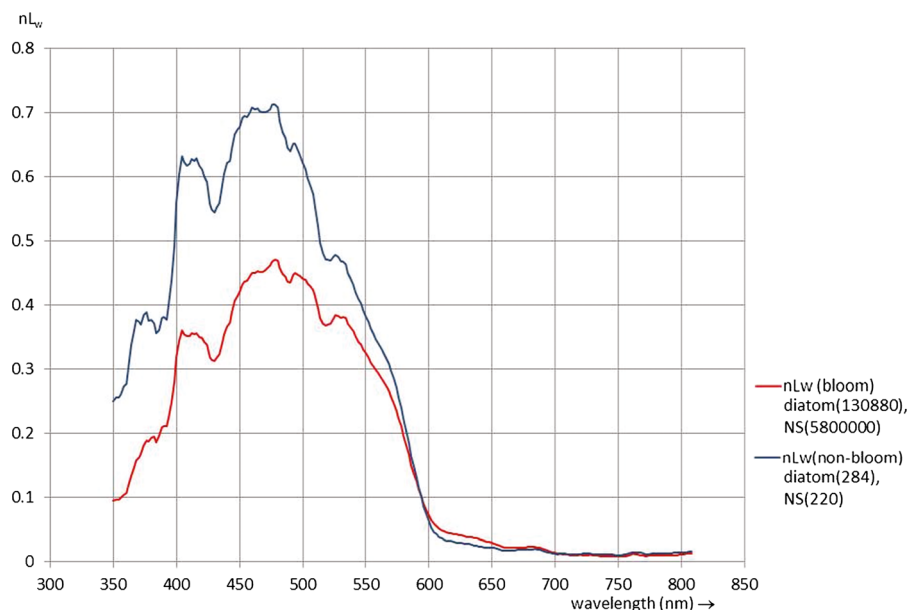
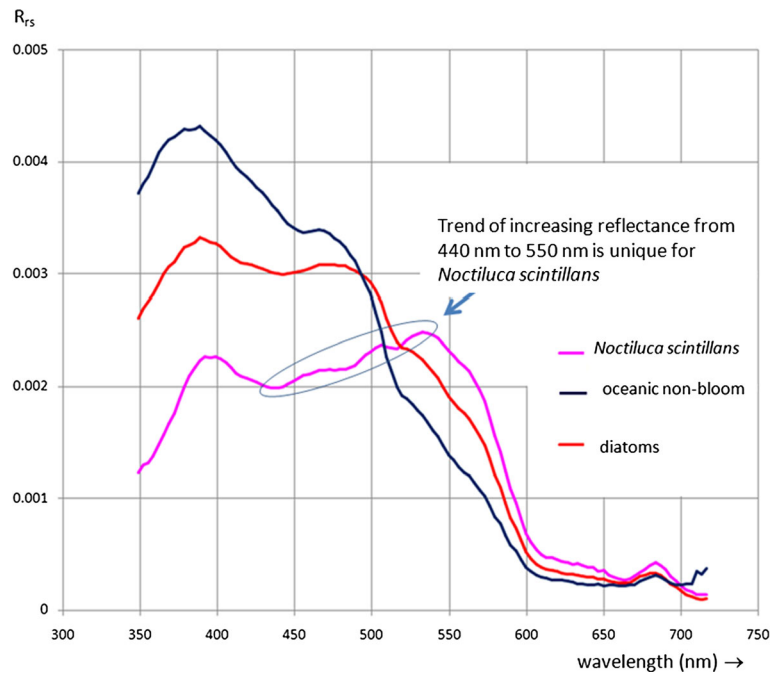
**Fig. 2** Comparison of normalized water-leaving radiance ($\mu\text{W cm}^{-2} \text{ nm}^{-1} \text{ sr}^{-1}$) from bloom and non-bloom waters

