Phytoplankton bloom in the Bay of Bengal during the northeast monsoon and its intensification by cyclones

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[1] Satellite derived chlorophyll a imageries are used to present a phytoplankton bloom in the Bay of Bengal during the northeast monsoon (November–February) and the mechanisms that can upwell nutrients to sustain the bloom are investigated using sea level anomalies and winds. OCTS and SeaWiFS chlorophyll *a* images show that there is a phytoplankton bloom in the southwestern part of the bay during November–January. The chlorophyll *a* concentration of the bloom can be as high as 2 mg m^{-3} compared to near zero value before the bloom. Open ocean upwelling driven by Ekman pumping causes the bloom. The cyclones which are common during this period lead to localized intense blooms in the western Bay of Bengal. The offshore extent and the intensity of the bloom varies from year to year. The bloom was absent during 1997 due to weak Ekman pumping. *INDEX TERMS:* 4223 Oceanography: General: Descriptive and regional oceanography; 4572 Oceanography: Physical: Upper ocean processes; 4279 Oceanography: General: Upwelling and convergences; 4855 Oceanography: Biological and Chemical: Plankton. **Citation:** Vinayachandran, P. N., and S. Mathew, Phytoplankton bloom in the Bay of Bengal during the northeast monsoon and its intensification by cyclones, *Geophys. Res. Lett.*, *30*(11), 1572, doi:10.1029/2002GL016717, 2003.

1. Introduction

[2] The Bay of Bengal (hereafter referred to as the BoB) is a semi-enclosed tropical ocean basin that is highly influenced by monsoons and receives large volume of freshwater from both river discharge and rainfall. The circulation in the BoB [see *Schott and McCreary*, 2001; *Shankar et al.*, 2002, and references therein] is forced by remote effects from the equatorial Indian Ocean in addition to monsoon winds and freshwater input. During the pre-monsoon months (February–May), there is a well-developed anticyclonic gyre in the BoB and a poleward east India coastal current (EICC) [*Shetye et al.*, 1993]. During the summer monsoon (June–September), the EICC flows poleward along the southern part of the Indian coast and equatorward farther north [*Shetye et al.*, 1991]. The EICC is equatorward all along the coast during November–December [*Shetye et al.*, 1996]. Further, model results show that, in the western BoB there exist thermal domes associated with cyclonic circulation and upwelling [*Vinayachandran and Yamagata*, 1998]. Do these circulation features have an expression on the primary productivity of the BoB? *Gomes et al.* [2000] found that although the phytoplankton regime along the east coast of India is inhibited by stratification caused by river discharge and monsoonal cloud cover, physical processes such as ocean currents and eddies are able to erode stratification and upwell nutrients. However, the implications of the gyres in the open bay to the primary productivity remains unknown.

[3] Using chlorophyll *a* concentration (chl *a* hereafter) images derived from Sea-viewing Wide Field of view Sensor (SeaWiFS) for the Indo-Pacific region from October 1997 to September 1998, *Murtugudde et al.* [1999] found elevated chl *a* south of Sri Lanka during August 1998. Using Ocean Color Monitor images *Nayak et al.* [2001] examined the impact of a cyclone on the chl *a* off the coast of Orissa. Phytoplankton bloom in the Arabian Sea during both summer [*Brock et al.*, 1991] and winter [*Banse and McClain*, 1986] monsoons have been studied but the BoB still remains largely unexplored. In this paper, we first show that there is a bloom in the southwestern BoB, followed by a description of its interannual variability and finally the mechanisms that can upwell nutrients to the near-surface layer to cause the bloom are examined.

