

Suppressed biological production in the coastal waters off Visakhapatnam, India under the impact of the Very Severe Cyclonic Storm “Hudhud”

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Abstract

Tropical cyclones generally enhance biological production due to increase in nutrients inputs due to vertical mixing. In contrast very severe cyclone storm (VSCS) ‘Hudhud’ decreased primary production due to strong stratification associated with torrential rainfall and high suspended load from the major city where cyclone made landfall. The study region received nutrients from cold core eddy and coastal upwelling in the offshore and inshore region respectively during pre-cyclone period and the same was suppressed under the influence of cyclonic winds led to convergence by shoreward Ekman transport. Though land runoff brought nutrients to the coast during cyclone Hudhud, however, their concentrations were less than that of during other cyclones (Orissa Super Cyclone, Sidr and Phalin). Such low nutrients levels were resulted from crossing of VSCS Hudhud at urban region (Visakhapatnam city) whereas other cyclones crossed coast over fertile agricultural lands led to high nutrients input associated with phytoplankton blooms. Therefore, the biological response to cyclone not only depends on the intensity of the cyclone but also on the region where it crosses the land.

Keywords: biological production, hudhud, TSM, biogeochemistry, BoB

Introduction

Atmospheric extreme events, such as deep depressions, cyclones and heavy precipitation, occur at variable time-scales from a few hours to several days, but the perturbations of these events may last for several days to months (Dagg, 1988; Furnas et al., 1989; Gagan et al., 1990). Episodic heavy precipitation associated with land runoff bring substantial amount of nutrients to the coastal ocean (Pearl, 1985; Willey and Pearl, 1993; Pant and Desai, 1992) lead to formation of phytoplankton blooms for several weeks (Tummala et al., 2009; Maneesha et al., 2011; Lotliker et al., 2014). On the other hand strong winds, associated with cyclone, churn up the upper ocean resulting in vertical entrainment of cold and nutrient rich waters to the surface along cyclone track (Malone et al., 1993; Shiah et al., 2000; Naik et al., 2008; Chiang et al., 2011; Vincent et al., 2012). Enhanced phytoplankton biomass was reported in association with cyclone/super cyclones due to increased nutrients inputs (Di Tullio and Laws, 1991; Subrahmanyam et al., 2002; 2005; Naik et al., 2008; Lotliker et al., 2014).

The Bay of Bengal experiences tropical cyclones throughout the year with its minimal frequency in December-February and maximum in April-May and October-November (Varkey et al., 1996). Impact of a cyclone on the occurrence of phytoplankton blooms were studied in the coastal Bay of Bengal (Nayak et al., 2001; Madhu et al., 2002; and Maneesha et al., 2011; Lotliker et al., 2014; Piontkovski and Al-Hashmi, 2014). Several fold increase in Chlorophyll was observed off Orissa coast after the super cyclone hit the Paradip coast (Orissa, East coast of India) in October 1999 (Nayak et al., 2001). Madhu et al. (2002) noticed an increase in phytoplankton biomass and primary productivity in the southeast coast of India about 15 days after the super cyclone hit the Orissa coast and it was attributed to nutrients brought through land fall to the coastal Bay of Bengal. Similarly, increase in phytoplankton biomass was noticed after cyclone 'Sidr' hit Bangladesh coast due to spreading of nutrients-rich water along the east coast of India through equatorward flowing East India Coastal Current (EICC) (Maneesha et al., 2011). Recently Lotliker et al. (2014) observed 295% increase in Chl-a after cyclone 'Phailin', that hit off Gopalpur coast (Orissa, East coast of India), compared to pre-cyclone period. Chakraborty et al., (2018) also pointed out that light is one of the key factors controlling the oceanic primary production during and after cyclone. In all these cases, increase in nutrients, relative to pre-cyclone conditions, was associated with low saline waters suggesting that land fall brought significant amount of nutrients to the coast leading to enhanced phytoplankton biomass in the coastal Bay of Bengal.

The VSCS 'Hudhud' crossed the Visakhapatnam coast on 12 October 2014 and it was the strongest and most destructive tropical cyclone of 2014 in the North Indian Ocean. Before land fall,

winds reached to its peak strength of 217 km/h over a period of 2-3 minutes with a minimum central pressure of 960 hPa. This is the first cyclone that ever hit major coastal city along the east coast of India as other cyclones crossed coast over fertile lands. Hence, it can be hypothesized that land fall during cyclone Hudhud may not bring significant amount of nutrients to the coast and its impact on phytoplankton biomass may be weaker than other cyclones crossed east coast of India. In order to test this hypothesis, field observations were carried out 4 days after the VSCS 'Hudhud' crossed Visakhapatnam coast and changes in the biogeochemical processes were compared with the data collected during same period about 1 year before the cyclone (i.e., October 2013).

1.1. Description of cyclone 'Hudhud'

A Very Severe Cyclonic Storm 'Hudhud' hit the east coast of India recently on 12 October 2014 and it was the strongest tropical cyclone of 2014 within the North Indian Ocean, as well as the most destructive tropical cyclone that ever crossed India since past two decades. Cyclone 'Hudhud' originated from a low pressure system that formed under the influence of an upper-air cyclonic circulation in the Andaman Sea on 6 October 2014. 'Hudhud' intensified into a cyclonic storm on 8 October and as a Severe Cyclonic Storm on 9 October 2014. 'Hudhud' underwent rapid strengthening in the following days and was classified as a Very Severe Cyclonic Storm by the Indian Meteorological Department (IMD). Shortly before landfall near Visakhapatnam city, Andhra Pradesh, on 12 October, 'Hudhud' reached its peak strength with three minute wind speeds of 217 km h⁻¹ and a minimum central pressure of 960 mbar. After the landfall, the system drifted northwards towards Chhattisgarh, Uttar Pradesh and Nepal, causing widespread rains in those areas and heavy snowfall in Nepal. 'Hudhud' caused extensive damage to the city of Visakhapatnam and the neighbouring districts of Vizianagaram and Srikakulam of Andhra Pradesh.

