TEHNICAL REPORT **Report No.:** ESSO/INCOIS/ASG/TR/11(2016)

An optical approach for synoptic monitoring of red *Noctiluca scintillans* bloom and its associates from space

by

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HYDERABAD, INDIA
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20 SEPTEMBER, 2016

DOCUMENT CONTROL SHEET

Earth System Science Organization (ESSO)
Ministry of Earth Sciences (MoES)
Indian National Centre for Ocean Information Services (INCOIS)

ESSO Document Number: ESSO/INCOIS/ASG/TR/11(2016)

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Originating unit: Advisory Services and Satellite Oceanography Group (ASG), INCOIS

Type of Document: Technical Report (TR)
Number of pages and figures: 14, 7
Number of references: 30

Keywords: algal bloom, diatom, red *Noctiluca*, green *Noctiluca*, remote sensing, Bay of Bangal

Security classification: Open
Distribution: Open
Date of publication: 20 September, 2016

Abstract (100 words)
Reddish discoloration of coastal waters along the east coast of India at latitude 19.3 was observed during April 2014. Phytoplankton analysis revealed presence of Red *Noctiluca scintillans* cells in the water samples. A technique of detecting green *Noctiluca scintillans* was developed earlier, which is based on the principle of recognition of spectral shapes remote sensing reflectance spectra for Aqua-MODIS bands. This was appropriately modified to detect red *Noctiluca* in the coastal waters of the bay of Bengal. Phytoplankton species images generated using the modified approach were validated using information on reported events of red and green *Noctiluca* in the coastal waters. In addition to this, the study reported here highlights two major developments. One is, the classified species image reveals co-existence of diatom, red and green *Noctiluca* in coastal waters of the east coast and the second, it has been demonstrated with satellite time-series images that red *Noctiluca* succeeds diatom.

ABSTRACT

Reddish discoloration of coastal waters along the east coast of India at latitude 19.3 was observed during April 2014. Phytoplankton analysis revealed presence of Red *Noctiluca scintillans* cells in the water samples. Time-series *in situ* measurements were taken at this location and it was found that the cell density varied from $34x10^4$ to $2x10^4$cells.l^{-1}. A technique of detecting green *Noctiluca scintillans* was developed earlier, which is based on the principle of recognition of spectral shapes remote sensing reflectance spectra for Aqua-MODIS bands. This was appropriately modified to detect red *Noctiluca* in the coastal waters of the bay of Bengal. The classification scheme also discriminates red *Noctiluca* from green *Noctiluca* and diatom. Phytoplankton species images generated using the modified approach were validated using information on reported events of red and green *Noctiluca* in the coastal waters. In addition to this, the study reported here highlights two major developments. One is, the classified species image reveals co-existence of diatom, red and green *Noctiluca* in coastal waters of the east coast and the second, it has been demonstrated with satellite time-series images that red *Noctiluca* succeeds diatom.

Introduction

Phytoplankton booms in ocean are the rapid increase in species cell density over time which is observed in world ocean in past decade (De Baar et al. 1995; Coale et al. 1996; Vinayachandran, P. N., & Mathew, Dwivedi eta l. 2016, Baliarsingh et al. 2016). The phytoplankton blooms are more often mono-specific and sometimes caused by mixture of species. Variation of oceanographic environmental variables triggers phytoplankton growth leading to bloom (Anderson et al. 2002). Intense phytoplankton blooms have adverse impacts on marine ecosystems and fishery resources (Naqvi et al. 1998). *Noctiluca scintillans* (hereafter *Noctiluca*), a bloom forming dinoflagellate forms red as well as green tide in various parts of world ocean. The red tides are caused by red forms of *Noctiluca* species with complete heterotrophy mode of feeding by predating upon a wide array of other phytoplankton with utmost preference of diatom and small zooplankton. Though it is a non-toxic bloom can result in fish mortality during its degradation stage depleted oxygen in the waters and increased level of ammonia. Red *Noctiluca* is heterotrophic and diatom is its preferred food, also feeds on microzooplankton. In the contrary, the green forms of *Noctiluca* gives shelter to a prasinophyte "*Pedinomonas noctilucae*" which resides within the cell of *Noctiluca* as endosymbiont and transfers energy to the host by means of photosynthesis (Madhu et al. 2012). In general, *Noctiluca* blooms puts significant influence on the food chain by voraciously predating upon species of both first and second trophic level during heterotrophy as well as rapidly utilizing nutrients of the ambient medium during endosymbiotic autotrophy (Baliarsingh et al. 2016;