2. Data

[4] The data sets used in this study are: 1) Weekly composite maps (version 4) of chl *a* derived from ocean color imageries obtained by Ocean Color and Temperature Scanner (OCTS) at 10 km spatial resolution from Earth Observing Research Center(EORC), National Space Development Agency (NASDA) of Japan, 2) SeaWiFS images of chl *a* (Level-3 GAC) at a spatial resolution of 9 km from Goddard Space Flight Centre (GSFC), USA, 3) TOPEX/Poseidon (T/P) sea level anomalies (SLA) at a spatial resolution of 1° × 1° from the University of Texas and 4) Monthly mean winds from Florida State University (FSU) and weekly winds from ERS-2, both at a spatial resolution of 1° × 1°.

3. Phytoplankton Bloom

[5] Selected weekly composite images of chl *a*, when it is relatively cloud free, during November 1996–February 1997 are shown in Figure 1. During November 3–9, the chl *a* in the open bay is very low (<0.15 mg m^{-3}) but for a patch of high chl *a* (>2 mg m^{-3}) off the east coast of India, north of 16°N. Chl *a* increases dramatically in the southwestern BoB during December (Figure 1, top right and bottom left panels). This bloom is located to the west of about 88°E between 8–16°N. Within the bloom, the chl *a* values range from 0.5 to 1 mg m^{-3} in general, but patches exceeding 2 mg m^{-3} are also seen. Surface chl *a* at six offshore locations in the southwestern BoB during November 1999

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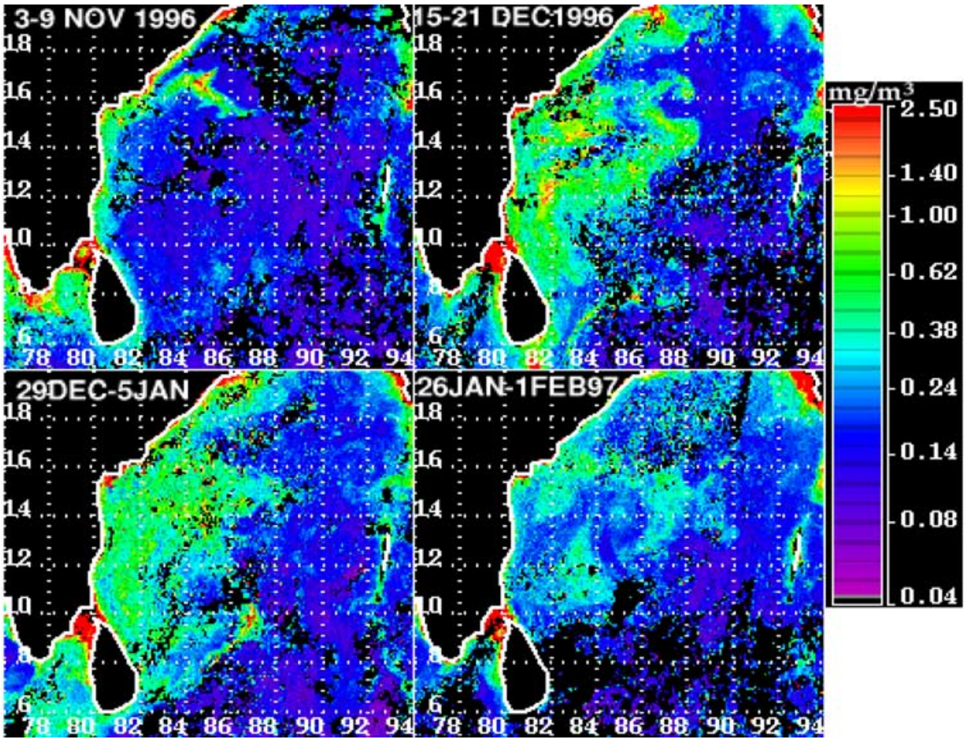

Figure 1. Selected weekly composite images of chl *a* (mg m^{-3}) derived from OCTS, during the northeast monsoon of 1996.

