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The response of the upper ocean to tropical cyclone Viyaru over the Bay of Bengal

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Abstract

Better forecast of tropical cyclone (TC) can help to reduce risk and enhance management. The TC forecast depends on the scientific understanding of oceanic processes, air-sea interaction and finally, the atmospheric process. The TC Viyaru is taken as an example, which is formed at the end of 11 May 2013 and sustains up to 17 May 2013 during pre-monsoon season. Argo data are used to investigate ocean response processes by comparing pre- and post-conditions of the TC. Eight oceanic parameters including the sea surface temperature (SST), the sea surface salinity (SSS), and the barrier layer thickness (BLT), the 26°C isotherm depth in the ocean (D_{26}), the isothermal layer depth (ILD), the mixed layer depth (MLD), the tropical cyclone heat potential (TCHP) and the effective oceanic layer for cyclogenesis (EOLC) are chosen to evaluate the pre- and post-conditions of the TC along the track of Viyaru. The values of the SST, D_{26}, BLT, TCHP and EOLC in the pre-cyclonic condition are higher than the post-cyclonic condition, while the SSS, ILD and MLD in the post-cyclonic condition are higher than the pre-cyclonic condition of the ocean due to strong cyclonic winds and subsurface upwelling. It is interesting that the strong intensity of the TC reduces less SST and vice versa. The satisfied real time Argo data is not available in the northern Bay of Bengal especially in the coastal region. A weather research and forecasting model is employed to hindcast the track of Viyaru, and the satellite data from the National Center Environmental Prediction are used to assess the hindcast.

Key words: effective oceanic layer for cyclogenesis, sea surface temperature, tropical cyclone, tropical cyclone heat potential, tropical cyclone viyaru, weather research and forecasting model

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1 Introduction

Tropical cyclone (TC) formation areas of the global ocean are divided into seven basins in which the northern Indian Ocean is one of them. It has two wings, the Arabian Sea and the Bay of Bengal (BoB). The Indian sub-continent is one of the worst areas in the world affected by the TCs. According to global cyclone statistics, only 7% of the TCs occur in the northern Indian Ocean, but five to six times as many occur in the BOB as in the Arabian Sea (Akter and Tsuboki, 2014). Since the BoB is a semi-enclosed basin, most of the TCs that form make landfall, giving the BoB TCs a disproportionately high societal importance relative to their small total number. Among major natural hazards, the TCs are considered as one of severe threats to human life, property, and ecosystem which are accompanied with strong gusty winds, torrential rains, and storm surges. In the event of TC landfall, it is enormously difficult task to evacuate population from the affected coastal regions for the developing countries (e.g., Bangladesh, India, Myanmar, etc.) due to socio-economic factors (Emanuel, 1999; Wang and Wu, 2004). The TC Viyaru was one of the destructive cyclones in the BoB. A total of 95 003 poorly constructed huts were damaged or destroyed, 17 people died, and nearly 1.3 million people were affected across the country. Losses to crops exceeded ৳ 400 million (US$ 5.14 million). Myanmar was spared damage and further casualties (https://en.wikipedia.org/wiki/Cyclone_Viyaru, retrieved on 25 March 2016). Hence, it is essential to improve the TC track and intensity forecasting. Efforts are made to improve the TC track forecast significantly, whereas the TC intensity forecast needs more attention and understanding (Emanuel, 1999; Wang and Wu, 2004).

The importance of the sea surface temperature (SST) in the formation and maintenance of the TCs has long been recognized since Palmen (1948) first shows almost all hurricanes form over oceans with the minimum SSTs higher than 26°C. The SST was found to be a crucial parameter in the genesis and intensification process (Bender et al., 1993; Mahapatra et al., 2007). The freshwater discharge from the Ganges, Brahmaputra, and Irrawaddy river systems cause the uniform density mixed layers to become shallower than the uniform temperature isothermal layers due to salinity effect, leading to the formation of salt-stratified barrier layers in the BoB (Sprintall and Tomczak, 1992). The formation of thick barrier layers that stably stratify the upper ocean, is the primary reason for enhanced TC activity (McPhaden et al., 2009; Sengupta et al., 2007). The TC intensification rate is nearly 50% higher over regions with barrier layers (Balaguru et al., 2012). The scholars of oceanography were informed that cyclones are responsible for the decrease in the SST by 0.3–3.0°C over the BoB depending on the strength and path of the cyclones (Rao, 1987; Gopalakrishna et al., 1993; Chinthalu et al., 2001; Subrahmanyam et al., 2005; Sengupta et al., 2007). The salinity stratification in the southern and western parts of the BoB is weak in May, lar-

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ger SST cooling up to 2–3°C and deepening of mixed layer up to 80 m due to cyclones (Rao, 1987; Gopala Krishna et al., 1993). The salinity stratification in the northern part of the BoB is intense; the SST cooling due to monsoon depressions was only up to 0.3°C, as entrainment of cold waters did not reach up to sea surface (Murty et al., 1996; Sengupta et al., 2007). The objective of the research was to predict and investigate the TC. The study has been conducted with the following objectives: (1) to investigate the different oceanic parameters during pre- and post-TC along the track, sea surface temperature (SST), sea surface salinity (SSS), isothermal layer depth (ILD), mixed layer depth (MLD), barrier layer thickness (BLT), 26°C isotherm depth in the ocean (D_{26}), tropical cyclone heat potential (TCHP) and effective oceanic layer for cyclogenesis (EOLC); and (2) to investigate the anomaly of upper ocean thermal feature along the track of the TC.

2 Data and methodology

The area selected for the present study was the BoB located within 4°–27°N and 80°–100°E (Fig. 1). The following oceanographic and atmospheric data are used in the present study: Argo data (*in situ* data), remote sensing data of SST and Viyaru observed track data are used as oceanographic data; remote sensing data of NCEP revised data are also used to air-sea fluxes and upper ocean heat budget in the present study.

The MLD is estimated upon variable density criteria by Kara et al. (2000) formulation:

$$\Delta\sigma_t = \sigma_t(T + \Delta T, S, p) - \sigma_t(T, S, p), \qquad (1)$$

where T, S and p corresponds to temperature, salinity and pressure on the near surface from the Argo profiling float, respectively. The ILD is the depth at which the ocean temperature is 1°C lower than that at 5 m. The BLT is defined as ILD minus MLD. The TCHP, values of temperature and salinity at 5 m depth in Argo profiles are considered as SST and SSS, respectively.