Fig. 3 Remote sensing reflectance (sr^{-1}) spectra for *N. scintillans*, diatoms, and non-bloom oceanic waters generated for NEAS waters using underwater radiometer. Difference in the spectral shapes can be noticed in the case of diatoms, *N. scintillans*, and non-bloom waters



Threshold determination for class identification

The observed difference in shapes of the reflectance spectra as shown in Fig. 3 has been utilized as a signal for detection and identification of bloom and bloom-forming species. Derivative analysis is one of the approaches to quantify spectral shape into a number, which also enhances small variability in spectral reflectance. The first derivative of the MODIS-derived reflectance was computed and plotted as a function of wavelength (Fig. 4). It can be seen that the three water categories *N. scintillans*, diatoms, and non-bloom (oceanic) are distinctly separated by the first derivative at 488 nm. These classes can be seen either inter-mixed or closely located at other wavelengths in the derivative plot (Fig. 4). Hu and others have found that uncertainty in the retrieval of R_{rs} from MODIS data increases with increase in wavelength (Hu et al. 2013). And this was the other reason for selecting derivatives at 488 nm (short wavelength) for species discrimination. Derivative for *N. scintillans* class is positive and of relatively larger magnitude at 488 nm (Fig. 4). In the case of diatom, this is of relatively smaller magnitude and is distributed on either side of origin, whereas in the case of non-bloom pixel in oceanic waters, this value is of larger magnitude on negative derivative axis.

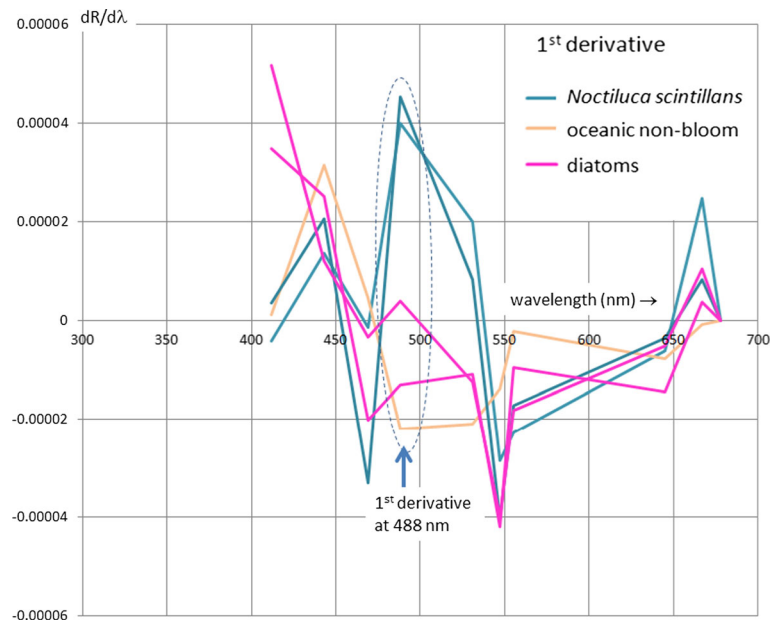
Differences in remote sensing reflectance, $R_{rs}(488) - R_{rs}(443)$ and $R_{rs}(488) - R_{rs}(531)$, for different water

types were obtained from MODIS data and plotted as shown in Fig. 5. It can be seen that four distinct non-overlapping clusters exist corresponding to the respective classes (*N. scintillans*, diatoms, non-bloom oceanic, and non-bloom coastal waters) and it enabled fixing of thresholds (range of R_{rs} differences) corresponding to each class. Thus distinct groups formed the basis for the classification scheme developed here.