Material Methods

2.1. Sampling and methods

As a part of Ocean Finder program, *in situ* measurements were carried out in the coastal Bay of Bengal, off Visakhapatnam (Transect A) and off Achutapuram (Transect B), from close to coast to about 22.5 and 30 kms offshore respectively where water depth was up to 75m (Fig. 1). The transect A is our time-series observation region since 2007 (Sarma et al., 2013) and transect B is sampled during this period as cyclone crossed coast at this location. Five stations were occupied along each transect and water samples were collected at standard depths from surface to bottom of the water column using 10 L Niskin sampler. Water column temperature and salinity was measured using portable conductivity-temperature-depth profiler (CTD; Sea Bird Electronics, USA). Vertical

variations in photosynthetic available radiation (PAR) were measured using sensor mounted to the CTD (QCP 3600; Biospherical Instrumentation, USA). Dissolved oxygen was measured using Winkler titration method following automated potentiometric detection technique (Carritt and Carpenter, 1966) and nutrients (nitrate, nitrite, ammonium, phosphate and silicate) were measured following spectrophotometric method (Grashoff et al., 1983). About 3 liters of water was filtered through glass fibre filter (GF/F; 0.7 μm ; Whatman) and pigment retained on the filter was extracted to dimethyl formamide (DMF) and the fluorescence of the extract was measured using spectrofluorophotometer (Varian Instruments, USA) following Suzuki and Ishimaru (1990). About one liter of the sea water sample was filtered through pre-weighted 0.22 μm polycarbonate (Millepore) filter and dried at 60° C and reweighed. The weight of the material retained on the filter was taken as the total suspended particulate matter (TSM; mg l^{-1}).

2.2. Primary production incubation measurements

Sea water samples from surface, 5 and 10 m depth were collected in transparent 1 liter acid-cleaned polycarbonate bottles and were spiked with 1 ml of 2 mM $^{13}\text{C-NaHCO}_3$ (99 atm% ^{13}C ; Sigma-Aldrich Chemicals, Lot no#MBBB2161VpCode:1001847725) solution. The ^{13}C enrichment was about 10% of the total inorganic carbon in the ambient water. The samples were incubated for 24 h on deck and maintained the same temperature of water by passing surface water in to the incubation chamber. Initially vertical profile of the PAR was measured and the irradiance at the original sampling depths was determined and the same was maintained by use of various combinations of neutral-density filters in the deck incubation. Immediately following incubation, the samples were filtered directly through pre-combusted (450°C for 4 h) Whatman GF/F filters under gentle vacuum (<200 kilopascals), and the particulate matter on the Whatman GF/F filters was rinsed with prefiltered seawater. The filters were treated with hydrochloric acid fumes for 4 h to remove inorganic carbon and were completely dried in vacuum desiccators. The isotopic ratios of ^{13}C to ^{12}C and concentrations of particulate organic carbon were determined by a combined system of Elemental analyser and Isotope Ratio Mass Spectrometer (DELTA V Plus; Thermo Electron, Germany). Primary productivity was calculated according to the equation described by Hama et al. (1983).

2.3. Satellite remote sensing data

Weekly mean Advanced Very High Resolution Radiometer (AVHRR) measured sea surface temperature (SST), merged sea surface height (SSH) and the derived geostrophic currents and Ocean Color (Chlorophyll) data from Aqua Moderate Resolution Imaging Spectroradiometer (MODIS)

were obtained from National Ocean Atmospheric Administration (NOAA) (<http://oceanwatch.pifsc.noaa.gov/las/servlets/dataset>). High resolution Ocean Surface Current Analyses Real-time (OSCAR) zonal and meridional currents data in the upper 15m were obtained from Bonjean et al. (2002; <http://www.esr.org/oscar/oscar-main.html>).

3. Results and discussion

Variations in the observed surface water properties before and after cyclone 'Hudhud'

In order to understand the different oceanographic conditions prevailed in the upper ocean and to examine the impact of the VSCS 'Hudhud', the weekly mean AVHRR SST, SSH and Chlorophyll (as phytoplankton biomass) were analyzed during before (September 2014) and after cyclone Hudhud. The AVHRR SST showed a patch of cooler waters by 0.3 to 0.5° C than surrounding coinciding with lower SSH (30 ± 3 cm) at off Visakhapatnam. The geostrophic currents pattern suggested the existence of a cyclonic eddy leading to divergence of cold subsurface waters to the surface (Fig. 2). The time-series variations in SSH at a location along the east coast of India during October 2009 to 2013 suggests persistent existence of the cold core eddy at round the study regions (Supplementary Figure S1). The satellite chlorophyll images suggest six times higher chlorophyll concentrations in the region of cold core eddy compared to surrounding region suggesting that eddy derived nutrients supported phytoplankton biomass during September 2014 (Fig. 2). On the other hand, the region of low SSH along the cyclone track during October 2014 was associated with westward flowing surface currents on the north of the cyclone track and eastward flowing on the south of the track. These surface currents form the cyclonic circulation that lead to divergence and vertical mixing in the upper layer in the open sea region (Fig. 2). Cooling of surface water temperature by $\sim 1.6^\circ$ C and shallow SSH (15-25 mm) were observed along the 'Hudhud' cyclone track compared to those of outside suggesting that divergence of water from the subsurface layers in the offshore region. Enhanced Chl-a concentrations by 200% was seen along the cyclone track in the offshore Bay of Bengal (Fig. 2). Cooling of $\sim 2^\circ$ C was noticed along the track of cyclone 'Sidr' associated with increase in Chlorophyll by 2 to 3 times (Maneesha et al., 2011) in the central Bay of Bengal. In contrast, under the influence of cyclone winds, shoreward Ekman transport and equatorward flow of coastal currents lead to accumulation of low saline waters and convergence at the coast (Figure 3 and Supplementary figure S2). As a result, cyclonic eddy was absent during October 2014 when higher SSH by ~ 20 cm compared to October 2013 suggesting that supply of nutrients from subsurface was inhibited due to VSCS 'Hudhud'. The weekly mean concentration of MODIS Chlorophyll at the study region about one week prior to VSCS 'Hudhud' was 0.26 mg m^{-3} on 5 October and it was increased to 2.76 mg m^{-3} on 13 October 2014 soon after the 'Hudhud'

crossed the coast at Visakhapatnam. The Chlorophyll then decreased sharply to 0.88 mg m^{-3} by 17 October 2014 and further decreased to almost initial Chlorophyll concentrations (0.33 mg m^{-3}) in 3 weeks time, *i.e.*, by 25 October 2014. This suggests that land runoff associated with cyclone 'Hudhud' might have brought nutrients to the coast to support phytoplankton biomass for about 2 weeks, *i.e.*, 17 October 2014.

