Signatures of very severe cyclonic storm *Phailin* in met–ocean parameters observed by moored buoy network in the Bay of Bengal

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The moored buoy network deployed in the Bay of Bengal played a critical role in the collection and transmission of surface meteorological and oceanographic conditions in real time through satellite telemetry, enabling constant monitoring of the cyclone Phailin. It is the first report of in situ time-series measurement of a very low pressure taken during cyclones in the northern Indian Ocean. The BD10 buoy recorded a minimum atmospheric pressure of 920 hPa, which happened to be within the eye of the cyclone. This article presents an account of important changes that were observed in the surface meteorological and oceanographic parameters under the influence of the very severe cyclonic storm Phailin. An attempt has been made to understand the role of stratification in intensifying the cyclone Phailin in comparison with the cyclone Lehar which weakened in the ocean itself, based on subsurface data from the moored buoys which were on the track of the respective cyclones. Both the cyclones traversed across the Bay of Bengal in a similar way and the buoys were very close to the cyclone track withstood the rough sea conditions during the storms with their specially designed body. The BD09 buoy which happened to be on the right side of the track of cyclone Phailin moved in a circular path as a result of the inertial oscillation forced by the strong cyclonic winds.

Keywords: Cyclonic storm, met–ocean parameters, moored buoy, real-time observations.

THE Bay of Bengal (BoB) is prone to cyclonic storms during pre-monsoon months of April and May and post-monsoon months of October and November[1]. During pre-monsoon period the Bay is pre-conditioned by warm sea-surface temperature (SST > 30°C) and low sea-surface salinity (<33 PSU), which is highly conducive to the formation cyclonic storms[2]. The cyclonic storms are associated with low atmospheric pressure and strong winds which induce divergent circulation in the upper ocean. The response to these episodic events can be seen in the uppermost layer (200–300 m) of the ocean. Deepening of mixed layer by tens of metres and cooling of SST by 0.3–6°C are observed during cyclones[3–7]. Deep convective clouds formed over the oceans during cyclones will reduce the incoming solar radiation incident on the surface of the ocean. The high winds produce large amounts of air–sea energy exchange, which leads to the subsequent cooling of the sea surface. The impact of the cyclone in the ocean as well as in the atmosphere is rapid due to the presence of strong winds. The entrainment of deeper waters into the mixed layer also plays a major role in the surface layer cooling during the cyclone period[8]. The severe cyclone *Nargis* that formed in the northern BoB on 28 April 2008 was captured by the RAMA (Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction) buoy and its impact on the ocean as well as the atmosphere was pronounced. The SST dipped by 2–3°C and a significant wave height of 3–4 m was measured[9]. The DS-3 (13°N/87°E) data buoy deployed in the central BoB by the National Institute of Ocean Technology (NIOT), Chennai captured the response of two super cyclones that formed during October 1999. A SST drop of 0.7°C and 0.9°C was recorded during the Gopalpur and Paradip super cyclones respectively[10]. The influence of cyclone in the subsurface levels in the northern BoB during post-monsoon period is mainly determined by the presence of barrier layer[11]. The northern Indian Ocean is covered by a network of buoys both, in the eastern Arabian Sea and BoB, which transmit met–ocean data to the shore at 3 h interval via INMARSAT (International Maritime Satellite Organization) communication system. The

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buoy network is further classified into Ocean Moored Network for Northern Indian Ocean (OMNI) and data buoys based on the sensors used. The OMNI buoys are equipped with additional meteorological measurements for radiation, rainfall and subsurface measurements on conductivity, temperature and currents[12]. The data buoys are further categorized as coastal buoys which are deployed within 25–30 m depths in the coastal waters and deep sea buoys, if they are further offshore. These data are transmitted through the Global Telecommunication System (GTS) worldwide for operational weather, climate and ocean forecasting applications.

