

Contrasting Chl-a responses to the tropical cyclones Thane and Phailin in the Bay of Bengal

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Key Points:

- First comparative study of cyclone intensity and Chl a production in the BoB
- Cyclone-induced the intensity of the cyclonic eddy after its passage
- Strong stratification in the northern Bay impacts the Chl-a bloom after cyclone

Abstract

Satellite-derived ocean colour data was used to identify the phytoplankton bloom associated with tropical cyclones Thane and Phailin in the Bay of Bengal (BoB). Cyclone Thane was category 2 cyclone (25-31 December 2011), and Phailin was category 5 cyclone (8-14 October 2013), and both occurred during the post-monsoon season. The present study examined the effect of cyclone intensity difference on the chlorophyll a (Chl-a) production in the BoB. Two and seven times Chl-a enhancement was observed after the passage of Phailin and Thane respectively. Possible causes were examined using the satellite-derived sea surface temperature, sea surface height anomalies and sea surface winds. In both cases, cyclone intensified the strength of the pre-existing cyclonic eddies after its passage. Our study shows that the strong stratification along the Phailin track suppresses the Chl-a enhancement after its passage. However, comparatively weaker stratification along the Thane track promotes entrainment of more nutrients and enhances the Chl-a production even though with lesser intensity. In this study, the extent of Chl-a production associated with cyclones was attributed to upper ocean physical processes than the intensity.

Key words: Cyclones, Thane, Phailin, Bay of Bengal, Chl-a

1. Introduction

Bay of Bengal is a semi-enclosed basin located in the eastern part of the north Indian Ocean (Figure 1). The region is strongly forced by semi-annually reversing monsoon winds blowing from the southwest during summer (June-September) and from the Northeast (NE) during winter (December-March). Besides the summer and winter monsoons, there are inter-monsoon transition periods in spring (April - May) and fall (October – November) seasons. Large fresh water influx from oceanic precipitation [Prasad, 1997] and runoff [Subramanian, 1993] from the adjoining rivers make the Bay of Bengal highly complex [Varkey et al., 1996; Schott and McCreary, 2001; Shankar et al., 2002] and well stratified [Rao and Sivakumar, 2003]. This stratification may inhibit nutrient transport from deep layer to the surface layer and make the region strongly oligotrophic during summer [Prasanna Kumar et al., 2002], fall inter-monsoon [Jane et al., 2008].

In such oligotrophic region, physical processes associated with tropical cyclones bring nutrient-rich subsurface water to the surface and enhance the phytoplankton production [Eppley and Renger, 1988] through strong vertical mixing and upwelling [Price, 1981; Chen et al., 2003]. It is believed that the strong winds associated with the cyclone, pump nutrients from the subsurface water to the surface by upwelling and entrainment, subsequently enhancing the Chl-a concentration in the open ocean [Vinayachandran and Mathew, 2003; Babin et al., 2004; Byju and Prasanna Kumar, 2011]. In the BoB basin, the maximum frequency of tropical cyclones occurs during the post-monsoon period (i.e., October-December) [Neetu et al., 2012; Li et al., 2013], compared to the pre-monsoon period (April-May) [Girishkumar and Ravichandran, 2012]. This is mainly due to the absence of upper jet streams during the above periods leading to low vertical shear in the lower troposphere and supporting the formation of cyclones over BoB. The large rainfall and freshwater discharge [Sengupta et al., 2006] during summer monsoon periods leads to the formation of a strong barrier layer in the northern bay and subsists all over the post monsoon season [Thadathil et al., 2007]. Thus, it prevents the entrainment/mixing during the cyclone event and subsequently may affect the chlorophyll production after the cyclone event. Keeping this in mind, the present study tries to compare the response of two tropical cyclones formed over the BoB, Thane, and Phailin, with different intensity (category 2 & 5), during post-monsoon seasons.

Due to the violent atmospheric disturbances during the cyclone periods, direct ship-borne measurements are not feasible. Satellite-based Measurement is the best method to study the oceanic variations during the above episodic events. There have been several studies using ocean-color satellite [Nayak et al., 2001; Vinayachandran and Mathew, 2003; Rao et al., 2006; Patra et al., 2007; Madhu et al., 2007; Tummala et al., 2009; Maneesha et al., 2011; Das, 2012; Chen et al., 2013;

Sarangi et al., 2015] as well as in situ [Madhu et al., 2007] data on chlorophyll variability enhanced by the tropical cyclones in the BoB. However, none of the studies has discussed the relation between the intensity of the cyclone and chlorophyll production in the BoB in connection with associated physical processes. Researchers believe that high-intensity cyclones trigger high chlorophyll production. However, in this study different intensity cyclones have triggered contradicting production being in the same basin.

Here, we have compared the oceanic response to the two tropical cyclones (Thane: 25-31 December 2011 and Phailin: 8-14 October 2013) in the BoB with different intensity (category 2 and category 5) during the post-monsoon season. We summarize how the location of the cyclone track affects the chlorophyll-a (Chl-a) production and SST variations in the BoB. The present study highlights that in BoB, irrespective of the intensity of the tropical cyclone, its response depends on upon the spatial location of the cyclone track. This study is the first comparative study in the BoB, which gives a consistent explanation for the Chl-a response to the two different category cyclones.

2. Cyclone cases

2.1 Definition and classification of Cyclones

A tropical cyclone is defined as the rotational low-pressure system in the tropics when the central pressure falls by 5 to 6 hPa from the surroundings (India Meteorological Division). The classification of tropical cyclone systems by India Meteorological Division (IMD) with respect to wind speed (in knot; kt) are +-Depression (D) (17-27 kt or 32-50 kmph), Deep Depression (DD) (28-33 kt or 51-59 kmph), Severe Cyclonic Storm (SCS) (48-63 kt or 90-119 kmph), Very Severe Cyclonic Storm (VSCS) (64-119 kt or 119-220 kmph), and Super Cyclonic Storm (SuCS) (>120 k or > 220 kmph) respectively [IMD]. National Oceanic and Atmospheric Administration's hurricane forecasters use the Saffir-Simpson category scale (1-5 based on the Cyclone/Hurricane intensity at the indicated time) which assigns storms/cyclones to five categories [<http://www.aoml.noaa.gov/general/lib/laescae.html>]. World Meteorological Organisation also follows the Saffir-Simpson category scale. As per the Saffir-Simpson category scale, Thane (VSCS) coming under category 2 and Phailin (SuCS) coming under category 5. Hereafter, we follow the Saffir-Simpson category scale in this study.

2.2 Description of cyclone Thane and Phailin

The two cases of cyclones investigated in the present study are cyclone Thane and Phailin (Figure 1). Thane was a category 2 tropical cyclone (Saffir-Simpson scale) which developed over the BoB during the last week of December 2011. Thane formed as a deep depression over the southeast BoB

on 25th December 2011 and gradually moved north-northwestwards and formed as a cyclonic storm in the midnight of 26th December 2011. Moreover, then it further moved northwestwards and intensified into a severe cyclonic storm on the evening of 28th December 2011 (category 2). Then, it moved southwards and crossed north Tamil Nadu and Puducherry coast on 30th December 2011 with a wind speed of 120-140 kmph and a minimum pressure of 972 mbar [IMD]. Phailin was a category 5 cyclone (Saffir-Simpson scale) which developed as a depression over the north Andaman Sea on 8th October 2013, intensified into a deep depression on 9th morning and further into the cyclonic storm (CS), 'Phailin', the same evening. Moving northwestwards, it further intensified into a severe cyclonic storm (SCS) and a very severe cyclonic storm (VSCS) in the forenoon of 10th October 2013, over the east central Bay of Bengal. It crossed Odisha and adjoining north Andhra Pradesh coast near Gopalpur (Odisha) around 2230 hrs IST of 12th October 2013 with a Sustained maximum surface wind speed of 200-210 kmph [IMD] (Figure 1). Since both the events occurred during the post-monsoon season (Thane in December 2011 and Phailin in October 2013) over the BoB, the present study focused on the response of these two events on the upper ocean (Chl-a) production in the BoB.

3. Data and Method

Cyclone intensities, tracks, and the winds were obtained from the India Meteorological Department (www.imd.gov.in). Merged altimeter data from multiple satellite sensors (Jason-1, TOPEX/Poseidon, Geosat Follow-On (GFO), European Remote Sensing 2 (ERS-2), and Environmental Satellite (ENVISAT)) were used. Daily, near real-time merged sea surface height anomaly (SSHA) data with spatial resolution 0.33° x 0.33° were taken from www.aviso.oceanobs.com. The closed contours of -6 cm SSHA was considered as a cyclonic eddy [Lin et al., 2008]. Composite maps of 8 days (Level 3) Chl-a with spatial resolution 4 km derived from Moderate Resolution Imaging Spectroradiometer (MODIS) (<http://oceandata.sci.gsfc.nasa.gov/MODISA/>) were used to understand the chlorophyll variability before and after the cyclone. The SST before and after cyclone was taken from Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) which measures SST under both clear and cloudy conditions, day and night (<http://www.remss.com/missions/tmi>).

The daily wind speed with 25 km resolution was obtained from ASCAT (<http://manati.star.nesdis.noaa.gov/products/ASCAT.php>). Using the above data Ekman pumping velocity (EPV) was calculated [Smith, 1968]

$$EPV = \frac{1}{\rho f} \nabla \times \tau$$

(units = ms^{-1}), where $\nabla \times \tau$ is the curl of the daily wind stress vector, ρ is the density of the sea water and f is the coriolis parameter. EPV is used as an index for the upwelling in the ocean and the positive values indicate upwelling and negative values indicate downwelling.

