Indian Journal of Geo Marine Sciences
Vol. 48 (01), January 2019, pp. 9-17

Sea surface temperature cooling induced by Tropical cyclone Hudhud over Bay of Bengal

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Received 03 August 2017; revised 17 November 2017

Hudhud was a very severe cyclone storm occurred in October 2014 over Bay of Bengal (BoB). This paper deals with the sea surface temperature (SST) cooling occurred due to Hudhud. When compared the SST difference between before cyclogenesis and landfall, cooling of 3°C observed. Maximum cooling of SST occurred on 11-12 Oct due to strong winds covered and robust convection all over BoB. Buoy data clearly indicating SST cooling and entrainment of subsurface waters to mixed layer. ARGO data also clearly signifying the SST cooling, however the cooling magnitude is lower (-1.25°C) due to difference in profile timing.

[**Keywords**: Hudhud, SST cooling, ARGO, Buoy, Bay of Bengal]

Introduction

Tropical cyclones (TCs) are severe weather systems with intense air-sea interactions over warm oceans. Warm sea surface temperature (SST) is fundamental factor in TC formation[1], however various large scale environment factors are also impact for TCs genesis and development. The tropical warm north Indian Ocean (NIO, including both the Bay of Bengal (BoB) and Arabian Sea) is a causing for the disastrous TC phenomenon and is seasonal. Cyclogenesis mainly occurs in pre and post monsoon seasons and post monsoon storm are found to be more intense and cause for economical and human loses[2,3]. Over the BoB area between 5°N–20°N and 87°E–91°E is more suitable region for the formation of cyclonic disturbances3. It is well known that TC develops only over warm oceans with SSTs of 26°C or higher[4]. During the cyclogenesis and storm development stages, a positive feedback occurs between tropical cyclone and ocean system. Impact of SST on the genesis and intensification of TC has long been recognized. As the tropical cyclone strengthens, the evaporation rate grows due to the increase in the surface wind speed. The enhancement of the moisture supply from the ocean leads to an increase in the latent heat energy that drives the circulation of the tropical cyclone. The rapid intensification was observed when these hurricanes passed over warm ocean features or sharp gradient of SST with the deepening of the mixed layer[5,6,7].

The response of the surface ocean to asymmetric wind stress and stress curl is an active area of research[8,9]. TC-forced SST cooling is a striking phenomenon that of central importance to the interaction between ocean and cyclones[10]. TC induced temperature cooling often reveals on the right side of the track, which was attributed to wind stress vector turned clockwise[11,12,13]. TC can induce cooling wakes at the ocean surface due to strong cyclonic winds, resulting lower SST along their track[11,14,15,16,17]. Differential SSTs near the TC center ensues the wind field, intensity and track[18,19,20]. TC translation speed will cause a significant drop in SST due to entrainment of subsurface waters[21,22]. The upper ocean response characteristics of the ocean to TC are asymmetric in both sides of the track[23,24,25]. TC intensity promotes increases of cold wake by ocean mixing and upwelling with respect to wind intensity[10,25]. Bender[26] found that the cyclone induced sea surface cooling has a significant impact on the storm intensity.

Recent studies over NIO region reveal the facts about the relation between the convection and the SST gradient. Surface winds and convection is having significant impact on not only the SST magnitude but also SST gradient. TCs change ocean surface and subsurface temperatures mainly through vertical mixing and upwelling processes in the ocean due to very strong winds and torrential rains. Vertical mixing is associated entrainment process in the upper ocean, produced by wind-induced current velocity shear[5,27]. Upwelling induced by TCs strong cyclonic wind field at the ocean surface throughout the water column by Ekman pumping[8,28] in the right side of the TC track. Vertical mixing mainly explains the surface temperature cooling in the open ocean[29].

Previous studies explained the precipitation structures are complex and different from each of the TC[30,31,32,33]. Rainfall intensity of TC increases with its intensity[34]. The heaviest precipitation generally takes place in the front of a TC and the asymmetry in precipitation varies with intensity[35]. In some cases, strongest precipitation occurred in the rear of a TC[36]. TC translation speed can have significant effects on the asymmetric distribution in rainfall24. Some of the TCs impact coastal area with powerful winds and severe rainfall[37]. Owing to the severe weather condition during the TC passage, in situ observations are very difficult to obtain over the ocean. Variations in upper-ocean conditions can elucidate the effect of TC intensity and affects on magnitude[5,25,38,39,40,41]. Some studies have been carried out the effect of Hudhud on coastal waters off Visakhapatnam[42,43], however Hudhud effect over BoB is not been documented. In this study, SST, wind and rainfall data have used to investigate Hudhud very severe cyclonic storm induced SST variations during the typhoon and after landfall. To emphasize the typhoon induced SST cooling due to Hudhud.

