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Investigating Physics Behind the Rapid Intensification and Catastrophic Landfall of Cyclone 'Titli' (2018) in the Bay of Bengal

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The present study delineates the role of ocean conditions in the genesis and rapid intensification (RI) of a very severe cyclonic storm (VSCS) 'Titli' (2018). The tropical cyclone (TC) formed over the warm waters of the east-central Bay of Bengal during 08-13 October 2018. According to the India Meteorological Department (IMD), the cyclone was the most damaging storm to hit any coast of India in the year 2018, making it a special case of analysis. In the present study, 10 m winds , Sea Surface Temperature (SST), Latent heat flux, and relative vorticity (RV) during the lifespan of the cyclone are studied using ECMWF reanalysis V5 (ERA5) prepared by European Centre for Medium Range Weather Forecasts (ECMWF). Further, the Tropical Cyclone Heat Potential (TCHP) data generated by the Indian National Centre for Ocean Information Services (INCOIS) in Hyderabad is used to study the important information about the oceanic conditions of the TC. The investigation of the TC's sea surface temperature data from satellites reveals that a relatively warmer SST prevailed during the cyclone's occurrence, which may have been the primary factor in the TC's rapid intensification. Further, the latent Heat flux (LHF) and TCHP values were also found high in conjunction with SST values. Our in-depth analysis reveals that the 10 m winds embedded into the TC were extremely strong, exceeding 12 m/s prior to the landfall. A positive and large value of RV was found when the TC was about to hit the coast. This may be one of the reasons behind the 'catastrophic landfall' of the cyclone.

Keywords: Tropical cyclones; Sea surface temperature; Latent heat flux; Tropical cyclone heat potential; Relative vorticity

1 Introduction

Rapidly intensifying tropical cyclones continue to be the most dangerous type of natural climate hazard, as they are responsible for an unacceptable number of fatalities and ravage to property and infrastructure. The internal dynamics and process of intensification of these cyclones are poorly understood, making them difficult to predict during real-time operations. The sudden intensification and intense nature of cyclones are attributed to various 'physics-related' parameters *e.g*., SST, surface heat fluxes (*i.e*., Latent and sensible heat fluxes), TCHP and potential vorticity mixing, *etc*.[1-6]. Despite the fact that these parameters have been analyzed for rapidly intensifying cyclones around the world, they have been less frequently used to examine the rapid intensification of cyclones forming in the North Indian Ocean (NIO) region (*i.e*., Bay of Bengal and Arabian Sea). In light of the dearth of prior work for NIO basins, the present exploratory study attempts to identify the factors that contributed to VSCS Titli's immense intensification.

According to IMD, a low-pressure area formed over the southeast Bay of Bengal and the adjacent Andaman Sea in the early hours (*i.e*. 0830 IST) of the 7th of October 2018 marking the beginning of the VSCS Titli. Further, the low-pressure area respectively turned into a 'Depression (D)' and 'Deep Depression (DD)' in the morning (0830 IST) and mid-night (2330 IST) on the 8th of October 2018. The Deep-Depression further grew stronger around 0230 IST on the 10th of October 2018, and was classified as a 'Severe Cyclonic Storm (SCS)'. The storm subsequently continued to intensify and turned into a 'VSCS' around noon (1130 IST) of 10th October. It then made landfall during 0430-0530 IST on 11th October 2018, near 'Palasa' town (latitude 18.8^{0}N, longitude 84.5^{0}E) in the Srikakulam district

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*Corresponding authors: (E-mail: vivek.sgh1@gmail.com) of Andhra Pradesh. The cyclone showed a pre-landfall rapid intensification on the 10th of October 2018. It had accumulated cyclone energy of 3.85×10^4 knots^2. The system was so powerful that it maintained winds of the "cyclonic storm (CS)" category for 15 hours, even after making landfall. Fig. 1(a) shows the observed track of the VSCS 'Titli' along with its different developmental stages (*i.e.*, 'Depression (D), Deep Depression (DD), Cyclonic Storm (CS), Severe cyclonic storm (SCS) and Very severe cyclonic storm (VSCS)). Fig. 1(b) depicts the daily variations in the Maximum Sustained Wind (*i.e.*, MSW, in 'knots' unit) and Mean Sea Level Pressure (*i.e.*, MSLP, in hectopascal pressure unit) during the TCs lifespan.

