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Variations in intensity of Bay of Bengal tropical cyclones with surface latent heat flux and other parameters

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सार – यह अध्ययन समुद्र की सतह के तापमान, मध्य-क्षोभमंडलीय सापेक्ष आर्द्रता, मध्य-क्षोभमंडलीय अस्थिरता, ऊर्ध्वाधर पवन अपरूपण, 200-**एचपीए अपसरण, तीव्र उष्णकटिबंधीय चक्रवात की अवधि के दौरान गुप्त ऊष्मा प्रवाह और सतह के साथ तीव्र उष्णकटिबंधीय चक्रवातों (उष्ण कटिबंधीय चक्रवात) के केंद्रीय दाब (तीव्रता) की भिन्नता का पता लगाने के लिए किया गया है। इस अध्ययन का उद्देश्य तीव्र उष्ण कटिबंधीय चक्रवात की अवधि के दौरान केंद्रीय दाब (तीव्रता) के साथ उच्चतम सहसंबंध को दर्शाने वाले महत्वपूर्ण प्राचल को निर्धारित करना भी है। इन सभी प्राचलों में एसएलएचएफ तीव्र उष्ण कटिबंधीय चक्रवात के केंद्रीय दाब (तीव्रता) के साथ अत्यधिक सहसंबद्धित** (आर = 0.74) **है। एसएलएचएफ की वृद्धि और कमी उष्ण कटिबंधीय चक्रवातों के केंद्रीय दाब (उष्ण कटिबंधीय चक्रवात तीव्रता में वृद्धि और कमी) को दर्शाती है। उच्चतम एसएलएचएफ न्यूनतम केंद्रीय दाब (उच्चतम तीव्रता) को दर्शाता है।**

ABSTRACT. This study has been undertaken to find out the variation of central pressure (intensity) of intense Tropical Cyclones (TCs) with Sea Surface Temperature (SST), Mid-tropospheric Relative Humidity (MRH), Mid-tropospheric Instability (MI), Vertical Wind Shear (VWS), 200-hPa divergence, and Surface Latent Heat Flux (SLHF) during the lifetime intense TCs. This study also aims to determine the most crucial parameter which shows the highest correlation with central pressure (intensity) of intense TCs during their lifetime. Out of all these parameters, SLHF is highly correlated (R = 0.74) with the central pressure (intensity) of intense TCs. Increase and decrease of SLHF correspond to decrease and increase of TCs central pressure (increase and decrease in TCs intensity). The highest SLHF corresponds to the lowest central pressure (highest intensity).

Key words – Intense tropical cyclones, Surface latent heat flux, Bay of Bengal, ERA5.

1. Introduction

Tropical cyclones (TCs) are one of the most frequently occurring destructive weather phenomena of the world. They cause recurrent damages such as human fatalities, structural damages and economic losses worldwide. They are large-scale rotary systems which originate over warm ocean waters in the tropical or sub-tropical regions and are associated with organized convection, huge waves, storm surge, devastating winds and heavy precipitation. TCs have surface wind speeds of 34 knots or more for at least one 6-h period (Bhardwaj and Singh, 2020). On an average, the North Indian Ocean (NIO), including the Bay of Bengal (BoB) and the Arabian Sea (AS), accounts for 7% of the global TCs (Neumann, 1993). India is affected mainly by the TCs, which develop in the NIO, including the BoB and the AS. About 80% of these cyclones form in the BoB (Singh, 2007), and are highly variable in their movement and intensification. They develop in the pre-monsoon (March-May) and the post-monsoon (October-December) seasons of India and generally move west-northwestwards to northwestwards (Chinchole and Mohapatra, 2017). The average life period and frequencies of these TCs over the BoB are 4-5 and 4 days, respectively (Mohapatra *et al*., 2014b; Kumar *et al*., 2017). India Meteorological Department (IMD) classifies TCs into five categories based on their wind speeds, starting from Cyclonic Storm (CS) to Super Cyclonic Storm (SuCS). Very Severe Cyclonic Storms (VSCS), Extremely Severe Cyclonic Storms (ESCS) and SuCS are the most destructive and intense TCs. Therefore accurate prediction of their genesis, intensification and tracks are essential for better disaster preparedness and management.