Modification of water column characteristics in the coastal Bay of Bengal after VSCS 'Hudhud'

The mean water temperature and salinity in the upper 10 m was 29.1°C and 31.57 respectively during October 2013 (Fig. 3). The thermal structure along the transect showed upsloping of isotherms towards the coast indicating signatures of upwelling from a depth of 20 m during September 2014 (pre-cyclone period). The hydrographic features just before cyclone were not measured. Hence we compared with hydrographic features measured during (October 2013) the same period a year before. In order to examine variations in hydrographic properties during October, the time series observations from 2007 to 2014 were depicted in supplementary figure S3. This figure suggests that the lowest salinity was observed during October 2014 with cyclone where relatively lower salinity was observed during 2007 associated with heavy local rainfall (Maneesha et al., 2011). Therefore the hydrographic feature during October 2013 may represent non-cyclonic features. The study region received substantial amount of precipitation (145-527 mm; www.vagaries.in/2014/10/) during VSCS 'Hudhud' that complexed the hydrography in the study region. The surface currents, as derived from the SSH variations, during this period were towards coast (westward flowing) that led to advection of low saline waters to the coast (middle and lower panels in Fig.4). The salinity in the entire water column, up to 75 m, was freshened during October 2014 due to convergence of waters towards the coast. The water column temperature in the upper 50 m was warmer by $>1^\circ \text{C}$ and freshened by ~ 10 during October 2014 compared to October 2013 (Fig. 3). Suppression of upsloping of isolines can be noticed during October 2014 due to convergence of low salinity surface waters in the upper 40 m of water column along the transects A and B (middle and lower panels of Fig. 3). The freshwater lens was thick until 25 km from the coast and then slowly thinned towards offshore along the transect B. Relatively warmer and fresher waters were noticed along transect A compared to transect B and such spatial variations could possibly be related to variations in local precipitation and mixing patterns.

The upsloping of nitrate from 25 m depth was observed resulting in higher concentrations (2 to $3 \mu\text{M}$) close to the coast (up to 5 km) than offshore ($\sim 0.5 \mu\text{M}$) during October 2013 (Fig. 4). The concentrations of nitrate were relatively lower (0.5 to $1.5 \mu\text{M}$) in the upper 25 m of water column along transect A than those along transect B (2.2 to $4 \mu\text{M}$) with weaker vertical gradients in the

upper 50m. In contrast, the concentrations of nitrate below 50 m were significantly lower during October 2014 than October 2013. The down-sloping of nitrate contours during October 2014 suggests the convergence of surface waters from the coast to over a distance of 20 km. This can be further evidenced from the salinity which was significantly lower by 1 unit in the upper 75 m during October 2014 than 2013 (Fig. 3). Similarly higher phosphate concentrations were noticed during October 2014 (2.1 to 3.2 μM) compared to those in 2013 (0.5 to 2.4 μM) with relatively higher concentrations along transect B than transect A (lower and middle panels in Fig. 4). On the other hand, silicate concentrations during 2014 were higher along transect A (17 to 23 μM) than transect B (11.5 to 21.1 μM) which was significantly lower by half (4.2 to 12.5 μM) compared to 2013. It can be noticed that higher concentrations of nutrients in the upper 40 m were associated with low salinity suggesting that land run-off, resulted from heavy precipitation during the VSCS 'Hudhud', could be a major source of nutrients to the study region. Maneesha et al. (2011) noticed increased silicate concentrations in the coastal waters at off Visakhapatnam associated with heavy precipitation. Madhu et al. (2002) suggested that higher nutrients were associated with low salinity waters in the southeast coast of India and it was attributed to land run-off associated with Orissa Super Cyclone. Dissolved silicate is a good proxy for land run-off as the major source is from soil/rock dissolution and higher concentrations of silicate indicates major source from land runoff during October 2014. The N:P ratio was relatively higher during 2013 (3.40) compared to that in October 2014 (1.20) suggesting that less nitrate was brought through land run-off relative to phosphate. However, Sarma et al. (2013) suggested nitrate limits the phytoplankton growth during October in the coastal Bay of Bengal. In contrast, Si:N ratios were significantly higher (4.1 to 9.3) during October 2014 than that of October 2013 (2.56) (Table 1) suggesting that land run-off brought higher silicate and it is much higher than the limiting level for phytoplankton growth. The concentrations of both nitrate and phosphate were higher along transect B than transect A. Though these two transects were apart by 25 km from each other but the VSCS 'Hudhud' reported to hit the land at the location of transect B. On the other hand, lower consumption of nutrients at transect B may also lead to the accumulation of nutrients. In order to examine the same, the concentrations of phytoplankton biomass and total suspended matter (TSM) were measured in the study region. Relatively higher phytoplankton biomass (as chlorophyll-a) was observed at transect A ($0.39 \pm 0.2 \text{ mg m}^{-3}$) compared to transect B ($0.18 \pm 0.1 \text{ mg m}^{-3}$). Interestingly, phytoplankton biomass were significantly lower during October 2014 than those of 2013 ($0.69 \pm 0.3 \text{ mg m}^{-3}$) suggesting that VSCS 'Hudhud' did not promote phytoplankton blooms unlike cyclone 'Sidr', Phailin and super cyclone (Madhu et al., 2001; Tummala et al., 2009; Maneesha et al., 2011; Lotliker et al., 2014). In order to examine the potential reasons for low phytoplankton biomass, the

turbidity (TSM) levels were examined. It was noticed that the mean concentrations of TSM almost doubled along the transect B ($18.4 \pm 3 \text{ mg l}^{-1}$) than along transect A ($10.2 \pm 4 \text{ mg l}^{-1}$) and it was much lower during 2013 ($5.8 \pm 1 \text{ mg l}^{-1}$) suggesting that inhibition of light to water column leading to decrease in phytoplankton biomass. Significant decrease in PAR by more than 50% was observed during post-cyclone compared to pre-cyclone period (Supplementary Figure 4). It was further confirmed that dissolved oxygen concentrations were significantly higher along transect A compared to transect B possibly due to active biological processes at transect A. Our observation suggesting that light seems to be controlled the phytoplankton biomass after VSCS 'Hudhud' hit the land than nutrients alone. In contrast to observed Chl-a, increase satellite Chl-a on 13th October 2014 was observed (2.76 mg m^{-3}) than before cyclone on 5th October 2014 (0.26 mg m^{-3}). Since the observations were carried out close to the coast (<30 km from the coast), the accurate measurements of satellite Chl-a is unlikely due high TSM and coloured organic matter.

