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Unusual phytoplankton blooms in the southwestern Bay of Bengal: a comparative study

Xiaoyan Chen [*a], Yan Bai [a], Xianqiang He [a], Shaolei Lu [a] and Shujie Yu [a]
[a]State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, State Oceanic Administration, Hangzhou, China

ABSTRACT

Two unusual phytoplankton bloom events were identified in the southwestern Bay of Bengal from MODIS-derived chlorophyll-a concentration data collected between 2003 and 2015. The occurrence of the unusual phytoplankton bloom in December 2005 (called Bloom 1 in this study) has been reported in the literature to be triggered by multiple forcings, including strong cyclonic eddy, frequent typhoons, and strong wind-induced mixing. Interestingly, the other unusual phytoplankton bloom (called Bloom 2 in this study) was identified in almost the same location in December 2013. Further, it is the strongest bloom during our study period with large area of high Chl-a > 1.0 mg/m^3 and shared some similar features with Bloom 1, such as wide coverage and long duration. At the same time, there were also frequent typhoons and a cyclonic eddy. The possible causes of Bloom 2 were examined using time series of multi-satellite datasets, including sea surface height anomalies (SSHA), sea surface temperature (SST), together with Argo profile data. We found that the cyclonic eddy might be not yet the dominant factor for Bloom 2 as the eddy was much weaker than that of Bloom 1. Specially, SST in December 2013 was lowest among all the December from 2003 to 2015. That is, the stratification is weakest. Therefore, the weak stratification can be broken easily by mixing induced by typhoons and cyclonic eddies and finally result in the strong bloom. This comparative studies could provide us some insight in understanding the role of eddies and tropical cyclones in phytoplankton dynamics in the Bay of Bengal.
Keywords: Phytoplankton bloom, Bay of Bengal, eddy, typhoon, stratification

1. INTRODUCTION

The Bay of Bengal, located in the eastern part of the north Indian Ocean (Fig. 1), is a semi-enclosed tropical basin driven by seasonally reversing monsoons, that blow southwesterly in summer and northeasterly in winter. It is traditionally considered to be a region of low biological production compared with its western counterpart, the Arabian Sea (Prasanna Kumar et al., 2002). This strong stratification leads to the formation of a barrier layer (Thadathil et al., 2016), which prevent the turbulent entrainment of cool nutrient-riched water in the deep layer from being transported to the surface layer, resulting in low productivity in the basin of the Bay of Bengal.

However, episodic events such as cyclones (Vinayachandran and Mathew, 2003; Maneesha et al., 2011) and mesoscale processes such as eddies (Prasanna Kumar et al., 2004, 2010), which can erode the stratification of the upper layer and pump deep-layer nutrients into the euphotic zone, are capable of enhancing the biological productivity.

In this study, we investigated the spatial and temporal variations of chlorophyll-a concentration in the Bay of Bengal using the monthly mean chlorophyll-a products of MODIS from January 2003 to December 2015. We identified two unusual phytoplankton blooms in the southwestern Bay of Bengal with large spatial coverage and long duration. One bloom occurred in December 2005 (called bloom 1 in this study) and the other in December 2013 (called Bloom 2 in this study). The occurrence of Bloom 1 has been reported by Chen et al. (2013) to be triggered by multiple forcings, including strong cyclonic eddy, frequent typhoons, and strong wind-induced mixing. We will discuss the possible causes of Bloom 2 in comparison with Bloom 1 in this study.

