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Extreme events enhance phytoplankton bloom in the south-western Bay of Bengal

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A study on MODIS (Moderate Resolution imaging Spectroradiometer)-derived chlorophyll-a concentration data was carried out for 12 years (2003 to 2014), to know the reasons for two episodic phytoplankton bloom events occurred in 2005 and 2013. During the month of December 2005 and 2013, magnitude of the production increased to two to three times of climatological value over the south-western Bay of Bengal region. Reasons for the bloom were examined with the available satellite resources and it was identified that the strong cyclonic eddy, with long residence time, caused the increase of the production. This production intensified when cyclones passed through or were close to the eddy. The vertical mixing enhanced (2013) when very severe cyclonic storms passed through or moved close to the eddy compared to depressions passing over it which caused further intensification of the primary production.

[Keywords: Cyclonic eddy, Cyclones, Chlorophyll, SST, SLA]

Introduction

The Bay of Bengal (BOB), located in the north-eastern part of the Indian Ocean, is a semi-enclosed tropical basin, influenced by seasonally reversing monsoon, transient cyclonic storms, and freshwater discharges. It is unique compared to many other Oceanic basins[1]. The immense freshwater is through excess precipitation over evaporation[2] and huge river runoff from several rivers. This causes high stratification with low salinities at the upper layers in the BOB[3,4]. This strong stratification leads to the formation of thick barrier layer[5,6], which may inhibit the vertical transport of the nutrients from deeper depths to surface layer, resulting in low productivity in the bay[7]. However, extreme events such as cyclones[8-11] and meso scale eddies[9,11-17]erode the stratification of the surface layer and transport nutrients from deep-layers to the surface, which are capable of enhancing the biological production. Meanwhile, runoff driven by episodic heavy rainfall also helps to increase the biological production[10]. In addition to these forces, climatic events such as ElNino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD)[18] can also influence biological productivity. Murtugudde et. al.[19], observed the occurrence of blooms in the tropical Indo-Pacific basin during the ElNino and IOD year of 1997-98. Girish kumar et. al.[6], reported a phytoplankton bloom in the southern BOB during the winter of 2006-07. Chen et. al.[11], observed a phytoplankton bloom in the south-western bay during the winter of 2005. They all attributed the association of blooms with shoaling of the thermocline and weakening of the barrier layer as a result of anomalous westward-propagation Rossby waves due to strong wind fields.

In this study, we explored the bloom in the south-western BOB (11 to 13°N and 82 to 84°E; Fig. 1) using the monthly mean chlorophyll-a (Chl-a) products, followed by its variability, and finally the mechanisms that can bring the nutrients to the near surface layer which cause the bloom are studied.

Data and Methodology

High spatial resolution (4 km) of monthly mean Chl-a data derived from MODIS Aqua (oc3 algorithm)

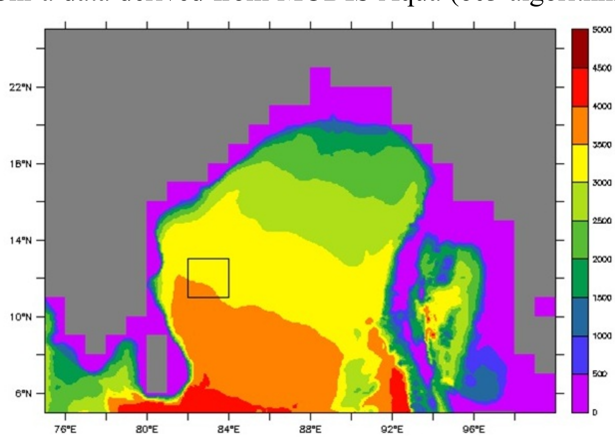

Fig. 1 — Location of the study region (marked with box; 11-13^{0}N, 82-84^{0}E) with isobaths.