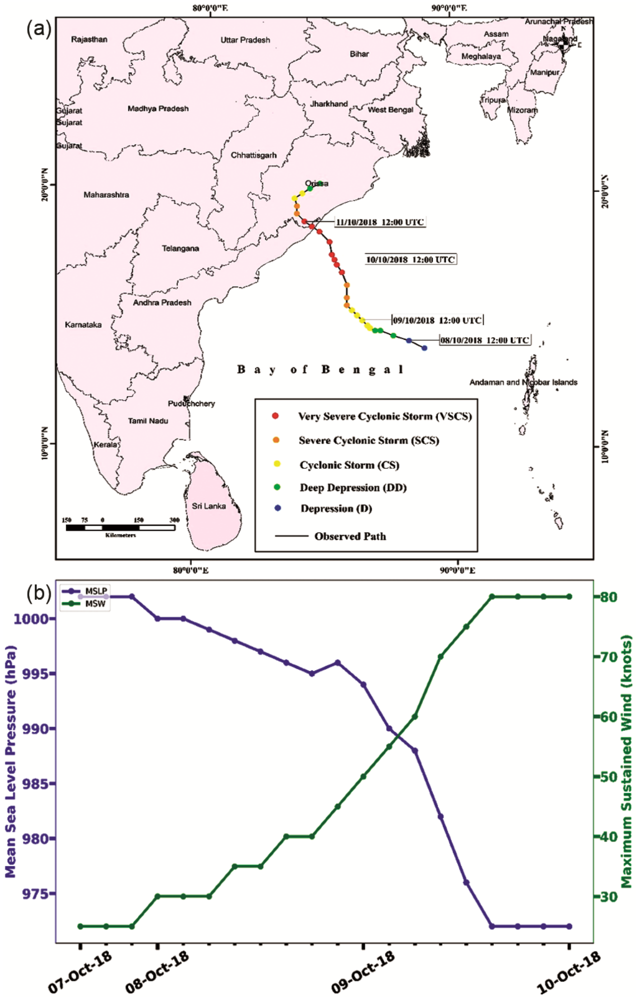

Fig. 1 — (a) Observed track of VSCS 'Titli'. The observed track has been plotted using India Meteorological Department (IMD) best track data. (b) Mean Sea level pressure (unit: 'hPa', blue line) and Maximum sustained Wind (unit 'knots', Green line) for the VSCS 'Titli'. The Fig. 1(a) has been plotted using ArcGIS while Fig. 1(b) has been generated using a python programme.

2 Materials and Methods

In the present study, satellite measurements of daily sea surface temperatures (SSTs) obtained from the ERA5 platform, have been utilized to study the intense nature of the cyclone. The SST data used is the level4 global data product, which is obtained from multiple sensors. The more details about SST data is available at ECMWF website. Similarly, the ERA5 'surface latent heat fluxes', '10 meter winds' and 'relative vorticity' data are also used. The ERA5 hourly data on single levels from 1959 to present can be downloaded from the link. The observed best track data, Mean Sea level pressure, and maximum sustained wind values of the cyclone were obtained from IMD, New Delhi. The more details about the VSCS Titli can be obtained from IMD's website. The TCHP data was provided by the INCOIS, Hyderabad upon request.

3 Results and Discussion

The causes of rapid intensification and the fierce nature of the TC has been attributed to four prime factors *i.e.* 'winds', 'sea surface temperature', 'latent heat flux' and 'relative vorticity with relative humidity (RH)'. The following sub-sections separately discuss all the results in details.