*cxy_hz@163.com; phone +86-571-81963198

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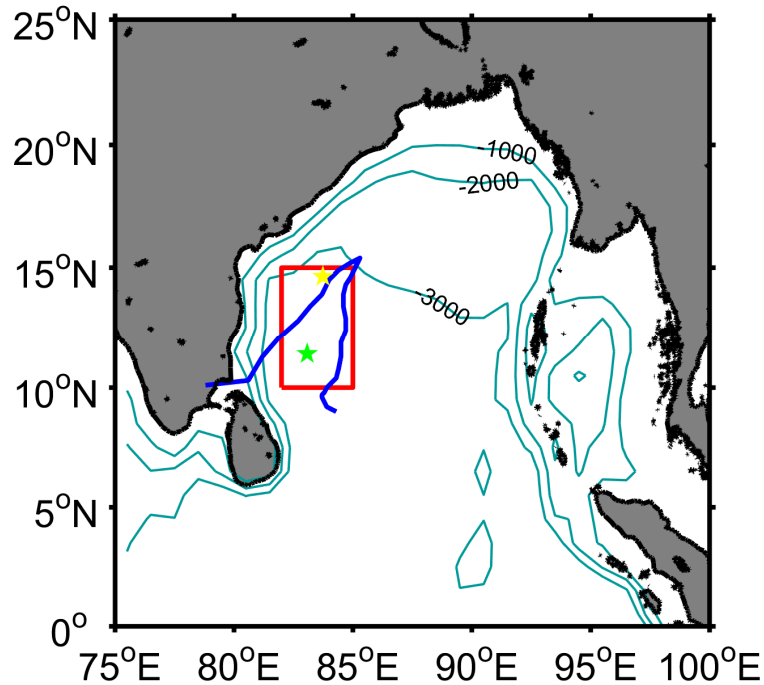

Fig.1 Map of the Bay of Bengal with 1000, 2000 and 3000 m isobaths. Red box (10°–15°N, 82°–85°E) corresponds to the locations of two unusual phytoplankton blooms that occurred in December 2005 and 2013, respectively. Green star is the location of Argo float with ID 2900106 on 6 December 2005 and yellow star is the location of Argo float with ID 2901288 on 3 December 2013. Blue line is the track of typhoon MADI passed through the study area from 6 December 2013 to 12 December 2013.

2. DATA AND METHOD

2.1 Satellite data

Monthly mean chlorophyll-a (Chla) data retrieved by MODIS from 2003 to 2015 were used to investigate the spatial distribution and temporal variation of phytoplankton and discover the unusual blooms. The data were obtained from the NASA ocean colour website (http://oceancolor.gsfc.nasa.gov/) with a spatial resolution of 4 km.

Daily optimally interpolated sea surface temperature (SST) data with a spatial resolution of 9km were provided by the Remote Sensing Systems (http://www.remss.com/), which produces the microwave plus infrared (MW_IR) OI SST by combining the through-cloud capabilities of the microwave data (MW) with the high spatial resolution of the Infrared (IR) SST data.

Monthly sea surface height anomaly (SSHA) data with a spatial resolution of 0.25° came from the Archiving Validation and Interpretation of Satellite Oceanography (AVISO) data (http://www.aviso.oceanobs.com/).The SSHA data were used to examine the existence of eddies.

Time series of monthly Chla，SST and SSHA anomaly data were calculated by subtracting the climatology data (2003-2015) from the monthly data.

2.2 Typhoon data

The typhoon track data used in this study were downloaded from the Joint Typhoon Warning Center (JTWC). The data include typhoon center position in latitude and longitude, time (UTC), maximum sustained winds in knot and typhoon scale every 6 h. Category 1 typhoon MADI passed through the study area from 6 December 2013 to 12 December 2013, which track is shown in Fig. 1. It lingered in the southwestern BOB for 7 d with a relative slow moving speed.

2.3 Argo data

Two Argo floats with ID 2900106 (green star in Fig.1) and 2901288 (yellow star in Fig.1) happened to be located at the bloom area. The Argo profiles of temperature and salinity during the bloom period were obtained from China Argo Real-time Data Center (http://www.argo.org.cn/).