Materials and Methods

The first TC to strike the Port city, Vishakhapatnam, with intensity of 100 knots (180 kmph) since 1891 is 'Hudhud' over the Bay of Bengal (BoB). Figure 1 depicts the Hudhud track and intensity variations. A very severe cyclonic storm, Hudhud, equivalent to a category-4 hurricane on the Saffir–Simpson hurricane wind scale (SSHWS), originated in the Andaman Sea on 6 Oct 2014. The cyclone propagated west-northwest ward and made landfall near Visakhapatnam, concentrated into a Depression on 7 Oct over the North Andaman Sea. Moving west-northwest wards it intensified into a Cyclonic Storm (CS) on 8 Oct and crossed Andaman Islands close to Long Island between 0830 and 0930 hrs IST of 8 Oct. Then emerged into Southeast Bay of Bengal and continued to move west-northwest. It intensified into a Severe Cyclonic Storm (SCS) on 9 Oct and further into a Very Severe Cyclonic Storm (VSCS) on 10 Oct. It continued to intensify while

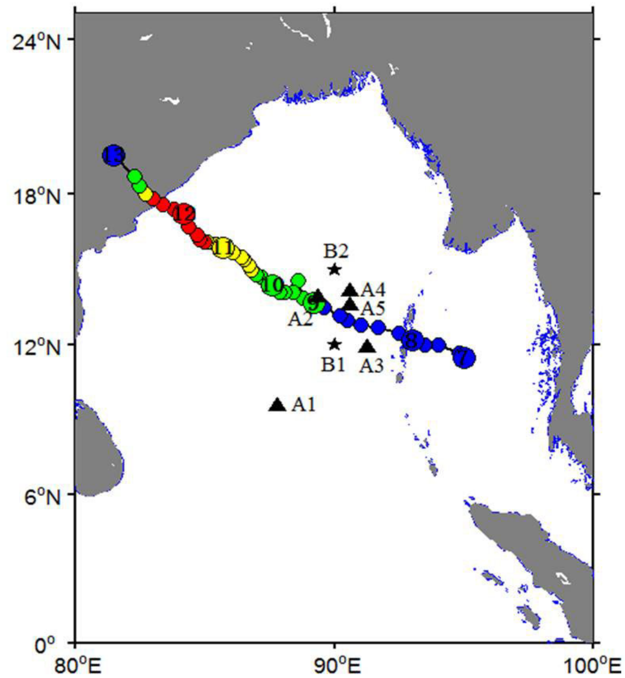

Fig. 1 — Study area for analysis of Hudhud saviour cyclonic storm. Includes the Hudhud track with its intensities (red colour indicates the very saviour intensity which landfall over Visakhapatnam). A1-A5 are the Argo data positions and B1-B2 are the buoy data positions

moving northwest and reached maximum intensity in the early morning of 12 Oct with a maximum sustained wind speed of 180 kmph over the West Central Bay of Bengal off Andhra Pradesh and northern coast of Andhra Pradesh on 12 Oct 2014. At the time of landfall on 12 Oct, the estimated maximum sustained surface wind speed in association with the cyclone was about 100 Knots. The estimated central pressure was 950 hPa with a pressure drop of 54 hPa at the centre compared to surroundings which caused very heavy to extremely heavy rainfall. Description of the Hudhud is given in Cyclone Warning Division, India Meteorological Department[44].

