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# Tide induced annual variability of selected physico-chemical characteristics in the northern Bay of Bengal (nBoB) with a Special emphasis on Tropical Cyclone-Phailin, 2013.

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Daily monitoring (in the day time) of sea surface temperature (SST), sea surface salinity (SSS), pH and weekly measurement of dissolved oxygen (DO) were carried out in the northernmost sector of the Bay of Bengal for the first time, covering roughly an area of ~750 sq. km throughout an annual cycle from 1st June, 2013 to 31st May, 2014. SSS, pH and DO maintained a higher and lower value during the highest high tide (HHT) and lowest low tide (LLT) hours respectively, throughout the year, except in some weeks of monsoon. But SST did not follow any such type of tide influence trend. The strong physical forcing and high energy tidal surges caused by the tropical cyclone (Phailin) increased the SSS, pH and DO by 33.11%, 3.73% and 40% respectively. In contrast, a massive cooling in SST by 15.38% was observed. Though SST returned to normal range within one week, DO and SSS took almost 10 days to reach equilibrium. However, tropical cyclone poses a short term strong impact on the physico-chemical properties and ecology of the shallow continental shelf coastal water.

**[Key words:** Tidal influence, physico-chemical parameters, shallow continental shelf, Phailin]

## Introduction

The shallow continental shelf coastal waters are one of the most fluvial-dynamic ecological systems which undergo incessant natural erosion and accretion at the mouth of the open sea. These zones receive the daily tidal floods and river run-off, while wind and waves bring frequent alteration to the shoreline, which in turn influences the overall ecology of that region[1]. In the Indian context, the coast line of northern Bay of Bengal lying adjacent to the Sundarban mangrove forest has a wide and shallow continental shelf with very low bathymetric depth up to almost 60 km from the shoreline[2]. This region receives a huge supply of freshwater from the main channel of River Hugli[3]. Apart from this, the Bay also experiences heavy precipitation during the summer monsoon[4] and characterized by an intense semidiurnal tide of meso-macrotidal nature (2.5 – 7 m)[5].

Another crucial climatic phenomenon that frequently takes place in this Bay are the tropical cyclones (TC). On an average, the Bay of Bengal (BoB) experiences four tropical cyclones (TCs) in each year, which accounts for ~5% of the total annual TC numbers worldwide[6]. Previous studies also reported that out of the top twenty deadliest TCs in the world history, fourteen took place in the BoB[7]. These calamitous events usually originate in the Bay of Bengal during the summer (April-May) and fall (October-November) inter-monsoon[8]. TCs cause catastrophic damage to life and property in the coastal states of India and the neighboring country, Bangladesh[9].

However, higher SST was reported to be one of the crucial parameters for the origin and strengthening processes of TC[10, 11]. The associated stronger winds of TC result in deepening of mixed layer (ML). Deepening of ML leads to cooling of sea surface by several degrees after TC passage[12, 13] and increased sea surface salinity[14].

The variability of the basic physico-chemical parameters like sea surface temperature (SST), sea surface salinity (SSS), pH and dissolved oxygen (DO) is very crucial from the perspective of biogeochemical cycling and existence of various flora and fauna in these coastal waters. The continental shelf waters of nBOB represent a transition zone between an estuary and an open sea. In such transition zone, turbid, nutrient rich river discharge mixes with the relatively clear, nutrient poor ocean water[15,16]. This mixing gives rise to a wide continuum of salinity throughout the entire stretch of the transition zone[17]. Apart from the mixing effect, the SSS also experiences a diurnal variation due to the effect of tides. Similarly the daily fluctuation of pH could be regulating by the tide duration and season in the estuary[18]. Like pH and SSS, the distribution of dissolved oxygen (DO) is dependent on the tides too (http://www.ozcoasts .gov.au/indicators/dissolved_oxygen.jsp)[19]. Moreover, DO is known to play an important role on the physical and chemical processes in sea water[20]. However, tidal waters that flow in and out of these transition zones support a wide diversity of living resources, including several invertebrate communities, zooplankton, phytoplankton and so forth[21]. Despite widespread recognition that tidal waters provide essential ecological services, the short-term variability and longer-term spatial and temporal changes in estuarine water parameters are still inadequately studied in most of the estuaries and adjoining shelf waters throughout the globe[22, 23].

