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Chlorophyll blooms induced by tropical cyclone Vardah in the Bay of Bengal

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The present study documented the formation of surface and subsurface chlorophyll a (Chla) blooms after the passage of tropical cyclone Vardah in the Bay of Bengal, using remote sensing and Bio-Argo float data. Surface Chla bloom occurred in the cyclonic eddy waters and lasted for three weeks, longer than the surface and subsurface Chla blooms in the anti-cyclonic eddy waters (lasted for two weeks). Thickness of the subsurface Chla bloom and depth-integrated Chla increased after the Vardah passage. Analysis shows that Vardah-induced upwelling and vertical mixing transported nutrients to the upper layer and supported the Chla bloom. The fast translation speed and pre-existed anti-cyclonic eddy were the reason of the relatively weak subsurface Chla bloom compared with other studies.

[**Key words**: Tropical cyclone; Subsurface Chlorophyll *a*; Bio-Argo; Bay of Bengal; Vardah]

Introduction

The Bay of Bengal (BoB) is a semi–enclosed tropical ocean basin highly influenced by southwest monsoon in summer (June–September) and northeast monsoon in winter (November–February)[1], it also experiences intense tropical cyclones (TCs) during May–June and October–December[2,3] and receives large volume of freshwater from both river discharge and precipitation. This characterized the BoB by strong stratification and weak subsurface chlorophyll maximum (SCM, < 0.2 mg m^{-3}) between 50 and 100 m during the post–monsoon season[4]. The BoB had experienced three TCs during the post summer monsoon and one TC during the pre-summer monsoon season[3].

TCs are recurring extreme weather events that have profound influence on the marine ecosystem. Many studies reported that TCs are responsible for the cooling of sea surface temperature (SST)[5,6], increased dissolved oxygen[7], enhanced chlorophyll *a* (Chla) concentration[8,9] and primary production[10,11], changing of the sea surface partial pressure of CO_2[12,13,14], and increased fish abundance[15] due to TC–induced entrainment (vertical mixing), upwelling and wind-pump effects (also called wind-pumping)[5,8,16]. A contrasting Chla bloom responses to TCs Thane and Phailin was observed due to the strong stratification suppresses the Chla enhancement in the BoB[17]. The Chla bloom following a TC is due to the entrainment of subsurface phytoplankton and/or from phytoplankton reproduction resulting from nutrient transported into the euphotic zone[8]. Most of the studies on the biological response were based on satellite observations.

Subsurface biological observations are lacking because ship-borne measurement is highly dangerous and not feasible in the violent atmospheric disturbances during a TC passage. Our previous study reported a stronger and longer existed subsurface Chla bloom than surface Chla bloom followed by typhoon Nuri in the South China Sea using cruise survey data[8]. Bio–Argo floats which measured Chla concentration by fluorescence probe provide another method to study the subsurface biological variations during a TC passage. A study by Chacko (2017)[18] documented a high subsurface Chla concentration of up to 4.5 mg m^{-3} after TC Hudhud passage in a cyclonic eddy water using a Bio-Argo float over the BoB. More studies remain to be done, however, about the effects of TCs on the subsurface Chla under the presence of anti-cyclonic eddy. This paper uses observations from a Bio-Argo float located at about 86 km away from Vardah track to document the biological response of the subsurface. The objective is to understand the evolution of the subsurface Chla bloom in response to the TC forcing.

Materials and Methods

TCs track data at every 6 hours, including central location and maximum sustained wind speeds at 10 m height were obtained from the Joint Typhoon Warning Center (JTWC) (weather.unisys.com/hurricane/). Observations from a Bio-Argo float (2902086) are used in this study to document the subsurface Chla variation associated with the TC. In addition to Chla, temperature and salinity from the Bio-Argo are also used to show the subsurface responses. The float gives observations in 5 day cycle, however, no data were retrieved because Vardah crossed the float over head on 8 December 2016.