The international Best Track Archive for Climate Stewardship (IBTrACS)[45] included best-track data from the IMD. SST data is obtained from Operational SST and Sea Ice Analysis (OSTIA) system produces a high resolution (1/20° - approx. 5km) daily analysis of the current SST over the global ocean. OSTIA uses satellite data provided by the GHRSST project together with in-situ observations to determine the SST[46]. Rainfall data has been used from Tropical Rainfall Measuring Mission (TRMM)-Multi-satellite Precipitation Analysis (TMPA) 3B42 precipitation product version 7[47] has spatial resolution of 0.25° grid and covering the globe from 50° S to 50° N. TRMM 3B[42] has been frequently used for TC rainfall analysis regionally and globally[34,48,49]. Argo Profiling floats vertical profiles of the water temperature were obtained from profiling floats during their ascents. Real-time quality control was performed before the data were made available on the Argo Real Time Data Base (http://www.argo.ucsd.edu, http://argo.jcommops.org). The aim of this work is to check and describe how SST cooling occurred in Argo floats and the reasons for cooling and the factors influenced by Hudhud in the BoB. Buoy data is obtained from the website https://www.pmel.noaa.gov/tao/drupal/ disdel/ over BoB to explain the variations in temperatures during the Hudhud period by using high resolution data and daily temperature data. Wind data used for this analysis is from MERRA. The Modern Era Retrospective-Analysis for Research and Applications (MERRA) was undertaken by NASA's Global Modelling and Assimilation Office. MERRA generated with version 5.2.0 of the Goddard Earth Observing System (GEOS) atmospheric model and data assimilation system (DAS), and covers the modern satellite era from 1979 to the present[50].

Results and Discussion

Hudhud is severe cyclonic storm occurred in the BoB, SST, wind and rainfall variations are depicted in figure 2. Tropical cyclones develop only over warm oceans with SSTs of 26°C or higher4. On 6 Oct a low pressure system formed in the Andaman Sea. Over the genesis area temperatures are around 28°C, which is a favourable condition for the formation of low pressure system. Intensifying of cyclonic winds observed on 6 Oct with rainfall over 60 mm. There are small patches of cooler water can be observed with SST (27.5°C) over central BoB and southern side of Andaman around 5-10°N, however low pressure intensified and form as storm on 7 Oct and moving towards Andaman islands. Wind speed increased and rainfall is spreading over Andaman Island also over preceding side of the cyclone. Figure 2 clearly indicates that on 8 Oct cyclonic wind field moving from Sri Lanka and increases intensity of Hudhud. The total moisture flux contributed by wind convergence at the center of typhoon is from far larger than that of moisture advection[51]. Winds are converging at the center of the Hudhud eye, which contributing for moisture incursion towards the center of Hudhud leading to higher rainfall over BOB.