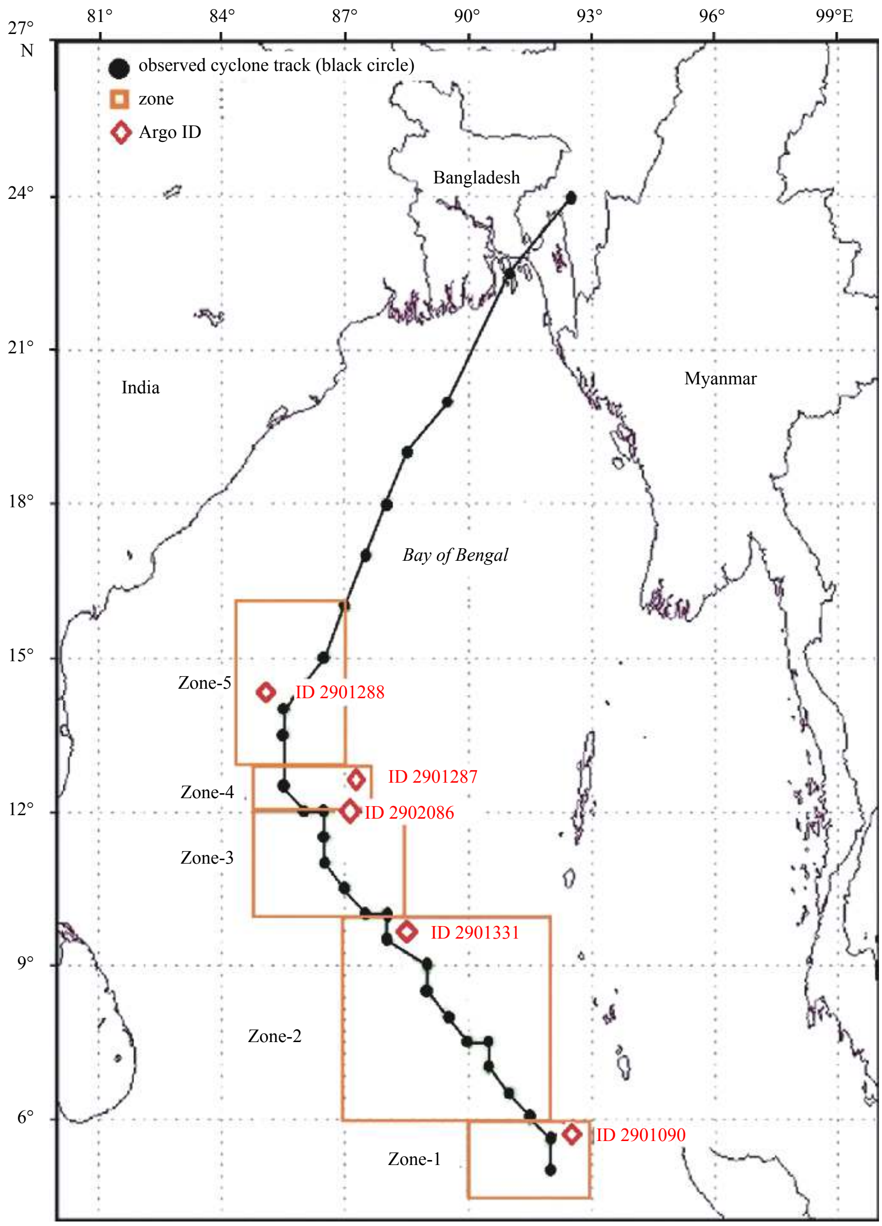

Fig. 1. The study location with zone wise Argo ID along the track of the tropical cyclone Viyaru.

$$p_n = \rho c_p \int_0^{D26} [T(z) - 26]\,dz, \quad (2)$$

where p_n is the TCHP; ρ is the density of seawater; c_p is the specific heat of seawater at constant pressure; and T is the average temperature of the layer z. The EOLC is defined as

$$L_c = \int \alpha dp, \quad (3)$$

where the L_c is the EOLC; and dp is the pressure interval and the limits of integration extends from surface to 30 m. These limits of integration vary from approximately 5 to 30 m depth for Argo profiles. The weather research and forecasting model is used to identify the track of the TC Viyaru only.

3 Results and discussion

3.1 *Synoptic feature of TC Viyaru*

Viyaru formed over the BoB on 10 May 2013 near the location (5.0°N, 92.0°E), initially moved northwestward and intensified during 11–12 May 2013. It moved to the north and northeast on 13 and 14 May respectively. On 15 May, under the influence of the mid-latitude westerly trough running roughly along 87°E, which further helped in enhancing the north-northeastward speed of the tropical storm, the tropical storm finally crossed the Bangladesh coast near the location (22.8°N, 91.4°E).

3.2 *Estimated changes in the oceanic parameters from Argo data*

During the passage of the Viyaru cyclone, five Argo profiling floats were located within a vicinity of 150 km from the center of the storm. The locations of the Argo profiling floats with their float ID numbers and five zones along the track of the TC Viyaru are shown in Fig.1. The estimated-changes in the eight oceanic parameters (SST, SSS, ILD, MLD, BLT, D_{26}, TCHP and EOLC) using the Argo floats are shown in the Table 1.

3.3 *Comparison of the ocean vertical profiles along the TC Viyaru between pre- and post-cyclone*

The Argo data in Zone-2 (6°–10°N, 87°–92°E) were collected for analysis. The Zone-2 was located in the southern BoB. The second Argo profiling float (Argo ID 2901331) was active in this Zone. On 11 May 21:00 UTC, the center of Viyaru situated at the location (9.5°N, 88.5°E). Float was situated at the right hand of the storm 24 km off the storm center. The SST and SSS pre-cyclonic condition of Viyaru were 31.20°C and 32.75, respectively. These values signify the high SST and low salinity. The surface low salinity waters enhanced salinity stratification and the formation of barrier layer. The depths of the ILD, the MLD and the BLT were 39, 16 and 23 m, respectively. The depth of the BLT was deeper than the MLD. The depth of 26°C isotherms was 81 m. The TCHP and EOLC were 103.88 kJ/cm^2 and 1.273 1 m^2/s^2, respectively. These values elicit the high D_{26}, high TCHP and high EOLC. All these oceanic physical parameters were suitable for the cyclogenesis of Viyaru. For the post-cyclonic condition of Viyaru, the SST and SSS were 29.43°C and 34.12, respectively. The SST decreased and SSS increased due to cyclonic strong wind and high surface waves which enhance the vertical mixing and the sea surface and subsurface upwelling, and result in the reduced BLT and increased MLD. The MLD was deepening up to 38 m depth which has been shown in Fig.2. The depth of the D_{26} was 60 m. The TCHP and EOLC were 59.955 kJ/cm^2 and 1.176 m^2/s^2, respect-

Table 1. Estimated oceanic parameters from Argo data, including sea surface temperature (SST), sea surface salinity (SSS), isothermal layer depth (ILD), mixed layer depth (MLD), barrier layer thickness (BLT), 26°C isotherm depth in the ocean (D_{26}), tropical cyclone heat potential (TCHP) and effective oceanic layer for cyclogenesis (EOLC).