Five different satellite daily data sets are used in this study to examine atmospheric and oceanographic conditions at the sea surface of the BoB before, during and after the passage of Vardah. The remote sensing fields of sea surface winds (at 10 m above the sea surface) and wind stress vector ($\vec{\tau}$) with a 0.25º×0.25º resolution were obtained from the Advanced Scatterometer website at ftp.ifremer.fr/ ifremer/cersat/products/gridded/MWF/L3/ASCAT/. The microwave and infrared optimally interpolated SST products with spatial resolution of 9 km were obtained from the Remote Sensing Systems at ftp://data.remss.com/. The Aqua Moderate Resolution Imaging Spectroadiometer derived sea surface phytoplankton Chla product with 4 km resolution was obtained from the National Aeronautics and Space Administration (http://oceancolor.gsfc.nasa.gov/). Fields of absolute geostrophic velocities at the sea surface derived from the merged altimeter products and merged sea level anomaly were obtained from the Archiving Validation and Interpretation of Satellite Oceanographic data at www.aviso.oceanobs.com. The rainfall fields with the same horizontal resolution of 0.25º×0.25º were obtained from the website for the Tropical Rainfall Measuring Mission at disc2.nascom. nasa.gov/data/TRMM/.

In the present study, the translation speeds of a TC were estimated from time-varying positions of its center. The phytoplankton bloom corresponded to Chla concentration ≥ 1 mg m^{-3}. The mixed layer depth (MLD) is defined as the depth at which the density is 0.2 kg m^{-3} higher than the surface density[19]. The Ekman Pumping Velocity (EPV) is calculated from the surface wind stress vector ($\vec{\tau}$) as follows:

$$\mathrm{EPV} = -\mathrm{Curl}_z\left(\frac{\vec{\tau}}{\rho_o f}\right) \qquad \ldots (1)$$

where ρ_0 is the sea water density and equal to 1025.0 kg m^{-3} and f is the Coriolis parameter.

Results

Vardah (2016) was a Category 1 (based on Saffir–Simpson scale) tropical cyclone which moved northwards after its generation on 7 December 2016 as a tropical storm (Fig. 1). The TC moved westward after 8 December 2016 and intensified to category 1 on 10 December 2016. Vardah passed the Bio-Argo float on 10 December 2016 with the translation speed of about 5.91 m s^{-1} and maximum wind speeds of 32.5 m s^{-1}. From 11 to 12 December, Vardah reached its wind speeds of 36 m s^{-1} and translation speed of 4.17 m s^{-1}. Vardah made a landfall and disappeared at 0600 UTC on 12 December 2016.

Distributions of the EPV shown in Figure 2A–a indicate that the wind–induced upwelling before Vardah was very weak over the whole region. During the passage of Vardah on 10 December 2016 the large and positive EPVs (> 2 × 10^{-4} m s^{-1}) occurred along the TC track (Fig. 2A–b). The negative EPVs over small areas indicate that the wind–induced downwelling over these areas. After the Vardah, the EPVs suddenly weakened to the level of before the TC (Figs. 2A–c and 2A–d).

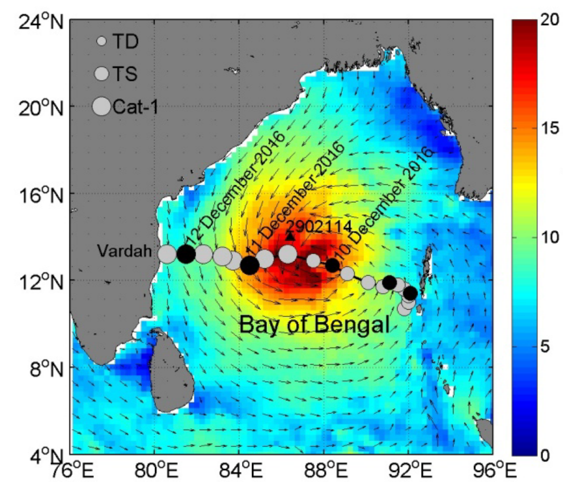

Fig. 1 — Geographical location of the Bay of Bengal. The 6 hourly positions of tropical cyclone Vardah centers are marked by dots, of which sizes reprensent the intensity. Abbreviations are used for tropical depression (TD), tropical storm (TS) and Category-one tropical cyclone (Cat-1). In the background is a composite image of the surface wind speeds (color, m s^{-1}) and directions (arrows) during Vardah on 10 December 2016. The solid triganle respresent the location of the Bio-Argo float 2902114.