With respect to the above mentioned scarcity in data, the present research was framed to study the variation of some basic physico-chemical parameters with varying tidal pool in the continental shelf waters of nBOB. The objectives of the present study were to i) monitor the variation of SST, SSS, pH and DO in the highest high tide (HHT) as well lowest low tide (LLT) hours throughout an annual cycle (June, 2013 to May, 2014) during the day time only and to ii) examine the variability of physico-chemical parameters before and after the cyclones that passes in vicinity of this study area.

## Materials and methods

### Study area

The present study has been conducted in the northernmost part of the Bay of Bengal lying adjacent to the Sundarban Delta (Fig. 1). This tropical basin receives enormous amounts of freshwater by river discharge that peaks during the monsoon[24, 25]. The Hugli estuary is a tributary of river Ganges and acts as the main artery of the Indian part of the Sundarban mangrove ecosystem. This estuary is drained by the freshwater flow from the Farakka barrage situated 286 km upstream from the river confluence[26]. There are several other distributaries like (from west to east) the rivers Muriganga, Saptamukhi, Thakuran, Matla, Gosaba and Bidya which have further aided the delta formation. This region is a ‘‘well-mixed’’ estuary characterized by an intense semidiurnal tide of meso-macrotidal nature (2.5–7 m) having mean current velocities range between 117 cm $s^{-1}$ and 108 cm $s^{-1}$ during low and high tide respectively[5]. In addition to this, the study site is also affected by episodic events, such as heavy precipitation associated with cyclones, land drainage and seasonal coastal upwelling etc[27].

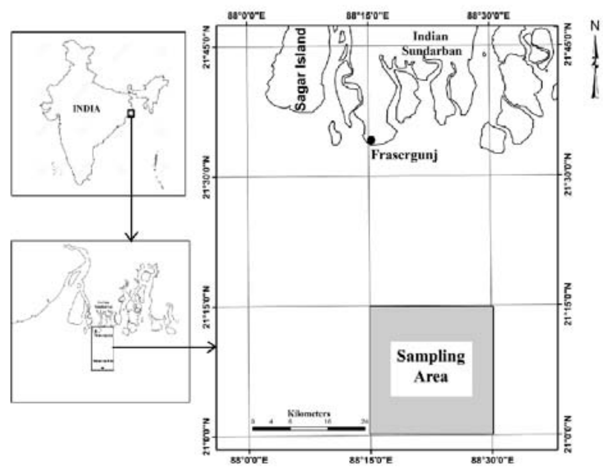


Fig. 1—Study site showing the sampling area

### Sampling strategy

Daily measurement of SST, SSS, pH and weekly monitoring of DO were done throughout the annual cycle from June 2013 to May 2014 by availing local fishing trawlers from the Frasergunje Harbour. The entire sampling was conducted within the latitudinal extent of 21° 15' 00’’ N and 21° 00' 00’’ N and longitudinal extent of 88° 15' 00’’ E and 88° 30' 00’’E respectively, covering roughly an area of ~750 sq. km (Fig. 1). SST, SSS and pH were measured every day during the highest high tide (HHT) and lowest low tide (LLT) hours according to the Sagar Island Tide table[28] of the daytime only. However, in the 2$^{nd}$ week of October, i.e. 7$^{th}$ to 14$^{th}$ October; 2013, the sampling could not be done due to the tropical cyclone (TC) ‘Phailin’. All through the annual cycle DO was measured at weekly intervals. Moreover, DO was measured daily for 16 days (16$^{th}$ Oct to 31$^{st}$ Oct, 2013) in the post-Phailin period to characterize Phailin’s impact. All the water samples were collected in 300-ml BOD bottles a few centimeters below the water surface and the physico-chemical parameters were immediately analyzed on board.

