Cyclone *Phailin* enhanced the productivity following its passage: evidence from satellite data

Over the past decade (2002–2013) the Bay of Bengal has experienced 12 cyclones and 27 tropical storms. The recent one was the cyclone *Phailin* which was equivalent to a category-5 hurricane on the Saffir–Simpson hurricane wind scale (SSHWS). The cyclonic storm developed over the north of Andaman and Nicobar Islands on 9 October 2013. Subsequently, it propagated towards north-northwest and made a landfall at the Gopalpur coast of south Odisha on 12 October. Although the cyclone sustained in the ocean for a short span of four days, an elevated concentration of chlorophyll *a* (Chl *a*) and decrease in sea-surface temperature (SST) were observed along the cyclone track in Moderate Resolution Imaging Spectroradiometer (MODISA) images (Figure 1). The strong cyclonic winds often result in the mixing of surface water layer to the greater depths. This introduces nutrients to the mixed layer and result in increase in Chl *a* and decrease in SST, thus enhancing the productivity of the water column[1]. We studied the case further to quantify the increase in Chl *a* and decrease in SST due to the cyclone *Phailin*.

The entire track of the cyclone was divided into four sectors (B1–B4, Figure 1) based on the difference coerced on each day. Further, 12 years of MODISA L1A data for the period 1–17 October were processed for each sector to generate Chl *a* and SST. Subsequently, Chl *a* and SST climatology was generated using the data for the years from 2002 to 2012 (solid line, Figure 2). The accuracy of Chl *a* and SST products, generated from MODISA, in oligotrophic open ocean waters has been well documented. The SST derived from MODISA is comparable in accuracy to that derived by Advance Very High Resolution Radiometer (AVHRR)[2] whereas the Chl *a* retrieved from MODISA has an estimated error of maximum 25% in oligotrophic waters[3]. However, OC3M algorithm produces better estimates of Chl *a* from MODISA in Indian coastal waters, with an estimated error of 11% (ref. 4).

This correspondence reports two dimensions of analysis. The first is to quantify pre- and post-cyclonic changes in Chl *a* and SST. The second is to address the anomalies in Chl *a* and SST with respect to climatology. The temporal variability in Chl *a* and SST was almost followed the climatology in all four sectors prior to the cyclone (Figure 2). In sector B1, where the cyclone passed on 9 October, the peak Chl *a* (0.65 mg m^{-3}) and minimum SST (28.46°C) were observed on 12 October. With reference to pre-cyclonic condition, Chl *a* increased by 295% with a positive anomaly of 0.51 mg m^{-3}. The SST decreased by 0.3°C compared to pre-cyclonic condition, with a negative anomaly of 0.6°C. Subsequently, after 14 October the system was stable with both Chl *a* and SST close to climatology. The cyclone passed sector B2 on 10 October. Subsequently, an increase in Chl *a* and decrease in SST were observed. The peak Chl *a* (0.69 mg m^{-3}) and minimum SST were observed on 15 and 13 October respectively. The Chl *a* peaked to 0.51 mg m^{-3}, whereas the SST decreased to 28.7°C. The post-cyclonic condition showed 250% increase in Chl *a* and 0.41°C decrease in SST. Further, Chl *a* showed positive anomaly of 0.38 mg m^{-3} and SST showed a negative anomaly of 1.0°C. After 15 October the system moved towards equilibrium, showing values similar to climatology. In sector B3, peak Chl *a* (0.69 mg m^{-3}) and minimum SST (27.3°C) were seen on 15 October with an anomaly of 0.5 mg m^{-3} in Chl *a*. Also, this sector showed

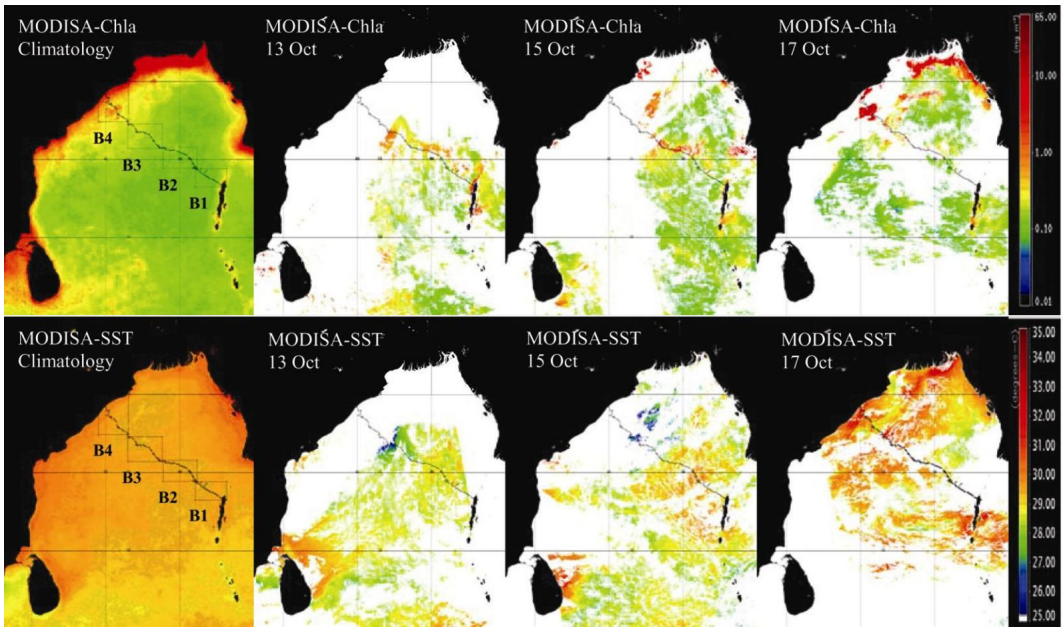

Figure 1. Spatial distribution of MODISA-derived chlorophyll *a* (Chl *a*) and sea-surface temperature (SST) after passage of the cyclone *Phailin*. The extremely left panel shows Chl *a* and SST climatology for the month of October overlaid with the cyclone track.