Padmakumar et al. 2016). Red Noctiluca reported in this study discolored coastal waters of the northeast coast of India in brown to dull red during April 2014 and persisted for 12 days. Taxonomic analysis confirmed presence of red NS, cell den. 0.15 – 32.87×10^4 cells.l^{-1}. Earlier Mohanty et al. 2007 had reported report of ‘red tide’ formation by *Noctiluca scintillans* during April 2005 at the same location of the observation of 2014. In some regions of world ocean, recurrent bloom of *Noctiluca* have been observed. Arabian Sea, the northeastern part of Indian Ocean is experiencing annual episodes of green *Noctiluca* bloom in the offshore region during winter (Gomes et al. 2014). In similar, events of red *Noctiluca* bloom are of occurrence specifically in the coastal waters of the Bay of Bengal, east coast of India. (Baliarsingh et al. 2016) . The ecological consequence of both forms of *Noctiluca* blooms is observed to deteriorate ambient water quality. Hence, regular spatio-temporal monitoring of *Noctiluca* bloom is imperative to understand the preconditioning factors, onset, sustenance, termination and subsequent environmental consequences of *Noctiluca* bloom. As like most of the phytoplankton species, both forms of *Noctiluca* also have unique spectral signatures according to the dominant light absorbing pigment. Hence, optical detection of *Noctiluca* using ocean colour remote sensing datasets provides scope of synoptic monitoring (Van Mol et al. 2007; Simon & Shanmugam 2012; Dwivedi et al. 2015). The bio-optical algorithm for remote detection of green form of *Noctiluca* have been found useful in studying the bloom dynamics of Arabian Sea (Dwivedi et al. 2015; 2016). The same algorithm is operational at Indian National Centre for Ocean Information Services (Government of India) for monitoring of green *Noctiluca* bloom in Arabian Sea and Bay of Bengal (http://www.incois.gov.in/portal/ChloroGIN). In comparison to green *Noctiluca*, the optical detection of red form needs careful assessment due to heterotrophy mode of ecology. Hence, the intracellular content, specifically the diet often determines the optical properties (Van Mol et al. 2007). Based on the requisite of remote detection algorithm for red *Noctiluca*, an approach for satellite based automated algorithm for operational detection and monitoring of red *Noctiluca* bloom in Indian waters was developed and implemented on MODIS data of 16 April 2014. This species was detected in coastal waters of the east coast of India (19.3°N, 85.°E) during time-series *in situ* measurements (13-27 April, 2014) as a part of this centre's on-going research project SATCORE. Earlier, Mohanty et al. (2007) had reported this bloom in the Bay of Bangal on 5 April 2005 at the same location. MODIS-Aqua derived species image for this date revealed presence of this bloom as well.

Materials and methods

Phytoplankton analysis:

Time-series *in situ* measurements were taken in the coastal waters of east coast of India during 2014 to include biological, physical, chemical and optical parameters. The measurements were taken at regular interval from 1000 to 1400 hours and the data matching with equatorial crossing time of MODIS-Aqua (1330 hours) were considered for development of the species identification approach.

In situ radiometric data:

In-water upwelling/downwelling radiance/irradiance in a range of 350 - 800 nm were collected from the noctiluca infested regions off the Rushikulya estuary in north-western Bay of Bengal using free-falling optical profiler of Satlantic hyperspectral radiometer. Location of this time-series station is shown in Figure 1. SatView™ software was used for data logging and Prosoft™ for raw data processing to different data levels.

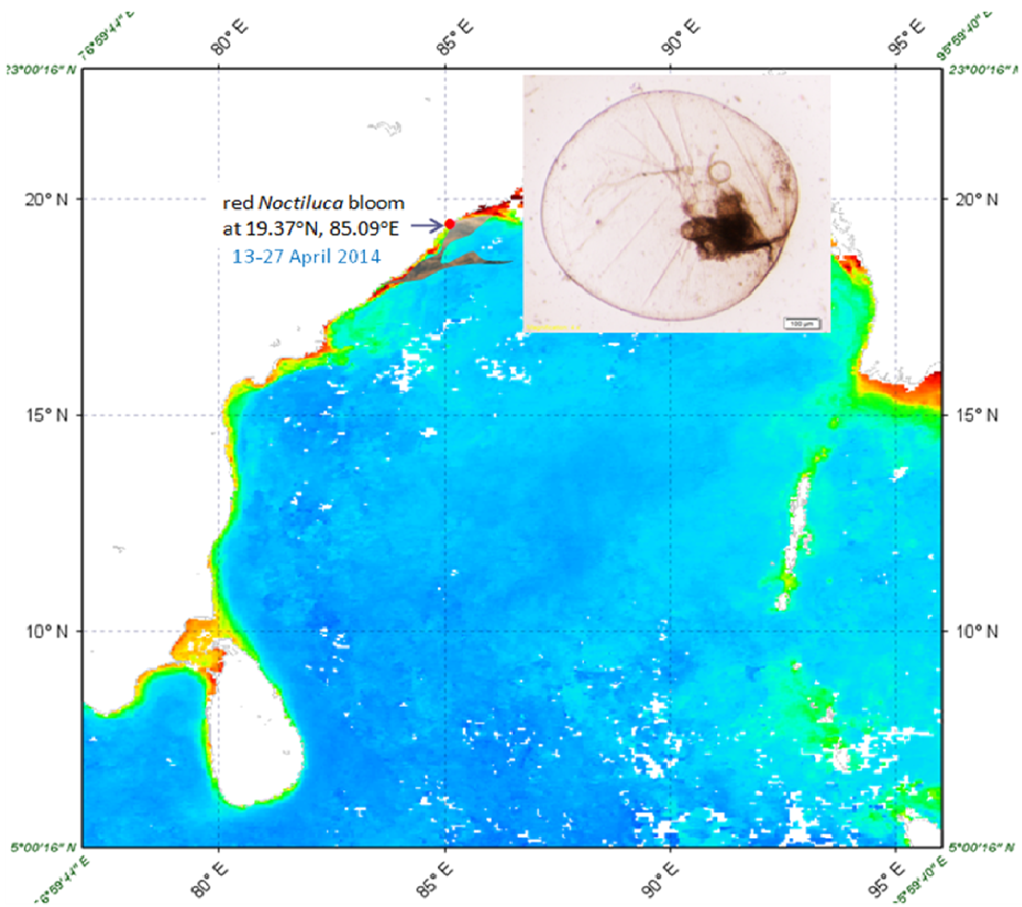

Figure 1. Location showing time-series is situ measurements

Satellite data processing:

The at-surface remote sensing reflectance (R_{rs}) at 443, 488, 531, 667 and 678 nm bands (MODIS-Aqua Level 2 and 3) were downloaded from NASA's OceanColor Web (http://oceancolor.gsfc.nasa.gov) for the dates corresponding to the reported occurrences of red Noctiluca (Mohanty et al. 2007, Sahayak et al. 2005, Padma kumar et al. 2010 and phytoplankton data from FORV *Sagar Sampada* cruise No. 343).