[*Madhu et al.*, 2002] ranged from 0.22–0.49 mg m^{-3}, similar to the values obtained from ocean color images (Figure 1). Winter blooms in the Arabian Sea also has similar values of chl *a* [*Banse and McClain*, 1986]. Shipboard measurements during December 1991 [*Gomes et al.*, 2000] showed a patch of high depth integrated chl *a* (>45 mg m^{-2}) separated from the coast in the southwestern part of the BoB. Consistent with this, the ocean color images show low chl *a* near the coast compared to the bloom farther offshore. The bloom weakens in January and only isolated patches are seen (Figure 1, bottom right panel). The bloom disappears entirely by the middle of February.

[6] Five years of SeaWiFS data suggest that the bloom is an annual feature (Figure 2). However, there was no bloom during 1997 except for a patch of chl *a* of about 0.3 mg m^{-3} around 14°N. The bloom was present in all other years, although its offshore extent, duration and maximum chl *a* within the bloom varied from year to year; examples being (a) the bloom developed early (in November) during 1999 and (b) the bloom weakened rather late (in February) during 2001. The elevated chl *a* seen in the southeastern part of the BoB during 1997 (Figure 2) is caused by the Indian Ocean dipole [*Murtugudde et al.*, 1999].

4. Mechanisms

[7] What causes the bloom? Since the phytoplankton population in this region during the northeast monsoon is

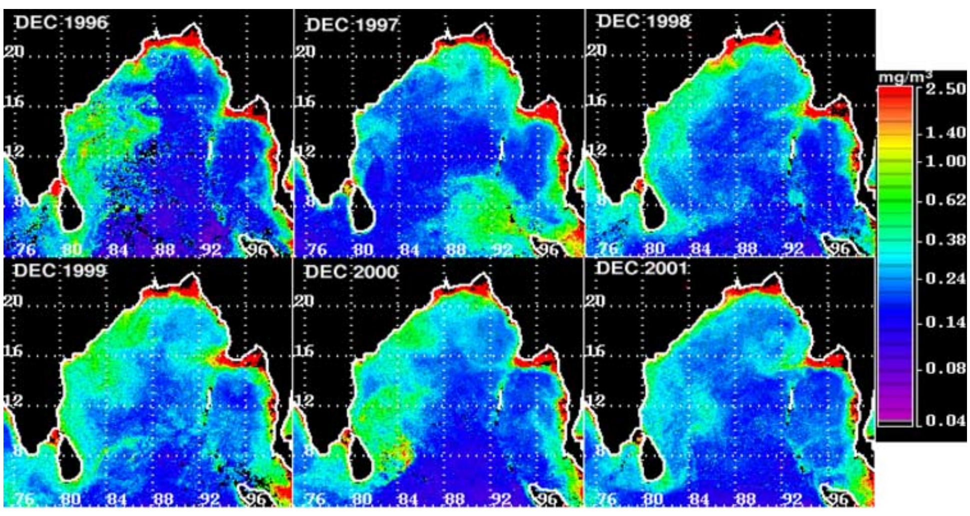

Figure 2. December composites of chl *a* (mg m^{-3}) derived from OCTS for 1996 and from SeaWiFS for 1997–2001.

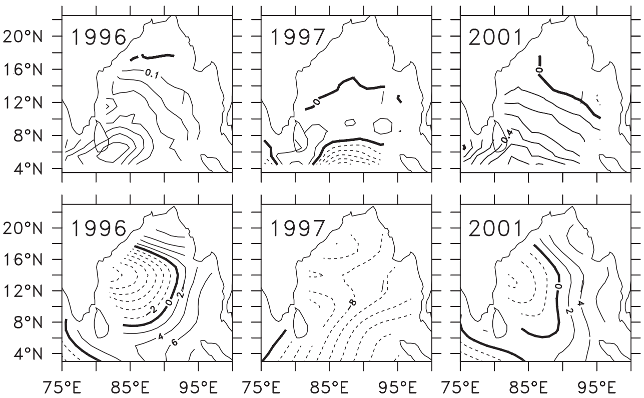

Figure 3. Upper panels: Mean EP for November–December calculated from FSU winds for 1996, 1997 and 2001. Contour interval is 0.1 m/day. Thick, continuous and dashed contours correspond to zero, upward and downward EP respectively. Lower panels: Mean SLA from the six T/P cycles for the months of November–December for 1996, 1997 and 2001. Contour interval is 2 cm. Thick, continuous and dashed contours correspond to zero, positive and negative SLA respectively.