Implementation of classification criteria on MODIS data

Specific ranges of derivatives were used to determine phytoplankton class on pixel by pixel basis using MODIS data of 7 March 2013 and ERDAS' Model Maker. MODIS-derived remote sensing reflectance images for 443-, 488-, and 531-nm band were used as input images, and a color-coded classified output image was generated. This can be seen in Fig. 6a. The image provides information on the distribution (spatial extent) of *N. scintillans*, diatoms, and normal (non-bloom) waters in the basin according to the step wedge. Simon and Shanmugam (2012) have presented an approach to detect *N. miliaris* bloom in the Gulf of Oman using MODIS-Aqua data. However, this bloom is not a mono-species bloom in this area, and the approach does not detect diatom bloom collocated with *N. miliaris*. *Noctiluca* does not exist in isolation, and there are

Fig. 4 First derivative spectra generated from MODIS-derived remote sensing reflectance (sr^{-1}) for different water types in NEAS during dominance of the winter bloom



reports mentioning the requirement of high concentration of phytoplankton/diatom prey to support optimal growth of *Noctiluca* (Lee and Hirayama 1992; Kiørboe and Titelman 1998; Kiørboe 2003). Thus, it is reasonable to expect diatoms in the vicinity of *N. scintillans*. The approach presented in this paper discriminates among *N. scintillans*, diatoms, and non-bloom pixels.

It is noticed from Fig. 6b that the pattern of chlorophyll closely matches with phytoplankton species as seen in the adjacent image (Fig. 6a). *N. scintillans* corresponds to relatively high chlorophyll concentration; it is moderate for diatoms and the lowest for non-bloom waters. Higher chlorophyll corresponding to *N. scintillans* may be due to the fact that *Noctiluca* cells

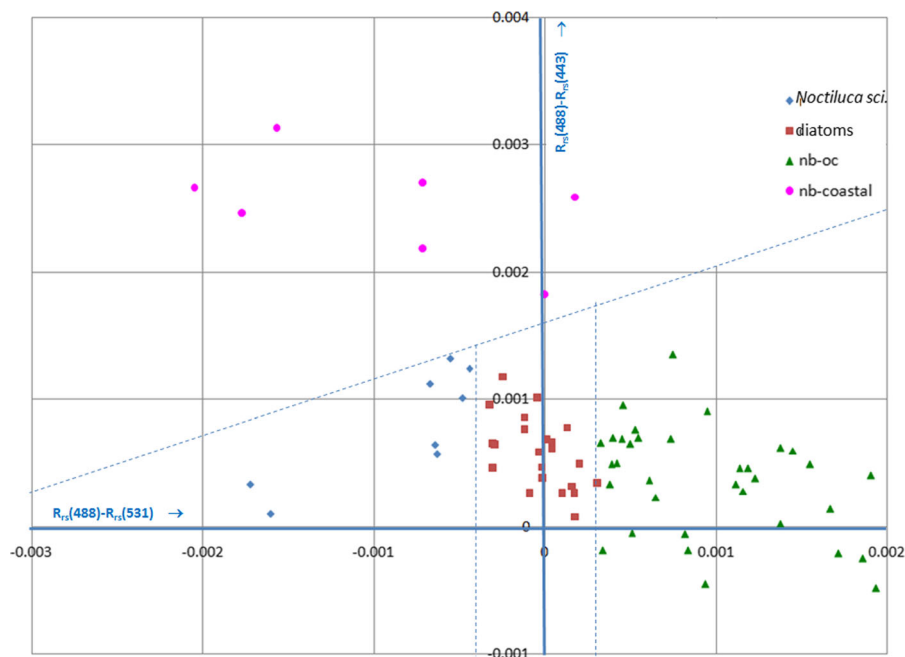


Fig 5 Distinct clusters of *N. scintillans*, diatoms, and non-bloom oceanic waters

