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Modifications in the trace gases flux by a very severe cyclonic storm, Hudhud, in the coastal Bay of Bengal

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A very severe cyclonic storm, *Hudhud*, made landfall at Visakhapatnam city, the central east coast of India, on 12 October 2014 and it is the most destructive cyclone to ever hit the Indian subcontinent since the past two decades. In order to examine its impact on the flux of trace gases into the atmosphere, a study was made in the coastal Bay of Bengal, off Visakhapatnam, after the cyclone and compared with the pre-cyclone conditions. Hudhud suppressed the vertical mixing of the water column due to the occurrence of strong salinity stratification associated with torrential rainfall. The land run-off and precipitation brought significant amount of ammonium to the coastal waters, resulting in increased pH. The increased pH shifted the inorganic carbon equilibrium towards the formation of bicarbonate, resulting in decreased partial pressure of carbon dioxide (pCO_2) after the cyclone Hudhud. The undersaturation of carbon dioxide (CO_2) and nitrous oxide (N_2O) with respect to atmospheric equilibrium was observed during the post-cyclone period compared to the pre-cyclone period. About 80% of the post-cyclone decrease in N_2O (>2 nM) and pCO_2 (150–200 µatm) was contributed by the dilution of coastal waters with the precipitated waters. In contrast, methane (CH_4) concentrations were increased by 0.5–2.8 nM during the post-cyclone period than in the pre-cyclone period, and were attributed to the input of domestic sewage through land run-off. Dimethyl sulphide (DMS) and the total dimethyl sulphonio-propionate ($DMSP_t$) concentrations decreased by 0.4–3.9 and 0.2–6.0 nM, respectively, during the post-cyclone period in comparison with the pre-cyclone period and it was consistent with lower phytoplankton biomass during the former than the latter. The sea-to-air flux of CO_2, N_2O and DMS were 1.3 ± 0.5 mmol C $m^{-2}d^{-1}$, 0.9 ± 0.3 µmol m^{-2} d^{-1} and 5.8 ± 3 µmol m^{-2} d^{-1} during the pre-cyclone period, respectively. The corresponding values during the post-cyclone period were lower at −2.0 ± 1 mmol C m^{-2} d^{-1}, −0.4 ± 0.1 µmol m^{-2} d^{-1} and 2.8 ± 2 µmol m^{-2} d^{-1}, respectively. In contrast, the sea-to-air flux of CH_4 increased from 0.6 to 1.5 µmol C m^{-2} d^{-1} from the pre- to the post-cyclone period. This study suggested that the cyclone Hudhud modified the magnitude of the biogenic gas flux to the atmosphere from the coastal Bay of Bengal than hitherto hypothesised.

Keywords. Trace gases; carbon dioxide; tropical cyclone; fluxes; Bay of Bengal.

1. Introduction

Tropical cyclones are extreme atmospheric events which strongly affect the physical structure of the upper ocean along their track (Cione and Uhlhorn 2003; D'Asaro 2003; Levy *et al.* 2012). As a response to tropical cyclones, sea surface temperature significantly cools by several degrees (2–10°C; Chiang *et al.* 2011; Maneesha *et al.* 2011), in association with the increase in phytoplankton biomass (Di Tullio and Laws 1991). This is mainly caused by the wind-driven entrainment of subsurface cold and nutrient-enriched waters (Price 1981; Vincent *et al.* 2013).

The influence of cyclones on trace gases flux has been studied in several regions (Perrie *et al.* 2004; Nemoto *et al.* 2009). It was noticed that hurricanes in the North Atlantic Ocean removed significant amount of CO_2 from the ocean surface, resulting in its undersaturation (Bates *et al.* 1998). It was reported that cyclones cause enormous efflux of CO_2 from the ocean to the atmosphere to the extent of affecting the annual local efflux (Perrie *et al.* 2004; Nemoto *et al.* 2009). Although cyclones are short-lived and travel at considerable speed, they affect significant areas (several hundred kilometres) (Willoughby *et al.* 2006). It was hypothesised that they exert a significant influence on the global air–sea flux of CO_2 (Bates *et al.* 1998); however, the measurements, under cyclonic conditions, are rather sparse to examine their influence. Crosswell *et al.* (2014) observed extensive CO_2 emissions from the shallow coastal waters during the passage of Hurricane Irene over the Mid-Atlantic Coast of the USA. Huang and Imberger (2010) modelled the impact of Hurricane Frances on CO_2 fluxes using a coupled three-dimensional hydrodynamic and carbon model. They noticed that the passage of Hurricane Frances was estimated to have caused a CO_2 efflux of about 3.5–10.3 Tg C (1 Tg $= 10^{12}$ g) from the ocean to the atmosphere. Levy *et al.* (2012) noticed that tropical cyclones influence CO_2 fluxes significantly at the regional levels; however, their impact on the global level is rather insignificant at longer time scales due to the consequential removal of CO_2 through the biological processes promoted by the entrained nutrients.

Naik *et al.* (2008) observed that a tropical cyclone in the Arabian Sea cooled the surface water temperature by ∼4°C and increased nutrients and primary production. The new production supported by the cyclone was estimated to be equivalent to ∼5% of the annual organic carbon export to the deep sea (beyond the continental margin) for the entire Arabian Sea. They further noticed that the entrainment of N_2O from the thermocline led to more than doubling of its concentration in the mixed layer. Unlike the Arabian Sea, which is weakly stratified due to less fresh water discharge from the rivers, the Bay of Bengal receives significant amounts of freshwater from various rivers such as the Ganges, Brahmaputra, Mahanadi, Godavari, etc., resulting in low surface water salinity by 3–5 units compared to the Arabian Sea (UNESCO 1979; Varkey *et al.* 1996).

The Bay of Bengal is considered to be a low productive zone due to the inhibition of vertical mixing by a strong vertical salinity gradient (Prasanna Kumar *et al.* 2002). The faster removal of organic matter through mineral ballast further lowers the decomposition of organic matter in the water column (Ittekkot *et al.* 1991). As a result, Kumar *et al.* (1996) suggested that the Bay of Bengal is a net sink for atmospheric CO_2. Based on the seasonal observations in the surface waters during the pre- and post-monsoon period, it was observed that the Bay of Bengal is a mild source of N_2O to the atmosphere (Naqvi *et al.* 1994; Hashimoto *et al.* 1998). Recent observations along the east coast of India suggested that river discharge from the peninsular region of India brought CO_2- and N_2O-rich waters to the coastal region and acted as a mild source to the atmosphere (Sarma *et al.* 2012; Rao and Sarma 2013). More recently, Sarma *et al.* (2015a) found enhanced acidification in the northern than in the southern Bay of Bengal due to increased air pollution associated with the recent increase in industrial activities and concluded that the northern Bay of Bengal acts as a perennial source of CO_2 to the atmosphere. Very few observations have been carried out so far on CH_4 in the water and over the atmosphere in the Bay of Bengal. Berner *et al.* (2003) measured CH_4 concentrations in the northern Bay of Bengal during the north-east monsoon and reported that the strong sources of CH_4 to the atmosphere at the mouth of the Ganges and the Brahmaputra rivers, and on annual scale, the Bay of Bengal acts as a source ($6.65 \pm 7.36\,\mu$mol m^{-2} d^{-1}) to the atmosphere. No studies have been carried so far in the coastal Bay of Bengal to examine its contribution to the atmospheric CH_4. Shenoy *et al.* (2006) and Rao *et al.* (2015) noticed that the coastal Bay of Bengal is a strong source for atmospheric dimethyl sulphide (DMS) during monsoon. Therefore, in all earlier studies, coastal Bay of Bengal has been observed

as a strong to mild source of several trace gases (CO_2, N_2O, CH_4 and DMS) into the atmosphere.