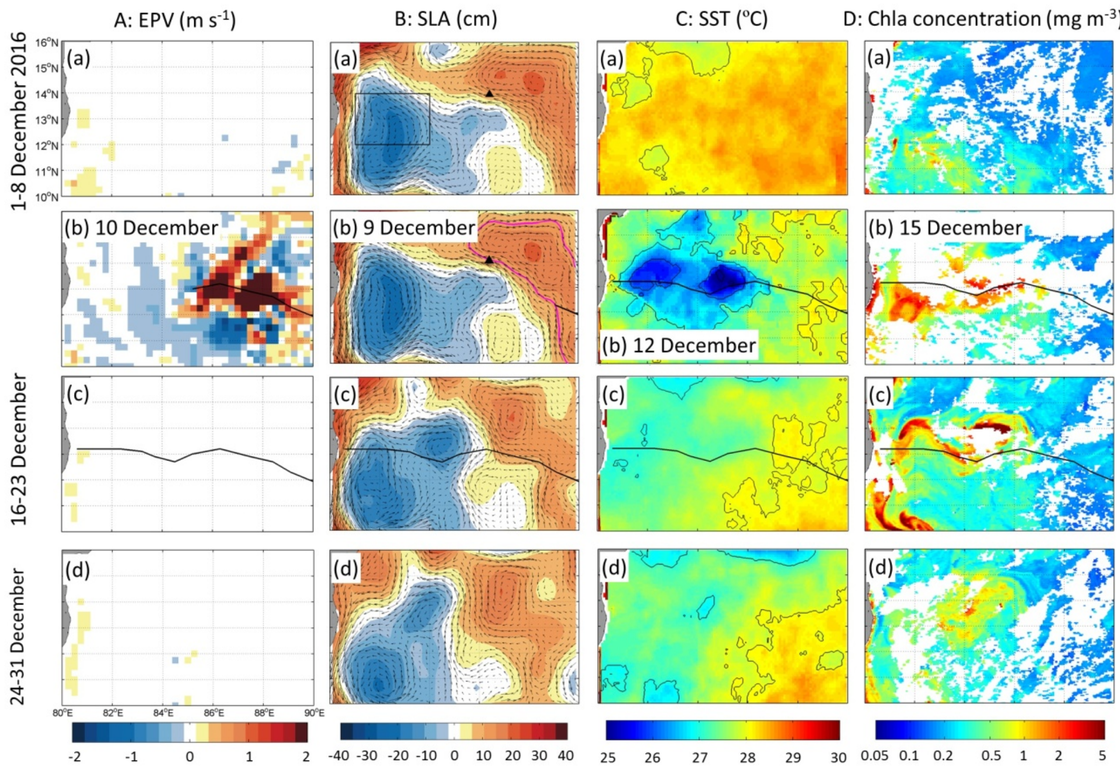

Fig. 2 — Satellite remote sensing data of (A) Ekman pumping velocity (EPV, m s^{-1}); (B) sea level anomalies (SLA, cm) and absolute geostrophic currents at the sea surface (m s^{-1}), bold pink line shows anti-cyclonic eddy, black solid triangles represent the location of Bio-Argo float 2902114; (C) sea surface temperature (SST, ºC); and (D) MODIS-Aqua derived chlorophyll a (Chla) concentration (mg m^{-3}) over the Bay of Bengal. Black solid lines represent the track of Vardah.