Cyclone *Phailin* and buoy observations

Cyclone *Phailin* was one of the most severe cyclones in the past 14 years to hit the Indian coast, with wind speeds reaching a maximum of 215 km/h during landfall (http://www.imd.gov.in/section/nhac/dynamic/phailin.pdf). Accurate predictions regarding the track and intensity of this cyclone by the India Meteorological Department (IMD) helped in saving many lives. The cyclone hit the Gopalpur coast of Odisha state on 12 October and was declared as a very severe cyclonic storm (http://en.wikipedia.org/wiki/Tropical_cyclone_scales). The seven moored buoys deployed in BoB by NIOT were within a radius of 4–160 nmi away from the cyclone track, which enabled constant monitoring of the cyclone, from evolution to the landfall. The OMNI buoys deployed in BoB withstood the strong winds and currents associated with the cyclone. Since October 2010 they have survived eight cyclonic storms that formed in BoB, constantly delivering valuable data during the cyclone as well as normal times. The mooring configuration was designed using advanced computing tools and this ability to model mooring performance, both statistically and dynamically, permitted to conduct extensive design studies before installation of the buoy at sea. However, regardless of the amount of expertise in designing, modelling and fabrication of mooring, the success of deployment often depends on the ability of the trained personnel to deploy the buoy system at sea. The combination of these activities resulted in the network of buoys withstanding severe weather conditions, thereby transmitting valuable data in real time during cyclone *Phailin*.

Surface meteorology

Very severe cyclonic storm *Phailin* was initially formed within the Gulf of Thailand on 4 October 2013 as a tropical depression (http://www.imd.gov.in/section/nhac/dynamic/phailin.pdf). It moved westward into the Andaman Sea and intensified into a tropical cyclone on 7 October 2013. There were six OMNI buoys and one coastal buoy located within 160 nmi radius of the track of *Phailin*. The locations of these buoys in BoB along with the track of the cyclone are shown in Figure 1.

Atmospheric pressure, air temperature and wind: Initially two buoy systems, CB01 and BD12, operational in the Andaman Sea showed the response of the cyclonic depression by a drop in atmospheric pressure and increased wind speed on 9 October 2013 (Figure 2). After entering the BoB waters, it further intensified and moved in a northwest direction. The cyclone rapidly intensified into a very severe cyclonic storm of Category 1 in Saffir-Simpson scale on 10 October 2013. The buoy BD13 on the left side of the cyclone track was the first one to show the response of the cyclone as soon as it entered BoB. The response captured by the buoy BD13 was less since it was located 160 nmi away from the cyclone track (Table 1).

The cyclonic storm further intensified to Category 5 with wind speeds greater than 70 m/s on 11 October. The responses in both meteorological and oceanographic parameters were pronounced at the BD10 location due to its proximity to the eye of the cyclone. The drop in the air pressure by 83.7 hPa within a day clearly indicates that the location of the buoy was within the eye of the cyclone. The estimated pressure during the cyclone *Phailin* by satellite observations was around 910 hPa, one of the lowest pressures ever observed in the northern Indian Ocean[13]. The minimum recorded pressure of 920.6 hPa at BD10 was the lowest value recorded till date by any instrument in the northern Indian Ocean. The NIOT buoy data have earlier recorded a minimum pressure of 991.8 hPa at 12.5°N and 72°E during the severe cyclone in 2004 (ref. 14) and 997.4 hPa at 15.5°N and 69.3°E during the severe cyclone in 1998 (ref. 15) respectively.

The highest drop in air temperature was recorded by the OMNI buoys BD08 and BD09 which were on the right side of the cyclone track and located 140 and

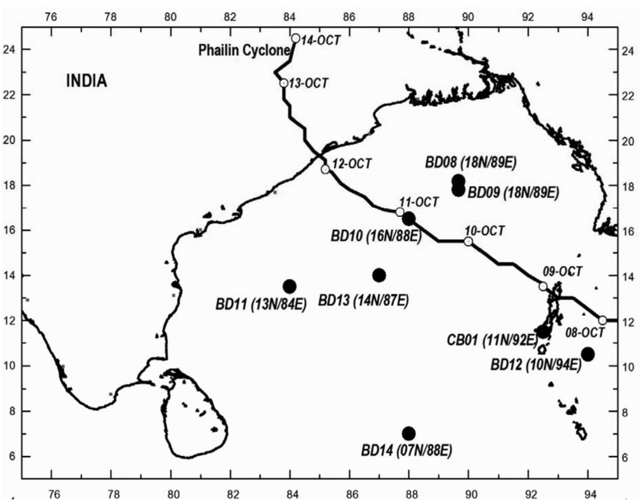

Figure 1. The track of cyclone *Phailin* and location of seven moored buoys in the Bay of Bengal.

