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# MODIS-Aqua detects *Noctiluca scintillans* and hotspots in the central Arabian Sea

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**Abstract** Northern Arabian Sea is considered as an ecologically sensitive area as it experiences a massive upwelling and long-lasting algal bloom, *Noctiluca scintillans* (green tide) during summer and spring-winter, respectively. Diatom bloom is also found to be co-located with *N. scintillans* and both have an impact on ecology of the basin. In-house technique of detecting species of these blooms from Moderate Resolution Imaging Spectroradiometer (MODIS)-Aqua data was used to generate a time-series of images revealing their spatial distribution. A study of spatial-temporal variability of these blooms using satellite data expressed a cyclic pattern of their spread over a period of 13 years. An average distribution of the blooms for January–March period revealed a peak in 2015 and minimum in 2013. Subsequently, a time-series of phytoplankton species images were generated for these 2 years to study their inter-annual variability and the associated factors. Species images during active phase of the bloom (February) in 2015 indicated development of *N. scintillans* and diatom in the central Arabian Sea also, up to 12° N. This observation was substantiated with relevant oceanic parameters measured from the ship as well as satellite data and the same is highlight of the paper. While oxygen depletion and release of ammonia associated with *N. scintillans* are detrimental for waters on the western side; it is relatively less extreme and supports the entire food chain on the eastern side. In view of these contrasting eco-sensitive events, it is a matter of concern to identify biologically active persistent areas, hot spots, in order to study their ecology in detail. An ecological index, persistence of the bloom, was derived from the time-series of species images and it is another highlight of our study.

**Keywords** Algal bloom · *Noctiluca scintillans* · Hot spots · Remote sensing · Arabian Sea

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## Introduction

The Arabian Sea is characterized by semi-annual reversal of monsoon winds caused by thermal difference between continental land and ocean and eventually the surface current (Banse and McClain 1986; Smith et al. 1998). Ship-based observations have indicated that waters of the Arabian Sea become more productive in summer monsoon not only along the coastal region of Somalia, Arabia and southern part of the west coast of India due to coastal upwelling but also in the open waters of the central region (Prasanna Kumar et al. 2000). As the summer monsoon comes to an end, primary productivity of the Arabian Sea starts decreasing. Again with onset of winter monsoon, the productivity increases significantly. During the northeast monsoon, surface waters of the northern Arabian Sea (NAS) cool because of wind-induced evaporation in addition to normal seasonal surface cooling.

The combined effect tends to increase salinity and density of the surface waters and thus leads to convective mixing and subsequently, unusually high primary production results (Banse 1987; Weller et al. 1998; Shi et al. 1999; Prasanna Kumar et al. 2000; Dwivedi et al. 2008). Productivity in the tropical waters is limited by nutrients, and for this reason, changing pattern of the wind influences availability of nutrients in the euphotic zone and hence production in the Arabian Sea. Thus, the physical and biological processes are coupled in the basin. Nutrient enrichment triggered by convection in the NAS during winter results in formation of diatom bloom followed by *Noctiluca scintillans* (*N. scintillans*, green tide). Strength of the physical forces and their biological response vary spatially and seasonally in the Arabian Sea. Seasonal variability of this nature has been observed from ship measurements and documented by a number of scientists (Prasanna Kumar et al. 2000; Dickey et al. 1998; Wiggert et al. 2005). However, spatial as well as temporal variability in the productivity can be studied with satellite data more effectively without requiring multiple ship cruises. Chlorophyll is an indicator of primary production in the ocean and can be used to indicate presence of algal bloom. Nevertheless, in this study, occurrences of the algal bloom in the NAS and its class/species were mapped explicitly using Aqua/MODIS data (Dwivedi et al. 2015). Multi-date and multi-year species images were generated to facilitate the study of space-time and inter-annual variability. Species image of 10–17 February revealed the presence of diatom and *N. scintillans* in the open waters of Central Arabian Sea extending down up to 12° N. Knowledge of spatial distribution of the species from satellite data and their monitoring enables detection of the stable high productivity patches in the oceanic waters, which could be of biological interest. There are records of fish mortality due to bloom-forming dinoflagellate *N. scintillans* in the Gulf of Oman (Adnan et al. 2007). However, the observations indicated that *N. scintillans* bloom in open ocean waters of northeastern Arabian Sea (NEAS) is not having any adverse effect on the ecosystem, rather supporting at all levels in the food chain and therefore, it is eco-friendly (Dwivedi et al. 2012). Sudden increases in zooplankton and high hooking rates of tuna have been observed in the bloom waters. An approach for detecting persistent areas of high productivity has been presented in this paper, which makes use of multiple satellite-derived phytoplankton species images.

## Materials and methods

Ship data: Water samples from the bloom stations were analyzed for taxonomy using the ship data collected during March 2013 (cruise FORV *Sagar Sampada,* SS-313). These data facilitated validation of the species detection approach, which was developed earlier using MODIS data. Algal bloom species images were generated during February–March 2015 from MODIS data and the same were communicated to the ship (cruise FORV *Sagar Sampada* SS-336) by e-mail to locate the intense bloom areas. In situ density was calculated using temperature and conductivity data recorded by CTD sampler, and from this, vertical profiles of density were plotted for 2013 and 2015 (nearest dates and ship stations).