The photic depth in the study region varied between 8 to 12 m during October 2014 and it increased from close to coast to offshore. The integrated primary production in the upper 10 m of water column showed significant spatial and temporal variability. The coastal (<5 km from the coast) production was 5 times higher than that offshore (>10 km from the coast) and it is consistent with the distribution of nutrients and phytoplankton biomass (Table 1). The primary production along transect A during October 2014 was almost same as that in October 2013 in the near-coastal region (<2 km from the coast) and decreased rapidly towards offshore (Table 1). The primary production during October 2014 was far less along transect A in the offshore regions when compared to that along transect B. More interestingly, the production in the near-coastal region was higher by 18 times than that in the offshore. The mean primary production in the upper 10 m along the transect in October 2013 was relatively higher ($552.3 \text{ mgC m}^{-2} \text{ d}^{-1}$) compared to 2014 ($467.8 \text{ mgC m}^{-2} \text{ d}^{-1}$ along transect A and $389.2 \text{ mgC m}^{-2} \text{ d}^{-1}$ along transect B). This suggests that VSCS 'Hudhud' decreased the primary productivity by 15 to 30% in the coastal Bay of Bengal. Though the VSCS 'Hudhud' brought land-derived nutrients to the coast, decrease in photic depth did not allow phytoplankton to produce. In contrast, Madhu et al. (2002) observed increase in primary production by two to three folds in the southeast coast of India after super cyclone associated with increase in nutrients. Their study region received nutrients through advection from the cyclone hit zone by equator ward flowing of EICC. Though Madhu et al. (2002) did not measure TSM during their study, however, it is also possible that most it might have been settled in the en route as their study region was >300 km away from the cyclone hit zone. As a result increase in phytoplankton biomass and primary production was noticed away from the cyclone hit zone. Similarly, Maneesha et al. (2011) were also noticed increase in

phytoplankton biomass at off Visakhapatnam about two weeks after cyclone 'Sidr' hit the Bangladesh coast. Our study suggests that cyclone suppressed nutrients input through vertical mixing due to strong stratification and convergence in the coastal Bay of Bengal and increased TSM load resulting in decrease in phytoplankton biomass and production. It was further observed that fishery catch significantly decreased after VSCS 'Hudhud' hit the Visakhapatnam coast due to low plankton biomass (Scientist-In-Charge, Central Marine Fisheries Research Institute, Visakhapatnam, personal communication, 2015). Our study further confirmed that VSCS 'Hudhud' deserted on the land hit zone of Visakhapatnam, Vizianagaram and Srikakulam districts of Andhra Pradesh, India through uprooting of plants as well decreased phytoplankton biomass due to land fall in the coastal sea. The contrasting response of phytoplankton to cyclone Hudhud compared to other cyclones (Orissa Super Cyclone, Sidr, Phailin) could be due to soil characteristics of the region where cyclone hit the land. The regions where Orissa Super cyclone (Pradip village), Sidr (Bangladesh) and Phailin (Gopalpur village) are highly fertile region where significant amount of agricultural activities are undergoing. As a result, the land fall brought significant amount of nutrients to the coastal Bay of Bengal close to the cyclone hit zone. In contrast, the cyclone 'Hudhud' hit one of the major city (Visakhapatnam) which is completely concrete zone with no agricultural activities resulting in less nutrients inputs (Fig.5). Several civil engineering constructions and other sewage related materials flushed to the coast along with landfall leading to increase in suspended load resulting in decreased phytoplankton biomass and productivity. This study suggests that not only intensity of the cyclone but also the soil characteristics of the zone where cyclone hits influences the biological response to the cyclone in the coastal region.

Summary and Conclusions

Influence of VSCS 'Hudhud' on hydrography and biogeochemistry of nutrients and phytoplankton production was studied after cyclone and compared with pre-cyclone conditions. The cyclone 'Hudhud' suppressed the nutrients input through upwelling in the coast and cold core eddy in the offshore due to convergence of waters in the coast. The land runoff brought low concentrations of nutrients and high concentrations of TSM led to decrease in phytoplankton biomass and primary production by 15-20% compared to pre-cyclone period. Our study suggested that VSCS 'Hudhud' did not increase primary production, unlike other cyclones formed in the Bay of Bengal, due to crossing the major city unlike other cyclones that crossed fertilized lands.

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Table 1: Comparison of the mean physico-chemical characteristics of coastal waters measured off Visakhapatnam 4 days after the ‘Hudhud’ cyclone with those measured one year before (October 2013) the ‘Hudhud’.

Parameter (units)	1 year before the ‘Hudhud’ (October 2013) Transect A	4 days after the ‘Hudhud’ (October 2014)	
		Transect A	Transect B
SST (°C)	29.22±0.4	30.02±0.1	30.06±0.1
SSS	31.06±1.9	21.22±1.6	23.29±1.4
Chl-a (mg m ⁻³)	0.69±0.3	0.39±0.2	0.18±0.1
Turbidity (mg l ⁻¹)	7.6±2	10.2±4	18.4±4
NO ₃ (μM)	3.2±2	0.79±0.3	4.3±2
NH ₄ (μM)	0.5±0.3	1.7±0.7	0.9±1
PO ₄ (μM)	1.8±0.8	2.3±0.6	2.2±0.4
SiO ₄ (μM)	11.0±4	20.9±2	18.0±2
N:P	3.4±0.8	1.2±0.3	1.4±0.2
Si:N	2.6±0.7	9.3±1.0	4.1±0.8
PP (mgC m ⁻² d ⁻¹)	552.3±110	467.8±240	389.2±213

Legend to figures

1. Sampling stations occupied along transects A (Red fill circle) and B (blue star) in the coastal Bay of Bengal. Track of the cyclone 'Hudhud' is also shown.
2. A comparison of the satellite imageries of merged sea surface height (SSH; mm) and the derived geostrophic currents, sea surface temperature (SST, °C) and surface chlorophyll (mg m^{-3}) about 1 year prior to the cyclone 'Hudhud' in October 2013 (upper panel) and about 4 days after the 'Hudhud' in October 2014 (lower panel). The cyclone track is also shown.
3. A comparison of the water column temperature (°C), salinity, dissolved oxygen (μM) and Chlorophyll-a (mg m^{-3}) in the coastal Bay of Bengal about 1 year prior to the cyclone 'Hudhud' in October 2013 (upper panel) and about 4 days after the 'Hudhud' in October 2014 along the transect A (middle panel) and the transect B (lower panel) in October 2014.
4. A comparison of the concentrations of ammonium (μM), nitrate (μM), phosphate (μM) and dissolved silicate (μM) in the coastal Bay of Bengal about 1 year prior to the cyclone 'Hudhud' in October 2013 (upper panel) and about 4 days after the 'Hudhud' in October 2014 along the transect A (middle panel) and the transect B (lower panel) in October 2014.
5. A comparison of the contrasting response of phytoplankton to cyclone Hudhud compared to other cyclones