Argo ID	Date	North latitude	East longitude	SST (5 m) /°C	SSS (5 m)	ILD /m	MLD /m	BLT /m	D_{26}/m	TCHP /kJ·cm^{-2}	EOLC /m^2·s^{-2}	Remark
Zone-1 (4°–6°N, 90°–92°E)												
2901090	2013-05-03	5.920°	92.57°	30.33	33.75	40	33	7	71	87.070	1.206 6	on 10 May 12:00 UTC, Viyaru passed over 5.5°N, 92.0°E. Argo float is located within 50 km range
	2013-05-13	5.793°	92.31°	29.82	33.85	48	37	11	64	73.637	1.198 9	
	2013-05-23	5.439°	92.14°	29.39	34.11	79	70	9	119	113.19	1.174 5	
Zone-2 (6°–10°N, 87°–92°E)												
2901331	2013-05-06	9.397°	88.35°	31.20	32.75	39	16	23	81	103.88	1.273 1	on 11 May 21:00 UTC, Viyaru situated at 9.5°N, 88.5°E. Argo float is situated on the right hand of the storm within 24 km of the center of storm
	2013-05-11	9.394°	88.31°	31.30	33.45	28	25	3	76	100.28	1.242 6	
	2013-05-15	9.465°	88.20°	29.43	34.12	79	38	5	60	59.955	1.175 7	
	2013-05-16	9.522°	88.12°	29.73	34.07	38	25	13	55	54.900	1.183 0	
	2013-05-17	9.752°	88.02°	29.64	34.10	46	38	8	60	62.620	1.180 4	
	2013-05-18	9.900°	88.05°	29.75	34.09	41	39	2	62	63.140	1.187 9	
Zone-3 (10°–12°N, 85°–88°E)												
2902086	2013-05-07	11.95°	87.02°	31.02	33.10	21	19	2	88	86.492	1.252 4	on 13 May 03:00 UTC, Viyaru passed over 12°N, 86.5°E
	2013-05-12	11.98°	87.12°	29.88	32.13	31	11	20	93	96.226	1.273 7	
Zone-4 (12°–13°N, 85°–87.5°E)												
2901287	2013-05-06	12.21°	87.25°	31.02	32.99	25	23	2	93	97.140	1.258 5	on 13 May 15:00 UTC, Viyaru situated at 12.5°N, 86°E. Argo float is located on right hand of the storm within 150 km
	2013-05-11	12.15°	87.32°	31.357	33.07	24	23	1	94	88.610	1.261 8	
	2013-05-16	12.09°	87.44°	29.674	33.07	39	32	7	80	67.585	1.226 0	
Zone-5 (13°–16°N, 84.5°–87°E)												
2901288	2013-05-07	14.34°	85.29°	30.80	32.64	20	10	10	83	67.099	1.269 9	on 14 May 12:00 UTC, Viyaru situated at 14.5°N, 86°E. Argo float is located on left hand of the storm within 100 km
	2013-05-12	14.37°	85.14°	30.98	32.74	42	19	23	104	87.160	1.269 0	
	2013-05-17	14.42°	84.90°	29.75	32.83	36	17	19	105	104.47	1.238 0	

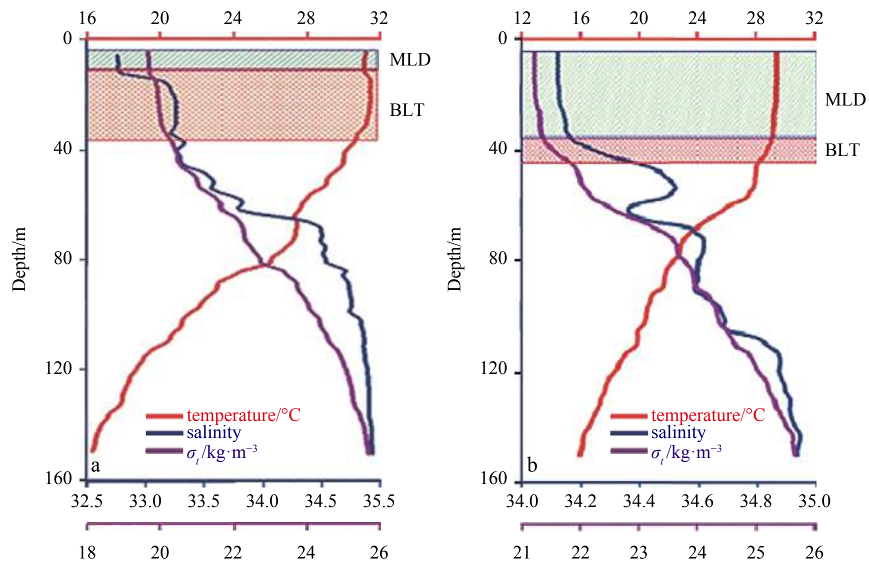

Fig. 2. The vertical profiles of ocean temperature, salinity and density along the tropical cyclone Viyaru between pre- and post-cyclone at 9.397°N, 88.351°E.

ively. The D_{26}, TCTP and EOLC are comparatively less than the pre-cyclonic condition of the TC Viyaru. These eight oceanic parameters have been shown in Fig. 3 by the line graph.