### Analytical protocol

SSS was measured using a Multikit (WTW Multi 340 i Set; Merck, Germany) fitted with the probe WTW Tetracon 325. DO was measured by using Winkler's titrimetric method. pH and SST were measured instantaneously with a micro-pH meter (pH 620; Eutech Instruments, Singapore) having a precision of 0.001 pHu. The glass electrode for pH measurements were calibrated daily in the NBS scale with technical buffers of pH 4.01 (Part no: 1.09475.0500; Merck), pH 7 (Part no: 1.09477.0500; Merck) and pH 9.0 (Part no: 1.09476.0500; Merck) at a controlled temperature of 25ºC. The pH readings taken on-board at the respective temperatures were corrected for the standard temperature of 25ºC. All data were expressed in terms of mean ± SD (standard deviation). The Pearson correlation coefficient (*r*) was computed between corresponding physico-chemical parameters using SPSS 16.0, USA.

## Results and discussion

### Seasonal variation of SST

The SST during the sampling period varied over a range of ~24.1°C to ~32.7°C. The maximum mean monthly SST was recorded to be 30.9 ± 0.9°C in the month of May while the minimum mean value was 24.4 ±0.2 in February (Fig. 2a). A slight decrease in the mean monthly SST was observed from June to August, which might be due to the effect of monsoon rain. However, a sharp consistent decline in the SST was observed from the month of September to January through the winter months. This change could be solely attributed to the decline in the ambient temperature as the winter approached. Again from February onwards, the SST showed an increasing trend. We measured the SST in HHT and LLT hours, however, no significant tidal variation was observed on the SST throughout the annual cycle. Mitra *et al*[8], while working in the lower Gangetic delta region had a similar observation. The high specific heat capacity of water is the principal reason behind such uniformity in the short term interval of SST and it protects the aquatic biodiversity from any drastic thermal shock[8]. Since the phytoplankton diversity is primarily regulated by the SST[29], their community structure and composition is least likely to get disturbed due to sudden changes in SST.

### Tide induced daily and seasonal SSS variability

The SSS values ranged from 11.1 to 34.2 ppt during HHT and 8.2 to 34.0 ppt during LLT throughout the annual course of sampling. A significant seasonal variability in SSS was observed. The SSS values (mean of HHT and LLT) were highest in the pre-monsoon season (29.4 ± 1.5 ppt) followed by the post-monsoon season (26.0 ± 4.6 ppt). The least was observed during the monsoon months (20.9 ± 6.2 ppt).

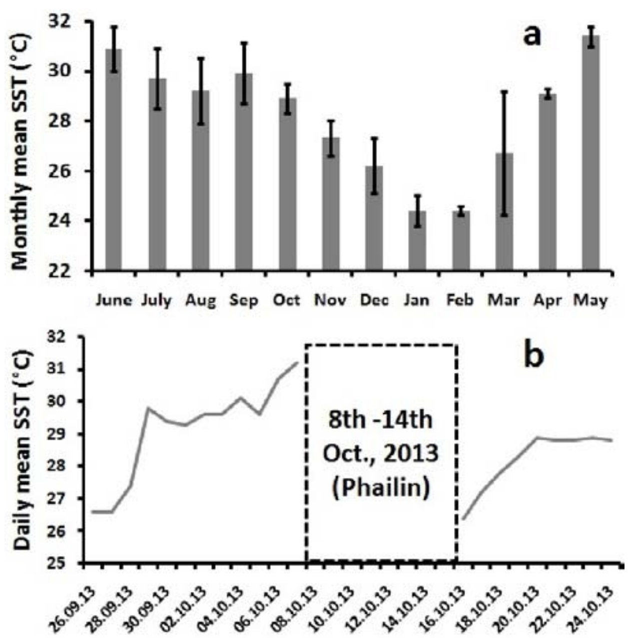


Fig. 2─(a) Monthly mean sea surface temperature (SST) throughout the annual cycle and (b) daily mean SST before and after the cyclone Phailin

It is noteworthy that in the monsoon season, maximum standard deviation in SSS was observed as the SSS varied over a large range during this season (8.2 to 32.3 ppt). The rainfall in this region does not occur uniformly throughout the monsoon season; instead it happens in an intermittent and erratic fashion which is responsible for such a range of SSS. The lower values of SSS is mainly due to the dilution effect driven by the pouring of salinity free rain water and enhanced freshwater discharge from the perennial rivers upstream, while during the non-rainy sessions, the SSS remained on the higher side. SSS had significant tidal variation in all the three seasons. During high tide, water mass from the Bay of Bengal (average salinity ~32 ppt) dominates in this transition