The vertical profiles of daily temperature and salinity with resolution 1/12 degree were taken from Hybrid Coordinate Ocean Model (HYCOM; source: apdrc.soest.hawaii.edu/las/v6), and this data was further used to compute the potential density (σ_t) and Mixed Layer Depth [MLD]. We defined MLD as the depth at which density exceeds 0.2 kgm^{-3} from its surface value. We have also calculated static stability [E] of the upper 100 m water column [Pond and Pickard, 1983]

$$E = \frac{1}{\rho} \frac{\partial \rho}{\partial z}$$

Where ' ρ ' is in insitu density and 'z' is the depth taken as negative. Positive values of E indicate stratified water column and negative values indicate unstable water column. The climatological nitrate profiles were taken from the WOA13 [Garcia et al., 2014; <http://www.nodc.noaa.gov/>].

All the parameters were analysed for pre and post-cyclone periods. The pre Thane period is 11-19 December 2011 and the post-Thane period is 01-08 January 2012. Similarly, the pre-Phailin period is 01-08 October 2013 and post-Phailin period is 16-24 October 2013.

4. Results and Discussions

In this paper, we investigated the reasons for the difference in Chl-a enhancement after the passage of category 2 (Thane) and category 5 (Phailin) cyclones during the post-monsoon season in BoB. Figure 2a & 2b illustrate the pressure (black line) and wind speed (red line) along the cyclone track Thane and Phailin respectively. The minimum pressure of 969 mb and wind speed 38 ms^{-1} indicate that cyclone Thane comes under category 2. Similarly, the minimum pressure of 940 mb and wind speed 59 ms^{-1} indicate that cyclone Phailin comes under category 5. The spatial wind speed during the days when the cyclones attained maximum intensity was also analyzed to understand the region where cyclone showed maximum intensity (Figure 3a & b). Since wind speed showed highest value in the region where the cyclone attained maximum intensity, most of the oceanographic variations associated with the cyclone are expected to be within the same domain. Hence in further discussion, we will be concentrating on the regions where the cyclone attained maximum intensity which is represented by a rectangle shown in Figure 4-7. For cyclone Thane, we have taken the temporal evolution of SST, Chl-a and MLD centred over the box $10\text{-}13^\circ\text{N}$; $82\text{-}86^\circ\text{E}$ and for Phailin it was $16\text{-}19^\circ\text{N}$ and $84\text{-}88^\circ\text{E}$. High wind speed along the tracks of Thane (Figure 3a) and Phailin (Figure 3b) during the cyclone event may be congenial for strong nutrient mixing and new production. To further

understand the impacts of these two cyclones, representative SST images before and after Cyclone Thane and Phailin (Figure 4 & 6) and the corresponding Chl-a images (Figure 5 & 7) have been analyzed.

Before Thane's (category 2) arrival, the region (see black rectangle) was characterized by warm SST above 28.5°C (Figure 4a) and after the passage of Cyclone, SST showed a value less than 26°C (Figure 4b). The Chl-a over the region before Thane was 0.1 mgm⁻³ (Figure 5a) and after one week of its passage, the Chl-a showed an enhancement and reached up to 0.7 mgm⁻³ (Figure 5b) over the region (10-13°N; 82-86°E). Similarly, before the passage of Phailin (category 5), the SST over the region was above 29°C (Figure 6a) and after the cyclone it has dropped to less than 27°C (Figure 6b), while the Chl-a was 0.4 (Figure 7a) mgm⁻³ before the cyclone and enhanced to 0.9 mgm⁻³ (Figure 7b) after the cyclone. Consistent with this, particulate organic carbon (POC) also showed an enhancement after the passage of both the Cyclones. After the Thane, POC showed 2.8 times (Figure S1) enhancement, while Phailin showed only 1.2 times (Figure S2) enhancement after its passage. Though Phailin falls under category 5, Chl-a enhancement showed only double, and there was about ~2°C fall in SST after its passage, but Thane, which falls under category 2, enhanced Chl-a, 7 times and reduced SST ~2.5°C. Though the cyclones crossed the same BoB basin during the post-monsoon season (October-December), enhancement of Chl-a due to these events varied significantly which is worth exploring.

In a normal circumstance, Chl-a production in the ocean surface layer depends on the amount of new nutrient coming from the subsurface depth through upwelling and entrainment [Price, 1981]. Strong upwelling, characterized by positive wind stress curl or positive Ekman pumping velocity (EPV), after the two days of cyclone initiates upwelling [Gierach and Subrahmanyam 2008; Wang and Zhao, 2008; Byju and Prasanna Kumar, 2011] of cold, nutrient water to the surface, and afterwards deepening of the mixed layer helps to sustain the nutrient enrichment for a few days [Zhao et al., 2009]. The extent of the Chl-a production after the cyclones mainly depends on the intensity of the upwelling and mixed layer deepening followed by the cyclone.

4.1 Upwelling and vertical mixing/entrainment

EPV is an index used to understand the upwelling in the ocean. The positive EPV indicate upwelling and negative EPV indicate downwelling. Just after the cyclone formation the strong winds along the cyclone track lead to strong upwelling (positive EPV) of subsurface water. After the upwelling, the strong winds during the cyclone event can stir the water column and deepen the mixed layer by vertical mixing. The extent of phytoplankton production brought by the cyclone also depends upon

the deepening of the mixed layer and nitracline variation. During Thane (29th December 2011) EPV reached a maximum value of $2.5 \times 10^{-4} \text{ ms}^{-1}$ (Figure 8a, black line) and the corresponding MLD was 35 m. Afterwards, MLD started shoaling and reached a minimum value of 20 m on 02 January 2012 and then it started deepening again. On 15th January 2012, MLD reached its initial value of 34 m. This indicates that the upwelling of cold nutrient-rich water to the surface followed by deepening of the MLD. On the contrary, during Phailin EPV reached a maximum value of $1 \times 10^{-4} \text{ ms}^{-1}$ on 12th October 2013 (Figure 8b, black line). Consistent with this, MLD also showed sudden deepening from 2 m (10th October 2013) to 29 m (12th October 2013). This indicates that positive EPV did not support for the upwelling; instead, it supported for vertical mixing/entrainment. MLD has reached its initial value of 2m on 16 October 2013. The higher EPV (2.5 times higher) followed by MLD deepening during Thane indicated the strong upwelling of nutrients from the subsurface depth. However, no such upwelling was observed along the Phailin track. The comparison of the oceanic environment regarding SST, Chl-a, EPV and MLD (Thane: 10-13°N& 82-86°E; Phailin: 16-19°N & 84-88°E) before and after the passage of both the Thane and Phailin have been represented in the Table. 1.

To decipher the relation between MLD and nitracline depth variation, the vertical profiles of sigma-t (computed from Temperature and Salinity profiles; 9a & 9c) and nitrate profiles (WOA13) were analyzed (Figure 9b & 9d), as they have a direct link with the phytoplankton production in the upper ocean. During Thane (27th December 2011), the 20.5 kgm^{-3} isopycnals were located at ~40 m and it started shoaling as upwelling proceeded and reached up to the surface (Figure 9a). Similarly, during Phailin (11-14th October), 21 kgm^{-3} isopycnals shoaled up to the surface and supports mixing. The only difference is that during Thane both upwelling and entrainment supported for the Chl-a production (~15 days), while during Phailin only entrainment (~4 days) contributed towards the Chl-a production. The depth at the top of the maximum slope of nitrate is called the nitracline depth. This depth has taken as the nitracline depth for the Thane (black dash line in Figure 9b) and Phailin (Figure 9d) respectively. In a stratified oligotrophic region like BoB, most of the subsurface chlorophyll maxima (SCM) are closely associated with the nitracline depth [Martin et al., 2012]. Vertical advection of sub surface chlorophyll maxima (SCM) from the deeper depth also contributes towards the Chl-a enhancement. Hence, we expect the changes in nitracline depth may alter the SCM and contribute towards the Chl-a enhancement after the passage of the cyclone. Based on the measurements, few studies show that SCM exists in BoB between 20 and 60 m [Sarma and Aswanikumar, 1991; Prasanna Kumar et al., 2002]. SCM showed 5 times higher than the background value in the South China Sea after the passage of cyclone [Ye et al., 2013]. As a caveat, part of the

satellite-observed cyclone induced enhanced Chl-a concentrations may be due to the dilution of the pre-existing SCM via. vertical mixing [Mei et al., 2015]. Using satellite-derived Chl-a data, quantification of SCM contributed Chl-a enhancement is not feasible. Lack of in situ measurements of vertical chlorophyll distribution in the BoB prevents us from the exact quantification of surface Chl-a bloom contributed by SCM after the cyclone passage. Hence in the present study, we will not be discussing on the contribution of SCM towards the Chl-a enhancement after the cyclone passage. Though Phailin was category 5, only vertical mixing/entrainment occurred along the track, while both upwelling and entrainment occurred along the Thane track (category 2). In order to understand in detail, we have computed the water column static stability which plays a major role in the upper ocean dynamics.