Figure 1

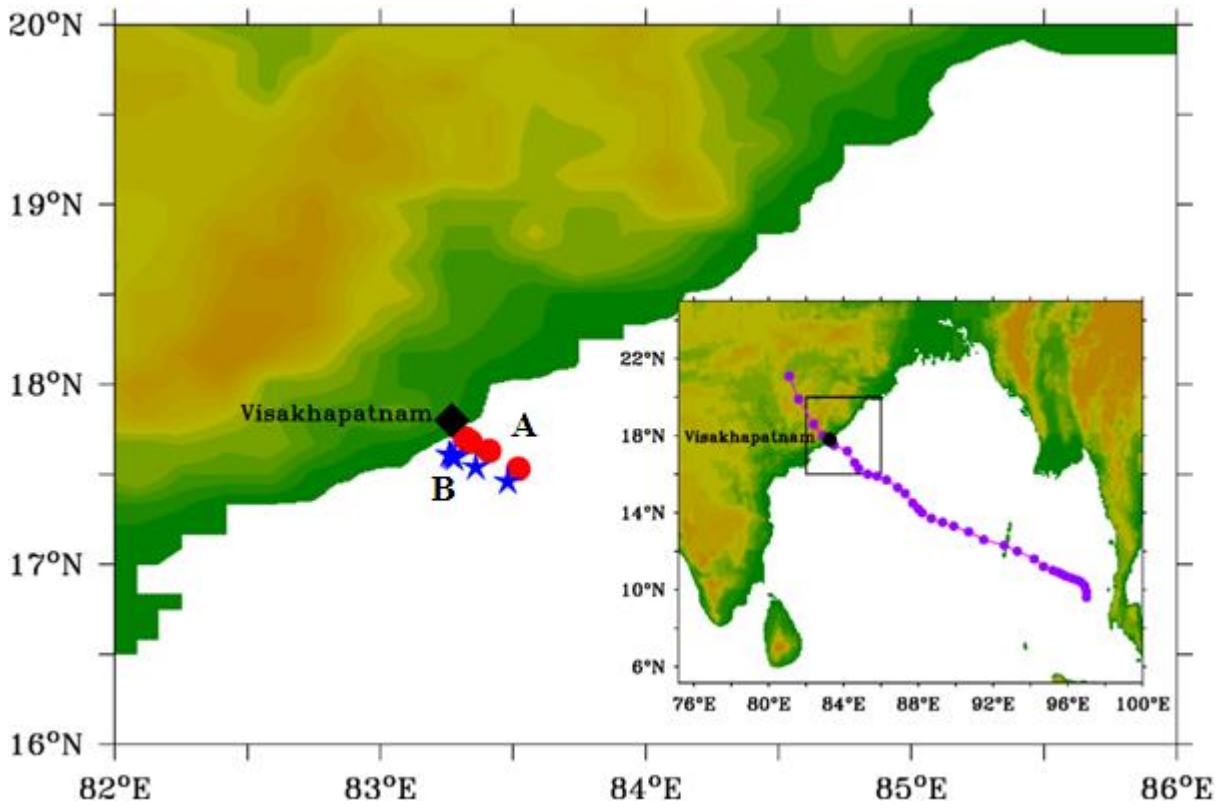


Figure 2

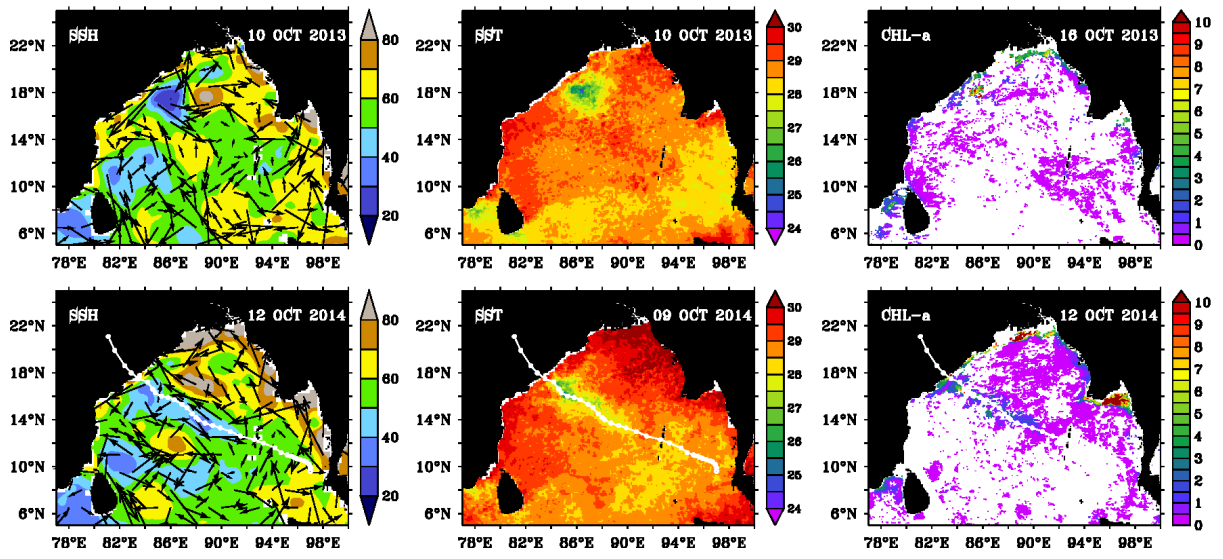