Before the Vardah on 1-8 December 2016, a large-size cyclonic eddy occurred over the western part of the BoB, with its location at about 82 ºE, 12.5 ºN (Fig. 2B–a). To the north of this cyclonic eddy, a small-size cyclonic eddy occurred. A large-scale anti-cyclonic eddy occurred over the northeast part of the BoB. During the passage of Vardah on 12 December 2016, the anti-cyclonic eddy reduced its size and moved gradually westward (Fig. 2B–b). This anti-cyclonic eddy further reduced after the Vardah on 16-31 December 2016 (Figs. 2B–c and 2B–d). The large-szie cyclonic eddy separated into two cyclonic eddies during and after the Vardah. The small-size cyclonic eddy weakened during the Vardah and disappeared after the Vardah.

Distributions of the averaged SST on 1-8 December 2016 are characterized by high SST of > 28 ºC prevailing in the study region before the Vardah (Fig. 2C–a). The slightly low SST of < 28 ºC over the western part matched well with the cyclonic eddies. During the passage of Vardah, significant SST cooling along the track occurred (Fig. 2C–b). Maximum SST cooling of about 4 ºC was observed on 12 December 2016. The SST cooling was biased to the right side of the track, which is consistent with previous findings[5,6]. After the passage of Vardah, patchy signatures of cooler SST were observed on 16-31 December 2016 (Figs. 2C–c, and 2C–d).

Chla distributions had significant spatial variability over the BoB (Fig. 2D). Before the Vardah on 1-8 December 2016, the low averaged Chla (< 0.2 mg m^{-3}) occurred over the northeastern part of the BoB (Fig. 2D–a). High Chla of > 0.4 mg m^{-3} occurred over the southwestern part which matched well with the large-scale cyclonic eddy and absolute geostrophic currents. A strong surface Chla bloom (0.5–5 mg m^{-3}) appeared along the track on 15 December 2016 (Fig. 2D–b). The Chla increases significantly reaching up to about 8 mg m^{-3} on 16-23 December 2016 and moved with the absolute geostrophic currents (Compare Fig. 2D–c with Fig. 2B). During the last six days of 2016, the Chla was decreased to about 0.8 mg m^{-3} on 26-31 December (Fig. 2D–d), giving a timescale for the TC-induced surface Chla bloom of three weeks. The significant spatial variability indicated that the absolute geostrophic currents have much impact on the Chla distribution.

Bio-Argo float 2902114 was located at the edge of the large-scale anti-cyclonic eddy and about 86 km right to the Vardah track (Fig. 1). The vertical profiles of Chla, temperature and salinity in the upper 150 m of the water column observed by the Bio-Argo float were shown in Figure 3. Before the passage of Vardah, the high subsurface temperature (28.7–29 ºC) and low subsurface salinity (32.6–33.2 psu) occurred in the upper 40 m layer (Figs. 3A and 3B). Unfortunately, there is no data during the Vardah passage on 8 December 2016. After the Vardah passage on 13 December 2016, the decreased subsurface temperature (~ 28.2 ºC) and increased subsurface salinity (~ 33.5 psu) in the upper 45 m indicated very strong vertical mixing caused by the Vardah. The increased temperature between 45 m and 85 m (the 25 ºC isotherm), and decreased salinity between 42 m and 55 m indicated the mixing was occurred in the upper 55 m depth. The low temperature (~ 27.8 ºC) and high salinity (33.5–33.6 psu) also observed in the following two measuring cycles. Until three weeks after the Vardah, the subsurface temperature decreased to 28.15 ºC and salinity increased to 33.25 psu. During the whole period, the MLD increased from 28–42 m before the Vardah to 42–48 m after the Vardah indicated strong upwelling caused by the Vardah (Fig. 3A). Similarly, the depth of the 22 ºC isotherm decreased from 123 m on 3 December 2016 to 110 m on 13 December 2016.