limited by nutrients but not light [*McGill*, 1973; *Gomes et al.*, 2000], in this section we examine processes that can bring nutrients into the near surface layer. Entrainment of nutrient-rich water by wind mixing is not efficient in the BoB [*Shenoi et al.*, 2002]. The northeasterly winds during November–February do not favor coastal upwelling along the east coast of India. The low salinity water advected by the equatorward EICC from the northern BoB forms a narrow band close to the coast. A thin chl *a* band, the intensity of which decreases southward can be seen along the Indian coast in OCTS data (Figure 1, top left panel). This is consistent with the observations during December 1991 [*Gomes et al.*, 2000]. Chl *a* carried by the EICC cannot be advected offshore in the southwestern BoB because (a) the Ekman transport is towards the coast and (b) between about 13–15°N a northwestward flow pushes the water towards the coast [*Shetye et al.*, 1996].

[8] A major contribution to the bloom comes from Ekman pumping (EP). The circulation in the southwestern BoB during northeast monsoon consists of a cyclonic gyre [*Schott and McCreary*, 2001; *Vinayachandran and Yamagata*, 1998]. This cyclonic gyre is forced primarily by upward EP caused by positive (anticlockwise) wind stress curl and the upwelling within this gyre cools the sea surface. The wind stress curl was anticlockwise and consequently the EP upward during the northeast monsoon of 1996 (Figure 3, upper left panel). The SLA during 1996 (Figure 3, lower left panel) clearly show the presence of a cyclonic gyre. Note that the maximum in SLA and EP are not located at the same place because the SLA are enhanced by westward propagating Rossby waves. Between 11 and 13°N, a patch of chl *a* higher than in the coastal region was observed by *Gomes et al.* [2000] which was located within a cyclonic circulation [*Shetye et al.*, 1996]. A source of nutrient in the open ocean is mandatory for the patches of chl *a* (Figures 1b and 1c) separated from the coast. Therefore, we conclude that the phytoplankton bloom is associated with the cyclonic gyre driven by the EP.

[9] During 1997, the Indian Ocean exhibited a climate anomaly known as dipole [*Saji et al.*, 1999] which was associated with warm sea surface temperature (SST) anomalies in the west and cold SST anomalies in the east. The SLA were positive in the west and negative in the east. These negative SLA propagated northward along the eastern boundary of the BoB and then radiated westward [*Vinayachandran et al.*, 2002b; *Rao et al.*, 2002]. There were negative SLA everywhere in the Bay (Figure 3, lower middle panel). This is quite unlike other years in which the SLA is negative in the southwestern part of the Bay and positive elsewhere. The EP over the BoB was weak during 1997 (Figure 3, upper middle panel). Thus the circulation and its forcing during 1997 was anomalous compared to the other years. During 1997, there was no bloom comparable to other years, confirming that the bloom is caused by open ocean upwelling.

[10] The BoB fosters several cyclones during October–December (Figure 4). How crucial are these cyclones for the bloom formation? During 1996, there was a deep depression in the BoB from 25–27 October, and two severe cyclones with maximum estimated winds of 100 km/hour during 5–7 November and 28 November–8 December [*Dikshit et al.*, 1997]. OCTS chl *a* during 3–9 November shows a patch of high chl *a* around 16.5°N, 84°E (Figure 1) corresponding to a region of EP amounting to 0.9 m/day (not shown). The latter cyclone made a loop over the Bay, thus had an unusually long residence period, and caused EP as high as 1.8 m/day (Figure 4). Chl *a* distribution for the week 15–21 December 1996 shows elevated levels in the vicinity of the cyclone track. Other clear evidences for the intensification of the bloom by cyclones are along 12°N off the Indian coast and east of Sri Lanka during 2000. Thus the cyclones intensify the bloom in their region of influence. Evidences