These products make use of NIR bands (MODIS-Aqua 748 and 869 nm) for atmospheric correction. Aerosol optical depth is estimated based on the long wavelength approach developed by Gordon and Wang (1994). Rrs spectra were generated for the specific locations of the reported blooms of this species. An approach of detecting green *Noctiluca* developed earlier (Dwivedi et al. 2015), which considered differential remote sensing reflectance at 488 nm and 531 nm bands was found working for red *Noctiluca* also. However, it did not discriminate between the two. Characteristics of red *Noctiluca* of prominent back scatter in the red bands (645, 667 and 678 nm) was utilized to distinguish red *Noctiluca* from the green. The approach to detect and discriminate red *Noctiluca* was validated using the information on occurrence of this bloom in the Bay of Bengal during April 2014 (Baliarsingh et al. 2016).

Results and discussion

Reasons for the occurrence of Red *Noctiluca*:

Red *Noctiluca scintillans* bloom was detected in the coastal waters of northeast coast of India during 13-27 April 2014. In the Bay of Bengal, East India Coastal Current (EICC) flows northeastward from February until September with a strong peak in March–April (Schott and McCreary 2001). Coriolis force acting on moving particle on the earth is directly proportional to its velocity with respect to rotating system. And therefore, high magnitude EICC in April effect Ekman transport of the water mass along the coast to cause upwelling and nutrient transport subsequently. Signature of cool water due to coastal upwelling around 19^{o} north latitude (SST image) and resulting higher level of productivity (chlorophyll image) can be seen in satellite images of 5 April 2005 in Figure 2.

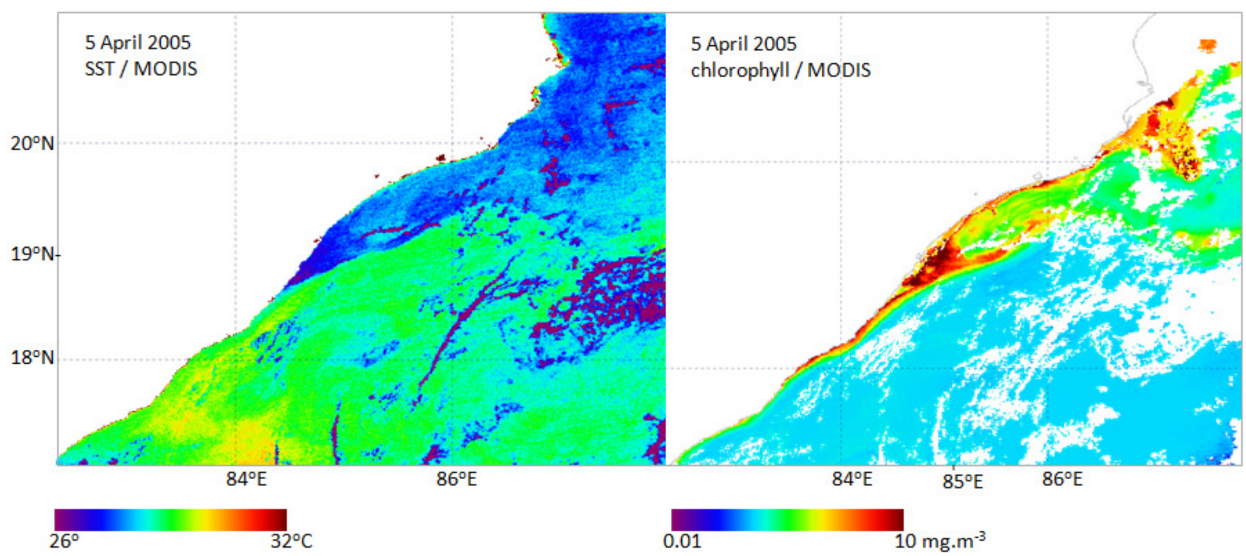

Figure 2. Signature of coastal upwelling 19^{o} north latitude

Abundance of nutrients, particularly silicate, leads to formation of diatom and red as well as green *Noctiluca* feed voraciously on phytoplankton (especially diatoms being the favored prey) by phagotrophy (Baliarsingh et al. 2016). Moreover, Sahayak et al. (2005) have mentioned suitability of relatively low temperature for triggering the red *Noctiluca* bloom. Mohanty et al. (2007) also recorded a relatively low sea-water temperature of 28.5°C was during the bloom period (April 2005) compared to that in March and May. Red Noctiluca observed in the Bay of Bengal during 16 April 2014 (this paper) also revealed sea surface temperature of 28.35°C and the bloom and the cell density decreased over a period of time (3.4×10^5 cells.l^{-1} on 13 April to 0.2×10^5 cells.l^{-1} on 27 April) when the surface temperature increased during when the prevailing upwelling turned weak.

Technique development for detection of Red *Noctiluca*:

Upwelling radiance and downwelling irrdaiance were measured using a profiler of Satlantic hyper spectral radiometer on 13April 2014 when red *Noctiluca* bloom was at the peak in the coastal waters of east coast of India. Discrete R_{rs} spectra corresponding to MODIS bands using the radiometer is presented in Figure 3(A).