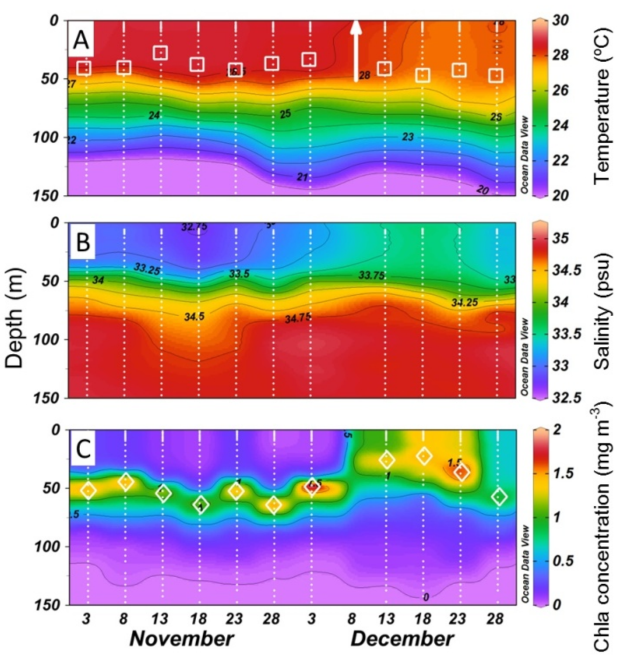

Fig. 3 — Vertical distribution of (A) temperature (ºC), (B) salinity (psu) and (C) chlorophyll a (Chla) concentration (mg m^{-3}) in the upper 150 m from the Bio-Argo float in the Bay of Bengal. The white squares in the panel (A) represent the MLD and the arrow correspond to tropical cyclone Vardah. The white diamonds in the panel (C) represent the depth of the subsurface Chla maximum.

The time series Chla observations precisely (Fig. 3C) showed the evolution of the subsurface Chla bloom (≥ 1 mg m^{-3}) and variation of the depth of the SCM. Before the Vardah on 3 November–3 December 2016, the Chla concentration was observed to be 0.05–0.24 mg m^{-3} in the upper 40 m. Three days after the Vardah, the subsurface Chla concentration in the upper 40 m increased to 1.03 mg m^{-3} and increased to 1.41 mg m^{-3} in the next two measuring cycles. On 28 December 2016, the subsurface Chla concentration decreased to 0.64 mg m^{-3} in the upper 40 m. This indicated TC-induced subsurface Chla bloom lasted about two weeks. The thickness of subsurface Chla bloom increased from 14 m averaged on 3 November–3 December 2016 to 46 m on 13-23 December 2016. Before the Vardah, the depth of the SCM ranges between 42 m and 63 m and below the MLD. The depth of the SCM shoaled to 23–43 m and became shallower than the MLD after the Vardah on 13-23 December 2016. During the last measuring cycle of 2016 (28 December 2016), the depth of the SCM restored to the pre-existing values. The deepened MLD indicated an entrainment (vertical mixing) and the shoaled depth of the SCM indicated an upwelling were induced by the Vardah.

To investigate the relationship between Chla concentration and oceanic conditions, we chose the Box (12-14ºN, 81-84ºE) in Figure 2B-a for the time series. Decrease of SST is significant, with a maximum cooling of 2 ºC two days after the Vardah on 12 December 2016 (Fig. 4A). In the Bio-Argo float location, the maximum SST cooling of 1 ºC was observed during the Vardah. The SST was not returned to the level before the Vardah because of the reduction of solar irradiance in the winter.