The density-based mixed layer depth (MLD) is more suitable than the temperature-based mixed layer depth used in this study, as the barrier layer cannot be negligible in the Bay of Bengal. The mixed layer depth can be defined from a threshold method, for which the mixed layer depth is the depth at which density changes more than 0.03 kg/m^3 relative the density of depth 10 m (de Boyer Montégut et al., 2004).

Time series of Argo averaged temperature anomaly of the selected box in the upper 100 m were created by the Global Marine Argo Atlas (http://www.argo.ucsd.edu/Marine_Atlas.html). The Atlas makes it easy for users to look at Argo data and compare it to other global data sets in one free program.

2.4 Nitrate data

Climatological monthly mean nitrate data with a spatial resolution of 1° were obtained from the World Ocean Atlas 2013 (http://www.nodc.noaa.gov/OC5/ WOA13/pr_woa13.html), which is a set of objectively analyzed climatological fields of in situ temperature, nitrate, and other fields at standard depths. We estimated the depth of nitracline as the depth where nitrate concentration is over 1 μm (Menkes et al., 2016).

3. RESULTS

3.1 Two unusual phytoplankton blooms

We identified two unual phytoplankton blooms in the southwestern Bay of Bengal (Figs. 2a and b) with large spatial coverage and long duration by analysing the monthly Chla data between January 2003 and December 2015. One bloom occurred in December 2005 and the other in December 2013. For Bloom 1, the Chla of the Bloom ranged from 0.5 to 1 mg/m^3 in general, but patches reaching about 1.5 mg/m^3 were also seen. For Bloom 2, the bloom patch had a Chl-a value magnitude similar to that of Bloom1, but the area of patches with Chla concentration close to or over 1 mg/m^3 was larger.

To further examine these two blooms, we selected one sampling region (10°–15°N, 82°–85°E) as shown in Fig.1, within the bloom area where the depth was almost more than 3000 m to ensure that the study regions were in deep ocean to avoid terrestrial influence. The temporal variations in Chla concentration in the selected area from January 2003 to December 2015 are shown in Fig. 2c. The maximum Chla concentration each year usually appeared in December or one month before or behind. However, the Chla concentration reached 0.88 mg/m^3 in December 2005 and 1.01 mg/m^3 in December 2013, which were almost two to three times the maximum for other years. In addition, the Chla concentration in January 2014 was about 0.5 mg/m^3, which was the maximum value of the same month during the study period.

3.2 Ocean physical environment

We compared the ocean physical environment in terms of SSHA and SST in the Bay of Bengal in December 2005 and December 2013. As Fig. 3a and b show, the SST distribution in December 2005 and December 2013 has a similar pattern with low SST in the southwestern and northern Bay of Bengal and high SST in the southeaster and southern Bay of Bengal. The temperature of the cold patches in the southwestern Bay of Bengal was lower than 27 °C. Additionally, SST in the southwestern Bay of Bengal was about 0.5 °C lower than that of December 2005. The Bay of Bengal was covered with negative SSHA in the southwestern part and positive SSHA in the northeastern part in December 2005 and December 2013 (Figs. 4a and b). A strong cyclonic eddy with the amplitude larger than 30 cm occupied in the southwestern part of the bay in December 2005. However, the cyclonic eddy in December 2013 was much weaker. The location of both blooms roughly matched that of the cold path and the cyclonic eddy, indicating a close correlation between them. This correlation is examined further in section 4.