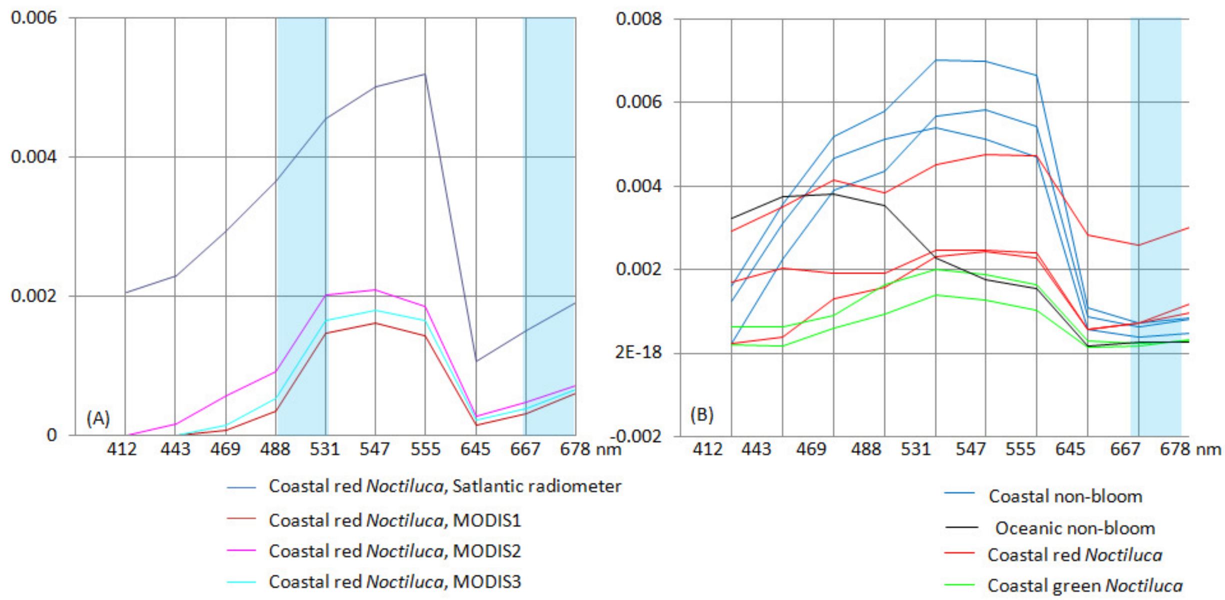

Figure 3. (A) Discrete R_{rs} spectra corresponding to MODIS bands using the radiometer (B) Typical R_{rs} spectra for red, green Noctiluca and non-bloom waters (coastal and oceanic)

MODIS R_{rs} data downloaded from NASA's OceanColor Web were also plotted for the bloom waters and are included in the figure. The spectra in red colour (MODIS1) in Figure 3(A) is for the same date and location where the radiometer was operated. Other two spectra labeled as MODIS2 and MODIS3 are also for the coastal red *Noctiluca* in vicinity. It can be noticed that MODIS R_{rs}, which is derived using standard long wavelength atmospheric correction scheme is underestimated over all. However, shape of the spectra are still similar. Phytoplankton species detection approach developed for green *Noctiluca* (Dwivedi et al. 2015) and the one for red *Noctiluca* (this paper) checks for the slopes (R_{rs} differences) of the segments from 488 nm to 531 nm and 667 nm to 678 nm and compares with a set of values determined from the archived data on different classes like red/green Noctiluca, diatom, non-bloom oceanic, non-bloom coastal waters etc.. The slope values are found matching in both the cases, Satlantic radiometer and MODIS-derived spectra. In other words, amplitude of the ranges for slopes are wide enough to absorb the uncertainty in R_{rs} retrieval with use of standard atmospheric correction method in the coastal environment.

The absorption spectra for *Noctiluca* reveals absorption peak at 488 nm and sharper decrease from 520 nm to 580 nm (Barbara et al. 2007). This causes relatively lower R_{rs} at 488 nm and higher at 531 nm. This can be seen as increasing trend of R_{rs} from 488 nm to 531 nm in case of *Noctiluca* unlike the class of oceanic non-bloom waters (Figure 3(B)). This trend is unusual and specific to Noctiluca. Though coastal non-bloom spectra (in blue colour) also reveal increasing trend of R_{rs} from 488 nm to 531they can be discriminated from *Noctiluca* using their high value of slope from 443 nm to 488 nm.

In the next step, spectra for green *Noctiluca* were discriminated from red using 667 nm and 678 nm bands. The fact that carotenoid (red pigment) dominates in red *Noctiluca*, was exploited to distinguish it from green. MODIS bands in the red were used for this purpose. There is a slight decline in R_{rs} at 667 nm usually due to secondary absorption peak of chlorophyll and absorption by water. However when red *Noctiluca* is present R_{rs} is significantly higher at 678 nm due to back scattering from red pigment. Thus, slope of the segment from 667 nm to 678 nm is relatively more in case of red *Noctiluca*. Green *Noctiluca* reveals almost a flat response in these red bands (Figure 3(B)).

Technique validation:

Phytoplankton analysis of the samples collected during time-series *in situ* data in the coastal waters of east coast of India (13-27 April 2014) revealed red tide of *N. scintillans* at 19.27^{o}N, 84.99^{o}E. Phytoplankton species image was generated from MODIS Level2 data using an approach developed here for 16 April 2014. The species classified image confirmed presence of red *Noctiluca* at the same location.

In an another comparison; Phytoplankton species image was generated from MODIS data for 5 April 2005. Mohanty et al. (2007) had detected red tide of *N. scintillans* at 19.37^{o}N, 85.03^{o}E with density 3x10^{5} cells.l^{-1} on the same day. The processed data in Figure 3(B) reveals a signature of red *Noctiluca* at this location.

Role of water temperature:

Upwelling resulting from EICC/WBC along the east coast in April causes diatom bloom due to prevailing nutrient-rich waters. Diatom is a favored prey for red *Noctiluca* and availability of prey, is a necessary condition for its growth. However, it is not a sufficient condition.