from January 2003 to December 2014 from the NASA ocean colour (http://oceancolor.gsfc.nasa.gov/) are used to examine the spatial and temporal distribution of phytoplankton bloom. Monthly mean Sea Surface Height Anomaly (SSHA) data with spatial resolution of 0.25° is retrieved from Archiving Validation and Interpretation of Satellite Oceanography (AVISO) (http://aviso.Oceanobs.com/). Monthly mean Sea Surface Temperature (SST) from Tropical Rainfall Measuring Mission's (TRMM's) microwave imager with resolution 0.25° is retrieved from INCOIS (http://www.incois.gov.in). Geostrophic currents with sea surface height data are used for determining eddies and are obtained from the ocean watch (http://oceanwatch.pifsc.noaa.gov). For wind fields, Quick scat (2004-2008) and Ascat (2009-2014) provided by Asia Pacific Data Research Centre are considered (http://apdrc.soest.hawaii.edu). Monthly wind stress and Ekman pumping velocity are calculated using the equation given by Enriquez and Friehe[20]. Monthly anomalies for each dataset are calculated by subtracting the long-term monthly mean value of the respective period from the value during each individual period.

To understand the extent of episodic phytoplankton bloom events, weekly SSH superimposed with geostrophic current data is used. Cyclone track data is obtained from the India Meteorological Department (http://www. imd.gov.in/). Apart from the satellite data, vertical profiles of temperature and salinity from Argo floats are also used during bloom period (http://www.incois.gov.in).

Results

Spatial distribution of December month Climatological Chl-a concentration present in figure 2a whereas figures 2b and 2c represent the December month mean Chl-a concentration of 2005 and 2013, respectively. Temporal distribution of monthly mean Chl-a concentration over the south-western BoB (marked in box in Fig. 1) is shown in Figure 2d. The Chl-a concentration is very less, except along the narrow shelf of the bay and the south-western bay. In the south-western region, the Chl-a concentration during December is varying between 0.1 to 0.4 mg m^{-3} except for two episodic events with large spatial coverage with long sustain (Figs. 2b& c).

One event occurred in December 2005 (~ 1.1 mg m^{-3}) (Fig. 2b) and another in December 2013 (~1.3 mg m^{-3}) (Fig. 2c) where the water column depth was more than 1000 m. To understand these bloom events, here a region is selected (11-13°N, 82-84°E; marked with square in Fig. 1) within the bloom area and plotted the monthly averaged variations of Chl-a from January 2003 to December 2014 as shown in figure 2d. The maximum Chl-a concentration for each year is noticed in the vicinity of December month.

The spatial distribution of (SST), Sea Level Anomaly SLA, surface wind stress and Ekman pumping are shown in figure 3 during bloom years along with climatology. Relatively cold SSTs (~1°C less) are distributed in south-western bay during

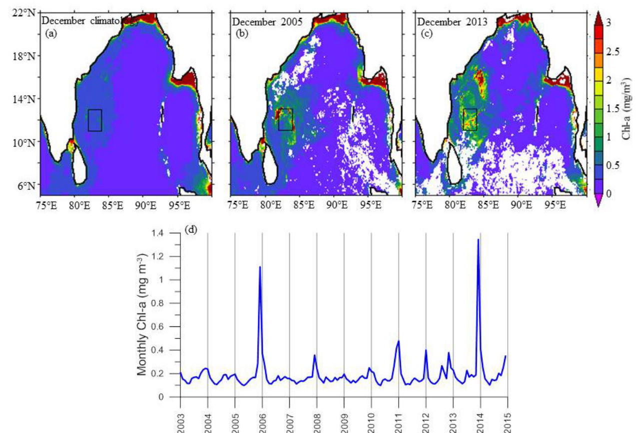

Fig. 2 — Monthly climatological Chl-a concentration for (a) December; monthly Chl-a concentration for (b) Dec 2005 and (c) Dec 2013; (d) monthly averaged Chl-a centration for the selected region obtained from MODIS during 2003 to 2014.