Before the Vardah in the Box, there was generally low Chla concentration of 0.28 mg m^{-3} (Fig. 4B). Although there were not so much remote sensing data during and after the Vardah due to cloud coverage, strong surface Chla bloom (1.31 mg m^{-3}) five days later and high Chla concentration (0.53-1.45 mg m^{-3}) until 31 December 2016 were observed. In the Bio-Argo float location, the high variability of the

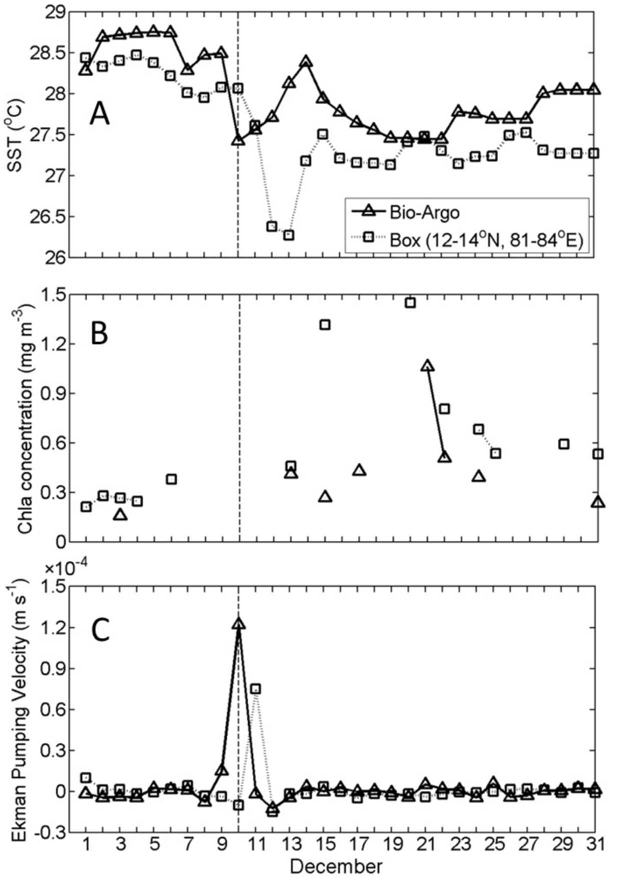

Fig. 4 — Time series of (A) sea surface temperature (ºC), (B) chlorophyll a concentration (mg m^{-3}) and (C) Ekman Pumping Velocity (m s^{-1}) based on a box in Figure 2B-a and the Bio-Agro float location. The dashed lines correspond to tropical cyclone Vardah.

MODIS-Aqua derived Chla concentration (0.1º×0.1º) indicated the Chla was highly affected by the absolute geostrophic currents. Meanwhile, the Chla concentration was increased from 0.16 mg m^{-3} before the Vardah to 0.39 mg m^{-3} on 24 December 2016. On 31 December 2016, the Chla concentration restored to the pre-TC values (0.23 mg m^{-3}). The surface Chla bloom in the Box lasted for three weeks, longer than two weeks in the Bio-Argo float location.

In the Bio-Argo float location, the typical values of EPV (< 0.02 $\times 10^{-4}$ m s^{-1}) before the Vardah is quite low (Fig. 4C). But the EPV increased to 0.15×10^{-4} m s^{-1} on 9 December 2016 and 1.22×10^{-4} m s^{-1} on 10 December 2016 suggesting strong upwelling in the Bio-Argo float location. The estimated wind-driven upwelling during the Vardah is about 12 m, which is comparable to the observed uplift of the 22 ºC isotherm by about 13 m. The slightly enhanced EPV (1.03×10^{-4} m s^{-1}) in the Box during the Vardah on 11 December 2016 was due to the compensation of wind-induced downwelling. Suddenly after the Vardah, the EPVs in the Bio-Argo float location and the Box were restored to the pre-existing values.

Discussion

Chla bloom following a TC is due to the upward entrainment of phytoplankton from the subsurface high Chla water and/or the transportation of nutrients from the deep water by vertical mixing, upwelling and SST front, via ‘Wind-Pump’ effects which occurred during the passage of a TC[8,18,20,21,22]. The enhanced Chla concentrations can last for several days to one month[18,20,21,23,24]. In the present study, the surface Chla bloom in the large-size cyclonic eddy region and the subsurface Chla bloom at the edge of the large-size anti-cyclonic eddy in the Bio-Argo location were observed (Figs. 2B, 2D, 3C and 4B).