3.4 *The SST cooling due to the TC Viyaru*

Holland (1997) and Emanuel (2003) proposed that high evaporation due to strong winds over warm water sustains the thermodynamic cycle of a TC. Deepening of the ocean-mixed layer cools the SST by several degrees Celsius under the track of the intense TCs (Price, 1981; Wentz et al., 2000; Lin et al., 2003). The maximum cooling was observed in the wake to the rear of the TC and adjacent to its track. The greatest reductions in the SST are generally found to the right of the TC's track in the Northern Hemisphere (Black and Dickey, 2008), and to the left of the track in the Southern Hemisphere (Berg, 2002). Figure 4 reveals the SST gradually cooling due to the passage of the TC Viyaru. Figure 4 shows the decreasing SST due to passage of the TC Viyaru. On 8 May 2013, the SST of the BoB center was above 31.2°C, and the SST near the equator was above 30.5ºC. The TC Viyaru was formed near the equator (5°N and 92°E). On 10 May 2013, the tropical storm Viyaru passed this region. On 13 May, the SST of the central BoB was below 30.0°C due to strong wind and surface waves. On 14 May, the SST was decreased in the vicinities of the track of the TC Viyaru below 29.5°C. On 15 May, the SST was more decreased than the previous day. This day the SST was below 29.3°C along the track of Viyaru due to the passage of cyclone. On 16 May 2013, the TC Viyaru hit over the Chittagong coast of Bangladesh. In this day, the SST was similar to the previous day. The strong winds and deepening of the MLD associated with the Viyaru helped to reduce the SST. The SST pattern of the satellite data was very similar to the in-situ Argo profiling data of surface temperature.

3.5 *Comparison of the temperature and salinity between pre- and post-cyclone*

Figure 5 shows the vertical profile of temperature in the ocean at pre-cyclone and post-cyclone along the track of the TC Viyaru. This vertical profile of temperature has been shown along the latitude (5°–15°N). In the pre-cyclone (Fig. 5a), the SST was above 31.5°C in the southern BoB and above 30.0°C at the near equator of the BoB and 31.0°C at the central BoB. These values signify the high SST which is responsible for cyclogenesis. In the post-cyclone (Fig. 5b), the SST was decreased due to the strong surface winds and surface waves associated with the tropical storm Viyaru. The SST was below 29.5°C at the near equator of the BoB, in the southern BoB and the central BoB. The upwelling occurred in the ocean during the passage of cyclone. This upwelling could not reach the sea surface to break down the subsurface stratified layer (barrier layer). It pushed up and mixed with the subsurface stratified layer. As a result, the BLT became shallower. So the vertical temperature (above 26°C) in the ocean also became shallower along the track of the TC Viyaru.

Figure 6 shows the vertical profile of salinity in the ocean at pre-cyclone and post-cyclone along the track of the TC Viyaru. In the pre-cyclone (Fig. 6a), the SSS was about 34.0 in the near equator of the BoB and 33.5 and below 33.0 in the southern and central BoB, respectively. In the central BoB, the SSS was low which should be presence of freshwater from the Krishna-Godavari River. Han and McCreary (2001) proposed that the surface salinity is affected also by the larger freshwater input from rivers. The freshwater from rivers inhibits vertical mixing near the surface. The low saline profile (about 33.0 was almost 35 m deep in the southern BoB and about salinity 33 (low saline profile) was approximately 45 m deep at 10°–11°N and 14°–15°N in the central BoB. Murty et al. (2000) mentioned that the saline stratification in the top 30 m (with low SSS) would help maintain warmer SSTs by trapping the net heat gain on sea surface within the thin top layer due to little or absence of vertical mixing across the base of the stratified layer.

Thus the thin oceanic stratified layer couples closely to the intense convection in the lower atmosphere. In the post-cyclone, the SSS was increased along the track due to strong vertical mixing of the TC Viyaru. The saline profile also shows the high salinity in the southern and central BoB due to the upwelling and enhanced vertical mixing which bring the dense saline water from a deep ocean to a subsurface ocean.