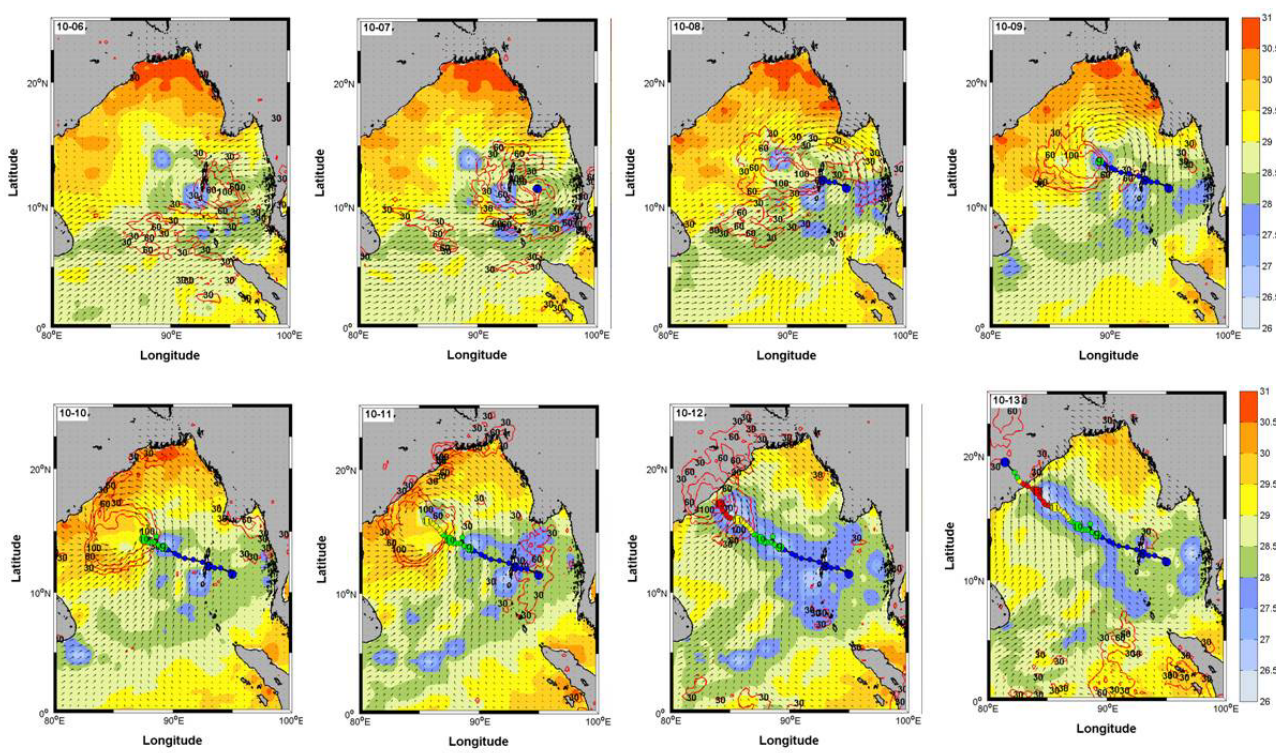

Fig. 2 — Variation of Sea surface temperature (°C in shading), surface wind (m/s as vectors) and rainfall (mm as contour in red colour) with Hudhud cyclone track during the cyclone period (6 October -13 October 2014). Cyclone intensity is represented as in different colours in cyclone track (red colour over the coast represents the very severe cyclonic storm, which land fall over Visakhapatnam)

On 8 Oct, storm crossed Andaman Island and moving towards west. Low temperature areas can observe in the preceding side of the Hudhud (eastern of Andaman Island) with 27.5°C. Lower SST patches in the southern Andaman retained in spatial and the temperature. However, Hudhud move western side and followed to the lower temperature patch observed in previous days. Left side of the track experience higher rainfall than on the right side. In the northern BoB and East coast of India are indicating higher SST (>30°C). Decrease in higher temperature spatial area can be observed as Hudhud intensifying day after day. Wind intensified and the cyclonic wind spatial area increased. The typhoons intensity of storms can exert a significant control by translation speed of a storm[25,52]. Convection process will increase with the warmer temperature. Warmer SST prepares the required energyfor TC to produces higher precipitation rate. On 9 Oct Hudhud intensified further and the translation speed is low, cyclonic winds are spreading all over the BoB. This clearly indicates the lower translation speed exerts an increase in intensity of Hudhud. Rainfall increased and spreading over a smaller area than the previous day in the right side however left side of the track experiences higher rainfall. On 10 Oct cyclone changes its direction to northwest with increase in intensity. The radius of the cyclone increased on 11 Oct and intensified further. Ocean surface cooling induced by cyclones can influence by intensity, upwelling and mixing[11]. Variations in SST can cause rapid alteration in the wind field20 and also depends on translation speed of the typhoon[11,22,25]. SST cooling of 2°C can see in the eastern to central BoB along the track. Hudhud further intensified to very saviour cyclonic storm and move towards coastal waters off east coast of India. Higher SST over the coastal waters supplies energy to cyclone to intensity further. On 12 Oct Severe cyclonic storm Hudhud landfall over Visakhapatnam with violent winds (180 KMPH) and heavy rainfall (100 mm). After landfall on 12 Oct at Visakhapatnam, Hudhud decreased its intensity and move towards north. On 13 Oct intensity of Hudhud decreased and changed its direction to north wards and dissipated on 14 Oct. on 12 Oct, lower temperature patches observed along the track from the genesis to landfall; however on 13 Oct lower temperature patches decreased their spatial area and temperature increase. On 14 Oct lower temperature patches are confined to coastal waters. Figure 3 illustrate the SST difference

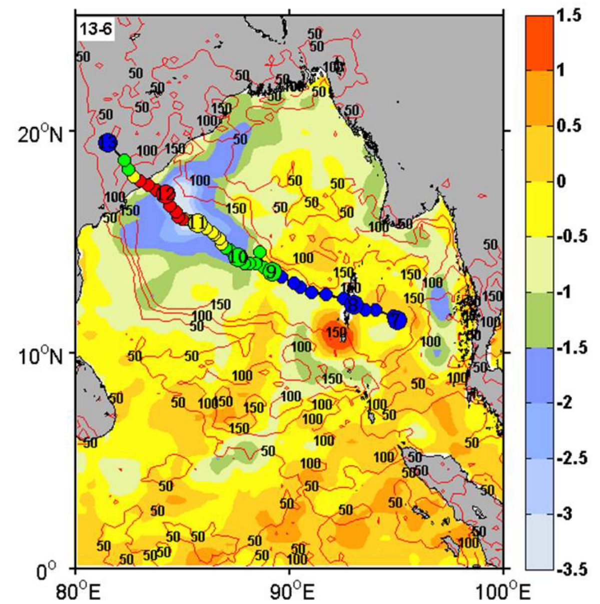

Fig. 3 — The difference in SST (°C) and cumulative rainfall (mm) occurred due to Hudhud (between 13 October and 6 October) with cyclone track. SST difference is indicating as in colour shading and rainfall as contours