4.2 Static stability

As the BoB is highly stratified, the observed response of Chl-a concentration is further understood using the water column static stability (Figure 10a & 10b). Before Thane, the upper 40 m of the water column showed positive values ($2 \times 10^{-5} \text{ m}^{-1}$) and then it becomes more negative ($-1 \times 10^{-5} \text{ m}^{-1}$) or close to zero as the vertical mixing/entrainment occurs (Figure 10a). Similarly, before Phailin the upper 50 m of the water column was highly stable ($8 \times 10^{-5} \text{ m}^{-1}$) and during the cyclone (11-14th October 2013) the values reached close to zero in the upper 40 m. This indicates the mixing of upper 40 m water column. Though the intensity of the cyclones is highly variable, the intensity of the mixing after the cyclone passage is similar in both the cases. The only difference is that the strong water column stability along the Phailin track (5 times higher than Thane) prior to the cyclone inhibits the upwelling. This is mainly because of the strong rainfall and fresh water influx [Rao and Sivakumar, 2003; Sengupta et al., 2006] in the northern bay (Phailin track), during the summer monsoon leads to the formation of the barrier layer which exists all over the post-monsoon season [Thadathil et al., 2007, Sengupta et al., 2008; Neetu et al., 2012]. This further affects the density stratification and vertical mixing [Vinayachandran et al., 2002] after the passage of the cyclone. Before the cyclone, the static stability also showed strong positive values in the upper 20 meters of the water column. The presence of thick freshwater cap in the upper 20 m in the northern Bay inhibits the SST to cool [Sengupta et al., 2008], and the nutrient-rich subsurface water to reach the surface. This causes the low SST cooling, low EPV and less mixed layer deepening along the Phailin track during post-monsoon [Sengupta et al., 2008]. The presence of this freshwater initially inhibits the cyclone-induced mixing then subsequently allow the nutrient-rich subsurface water to reach the surface and enhance the production. Though there is a large difference in the intensity between cyclone Thane and Phailin, the lower water column stability (before the cyclone) over the region

during the Thane led to the enhancements in Chl-a compared to Phailin. We have also analyzed the role of horizontal advection of nutrients/Chl-a by strong currents towards the cyclone tracks. Our analysis showed that horizontal advection (Figure S3a & S3b) does not contribute towards the Chl-a enhancement in both the cases.

4.3 Translation speed

In addition to the intensity of the cyclone, the translation speed also plays a major role in the Chl-a production after the cyclone passage. Translational speed is nothing but the forwarding speed of the cyclone. A strong and slow moving tropical cyclone can induce more Chl-a production than a strong and fast moving tropical cyclone [Mei et al., 2015]. The translational speed of cyclone Thane was 1.5 ms^{-1} at the beginning (i.e., the first day of the cyclone) and reached $\sim 2.5 \text{ ms}^{-1}$ on 28th December 2011, i.e., when cyclone attained maximum intensity (category 2). Then it increased and showed an averaged speed of 3.5 ms^{-1} . Similarly, the translation speed of cyclone Phailin was $\sim 3 \text{ ms}^{-1}$ in the beginning, and it attained a speed of $\sim 4 \text{ ms}^{-1}$ when the cyclone reached its maximum intensity (i.e., category 5) then it continued with an average speed of $\sim 4 \text{ ms}^{-1}$. The translation speed of the cyclone Thane and Phailin when it reached its maximum intensity was $\sim 2.5 \text{ ms}^{-1}$ and $\sim 4 \text{ ms}^{-1}$ respectively (Figure 11). This indicates that the slower moving (difference in $\sim 1.5 \text{ ms}^{-1}$ when the Cyclones attained maximum intensity) Thane can generate larger sst cooling and subsequently leads to more Chl-a production than the Phailin.

4.4 Cyclonic eddies

Though cold core eddies play a minor role in the surface Chl-a production in the oligotrophic region, they contribute to upper ocean dynamics [Walker et al., 2005, Shi & Wang 2007, Sun et al., 2009; Zheng et al., 2010; Chen et al., 2013]. As mesoscale eddies (cold-core or cyclonic) are capable of enhancing the phytoplankton biomass in the Bay of Bengal [Prasanna Kumar et al., 2004; Prasanna Kumar et al., 2007; Muraleedharan et al., 2007; Nuncio, 2007; Nuncio and Prasanna Kumar, 2012; Vidya and Prasanna Kumar, 2013; Chen et al., 2013], presence of eddies along the cyclone tracks [Sarangi et al., 2015] were analysed. We have analyzed sea surface height anomaly (SSHA) data before and during the Thane (Figure 12a & b) and Phailin (Figure 13a & b) period. The analysis of SSHA confirms the presence of cyclonic eddy near to both the cyclone tracks (Figure 12 & 13) which leads to the intensification of the pre-existing cyclonic eddies after the cyclone passage [Sun et al., 2014; Patnaik et al., 2014]. Though cyclonic eddy intensified after the Thane and Phailin, its contribution towards Chl-a enhancement needs to be studied in detail.

5. Conclusion

The difference in physical processes operating along the Thane and Phailin track make the region different in the aspect of Chl-a production after the cyclone passage during post-monsoon season. During Thane, less water column stability, strong EPV (upwelling), strong entrainment/mixing and slower translation speed help to transport a large amount of new nutrient to the upper ocean and which leads to the 7 times enhancement in Chl-a and 3 times enhancement in the particulate organic carbon after its passage. This indicates strengthening of the biological pump after the cyclone (category 2) passage. However, the strong stratification along the Phailin (category 5) track accompanied by only entrainment/mixing, supported for the enhancement of Chl-a (2 times) and particulate organic carbon production (1.2 times) comparatively less compared to Thane. Our study suggests that the strong stratification in the northern bay reduces the strength of the biological pump after the cyclone passage.

Our study showed that the category 2 (Thane) cyclones had a more notable impact on the Chl-a bloom than the category 5 (Phailin) cyclone. Another important finding was the presence of cyclonic eddies along the track of the cyclones which intensified after the cyclone passage. The strong stratification in the northern Bay (along the Phailin track) reduce the strength of the EPV (upwelling), and faster translation speed during the Phailin leads to the less entrainment of nutrient to the surface which subsequently affected the Chl-a production. The 7 times enhancement in Chl-a during the Thane was mainly contributed by the strong EPV (upwelling), less water column stability and slower translation speed which brought a large amount of nutrient towards the euphotic zone and enhanced the Chl-a production. Though we used multiple satellite data to understand the response of the two different category cyclones in the BoB, a detailed biogeochemical modeling study is suggested to quantify the amount of organic carbon export associated with different intensity cyclones .

Acknowledgement:

Authors are thankful to the Director, National Institute of Oceanography, Goa, for the permission to publish this paper. We thank the two anonymous reviewers for their critical review and suggestions to improve the quality of the manuscript. Data used in this study are freely available, and data sources are described in the data and methods section. This is NIO's contribution No. XXXX.

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Table

Table 1. SST, Chl-a, EPV (Ekman pumping velocity) and MLD during pre and post-cyclone periods and the difference in each

Parameter	Thane (Category 2)			Phailin (Category 5)		
	Pre	Post	Difference	Pre	Post	Difference
SST (°C)	28.5	26	-2.5 °C	29	27	-2°C
Chl-a (mgm ⁻³)	0.1	0.7	0.6 mgm ⁻³	0.4	0.9	0.5mgm ⁻³
EPV (x 10 ⁻⁴ ms ⁻¹)	0	2.5	2.5 x 10 ⁻⁴ ms ⁻¹	0	1	1 x 10 ⁻⁴ ms ⁻¹
MLD (m)	35	20	35 m	2	29	27 m

Figure captions

Figure 1. The cyclone tracks of Thane and Phailin (Red lines) are shown in the figure. Thane (category 2) occurred during 25-31 December 2011, and Phailin (category 5) occurred during 8-14 October 2013.

Figure 2. Pressure (black line) and wind speed (red line) along the track of the cyclone (a) Thane and (b) Phailin. The figures clearly depict that cyclone Thane comes under category 2 and cyclone Phailin under category 5.

Figure 3. Wind speed (ms^{-1}) during which cyclone (a) Thane (category 2) and (b) Phailin (category 5). The black rectangles represent the region where wind attained maximum intensity during the cyclone.

Figure 4. Sea surface temperature (SST in $^{\circ}\text{C}$) (a) before Thane, (b) after Thane and (c) Difference in sst between after and before Thane (category 2). Black rectangle indicates the region where the intensity of the cyclone reached its maximum.

Figure 5. Chlorophyll a (Chl-a in mgm^{-3}) (a) before Thane, (b) after Thane and (c) Difference in Chl-a between after and before Phailin (category 2). Black rectangle indicates the region where the intensity of the cyclone reached its maximum.

Figure 6. Sea surface temperature (SST in $^{\circ}\text{C}$) (a) before Phailin (b) after Phailin and (c) Difference in sst between after and before Phailin (category 5). Black rectangle indicates the region where the intensity of the cyclone reached its maximum.

Figure 7. Chlorophyll a (Chl-a in mgm^{-3}) (a) before Phailin (b) after Phailin and (c) Difference in Chl-a after and before Phailin (category 5). Black rectangle indicates the region where the intensity of the cyclone reached its maximum.

Figure 8. Ekman pumping velocity (EPV; black line) and Mixed Layer Depth (MLD in m; blue line) for (a) Thane [averaged over the region 11-13 $^{\circ}\text{N}$; 81-83 $^{\circ}\text{E}$] and (b) Phailin [averaged over the region 16-18 $^{\circ}\text{N}$; 84-86 $^{\circ}\text{E}$].

Figure 9. (a) Vertical structure of sigma-t along Thane (11-13 $^{\circ}\text{N}$; 81-83 $^{\circ}\text{E}$), (b) Vertical profile of Nitrate during December (Data from WOA13), (c) Vertical structure of sigma-t along Phailin (16-18 $^{\circ}\text{N}$; 84-86 $^{\circ}\text{E}$) and (d) Vertical profile of Nitrate during October (Data from WOA13). The black dashed horizontal lines represent the nitracline depth.