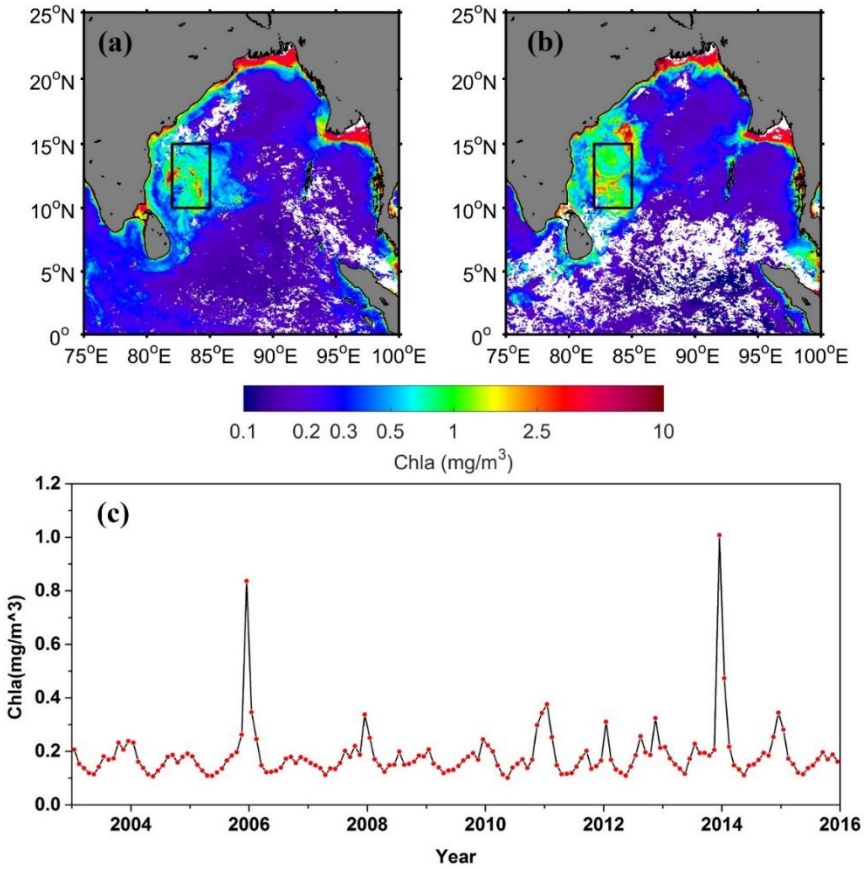

Fig. 2. Monthly Chla concentration for (a) December 2005 and (b) December 2013; (c) time series of the monthly averaged Chla concentrations for box in Figs. 2a and b. The box in Figs. 2a and b is same as that in Fig.1.

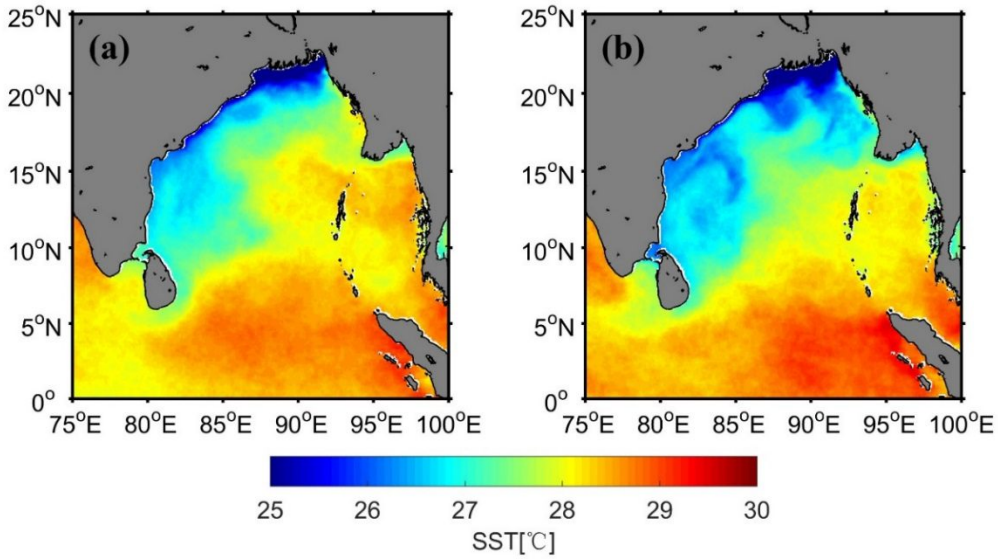

Fig. 3. Monthly SST for (a) December 2005 and (b) December 2013.