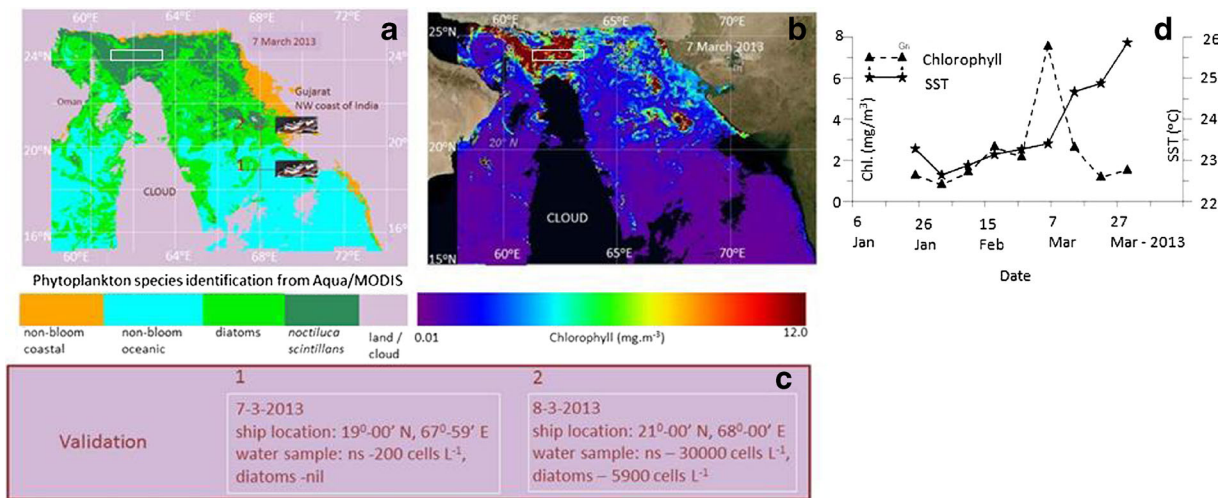


Fig. 6 **a** Image classified for phytoplankton class. **b** Chlorophyll image using MODIS/SeaDAS. **c** Phytoplankton analysis using water samples. **d** Temporal distribution of SST and chlorophyll

contain numerous green flagellate endosymbiont *Pedinomonas noctilucae* (hence, the name green *Noctiluca*). These are in abundance and therefore produce green discoloration of surface water, thereby indicating higher chlorophyll concentration.

Validation

Qualitative approach It can be seen from Fig. 6a that there is a large patch of *N. scintillans* in NWS seen in dark green color (north of 24° latitude and between 60° E and 64° E), unlike the northeastern part where *Noctiluca* distribution is patchy. Time series data on SST and chlorophyll (daily) in Fig. 6d for a box selected in the region indicate active convective mixing (SST < 23.5 °C) till the 25th of February, which gets weaker during early March as evinced with a higher SST (> 24 °C). Meanwhile, chlorophyll associated with this peak process was relatively low (< 2.5 mg m⁻³), and observed that upon relaxation of the process, the chlorophyll has increased drastically (~7 mg m⁻³). The peak value may be the reflection of the bloom we observed, and further during the second week of March, the concentration got reduced, which may be due to the increase in SST.

Observations from validation cruise Ship cruise FORV314 was conducted during March 2013 to validate the classified phytoplankton species image. It can be seen from Fig. 6c that *N. scintillans* concentration was 200 cells L⁻¹ and diatoms nil at 19°-00' N, 67°-59'

within core *N. scintillans* bloom. The white box in the figure shows the area for which time series on SST and Chl *a* is analyzed

E on 7 March 2013, indicating non-bloom waters. Location of corresponding point marked as '1' in classified image (Fig. 6a) is seen in cyan color. A step wedge at the bottom shows this color as oceanic non-bloom class, which is in agreement with ship observation.

N. scintillans and diatom concentrations were 3×10^4 and 0.59×10^4 cells L⁻¹, respectively, at 21°-00' N, 68°-00' E on 8 March 2013, indicating that the waters are dominated by *N. scintillans*. Optical response of the water is influenced by *N. scintillans*, and the location marked as '2' in phytoplankton class image (Fig. 6a) shows a dark green color. It is *N. scintillans* class according to the step wedge and thus complies with the water sample analysis. There is a point to notice that when the two species co-exist as in this case, optical response is dictated by the dominating species, for instance, *N. scintillans* suppressed the influence of diatoms.