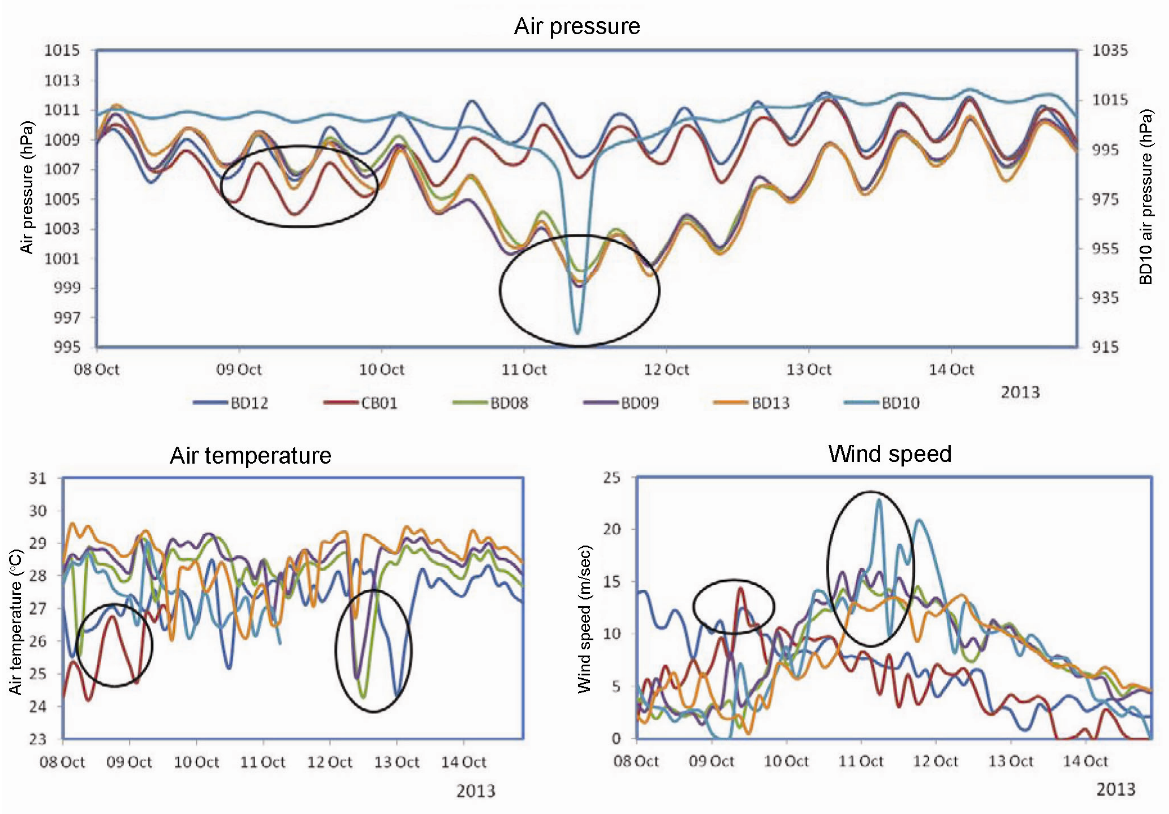

Figure 2. (Top panel) Response in the atmospheric pressure, with BD10 recording a maximum drop of 84 hPa, thus resulting in the minimum ever recorded pressure of 920.6 hPa during a cyclone in BoB, therefore represented in the secondary axis. (Bottom panels) Variations in the air temperature and wind speed recorded by the six buoys in the Bay during cyclone *Phailin*. Note the maximum wind speed of 22.7 m/s recorded by BD10.

Table 1. The respective distances of each moored buoy in BoB from the track of the cyclone *Phailin*

Buoy ID	Position	Depth (m)	Distance between cyclone track and buoy position (nmi)
BD12	10.5°N/94°E	3,150	130
CB01*	11.6°N/92.6°E	8	110
BD10	16.5°N/88°E	2,640	4
BD09	17.9°N/89.7°E	2,200	125
BD08	18.2°N/89.7°E	2,150	140
BD13	14°N/87°E	3,065	160

*Coastal buoy.