Figure 3

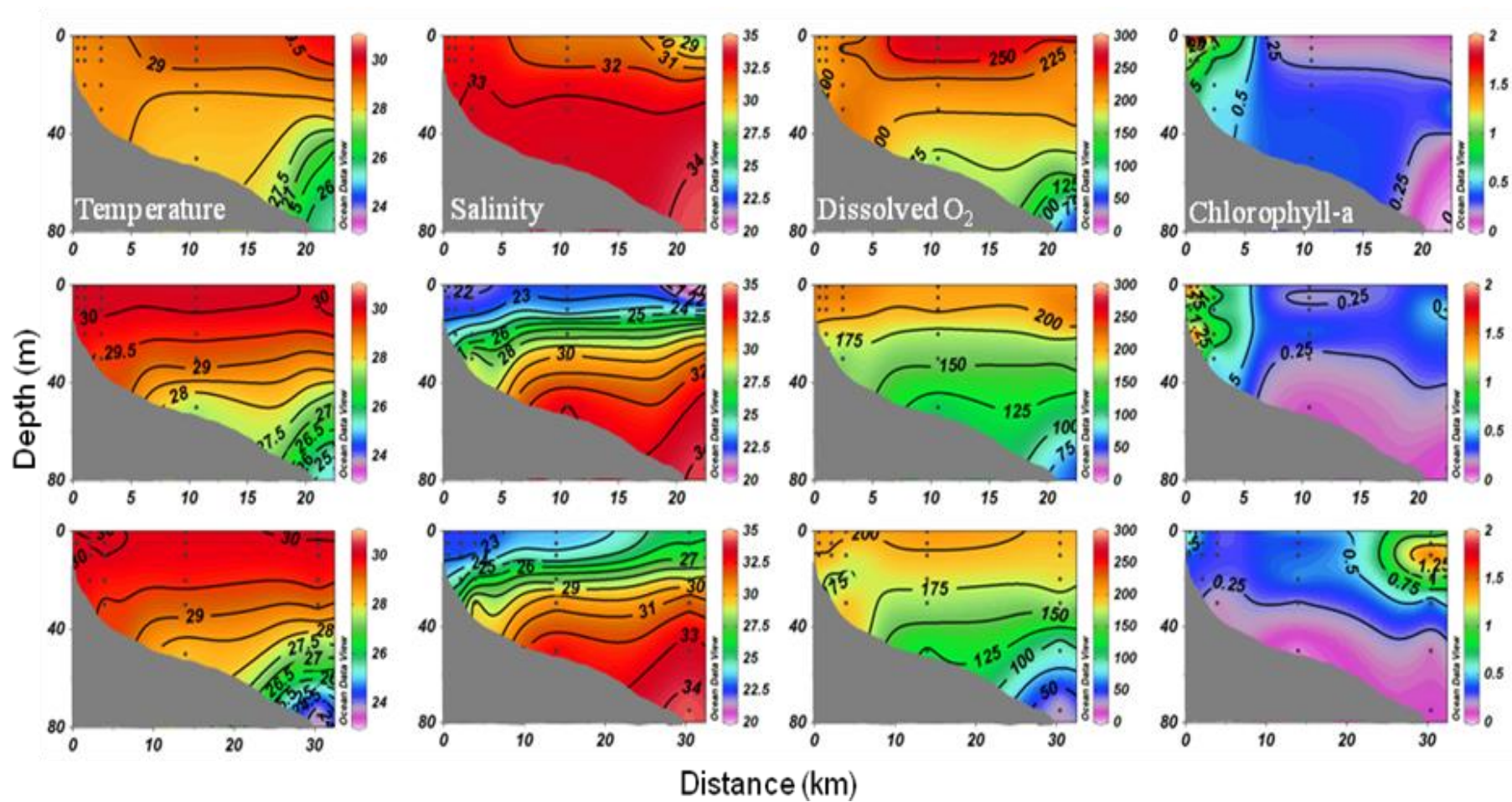


Figure 4

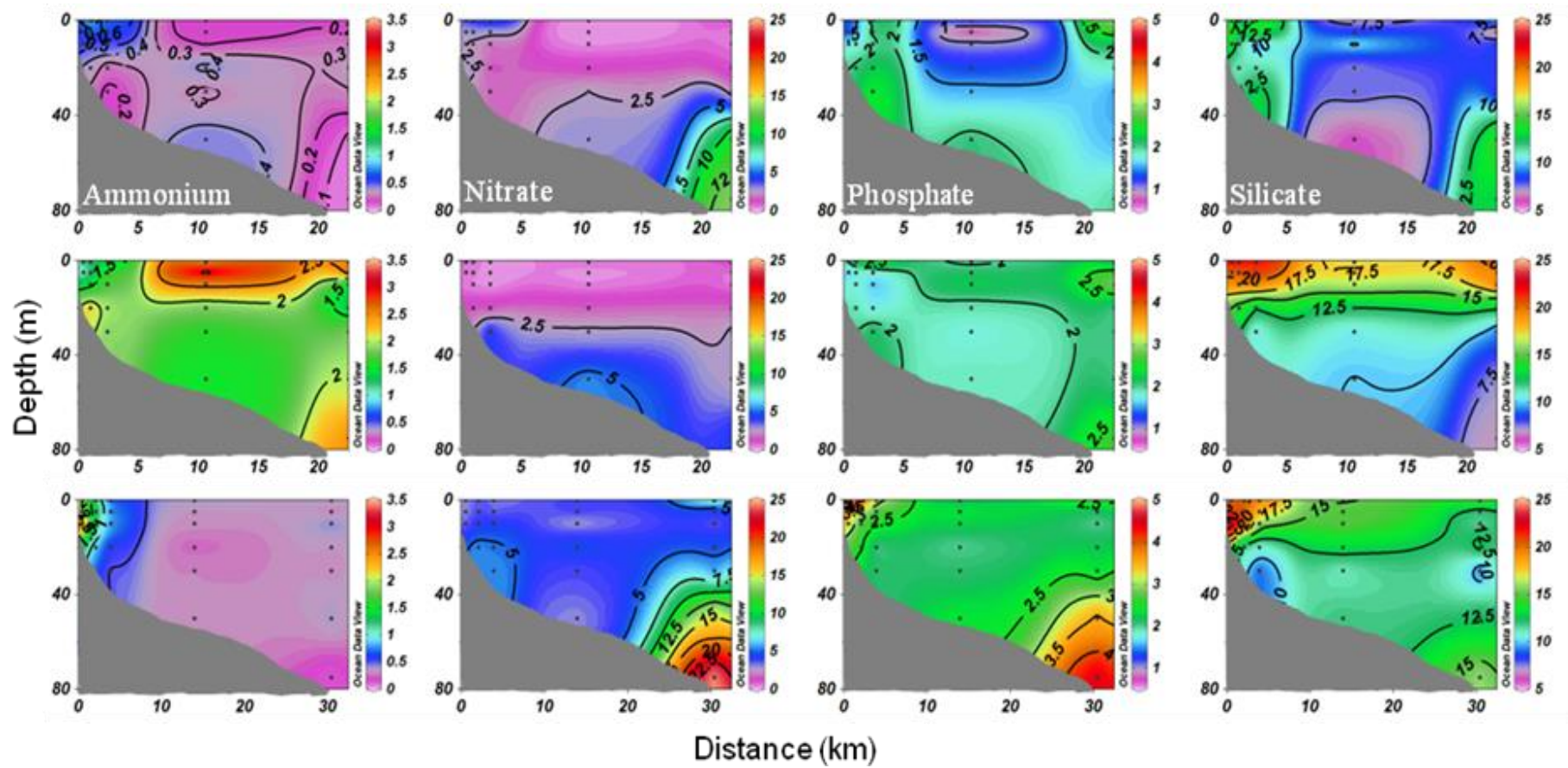