Satellite data: Chlorophyll images for the corresponding dates were downloaded from Giovanni—Interactive Visualization and Analysis of GES DISC and have been presented in Fig. 1b. MODIS-Aqua Level-3, 8-day aggregated/4 km remote sensing reflectance ($R_{rs}$) bands and sea surface temperature (SST) data were downloaded from NASA Internet server Ocean Color Web for the bloom period (January–March 2003 and 2015). The data were processed to generate a time-series of phytoplankton species images (Dwivedi et al. 2015). Quarterly species images were generated for different years to observe the trend of the bloom extent over the last 13 years. Typical phytoplankton species images for the peak bloom period (10–17 February 2013 and 2015) generated from 8-day MODIS data and can be seen in Fig. 1c. Phytoplankton species time-series was generated from 8-day MODIS $R_{rs}$ bands and existing software for 2013 and 2015 to study inter-annual variability in spatial extent of the bloom. Capability of phytoplankton species identification at pixel level was utilized to compute persistence of the bloom during the entire season. Binary images were generated indicating presence or absence of the bloom (diatom and *N. scintillans*) for the entire 8-day time-series of 2013 and 2015.

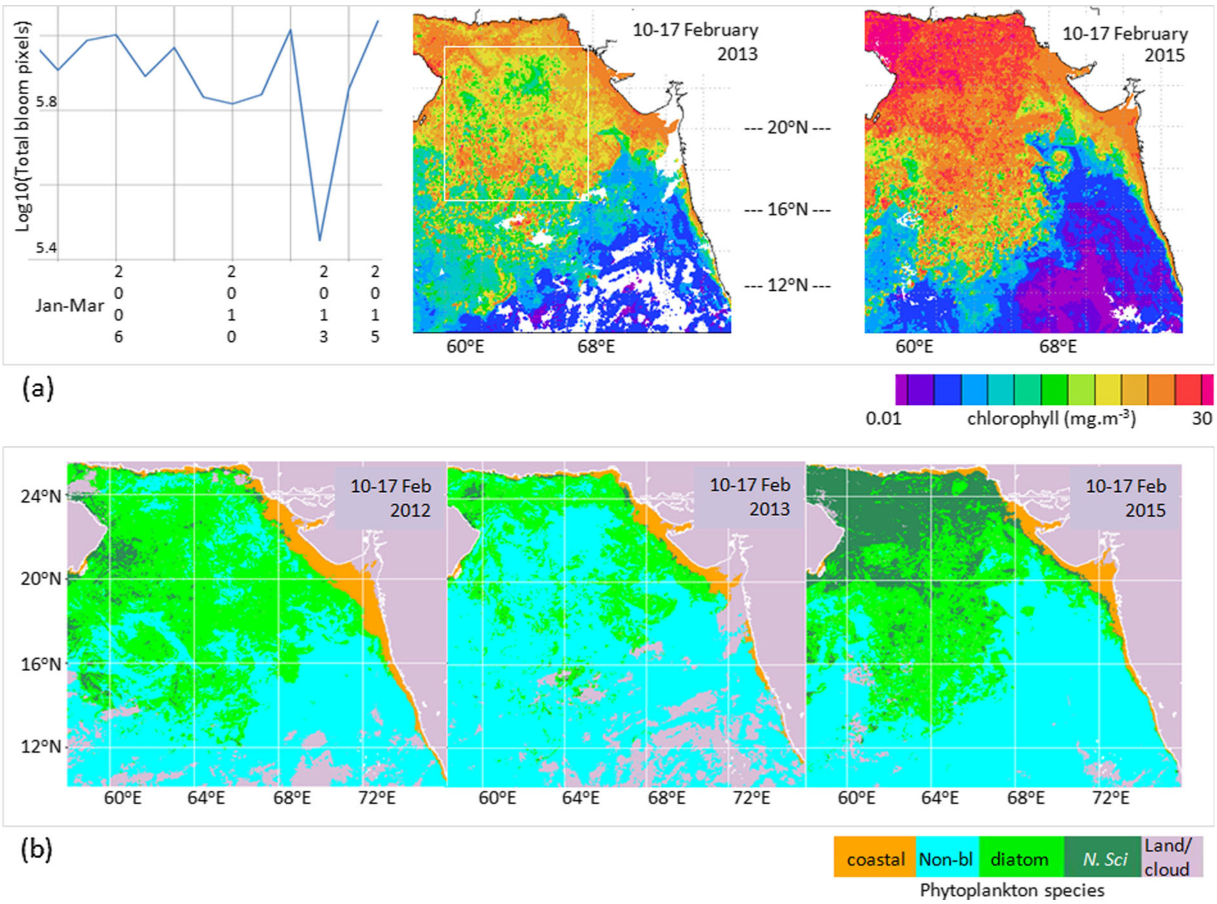



**Fig. 1** **a** Variations in total number of bloom pixels across the tears (*left*) and MODIS-derived chlorophyll images for 10–17 February 2013 and 2015 (*right*). **b** Phytoplankton class/species mapping using MODIS data

Numbers of bloom pixels for various images in the time-series were integrated with respect to time and persistence of the bloom, an ecological index, was derived. Persistence, in terms of number of weeks, represents either presence of diatom or *N. scintillans*. An output image was generated to reveal spatial distribution of this index. Comparison of persistence was made for the years 2013 and 2015. Area under the bloom (product of number of pixels and pixel size, $km^2$) was multiplied by persistence (weeks) to derive intensity of the bloom (Hansson and Hakansson 2007). Sea surface salinity was obtained from Aquarius L3 data from the Asia-Pacific Data Research Center (APDRC) site. Geostrophic current, wind vector and wind diffusivity current were downloaded from Jason-1, Topex, ERS-2, Envisat and ASCAT using the ERDDAP data server.