3.6 *Anomalies of the oceanic parameters due to TC Viyaru*

All Argo floats in this study except the Argo with ID 2902086

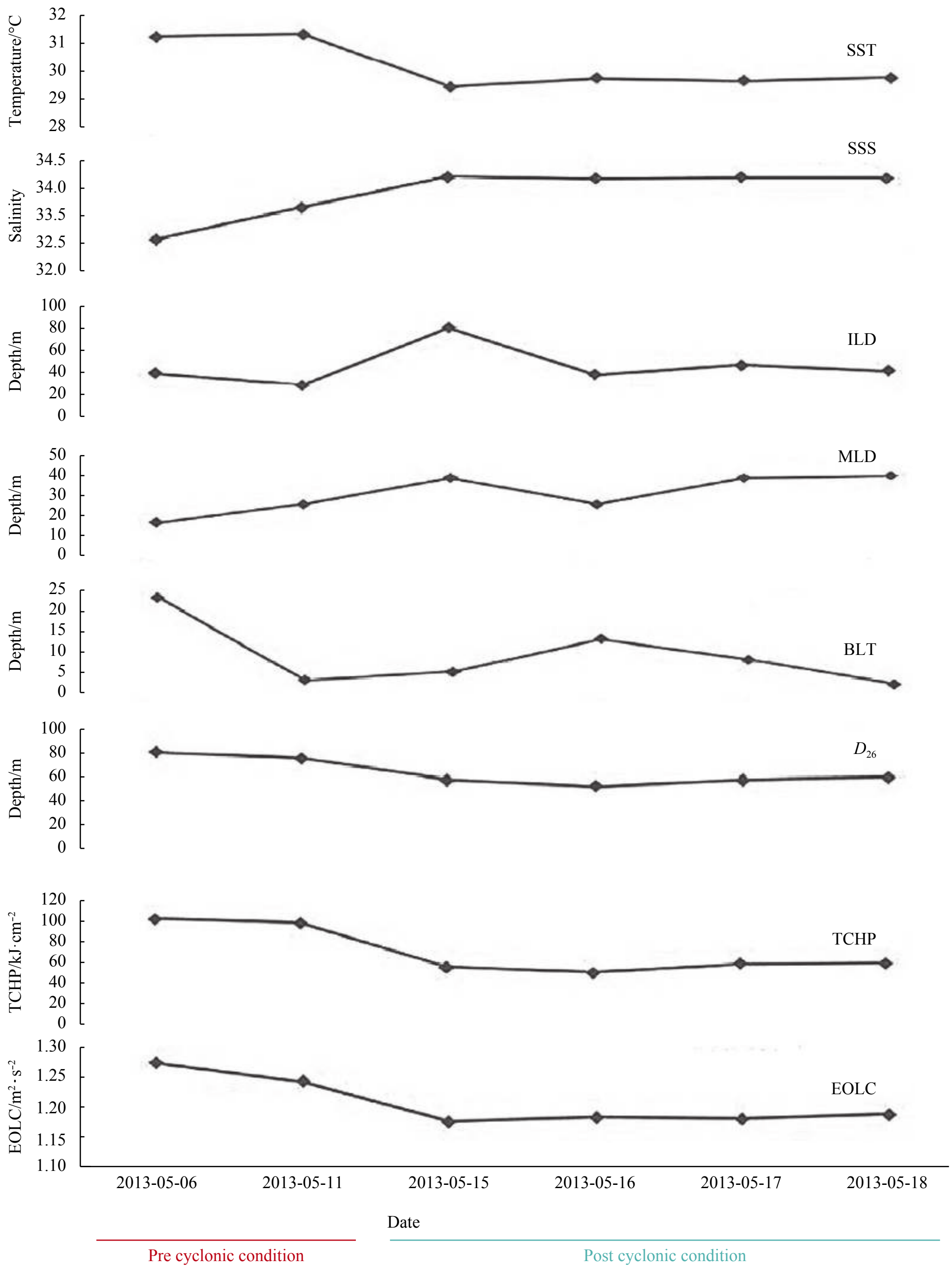

Fig. 3. The variation of sea surface temperature (SST, 5 m), sea surface salinity (SSS, 5 m), isothermal layer depth (ILD), mixed layer depth (MLD), barrier layer thickness (BLT), 26°C isotherm depth in ocean (D_{26}), tropical cyclone heat potential (TCHP) and effective oceanic layer for cyclogenesis (EOLC) in the Zone-2 along the track of the tropical cyclone Viyaru.

have been used to investigate the change or anomaly (mean post-oceanic condition minus pre-oceanic condition) of the passage of cyclone Viyaru, in the SST, SSS, D_{26}, ILD, MLD, BLT, TCHP and EOLC. The Argo with ID 2902086 is used for monitoring the change or anomaly in SST, SSS, D_{26}, ILD, MLD, BLT, TCHP and EOLC. These anomalies show the large-scale impact of Viyaru on the upper ocean. The Argo floats with IDs 2901090, 2901331, 2902086, 2901287 and 2901288 were situated in the Zone-1, Zone-2, Zone-3, Zone-4 and Zone-5, respectively. These Argo IDs were the nearest on either side of cyclone track over which the Viyaru intensified. The impact was larger on the right of cyclone track with a drop in the SST between –0.5 and –1.6°C (Fig. 7a). The highest SST drop was recorded by Argo with ID 2901331 in the Zone-2 due to the intensity of the TC Viyaru was weak. The TC Viyaru moved slowly, so the dominant wind stress forcing on the sea surface was relatively longer and well mix with the upper ocean in that area. The lowest SST was dropped at Argo ID 2901090 in the Zone-1 due to the intensity of the TC Viyaru that was strong and fast moving. Bender et al. (1993) pointed out that the TCs, grouped as "slow, medium and fast", moving result in a surface cooling off high, medium and low, respectively.

Other oceanic parameters were also affected by strong and

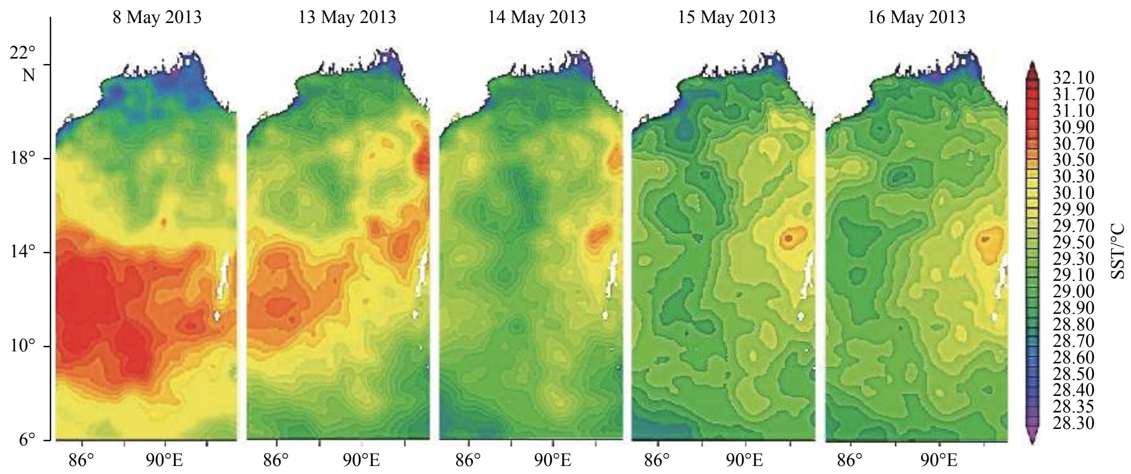

Fig. 4. The decreasing sea surface temperature (SST) due to the tropical cyclone Viyaru (8, 13, 14, 15 and 16 May 2013).

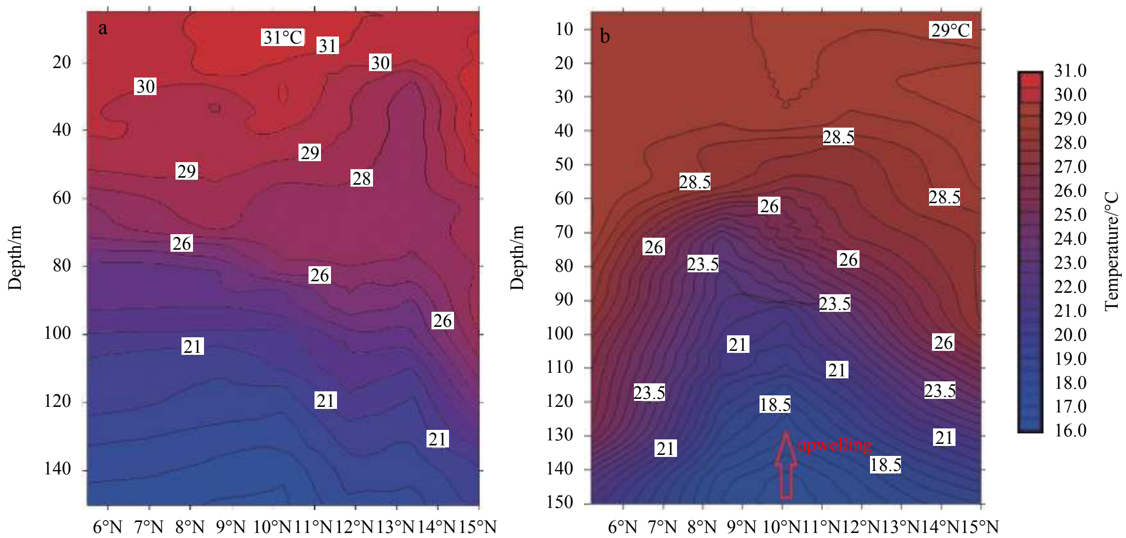

Fig. 5. The vertical profile (5°–15°N) of temperature in the ocean at pre-cyclone (a) and post-cyclone (b) along the track of tropical cyclone Viyaru.

