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Understanding the rapid intensification of tropical cyclone Titli using Hurricane WRF model simulations

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सार – उष्णकटिबंधीय चक्रवात (TC) के तीव्रता पूर्वानुमान कौशल और उष्णकटिबंधीय चक्रवात से जुड़ी आपदा तैयारियों में सुधार के लिए द्रुत तीव्रीकरण (RI) को समझना महत्वपूर्ण है। भौतिक प्रक्रियाएँ जिनसे RI होती हैं, का उत्तरी हिंद महासागर (NIO) क्षेत्र में अच्छी तरह से अध्ययन नहीं किया गया है। 2018 की मॉनसूनोत्तर ऋतु में आए दो उष्णकटिबंधीय चक्रवात (TC), यानी तितली (RI का प्रदर्शन किया) और फेथई (RI प्रदर्शित नहीं) से माना जाने लगा कि पर्यावरण की स्थितियाँ RI के लिए ज़िम्मेदार हैं। प्रचंड चक्रवात मौसम अनुसंधान और पूर्वानुमान (HWRF) मॉडल से तितली और फेथई के लिए तैयार सिमुलेशन का विश्लेषण किया गया जिससे तीव्रीकरण में हुए परिवर्तन को समझा जा सके। इस अध्ययन का उद्देश्य वायुमंडलीय और तूफान संरचना की विशेषताओं की जाँच करना है। उष्णकटिबंधीय चक्रवात पेथई की तुलना में उष्णकटिबंधीय चक्रवात (TC) तितली का द्रुत तीव्रीकरण (RI) हुआ। पेथई और तितली के सिमुलेशन का भारत मौसम विज्ञान विभाग (IMD) द्वारा सबसे अच्छे अनुमानों के रूप में वैधीकृत किया गया और इसकी तुलना पर्यावरणीय ऊर्ध्वाधर पवन अपरूपण के रूप में की गई। इस प्राचल को उष्णकटिबंधीय चक्रवात (TC) के तीव्रीकरण में अक्सर ही नकारात्मक माना जाता है। गहरे-स्तर और मध्य-स्तर ऊर्ध्वाधर पवन अपरूपण के औसत क्षेत्र दर्शाते हैं कि उष्णकटिबंधीय चक्रवात (TC) ने पर्यावरण पर पवन अपरूपण से तितली सिमुलेशन के तीव्रीकरण को प्रभावित नहीं किया। प्रारंभ में, तितली ने तूफान के संचरण के भीतर क्षोभमंडल में सापेक्षिक आर्द्रता के उच्च परिमाण को समाहित किया। फिर यह क्षोभमंडल में एक उच्च ऊर्ध्व द्रव्यमान प्रवाह की ओर अग्रसर हुआ और सतह पर किसी भी महत्वपूर्ण परिवर्तन से पहले मध्य क्षोभमंडल में सापेक्षिक भ्रमिलता (संचलन) के साथ द्रुत रूप से तीव्र हुआ। एक गहरा भ्रमिल स्थापित होने के बाद, द्रव्यमान प्रवाह (और निचले-क्षोभमंडल अभिसरण) में वृद्धि जारी रही, जिससे द्रुत तीव्रीकरण (RI) हुआ। ये परिणाम भविष्य के अनुसंधान के लिए द्रुत तीव्रीकरण (RI) के विकास को अच्छी तरह समझने और पूर्वानुमान के लिए एक आधार प्रदान करते हैं।

ABSTRACT. Understanding Rapid Intensification (RI) is crucial for improving the Tropical Cyclone (TC) intensity forecast skill and TC induced disaster preparedness. The physical processes that lead to RI are not well studied over the North Indian Ocean (NIO) region. Two TC cases, *i.e*., Titli (exhibited RI) and Phethai (not exhibited RI) from the 2018 post-monsoon season are considered to understand the environmental conditions responsible for making RI happen. The Hurricane Weather Research and Forecasting (HWRF) model produced simulations for Titli and Phethai are analyzed to understand the intensification changes. The purpose of this study is to investigate the environmental and storm structure characteristics that led to the RI of TC Titli when compared to TC Phethai. The Phethai and Titli simulations are initially validated against the best estimations by India Meteorological Department (IMD) and compared in terms of the environmental vertical wind shear as this parameter is often negatively correlated with TC intensification. Area averages of the deep-layer and mid-layer vertical wind shear over the TC environment suggest that shear did not affect the intensification of the Titli simulation. Initially, Titli contained higher magnitudes of relative humidity throughout the troposphere within the storm's circulation. This steered to a higher upward mass flux in the troposphere and rapid intensification of relative vorticity (circulation) in the middle troposphere prior to any significant change ensued at the surface. After a deep vortex was established, the mass flux (and lower-tropospheric convergence) continued to rise, leading to RI. These results offer a basis for future research to understand better and forecast the development of RI.

Key words – Rapid intensification, Tropical cyclone, Hurricane WRF.