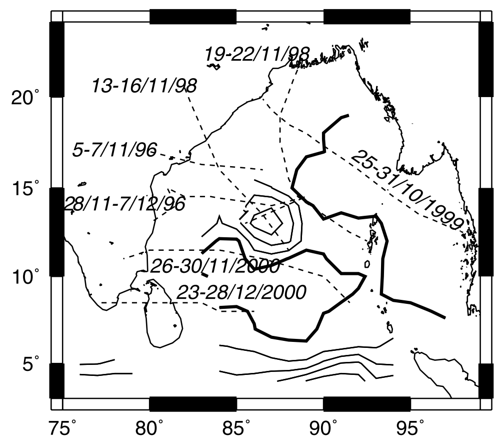

Figure 4. Tracks of cyclones (dashed lines) over the Bay of Bengal for the months of November and December during the 1996–2001 period. Depressions are not shown. The life period of the cyclones are written adjacent to each track. There were no cyclones during 1997 and 2001. Source: India Meteorological Department. Contours (continuous lines) are EP during the week 02–09 December, 1996 from ERS-2. Contour interval is 0.5 m/day and the zero line is shown as a thick contour.

for the enhancement of chl *a* along the east coast of India, following a cyclone during October, 1999 have been presented earlier using satellite derived ocean color observations [*Nayak et al.*, 2001] and using in situ data [*Madhu et al.*, 2002].

[11] In contrast, the chl *a* is found to be rather low during the years without cyclones. There were no cyclones during 1997 in the BoB (although the typhoon Linda from Gulf of Thailand crossed to the Andaman Sea, it dissipated in the central BoB) and there was no bloom either (Figure 2). Another cyclone-free year was 2001 when the upward EP (Figure 3, upper right panel) and the associated cyclonic gyre (Figure 3, lower right panel) caused a weak bloom confirming that EP causes the bloom and cyclones intensify it.

5. Discussion

[12] The phytoplankton bloom reported here assumes considerable importance as the BoB is believed to be a region of relatively low productivity compared to the Arabian Sea. Stratification caused by freshwater influx is thought to restrict upwelling of nutrients. However, stratification in the southern BoB is weaker than in the north [*Vinayachandran et al.*, 2002a; *Bhat et al.*, 2001], and our analyses show that this is not strong enough to prevent upwelling of nutrients. Upwelling by EP even during storm free periods are able to generate the bloom, though to a lesser intensity, as is evident from the image for 2001. The strong winds during cyclones mix water to deeper depths and thus induct nutrients to the mixed layer resulting in high chl *a* during the clear sky period that generally follows a cyclone.

[13] Winds over the BoB and the Equatorial Indian Ocean drive the seasonal circulation in the Bay. The fact that the EP, which is a major forcing during the northeast monsoon, enhances chl *a* points to the importance of wind as a physical process. The EP was weak over the southern Bay during the positive dipole of 1997 whereas there was an unusually large upward EP during the negative dipole of 1996 (Figure 3, upper panels). The former corresponds to a no-bloom scenario and the latter to an intense bloom. *Han and Webster* [2002] have suggested that negative wind curl (and hence downward EP) tends to appear in the southern bay during a positive dipole because of the possible linkage between winds over the bay and the equatorial Indian Ocean through large scale atmospheric system. Thus the bloom is affected by the Indian Ocean dipole because of its crucial dependence on EP. The SST of the BoB, on the other hand, was unaffected by the internal dynamics of the ocean during 1997 [*Rao et al.*, 2002]. Though cool temperature anomalies were present at subsurface levels the near surface stratification prevented the subsurface cooling from influencing the SST. These inferences suggest that relative control of winds and stratification on the primary productivity of the BoB are spatially dependent and a comprehensive study is required for its elucidation.

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