Figure 10. Vertical structure of static stability of the upper 100 m water column for the Thane and Phailin. The black line indicates the MLD.

Figure 11. Translation speed along the track of the cyclone (a) Thane (black line) and (b) Phailin (red line).

Figure 12. Sea surface height anomaly (a) before and (b) during cyclone Thane (category 2). Contours indicate the -6 cm SSHA, which represents the cyclonic (cold core) eddy. Black rectangle indicates the region where the intensity of the cyclone reached its maximum.

Figure 13. Sea surface height anomaly (a) before and (b) during cyclone Phailin (category 5). Contours indicate the -6 cm SSHA, which represents the cyclonic (cold core) eddy,). Black rectangle indicates the region where the intensity of the cyclone reached its maximum.

Supplementary figures captions

Figure S1. Particulate organic carbon (POC in mgC) before and after the cyclone Thane (category 2). Black rectangle indicates the region where the intensity of the cyclone reached its maximum.

Figure S2 Particulate organic carbon (POC in mgC) before and after Cyclone Phailin (category 5). Black rectangle indicates the region where the cyclone reached maximum intensity.

Figure S3 Longitude vs. times diagram of Chl-a for (a) Thane and (b) Phailin. In both the figures the black dash rectangle represent before cyclone period, red dash rectangle represents during cyclone period, and white dash rectangle represents the post -cyclone period.