In order to understand the contribution of entrainment on the subsurface Chla bloom, the degree of entrainment of subsurface Chla into the mixed layer is estimated using the simple formula given in Ravichandran et al. (2012)[19]:

$$We\,\frac{Chla_h - Chla_{h+\Delta h}}{h} \qquad \dots (2)$$

In equation (2), the term We represents the vertical velocity at the base of the mixed layer calculated by the difference of MLD. The terms $Chla_h$ and $Chla_{h+\Delta h}$ are the Chla concentration averaged in the mixed layer (whose depth is h) and Chla concentration 5 m below the mixed layer base. Under the effect of Vardah, the entrainment term increased from negative to 0.02 mg m^{-3} day^{-1}. Then it decreased less than 0.02 mg m^{-3} day^{-1}. This indicated that the entrainment process did not have much impact on the Vardah-induced subsurface Chla bloom.

Nutrients are crucial for growth and reproduction of Chla in the open ocean, however, it is often deficient in the upper layer but increase with depth[25]. The climatological vertical nitrate distribution in the central of BoB showed that the nitrate concentration is negligible in the upper 30 m and increases from 40 m[18]. In this study, the TC wind-induced strong upwelling (Fig. 4C), upper ocean cooling (Figs. 2C-b, 3 and 4A) and salty (Fig. 3B) and entrainment in the upper 55 m. Thus, the TC induced strong upwelling and vertical mixing, leading to elevated nutrient concentrations in surface waters and fueling phytoplankton bloom.

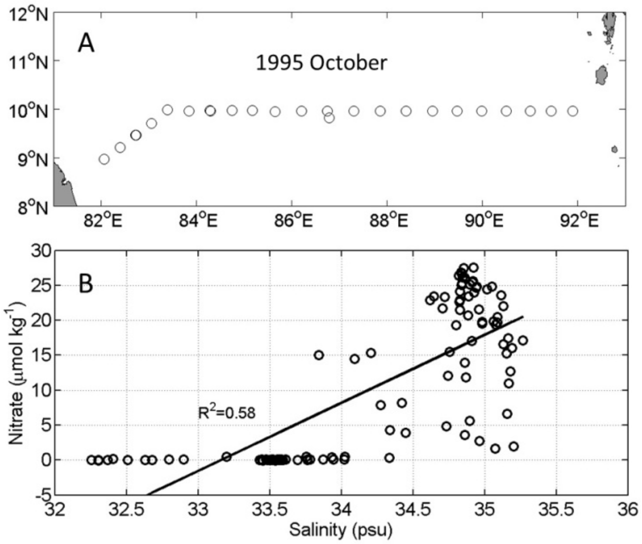

Fig. 5 — Stations of a World Ocean Circulation Experiment cruise in October 1995 in the Bay of Bengal (A) and Nitrate versus salinity in the upper 100 m (B). The data can be downloaded from the CLIVAR & Carbon Hydrographic Data Office (http://cchdo.ucsd.edu/).

During the postmonsoon season in October 1995, a World Ocean Circulation Experiment cruise was conducted in the BoB (Fig. 5A) and the data can be downloaded from the CLIVAR & Carbon Hydrographic Data Office (http://cchdo.ucsd.edu/). The nitrate (R^2=0.58, $p<0.001$) was highly correlated with salinity in the upper 100 m (Fig. 5B). Given the salinity by 33 psu before the Vardah and 33.5 psu after the Vardah in the Bio-Argo location, the nitrate was increased from zero to 4 µmol kg-1. The decreased salinity (33.2 psu) on 28 December 2016 represent the nitrate concentration was equal to zero, which coincided well with the decreased Chla concentration on 28 December 2016. Hence, the Chla blooms were likely triggered by high nutrient concentrations in the upper 40 m waters, caused by TC-induced vertical mixing (entrainment), upwelling and 'Wind-Pump' effects.