16 April 2014 image (Figure 4(A)): Sea surface temperature estimated was in a range 27.5° – 28.5°C during 13-27 April at the location where this bloom occurred. A prominent patch of red *Noctiluca* in Figure 4(A) corresponds to SST of 28.5°C. Also, the cell density of red *Noctiluca* was found decreasing (3.4×10^5 to 0.2×10^5 cells.l^{-1}) with increase of temperature from 27.6° to 29.6°C during time-series measurements from 13 to 27 April 2014.

5 April 2005 image (Figure 4(B)): Mohanty et al. (2007) have mentioned about a relatively low temperature as positive factor for causing this bloom. They have recored a relatively low sea-water temperature of 28.5°C was observed in April when the bloom flourished.

9 April 2003 image (Figure 3(C)): The coastal waters were warm (> 29°C) and red *Noctiluca* occurred only with thin spread very close to the coast where the waters were relatively cooler. Red Noctiluca did

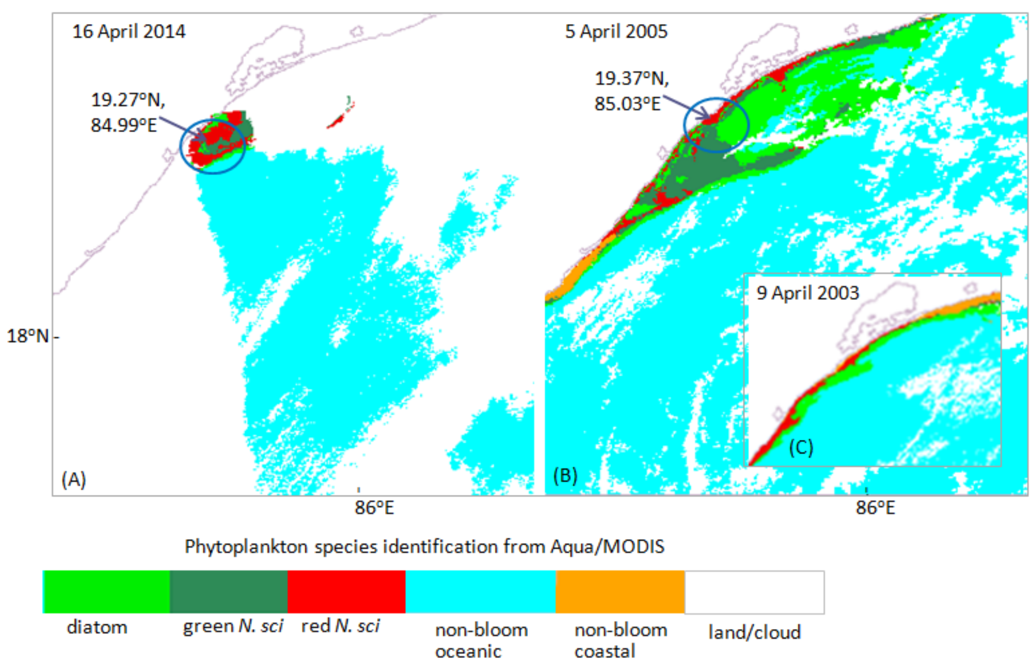

Figure 4. Phytoplankton species images generated from MODIS data

not develop in a larger patch even though diatom (prey) was available as seen with light green colour in Figure 3(C).

Elbrachter and Qi (1998) have mentioned that temperature affects mean doubling time of the cells. This is the reason, though coastal upwelling in summer in Bay of Bengal is a recurring process, red *Noctiluca* does not occur every year or occurs in small patches of short duration that remains un-noticeable.

Red and green *Noctiluca* co-exist with respect to space and time:

Red and green *Noctiluca* occur in the Indian coastal waters and Gulf of Oman at the same location but at different times. Green *Noctiluca* occur in the high productivity upwelling waters while red *Noctiluca* develops in the more oligotrophic warmer waters (Devassy 1989, Harrison et al. 2011). However, while processing MODIS data of 5 April 2005 and 16 April 2014 to observe ship-confirmed red *Noctiluca* (Figure 4) presence of green *Noctiluca* was also detected in vicinity. It Indicates that the two species co-exist at the same time also. The following discussion is to substantiate this finding.

Gopakumar et al. (2009) have reported green *Noctiluca* ($13.5x10^5$ cells.l^{-1}) in the coastal waters of Gulf of Mannar (southeast coast of India) during 2-10 October 2008. There is yet another report of green *Noctiluca* in the coastal waters of Bay of Bengal. Eashwar *et al.* (2001) observed *Noctiluca* in Port Blair Bay in July 2000 which turned the coastal waters to vivid green colour. On the west coast of India, Bindu et al. (2014) have observed Dinoflagellate green *Noctiluca* in the coastal waters of mangalore (west coast of India) on 12th May 2011. In short, green *Noctiluca* does occur in the coastal waters of both coasts of India. MODIS data were processed for identification of green *Noctiluca* reported by Gopakumar et al. (2009). It confirmed presence of green *Noctiluca* in these areas and can be seen in Figure 5 (2 and 9 October 2008 image).