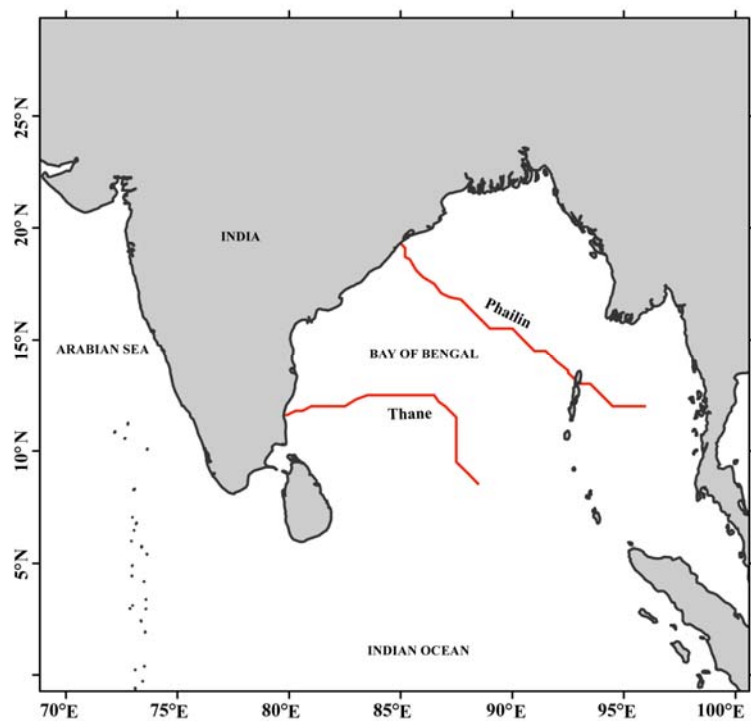


Fig.1

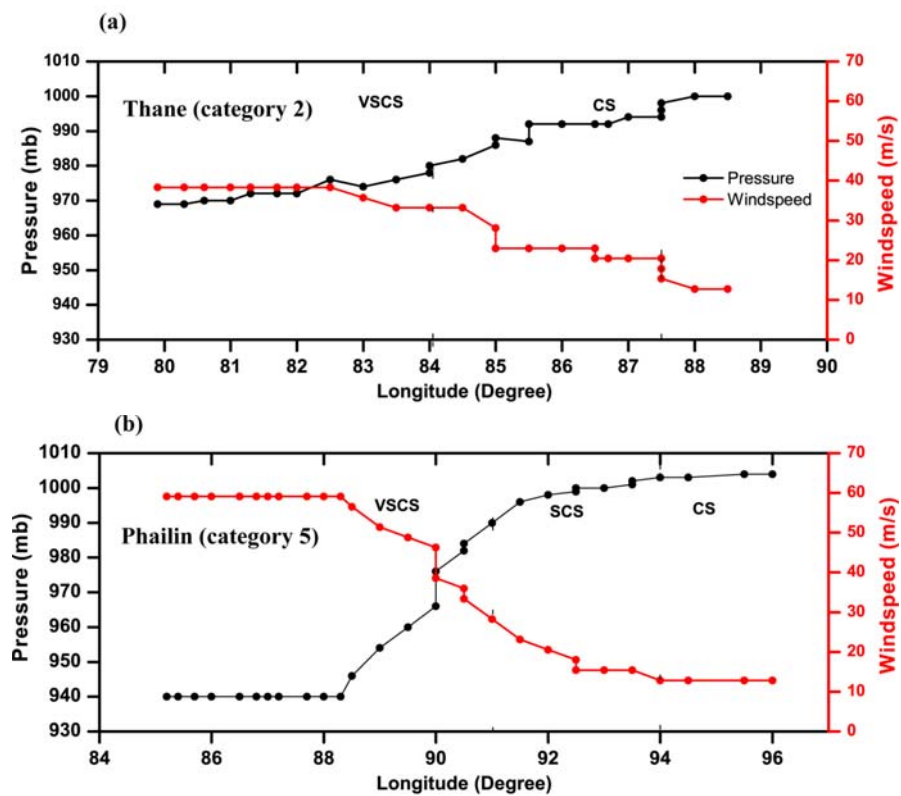


Fig. 2

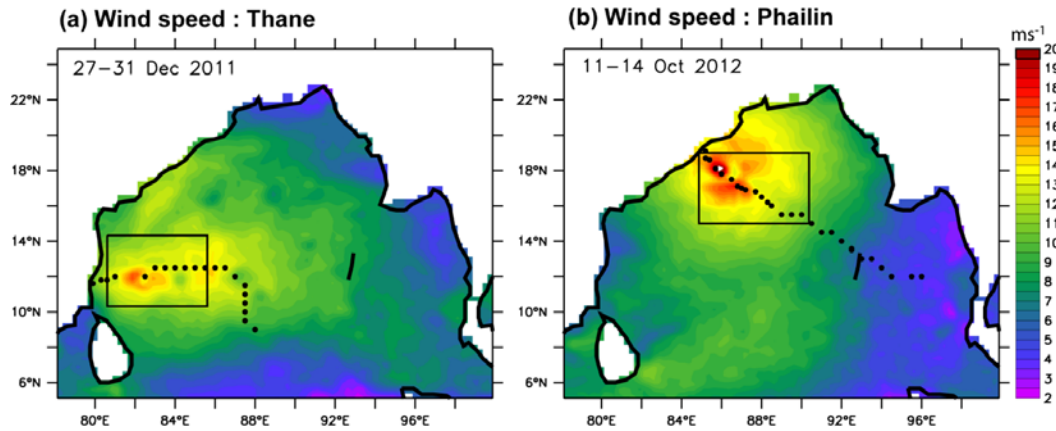


Fig. 3

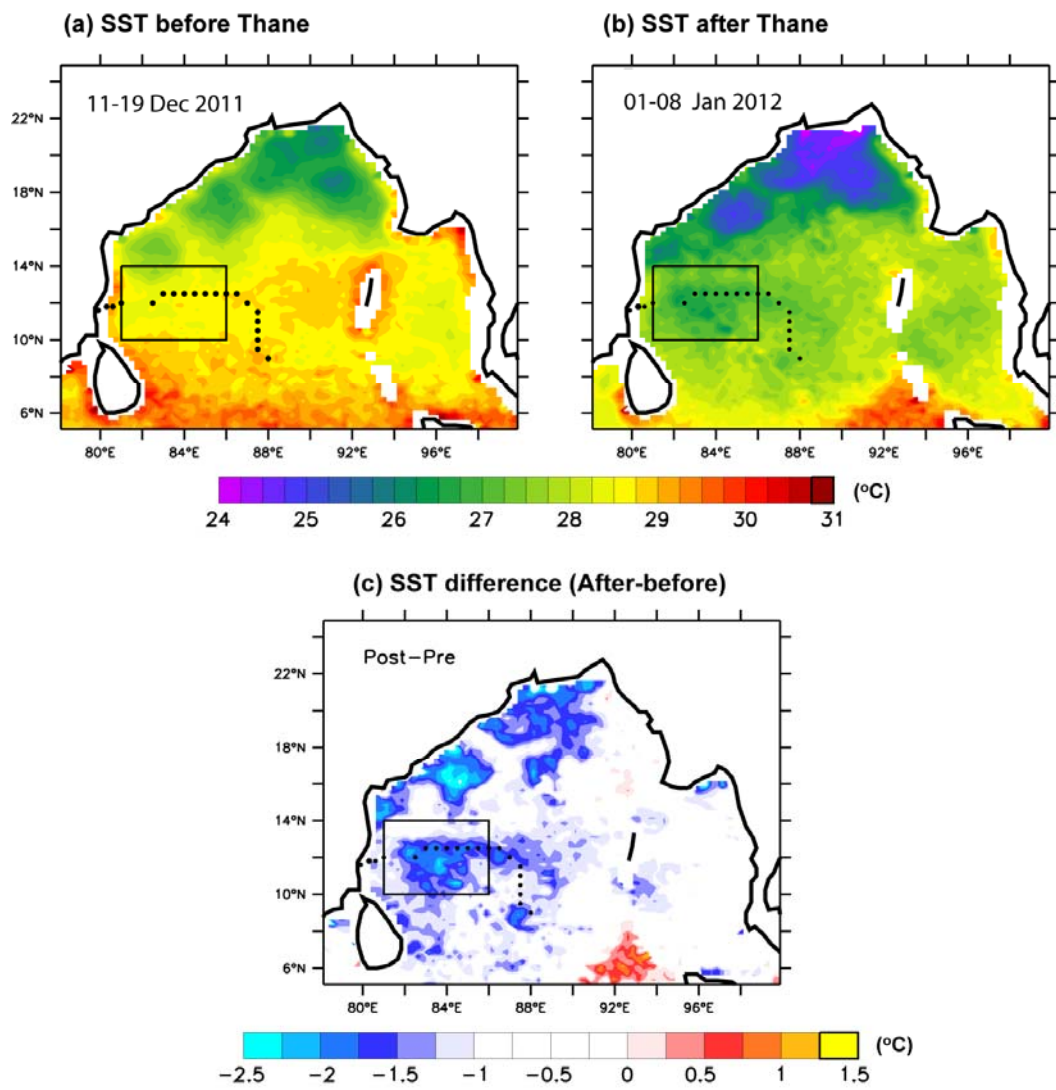


Fig. 4a, 4b, 4c