125 nmi respectively, away from the track. The temperature drop was felt more on the right side of the cyclone track, which can be attributed to the nonlinear response of the cyclone with stronger winds on the right side of the track[16]. The drop in air temperature can be due to the effect of strong air–sea fluxes induced by the strong winds as well as due to the local rainfall. The drop in air temperature by 4°C was recorded by BD08 and BD09 on 12 October at 12 GMT, whereas BD13 located 160 nm to the left of the cyclone track recorded a drop of only 2°C (Figure 2). These observations are consistent with the earlier recorded drop in air temperature by 3°C by the deep ocean buoy at 15.5°N and 69.3°E during the severe cyclone in the Arabian Sea in June 1998 (ref. 15). The buoy BD12 showed the first drop in air temperature by 2.3°C on 10 October during the initial stages of the cyclone and later showed a drop by 3.8°C on 13 October, though the cyclone was located further away from the buoy location. The secondary drop in air temperature can be associated with the local rainfall at BD12 as recorded by the buoy (Figure 3). The air temperature sensor failed both in BD10 and CB01 due to the damage caused to it by the strong winds associated with the cyclone. The decrease in wind speed by over 13.0 m/s from a maximum recorded value of 22.7 m/s on 11 October at 06 GMT to 9.8 m/s at 09 GMT (as highlighted in Figure 2), indirectly gives an indication for the proximity of the buoy (BD10) to the eye of the cyclone. The wind gust touched the maximum range of the wind sensor, i.e. 35 m/s by the same buoy.

Rainfall: The rainfall data are obtained from all the OMNI buoys, recorded as cumulative rain by the rain gauge sensor with a maximum capacity of 50 mm and the data are transmitted every 3 h. The data are then converted to daily rainfall by adding the entire rain rate (the difference between two consecutive readings) recorded by the rain gauge sensor in a day. The maximum rainfall during the cyclone *Phailin* was recorded by BD08, 85.0 mm/day on 12 October, based on the transmitted data. BD10 recorded rainfall of 31.4 mm/day on 9 October, but a better picture of the actual scenario was obtained after the retrieval of these buoys. The evaluation of the 2 min high-resolution data stored internally by the rainfall sensor measured rainfall with better accuracy than 3 h data. The high-resolution data recorded the multiple tipping-off by the rain gauge sensor within the 3 h duration. Therefore, the actual rainfall recorded at the BD08 and BD10 locations was 138 and 84.5 mm/day respectively (Figure 3). The data sampling interval of the rain gauge sensor has been increased to 2 min, with the foresight of capturing the high rainfall events, especially during cyclone and monsoon seasons.

Oceanographic response

Strong stratification during the cyclone Phailin: The reduction in SST associated with the cyclone is the result of strong mixing, air–sea fluxes and upwelling of subsurface cool waters to the surface[17,18]. The SST dropped by 0.7°C at the BD10 location and the drop happened in 3 days time as shown in Figure 4. The strong upwelling during the cyclone can contribute to an increase in sea-surface salinity (SSS)[19]. An increase of SSS by 2 psu was recorded by the buoy BD10, as shown in Figure 4. Additional data from all the conductivity–temperature (CT) sensors attached to the mooring at discrete depths give further insight into the thermal structure of the region prior to the cyclone. The high stratification observed by the buoy BD10 is one of the key factors for the intensification of the cyclone *Phailin*, while the other two very severe cyclonic storms which formed later in BoB weakened in the sea itself. During post-monsoon season with the availability of heavy river discharge, the formation of thick barrier layer[20] will reduce the response of the ocean to cyclonic forcing[21]. The thick barrier layer can even