## Results and discussion

Cyclic pattern of the bloom: Phytoplankton species images were generated from 3-month averaged 4 km MODIS level 3 data for the NAS for different years. Total number of bloom pixels (diatom and *N. scintillans*) was calculated for oceanic waters of the NAS (16°–24° N, 60°–68° E) for the years 2003–2015 and was plotted as shown in Fig. 1a. The area considered for calculation of bloom pixels is shown by a window in the adjacent chlorophyll image (10–17 February 2013, Fig. 1a). It can be seen that a pattern of variations of bloom pixels (spatial extent of the bloom) across the years is cyclic. This variability in the biological productivity could be attributed to the physical forcing caused by the northeast monsoon winds that result in winter cooling and convective mixing (Banse 1987; Weller

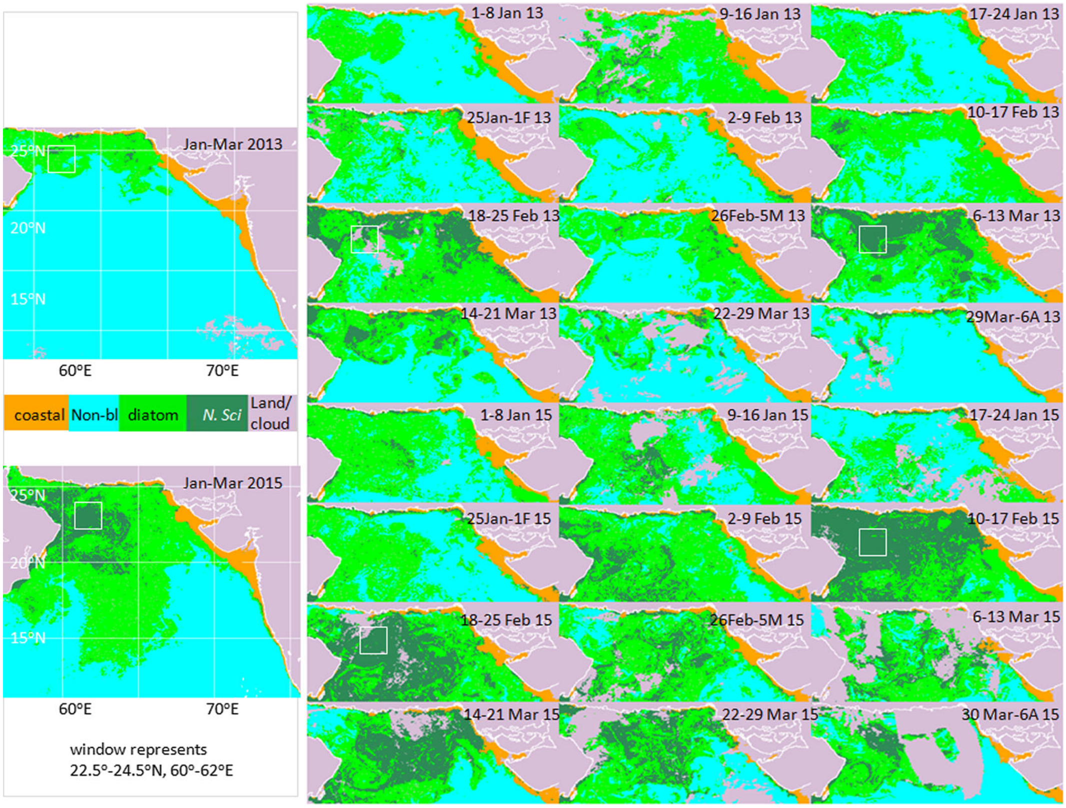



**Fig. 2** Eight day composites of algal bloom species in 2013 and 2015 using MODIS data

et al. 1998; Shi et al. 1999; Prasanna Prasanna et al. 2001; Dwivedi et al. 2008).

Selection of images for comparison: The plot in Fig. 1a reveals maximum extent of the bloom in 2012 and 2015 and minimum in 2013 in the recent years. Also, the chlorophyll image of 2015 in Fig. 1a, representative of active bloom period (10–17 February), displays a spectacular pattern of high chlorophyll over a large area (down south up to 12° N). This is in contrast with 2013 image and therefore, these 2 years were considered to study the inter-annual variability. Phytoplankton species images generated from MODIS $R_{rs}$ bands for these years can be seen in Fig. 1b. The images map two distinct classes; diatoms (light green) and *N. scintillans* (dark green) apart from oceanic and coastal non-bloom waters. It can be seen from the species image of 2015 (Fig. 1b) that green *Noctiluca* corresponds to high chlorophyll (Fig. 1a). This pattern is expected because *N. scintillans* feeds voraciously on phytoplankton and diatoms (Elbrachter and Qi 1998; Buskey 1995). However, the converse is not true (species image of 2013 (Fig. 1b)) because green *Noctiluca* occurs in the Arabian Sea at temperature less than 24 °C (Parab et al. 2006). That is to say, high chlorophyll is a necessary but not sufficient condition for the growth of green *Noctiluca*.

*N. scintillans* succeeds diatoms: Phytoplankton species images were generated from the quarterly MODIS data and are shown in Fig. 2 (left). It can be seen that spatial extent of the bloom is more in 2015 relative to the same in 2013. This is in compliance with the number of pixels' plot shown in Fig. 1a. Though *N. scintillans* has already been reported to occur after the diatom bloom (Kiorboe and Titelman 1998; Tiselius and Kiorboe 1998; Dela-Cruz et al. 2003), we have demonstrated here the sequence with the help of remote sensing. Time-series of phytoplankton species images generated from 8-day composite MODIS data is shown in Fig. 2 (right). It can be noticed that *N. scintillans* bloom (dark green in figure) appears, disappears and reappears during the entire season most probably due to variations in the coupled physical forces. Likewise, time-series images for both the years indicate that diatoms emerge first in the sequence and *N. scintillans* follows subsequently.