(in shading) and cumulative rainfall between before typhoon (6 Oct) and after landfall (13 Oct). Typhoon induced temperature cooling often reveals on the right side of the track, which was attributed to wind stress vector turned clockwise[11,12,13]. It is clearly evident that SST decreased over coastal area is higher. At the genesis area to SCS there exists a cooling of -0.5°C and at the peak intensity area i.e., from SCS to VSCS, cooling of -3°C. However, Hudhud induced SST cooling is -3°C over the coastal waters. Hudhud induced higher cumulative rainfall in left side of the track than right side. Over the coastal waters, the area of higher SST cooling happened at the right side of track due to strong upwelling occurred during the landfall. However, in the left side of the track SST cooling can observed over a larger spatial area due to heavy rainfall (150 mm) occurred due to Hudhud. Over southern Andaman Island, SST increased by 1.5°C when compared the SST difference between genesis to landfall even though 150 mm rainfall occurred. Southern Andaman is in the left side of the cyclone track higher rainfall occurred while cyclone passing and due to wind direction towards the Island leads to downwelling, however SST increased after Hudhud landfall. Figure 4 depicts the variations of SST (shading) and surface water transport (vectors) at different locations selected randomly over the cyclone track during the cyclone period. Vertical mixing is

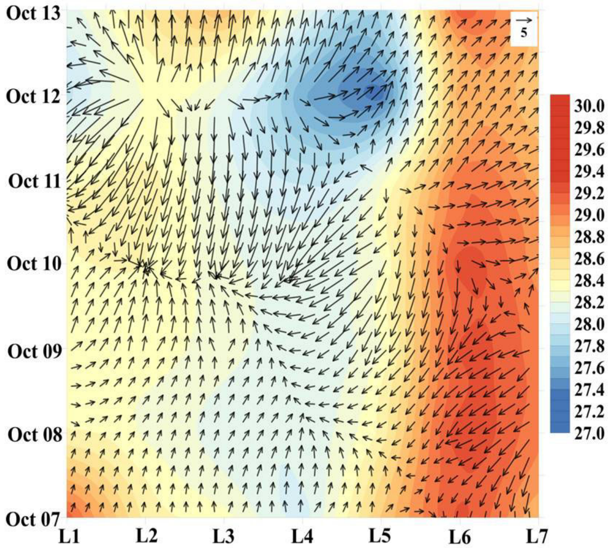

Fig. 4 — SST as shading (°C), and zonal surface water transport in vectors (Sv.) variations at different locations (L1-L7) during the Hudhud very severe cyclonic storm period. Zonal surface water moment indicates the upwelling where the vectors are diverged. Maximum divergence (upwelling) occurred at location L2 on 11 Oct., SST cooling occurred

associated entrainment process in the upper ocean produced by wind-induced current velocity shear, explains surface temperature cooling[5,27,29]. Upwelling can be induced by typhoons cyclonic wind field at the ocean surface throughout the water column by Ekman pumping[8,28]. Figure 3 clearly indicating that maximum divergence occurred at A2 on 12 Oct, which reveals that the cyclone attains its highest intensity leading to surface water divergence leading to strong upwelling. However, another surface water divergence occurred on the same day at A4 and 11 Oct at A5. Lower SSTs can observed at A5 on 12 Oct, indicating that, due to upwelling subsurface waters comes to surface and SST cooling occurred. SST decreased over the coastal waters during the cyclone landfall. Some of the typhoons influence coastal area with powerful winds and severe rainfall[37]. Typhoons can induce cooling wakes at the ocean surface due to strong cyclonic winds, resulting lower SST along their track[11,14,15,16,37]. Decrease in SST can clearly observe over the coastal waters (figure 1 and 2) during the cyclone period (7Oct to Oct13).