The flux of trace gases depends on the piston velocity and the difference of gas concentrations between the atmosphere and the ocean surface. The piston velocity which is a function of wind speed strongly increased during the cyclonic conditions (Liss and Merlivat 1986; Wanninkhof 1992; D'Asaro and McNeil 2007; McNeil and D'Asaro 2007). In addition to this, high surface winds churn up the upper ocean that causes the injection of cool water rich in nutrients and trace gases (mainly for CO_2, CH_4 and N_2O) to the surface (Malone *et al.* 1993; Shiah *et al.* 2000; Naik *et al.* 2008; Levy *et al.* 2012). The enhanced nutrients increase the primary production that would modify the production/consumption of some of the trace gases. In addition to this, heavy precipitation associated with cyclone and landfall brings land-derived nutrients that may have significant impact on trace gas concentrations in the coastal regions.

The flux of trace gases is expected to be modified under extreme atmospheric events such as cyclones. The objective of the present study is to examine the variability in trace gas concentrations and their flux in the coastal Bay of Bengal after cyclone *Hudhud* compared to the pre-cyclone period.

2. Material and methods

2.1 *Description of cyclone Hudhud*

A very severe cyclonic storm Hudhud hit the east coast of India on 12 October 2014 and it was the strongest tropical cyclone over the north Indian Ocean in the 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 3-min 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. Damages are estimated to be between US$9.7 and 11 billion. At least 96 deaths have been confirmed, a majority of them from Andhra Pradesh state.

2.2 *Sampling and methods*

As a part of Ocean Finder programme, in situ measurements were carried out in the coastal Bay of Bengal, off Visakhapatnam (transect A) and off Atchutapuram (transect B) during 14 and 15 October 2014, from close to the coast to about 22.5 and 30 km offshore, respectively, where water depth was up to 75 m (figure 1). The transect A has been our time-series observation region since 2007 (Sarma *et al.* 2013) and transect B is sampled during this period as the cyclone crossed the coast at this location. Five stations were occupied along each transect and water samples were collected at standard depths from the surface to the bottom of the water column using a 10-L Niskin sampler. Water column temperature and salinity were measured using a portable conductivity–temperature–depth (CTD) profiler (Sea Bird Electronics, USA). Nutrients (nitrate, nitrite, ammonium, phosphate and silicate) were measured by the spectrophotometric method (Grasshoff *et al.* 1983). About 3 l of water was filtered through glass fibre filter (GF/F; 0.7 μm; Whatman) and the pigment retained on the filter was extracted to dimethyl formamide (DMF) and the fluorescence of the extract was measured using a spectrofluorophotometer (Cary Eclipse, Varian Instruments, USA) following Suzuki and Ishimaru (1990).

The pH and total alkalinity (TA) were measured by potentiometric (Metrohm, Zofingen, Switzerland) gran-titration method following standard operating procedures suggested by the Department of Energy (DOE 1998). Dissolved inorganic carbon (DIC) was measured using a coulometer (model CM 5014; UIC Inc., Joliet, Illinois, USA) attached to an automated subsampling system (Sarma 1998). The precise measurements of pH, TA and DIC were ± 0.002, ± 2.0 and ± 1.8 μmol l^{-1}, respectively. Based on the certified reference material (CRM) supplied by Dr A.G. Dickson, Scripps Institute of Oceanography, USA, the accuracy of the measurements of DIC, TA and PH was estimated to be 0.03%, 0.05% and 0.02%, respectively.

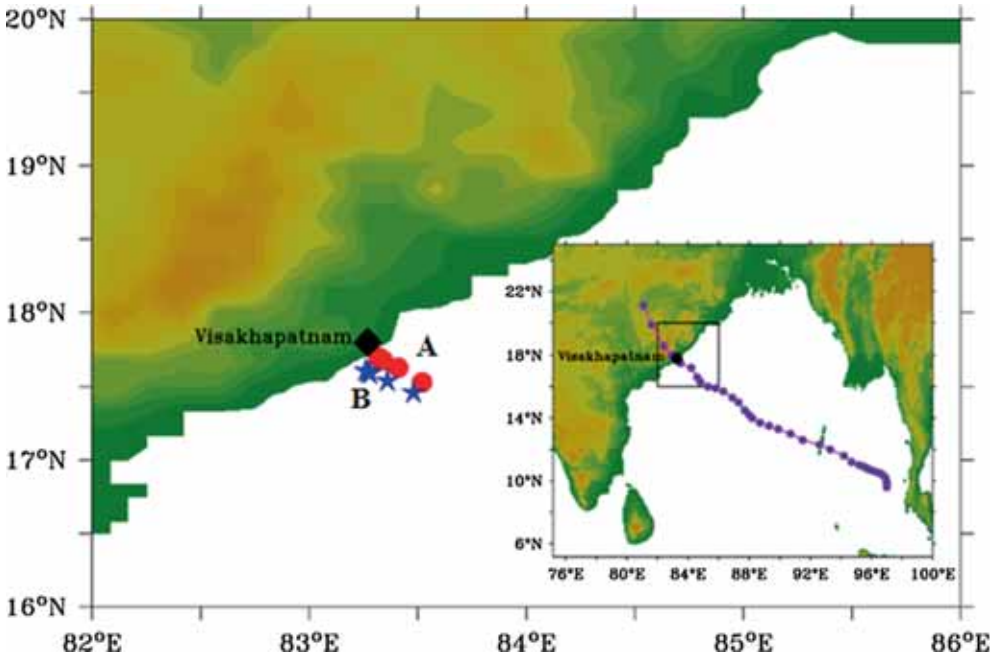

Figure 1. Locations of the stations where sampling was conducted in the coastal Bay of Bengal. The letters A and B denote transect A (red filled circle) and transect B (blue star), respectively. The track of cyclone Hudhud is shown in the inset.

Dissolved N_2O and CH_4 in the water were determined by a multiphase head space equilibration technique (McAuliffe 1971) coupled with gas chromatographic (GC) analysis. A predetermined volume (25 ml) was equilibrated with an equal volume of ultrapure helium in a gas-tight syringe by vigorously shaking the syringe at room temperature for 5 min using a wrist action shaker. After equilibrium, the head space was dried over drierite and removed CO_2 using an ascarite scrubber and then injected through a sampling loop into a gas chromatograph (Agilent 6820, USA) and separated over a chromosorb column (80/100 mesh) at 35°C. N_2O and CH_4 peaks were detected with an electron capture and flame ionisation detector, respectively, in accordance with Jayakumar *et al.* (2001) and Patra *et al.* (1998). The calibrated N_2O and CH_4 gases (Spectra Gases, USA) were used for calibration of GC. The precision of N_2O and CH_4 measurements was <3%.

DMS and total dimethyl sulphoniopropionate ($DMSP_t$) samples were collected into 40 ml amber colour glass bottles to prevent their photochemical decomposition and were analysed using the Agilent 7890 Series GC. The samples were stored in the dark at 4°C until analysis. The storage time never exceeded 4–6 h. Calibration of the instrument was carried out using standard DMSP (Research Plus, Netherlands) solutions. DMS and $DMSP_t$ in the samples were analysed using the purge and trap method (Shenoy 2002). A known volume (sample volume varied from 5 to 20 ml depending on the concentration of DMS) of a seawater sample was purged with ultrapure nitrogen gas (99.9995%) for 15 min. The released gases were trapped cryogenically in a Teflon column in line with a six port valco valve. The trapped gases were injected by inserting the Teflon column into boiling water (temperature >80°C) and switching the valco valve to inject position. The trapped and released gases were then separated over a Chromosil 330 column (Turner *et al.* 1990; Shenoy 2002) and detected using a flame photometric detector (FPD). The DMS was measured first followed by $DMSP_t$. About 2 ml of 10 M NaOH was added to the same samples, after DMS has been analysed, and purged immediately for 20 min to hydrolyse $DMSP_t$ to DMS. This results in the cleavage of $DMSP_t$ to DMS and acrylic acid (Turner *et al.* 1990) and the DMS produced by the cleavage was measured as detailed above. The precision of the DMS measurements was <8%(RSD).