These verifications were further substantiated with in situ reflectance spectra (Fig. 7c, d) generated from the stations 1 and 2 in Fig. 7b. Station 1 (7 March 2013) is non-bloom oceanic class according to the model output as well as phytoplankton analysis. The shape of the reflectance spectra of 7 March 2013 (Fig. 7c) matches with the reference signature of non-bloom waters generated from multiple-point average (Fig. 7a). Similarly, the spectra of 8 March 2013 (Fig. 7d) matches in shape with *N. scintillans* class in the reference plot (Fig. 7a).

In addition to the above, microscopic observations of the water sample of 16 March 2013 station (at 21° N, 66° E) revealed *N. scintillans* concentration of

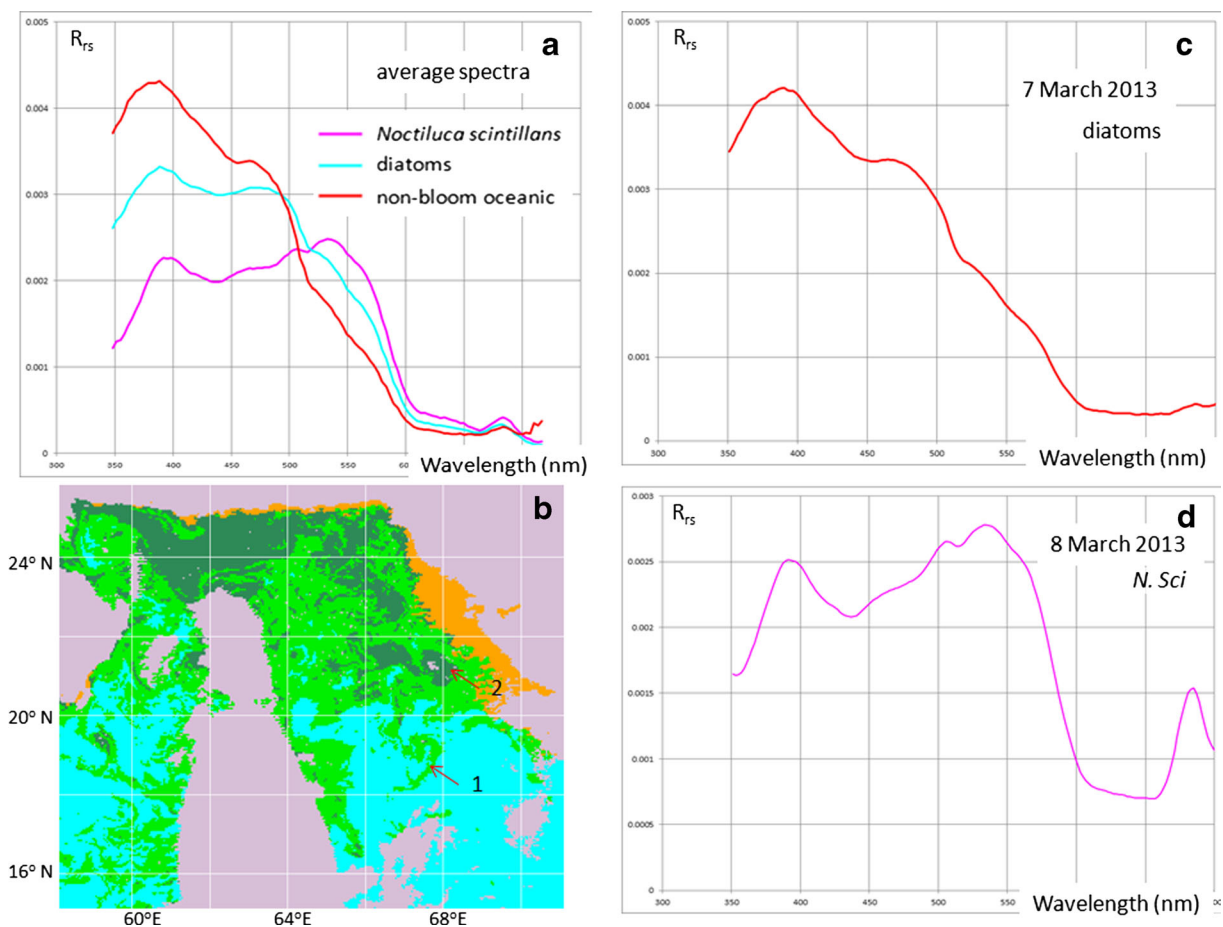


Fig. 7 **a** Typical reflectance spectra for different phytoplankton types generated from average of archived radiometer data. **b** Phytoplankton classified image. **c**, **d** Reflectance spectra generated using SatlanticTM profiling radiometer for non-bloom and

bloom stations of the validation cruise (FORV 314). Location 1 in Fig. **b** (**c**) corresponds to diatom plot, and location 2 Fig. **b** (**d**) corresponds to *N. scintillans*