Table 1—Seasonal mean (±SD) of SSS, pH and DO of nBoB

| | SSS | | pH | | DO | |
|---|---|---|---|---|---|---|
| Season | HHT | LLT | HHT | LLT | HHT | LLT |
| Monsoon* | 22.2 ± 6.0 | 19.6 ± 6.5 | 8.238 ± 0.097 | 8.083 ± 0.102 | 5.3 ± 0.3 | 5.2 ± 0.4 |
| Post-monsoon | 27.1 ± 4.6 | 24.9 ± 4.8 | 8.430 ± 0.126 | 8.301 ± 0.138 | 5.9 ± 0.5 | 5.7 ± 0.6 |
| Pre-monsoon | 30.1 ± 1.6 | 28.6 ± 1.5 | 8.404 ± 0.096 | 8.294 ± 0.115 | 5.7 ± 0.5 | 5.4 ± 0.6 |

*Monsoon = June, July, August and September; Post-monsoon = October, November, December and January; Pre-monsoon = February, March, April and May

zone due to which the SSS rises[9]. However, during low tide the effect of fresh water discharge from the upstream rivers coupled with Farakka discharge lowers the SSS of the study area[3]. The maximum difference in seasonal mean SSS during HHT and LLT was observed during the monsoon season, while the minimum was found in the pre-monsoon season (Table 1). In the summer months of the pre-monsoon season the ambient temperature as well as the SST remains fairly high which leads to the predominance of evaporation effect over the effect of precipitation. Hence due to excess evaporation, the SSS during low tide remains quite high and thus the difference between HHT and LLT diminishes. The daily data of SSS (during HHT and LLT hours) throughout the annual cycle is graphically represented in Fig. 3a. Fig. 4a illustrates the mean monthly SSS along with the difference between HHT and LLT hours.

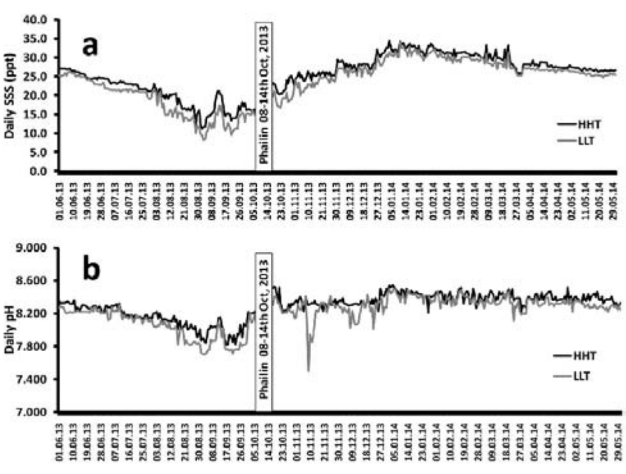


Fig. 3—Daily a) SSS and b) pH during the highest high tide (HHT) and lowest low tide (LLT) hours throughout the annual cycle

## Tidal effect on daily and inter-annual mean pH

Unlike SSS, pH varied over a narrow range from 8.014 to 8.597 during HHT and 7.497 to 8.504 during LLT. Between the pre-monsoon (8.349 ± 0.104) and post-monsoon season (8.365 ± 0.131), the pH did not show any significant variation, however, during the monsoon (8.160 ± 0.099) it was significantly lower than the other two seasons. The effect of tide in the variation of pH held true for the entire period of sampling (Table 1). Like SSS, the pH values were also relatively higher during the HHT and vice-versa. SSS and pH showed a significant correlation all through the year ($r = 0.819$, $p < 0.01$ during HHT; $r = 0.710$, $p < 0.01$ during LLT) under normal circumstances, the river and estuarine water carries heavy organic load from the runoffs of adjacent catchment area which reduces the pH of the aquatic medium. On the contrary the pH of the open sea water remains uniformly high. The higher values of pH during HHT are mainly due to the intrusion and dominance of sea water over riverine flow, while the reverse scenario prevailed during the LLT. The difference in seasonal mean pH between HHT and LLT followed the trend of SSS. Maximum difference was observed during the monsoon (Fig. 4b). The same attributes leading to maximum difference in SSS are responsible in case of pH also. The daily data of pH (during HHT and LLT hours) throughout the annual cycle is graphically represented in Fig. 3b.