RAMA buoys are situated in the BOB, two buoy have been used for this analysis are at locations 12°N; 90°E (B1, right panel) and 15°N; 90°E (B2, left pannel) and temperature variations during the Hudhud period are illustrated in the figure 5. High-resolution (10 minutes) data from buoy B2 used to check the variation of temperature over the Hudhud period and over the depth of 100m. Figure 5a one can observe higher temperatures before Hudhud pass through B2, surface temperature of 29.6°C observed on 6-7 Oct, however surface temperature decreased to 28.6°C on 9 Oct further temperatures decreased (28.3°C) on 12 Oct. Lowest temperatures observed on 10-11 Oct is due to Hudhud intensity increased and became SCS and the winds are covering all over the BoB and found higher latent heat transfer from ocean to atmosphere (figure not given), which leading to Hudhud to get more energy to become VSCS before landfall over Visakhapatnam. SST variations observed in buoy data clearly indicating severity of Hudhud, which can observe all over BoB. From the temperature variations (figure 5b), it is clearly observed that temperature decreased when Hudhud became SCS and then VSCS, temperature increased slowly. During 10-11 Oct subsurface waters entrained to surface and there is a strong upwelling can be observed at the surface leading to cooler surface water with decrease in temperature of more than 1°C. Temperature profiles of the buoy (B1) situated at 12°N are given in 5c. Temperature profiles clearly indicating that before typhoon the temperatures are higher, decreased while Hudhud is passing, further temperature increases. Surface temperatures decreased especially during 10-12 Oct. Temperature decrease is due to the intensity of Hudhud increased and the influence of strong cyclonic wind produce upwelling over the region11. Right panel figures 5 b and d are temperature variations during the Hudhud period over a depth of 100m at 15°N; 90°E location. B2 is in the right side of the Hudhud track, before Hudhud form, surface temperatures can be observed maximum of 29.6°C, however when Hudhud passes the temperature decreases to 28.2°C and attains minimum on 10-12 Oct with decrease in temperature of 1.4°C. After typhoon landfall the temperature increases and when we see the subsurface temperatures there is an inversion up to 15 Oct, which indicating subsurface warming, later surface temperatures are increasing, warming of surface reduced and attaining higher mixed layer depth. Temperature profiles are given in the figure 5d, indicating cooling of surface during Hudhud lifetime and when attained its maximum intensity, then slowly attaining to normal. Maximum cooling happened during 11-12 Oct after Hudhud landfall increases mixed layer depth is 20m. From the buoy observations, it is evident clearly that the