1300 cells L^{-1} and diatoms of 60 cells L^{-1} . The classified image generated from MODIS data (not shown) of the same date indicated non-bloom oceanic class at this location, which is in confirmation with the ship observations. Algal bloom stations of cruise SS-298 (March 2012) were not considered for the threshold determination and were available for validation. Dominating species (according to cell density) matched with the classes identified by the remote sensing approach.

Thus, it has been demonstrated that MODIS data can be used for identification of algal bloom species in the area and during the season as mentioned above. The operational use of the technique would enable monitoring of the bloom with species-wise knowledge of its spatial distribution. It would open up several new avenues of research in the future.

The product reveals anticipated temporal variability

A set of phytoplankton class images representative of various stages of the blooms such as pre-bloom, initial, peak, and post-bloom have been generated as shown in Fig. 8. Pre-bloom scenario in the NAS can be seen in Fig. 8a). The waters are dominated by non-bloom class except small patches of diatoms in Oman waters (at 24° N, 60° E) where salinity is unusually high and slight seasonal cooling could develop weak to moderate convection. Initial stage of the bloom can be seen during early January in Fig. 8b where spatial extent of diatoms is seen sufficiently increased. This could be due to convection triggered by northeast monsoon winds. *N. scintillans* is seen in Fig. 8c along with diatoms in the vicinity. A series of ship