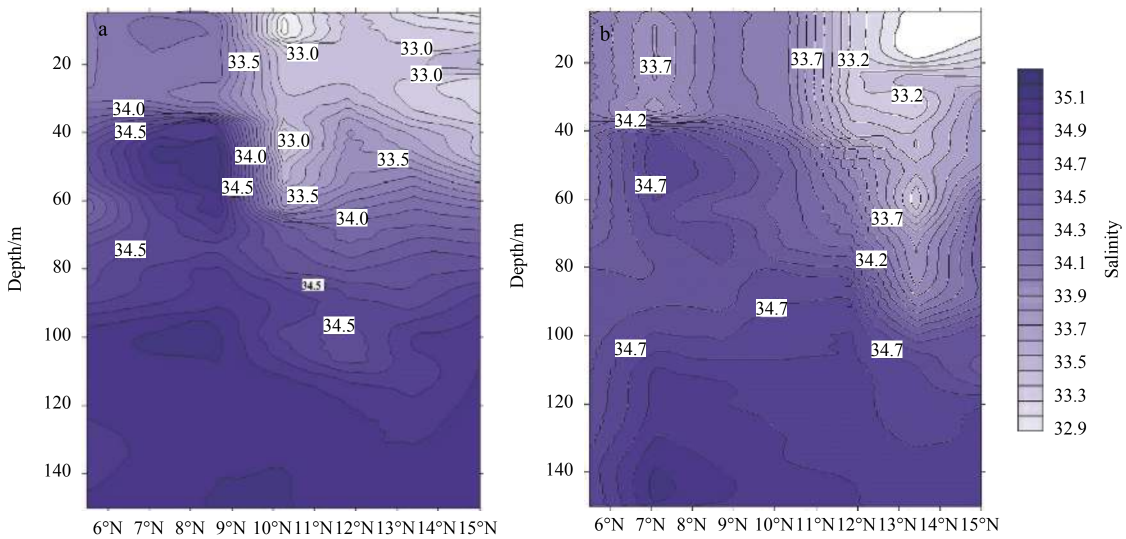

Fig. 6. The vertical profile of salinity in the ocean at pre-cyclone (a) and post-cyclone (b) along the track of the tropical cyclone Viyaru (5–15°N).

weak intensities of the TC Viyaru. Argo ID 2902086 in the Zone-3 also shows the SST is positive because it is 6 h before the tropical storm Viyaru passed in this region. The high SST is present at this time.

The SSS was more increased at Argo ID 2901331 in the Zone-2 due to the well mixing of the sea surface and also subsurface upwelling. The SSS was less increased at Argo ID 2901287 in the Zone-4 that has been shown in the Fig. 7b. At the Argo ID 2901090 in the Zone-1, the SSS was increased by 0.309 as the southern BoB belongs to the high salinity region than the northern BoB. The northern BoB is much affected by the Brahmaputra-Ganga-Meghna (BGM) River with large amount of freshwater discharge. At the Argo ID 2902086 in the Zone-3, the SSS was negative because it was 6 h before the tropical storm Viyaru passed in this region.

On the right side of the cyclone track, the ILD was deeper (between 5.0 m and 17.5 m) that has been shown in Fig. 7c. The deeper value of the ILD was found in the Zone-2 and shallower value was found in the Zone-3 that were 17.5 and 5.0 m, respectively. The MLD was deeper due to the strong surface winds and waves which enhanced the vertical mixing in the upper ocean. On the right side of the cyclone track, the MLD was deeper (between 4.0 and 14.5 m) (Fig. 7d). The highest ILD was deeper at Argo ID 2901331 in the Zone-2 and the lowest ILD was deeper at Argo ID 2901090 in the Zone-1. At the Argo ID 2902086 in the Zone-3, the MLD was negative because it was 6 h before the tropical storm Viyaru passed in this region.

Figure 7e shows the BLT anomaly in the upper ocean due to the TC Viyaru. The BLT was the sensitive subsurface oceanic layer and it was changing rapidly influenced by the ocean dynamic processes. Generally, the BLT was shallower after the cyclone. The BLT was shown the surprised anomaly except the Argo IDs 2901331 and 2902086 in the Zone-2 and Zone-3, respectively. The BLT was shallower in 6 m at the Argo ID 2901331 in the Zone-2. At the Argo ID 2902086 in the Zone-3, the BLT was deeper in 10 m because it was 6 h before the tropical storm Viyaru passed in this region. At this time, the thermal inversion was present in the float area. The deeper BLT was also found in this zone. The other Argo floats also showed the deeper BLT that may be the limitation of data or change of position and time.

The depth of the 26°C isotherm (D_{26}) in the upper ocean was shallower after the passage of cyclone. Figure 7f shows the anomaly due to the TC Viyaru. On the right side of the cyclone track, the D_{26} was shallower between 13.0 m and 19.3 m. The highest D_{26} was shallower at Argo ID 2901331 in the Zone-2. At the Argo ID 2901288 in the Zone-5, it was situated on the left of the cyclone track. In this zone, the D_{26} was much shallower in 1 m depth. This was the lowest D_{26} in the all Argo floats.

Figure 7g shows the TCHP anomaly due to the TC Viyaru. The estimated rate of change in the TCHP was negative and varied between –13.4 and –41.9 kJ/cm², suggesting larger heat loss in response to Viyaru. It appears that most of the TCHP loss occurred in the upper 150 m layer except the Argo ID 2902086 in the Zone-3. The highest TCHP was lost at the Argo ID 2901331 in the Zone-2 and the lowest TCHP was lost at the Argo ID 2901090 in the Zone-1 due to the highest and lowest SST drop that associated with the moving speed of the cyclone.