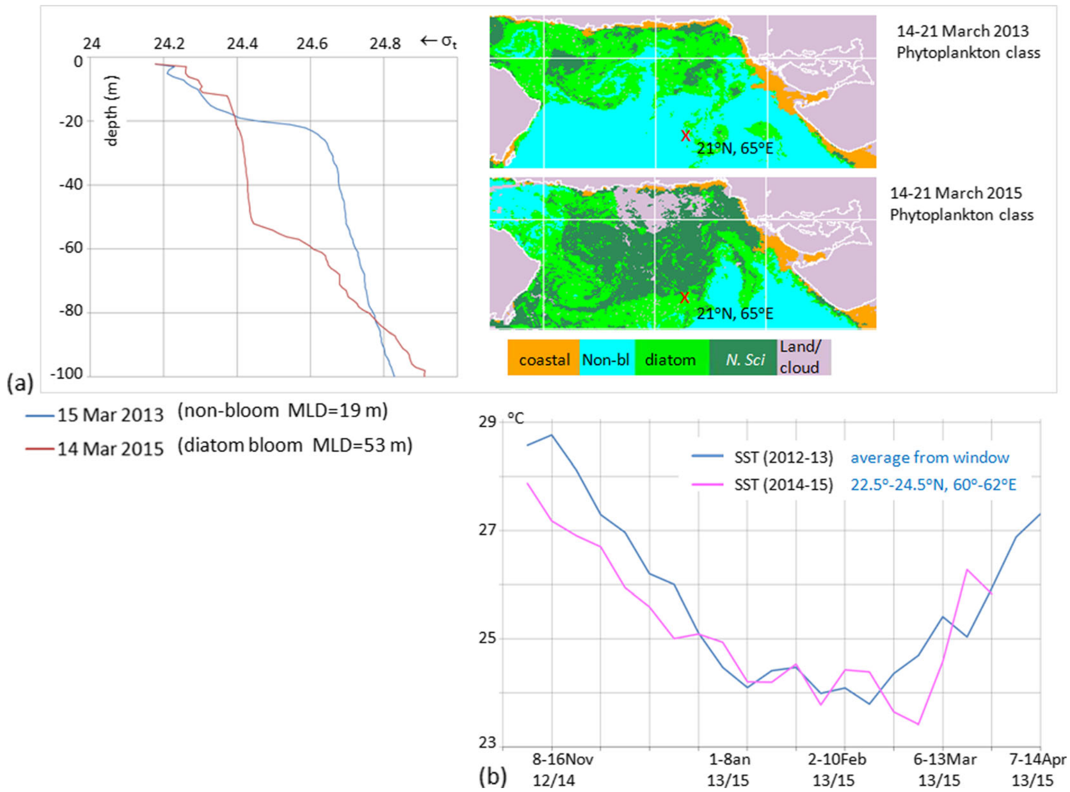
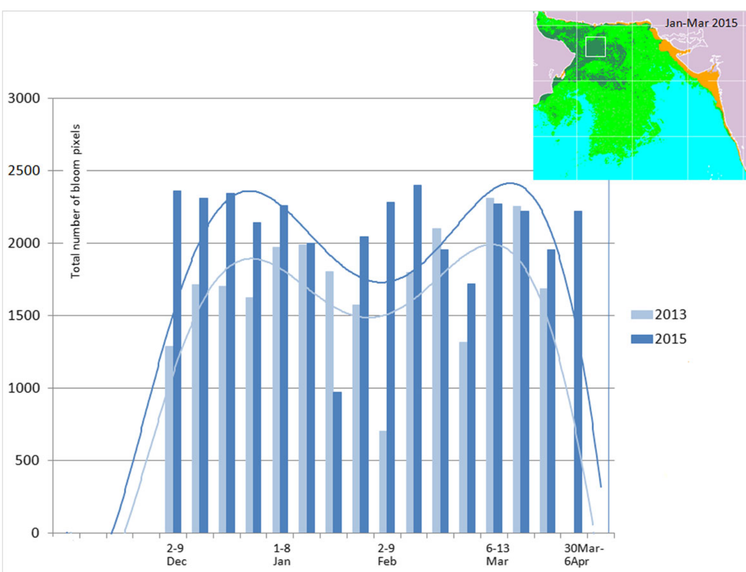



**Fig. 3** **a** Vertical profiles for density from common stations during March 2013 and 2015. **b** Temporal variations in SST in the NWAS waters for 2013–14 and 2014–15 using MODIS data

This is because the diatoms are autotrophs and thrive when nutrients and light in the upper mixed layer are favorable. Convective mixing during winter provides this environment in the NAS. In comparison to this, *N. scintillans* is heterotrophic (non-photosynthetic) and require abundant plankton, including diatoms for