2.3 *Computations*

The pCO_2 was computed using measured salinity, temperature, nutrients (phosphate and silicate), pH and DIC using the CO_2 SYS program (Lewis and Wallace 1998). The CO_2 dissociation constants given by Millero *et al.* (2006) in the 0–40 salinity

range were used. The estimated pCO_2 carries an error of 8 μatm. The solubility of N_2O and CH_4 was computed using in situ temperature and salinity, using coefficients given by Weiss and Price (1980) and Wiesenburg and Guinasso (1979), respectively. Wind speed data from the coastal Visakhapatnam city were obtained from the IMD at Visakhapatnam. The air–water flux of trace gases was estimated using formulations given by Wanninkhof (1992) based on the concentration of gas at the surface, solubility of gas in the surface waters at in situ temperature and salinity and wind speeds measured at 10 m above the sea level.

3. Results and discussion

3.1 *Variations in hydrographic properties in the coastal Bay of Bengal after cyclone Hudhud*

Sarma *et al.* (2018b) discussed the impact of cyclone Hudhud on the upper ocean physical processes, phytoplankton biomass and primary production in the coastal Bay of Bengal using field measurements, satellite data and models. However, we will briefly discuss the changes in the water column properties before and after the cyclone, and the mean variations in temperature, salinity, chlorophyll-a (Chl-a) and nutrients during, before and after Hudhud are given in table 1. For a comparison of the after-cyclone conditions (henceforth called the 'post-cyclone period') with pre-cyclone condition (henceforth called the 'pre-cyclone period'), the data collected during September 2014, 2 weeks prior to the cyclone were used. The satellite SST images evidenced a decrease in surface water by 1–3°C along the cyclone track offshore, whereas the decrease was <1°C close to the coast (Sarma *et al.* 2018b). The weaker cooling close to the coast was attributed to the strong vertical salinity stratification driven by heavy precipitation associated with the cyclone (figure 2). The sea surface height (SSH) was shallower along the cyclone track offshore compared to the outside suggesting that divergence may be possible (Sarma *et al.* 2015a). The existence of a cold core eddy was observed at the study regions during the pre-cyclone period and it was absent during the post-cyclone period due to divergence of waters close to the coast. Waters were relatively cooler and saltier during the pre-cyclone period compared to the post-cyclone period due to the influence of the cold core eddy during the former period (figure 2). The thermal structure along the transect showed upsloping of isotherms towards the coast indicating signatures of upwelling from a depth of 20–30 m during the pre-cyclone period. In contrast, the water column in the upper 75 m was relatively fresher (∼10) and warmer (>1°C) during the post-cyclone than the pre-cyclone period due to the convergence at the coast associated with deeper SSH. The upsloping of isolines during the pre-cyclone period changed to a thick lens of low saline water in the upper surface along both transects (figure 2). The thickness of the fresh water lens decreased offshore.

Relatively higher concentrations of ammonium were observed during the post-cyclone (1.5–3 μM) period compared to the pre-cyclone period (0.2 − −0.5 μM) (figure 3). Such high concentrations of ammonium in the entire coastal water column were attributed to the input through the land-run-off associated with heavy precipitation. In addition to this, ammonium was also added to the coastal water through rainwater and the concentration was as high as 300–500 μM (Sarma *et al.* 2018b). Relatively higher concentrations of nitrite (0.05–0.5 μM) and nitrate (3.4–6 μM) were observed during the post-cyclone period than the pre-cyclone period (<0.15 and <2 μM respectively; figure 3). Despite higher nutrients in the study region, the concentration of Chl-a (figure 2) and the column integrated primary production was low during the post-cyclone period than in the pre-cyclone period due to an increase in turbidity which led to a decrease in light penetration (Sarma *et al.* 2018b).

3.2 *Variations in inorganic carbon components and fluxes of CO_2*

The distribution of DIC followed salinity in the entire water column. Higher DIC concentrations (2035–2138 μM) were observed with upsloping of high DIC contours to the surface during the pre-cyclone period. In contrast, the concentrations of DIC in the upper 20 m along transects A and B decreased to ∼1650 and 1750 μM, respectively, compared to the pre-cyclone period and it is consistent with the salinity distribution (figure 4). Relatively basic waters (higher pH by 0.07–0.15) were observed in the entire water column during the post-cyclone period compared to the pre-cyclone period (figure 4). The

Table 1. *Mean physico-chemical characteristics of the coastal waters before and after the cyclone Hudhud.*

Parameter	September 2014 off Visakhapatnam	October 2014	
		Off Visakhapatnam	Off Atchutapuram
SST (°C)	28.85 ± 0.6	30.02 ± 0.1	30.06 ± 0.1
SSS	31.77 ± 2.0	21.22 ± 1.6	23.29 ± 1.4
Chl-a (mg m^{-3})	0.52 ± 0.1	0.39 ± 0.2	0.18 ± 0.1
Turbidity (mg l^{-1})	6.2 ± 1	10.2 ± 4	18.4 ± 4
NO_3 (μM)	1.8 ± 1	0.79 ± 0.3	4.3 ± 2
NH_4 (μM)	0.2 ± 0.1	1.7 ± 0.7	0.9 ± 1
PO_4 (μM)	2.0 ± 0.5	2.3 ± 0.6	2.2 ± 0.4
SiO_4 (μM)	8.1 ± 2	20.9 ± 2	18.0 ± 2
N:P	3.9 ± 1.0	1.2 ± 0.3	1.4 ± 0.2
Si:N	2.4 ± 0.9	9.3 ± 1.0	4.1 ± 0.8