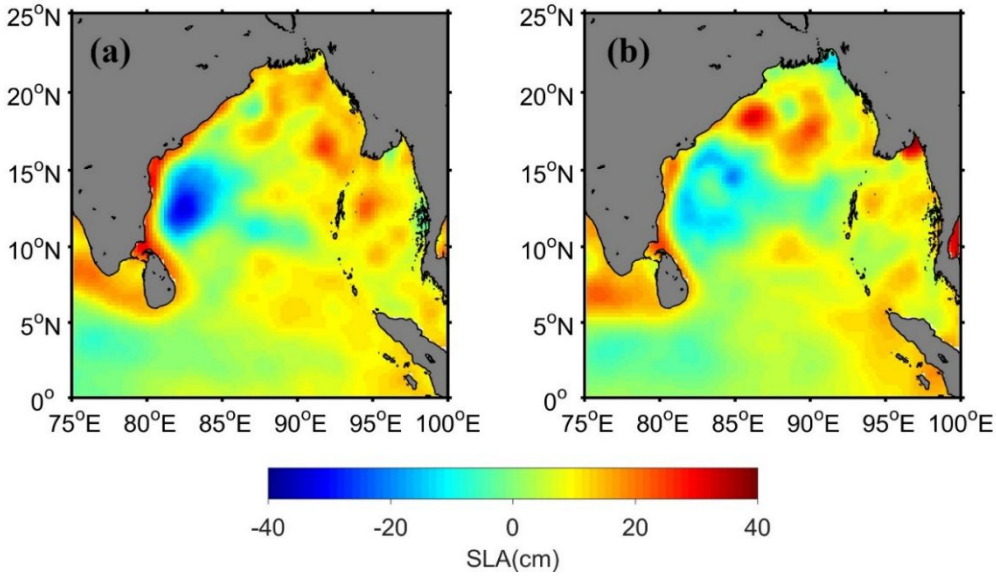

Fig. 4. Monthly SSHA for (a) December 2005 and (b) December 2013.

4. DISCUSSION

Phytoplankton growth, in general, is regulated by the availability of light and nutrients. Light is not usually a limiting factor in the Bay of Bengal and biological production is mainly limited by the availability of nutrients (Prasanna Kumar et al., 2002). Chen et al. (2013) has revealed the Bloom 1 triggered by multiple forcings, including strong cyclonic eddy, frequent tropical cyclones, and strong wind-induced mixing. Therefore, the reason for triggering Bloom 2 will be discussed in this study in comparison with Bloom 1.

4.1 Cyclonic eddies and typhoons

Mesoscale processes such as cyclonic eddies (Nuncio and Prasanna Kumar, 2012) and episodic events such as cyclones (Vinayachandran and Mathew, 2003; Maneesha et al., 2011) play a significant role in the re-supply of nutrients to the euphotic zone and further enhancing primary production. The strong cyclonic eddy with a long duration was the dominant factor responding to the continuous transport of nutrient-rich water from the deep layer into the euphotic zone by sustaining the phytoplankton bloom of December 2005 (Chen et al., 2013). As shown in Fig. 5, the cyclonic eddy was also the strongest during our study period. Although the magnitude of Bloom 2 was the largest of our study period, the cyclonic eddy was much weaker. Obviously, the cyclonic eddy was not the main contributor for Bloom 2. Chen et al. (2013) has revealed that three typhoons could have been additional factors for Bloom1. For Bloom 2, a Category 1 typhoon MADI happened to pass through the study area from 6 December 2013 to 12 December 2013. The MLD deepened (as shown in Fig. 6) and the Chl-a correspondingly increased along the typhoon track after the passage of typhoon (not shown in this paper). Therefore, typhoon was also a contributor.