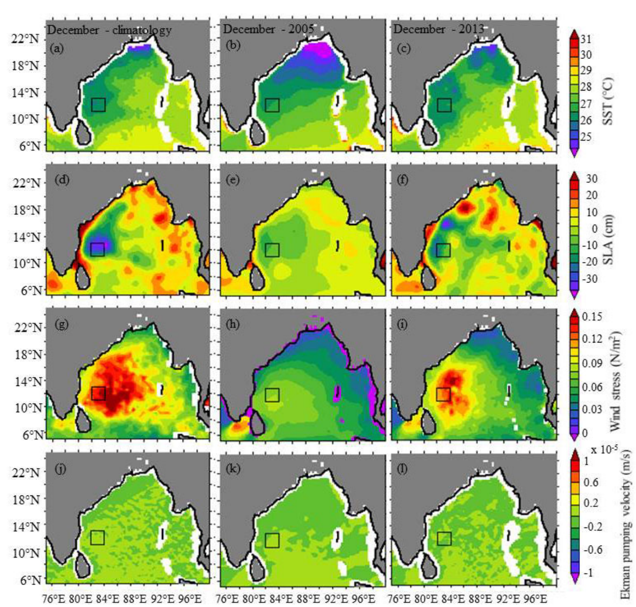

Fig. 3 — Climatological mean fields for December (left panel); monthly mean field for December 2005 (middle panel) and December 2013 (right panel) of ((a), (b) and (c)) SST; ((d), (e) and (f)) SLA; ((g) (h) and (i)) wind stress; ((j), (k) and (l)) Ekman pumping velocity.

bloom years as compared to climatology (Fig. 3a, b, c). Pattern of spatial distribution of SLA is similar to the climatology but relatively lesser SLAs during bloom years with magnitude ~15 cm (30 cm) which is less than climatology observed during 2005 (2013). Surface wind stress distribution during the bloom years is significantly different from that of the climatology. In Dec 2005, ~ 0.12 Nm^{-2} wind stress covered most of the central basin of the bay and ~ 0.1Nm^{-2} in Dec 2013 (Fig. 3g, h & i). There is not much difference in the Ekman pumping values between the climatology and during bloom years (Fig. 3j, k & l). The prevailing northeast winds during this period are not favourable for Ekman upwelling, but the strong wind stress along with radiated Rossby waves from east may be responsible for the cyclonic eddy circulation in this region[21]. Hence, here the Ekman pumping can be excluded as the direct cause of these events.

Summary and Discussion

Te primary production in the BOB is less than the production in the Arabian Sea[22,23] except along certain parts of the western boundary of the bay, due to availability of high nutrients[16,24]. Prasannna Kumar et. al.[7], noticed that biological production is mainly limited by the availability of nutrients in the BOB. The chlorophyll concentration could be enhanced by Ekman pumping, mesoscale eddies[9] and cyclones[10]. Henceforth all different mechanisms for the supply of the nutrients to the upper layer to support the blooms are examined except the Ekman pumping.

Influence of mesoscale eddies

Cold core eddies play very significant role in enhancing the production by supplying nutrients to the upper layers[9,11,25]. The wind, SST and SLA pattern during December 2005 and 2013 clearly indicate the presence of large cyclonic eddy (Fig. 3). The development of these eddies is studied by daily SLA (Fig. 4) and weekly SSH along with super imposed geostrophic currents (Fig. 5& 6). The strength and size of the eddy is larger in 2005 (Fig. 5) than that in 2013 (Fig. 6). During December, East India Coastal Current (EICC) is moving towards equator[26]. The daily negative SLA increases from mid November 2005 to first week of December 2005 of about 25 cm (Fig. 4a) with a geostrophic velocity of about 0.7 m/s along the periphery of the eddy (Fig. 4b). From the mid December, horizontally extended eddy turned parallel to the coast and is squeezed towards the east coast of India (Figs. 5d-f). By the end of January 2006, the eddy is completely eroded (Figure not included).

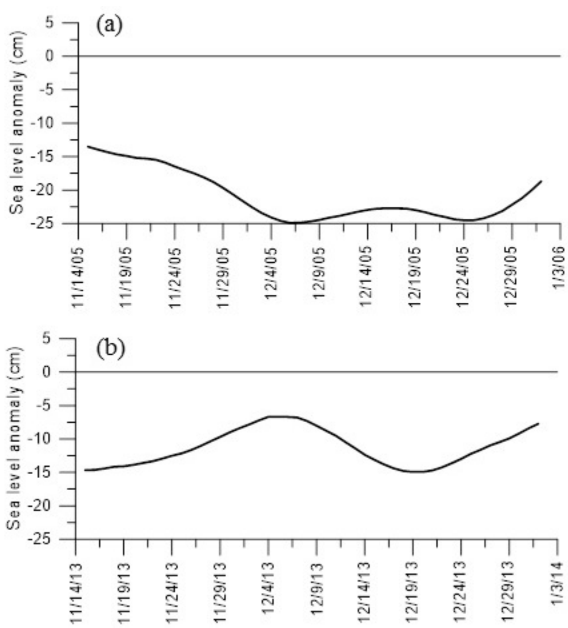

Fig. 4 — Daily Sea level variability during mid-November to December of (a) 2005 and (b) 2013.