Scientists have identified various processes such as large-scale circulations, air-sea interaction, vortex-scale convective circulations and cloud microphysical processes which influence the genesis and intensification of TCs. Several dynamic and thermodynamic factors such as high Sea Surface Temperature (SST) (>26.5 °C), low vertical shear of horizontal wind (VWS), increased low-level vorticity, significant Coriolis force, mid-tropospheric instability (MI), and high mid-tropospheric relative humidity (MRH), have been identified as crucial for genesis and intensification of TCs (Gray, 1979; Kotal *et al*., 2009). Apart from these parameters, Surface Latent Heat Flux (SLHF) is also an essential parameter for the genesis and intensification of TCs. It plays a vital role in coupling the atmosphere and the Ocean. As TCs primarily draw their energy from evaporation at the Ocean surface, SLHF plays a crucial role in their intensification (Gao and Chiu, 2010; Anderson *et al.*, 2013; Naskar and Naskar, 2021). Prediction of genesis and intensification of TCs continues to be a challenge and obviously more studies are needed in this area. A few case studies have been undertaken on TCs over the BoB, scientists have focused on a few individual dynamic and thermodynamic parameters associated with the genesis and intensification of a small group of TCs (Mohanty *et al*., 2019; Vishwakarma *et al*., 2022; Reshmi Mohan *et al*., 2022; Sanap *et al*., 2020; Ahmed *et al*., 2021).

The present study considers most of the important dynamic and thermodynamic parameters and the SLHF for a large group of TCs. This study is all about how the central pressure (intensity) of intense TCs over the BoB varies with these parameters during the lifetime of intense TCs. The study shows how the central pressure (intensity) is correlated with these parameters and will help identify the crucial parameter for genesis and intensification.

2. Data and methodology

The study region under consideration is the BoB (0° N-31° N, 79° E-111° E), which is shown in Fig. 1(a) with the genesis and landfall locations of intense TCs during the 30 year period 1990 to 2019. The red stars, dots and triangles are the genesis locations and blue stars, dots and triangles are the landfall locations of SuCS, ESCS and VSCS respectively during the above period. Here VSCS (wind speed 64-89 knots), ESCS (wind speed 90-119 knots) and SuCS (wind speed 120 knots and above) have been termed intense TCs. In this study, we have considered 31 intense TCs during the above period, out of which 22 originated in the post-monsoon and 9 in the pre-monsoon season. We have considered a total of 132 days (total lifetime of post-monsoon intense TCs) in the post-monsoon season and 57 days (total lifetime of pre-monsoon intense TCs) in the pre-monsoon season during this study period. We have also considered a total of 139 3-hourly positions in the post-monsoon season and 63 3-hourly positions in the pre-monsoon season during this period with at least one 3-hourly position in a day associated with the genesis and highest intensities of TCs. We have obtained the best track data from Regional Specialized Monitoring Centre (RSMC), New Delhi.