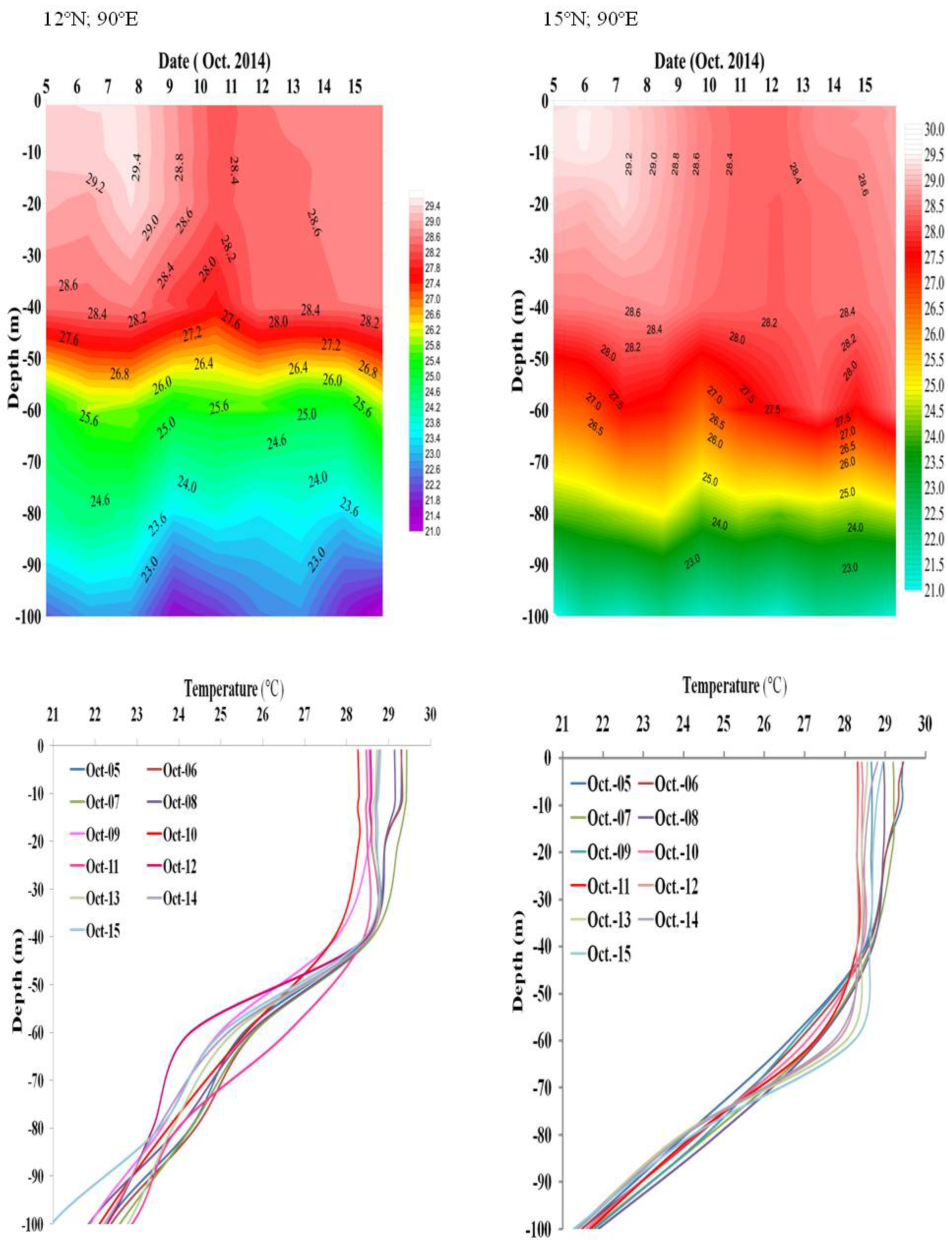

Fig. 5 — Temperature variations of RAMA buoy data during the Hudhud period. a) Temperature variations during the Hudhud period and up to 100 m depth at 12°N; 90°E, b) same as a) at 15°N;90°E. c) temperature profiles at 12°N;90°E (Oct.5 – 15, 2014) and d) temperature profiles at 15°N;90°E (Oct.5 – 15, 2014) . c and d clearly indicates the cooling of upper layer temperatures.

cooling occurred due to Hudhud and the maximum cooling occurred on 11-12 Oct

During the Hudhud period, there are 5 Argo data available, two Argos (A1 and A2) are in the left side and three (A2, A4 and A5 in figure 1) in the right side of the track. Argo at the position A1 is in the left side of the track, indicating there is SST cooling occurred on 12 Oct 0.1°C when compared with the profile on 3 Oct, however after typhoon landfall cooling is higher (0.43°C), this may be due to heavy rainfall occurred during the Hudhud period. Another Argo float A3 is available on left side of track, which reveals cooling of 1.0°C on 13 Oct compared with the profile on 3 Oct, this clearly explains that due to Hudhud there is strong cooling occurred. However, temperature increased 1.3°C after Hudhud landfall on 23 Oct warming of temperature occurred over BoB after Hudhud landfall. Another feature observed is mixed layer depth of 10m decreased on 13 Oct than before and after Hudhud period (3 and 23 Oct). Three Argos