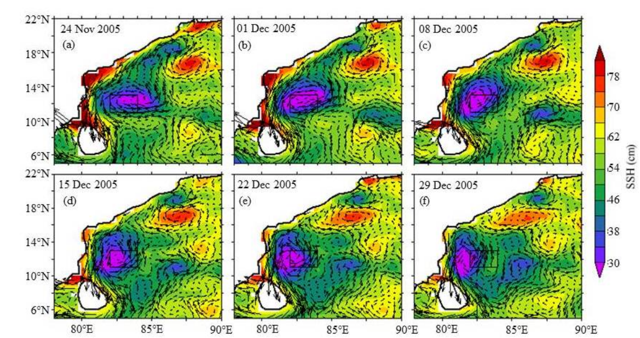

Fig. 5 — Weekly averaged SSH (cm) (shaded) overlaid by geostrophic currents on (a) 24 Nov 2005; (b) 01 Dec 2005; (c) 08 Dec 2005; (d) 15 Dec 2005; (e) 22 Dec 2005 and (f) 29 Dec 2005.

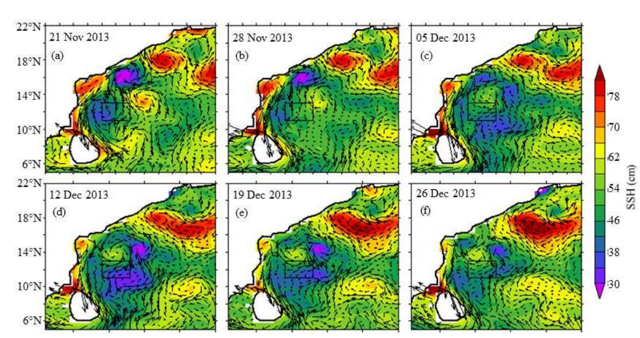

Fig. 6 — Weekly averaged SSH (cm) (shaded) overlaid by geostrophic currents on (a) 21 Nov 2013; (b) 28 Nov 2013; (c) 05 Dec 2013; (d) 12 Dec 2013; (e) 19 Dec 2013 and (f) 26 Dec 2013

Table 1─List of tropical cyclones formed in 2005 and 2013 (from November to December).

Cyclone name	Category	Duration	Avg. wind speed (m/s)
BAAZ	CS	27/11/2005 to 2/12/2005	18
FANOOS	CS	06/12/2005 to 10/12/2005	20
---	DD	17/12/2005 to 22/12/2005	14
HELEN	SCS	19/11/2013 to 23/11/2013	22
LEHAR	VSCS	23/11/2013 to 28/11/2013	28
MADI	VSCS	06/12/02013 to 12/12/2013	25

Note: DD: Deep depression; SCS: Severe cyclonic storm; CS: Cyclonic storm; VSCS: Very severe cyclonic storm

The daily negative SLA decreased from mid November 2013 to first week of December 2013 then an increase is observed until 20 December 2013 followed by a decrease (Fig. 4b), which clearly explains weaker eddy in 2013 than that in 2005. Unlike in December 2005, lesser negative SLA with lesser geostrophic velocities is noticed in December 2013 (Fig. 6). In both the events, SLA (Fig. 4), geostrophic currents (Figs. 5 & 6) and wind stress (Fig. 3) are higher in 2005 than those in 2013 but there is a higher bloom in 2013 than those in 2005 (Fig. 2).

Influence of Tropical cyclones

The BOB is a region of intense cyclones which increases the vertical mixing and brings nutrient-rich waters to upper layer. The frequency of tropical cyclones is more during October–December[6]. Recently, Maneesha et. al.[10], noticed the enhancement of the production when cyclones pass over eddies. Vinayachandran and Mathew[9], Rao et. al.[27], Tummala et. al.[28], also observed the enhancement of production during cyclones. But the intensity of the cyclones can be altered by mesoscale eddies[29]. In both the bloom years, three cyclones occurred in the BOB from mid November to December (Fig. 7) with different intensities. During 2013, the cyclones intensified to severe storms with average wind speed greater than 20 m/s and were less than 20 m/s in 2005 (Table 1).