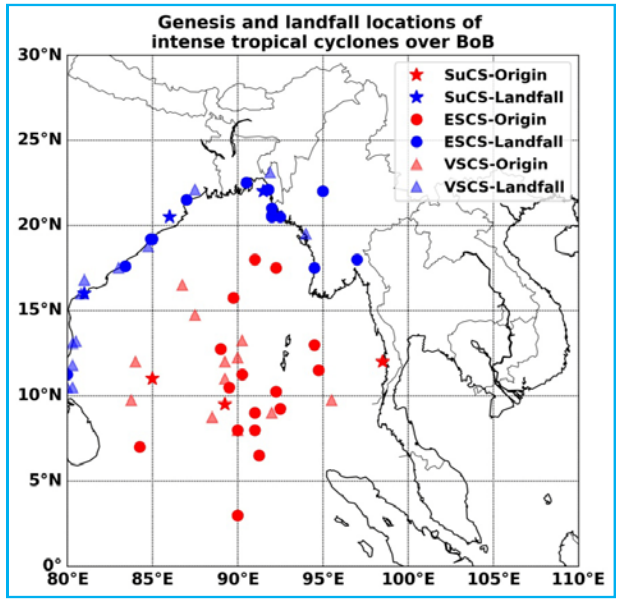


Fig. 1(a). Genesis and landfall locations of 31 intense TCs over BoB during 1990-2019

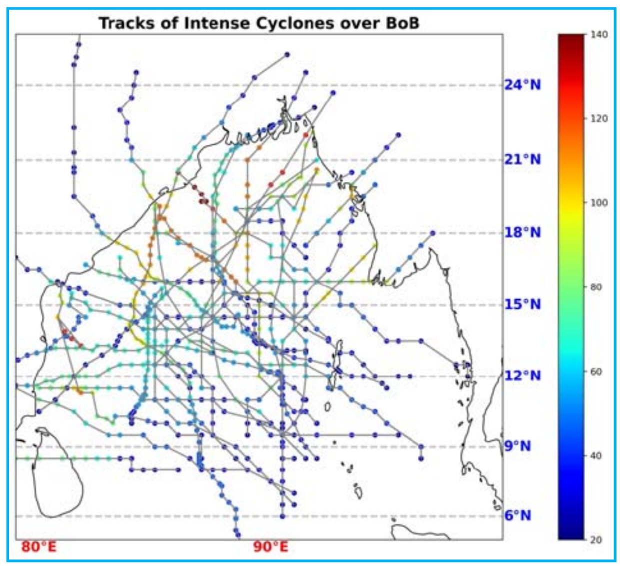
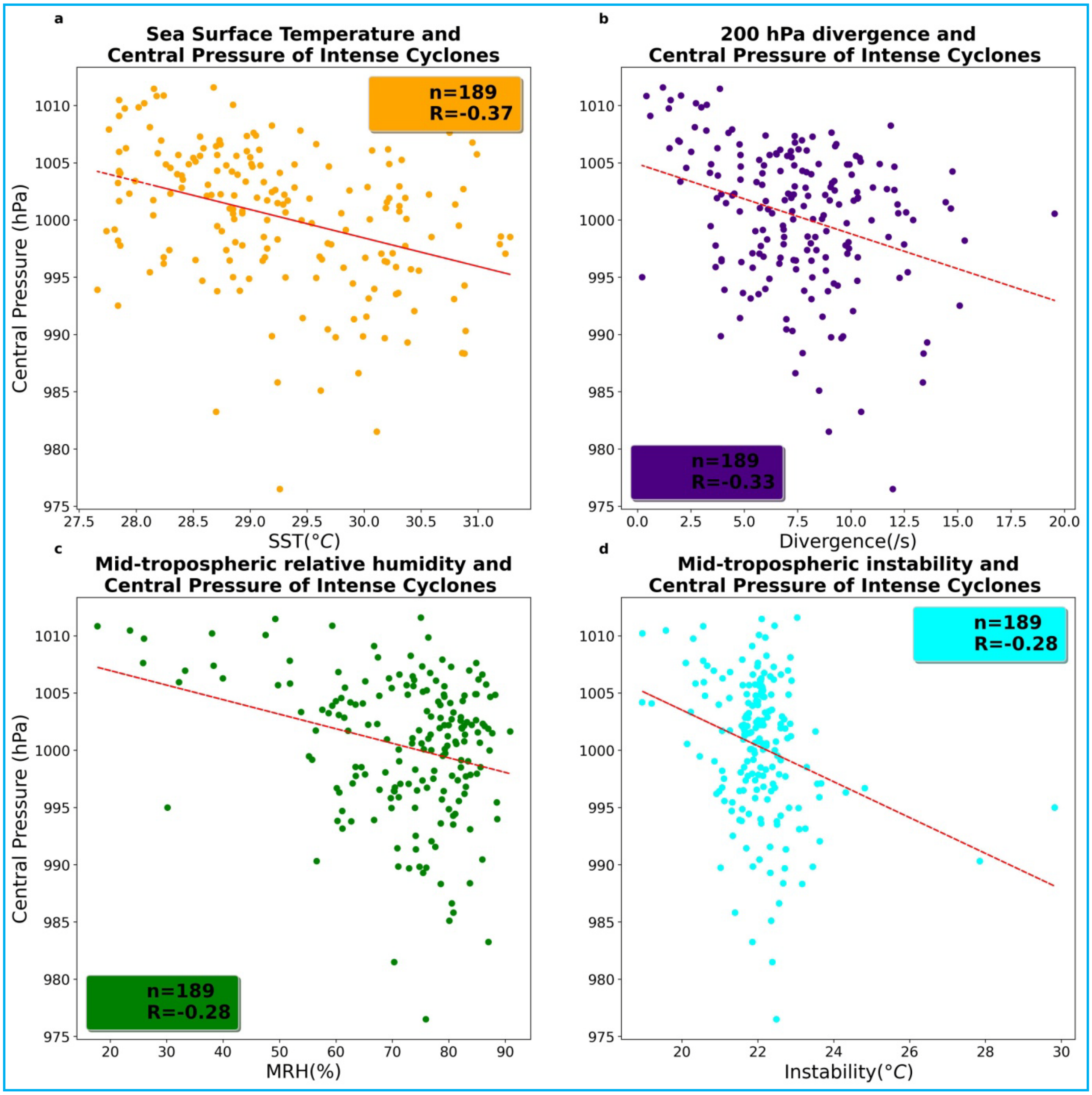