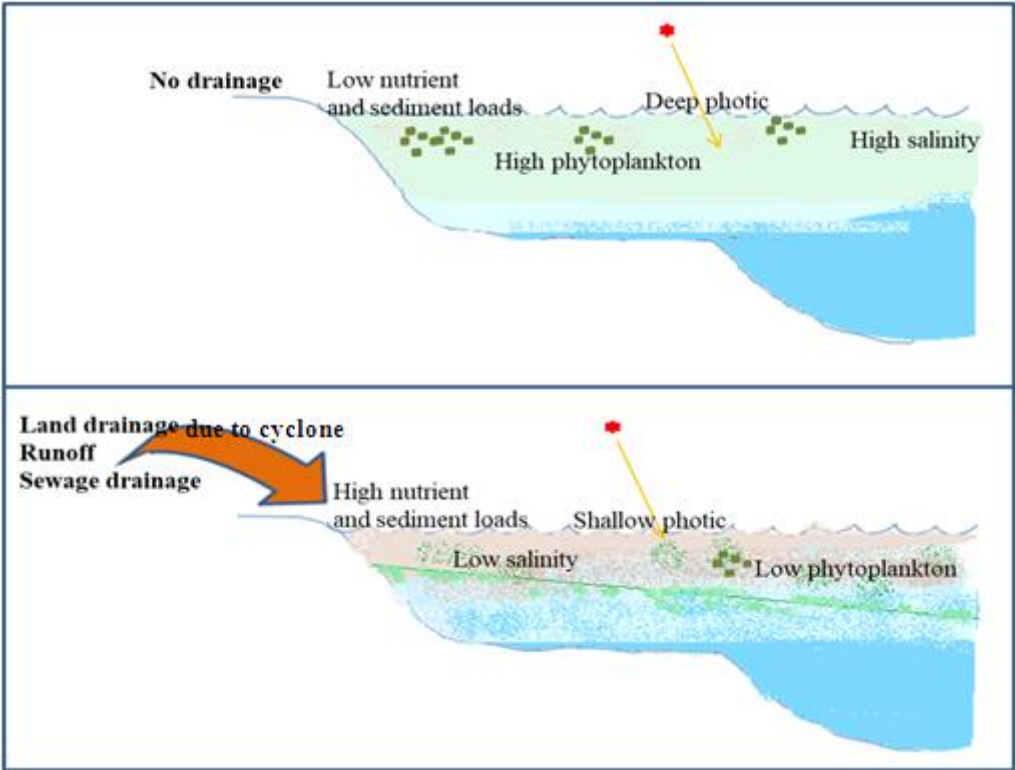
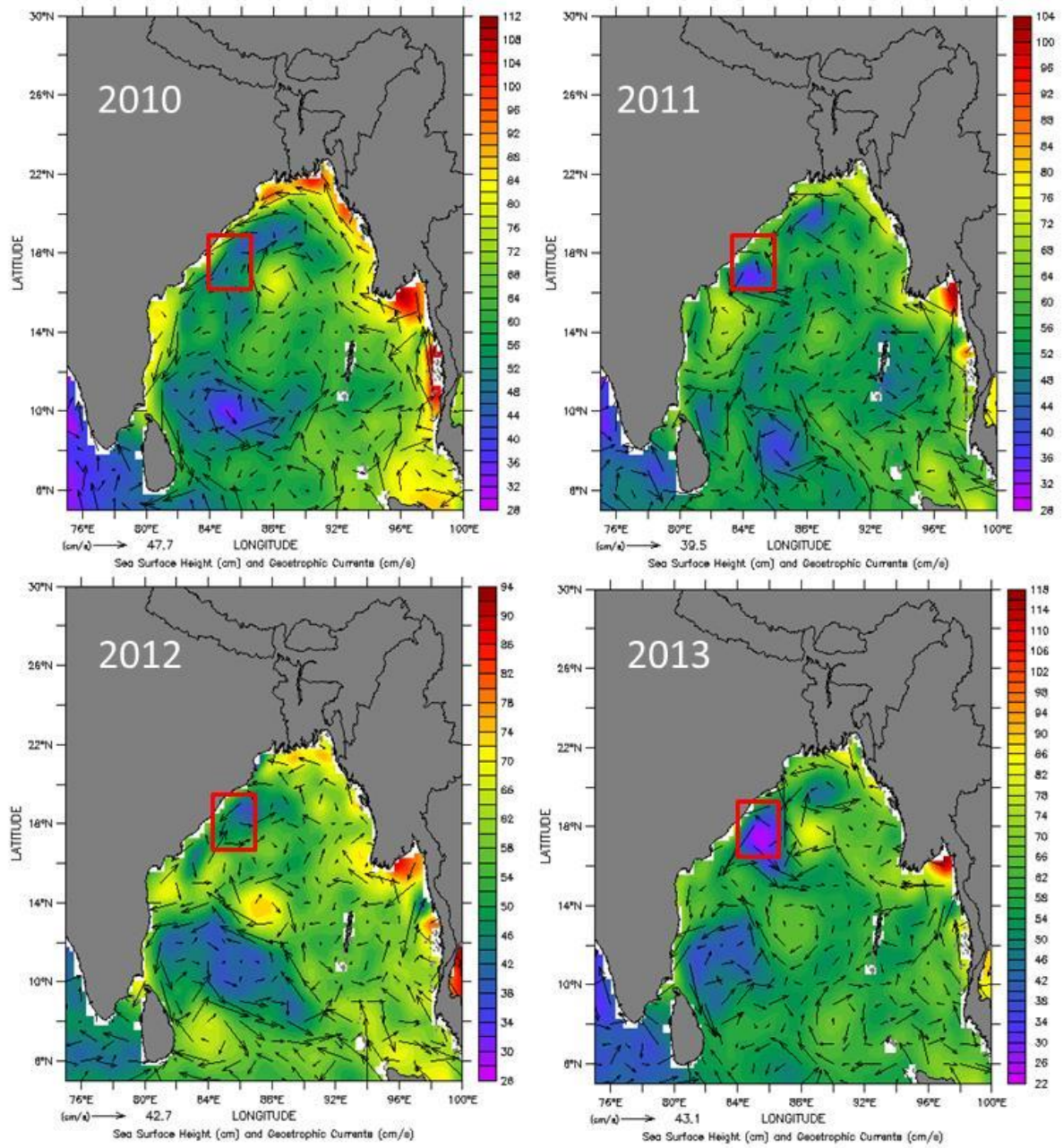