**Fig. 4** Comparison of total number of bloom pixels from the NWAS waters during 2013 and 2015



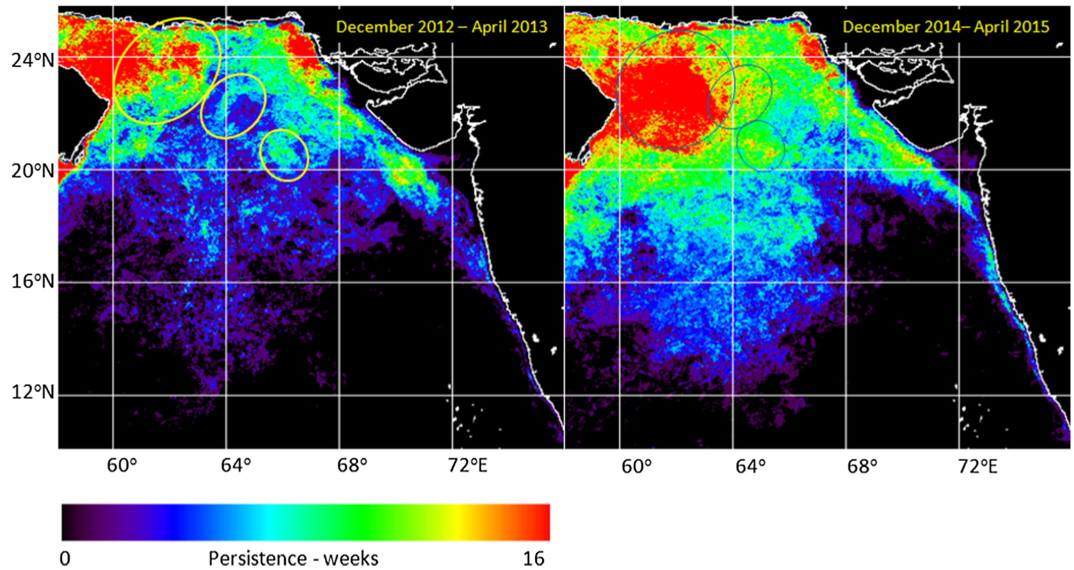



**Fig. 5** Quantification of temporal extent of the NAS/winter bloom, detection of hot spots using 2013 and 2015 MODIS data

feeding. Laboratory studies have reported their high growth rates on pure diets of diatoms (Buskey 1995).

First appearance of *N. scintillans* in 2013: A time-series of species images (Fig. 2) reveals a significant development of *N. scintillans* in 18–25 February 2013 image. Average of SST and density were computed using satellite data for the window (22.5°–24.5° N, 60°–62° E) as shown in Fig. 2 in the northwestern Arabian Sea (NWAS) and were found to be 23.9 °C and 24.76, respectively. Mohamed and Mesaad (2007) have observed presence of green *Noctiluca* in the NWAS during February 2004 and 2005 at temperature less than 25 °C. Fonda Umani et al. (Umani Fonda et al. 2004) have reported maximum growth of *N. scintillans* at 24 °C. As regards density, our ship-measured vertical density profiles have indicated that surface density greater than 24.5 in the NAS is high enough to generate convection.

Second appearance of *N. scintillans* in 2013: This can be seen in 6–13 March 2013 image. Diatoms were detected in abundance at this time (8700 pixels in the window, light green colour in the images) besides favorable SST. *N. scintillans* voraciously feeds on phytoplankton and diatoms. There are references of studies indicating need for a relatively high quantity of phytoplankton prey to support its optimal growth (Barbara Van Mol et al. 2007; Lee and Kazutsugu 1992; Miyaguchi et al. 2006; Luciana de Souza Cardoso 2012).

Appearance of *N. scintillans* in 2015: Large homogeneous patches of *N. scintillans* can be seen during 10–25 February and 14–21 March of 2015 (Fig. 2). All the three factors as discussed above, viz. SST near 24 °C, density greater than 24.5 and abundance of diatom (food), are found conducive in these cases. This observation is further elaborated as follows.

Comparison of temperature-density profiles: Ship cruises were conducted during these contrasting bloom events in March 2013 and 2015. Vertical profiles of sea water density for the common station (21° N, 65° E; shown in the images of Fig. 3a) were recorded with a modular CTD system on 14 March 2013 and 15 March 2015 and are presented in Fig. 3a. It can be seen from the figure that the mixed layer depth (MLD) was 19 m on 15 March 2013 and 53 m on 14 March 2015. Relatively higher MLD in 2015 could be repercussion of stronger convective mixing and it explains the extensive homogeneous bloom in 2015 (Fig. 1b). In addition to this, total number of *N. scintillans* pixels was calculated from the time-series species images for the window as shown in Fig. 2. There were 3650 *N. scintillans* pixels in 2013 and the same were 9465 during 2015 season. Average SST and surface density were also calculated for this window from the quarterly averaged (January–-March) satellite data. The values of SST were 25.72 °C in 2013 and 25.22 °C in 2015 and the corresponding density estimates were 24.08 in 2013 and 24.41 in 2015. The comparison indicates overall cooler