Fig. 1(b). Tracks of 31 intense TCs over BoB along with wind speed (in knots) during 1990-2019



Figs. 2(a-d). Variations of central pressure of intense TCs with (a) SST (b) 200 hPa divergence (c) mid-tropospheric relative humidity (d) mid-tropospheric instability (here the p value of two sample *t* test is 0 for all the pairs above, indicating 100% confidence level, no of pairs for each correlation n=189)

Based on this data we have plotted the tracks of intense TCs over the BoB during the study period. Fig. 1(b) shows the tracks of intense TCs along with wind speeds.

ERA5 is the fifth generation European Centre for Medium-Range Forecasts (ECMWF) reanalysis of the global climate and weather for the past few decades which uses about 24 million observations per day assimilating satellite remote sensing, Ocean buoy, surface observatory, upper air and ground-based radar data and provides hourly estimates for a large number of atmospheric, ocean-wave and land-surface quantities.

Past studies have shown that the ERA5 dataset well represents the evolution of many observed features of TCs (Sanap *et al.*, 2020; Malakar *et al.*, 2020). 0.25° × 0.25° resolution ERA5 reanalysis data for the parameters such as wind speed and direction, temperature, relative humidity at different pressure levels, Mean Sea Level Pressure (MSLP), 200-hPa divergence, SST and SLHF for the period 1990-2019 have been used in this study. Here we have taken the synoptic hour observations (0000-2100 UTC, every 3 hours) which show the genesis, maximum intensity and the abrupt changes in the intensity of the TCs with at least one observation per day. In this study, SST, MSLP, SLHF and 200-hPa divergence have been obtained directly from ERA5 and VWS, MI and MRH have been derived from wind, temperature and RH data respectively. The VWS has been calculated by taking the difference of 200-hPa and 850-hPa winds. The MRH has been calculated by taking the average of RH between 700 and 500-hPa. MI has been calculated by using the formula MI = (T_{850}-T_{500}) °C, where T_{850} and T_{500} are the temperatures at 850 and 500-hPa, respectively. The basic computation of Latent Heat Flux (LHF) is generally based on the bulk aerodynamic formula LHF= $\rho L_v C_h W_s(Q_s-Q_a)$, where ρ is the air density, L_v is the latent heat of vaporization, C_h is the bulk coefficient for latent heat flux, W_s is the 10-m surface wind speed, Q_s is the saturation specific humidity at the surface, and Q_a is the near-surface specific humidity (at atmospheric measurement level) (Kumar *et al.*, 2017a; Mathew *et al.*, 2020). But in this study SLHF has been directly obtained from the ERA5 database. The parameters such as max SLHF, min Shear, min MSLP, max SST, max 200-hPa divergence, mean MI, and mean MRH have been obtained within the 6°×6° box centring the eye of the cyclone. SLHF is positive downward and negative upward and is generally denoted with a negative sign unless there is a downward transfer of energy. Pearson's correlation method has been used to find the correlation among the parameters.