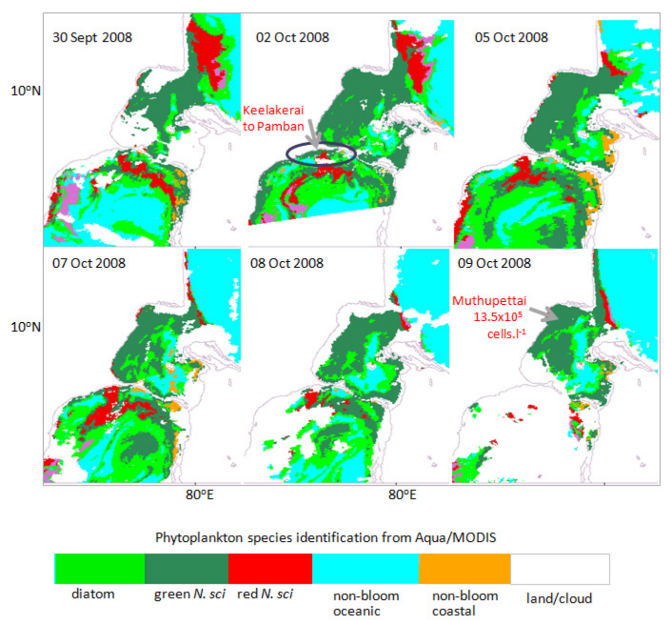

Figure 5. Detection of green Noctiluca in the coastal waters of SE coast of India

This establishes that the technique of detecting green Noctiluca (Dwivedi et al. 2015) performs in the coastal waters of Bay of Bengal also.

Green as well as red *Noctiluca* are associated with high productivity caused due to convection / upwelling. Both are voracious predators and requires abundant food supply of mainly phytoplankton and diatoms in order to maintain its high growth rate (Schaumann et al., 1988; Nakamura, 1998, Elbrachter and Qi 1998). It is visible from a classified image of 5 April 2005 in Figure 4(B,C) that diatom is extensively spread over the neighboring area and is available to both the species.

Another major environmental governing distribtion and abundance of these species is water temperature. Harrison et al. (2011) have documented a range of 25-50^{o}C for green *Noctiluca*. Gopakumar et al. (2009) have mentioned about 29.5^{o}C during waning phase of green *Noctiluca* in southeast coast of India. Sulochanan et al. (2014) have reported temperatures in 28.3-33^{o}C range for green *Noctiluca* in the coastal waters of west coast of India. As regards the red *Noctiluca*, Harrison et al. (2011) have a range of 29-30^{o}C. Mohanty et al. (2007) observed red *Noctiluca* in the coastal waters of east coast at 28.5^{o}C. The same species was observed at the same location on 16 April 2014 and water temperature was 28.8^{o}C. Thus, there is no exclusive temperature requirement for any of the species that could conflict their co-existence and both the species can occur at the same time as far as favorable temperature is concerned.

Sea surface temperatures were read for green as well as red *Noctiluca* pixels of 5 April 2005 image (Figure 4) and they were found in the range of 28-29^{o}C irrespective of species. Finally, reference spectra were generated for red and green *Noctiluca* by taking average of R_{rs} for confirmed ship detection. This is shown with broken lines in red and green colour in Fogure 6 corresponding to red and green *Noctiluca* respectively.

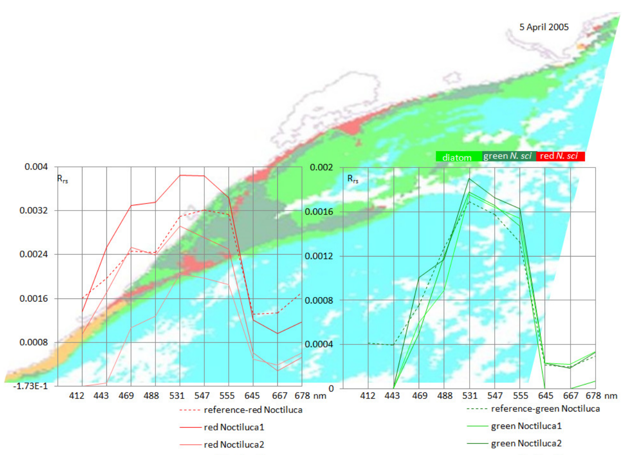

Figure 6. Reference R_{rs} spectra (discrete) for red and green Noctiluca and for the pixels for these species from 5 April 2005 image

On this, spectra from red and green *Noctiluca* pixels from 5 April 2005 image were superimposed. It can be seen from the figure that though magnitudes of R_{rs} are different from the same for reference spectra the spectra shapes are similar. In other words, range of the slopes for the segments 488-531 nm and 667-678 nm coincides with the reference spectra. With these verification, there is a reason to believe that the two species can occur at the same time in vicinity. While ship observations are restricted to finite distances, a synoptic coverage of satellite images and the species identification techniques enables this understanding. It is hypothesized that when the prey (diatom) is consumed locally, red *Noctiluca* might be giving shelter to symbiont Pedinomonas noctilucae (Prasinophyceae) and would appear green.

Red/green *Noctiluca* succeeds diatom:

Noctiluca scintillans blooms are known to occur after diatom blooms (Kiørboe, 1998; Tiselius and Kiorobe, 1998; Dela-Cruz et al., 2002). Diatom can proliferate when nutrients are available immediately after upwelling or convection even in the turbulent waters, whereas *Noctilua* prefers stable (Dwivedi et al. 2016) and specific water temperature. Temporal profile of SST (at 19.37^{o}N, 85.03^{o}E) in Figure 7(A) reveals intense upwelling during 22-29 March 2005. Corresponding SST image in Figure 7(B) confirms signature of upwelling. By the time upwelling/convection ceases and water starts warming; diatom has fully developed. Availability of prey (diatom) and conducive temperatures triggers the red/green