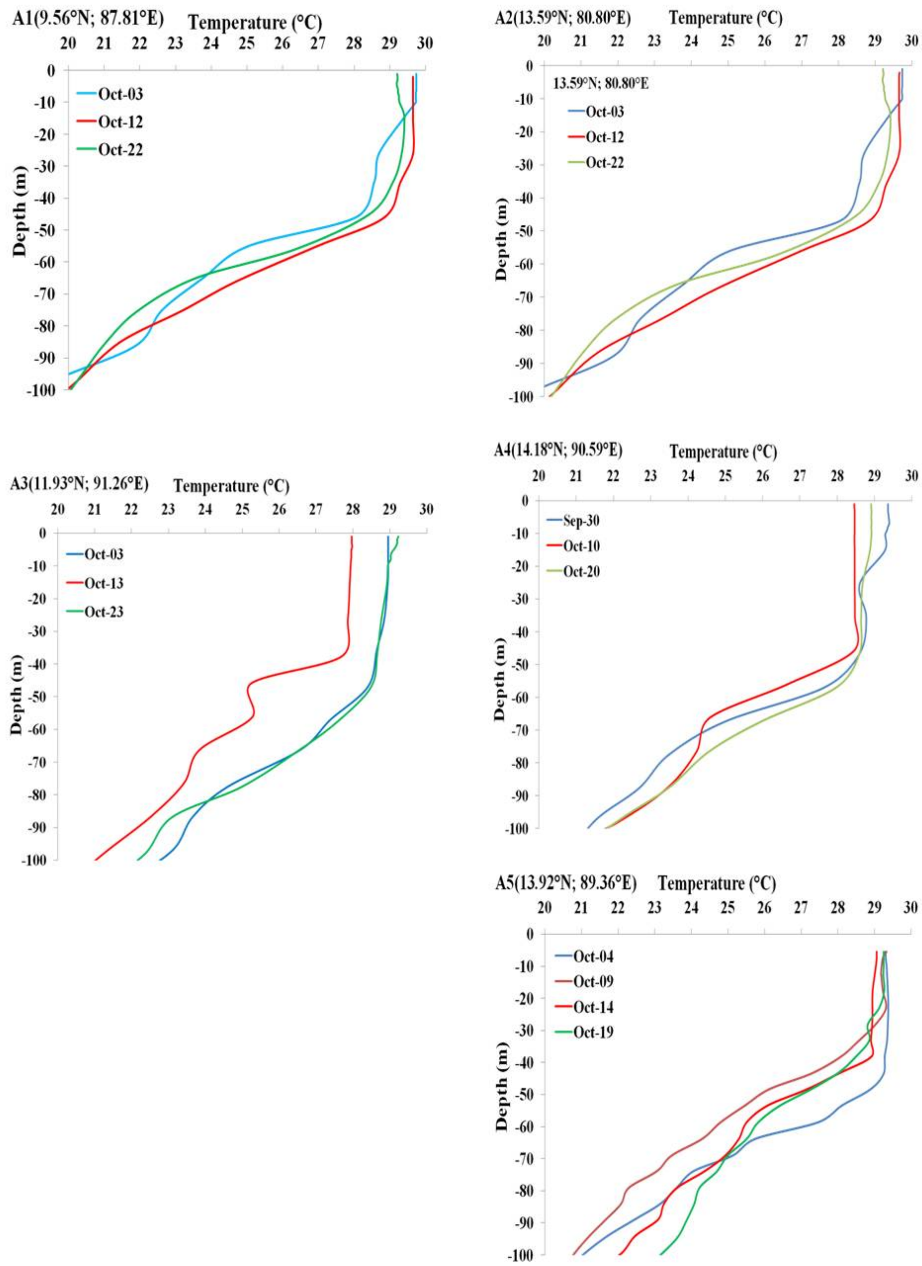

Fig. 6 — Temperature Profiles of Argo floats available during the Hudhud period at different locations (A1-A5 are shown in the figure 1; A1 and A3 are in the left side and A2, A4, A5 are in the right side of the track respectively) over Bay of Bengal. Mean position of Argo has been given for each plot.

floats data available in the right side of the Hudhud track. Temperature variations observed at the position A2 are indicating there is cooling of temperature of 0.1°C, however 0.5°C observed after landfall. Argo float A4 is at the right side of the track reveals there is cooling of temperature (0.9°C) on 10 Oct from the previous profile on 30 Sep. and increase of temperature on 20 Oct, by 0.5°C. The strong typhoon winds induced strong turbulent mixing and entrainment of cold water from below into the mixed layer, which results in the cooling of mixed layer water and deepening of the mixed layer depth[11,39].During the passage of Hudhud temperature cooling can be observed in the profile and increase in temperature and mixed layer depth after landfall. A5 is showing decrease in temperature 0.1 and 0.3°C while Hudhud passing (9 Oct) and after landfall (14 Oct), further there is an increase of 0.2°C in temperature (19 Oct).

This clearly indicates that temperature decrease during the typhoon passes and attains minimum temperature induced by the cyclone.

Conclusion

Hudhud is a VSCS, which influenced all over the BoB with strong cyclonic wind. Higher SSTs observed before formation of Hudhud. Hudhud induced SST cooling is 3°C over the coastal area. Over the BoB strong cyclonic wind influenced On 11 Oct leading to extensive latent heat produced heavy rainfall during the landfall. SST cooling of 1.4°C observed in buoys present in the BoB and 0.5°C cooling on Argo data. Divergence of ocean surface on 11 Oct at peak intensity area indicating a strong upwelling occurred due to strong cyclonic winds leading to higher SST cooling.

Acknowledgements

This work was supported by grants from National Basic Research Program (2013CB430302) and The Science and Technology Ministry, China (2016YFC1401905, GASI-IPOVAI-04, GASI-IPOVAI-06, 2017YFA0604900).

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