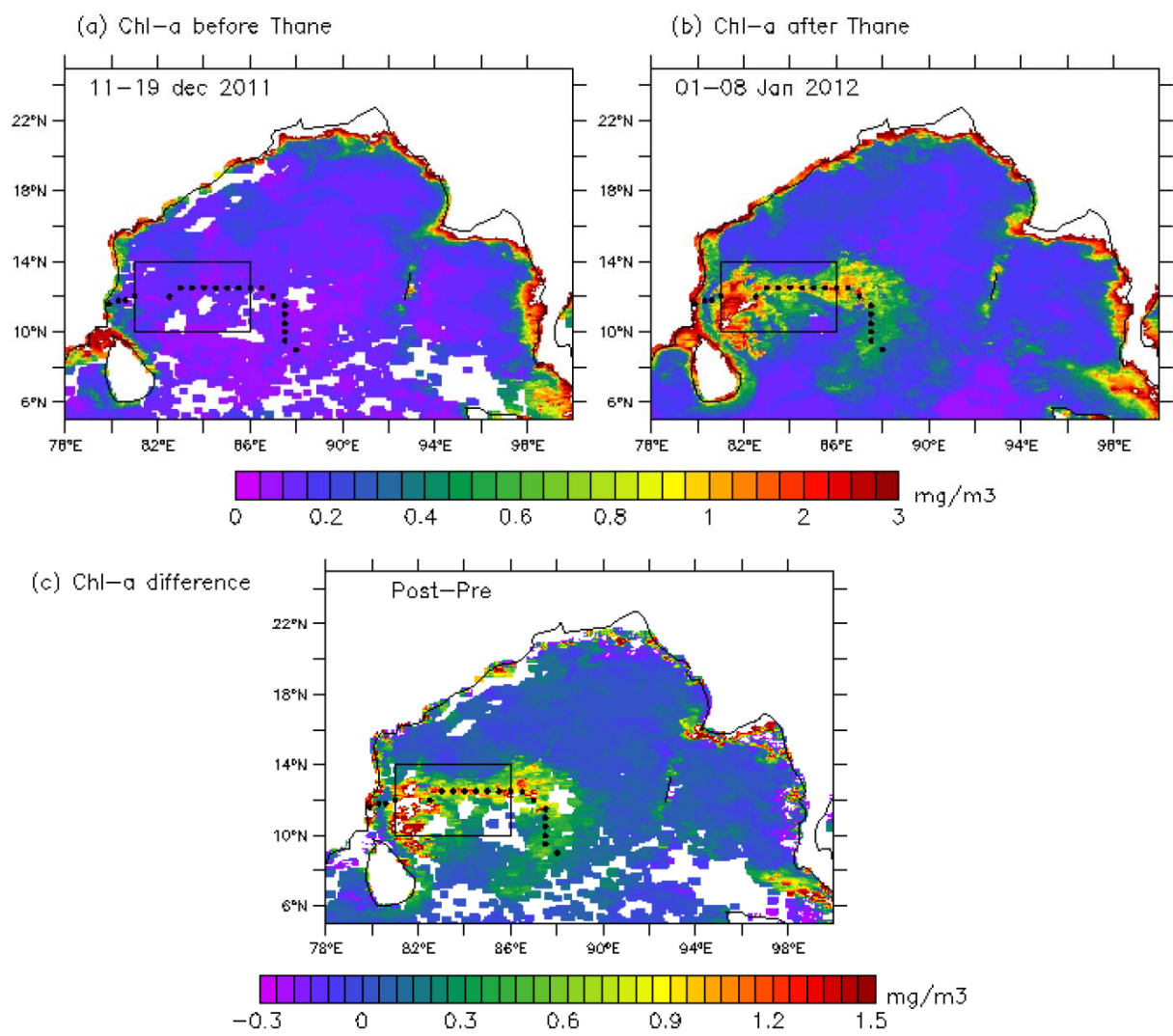


Fig. 5a, 5b, 5c

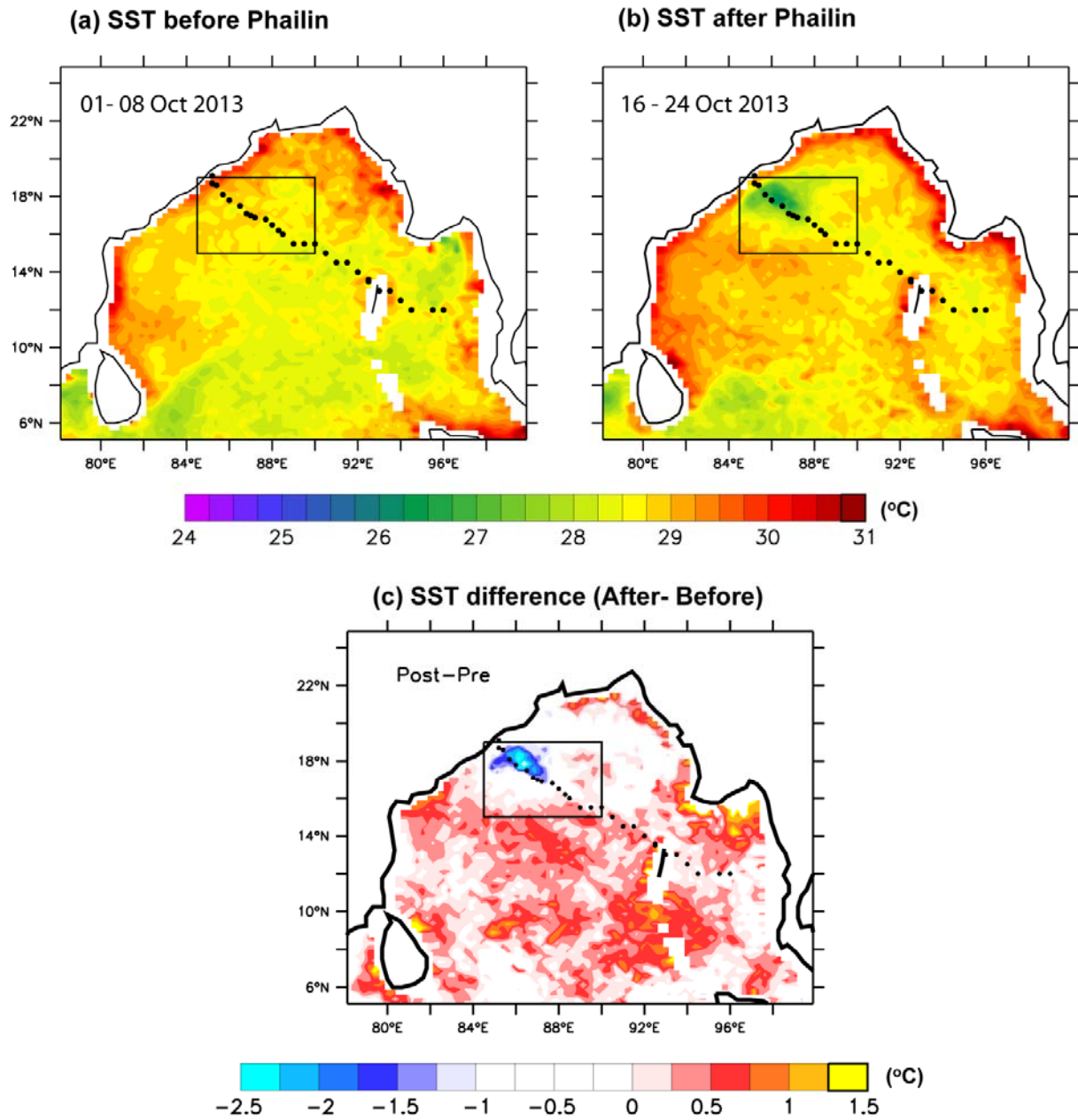


Fig. 6a, 6b, 6c

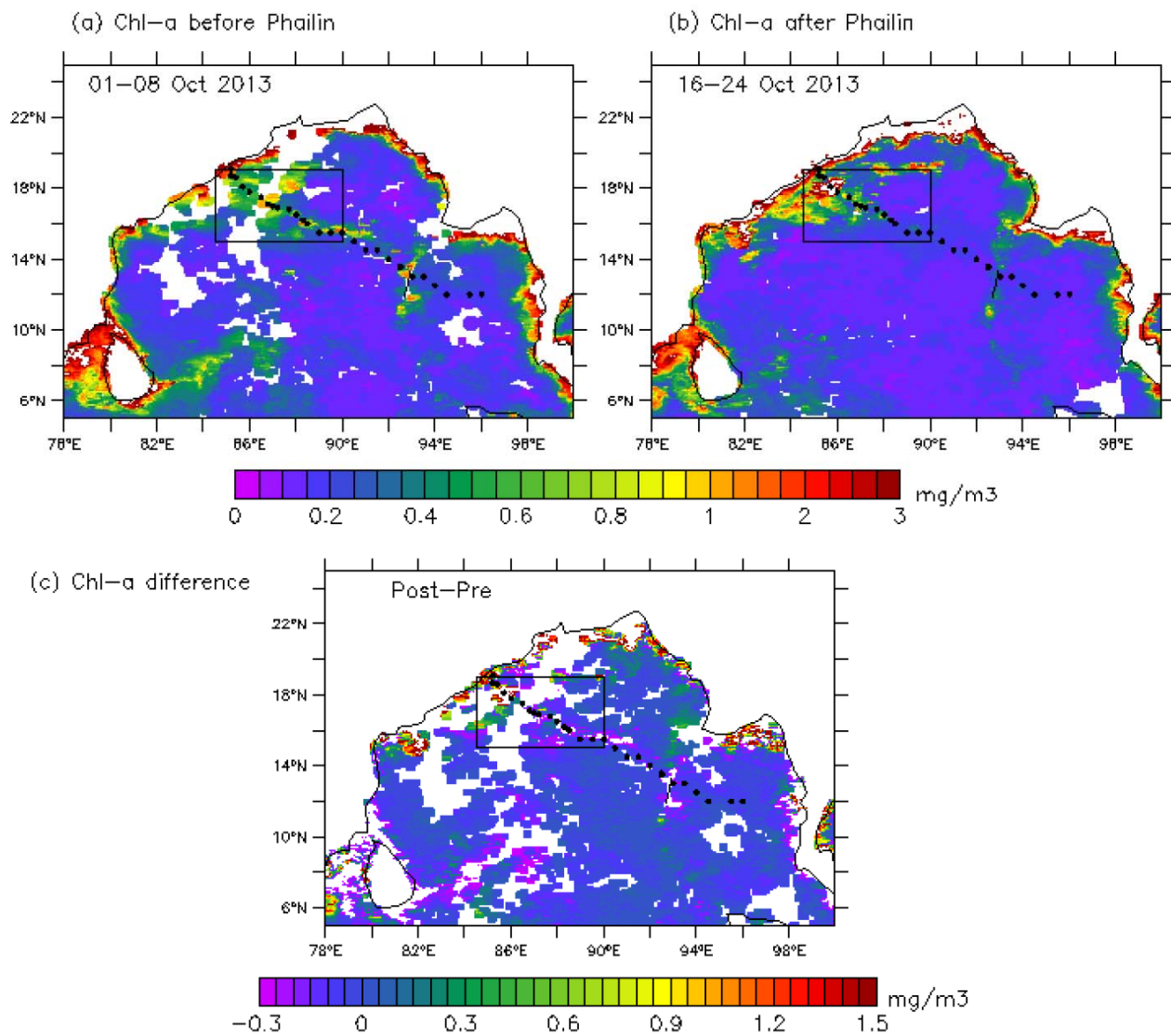


Fig. 7a, 7b, 7c

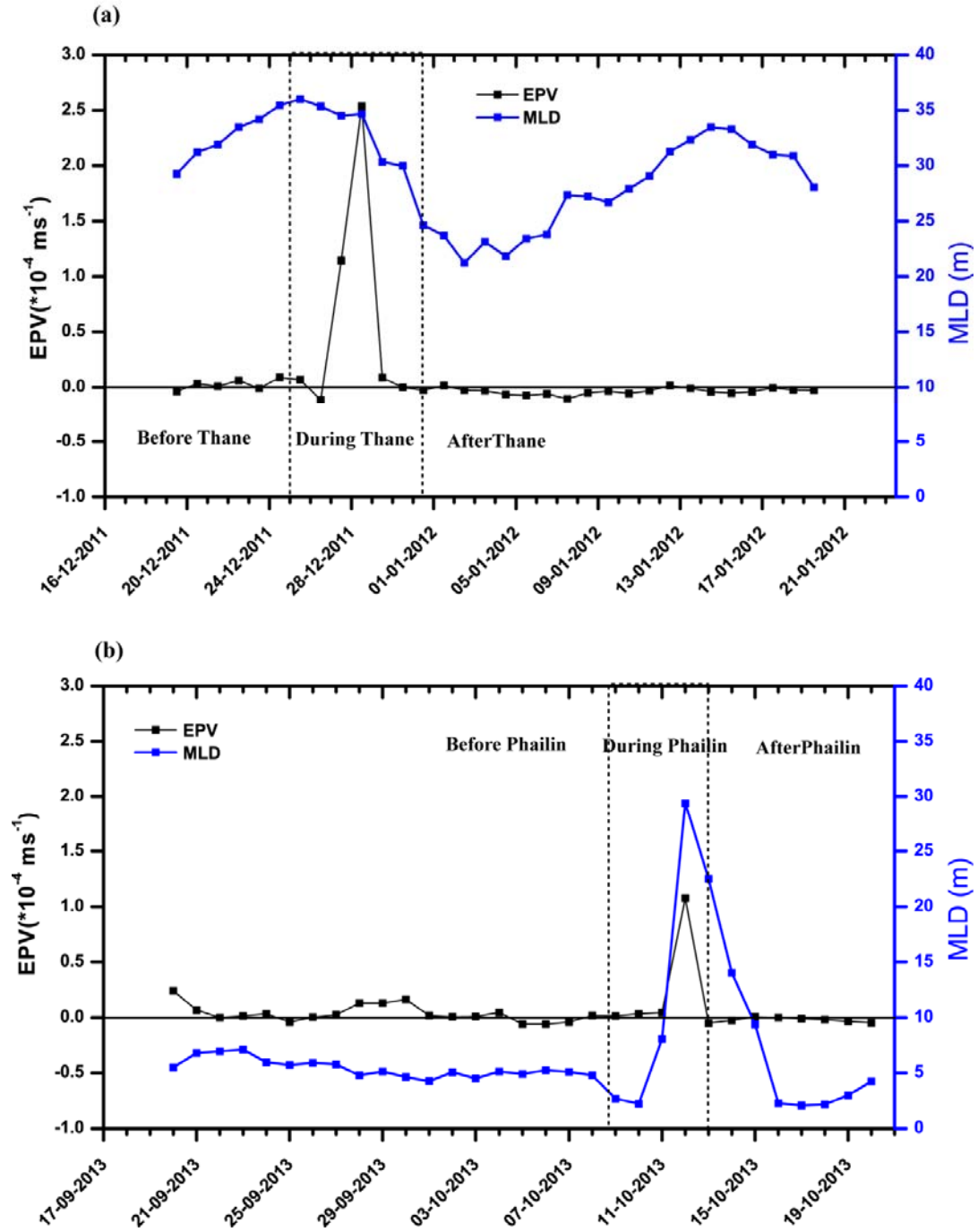


Fig. 8a, 8b