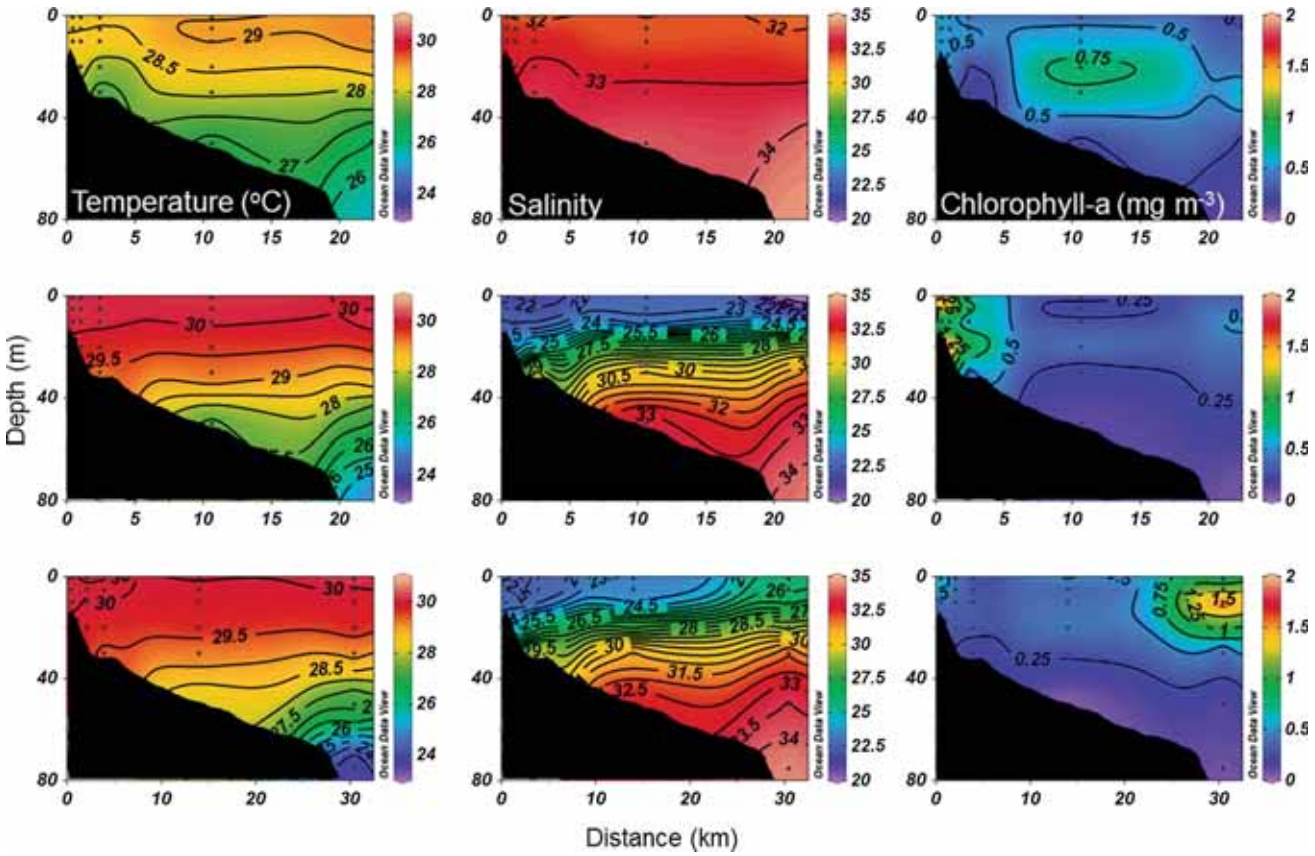

Figure 2. Water column temperature (°C), salinity, and Chl-a (mg m^{-3}) in the coastal Bay of Bengal during the pre-cyclone period (September 2014 in the upper panel), along transect A (middle panel) and transect B (lower panel) during the post-cyclone period.

magnitude of difference in pH between the pre- and post-cyclone periods was higher in the upper 20 m and decreased with depth. Relatively basic pH waters during the post-cyclone period are consistent with higher concentrations of ammonium, suggesting that land-derived sewage might be the potential reason. Upsloping of isolines of TA was noticed during the pre-cyclone period with higher levels (∼2250 μM) than during the post-cyclone period (1900–2000 μM) (figure 4). Land run-off brings significant amount of organic matter and terrestrial bacteria to the coastal Bay of Bengal; however, the decomposition rates may not have increased due to the salinity shock on bacteria (both marine and terrestrial), resulted in a sharp decrease in salinity. Hence, the biological

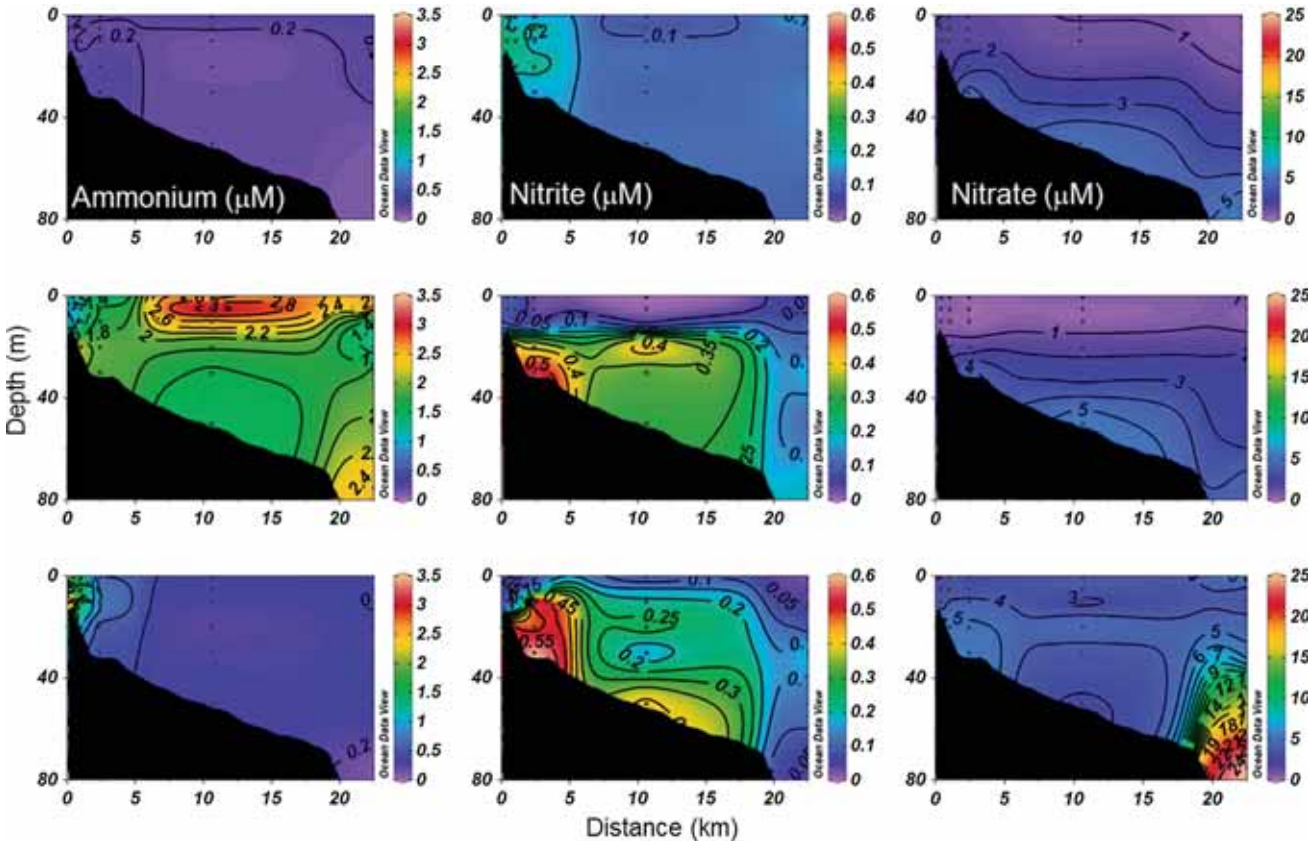

Figure 3. Concentrations of ammonium (μM), nitrite (μM) and nitrate (μM) in the coastal Bay of Bengal during the pre-cyclone period (upper panel), along transect A (middle panel) and transect B (lower panel) during the post-cyclone period.

influence on an inorganic carbon system may be rather minimal. Sewage also brings significant amount of DIC and TA to the coastal Bay of Bengal as their concentrations were higher in sewage (∼9350 and ∼9800 μM, respectively); however, its impact was masked by dilution by the precipitated water which is 4000 times less diluted than sea water. Hence, salinity (S) displayed a strong linear relation with DIC ($40.41S$+804.2; $r^2 = 0.97$; $P < 0.001$) and TA ($34.39S$+1143: $r^2 = 0.96$; $P < 0.001$) and an inverse relation with pH ($-0.022S$+8.882: $r^2 = 0.86$; $P < 0.001$), suggesting that freshwater inputs have significant impact on an inorganic carbon system in the study region. This study indicates that heavy precipitation associated with cyclone Hudhud brought significant changes in the inorganic carbon components and decreased concentrations of DIC, TA and increased pH in the coastal Bay of Bengal compared to the pre-cyclone conditions.