4.2 Stratification

This strong stratification in the Bay of Bengal may inhibit nutrients transported to the surface layer, resulting in low productivity in the basin of the Bay of Bengal (Prasanna Kumar et al., 2002). The climatological MLD of the bloom area in November and December was about 10~20 m (de Boyer Montégut et al., 2004). The climatological nitracline depth of the bloom area provided by WOA13 was about 30~35 m (not shown in this paper), which is deeper than the climatological MLD. Therefore, the phytoplankton bloom occurs only when the stratification is broken by the turbulence (such as eddies, typhoons, etc.). As shown in Fig. 6a, the MLD deepened in December 2005 to ~30 m due to the frequent typhoons (Chen et al., 2013). For Bloom 2, the MLD was deeper than that of Bloom 1 (as shown in Fig. 6b). Even if in November 2013, the MLD had reached ~30 m. Moreover, the MLD deepened to ~50 m in December 2013. That means the stratification was weaker and more nutrients would be brought to the surface layer for Bloom 2 than Bloom 1. In fact, the SST of Bloom 2 was the lowest during our study period (as shown in Fig. 5). At the same time,

the temperature in the upper 100 m as shown in Fig. 7 was extremely low and lasted about one year in 2013 while the low temperature only lasted about four months in 2005. Therefore, the weakest stratification in 2013 was the dominant factor for triggering Bloom 2.

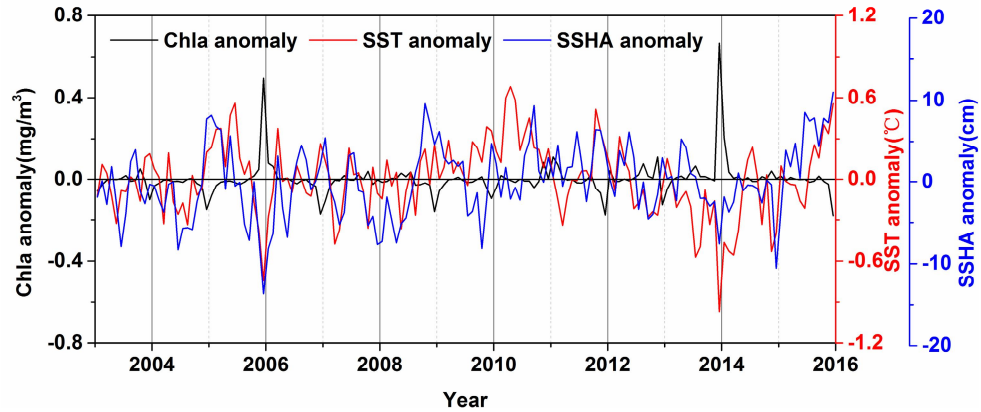

Fig.5. Time series of anomalies from January 2003 to December 2015 (Chla concentration (black line, left axis), SST (red line, middle axis) and SSHA (blue line, right axis)).