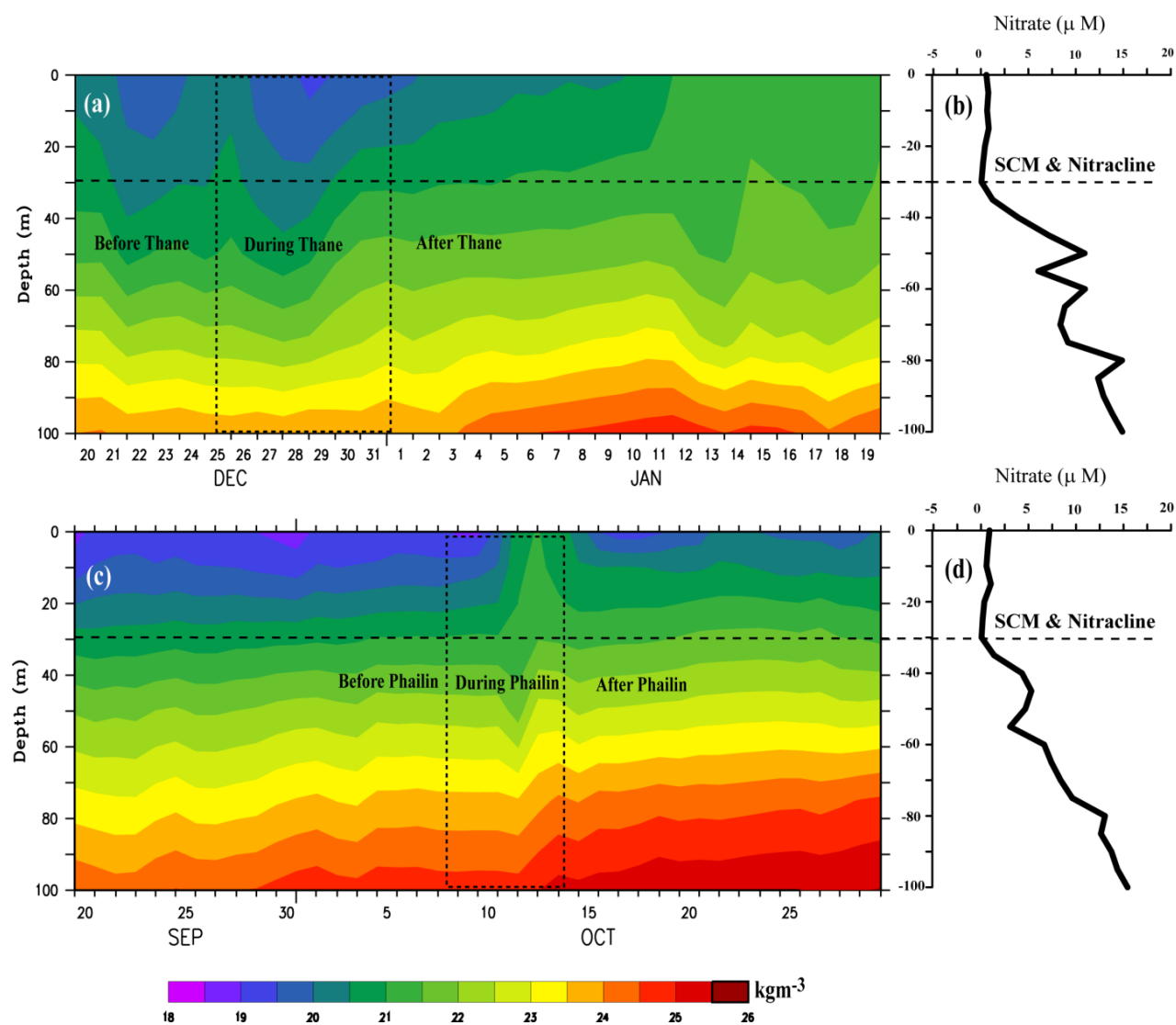


Fig. 9 a, 9b, 9c, 9d

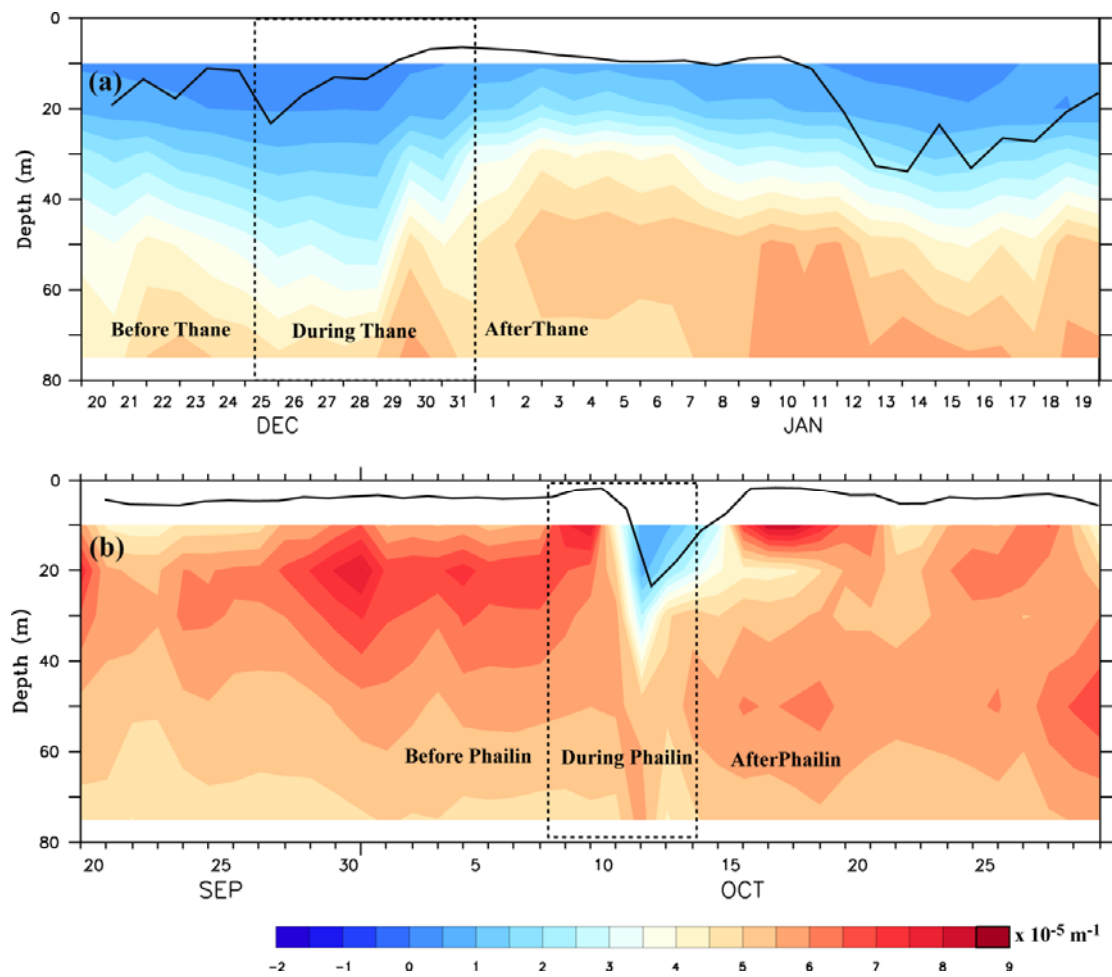


Fig. 10

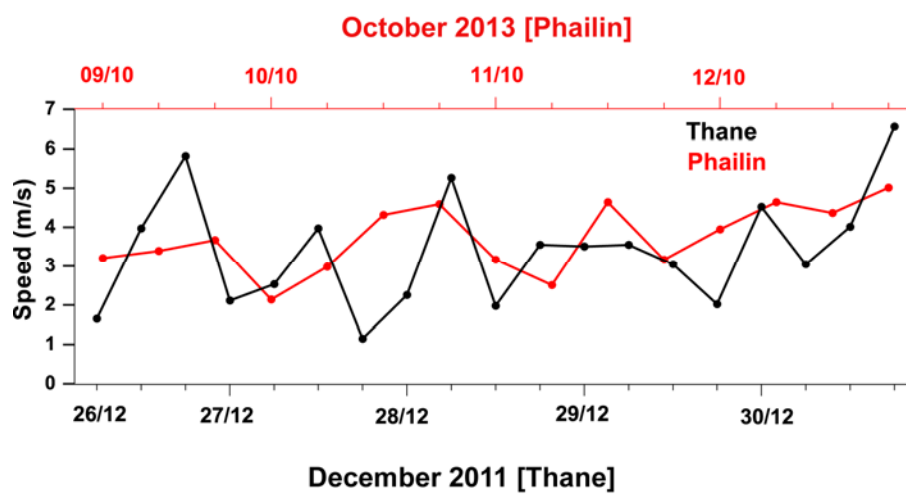


Fig. 11

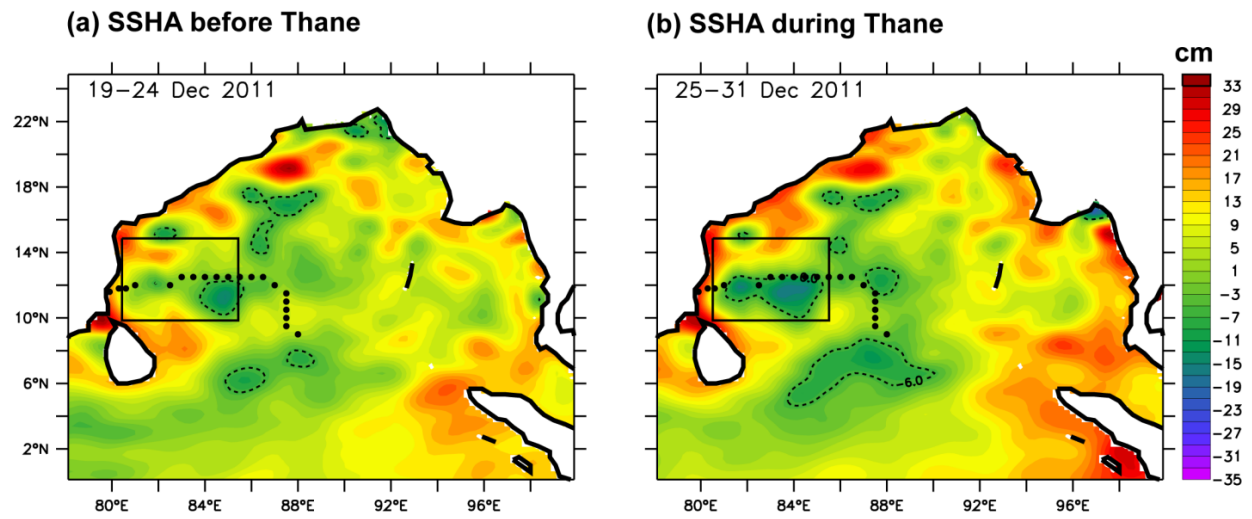


Fig. 12