3.1 Winds

Surface winds play a crucial role in the intensification and disastrous landfall of tropical cyclones. Tropical cyclones have horizontal wind speeds of 5 and 10 m/s at 100 and 200 km radii respectively[7]**.** The 10 m-wind associated with VSCS 'Titli' is depicted in Fig. 2(a-e). the 10 m-wind values are masked over land region for better clarity (represented by black shading over land region). Vectors (arrows) in the above figure show the wind's directional movement. The wind speed (unit: meter per second) is indicated by coloured shading in the background. In each of the sub-plots, a cross equatorial wind flow from southern to northern hemisphere is visible. During the pre-depression stage of the cyclone 'Titli', (*i.e.* 7th October plot), the winds were relatively calmer in comparison to other days. As cyclone turned into depression (D) stage on 8th October, winds started to organized in a form of an initial vortex (anti-clockwise rotation) with max wind magnitude ranging from 10 to 11 m/s. Further as the TC turned into "Deep depression" (DD) stage on 9th October, the initial vortex turned into a well-defined cyclonic circulation having max wind speed of

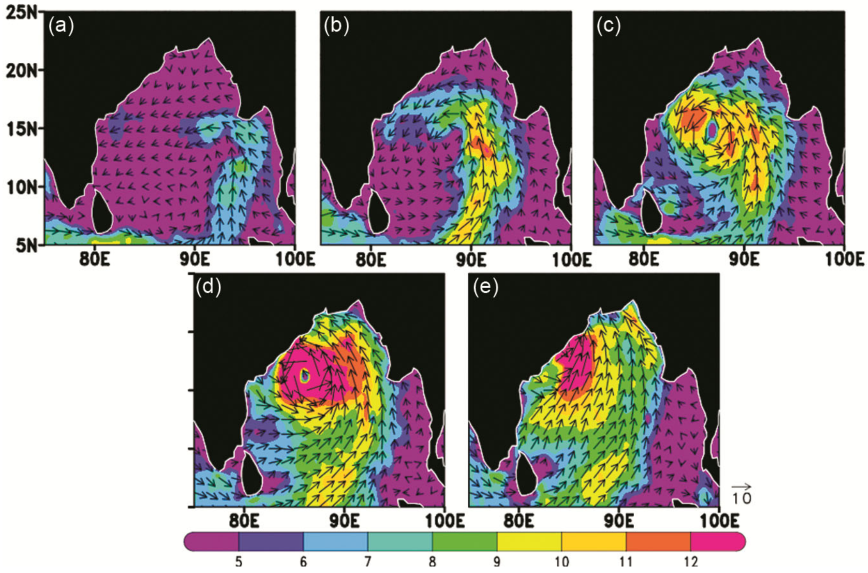

Fig. 2 — (a-e) ERA5 derived observed 10m-wind associated with VSCS 'Titli'(2018). The wind's direction is represented by vectors, while the wind's magnitude (unit: m/s) is shaded with various colour gradients in the background. The plot was produced using the GrADS and python programmes

11-12 m/s, all through in the eye-wall of the TC. The rapid intensification of the TC prior to its landfall is evident in the wind plots of 10th and 11th October, 2018, in which max wind speed exceeded 12 m/s. It is obvious from the plots that strong winds contributed in the disastrous landfall of the TC.

3.2 Sea Surface Temperature

The importance of SST in the development and intensification of TCs is widely accepted in the literature. The SSTs play a vital role in the intensification of tropical cyclones, and conversely, cyclones also alter SSTs. Strong winds, evaporation or dense clouds all have a significant impact on the SST, which is confined to a few millimetres of the ocean's surface. The majority (nearly 98.3%) of tropical cyclones form when SSTs are higher than 25.50 degree Celsius[8]. Further, the sudden rapid intensification of cyclones is linked to their movement toward warmer SST regions[9]**.** When TCs move through after rapid intensification, they cool the SST by a few degrees. In the present paper, the authors examined the variations in daily SST during the VSCS 'Titli's' occurrence in accordance with the 'SST theory' of rapid intensification. Fig. 3(a-e) delineates the observed SST values during the lifespan (7th October to 11th October 2018) of the VSCS 'Titli'. The cyclone's actual path is depicted by the black curve in the figure. From the figure, it is found that during 7-8 October 2018, a warmer SST pool (~ 29-30 degree centigrade) was lying over the south-eastern Bay of Bengal and adjacent north Andaman Sea. The SST in this genesis region was more than 2-3 degrees by its surrounding, making situations conducive for the formation of a strong system. This SST warm pool could have aided in the strengthening and progression of the VSCS 'Titli'. As, IMD had reported that the TC has undergone a rapid intensification on 10th October 2018, before its landfall, a stretch of warmer SSTs can be seen along the Andhra coast in Fig. 3(d). This warmer SST belt along the Andhra coast could have fuelled up the rapid intensification process before landfall. After the TC made landfall, relatively a cooler SST (temp~ 27-28 deg centigrade) is visible behind the observed path (Green round patch near landfall in 11th October plot).