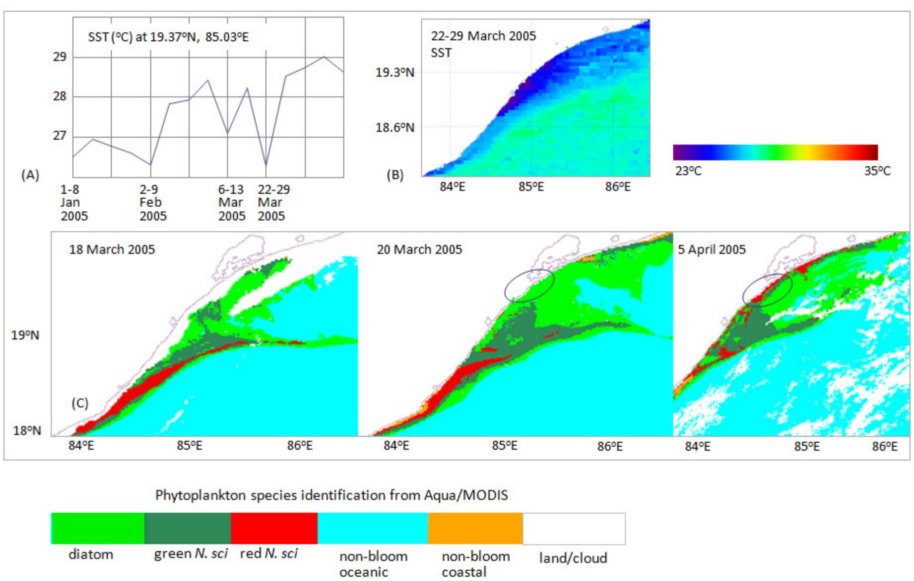

Figure 7. (A) SST, temporal profile at the site of time-series measurements (B) SST image for the period of intense upwelling (C) multi-date algal blooms distribution

Noctiluca growth. This sequence has been shown with multi-date phytoplankton species images generated from remote sensing data in Figuer 7(C). Signature of diatom can be seen within the marked ellipse in

Figure 7(C) as a consequence of prevailing upwelling (Figure 7(B)). This bloom is seen replaced by red and green Noctiluca in 5 April 2005 image; after a period of about two weeks. It is believed that the favored prey (diatom) is available and water temperature is 28.5^{o}C, which is suitable for *Noctiluca* growth.

Early detection of red *Noctiluca*:

The fact that *Noctiluca* blooms usually occur after eutrophication-induced diatom blooms and diatoms provide the abundant prey required for *Noctiluca* growth; the following two situations serve as an advanced indicator for *Noctiluca*,

(i) availability of diatom, early signal and (ii) detection of specific temperature, both these using remote sensing data.

Conclusion

The approach for species detection makes use of R_{rs} spectral differences and not the absolute vales and hence, the standard atmospheric correction scheme that uses long wavelengths was adequate in normal coastal waters. Red and green *Noctiluca* were found to co-exist in the coastal waters of Bay of Bengal at the same time. Sequential appearance of diatom and *Noctiluca* could be demonstrated with multi-date images classified for species.

References

Anderson D.M., Glibert P.M., Burkholder J.M. Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. Estuaries. 2002;25:704–726.

Baliarsingh, S. K., Lotliker, A.A., Trainer, V.L., Wells, M.L., Parida, C., Sahu, B.K., Srichandan, S., Sahoo, S., Sahu, K.C. & Sinivasa Kumar, T. Environmental dynamics of red Noctiluca scintillans bloom in tropical coastal waters. Marine Pollution Bulletin. (2016) doi:10.1016/j.marpolbul.2016.06.103

Barbara Van Mol, Kevin Ruddick, Rosa Astoreca, YoungJe Park and Bouchra Nechad, 2007, Optical detection of a *Noctiluca scintillans* bloom, EARSeL eProceedings 6: 130-137

Coale, K. H., Johnson, K. S., Fitzwater, S. E., Gordon, R. M., Tanner, S., Chavez, F. P., ... & Steinberg, P. (1996). A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. Nature, 383(6600), 495-501.

De Baar, H. J., De Jong, J. T., Bakker, D. C., Löscher, B. M., Veth, C., Bathmann, U., & Smetacek, V. (1995). Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean.

Dela-Cruz, J., Ajani. P., Lee, R., Pritchard, T., Suthers, I., 2002, Temporal abundance patterns of the red tide dinoflagellate *Noctiluca scintillans* along the southeast coast of Australia. *Mar. Ecol. Prog. Ser.*, **236**: 75-88.

Devassy, V P., 1989, Red tide discoloration and its impact on fisheries. *In*: Okaichi T, Anderson D M, Nemoto T eds. Red Tides: Biology, Environmental Science, and Toxicology. Elsevier Science Amsterdam, Netherlands. p.57-60.

Dwivedi, R., M. Rafeeq, B. R. Smitha, K. B. Padmakumar, Lathika Cicily Thomas, V. N. Sanjeevan, Prince Prakash, and Mini Raman. Species identification of mixed algal bloom in the Northern Arabian Sea using remote sensing techniques. Environmental monitoring and assessment 187, no. 2 (2015): 1-11.

Dwivedi, R., Priyaja, P., Rafeeq, M., & Sudhakar, M. (2016). MODIS-Aqua detects Noctiluca scintillans and hotspots in the central Arabian Sea. Environmental monitoring and assessment, 188(1), 1-11.

Eashwar, M., T. Nallathambi, K. Kuberaraj and G. Govindarajan, 2001. *Noctiluca* blooms in Port Blair Bay, Andamans. *Curr. Sci.,* 81(2): 203-205

Elbrachter, M., and Qi, Z. Y., 1998, Aspect of Noctiluca (Dinophyceae) population dynamics. In D. M. Anderson, A. D. Cembella, & M. G. Hallegraeff (Eds.), Physiological ecology of harmful algal blooms. NATO ASI series (Vol. 41, pp. 315–335). Berlin: Springer

Gomes, H. D. R., Joaquim, I. G., Matondkar, S. G. P., Edward, J. B., Basu, S., Parab, S. and Thoppil P., "Nature Communications 5, Article number: 4862 (2014). doi:10.1038/ncomms5862.