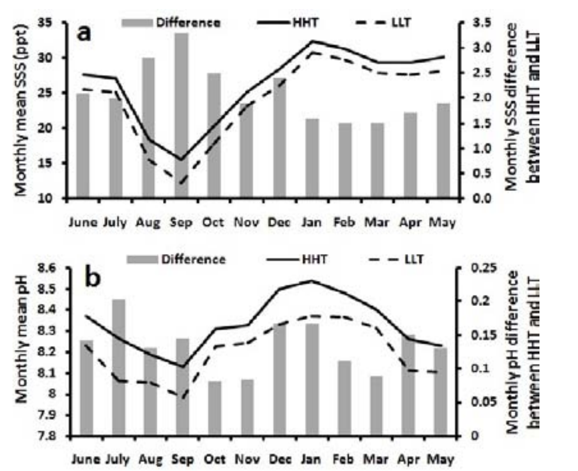


Fig. 4—Monthly mean along with the difference between HHT and LLT of a) SSS and b) pH

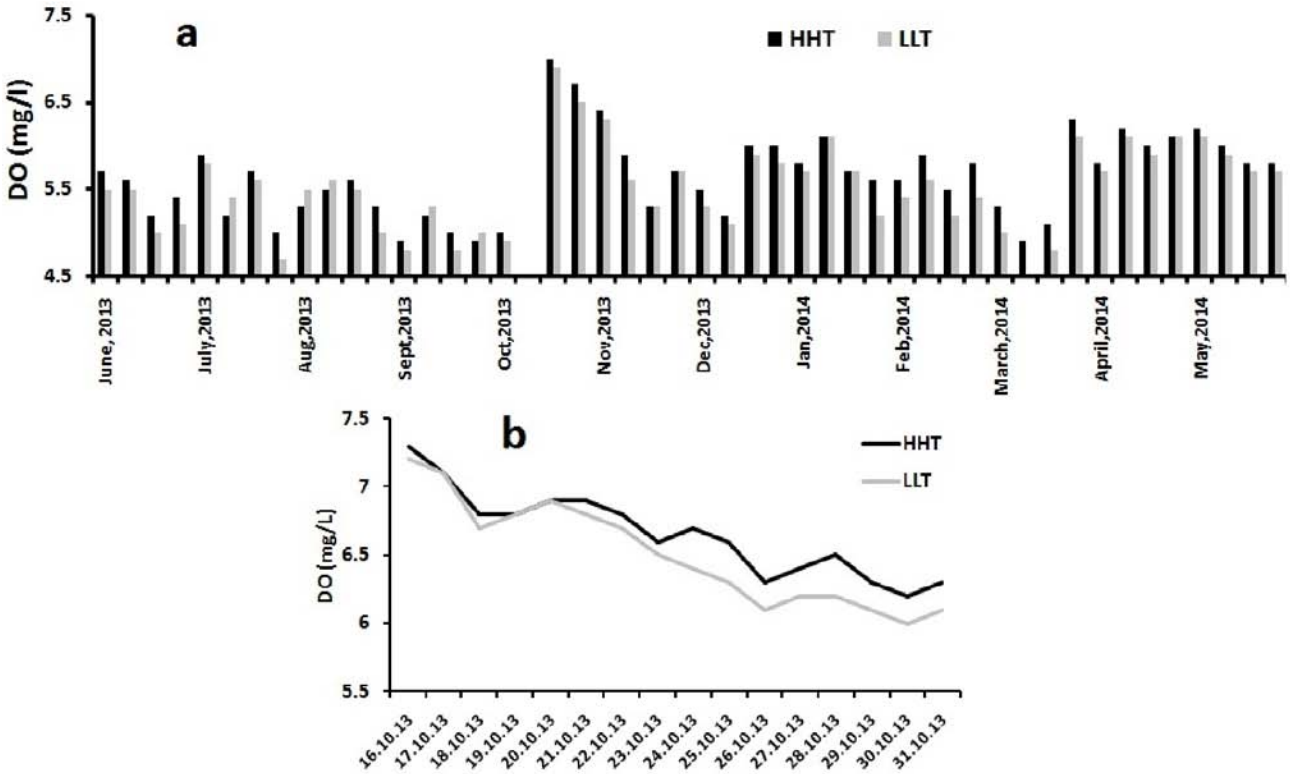


Fig. 5—(a) Weekly DO throughout the annual cycle along with (b) daily DO of the post Phailin period