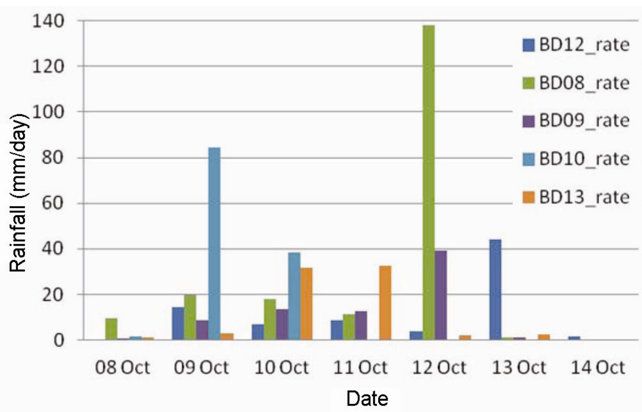

Figure 3. Daily rainfall measured by the OMNI buoys during the passage of cyclone *Phailin*.

contribute to the intensification of cyclones by 50% with reduced storm-induced mixing and SST cooling[22]. We have also looked into the thermal structure recorded by another buoy BD13 which was on the track of the very severe cyclonic storm *Lehar* during 23–28 November 2013, as shown in Figure 4. A detailed analysis of the subsurface data obtained from the buoys BD10 and BD13 shows very high stratification with temperature inversion near the BD10 location during the cyclone *Phailin*, as shown in Figure 4. However, the stratification is completely absent near the BD13 location during cyclone *Lehar*, close to which the cyclone has weakened on 27th afternoon. Despite the presence of highly stratified waters, the sea surface cooling was more intense during the cyclone *Phailin* compared to *Lehar*. This has incited to look into the other potential sources for the intensification of cyclone *Phailin*.

High tropical cyclone heat potential during Phailin: The BoB experienced four cyclonic storms during the northeast monsoon of 2013, while *Phailin* alone remained as very severe cyclonic storm until it moved into the land region. The other two cyclones, *Lehar* and *Madi*, which were under the category of very severe cyclonic storms weakened in the sea itself, while *Helen* never strengthened into very severe cyclonic storm. The SST along the northwestern part of BoB during the cyclone *Phailin* was very high compared to the other two cyclone periods based on the Tropical Rainfall Measuring Mission's (TRMM) Microwave Image (TMI)–SST data, as shown in Figure 5. The tropical cyclone heat potential (TCHP), another important parameter which determines the intensity of the cyclone, was computed following Leipper and Volgenau[23]. The very low ocean thermal energy (<50 kJ/cm^2) available from the west-central BoB and the entrainment of dry and cold air into the cyclonic fields are the main causative factors for the weakening of the cyclone *Lehar* (http://www.imd.gov.in/section/nhac/dynamic/lehar_2013.pdf). The subsurface information on temperature and salinity from the buoys BD10, BD13 and BD11 during cyclones *Phailin*, *Lehar* and *Madi* respectively, was used to compute TCHP at that location. During cyclone *Phailin* the TCHP was very high of the order of 400 kJ/cm^2, while during cyclones *Lehar* and *Madi* the buoys nearest to the cyclone track recorded very low TCHP of the order of 150 and 100 kJ/cm^2 respectively, as shown in Figure 5. The high SST and TCHP along with highly stratified waters in the northwestern BoB favoured the intensification of cyclone *Phailin*.

Surface current and inertial oscillation: The increase in the surface current speed due to high winds during the cyclone period was also recorded by the buoys in BoB. BD12 recorded a maximum current speed of 74.2 cm/s on 10 October, but an increased current peaking to 138.67 cm/s was recorded by BD10 (Figure 6*c*). BD13