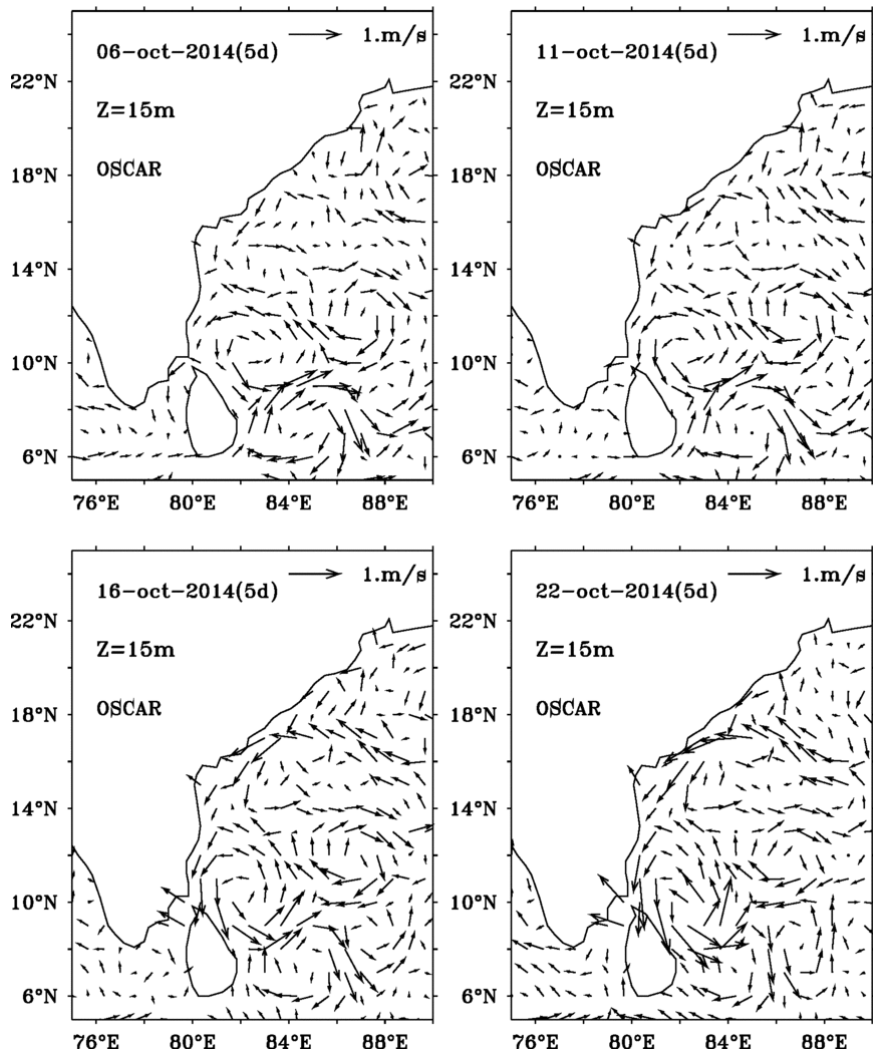
Figure 5



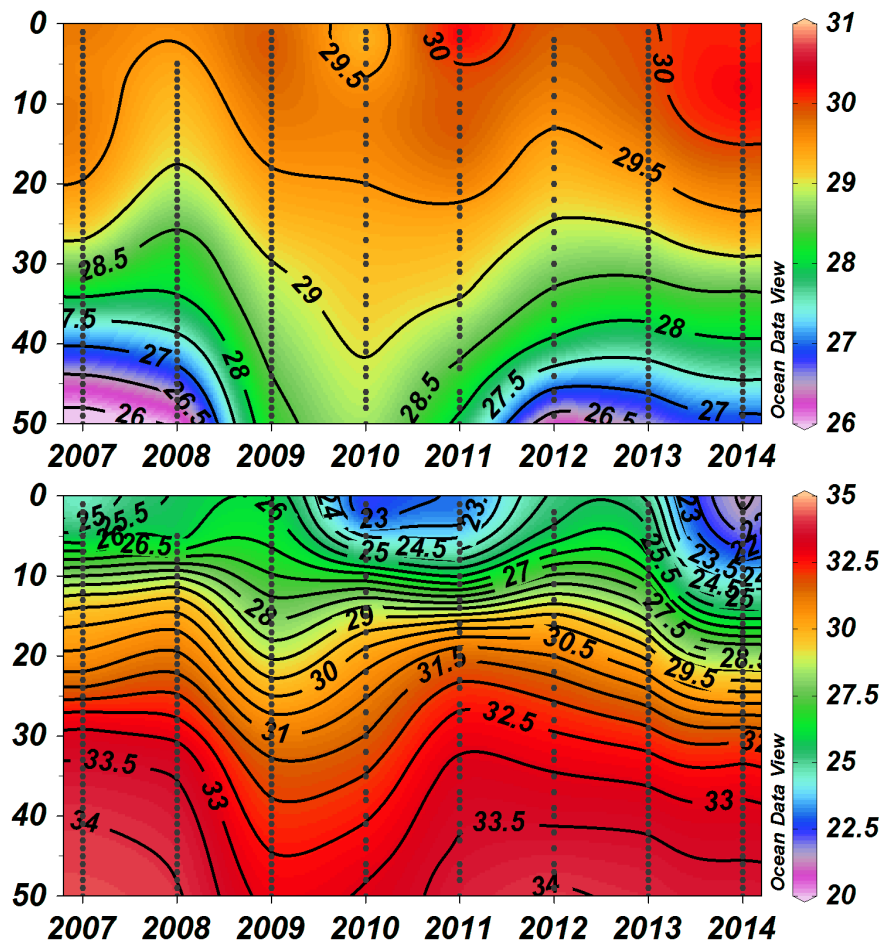
Supplementary Figure 1: Variations in distribution of merged sea surface height (SSH; cm) and the derived geostrophic currents during October 2010 to 2013. The circle shows the study region.



Supplementary Figure S2: Variations in OSCAR currents during and before cyclone Hudhud.



Supplementary Figure S3: Variability in salinity and temperature during 2007 to 2014



Supplementary figure S4: Variations in photosynthetic Active Radiation (PAR) during pre and post cyclone period along transect A and B.