The EOLC signifies the geopotential thickness of a near surface stratified layer where low salinity water was found. During the pre-cyclone, the higher EOLC is present and during the post-cyclone, the lower EOLC is found along the cyclone track. The Figure 7h shows the expecting rate of change in the EOLC was negative and varied between –0.007 7 and –0.076 1 m²/s², suggesting larger change in the thickness of near the surface strati-

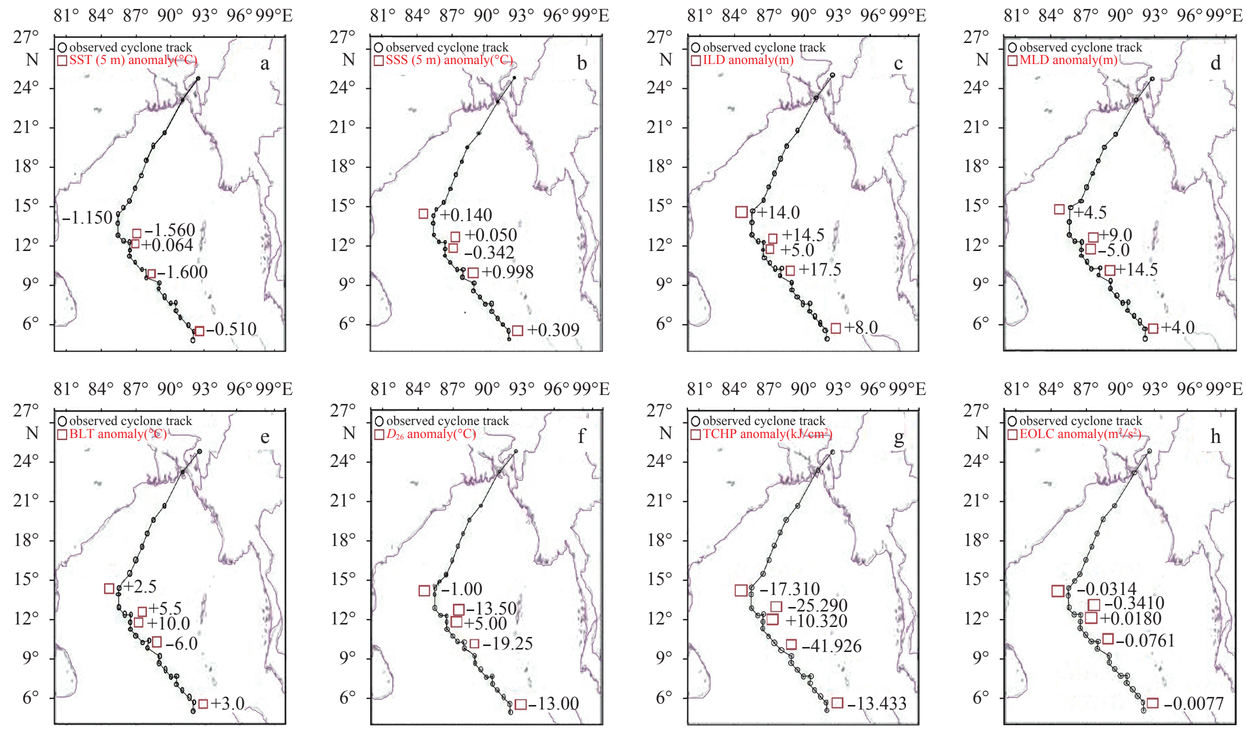

Fig. 7. Anomalies of sea surface temperature (SST) (a), anomalies of sea surface salinity (SSS) (b), anomalies of isothermal layer depth (ILD) (c), anomalies of mixed layer depth (MLD) (d), anomalies of barrier layer thickness (BLT) (e), anomalies of 26°C isotherm depth in the ocean (D_{26}) (f), anomalies of tropical cyclone heat potential (TCHP) (g) and anomalies of effective oceanic layer for cyclogenesis (EOLC) (h) due to the tropical cyclone Viyaru.

fied layer in response to Viyaru. The highest EOLC anomaly was found in the Zone-2 and the lowest EOLC anomaly was found in the Zone-1.

From the observation, the SST, BLT, D_{26}, TCHP and EOLC were more reduced and the SSS, ILD and MLD were more increased in the Zone-2 due to weak intensity of TC Viyaru. On the other hands, the SST, BLT, D_{26}, TCHP and EOLC were less reduced and the SSS, the ILD and the MLD were less increased in the Zone-1 due to strong intensity of the TC Viyaru.

3.7 *Variations of air-sea heat fluxes and upper ocean heat budget during Viyaru*

Based on the National Center Environmental Prediction (NCEP) reanalysis daily data, Table 2 shows the average net short wave (NSW), the net long wave radiation, the fluxes of latent heat (LHF), the sensible heat fluxes (SHF), the total heat loss and the surface net heat flux (NHF) in the BoB (5°–23°N, 84°–92°E) along the track of TC Viyaru during 8–17 May 2013. Under the impact of the cyclone Viyaru and associated higher cloudiness and stronger winds, the NSW shows a decreasing trend, the LHF shows an increasing trend (the LHF is a loss component and shows as negative values) and the NHF exhibits a decreasing trend. The negative NHF and its decreasing trend imply the net heat loss across the sea surface during Viyaru. The NSW shows the minimum values (200.1 W/m^2) on 12 May but the NSW value (228.6 W/m^2) is little increased on 15 May. The LHF shows the high value (–157.0 W/m^2) on 15 May (large negative value of heat loss), and the large decrease in the NHF to a minimum value (–26.2 W/m^2) on 14 May but not on 15 May. These reanalysis data for the Viyaru period give confidence in the overall behavior of the surface fluxes prior to and during the passage of the Viyaru.

3.8 *Comparison of upper ocean heat budget between the cyclone track domain and the whole BoB domain*

Figure 8 shows the difference between the averaged NSW of the cyclone track domain (5°–23°N, 84°–92°E) and the BoB domain (5°–23°N, 78°–100°E). In this figure, the NSW was decreased on 12, 13 and 14 May 2013 than the previous days due to strong winds associated with the tropical storm Viyaru and the presence of clouds in the sky. The NSW was gradually increased on 15 and 16 May 2013 due to the tropical storm Viyaru landfall on the Chittagong coast, Bangladesh on 16 May 2013. The NSW radiation along the track was less than the BoB domain. The tracks of the NSW and BoB NSW show the most similar patterns.

The LHF along the track is more than over the BoB domain. The LHF is increased on 12, 13, 14 and especially 15 May 2013 due to form condensation clouds from the water vapor (evaporation). The large LHF assists as fuel for the intensity of the cyclone. The increased LHF trend significantly reveals the decreased trend of the NHF. After landfall of Viyaru, the LHF was gradually decreased on 16 and 17 May 2013. The track LHF and BoB LHF show the similar patterns.