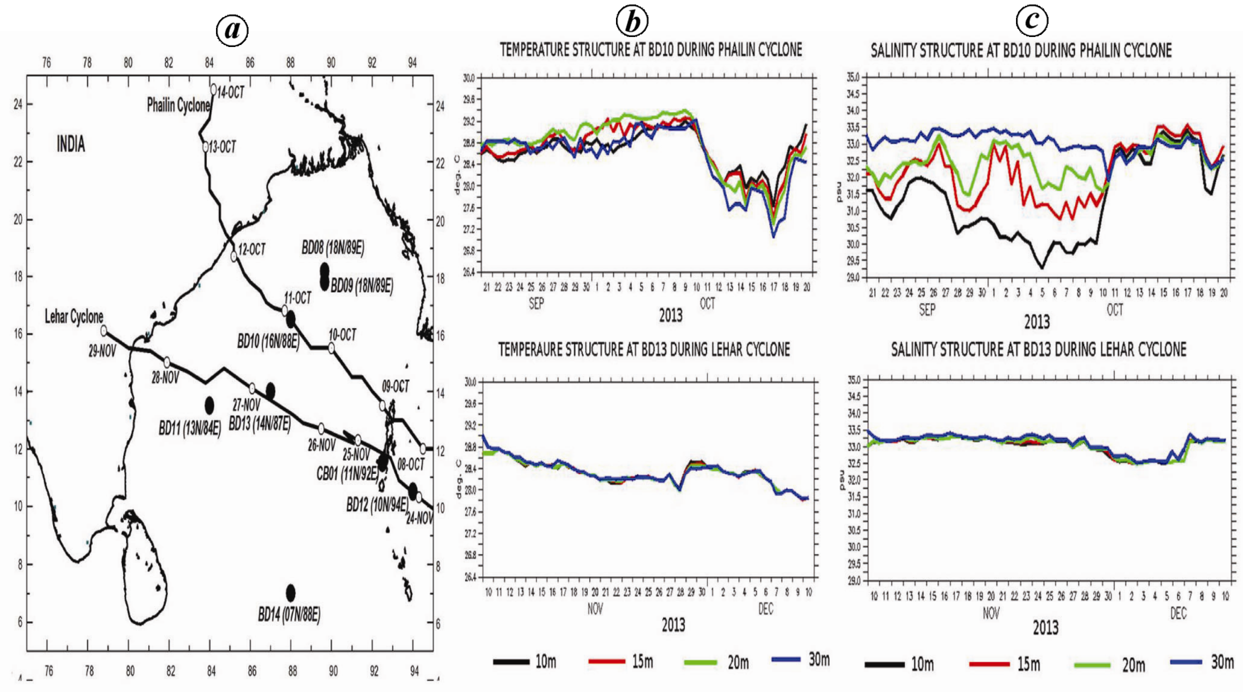

Figure 4. ***a***, The tracks of cyclones *Phailin* and *Lehar* with location of moored buoys in BoB. ***b***, ***c***, Temperature (***b***) and salinity (***c***) structure as recorded by the buoys BD10 and BD13 which were within the eye of the respective cyclones.