3.3 Latent Heat Flux

The rapidly intensifying cyclones are typically linked to a region of high surface latent heat fluxes, which are transferred from the ocean to the atmosphere during the strengthening phase of a TC[10,11]. According to Clausius Clapeyron equation, when water vapour is added to warmed saturated air, the air can hold more moisture. In an ascending air column, as the moist air rises and water vapour condenses, a substantial amount of latent heat is released in the eye-wall of a TC. Higher winds in TCs are fuelled up by the 'condensation process', as a small amount of energy released in condensation is

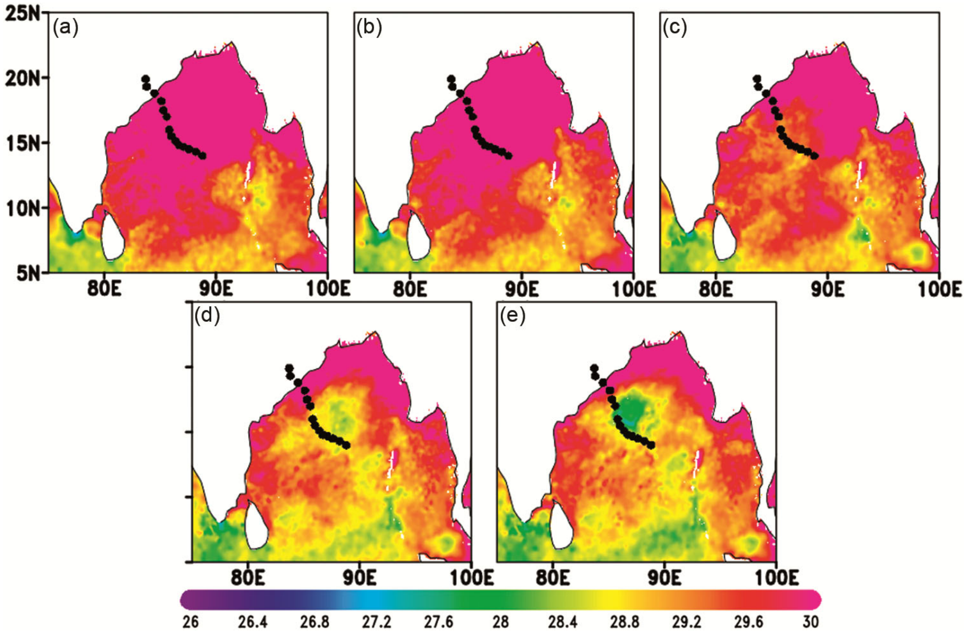

Fig. 3 — (a-e) Daily Sea surface temperature plots for the VSCS ‘Titli’. The SST data has been derived from satellite observations. The black line shows the observed path of the cyclone. The colour bar values show the observed SST values in degree centigrade. The plot has been generated using python and GrADS software.