The SHF along the track was less than over the BoB domain that possibly because of presence of the strong surface winds and precipitation. Green and Zhang (2013) proposed that the fluxes of the sensible and latent heats (i.e., moist enthalpy) affect the intensity of cyclone but do not significantly change the pressure-wind relationship. In a cyclonic track domain, the SHF was increased on 11 May and then gradually decreased and increased till on 15 May 2015. After the landfall of Viyaru, the SHF was decreased on 16 and 17 May 2013. Over the BoB domain, the SHF shows the increased trend than the cyclone track domain due to absence of strong surface winds except cyclone track domain.

Table 2. The upper ocean heat budget of the Bay of Bengal domain (5°–23°N, 84°–92°E) along the track during Viyaru

Date	Net short wave radiation/W·m^{-2}	Net long wave radiation/W·m^{-2}	Latent heat flux/W·m^{-2}	Sensible heat flux/W·m^{-2}	Total heat loss/W·m^{-2}	Net heat flux/W·m^{-2}
2013-05-08	219.3	–52.20	–122.7	–14.10	–189.1	30.20
2013-05-09	222.2	–54.12	–121.3	–14.84	–190.3	31.93
2013-05-10	214.9	–56.03	–105.0	–15.16	–176.2	38.75
2013-05-11	219.2	–59.40	–127.6	–22.72	–209.7	9.49
2013-05-12	200.1	–51.63	–134.5	–17.70	–203.9	–3.73
2013-05-13	200.3	–50.37	–155.9	–20.68	–226.9	–26.59
2013-05-14	200.5	–49.87	–154.8	–22.02	–226.7	–26.23
2013-05-15	228.7	–53.75	–157.0	–22.66	–233.4	–4.75
2013-05-16	238.6	–61.04	–132.7	–16.72	–210.5	28.09
2013-05-17	244.0	–60.65	–116.7	–16.74	–194.7	49.96
2013-05-18	219.0	–55.42	–150.3	–21.74	–227.5	–8.48

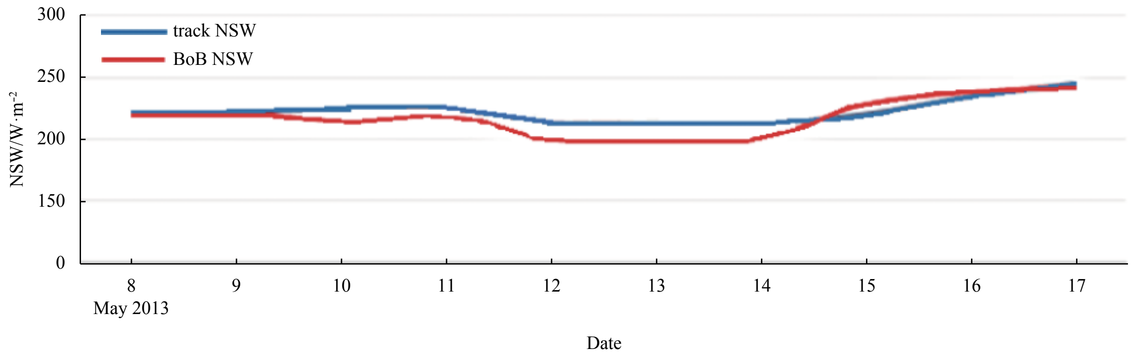

Fig. 8. Comparison between the average values of the net short wave (NSW) of the cyclone track and the Bay of Bengal domains.

The turbulent fluxes (the sensible and latent heat fluxes) act as fuel for intensification of cyclone.

In Fig. 9, the NHF along the track is rapidly reduced than over the BoB domain. The great net heat loss (the negative NHF value) was started on 12–15 May 2013, especially great heat loss on 13 and 14 May in the cyclone track domain. Over the BoB domain, the averaged negative NHF was increased on 12–15 May 2013, especially on 13 May. The track NHF and BoB domain NHF show the nearly similar patterns. These great net heat losses significantly reveal that the TC Viyaru was passed at this time and in domain area.

4 Conclusions

Most of the severe cyclones in the Bay of Bengal form during pre-monsoon (April–May) and post-monsoon (October–November) seasons. We take the TC Viyaru in 2013 as an example, Argo (*in situ*) observations in the upper ocean together with the satellite data from the NCEP revealed the structure of the upper ocean anomaly associated with air-sea interactions. The observations and model results signify the followings:

(1) The values of the SST, D_{26}, BLT, TCHP and EOLC in the pre-cyclonic condition are higher than post-cyclonic condition of the ocean;

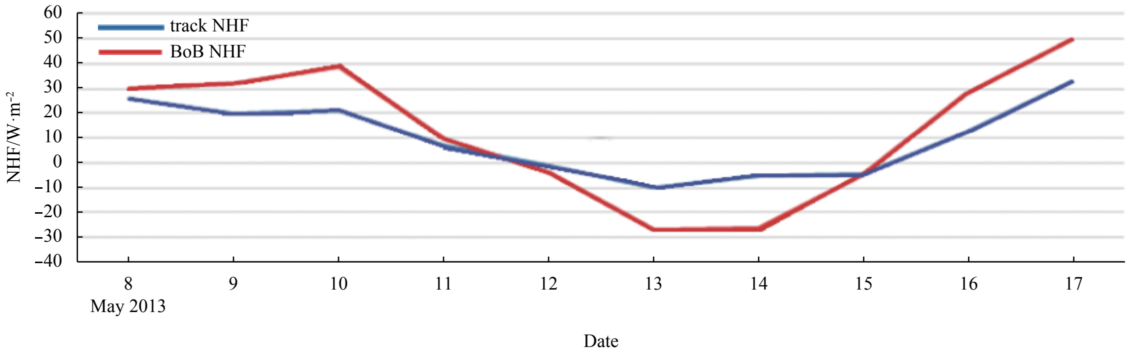

Fig. 9. Comparison between the average net heat fluxes (NHF) of the cyclone track and the Bay of Bengal domains.

(2) The values of the SSS, ILD and MLD in the post-cyclonic condition are higher than pre-cyclonic condition of the ocean due to strong cyclonic winds, surface wave and subsurface upwelling. The subsurface upwelling helps to reduce the BLT;

(3) The 26°C isotherm (D_{26}) exists more deepen in the southern BoB than that in the northern BoB;

(4) The strong intensity of cyclone reduces less SST and the weak intensity of cyclone reduces more SST;

(5) The great net heat losses can be seen one or two days before the cyclone hits the coast.

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