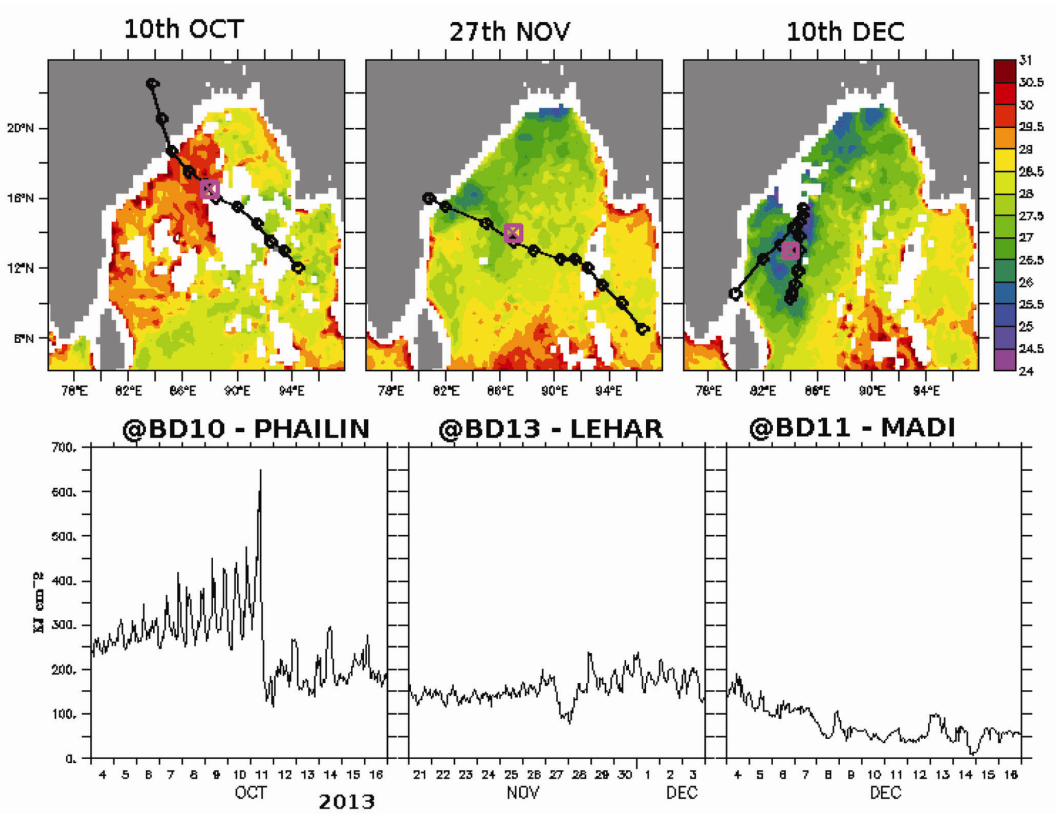

Figure 5. (Top panel) Sea-surface temperature on 10 and 27 November and 10 December 2013 with the location of the respective buoys closer to the tracks of cyclones *Phailin*, *Lehar* and *Madi*. (Bottom panel) Tropical cyclone heat potential obtained from the buoys BD10, BD13 and BD11 during period of cyclones *Phailin*, *Lehar* and *Madi*.