To further demonstrate the role of nutrient influx, the time series of the integrated Chla in the upper 150 m depth is shown in Fig. 6. The averaged integrated Chla is 46 mg m^{-2} before the passage of Vardah. Two days after the Vardah, the integrated Chla increased to 68 mg m^{-2} on 13 December 2016. The maximum integrated Chla of 93 mg m^{-2} occurred on 23 December 2016 and high values existed two weeks. If the bloom is due to the migration of subsurface Chla alone, the double integrated Chla would not occurr two weeks after the Vardah.

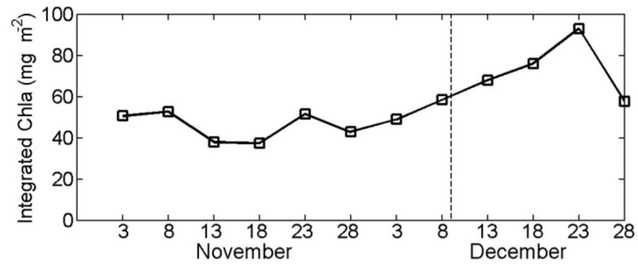

Fig. 6 — Time series of the integrated chlorophyll a concentration (mg m-2) in the upper 150 m depth observed by the Bio-Agro float. The dashed line represents the date of arrival of the Vardah. The data on 8 December 2016 were averaged from 3 December 2016 and 13 December 2016.

Therefore, it can be conclued that the observed Chla bloom is mostly triggered by the transportation of nutrients below.

Comparison with Other Studies

Previous studies indicated that intensity, translation speed, forcing time of TC and pre-ocean conditions such as eddy, MLD, stratification are important factors in triggering Chla blooms[5,17,23,26,27]. In the South China Sea, Typhoons with higher wind speed and slow translation speed (long forcing time) typically induce strong surface Chla bloom[26,27,28]. In the Gulf of Mexico, Walker et al. (2005)[21] observed a phytoplankton bloom in the cyclonic eddy waters and Shi and Wang (2007)[29] reported a Chla bloom at the location of a hurricane's highest intensity and slowest translation speed. In the BoB, Vidya (2017)[17] found a contrasting Chla bloom responses to TCs Thane and Phailin due to the pre-existing stratification. Under similar wind speed and translation speed, the surface Chla bloom in the large-size cyclonic eddy waters (lasted for three weeks) existed longer time than in the anti-cyclonic eddy water (lasted for two weeks) which consistent with previous studies.

A similar susburface Chla concentration of 1.31 ± 0.47 mg m^{-3} was reported under the impact of Typhoon Nuri, of which wind speed was 35 m s^{-1} and translation speed was 4.2 m s^{-1} passed an anti-cyclonic eddy in the northern South China Sea[8]. During the post-summer monsoon season, a strong subsurface Chla bloom (Chla concentration of 4.5 mg m^{-3} and 3-fold integrated Chla) was induced by TC Hudhud in the BoB[18] which was stronger than our findings (Chla concentration of 1.5 mg m^{-3} and 2-fold integrated Chla). This might be because of (i) the translation speed of 2 m s^{-1} by Hudhud is much slower than Vardah's of 5.91 m s^{-1} and (ii) the pre-existing cyclonic eddy before Hudhud and large-size anti-cyclonic eddy before Vardah which intensified the TC-induced upwelling. The upper two factors resulted the subsurface Chla bloom induced by Hudhud was stronger than Vardah totally.

Conclusion

The surface Chla bloom lasted for about three weeks and the subsurface Chla bloom and high depth-integrated Chla lasted for two weeks. Results indicate that both vertical mixing and upwelling have contributed to the subsurface Chla bloom observed. Enhanced biological response is a result of the transportation of the Chla and nutrients from below the mixed layer.

Acknowledgments

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