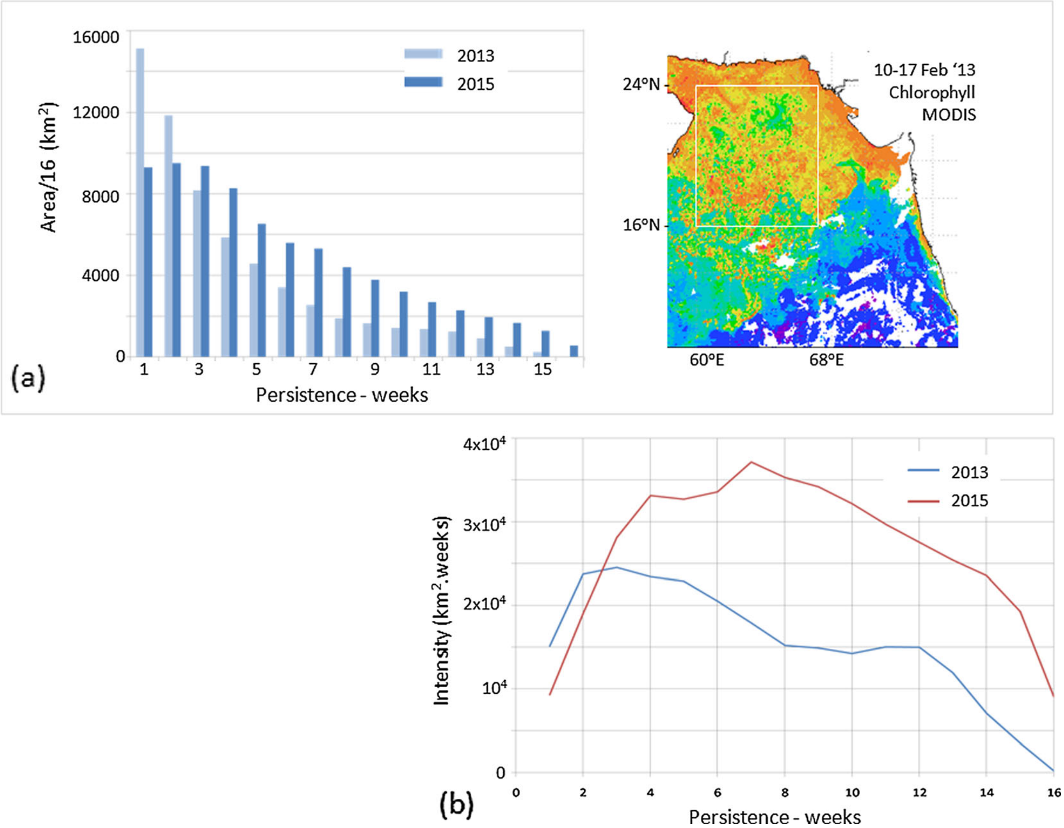



**Fig. 6** **a** Comparison of area under bloom with respect to persistence for 2013 and 2015. **b** Plot of intensity versus persistence for 2013 and 2015

and denser waters in 2015 as compared to the same in 2013. It was quoted earlier that *N. scintillans* can reproduce actively at temperature near 24 °C and in view of this; number of days for which SST persisted within a favorable range (23.5–24.5 °C) was computed in the NWAS window. It was noticed that the favorable temperature prevailed for 48 days in 2013 and for 72 days in 2015. This gets reflected in the temporal profile for SST shown in Fig. 3b. Yet another parameter to be considered for the inter-annual comparison is diatom, on which *N. scintillans* feeds. Diatom pixels were integrated in space (NWAS-window) and time (January–March) using the time-series species images and it was found that this number was 20,500 in 2013 as against 24,000 in 2015. Thus, favorable temperatures for a longer duration, higher surface density and availability of food in abundance for *N. scintillans* in 2015 resulted in an intense bloom event.

Temporal variations in bloom pixels, 2013 vs. 2015: Temporal variations in the total number of pixels under algal bloom (*N. scintillans* and diatom) in the NWAS-window for 2013 and 2015 have been shown in Fig. 4. It is evident that spatial extent of the bloom (number of bloom pixels) is more in 2015 overall. The trend lines show matching peaks and trough in both the years and this scenario can be visualized as expansion and contraction of the bloom during the season. Moreover, the bloom can be seen persisting till the first week of April in 2015, whereas it terminated earlier, by the end of March in case of 2013.

Mapping persistence: Persistence is one of the ecological indicators used to characterize the algal bloom. Its spatial distribution for the years 2013 and 2015 is shown in Fig. 5. In general, persistence (weeks) is found to be more in the NWAS waters as compared to the same in the NEAS in both the years. Moreover, comparison of the two images in the figure indicates that persistence is relatively higher in the NWAS during 2015 indicating productive waters for a longer duration. This also gets reflected in temporal profile of SST in Fig. 3b, which