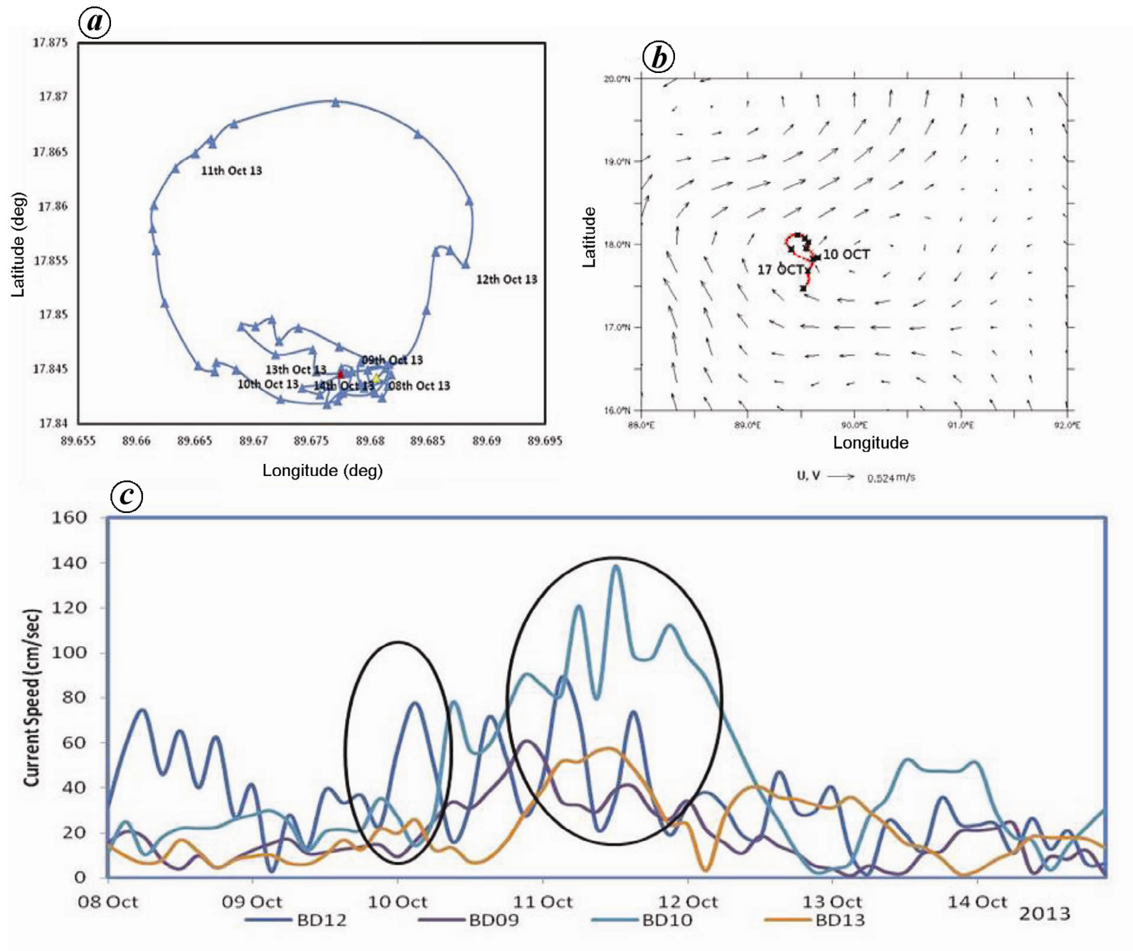

Figure 6. ***a***, The drift of the buoy BD09_18N/89E with the surface current following a clockwise path. ***b***, Progressive position vector drawn based on the surface current data obtained from BD09_18N/89E plotted against the OSCAR surface current for 11 October. ***c***, Increase in current speed as recorded by the OMNI buoys in BoB.

recorded maximum current speed of 56.6 cm/s on 11 October and BD09 recorded a current speed of 60.6 cm/s.

The cyclonic wind induces inertial oscillations in the ocean with a periodicity of $2\pi/f$, which drives clockwise circulation of the near-surface waters governed by the coriolis (f) and gravity (g) forces[24]. The periodicity and diameter of the inertial current vary with latitude, with increasing values towards the equator. The spectral peaks of the wind and SST data obtained during the September 1997 cyclone in BoB from DS4 (19°N/90°E) data-buoy have shown the frequency of inertial oscillation[25]. During *Phailin*, the BD09 OMNI buoy moved in a clockwise manner along with the surface current (Figure 6 *a*). This is due to the inertial oscillations driven by the sustained strong winds during the cyclone. The buoy movement is limited depending on the scope provided, i.e. the ratio of the total length of the mooring to depth. The BD09 location is at a depth of 2210 m and the total mooring length provided is 2750 m; thus there is scope of 1.24 for the free movement of the buoy. The inertial oscillation is expected to have a periodicity of 1.618 days at 18°N and the position vector plotted based on the surface current data obtained from BD09 reveals the inertial oscillation excited on the surface of the ocean due to the cyclone *Phailin* (Figure 6 *b*). The five-day mean surface current for 11 October obtained from Ocean Surface Current Analyses – Real time (OSCAR) (http://www.oscar.noaa.gov/datadisplay/oscar_datadownload.php) which is the sum of both Ekman and geostrophic current is plotted in the background.

Significant wave height: The intense winds during the cyclone induce high waves in the ocean. The increase in wave height is well reflected in the buoy observations with a recorded maximum significant wave height of 6.3 m as observed at BD08, which was 140 nmi away from the cyclone track. The buoy BD08 has been deployed at a location where the depth is 2150 m and much offshore; thereby the wave height must have increased further as the cyclone approached towards the Gopalpur coast. The INCOIS (Indian National Centre for Ocean Information Services) wave rider buoy located near Gopalpur at 19°N/85°E recorded a maximum wave height of 7.5 m on 12 October, when the cyclone made the landfall[26].

Conclusions

During the cyclone *Phailin* period, the availability of real-time observations from six operational data buoys in BoB has proved useful for monitoring the signatures of the cyclone. The moored buoys deployed in BoB clearly brought out the variations in the surface meteorological as well as oceanographic parameters based on *in situ* measurements taken during the cyclone evolution as well as during its intensification. The buoy BD10 located under the eye of the cyclone recorded the minimum pressure of 920.6 hPa, which is the lowest ever instrumentally recorded pressure during a cyclone in the northern Indian Ocean. The role of stratification of the western BoB in the intensification of the cyclone *Phailin* compared to cyclone *Lehar* during the northeast monsoon season is also made possible with the help of subsurface data on salinity and temperature. The high TCHP was measured during the cyclone *Phailin* compared to the other two very severe cyclonic storm periods, which was obtained from the respective buoys closer to the cyclone track. This study has clearly proved the importance of the met–ocean buoy network for studying the surface meteorological and oceanographic conditions in real time to monitor cyclones. It will also help various organizations to assimilate these data into their operational models and thus enables more accurate prediction of cyclonic weather systems.

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