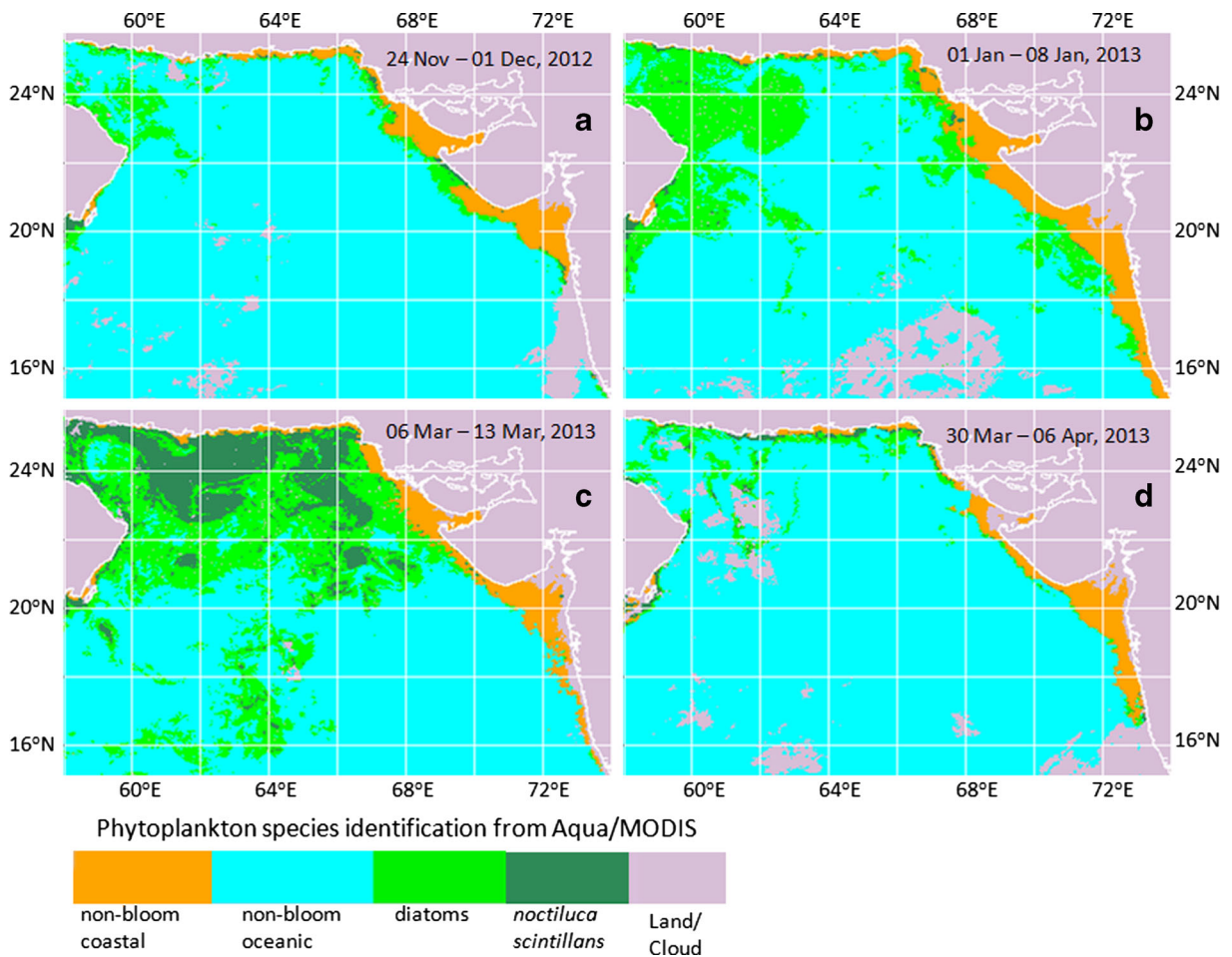


Fig. 8 a–d Phytoplankton species images reveal seasonal variations in *N. scintillans* and diatoms

cruises conducted during various stages of the bloom have indicated this period as a peak phase of green *Noctiluca*. Laboratory studies have reported that diatoms are prey for *N. scintillans*, and hence, its growth follows diatoms (Buskey, 1995; Zakaria and Ibrahim 2007; Gomes et al. 2010). Figure 8d represents post-bloom period of the bloom, and the waters of the northern basin is assigned non-bloom class. Thus, the approach of detection and species identification of the blooms from remote sensing data reveals the anticipated temporal variability.

Conclusion

NAS holds the bloom waters of mixed species, which co-exist. Remote sensing-based approach to detect algal

blooms in the Northern Arabian Sea during winter and species discrimination has been developed and proven here. Synchronous in situ water sample analysis from bloom and non-bloom waters were found matching with the classification results from MODIS-derived product. The classified output image provides knowledge of distribution of *N. scintillans* and diatoms in space and time. A product like this would facilitate the study of various biological aspects of the bloom.

It is envisaged that operational use of the classified images as presented here would help the exploration of fishery resources in the offshore waters as well as facilitate planning of ship cruises in the future for biological research. Development of the approach and availability of MODIS data with 1-day repeat cycle would also enable the implementation of satellite-based harmful algal bloom monitoring system in the NAS.

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