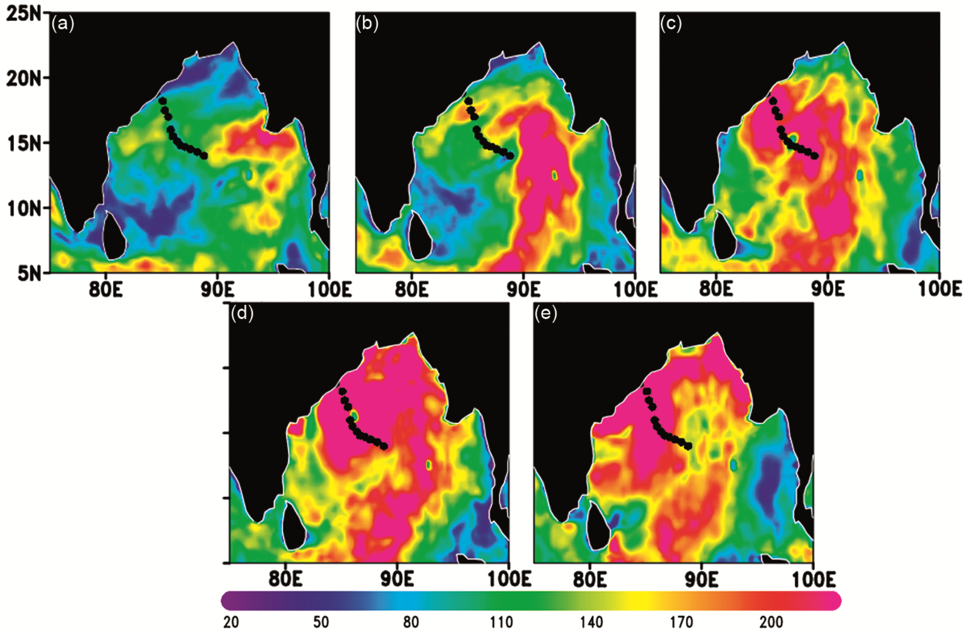

Fig. 4 — (a-e) Daily latent heat flux plots for the VSCS ‘Titli’. The latent heat data has been obtained from ERA-5 reanalyses. The black line shows the observed path of the cyclone. The colour bar values show the latent heat values in Watts/meter^2.Python and GrADS software were used for generating the figure.

converted into mechanical energy. The increased winds further cause more evaporation and hence more condensation. In this way, the positive feedback loop exist between condensation (or latent heat) and winds, and a cyclone acts as a heat engine. An ongoing supply of atmospheric moisture is required for a tropical cyclone’s heat engine to function, so it can only keep chugging along over warm waters of ocean. Hence, once a TC hits the coast, it dissipates. The Fig. 4(a-e) shows the daily variations in observed latent heat fluxes (Watts/meter^2) associated with the VSCS ‘Titli’. The latent heat fluxes in all the plots of

Fig. 4 are masked over the land region (masking is shown by the black colour over the land region). An initial, small-patch of latent heat associated with the precursor instability can be seen near the cyclogenesis region (Fig. 4(a)).With further evolution and systematic development of the TC, the latent heat fluxes increase reaching upto more than 200 Watts/meter^2 near the eye-wall region (Fig. 4(b-d)). The rapid intensification phase of the TC is captured in the 10th October plot (Fig. 4(d)), in which a huge amount of latent heat is released, over a very large area in central Bay of Bengal. After the landfall, the latent heat flux seems to be shallowing (Fig. 4(e)). So it is evident that a large amount of latent heat release was also one of the main factor contributing in intense nature of the TC 'Titli'(2018).