The CO_2 in the surface water was oversaturated with respect to atmospheric equilibrium in the entire study region during the pre-cyclone period (373–510 μatm), except at the offshore region (371 μatm) associated with low salinity (figure 4). These observations are consistent with earlier reports (Kumar *et al.* 1996; Sarma *et al.* 2012, 2015a). A sharp increase in pCO_2 was observed with depth following salinity. In contrast, the CO_2 concentrations were significantly undersaturated in the upper 30 m of the water column during the post-cyclone period along both transects A and B where pCO_2 levels were 150–200 μatm lower than that of the atmospheric levels (figure 4). It was further noticed that pCO_2 levels at deeper depths were also lower during the post-cyclone period compared to the pre-cyclone period due to convergence in the coastal region. Such low pCO_2 in the upper ocean could be due to the increase in pH in response to the increase in ammonium concentrations, resulting in a shifting of the inorganic carbon system towards the formation of bicarbonate, leading to a decrease in pCO_2. On the other hand, a decrease in pCO_2 in the upper 30 m could also be due to the increased flux of CO_2 to the atmosphere due to heavy winds associated with cyclone 'Hudhud'. The measured wind speed ranged from 50 to 100 km h^{-1} during the cyclone.

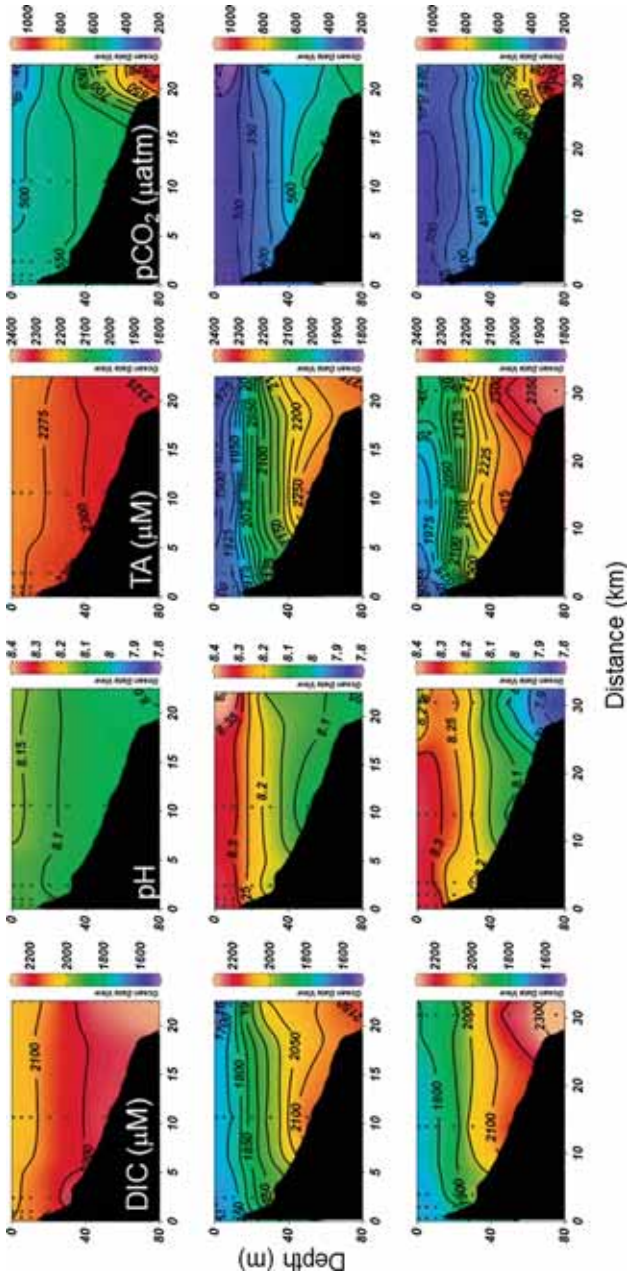

Figure 4. Distribution of DIC (µM), pH, TA (µM) and pCO_2 (µatm) during the pre-cyclone period (upper panel), along transect A (middle panel) and transect B (lower panel) during the post-cyclone period.

Such heavy winds increase piston velocity and thus, the flux of CO_2 to the atmosphere. Bates *et al.* (1998) observed an undersaturation of CO_2 at the Bermuda Atlantic Time-Series (BATS) location in the North Atlantic associated with hurricanes and attributed the enhanced flux to high wind speeds. Enhanced CO_2 fluxes due to Hurricane Irene and Frances were observed in the Atlantic Coast (Huang and Imberger 2010; Crosswell *et al.* 2014). In addition to this, enhanced biological production due to increased nutrient levels may contribute to the understaturation of CO_2. Sarma *et al.* (2018b) noticed that the depth integrated phytoplankton biomass and primary production to the photic zone did not increase in the study region after the cyclone compared to those before the cyclone and attributed it to the inhibition of light due to increased turbidity. Therefore, a decrease in pCO_2 may not be due to biological production.

In order to examine the dominant controlling process on pCO_2 variability during the post-cyclone period, the contribution of pCO_2 change due to flux and salinity dilution was computed. Salinity showed a linear relation with pCO_2 in the study region (figure 5). The regression analysis suggested that a decrease in salinity by one unit reduced the pCO_2 levels by 22.4 µatm. Compared to pre-cyclone conditions, salinity decreased by 8 units after the cyclone; therefore, it contributes to a decrease in pCO_2 by 179 µatm due to dilution, compared to the pre-cyclone period. Based on a pCO_2 level during the pre-cyclone period of ∼471 µtam (average pCO_2 during September 2014), mean mixed layer depth during September 2014 (∼12 m) and mean wind speed of 8.3 km h^{-1}, the flux of CO_2 to the atmosphere between 25 September 2014 and 11 October 2014 (pre-cyclone period observation to 1 day before cyclone 'Hudhud') was computed to be 40 µatm. Therefore, the resultant pCO_2, after removing the effects of dilution and removal to the atmosphere, would be expected to be 252 µatm (471 − (179 + 40) µatm), which is slightly lower than that of the measured pCO_2 of 274 µatm. At the same time, this study suggests that a decrease in pCO_2 after the cyclone was contributed to the dilution with precipitated water (80%) and that the impact of the sea-to-air flux was relatively small due to strong stratification that inhibits the mixing of the pCO_2-rich subsurface water with the surface. The sea-to-air flux of CO_2 was 1.3 ± 0.5 mmol C m^{-2} d^{-1} during the pre-cyclone period and it turned negative (−1.8± 0.9 and −2.2± 1 mmol C m^{-2} d^{-1} along transect A and B, respectively) after the cyclone. This study suggested that the freshwater input to the coastal Bay of Bengal due to heavy rainfall derived by cyclone and land run-off enhanced concentrations of ammonium and increased pH between 0.07 and 0.15 units that led to the undersaturation of CO_2. As a result, this region, which was previously a significant source of CO_2 to the atmosphere, turned into a sink after the cyclone 'Hudhud'.

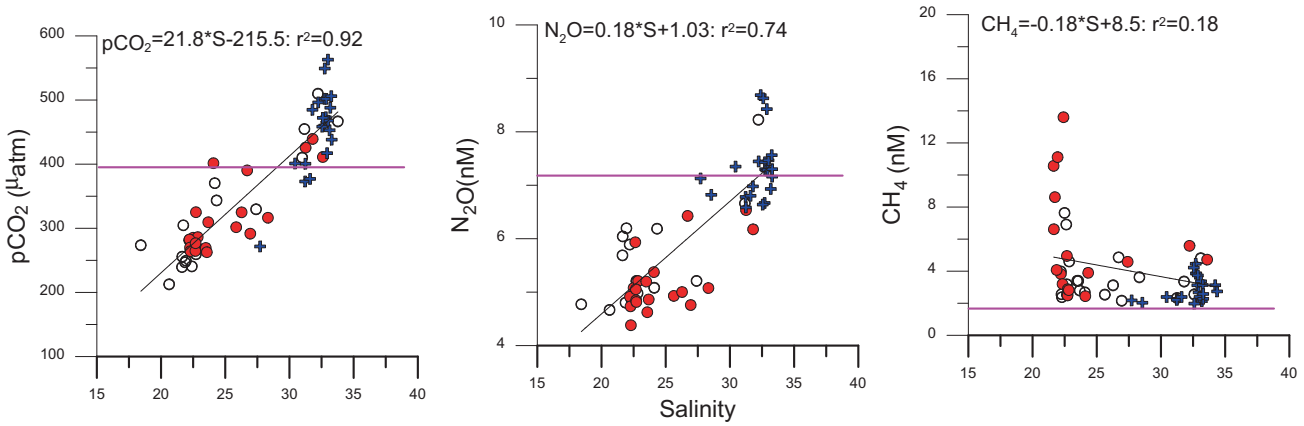

Figure 5. Relation of pCO_2, N_2O and CH_4 with salinity during both the pre- (blue) and post-cyclone periods (transect A: red closed circles and transect B: open circles). The horizontal line (pink) denotes atmospheric value.