In 2005, all three cyclones passed through or were close to the region where the phytoplankton bloom occurred (Fig. 7a) whereas in 2013, *MADI* (very severe cyclonic storm) cyclone passed through the bloom region and other two cyclonic storms wereclose to the bloom region (Fig. 7b). The intensity of the cyclones in 2013 was higher than that in 2005 (Table 1). After the passage of cyclones relatively higher salinities and lower temperatures were present in 2013 than in 2005 which confirmed the deeper mixed layer (Fig. 8). Tropical cyclones intensify the vertical mixing with decrease in SST and increase in surface salinity[11]. Even though the monthly distribution of wind stress is relatively less in 2013 (Fig. 3), very severe cyclonic storms enhance vertical mixing with higher densities in 2013 than in 2005 (Fig. 8c). Similar observations of intensification of primary production were identified in

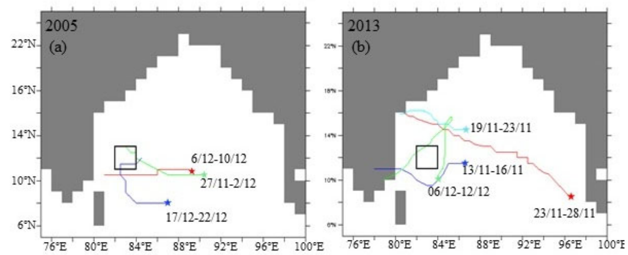

Fig. 7 — Tropical cyclone tracks during November to December of (a) 2005 and (b) 2013.

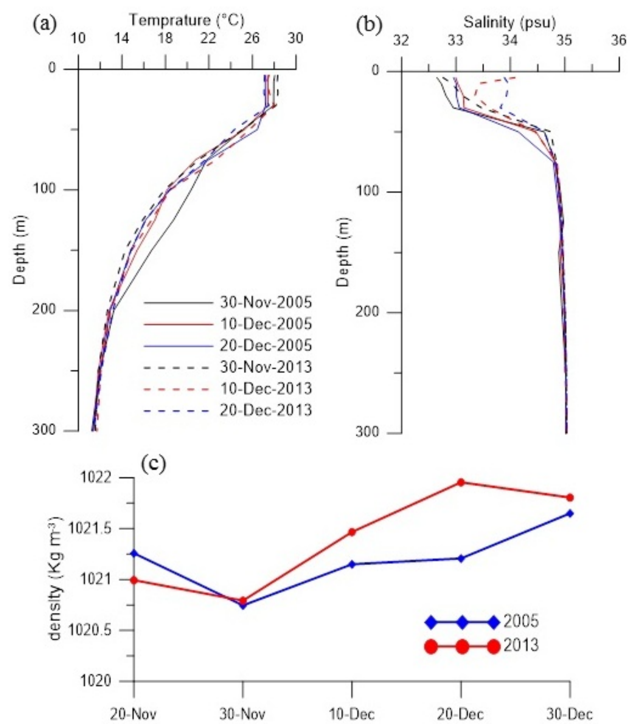

Fig. 8 — Vertical profiles (10–300 m) of (a) Temperature (b) Salinity and (c) Density of selected dates during November and December of 2005 and 2013 years.

2005 when cyclones passed over the region[11] and they attributed that higher production may be due to nIOD. The other evidences for intensification of the bloom via by cyclones: in November 2007, December 2010 and 2011. In contrast, the primary production was very less in 2006 and 2008 when no cyclones passed through it. However both the bloom events occurred during negative nIOD, years but 1998 is a nIOD year but no bloom was noticed[11]. Thus, the cyclones passing over the cold core eddy may be contributing more to the production than IOD effects.

In this study, we examined the factors controlling the bloom at the south-western BoB using SLA and chl-a data. The presence of the cold core eddy, which is a climatological feature, increased the production from 0.1 to 0.4 mg m^{-3}. The production doubled or tripled when cyclones passed through or moved close to the eddy during December 2005 and 2013. Both the events lasted for several months and covered a large spatial area. Even though these events occur during nIOD years, 1998 being a nIOD year also, no bloom was noticed. The reasons for the absence of the bloom in 1998 are beyond the scope of the present work. However, in the future, the effect of the IOD/ENSO, the interaction between eddies and tropical cyclones and how these contribute to the enhancement of production needs to be studied.

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