3. Results and discussions

Out of 31 TCs considered in this study nearly 70% originated in the post-monsoon season and 30% in the pre-monsoon season respectively. October month experienced the highest frequency of TCs at nearly 35%. No intense TC has been formed in January, February, March, June, July, August, and September. It is clear from Figs. 1(a&b) that almost 75% of these TCs originate between 8°-14° N, and nearly 65% of these TCs originate between 88-94° E. It is also seen that almost 60% of these TCs develop within the latitude/longitude box 8-14° N and 88-94° E.

During intensification of a TC, the central pressure falls. As such, this is one of the measures of a TC's intensity and damage potential (Chavas *et al*., 2017)**.** The central pressure of TCs and 10 m surface wind speed is related with a correlation coefficient of -0.97 (Bhardwaj and Singh, 2020). In this study, we have considered the central pressure as a measure of TCs intensity. This has been plotted against SST, SLHF, 200 hPa divergence, MRH, and MI during the lifetime of TCs to study the correlation if any between these parameters with the central pressure (intensity) during the entire life period of TCs. The scatter diagrams are presented in Figs. 2&3.

3.1. *SST*

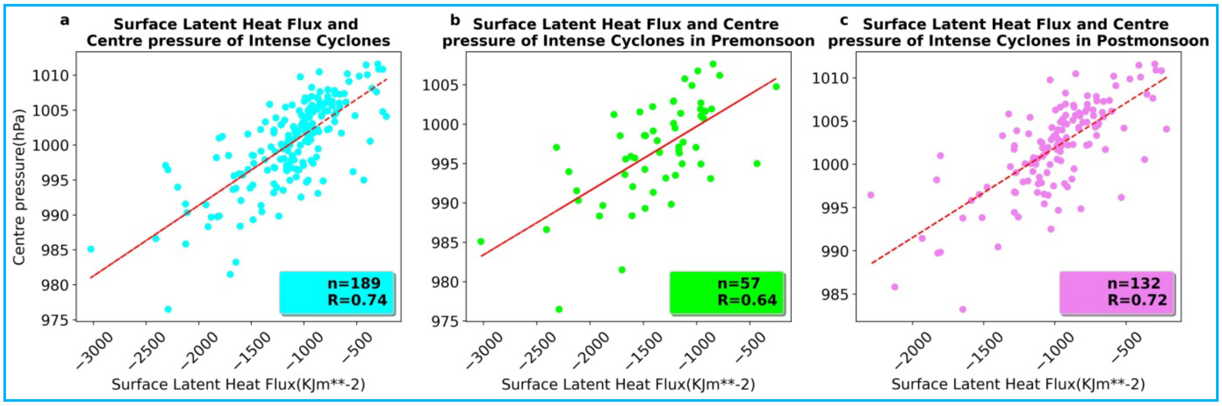
It has been observed in various studies that high SST (>26.5 °C or more) is one of the most favorable conditions for genesis and intensification/rapid intensification of TCs (Kaplan and DeMaria, 2003; Naskar and Naskar, 2021). The central pressure of all TCs has been plotted against max SST values within the 6°×6° box centring all TCs during their lifetime for the period 1990-2019 which is shown in Fig. 2(a). It is seen that when the central pressure (intensity) is low, SST is high and vice versa. But this relationship is not significant as many points show high SST corresponding to high central pressure (intensity) and low central pressure (intensity) corresponding to low SST. The R-value is -0.37 which signifies that SST and central pressure weakly correlated. The reason may be due to the movement of cyclones and TC induced cooling. It has been observed that during the movement of TCs strong surface winds exert stress on the sea surface that leads to vertical mixing and upwelling (Kuttippurath *et al*., 2022).