3.3 *Variations in concentrations of nitrous oxide (N_2O) and its fluxes*

The concentrations of N_2O ranged between 6.0 and 7.7 nM during the pre-cyclone period and its saturation varied from 113% to 138% at the surface (figure 6). The concentrations of N_2O increased with depth and its saturation reached >300% at a depth of 75 m. Similar to pCO_2, the concentrations of N_2O decreased by >2 nM in the upper 30 m of the water column during the post-cyclone period along both transects compared to the pre-cyclone period. Relatively lower concentrations of N_2O (by about 1 nM) were observed along transect B than transect A which was associated with higher ammonium concentrations along the former than the latter transect (figure 3). The concentration of N_2O below 40 m was relatively higher during the post-cyclone than the pre-cyclone period and it was associated with higher salinity. Salinity showed a linear relation with N_2O concentrations ($r^2 = 0.76$;pg $P < 0.001$; figure 5) suggesting that salinity controlled their concentrations in the coastal Bay of Bengal. There are two possible mechanisms responsible for the production of N_2O in the marine waters, and they are nitrification and denitrification. Since the coastal waters are well ventilated and oxygen concentrations are high (>200 μM at the surface and ∼50 μM at 75 m; Sarma *et al.* 2018b), denitrification may not be triggered (Sarma *et al.* 2013, Rao *et al.* 1994). Hence, nitrification is solely responsible for N_2O production in the study region. In our study region, a sharp decrease in salinity in the coastal waters associated with heavy precipitation decreased the activity of bacteria due to salinity shock. Fernandes *et al.* (2008) noticed that freshwater bacteria received by various rivers were inactive in the Bay of Bengal due to salinity shock. del Giorgio and Bouvier (2002) observed a decrease in growth and possible loss of activity of bacteria in the fresh- to salt water transition. This would result in a decrease in nitrification rates and production of N_2O and it is consistent with the decrease in nitrification at low salinity (Rysgaard *et al.* 1999; De Bie *et al.* 2002; Megalhaes *et al.* 2005; Bange 2006, Aslan and Simsek 2012; Rao and Sarma 2013). In addition to this, lower N_2O concentrations were observed in the sewage waters (1–2.5 nM) due to possible occurrence of denitrification as near anoxic conditions exist in the sewage. Therefore, a decrease in salinity due to heavy precipitation and land run-off associated with the cyclone might have decreased the nitrification rates and diluted with low N_2O waters that resulted in the lower concentrations of N_2O in the coastal Bay of Bengal.

The entire water column was supersaturated with N_2O (>120%) during the pre-cyclone period in the upper 50 m, suggesting that the study region acted as a strong source of N_2O to the atmosphere (figure 6). In contrast, the undersaturation of N_2O was noticed during the post-cyclone period in the upper 30 m, suggesting that this region became a sink for the atmospheric N_2O. On the other hand, waters below 40 m were relatively more saturated after the cyclone than in pre-cyclone period, suggesting that a greater production of N_2O may be linked to higher ammonium concentrations observed in the study region during the post-cyclone period. Though the

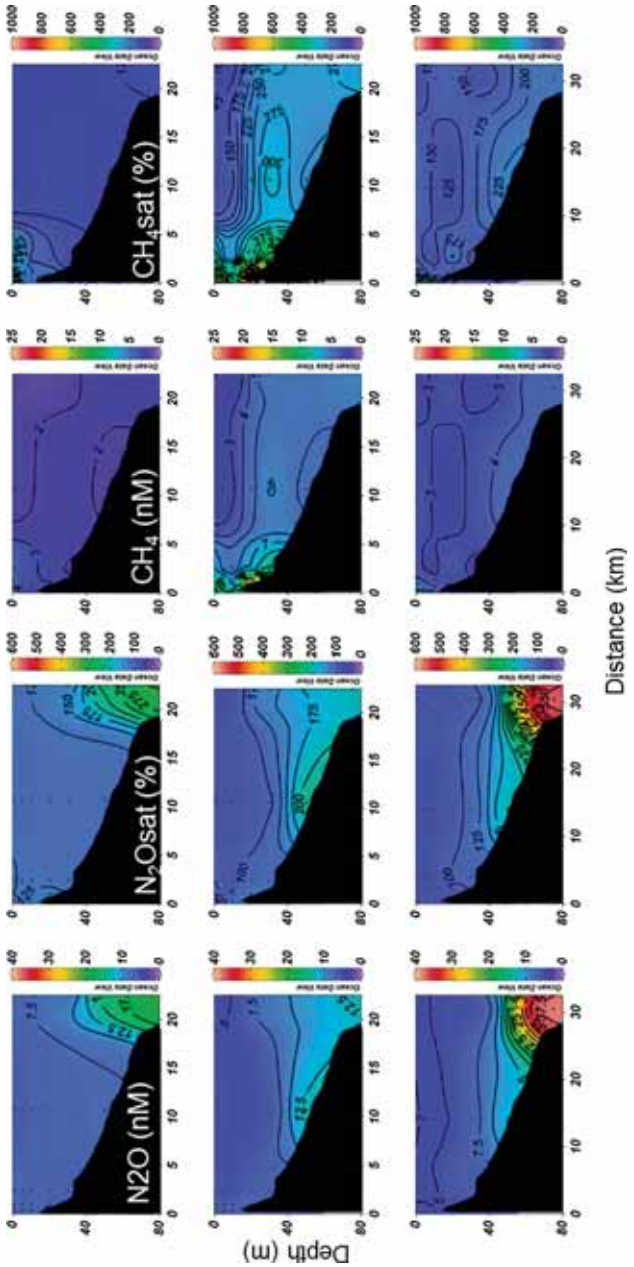

Figure 6. Distribution of concentration of N_2O (nM), its saturation (%), CH_4 (nM) and its saturation (%) during the pre-cyclone period (upper panel), along transect A (middle panel) and transect B (lower panel) during the post-cyclone period.

concentration of ammonium increased in the entire water column due to the land run-off associated with the cyclone, low salinity in the upper ocean did not favour intense nitrification due to a decrease in bacterial activity. In addition to this, the concentration of N_2O in the sewage was undersaturated (75–96%) due to the denitrification that resulted from the anoxic conditions. Hence, sewage did not contribute significant amount of N_2O to the coastal Bay of Bengal. Therefore, the variations in N_2O concentrations and saturation between the pre- and post-cyclone periods were contributed by a decrease in salinity and also the rapid removal of N_2O to the atmosphere associated with heavy winds.