**Relationship between tide and weekly mean DO**

The DO values ranged from 4.9 to 7 mg/l during HHT and 4.5 to 6.9 mg/l during LLT throughout the annual cycle. Krumme *et al.*[30] also reported DO contents co-varied with water level and maximum value always occurred around the high tide condition in the day time in a mangrove-depleted estuary of East Hainan (South China Sea). On the contrary, Mitra *et al.*[9] while working near the mouth of Hugli River, found DO values ranging from 4.60 mg/l to 6.63 mg/l during high tide and 4.81 mg/l to 6.88 during low tide, i.e. higher DO in the low tide phase and vice-versa. However, as per our observation, only 12% of the total sampling revealed higher DO during low tide and that to only during the peak of monsoon, while for the rest of the year the tide induced variability of DO behaved differently (Fig. 5a). The reason behind such anomalous behavior might be attributed to the distance of the present study area from the freshwater source of R. Hugli (~60 km from the river confluence). The influence of riverine freshwater seems to get diluted in our study area and the effect of seawater intrusion plays a pre-dominating role. Moreover, physical forcing (i.e. wind driven physical pump of atmospheric oxygen getting mixed with the surface water) also plays a crucial role in such an open estuary to offshore transition zone. The maximum difference in the seasonal mean values of DO during HHT and LLT were observed during the pre-monsoon season (0.27 mg/l), while the minimum was found in the post-monsoon season (0.12 mg/l).

**Short term variability of physico-chemical properties due to tropical cyclone – Phailin**

Earlier observations have documented the effect of tropical cyclone (TC) genesis on various ocean water regimes. Due to cyclone generation, some abnormal changes are found to occur in the ocean water, i.e. short term SST cooling, higher primary production and so forth. During our annual course of sampling, four severe cyclones; named Phailin, Helen, Lehar and Madi; happened in the Bay of Bengal (Table 2), out of which, only one major cyclone (Category 5) Phailin (wind speed – 215 km/h) had its track close to our sampling area (Fig. 6), where as other three has there track more distant from our study region. Throughout the entire year, DO was measured at weekly intervals. In order to get a snapshot of the short term changes that might have taken place due to the effect of the cyclone, we have analyzed carefully the daily data in the post–Phailin session, for 16 consecutive days (Fig. 5b).

Table 2─Severe cyclones originated on BoB during the present study period

| Fig. No. | Name of Cyclone | Date | Wind Speed (km/h) | Catagory | Severe impact on our study area (nBoB) |
|---|---|---|---|---|---|
| 6a | Phailin | 8-14 Oct, 2013 | 215 | 5 | Yes |
| 6b | Helen | 19-23 Nov, 2013 | 100 | - | No |
| 6c | Lehar | 23-28 Nov, 2013 | 140 | 1 | No |
| 6d | Madi | 6-13 Dec, 2013 | 120 | 1 | No |

We observed a maximum decrease of SST (~4.8°C) on the 16th October, 2013, i.e. just one day after the passing of Phailin (Fig. 2b). An SST of 26.4°C was observed on that day which marked the minimum for the month of October. Dare and McBride[31] also found maximum SST cooling one day after the cyclone passage on the global cyclone track. Similar observations are previously reported in other oceans[32,33,34] as well as in Bay of Bengal[35,36] in the post-TC period. The SST, however, returned back to normal range within 4-5 days after the passage of Phailin. Moreover, just prior to the generation of the cyclone the SST was found highest on 7th October, 2013. An SST of 31.2 °C was observed on that date which is quite unlikely keeping in view the onset of winter season that generally takes place in the mid of October. Such sudden increase in SST sometimes acts as an indicator of cyclone generation. Furthermore, this sudden rise of SST has adverse effect on the ecology of estuarine water.