3.2 *Upper-level divergence*

Upper-level divergence is an essential parameter for TCs intensification and acts as the outflow in the upper level which can modify TC's core structure so that TC outflow can access weak inertial stability in the environment. By minimizing the energy sink of the tropical cyclone secondary circulation TC outflow can lead to rapid intensification (Rappin *et al*., 2011). (Naskar and Naskar, 2021) showed that 200 hPa divergence reached its peak during the maximum intensity of SuCS Amphan. In Fig. 2(b), the central pressure of all TCs has been plotted against max 200-hPa divergence values for all TCs during their lifetime for the period 1990-2019. It is seen that there is an inverse relation between 200-hPa divergence and the central pressure of TCs. But this relation is weak as many points show high divergence corresponding to high central pressure and low central pressure corresponding to low divergence; the R-value is -0.33 which signifies weak correlation between upper level divergence and central pressure of TCs.

3.3. *MRH and MI*

MRH and MI are also essential factors for the genesis and intensification of TC.s (Gray, 1979; Kotal *et al*., 2009). High MRH ensures the moistening of the middle troposphere and helps TC's intensification. (Kotal *et al*., 2009) showed that MRH first increased slightly and



Figs. 3(a-c). Variations of central pressure of intense TCs with SLHF in (a) all observations (b) pre-monsoon (c) post-monsoon (here the p value of two sample *t* test is 0 for all the pairs above, indicating 100% confidence level, no of pairs for each correlation n=189)