In order to examine the influence of salinity and winds, the contribution of these two processes is evaluated. Based on the relationship between salinity and N_2O concentration, it was observed that 0.18 nM of N_2O decreased with a decrease per unit of salinity (figure 5). About eight units of salinity decreased after the cyclone compared with pre-cyclone conditions and would lead to a decrease in N_2O concentrations by ∼1.4 nM due to the lowering of salinity. The flux of N_2O to the atmosphere was computed using pre-cyclone N_2O concentrations and mean wind speed of 8.3 km h^{-1} before the cyclone. It was observed that the sea-to-air flux removed 0.9 ± 0.4 nM of N_2O to the atmosphere from the surface waters. The mean concentration of N_2O in the surface waters during the pre-cyclone and post-cyclone periods was 7.1 ± 0.6 and 5.3 ± 0.7 nM, respectively, suggesting that ∼2.0 nM of N_2O was decreased during the latter period. It is suggested that about 80% of the decrease in N_2O after the cyclone was contributed by freshwater dilution and associated with a decrease in nitrification. The flux of N_2O at the air–water interface suggests that the study region acted as a significant source of N_2O to the atmosphere during the pre-cyclone period (0.9 ± 0.3 μmol m^{-2} d^{-1}), but as a sink (−0.2± 0.1 and −0.6 ± 0.2 μmol m^{-2} d^{-1} along transects A and B, respectively) after cyclone due to the decrease in salinity and nitrification rates.

3.4 *Variations in concentrations of methane (CH_4) and its fluxes*

The concentration of CH_4 ranged between 1.8 and 6.1 nM during the pre-cyclone period and its saturation varied from 114% to 532% in the water column (figure 6). The concentration of CH_4 increased with depth with the maximum at the mid-waters (∼30 m) during both pre- and post-cyclone periods, associated with a sharp salinity gradient. This subsurface maximum is more prominent during the post-cyclone than the pre-cyclone period. The concentration of CH_4 was significantly higher during the post-cyclone period associated with relatively low salinity (figure 2). Unlike pCO_2 and N_2O, the concentration of CH_4 increased in

the water column after the cyclone (by 0.5–2.8 nM) compared to the pre-cyclone period (figure 6). A relatively higher concentration (by about 2 nM) was observed along transect B than transect A which is associated with higher ammonium concentrations. A concentration below 40 m was relatively higher during the post-cyclone than the pre-cyclone period and was associated with lower salinity. The concentration of CH_4 in the sewage was an order of magnitude higher than in the coastal waters ($\sim$500 nM). The salinity to the CH_4 relationship (figure 5) shows higher variability in concentrations of CH_4 at a lower salinity ($<$25) suggesting that the land drainage could be a potential source of CH_4 to the coastal Bay of Bengal. The higher concentration of CH_4 at deeper depths could be due to the diffusion of CH_4 from the benthic boundary layer. This gas, however, did not diffuse to the surface due to the strong vertical stratification leading to accumulation in the subsurface layer, resulting in higher concentrations (figure 2).

The water column was above saturation in CH_4 with reference to that at surface, in equilibrium with the atmospheric CH_4 during the pre-cyclone period (114–130%) and it increased to 140–200% after the cyclone (figure 6). The super-saturation of CH_4 increased with depth (up to 700%), suggesting that sediments may be a strong source of CH_4 as the production of CH_4 in the sediments was reported (Araujoe *et al.* 2018) and its further diffusion to the surface waters is possibly hindered by strong stratification. The saturation of CH_4 in the water column was relatively higher along transect A than B as the former transect is close to the urban region of Visakhapatnam city while the latter is close to the rural region. Hence, more sewage associated with the land-fall was expected at transect A than B, resulting in a higher concentration of CH_4 in the former than the latter. It was further confirmed by higher concentrations of ammonium as observed along the transect A than B (figure 3). It would be difficult to understand the source of CH_4 (in situ production or sewage) due to the lack of isotopic data in this study. The flux of CH_4 at the air–water interface suggests that the study region acts as a mild source of CH_4 to the atmosphere during the pre-cyclone period (0.6 ± 0.3 μmol m^{-2} d^{-1}) that turned into a significant source (1.9 ± 1 and 1.3 ± 0.8 μmol m^{-2} d^{-1} along transects A and B, respectively) after the cyclone Hudhud (table 1).

3.5 *Variations in concentrations of DMS and $DMSP_t$ and fluxes*

During the pre-cyclone period, the concentrations of DMS and $DMSP_t$ were in the ranges of 8.8–33.5 and 2.0–28.3 nM, respectively (figure 7) and decreased significantly after cyclone 0.4–3.9 nM (DMS) and 0.2–6.0 nM ($DMSP_t$) respectively. Both DMS and DMSP are produced through biological processes such as microbial activity or the bacterial conversion of DMSP to DMS, and microzooplankton grazing of particulate DMSP. The lower concentrations of DMS and DMSP after the cyclone are mainly caused by a decrease in phytoplankton biomass as evidenced from Chl-a (figure 2). Furthermore, a decrease in DMS and $DMSP_t$ during the post-cyclone period could also be due to the dilution of coastal waters with fresh water from the land-drainage which contains no DMS/DMSP. The strong linear relationships of DMS and $DMSP_t$ with salinity suggest the role of the dilution of freshwater in their distribution in the coastal waters of the Bay of Bengal (figure 8). The concentrations of DMS and $DMSP_t$ were relatively lower along transect A compared to transect B and it is consistent with the concentrations of Chl-a (figure 2) suggesting that higher phytoplankton biomass is responsible for the increased production of DMS along the latter transect. Though Chl-a concentration was not significantly higher during the pre-cyclone period compared to the post-cyclone period, lower DMS and DMSP during the post-cyclone period might have been caused by the dilution with land drainage (figure 2). The production of DMSP within the plankton's cell and the subsequent release of DMS would depend on a variety of factors such as phytoplankton species composition (Liss *et al.* 1997), physico-chemical parameters (salinity and temperature), microbial community (Taylor and Gilchrist 1991) and DMSP lyase activity (Steinke *et al.* 2002). Phytoplankton composition was dominated by diatoms during the pre-cyclone period, whereas picoplankton (cyanobacteria) was abundant during the post-cyclone period. The production of DMS by phytoplankton is species dependent (Turner *et al.* 1988). For instance, the high DMS concentrations were associated with the high abundance of DMSP-producing phytoplankton groups (prymesiophytes and dinoflagellates) over diatoms and cyanobacteria as the latter have relatively low intracellular DMSP concentrations compared to the former. Shifts in plankton speciation were also