3.4 Tropical Cyclone Heat Potential (TCHP; unit kj/cm^2)

Tropical Cyclone Heat Potential (TCHP) plays an important role in the rapid intensification and disastrous landfall of tropical cyclones over the Bay of Bengal[12]. The Bay of Bengal is known for its high sea surface temperatures, which create an ideal environment for the development and intensification of tropical cyclones. TCHP is a key factor in determining the intensity of these storms. During the rapid intensification phase, tropical cyclones draw energy from the warm ocean waters through LHF. TCHP helps to determine the amount of heat energy available in the upper ocean layers that can be used for conversion into LHF. Further, The integrated vertical temperature from the ocean's surface to the isothermal depth of 26 degree Celsius (D_{26}) is depicted by TCHP. For North Indian Ocean (NIO) region, the 26-degree isotherm can be found at depths ranging from 50 to 100 meters from the ocean surface. In shallow water of oceans, the heat potential of cyclones is normally low since there is less water to retain heat. Consequently, TCs generally intensify over deep ocean waters. The TCHP, which has accumulated from the time of TC formation through its mature stages, is more closely related to a drop in the central pressure of a cyclone[13]. The Fig. 5(a-e) depicts the daily variations of TCHP during the life cycle of VSCS Titli. The colour bar shows the magnitude of TCHP in 'kj/cm2' unit. Data from the INCOIS, Hyderabad was used to plot the TCHP variations. From the Fig. 5(a), it is found that 'Titli's' genesis occurred in a region where TCHP was nearly 70 kj/cm^2_or a little more. Further, there was a sustained build-up of TCHP from 8 to 10th October, 2018 (*i.e.* Fig. 5(b-d)). The 11th October plot (*i.e.* Fig. 5(e)) depicts a decrease in TCHP (cooling of ocean near landfall point) that occurred after VSCS 'Titli' passed.

3.5 Average Values and Anomaly of SST and LHF

The average SST and LHF prior to one week and during the life cycle of cyclone can provide important information about the potential for intensification and

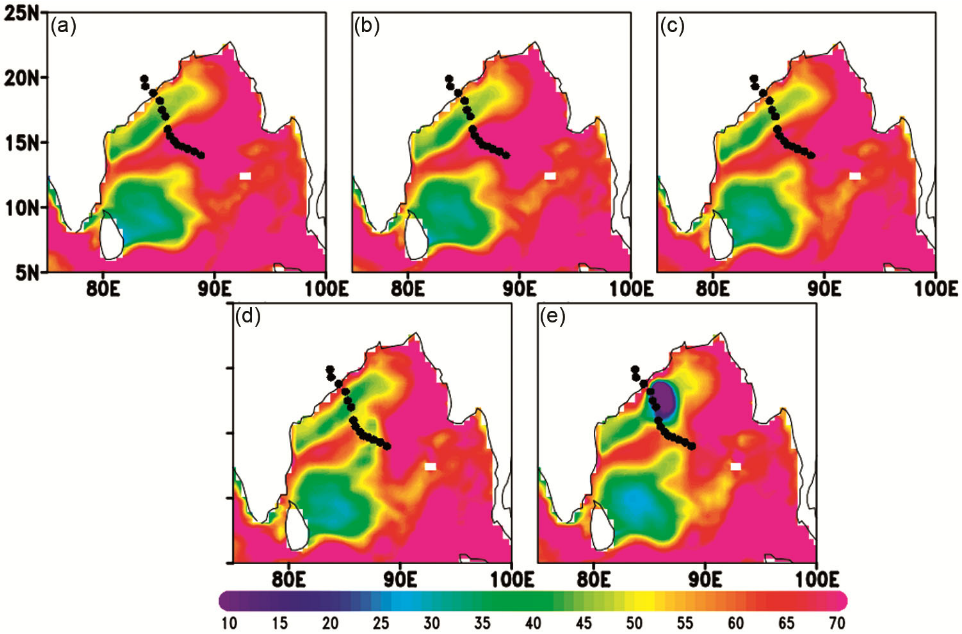

Fig. 5 — (a-e) Daily variations of Tropical Cyclone Heat Potential (TCHP) during the life cycle of VSCS Titli. The colour bar shows the magnitude of TCHP in 'kj/cm2' unit.

track of the storm. Higher values of average SST along the coast, prior to one week of a tropical cyclone indicates that the oceanic conditions were favourable for the formation and intensification of the TC (Fig. 6(a)). Further, the temporal average of SST during the life-time of tropical cyclone shows cooling along the path Fig. 6(b). A cooling SST can also affect the track of the storm. A decrease in SST values can lead to a decrease in the amount of atmospheric instability, which can affect the steering currents that guide the storm's movement. This can result in the storm moving in a different direction than previously forecasted. A higher magnitude of SST anomaly at the mid-oceanic region produced favourable conditions for the initiation of the cyclogenesis process (as shown in Fig. 6(c). This figure is obtained from the spatial difference of SST variation during the cyclone's lifetime, from the climatology of that particular duration. The climatology has been calculated using ERA5 dataset for the period 1978-2021. The enhancement of the exchange of air-sea enthalpy fluxes during the time of the tropical cyclone increases the magnitude of Latent heat fluxes Fig. 6(e), which is responsible for enhancing the sea surface temperature during tropical cyclone *i.e.* intensification of cyclone before landfall. Anomaly plots (Fig. 6(c) & (f)) depict the climatological variability at the mid-oceanic region with higher values of SST and LHF.