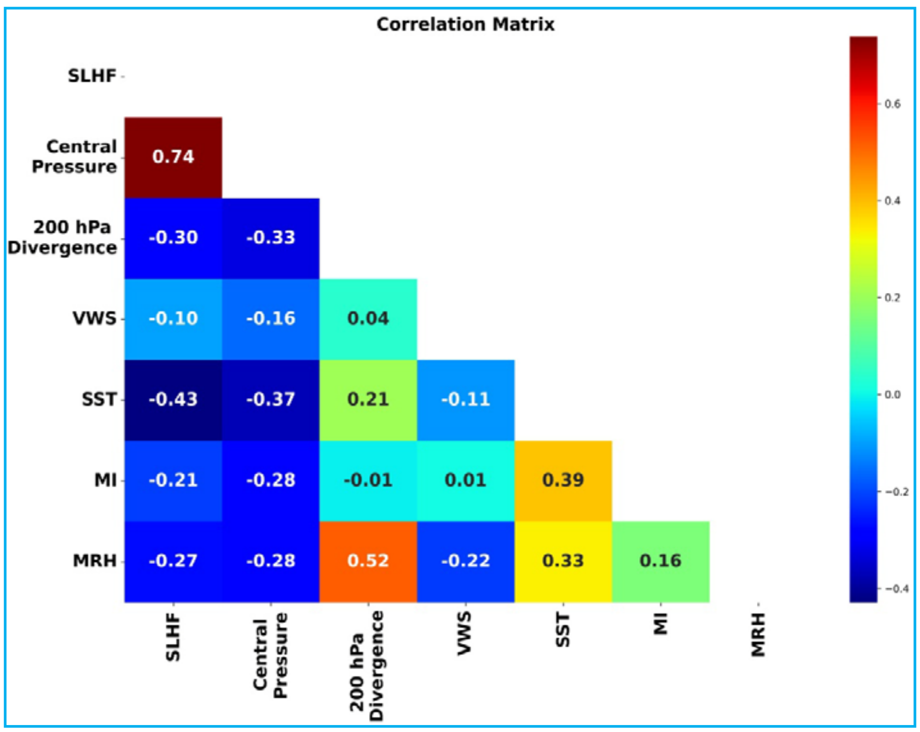


Fig. 4. Correlation matrix showing the correlation coefficients of different parameters with central pressure and among themselves during lifetime of intense TCs over BoB (here the no of pairs for all correlations is n=189, and the p value of two sample *t* test is 0 for all the pairs above, indicating 100% confidence level)

then became stable during their lifetime for developing systems. The genesis of TCs is characterized by intense convective activity, which is associated with MI. It increases during the initial stages of TCs and then decreases (Kotal *et al*., 2009). Figs. 2(c&d) show the variations of central pressure of all TCs with mean MRH and mean MI. Though there are decreasing trends of MRH and MI with central pressure, they are not significant (R values are -0.28 and -0.28 respectively). It is observed that MRH and MI do not change much during the lifetime of TCs. Most of the values of MRH and MI are between 70-95% and 21-23 °C, respectively. This suggests that TCs intensity is not explicitly related to MRH and MI.

3.4. *VWS*

VWS is also an essential factor for the genesis and intensification of TCs. It is the primary environmental

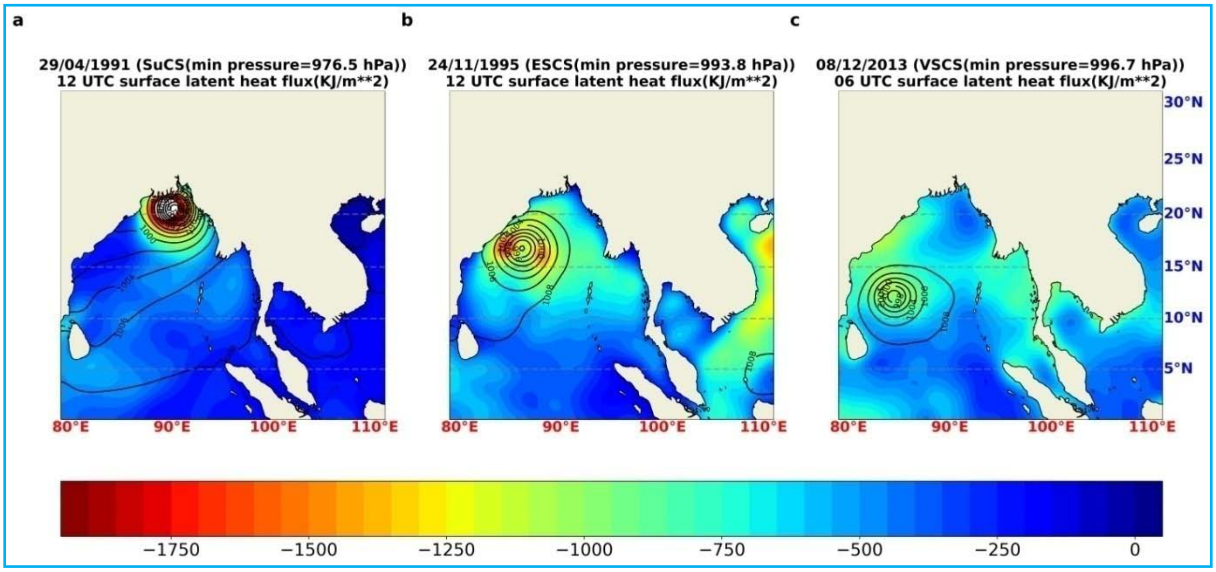


Fig. 5. Pictorial example showing maximum SLHF during minimum central pressure for 3 different intense TCs over BoB

control during the formation and early intensification stage over regions of significant Ocean heat content (Park *et al*., 2012). Low VWS acts in initiating a favorable environment for cyclone movement and sustainment. The relationship between VWS with central pressure has not been shown here, but the relationship is weak, as seen from the correlation matrix (Fig. 4).