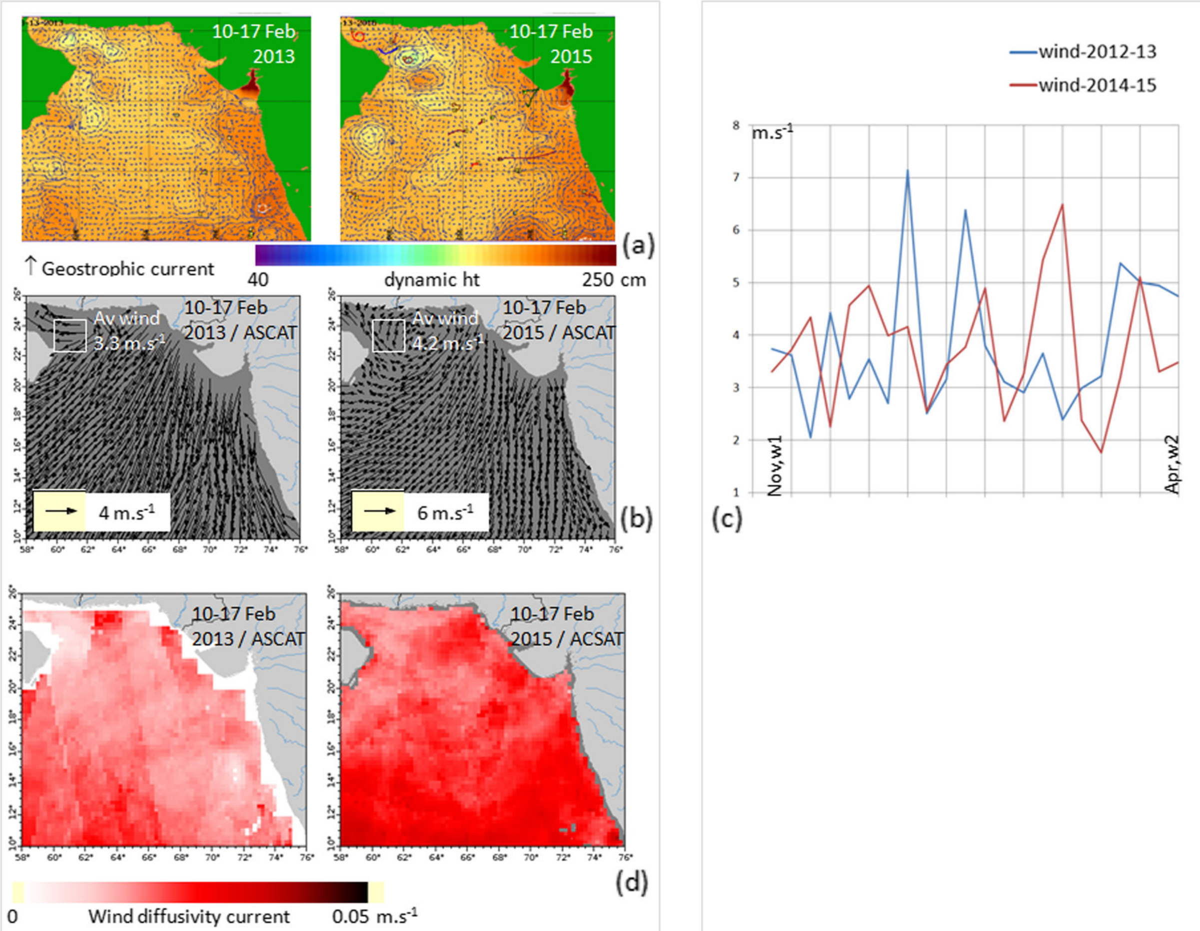



**Fig. 7** **a** Geostrophic current, **b** wind vector, **c** temporal variability of wind speed and **d** wind diffusivity current for 2013 and 2015

shows that SST < 24 °C as is preferred by *N. scintillans* prevailed for a longer period (till middle of March) in 2015. Persistent areas exist in the central Arabian Sea (CAS) also, which hold high productivity for several weeks and are marked with ellipses in Fig. 5. These stable areas, which hold productive waters due to prevailing algal bloom in the NWAS and CAS can be treated as hotspots because long-term high productivity is followed by degradation, which support the bacterial activity and, in turn, higher levels of population in the food chain including fish.

Distribution of persistence and intensity of the bloom: Area under bloom within the window covering oceanic waters of the NAS (16°–24° N, 60°–68° E) was plotted against persistence of the bloom as shown in Fig. 6a. First point in the figure shows number of bloom pixels from the entire window with 1 week duration and the last point show the same number with maximum stability (16 weeks). The comparison between 2013 and 2015 indicates shorter duration bloom in 2013. Product of persistence (weeks) and area (km$^2$) is equivalent to the intensity of the bloom (Hansson and Hakansson 2007). This has been plotted against persistence in Fig. 6b. It can be seen that the intensity is more in 2015 as compared to the same in 2013 overall. Also, unlike in 2013, maximum intensity occurs for a longer duration (7 weeks) in 2015, meaning that this bloom has more ecological impact in terms of microbial activities and on total productivity in general.

The bloom in central Arabian Sea: MODIS-Aqua observes *N. scintillans* bloom in the central Arabian Sea: Prasanna Kumar et al. (2000) had reported high productivity in the CAS due to summer upwelling. A similar pattern of high productivity can also be seen in open waters of the CAS due to this bloom. It can be seen from Fig. 1a that a pattern of high chlorophyll is not