3.6 Relative Vorticity (RV) and Relative Humidity

RV affects the intensification of TCs forming across the globe[14,15]. 'Shear', 'curvature' and 'Coriolis' are the triad that produce vorticity in a cyclone. Generally a positive and high value of RV in lower troposphere (upto 850 hPa pressure level) is favourable for cyclone formation and intensification. However the negative RV is associated with weakening of TCs. In TCs, RV at lower levels and within a radius of 100-200 kilometers is greater than $10*10^{-5}$ per second[7]. RV measures how the air rotates horizontally around a vertical axis, in relation to a fixed point on the earth surface. The advective effect causes the cyclonic vortex to move northward, if a tropical cyclone is headed in the direction of the maximum cyclonic relative vorticity tendency. The Fig. 7(a) & (b) shows the "relative vorticity ($*10^{-5}$ per second)" cross section overlaid by the relative humidity contours. The Fig. 7(a) shows the longitudinal cross section of RV at fixed latitude 18.4^0 N, however, the Fig. 7(b) is valid at fixed longitude 84.5^0 E. An intercomparison of the two sub-plots reveals that the higher magnitude of RV reached upto upper troposphere in the latitudinal variation. Further, both of these sub-plots suggests that the TC was a very well vertically aligned system with a strong rotating winds present till upper troposphere. It is worth mentioning that the cyclone 'Titli' made landfall at 18.4^0 N latitude and 84.5^0 E longitude. For cyclones, in order to quickly intensify and to attain vigorous

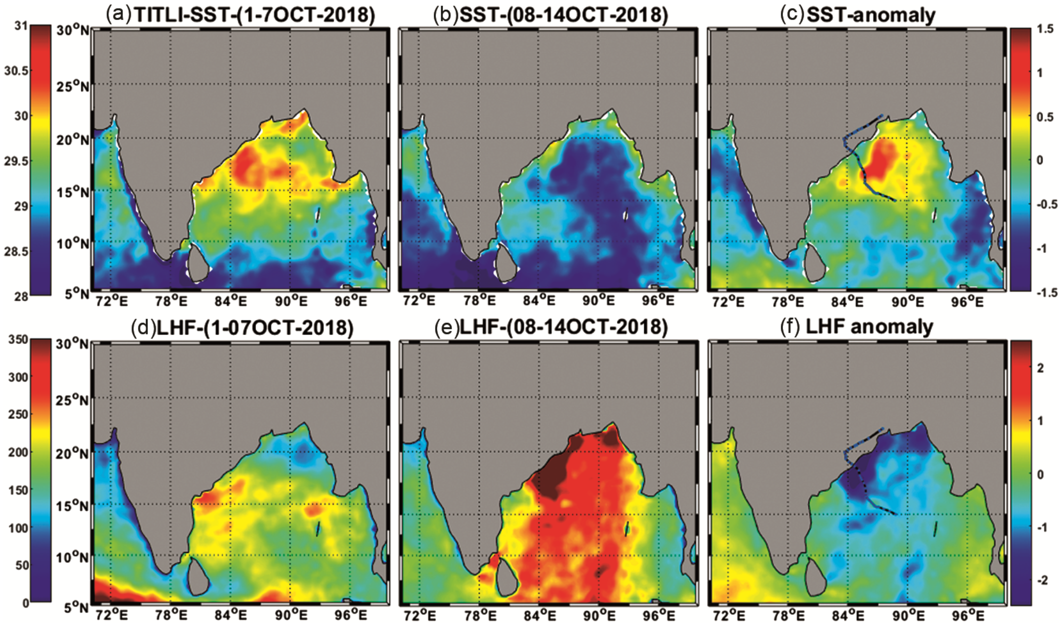

Fig. 6 — Spatial variation of SST (a and b) and LHF (d and f) prior to (*i.e.* 1-7 October, 2018) and during (*i.e.* 8-14 October, 2018) the occurrence of VSCS Titli. The Fig. 6(c) & (f) representthe SST and LHF anomaly respectively obtained by considering the last 60 yearsdataset.