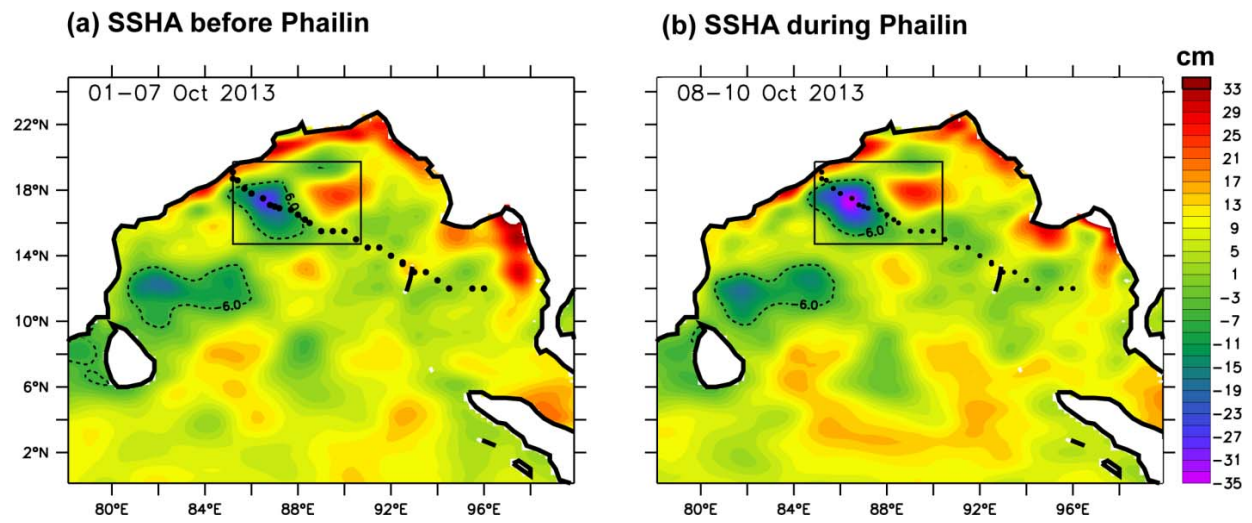


Fig. 13

Supplementary Figures

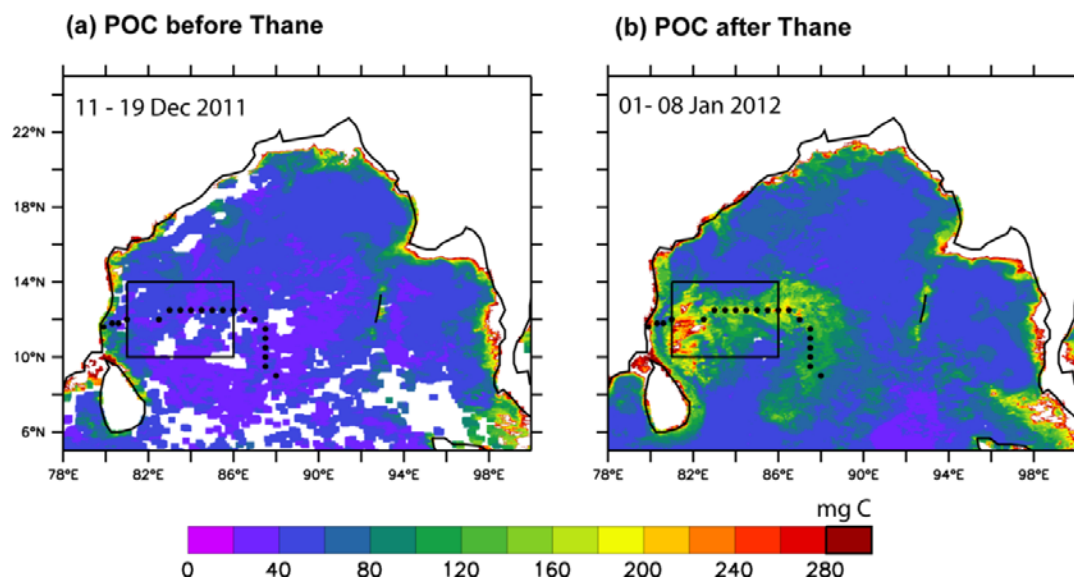


Fig. S1.

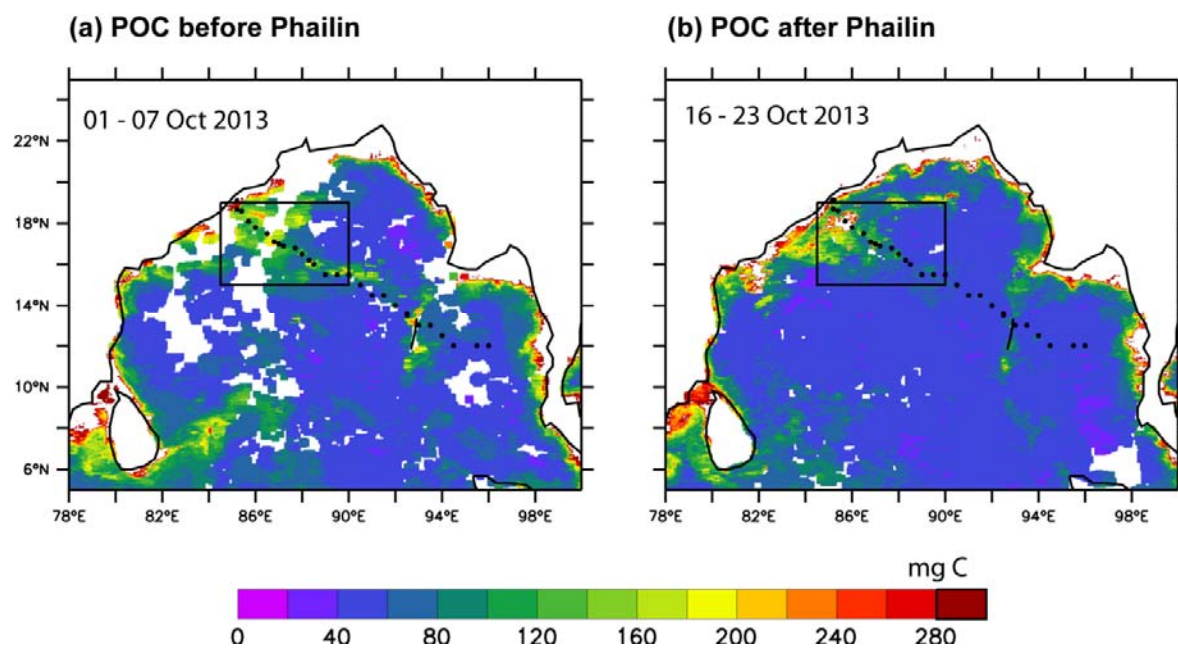


Fig. S2

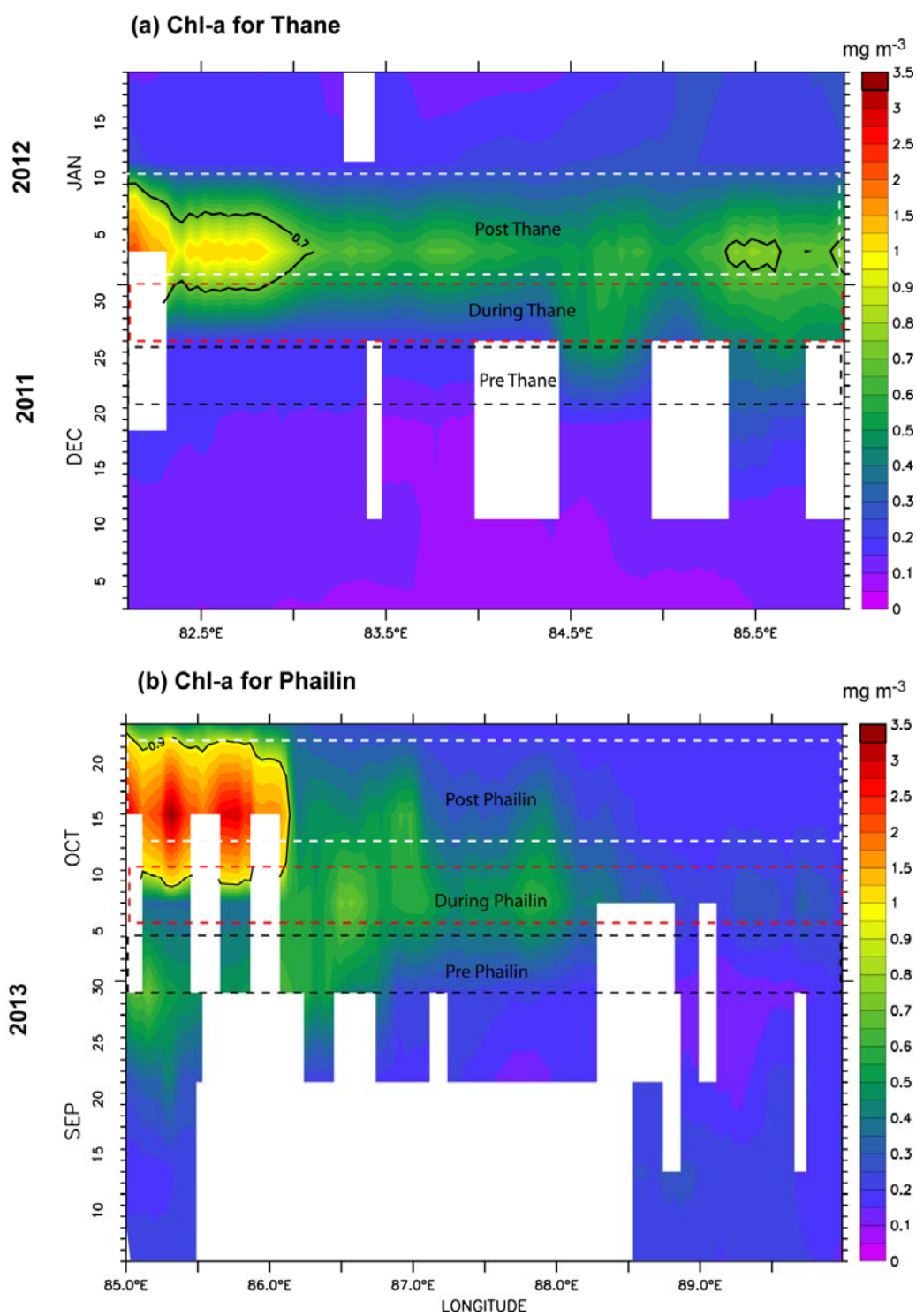


Fig. S3