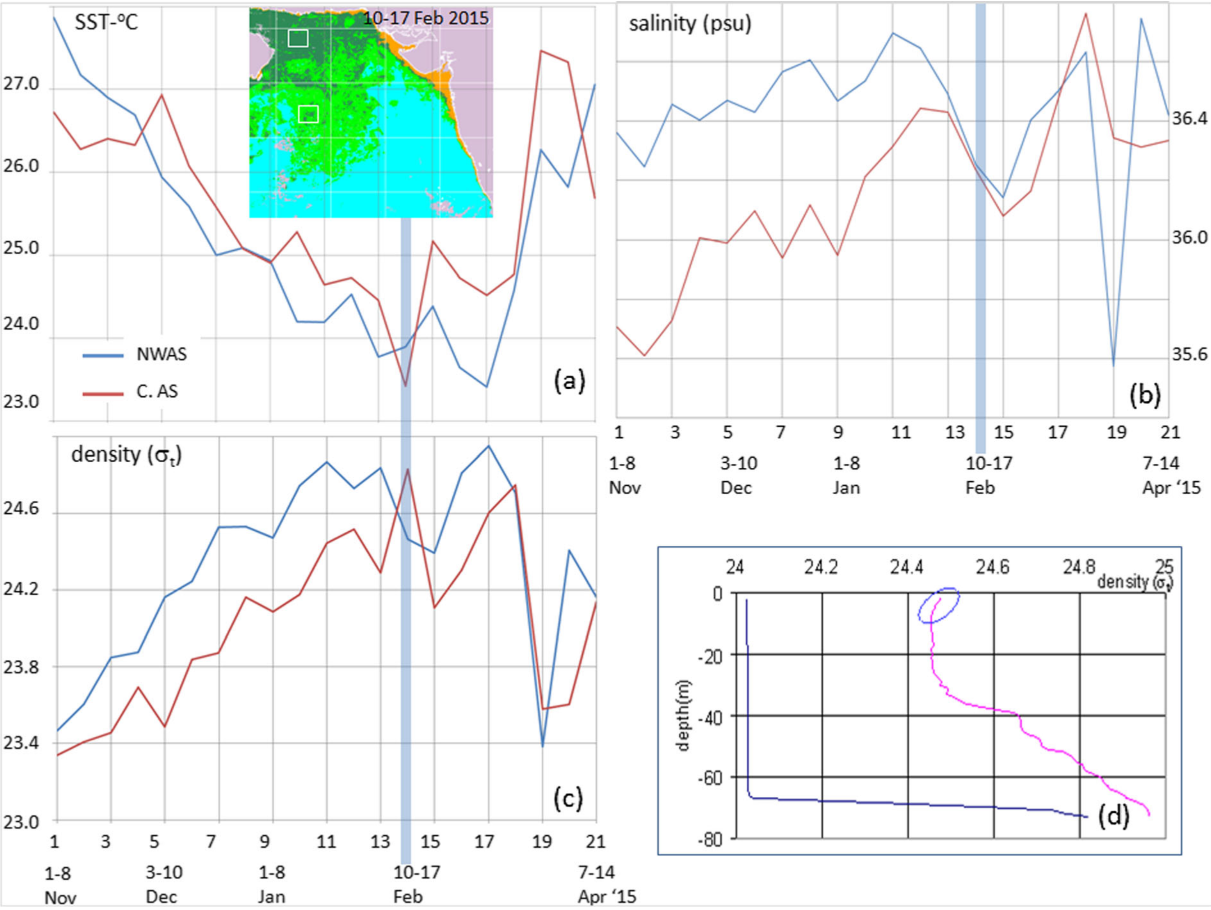



**Fig. 8** Temporal variations in **a** sea surface temperature, **b** sea surface salinity, **c** density during 10–17 February 2015 using MODIS data for the NWAS and CAS and **d** vertical profile for density in the NEAS during March 2003

confined only to the NAS during winter months but also extends down south up to 12° N in the CAS. Classified phytoplankton is mapped in Fig. 1b and a signature of diatom in homogeneous patch and *N. scintillans* in small scattered patches can be seen in open waters of the CAS in 10–17 February 2012 and 2015 images. Corresponding image for 2013 also reveals high productivity in the CAS though in a form of patchy distribution of diatoms.

The bloom observed in the CAS is not due to advection of waters from the north: Geostrophic currents in the NAS for 10–17 February 2013 and 2015 period are presented in Fig. 7a. No distinct pattern of southward current is noticeable. Though ASCAT/wind vectors in Fig. 7b reveal a northeasterly flow, wind speeds in 2013 (weak bloom) and 2015 (strong bloom) appear nearly comparable in the NWAS box as shown in Fig. 7b as well as in wind speed plot in Fig. 7c. This eliminates possibility of southward transport of productive waters from the north in 2015 due to wind forcing. In addition to this, it can be seen from the distribution of wind diffusivity current (Fig. 7d) that the magnitude of wind diffusivity current is too weak to cause shift of the NAS bloom up to 12° N. Thus, observed southward extension of the bloom up to 12° N in the CAS on 10–17 February 2015 is not due to north–south advection of high productivity waters.

The bloom observed in the CAS is a new development in 2015: Temporal profiles of SST, salinity and density shown in Fig. 8a–c were derived from the satellite data. These profiles represent the areas as shown with the two windows in the NAS and CAS (Fig. 8a). It can be seen from SST plot in Fig. 8a that in case of NWAS, SST is low (23.9 °C) at 10–17 February point. Corresponding to this, the adjacent species image reveals a homogeneous patch of

*N. scintillans* bloom in the NWAS window. Lee and Hirayama 1992 have reported maximum specific growth rate of *N. scintillans* at around 23 °C. Fonda Umani et al. (Umani Fonda et al. 2004) have also mentioned that *N. scintillans* was able to reproduce actively at low temperature, maximum growth, however, was detected at 24 °C. In case of the CAS, SST at the same point (10–17 February) is 23.4 °C, which is reported as conducive to *N. scintillans* development. Moreover, it can be noted that the favorable temperature at 10–17 February point in the CAS prevails for a short time; it is higher before (24. 5 °C) and after (25.2 °C) this point. Unlike in the CAS, low SST, close to 24 °C prevails for a longer period in the NWAS. Sea surface salinity is almost identical for the NWAS and CAS windows at 10–17 February point (Fig. 8b). Density profile in Fig. 8c indicates density of 24.5 at 10–17 February point in the NWAS window. Density values are found greater than 24.5 at a few points before and after 10–17 February. Vertical profile of density was generated for the NEAS waters from CTD data of another cruise in February and can be seen in Fig. 8d. The profile for the bloom station reveals a situation of high-density surface waters lying over relatively low-density waters at deep (marked with an ellipse in the figure). This is the signature of convection, and corresponding to it, surface density is close to 24.5. With this information and looking back at Fig. 8c; the density value of 24.5 in the NWAS waters can be considered high enough to cause convection. In case of the CAS, surface density is 24.8 at 10–17 February point and it is capable of triggering convective mixing and nutrient enrichment. Like in the case of SST plot (Fig. 8a), density is lower before (24.3) and after (24.1) the 10–17 February point. It is summarized that presence of favorable temperature and high-density waters at the surface could be the reason for high productivity in the CAS. Diatom is a preferred feed for *N. scintillans*, and hence, number of diatom pixels was counted from the uniform windows (18 pixels × 18 lines) in the NWAS and CAS. It was found that 224 pixels of diatoms in the previous week (2–9 February 2015) supported 312 *N. scintillans* pixels during the subsequent week (10–17 February 2015) in the NWAS. A similar pattern was also observed in the CAS. There were 224 pixels of diatoms in the previous week (2–9 February 2015) to support 312 *N. scintillans* pixels during 10–17 February. Concisely; favorable SST, high density of surface waters and abundant feed (diatom) in the CAS lead to development of new *N. scintillans*.

## Conclusion

Time-series of phytoplankton species images has been generated for the winter bloom seasons (January–March) for 2013 (weak bloom year) and 2015 (strong bloom year). Total number of pixels under bloom has been compared for these 2 years and the contributing factors are discussed. A technique of identification of the NAS/winter algal blooms has been extended for detection of the stable areas of high productivity (blooms) and is described as hot spots. The observed high productivity in the CAS is not due to advection of bloom waters from the north. The study clearly indicated that the mixed algal blooms *N. scintillans* and diatom are not confined to NAS only but also develops in the CAS.

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