Gopakumar, G., Bindu Sulochanan and Venkatesan. V., 2009, Bloom of *Noctiluca scintillans* (Macartney) in Gulf of Mannar, southeast coast of India, Journal Mar. Biol. Ass. India, 51(1): 75 - 80

Gordon, H. R., & Wang, W. (1994). Influence of oceanic whitecaps on atmospheric correction of SeaWiFS. Applied Optics 33, 7754–7763. http://dx.doi.org/10.1364/ao.33.007754

Harrison, P.J., Furuya, K., Glibert, P.M., Xu, J., Liu, H.B., Yin, K., Lee, J.H.W, Anderson, D.M.,Gowen, R., Al-azri, A.R., Ho, A.Y.T., 2011, Geographical distribution of red and green Noctiluca scintillans, Chinese Journal of Oceanology and Limnology, Vol. 29, No. 4: 807-831

Hu, C. “A Novel Ocean Color Index to Detect Floating Algae in the Global Oceans,” Remote Sensing of Environment, Vol. 113, No. 10, 2009, pp. 2118-2129. doi:10.1016/j.rse.2009.05.012

Kiørboe, T., 1998, Intensive aggregate formation with low flux during an upwelling-induced diatom bloom, Limnol. Oceanogr., 43, 104–116.

Kiorboe, T., Tiselius, P., Michell-Innes B, Hansen, J.L.S, Visser, A.W, Mari, X., 1998, Intensive aggregate formation but low vertical flux during an upwelling induced diatom bloom. *Limnol. Oceanogr.*, **43**: 104-116.

Madhu, N. V., Jyothibabu, R., Maheswaran, P. A., Jayaraj, K. A., Achuthankutty, C.T. Enhanced chlorophyll a and primary production in the northern Arabian Sea during the spring intermonsoon due to green Noctiluca (*N. scintillans*) bloom. Mar. Biol. Res., vol.8; 2012; 182-188.

Mohanty, A.K., Satpathy, K.K., Gouri Sahu, Sasmal, S.K., Sahu, B.K. and Panigrahy, R.C., 2007, Red tide of *Noctiluca scintillans* and its impact on the coastal water quality of the near-shore waters, off the Rushikulya River, Bay of Bengal, Current Science, Vol. 93, No. 5, 616-618.

Nakamura Y. 1998. Biomass, feeding and production of *Noctiluca scintillans* in the Seto Inland Sea, Japan. *J. Plankton Res*., **20**: 213-222.

Naqvi, S.W.A., George, M.D., Narvekar, P.V., Jayakumar, D.A., Shailaja, M.S., Sardesai, S., Sarma, V.V.S.S., Shenoy, D.M., Naik, H., Maheswaran, P.A., Krishnakumari, K., Rajesh, G., Sudhir, A.K., Binu, M.S., 1998. Severe fish mortality associated with ‘red tide’ observed in the sea off Cochin. Curr. Sci. 75, 543–544.

Padmakumar, K.B., SreeRenjima, G., Fanimol, C. L., Menon, N. R. and Sanjeevan, V. N., 2010, Preponderance of heterotrophic *Noctiluca scintillans* during a multi-species diatom bloom along the southwest coast of India, International Journal of Oceans and Oceanography, Vol. 4, No.1: 55-63

Padmakumar, K.B, Lathika, CT, Vimalkumar, KG, Asha Devi, CR, Maneesh, TP, Vijayan, A., Gupta, GVM., Sudhakar, M. Hydrobiological responses of the North Eastern Arabian Sea during late winter and early spring inter-monsoons and the repercussions on open ocean blooms. Journal of the Marine Biological Association of the United Kingdom.

Sahayak, S., Jyothibabu, R., Jayalakshmi, K.J., Habeebrehman, H., Sabu, P., Prabhakaran, M.P., Jasmine, P., Shaiju, P., Rejomon, G., Thresiamma, J. and Nair, K.K.C, 2005, Red tide of *Noctiluca miliaris* off south of Thiruvananthapuram subsequent to the ‘stench event’ at the southern Kerala coast, Current Science, VOL. 89, NO. 9: 1472-1473.

Schaumann K, Gerdes D, Hesse K J. 1988. Hydrographic and biological characteristics of a *Noctiluca scintillans* red tide in the German Bight, 1984. *Meeresforschung-Rep Mar. Res*., **32**: 77-91.

Schott, Friedrich A. and McCreary, Julian P., 2001, The monsoon circulation of the Indian Ocean, Progress in Oceanography: 1 - 123.

Simon, A., & Shanmugam, P. (2012). An algorithm for classification of algal blooms using MODIS-Aqua data in oceanic waters around India. Advances in Remote Sensing, 1(02), 35.

Van Mol, B., Ruddick, K., Astoreca, R., Park, Y., & Nechad, B. Optical detection of *Noctiluca scintillans*. EARSeL eProceedings 6, 2/2007

Sulochanan, Bindu, Dineshbabu, A.P., Raju Saravanan, Subramanya Bhat, G. and Lavanya, S., 2014, Occurrence of *Noctiluca scintillans* bloom off Mangalore in the Arabian Sea, Indian J. Fish., 61(1):42-48

Vinayachandran, P. N., & Mathew, S. (2003). Phytoplankton bloom in the Bay of Bengal during the northeast monsoon and its intensification by cyclones. Geophysical Research Letters, 30(11).