3.5. *SLHF*

SLHF plays a vital role in the Ocean surface energy balance. It is the primary source of energy fuelling TCs development and intensification. The variation of central pressure with SLHF during pre-monsoon and post-monsoon seasons has been plotted separately to observe any difference in the relationship during these seasons. Fig. 3(a) shows a strong relationship between central pressure and SLHF for all observations during the study period. It is seen that the central pressure is minimum when there is a strong upward release of latent heat energy in the form of surface latent heat flux and vice versa. The SLHF is highly correlated with the central pressure of TCs (R = 0.74). The variation of central pressure with SLHF in the pre-monsoon and the post-monsoon as depicted in Figs. 3(b&c) also shows high correlations (R = 0.64 and 0.72). This suggests that there exists a strong relation between SLHF and TCs intensity. From Figs. 3(b&c), it is also observed that SLHF is higher in the pre-monsoon season than in the post-monsoon season. In the pre-monsoon, the max value of SLHF reaches as high as -3025 kJ/m^2 with a mean value of -1386 kJ/m^2 whereas in the post-monsoon max value of SLHF goes to -2293 kJ/m^2 with a mean value of -1025 kJ/m^2. This higher SLHF value in the pre-monsoon season may be due to the higher SST.

3.6. *Correlation matrix*

From the correlation matrix depicted in Fig. 4 matrix, we can readily find out how the parameters correlate with the central pressure of TCs and how they correlate with themselves during the lifetime of TCs. The no. of observation points '***n***' for which the correlation coefficients have been computed and level of significance have been indicated. It is seen that during the lifetime of TCs, among all the parameters SLHF exhibits the highest correlation (R=0.74) with the central pressure of TCs. It has been observed that, generally, SLHF is closely associated with SST, an increase in SST directly contributes to the change in SLHF. (Yu and Weller, 2007) indicated that an increase in SLHF is mainly associated with an increase in SST. In this study, we have also examined the correlation of SLHF with SST during the lifetime of TCs. The correlation coefficient between SST and SLHF is -0.43 which implies that SST and SLHF are moderately correlated during the lifetime of TCs. We can see a weak positive correlation between SST and MI (R = 0.39), SST and MRH (R = 0.33) and SST and 200-hPa divergence (R = 0.21). There is good correlation between upper-level divergence and MRH (R = 0.52), which signifies that strong divergence in the upper level enhances moistening in the middle troposphere. Fig. 5 shows the variations of SLHF and central pressure for 3 different TCs in the categories of SuCS, ESCS and VSCS, respectively. It is seen that when the central pressure is minimum (976.3 hPa) the SLHF is maximum, and when the central pressure is maximum (1000.6 hPa) the SLHF is minimum.

4. Conclusions

From the discussions of Sec 3, we can draw the following conclusions:

(*i*) The maximum numbers of intense TCs in the BoB develop in the post-monsoon season and particularly in November. Almost 60% of these intense TCs originate in the region 8-14° N and 88-94° E.

(*ii*) The SLHF has higher values in the pre-monsoon season compared to the post-monsoon season.

(*iii*) The SLHF is very well correlated with the central pressure of intense TCs among the parameters discussed in this study. Increase and decrease of SLHF correspond to decrease and increase of TCs central pressure (increase and decrease in TCs intensity). The highest SLHF corresponds to the lowest central pressure (highest intensity). Thus it can be said that the SLHF is the most crucial predictor for TC intensification.

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Authors' Declaration

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Conflict of interest/competing interests: We do not have any conflict of interest to disclose.

Availability of data and material: All the data used in this study have been collected from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5 and it is readily available there.

Code availability : Not applicable.

Author's Contribution : Pravat Rabi Naskar - Concept, analysis, writing and modification, Dushmanta Ranjan Pattanaik - Writing and modification.

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