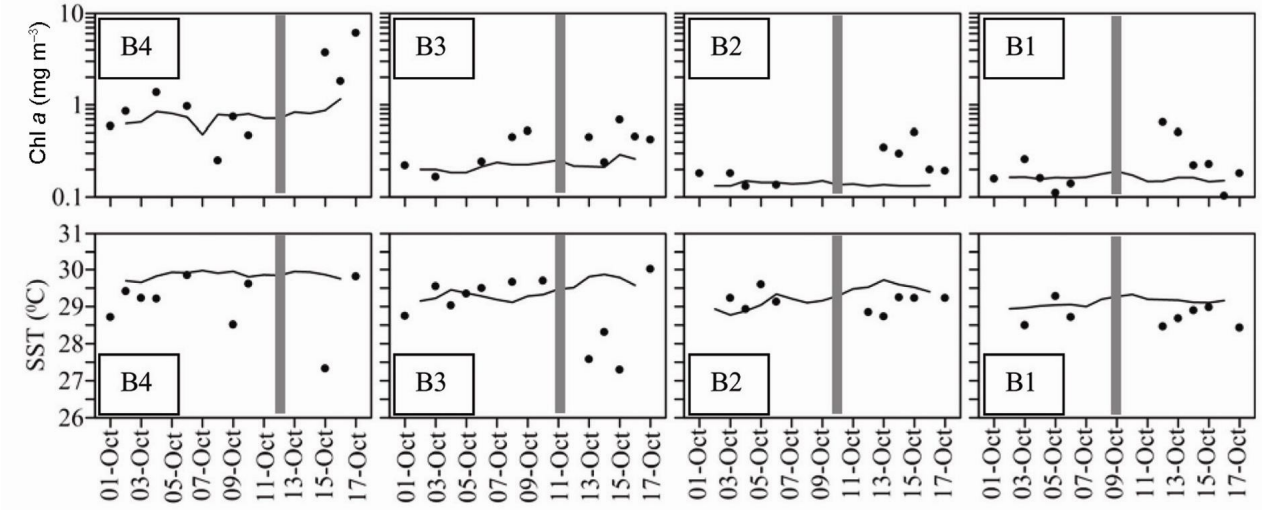

Figure 2. Time-series variability of spatially averaged Chl *a* and SST from MODISA in four sectors (B1–B4). The solid line is for 11 years climatology (2002–2012). The dots represent data corresponding to the year 2013. The vertical bar indicates passage of the cyclone.

maximum negative anomaly in SST (2.4°C). Further, Chl *a* increased up to 144% and SST decreased up to 2.4°C compared to pre-cyclonic condition. The variability of Chl *a* and SST in sector B4 was most dynamic. This sector experienced a combined effect of cyclone as well as coastal processes. Although the cyclone crossed B4 on 12 October, the precipitation was initiated much earlier. This must have resulted in positive anomaly in Chl *a* and negative anomaly in SST prior to landfall. Subsequent to landfall, Chl *a* peaked up to 6.16 mg m^{-3} and SST decreased up to 27.3°C on 17 and 16 October respectively. The increase in Chl *a* (710%) and decrease in SST (2.3°C) was compared to pre-cyclonic condition. The recorded anomaly for Chl *a* and SST was 4.35 mg m^{-3} and 2.5°C respectively.

The productivity in the Bay of Bengal is often low. The strong stratification resulted due to large river influx acting as a boundary and thus restricting supply of nutrients to the surface waters. However, in northern Bay of Bengal the stratification is not strong enough to prevent the upwelling of nutrients. The cyclonic circulation thus brings the subsurface nutrients that result in increase in Chl *a*, decrease in SST and thus increase in productivity[1,4]. The cyclone-induced high productivity has been reported earlier in the Bay of Bengal[5,6]. In the case of cyclone *Sidr*, a patch of 900 km phytoplankton boom was observed along the track. Chl *a* peaked up to 285% with a maximum cooling of 3.2°C compared to pre-cyclonic condition. The shoaling of mixed layer to 35 m was also reported after the cyclone[5]. The Odisha super cyclone has shown maximum impact on the productivity as well as SST. After passage of this super cyclone, a record decrease in SST (6°C) was reported[7]. Further, Chl *a* increased from 1 to 20 mg m^{-3}, as observed from IRS-P4-OCM data[6]. The surface cooling in case of cyclone *Phailin* was less intense compared to the Odisha super cyclone. However, the changes in Chl *a* and SST were significant, especially in the coastal area compared to the cyclone *Sidr*.

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