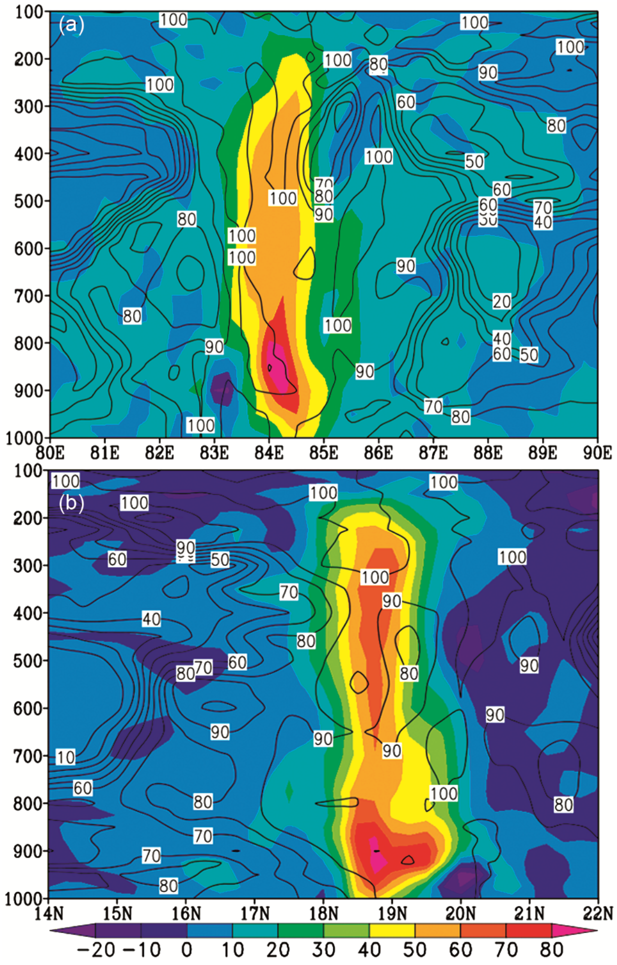

Fig. 7 — Snapshot of (a) longitudinal variation and (b) latitudinal variation of vertical cross section of relative vorticity (RV) during the landfall time (*i.e.* 0000 UTC of 11th October, 2018) of the VSCS 'Titli'. RV data has been obtained from ERA-5 reanalyses. In both the plots, relative humidity (unit: percentage) has been presented by black contoursThe y-axis values show the vertical pressure levels (hPa). The colour bar shows the RV*10^{-5} values in 'per second' unit.

nature, a high value of RH in the middle of the troposphere is required[16]. The presence of weak upper level divergence and moisture in the form of 'relative humidity' helps in the fuelling of a TC. The 100 percent RH value is crossing the middle troposphere (*i.e.* 500 hPa) in both the sub-plots of Fig. 5. Therefore it can be concluded that both, RV and relative humidity served as the foundation for the TC's disastrous landfall.

4 Conclusions

The present study identified the causes of the rapid intensification of the very severe cyclonic storm 'Titli' (2018) that formed over Bay of Bengal. The causes of rapid intensification of the TC can be summarised under the following points.

- A very warm SST (29-30 degree centigrade) and latent heat flux release provided conducive situation for pre-landfall rapid intensification of the TC.
- Relatively higher and sustained build-up of TCHP during the cyclogenesis and mature phase of the VSCS 'Titli' led to its intensification.
- Higher 10 m wind magnitudes (~12 meter per second) and relative vorticity further supported the disastrous landfall.

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