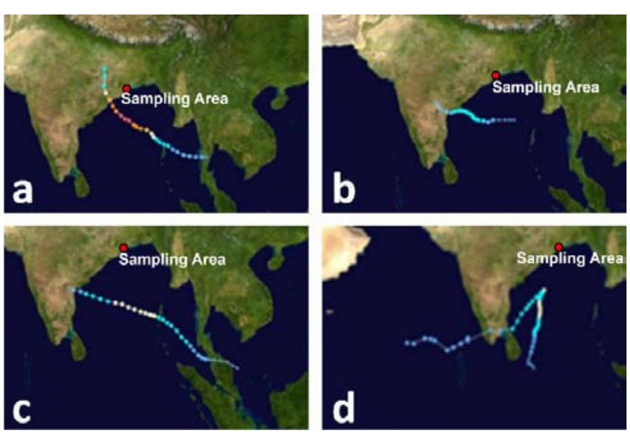


Fig. 6─Track of severe cyclones a) Phailin b) Helen c) Lehar and d) Madi generated on BoB in the year 2013-14

Prior to the onset of Phialin, DO in our study area was 5.0 mg/l while just after the cyclone it steeply increased to 7.3 mg/l on 16th October, 2013. Throughout the entire annual cycle, DO never attained such a high value. Unlike SST, the DO took almost 10 days to come back to natural range observed in this study (4 – 6 mg/l). Another important observation which is worth mentioning is that the difference in DO between HHT and LLT was virtually nil during the post-Phailin four days (Fig. 5b). The intense physical forcing due to the passing of cyclone might have dominated over the tidal influence during this period.

pH and SSS were also found to show a steep rise just after the passing of this cyclone. SSS increased from 15.1 ppt (before Phailin) to 20.1 ppt (just after Phailin) while pH increased from 8.203 to 8.500 after the cyclone (Fig. 7a and 7b). SSS and pH are comparatively higher in the oceanic domain compared to the inland freshwater. The main reason behind such an increase is the pre-dominance of ocean water and its intrusion due to the physical forcing created by the TC.

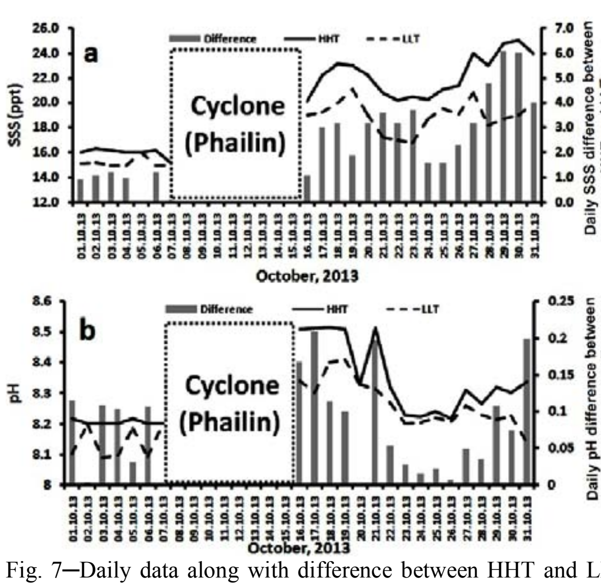


Fig. 7─Daily data along with difference between HHT and LLT of a) SSS and b) pH for the month of Oct, 2013 excluding the period of Phailin.

## Conclusion

Analyzing the entire data set of the four physico-chemical parameters studied throughout the year, it could be concluded that tide plays a role in regulating these basic parameters. SST was the only exception which did not show any significant trend with varying tides. SSS, pH and DO consistently showed higher values during the HHT hours and vice-versa throughout the year in the shallow continental shelf water. During the monsoon, owing to the combined effect of enhanced freshwater flow and high precipitation, DO in some weeks showed higher values during LLT hours. The effect of Tropical Cyclone (TC) was also fairly prominent in the present study area. A drastic cooling from the perspective of SST along with a sudden increase in SSS, DO and pH were noticed in the post Phailin days. Prior to the cyclone an anomalous increase in the SST was also observed which must have adverse effect on the biota of this marine ecology. In future, the night time data should be acquired throughout the year to have a clear idea with a more holistic approach. Moreover, other key parameters like turbidity, under water photosynthetically active radiation, nutrients and light extinction coefficient should be studied to build a strong database of such an important bio-climatic region.

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