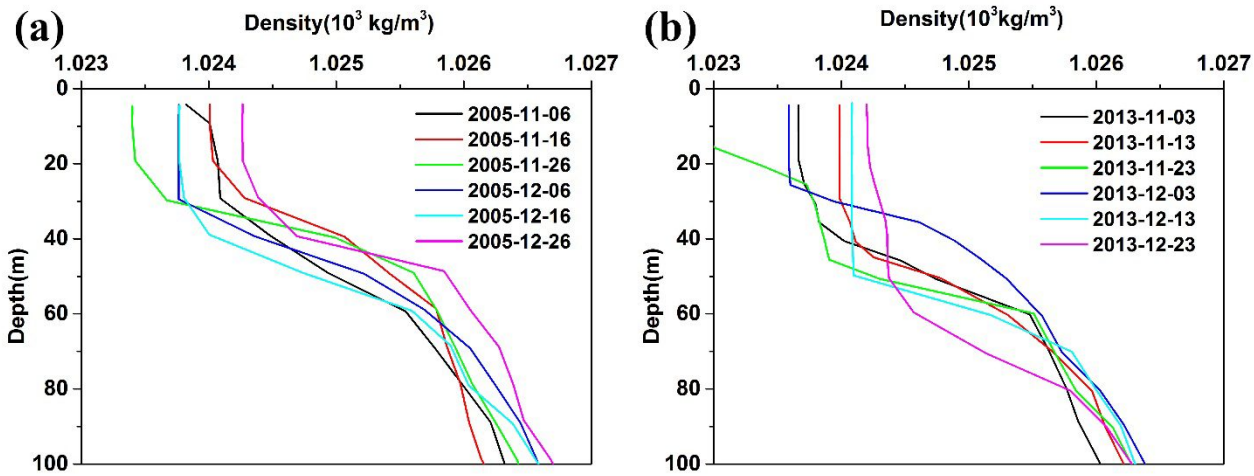

Fig.6. Density profiles derived from Argo temperature and salinity data of (a) ID 2900106 and (b) ID 2901288 in the upper 100 m. Both Argo floats were located in the bloom area as shown in Fig.1.

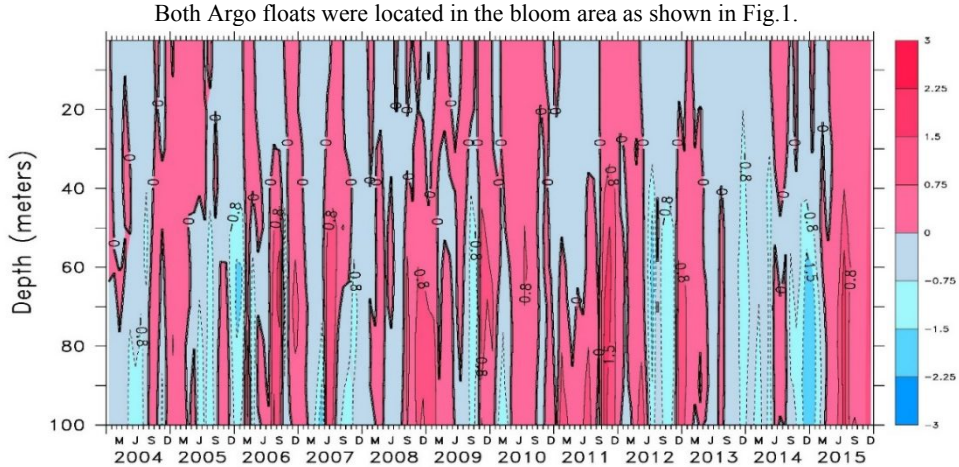

Fig.7. Time series of Argo averaged temperature anomaly of the selected box in the upper 100 m. The map was created by the Global Marine Argo Atlas.

5. SUMMARY

Two unusual phytoplankton bloom events were identified in the southwestern Bay of Bengal from MODIS-derived chlorophyll-a concentration data collected between 2003 and 2015. The occurrence of Bloom 1 in December 2005 has been reported to be triggered by multiple forcings, including strong cyclonic eddy, frequent typhoons, and strong wind-induced mixing (Chen et al., 2013). Interestingly, the Bloom 2 was identified in almost the same location in December 2013. Further, it is the strongest bloom during our study period with large area of high Chl-a > 1.0 mg/m^3 and shared some similar features with Bloom 1, such as wide coverage and long duration. At the same time, there were also frequent typhoons and cyclonic eddies. We found that the cyclonic eddy was not the dominant factor for Bloom 2 as the eddy was much weaker than that of Bloom 1. Specially, the strafication in December 2013 was lowest during our study period. Therefore, the weak stratification can be broken easily by mixing induced by typhoons and cyclonic eddies and finally result in the strong bloom. This comparative studies could provide us some insight in understanding the role of eddies and typhoons in phytoplankton dynamics in the Bay of Bengal.

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