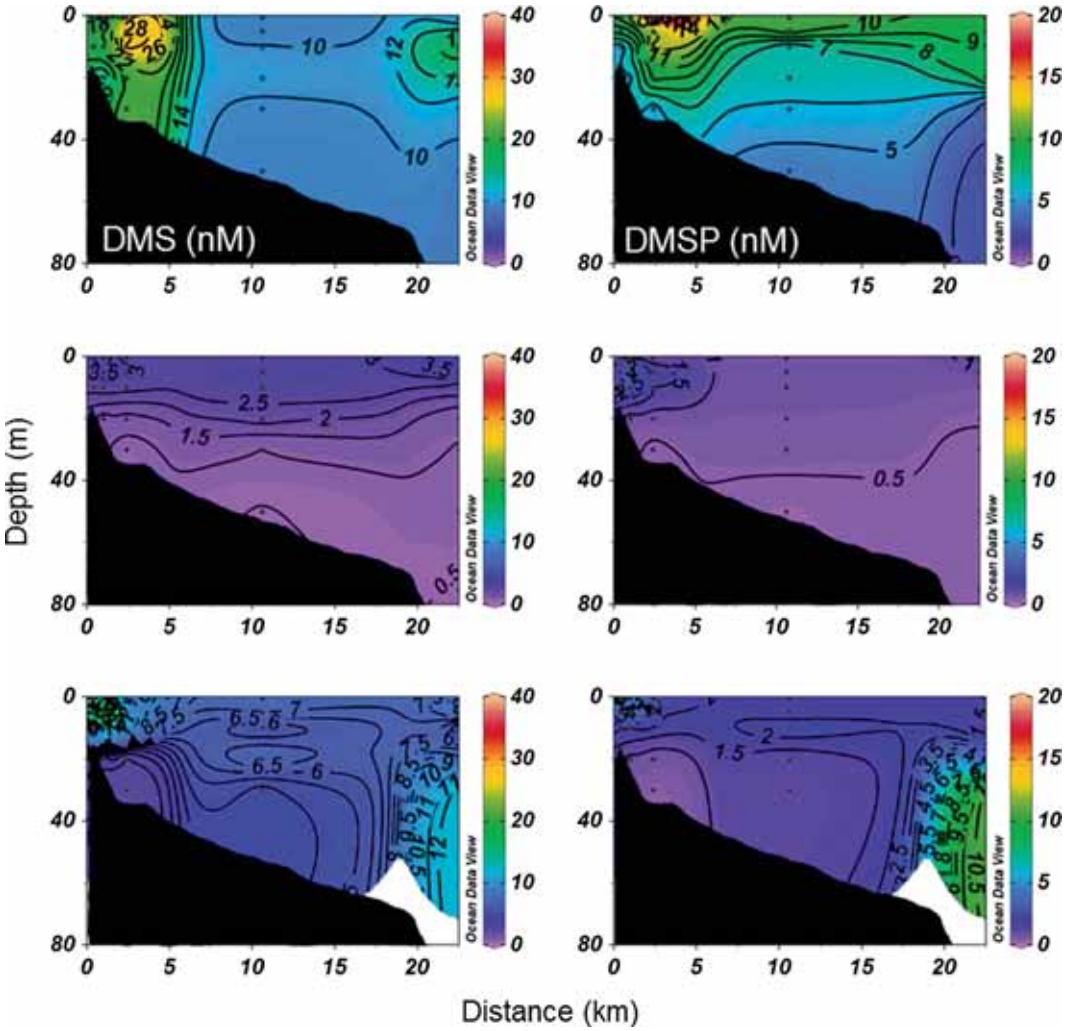

Figure 7. Distribution of DMS (nM) and DMSP (nM) during the pre-cyclone period (upper panel), along transect A (middle panel) and transect B (lower panel) during the post-cyclone period.

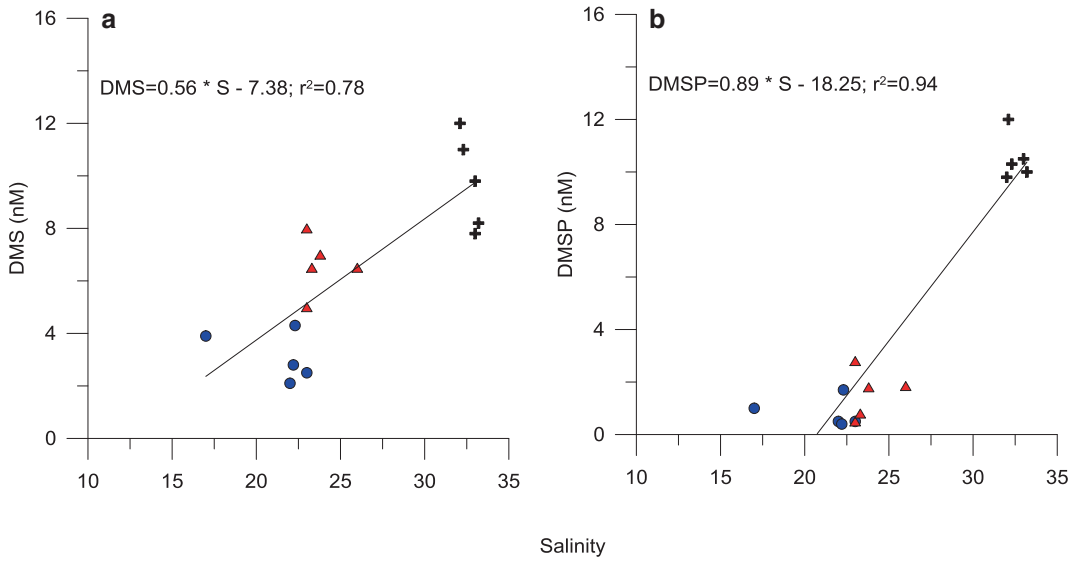

Figure 8. Relationship of DMS and DMSP with salinity during the pre- (black) and post-cyclone periods (transect A – red triangle and transect B – blue circles).

noticed in association with modifications in the concentrations and ratios of nutrients (Lancelot *et al.* 1987; Mee 1992; VandenBerg *et al.* 1996). Significant modification in the concentrations and the ratio of nutrients were observed between the pre- and post-cyclone periods (table 1; Sarma *et al.* 2018b). In addition to this, microzooplankton grazing of particulate DMSP and bacterial conversion to DMS is also responsible for the variations in the concentrations of DMS and $DMSP_t$ (Jones *et al.* 1998; Stefels *et al.* 2007). We have not measured zooplankton grazing during this study; hence are not able to confirm the possible mechanism responsible for lower DMS and $DMSP_t$ after the cyclone 'Hudhud'. In addition to this, a lower concentration of DMS and $DMSP_t$ after cyclone Hudhud could also be due to the higher suspended particulate matter and low Chl-a concentration as the former decreased the light availability, resulting in low production of DMS and $DMSP_t$. Therefore, the dilution of low DMS/DMSP waters from the precipitation, a decrease in production due to increased suspended load and also variations in the composition of phytoplankton might have contributed to lower DMS/DMSP concentrations during the post-cyclone period compared to pre-cyclone conditions.

The flux of DMS at the air–water interface suggests that the study region which acts as a strong source of DMS to the atmosphere during the pre-cyclone period (5.8 ± 3 μmol m^{-2} d^{-1}), turned into a mild source (1.2 ± 0.5 and 3.8 ± 2 μmol m^{-2} d^{-1} along transects A and B respectively) after the cyclone 'Hudhud'.

4. Summary and conclusions

In order to examine the influence of the very severe cyclonic storm Hudhud on the concentrations and fluxes of trace gases such as CO_2, N_2O, CH_4 and DMS to the atmosphere, a study was conducted in the coastal Bay of Bengal, and the results were compared with the pre-cyclone period measurements. The study region received nutrients through upwelling during the pre-cyclone period and the same was suppressed due to the cyclone 'Hudhud'. High precipitation associated with the cyclone brought land-derived nutrients such as ammonium that increased the pH of the coastal waters. In contrast, the inorganic carbon components (DIC, TA and pCO_2) were significantly low during the post-cyclone period compared to their measurements during the pre-cyclone period. The concentrations of N_2O also decreased during the post-cyclone period compared to the pre-cyclone period, and this was attributed to the decrease in nitrification due to low salinity and lower concentrations of N_2O in the sewage waters. The relation of pCO_2 and N_2O with salinity suggested that about 80% of the decrease is attributable to the dilution with rain water and the remaining, to enhanced gas fluxes in the atmosphere by the cyclonic winds. In contrast, CH_4 concentrations were significantly higher during the post-cyclone than the pre-cyclone period due to the input of anthropogenic CH_4 through land run-off. The DMS and $DMSP_t$ concentrations decreased during the post-cyclone in comparison with the pre-cyclone period and it is consistent with low phytoplankton biomass during the former than the latter. Due to a lack of isotopic data, the process responsible for higher concentrations of CH_4 could not be unequivocally explained in this study. This study suggests that the very severe cyclonic storm Hudhud changed the magnitude of trace gas emissions from a significant source to sink, except CH_4, in the coastal Bay of Bengal in contrast to the existing belief.

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