1. Introduction

Tropical Cyclones (TCs) in the North Indian Ocean (NIO) are among the most devastating natural phenomena over the globe when compared to other ocean basins (Mohanty and Gupta, 1997; Mohanty *et al*., 2012). These storms' perilous nature has driven the efforts to improve the TC track and intensity changes forecast. Under the Forecast Demonstration Project for Tropical Cyclone (FDP-TC), India Meteorological Department (IMD) has established collaborations with various national and international operational, research and academic institutes for accelerating the efforts to improve the forecast of TC (Mohanty *et al*., 2015, 2019; Nadimpalli *et al*., 2016). With the advancements in the dense observational network such as *in situ*, satellite, radar and other remote sensed platforms, the prediction accuracy of the TC movement has been improved from the last few decades (Mohapatra *et al*., 2013). Significant improvements have been achieved in the prediction track of TC from last few years due to the advancements in numerical weather prediction models and data assimilation techniques over the NIO basin (Gopalakrishnan *et al*., 2011, 2012; Pattanayak *et al*., 2012; Osuri *et al*., 2012a, 2012b, 2013, 2015, 2017; Nadimpalli *et al*., 2016, 2019, 2020a, Mohanty *et al*., 2015, 2019; Busireddy *et al*., 2019). Despite these efforts, the forecast of TC intensification continues to have limited success (DeMaria *et al.*, 2007; Osuri *et al*., 2017; Mohanty *et al*., 2019; Nadimpalli *et al*., 2020a). One predominantly challenging task is to forecast the form of TC intensification is rapid intensification (RI), which is defined as an increase in the 3 minutes averaged maximum sustained surface wind speed of 15.4 ms^{-1} (at least) in 24 hours (Osuri *et al*., 2017 and Gopalakrishnan *et al*., 2019). The physical mechanisms associated with RI are still poorly understood.

Several studies have evaluated the processes that affect TC progress and intensification (Gray, 1968; Merrill, 1988; Frank and Ritchie, 1999). Nadimpalli *et al.*, 2020b reported the climatological characteristics of these RI TCs over Indian region. However, only limited studies have explicitly examined RI processes (Kaplan and DeMaria, 2003). We built our research on the factors that are generally related to TC intensification and the same has been reviewed. Several studies concentrating on atmosphere-ocean interactions have documented sea surface temperature (SST) to indicate cyclones' maximum potential intensity (Malkus and Riehl, 1960; Emanuel, 1986). The latent heat flux, or energy transfer between the ocean surface and the atmosphere augmented by higher SST; thus supports cloud formation mechanism, as evaporation takes place over warm waters. Merrill (1988) claimed that major storms never reach the peak intensity based on SST and suggested that unfavorable atmospheric conditions prevent the intensification of the TCs. The findings indicate that low environmental vertical wind shear could be favorable to the intensification of TCs and the same has been supported by various recent studies (Osuri *et al*., 2017; Nadimpalli *et al*., 2019; Bhalachandran *et al*., 2019). However, there is still much understanding required to learn about the particulars of the various physical processes involved in RI of TCs.

Further studies have highlighted the importance of inner core dynamics in altering the TC intensification changes (Tallapragada *et al*., 2015; Fischer *et al*., 2017; Chen *et al*., 2018; Bhalachandran *et al*., 2019; Gopalakrishnan *et al*., 2019). Shapiro and Willoughby, (1982) and Willoughby *et al*., 1982 documented the linkage between the inner core dynamics of TCs and intensity changes with eyewall. Other studies discussed the role of potential vorticity anomalies in TC intensification (Montgomery and Kallenbach, 1997; Molinari, 1998).Tang and Emmanuel (2010 and 2012) explained the importance of mid-level ventilation in TC intensification processes.

The high-resolution Hurricane Weather Research and Forecasting (HWRF) model was jointly developed by the National Oceanic and Atmospheric Administration (NOAA)'s National Weather Service/National Centers for Environmental Prediction (NWS/NCEP) and the Hurricane Research Division (HRD) of the Atlantic Oceanographic and Meteorological Laboratory (AOML) (Gopalakrishnan *et al*., 2011, 2012, 2013; Bao *et al*., 2012; Tallapragada *et al*., 2014; Atlas *et al.*, 2015). The modeling system is designed mainly to address the next-generation TC prediction problem and now plays a crucial role in removing the primary barriers associated with predicting intensity changes, the dynamical prediction of which was nearly non-existent before 2009 (Gopalakrishnan *et al*., 2019). HWRF has been an operational model in all global basins (Tallapragada *et al*., 2015). Since 2011, HWRF intensity predictions over the NIO basin have improved by about 36-83% (Das *et al*., 2015; Mohanty *et al*., 2015; Nadimpalli *et al*., 2019; Nadimpalli *et al*., 2020a).

This study aims to understand the environmental and structural characteristics that led to Very Severe Cyclonic Storm (VSCS) Titli's simulated RI and no RI case, Severe Cyclonic Storm (SCS) Phethai [Brief about TC Titli and TC Phethai are given in Section 2]. The methodology followed in the study, results and conclusions from the study is reported in Section 3, 4 and 5, respectively.

2. A synoptic overview of VSCS Titli and SCS Phethai

Titli : On 7th October, 2018, a low-pressure area was formed over southeast BoB and later, it was intensified into a cyclonic storm Titli on 9th October, 2018 noon under favorable conditions. Further, it strengthened into a VSCS by exhibiting rapid intensification during 1200 UTC 0900-1200 UTC 10th October, 2018 (40 knots change in 24 hour time period) with a north-northwestward movement. In the early hours (0430-0530 IST) of 11th October, 2018, it crossed north Andhra Pradesh and south Odisha coasts near Palasa (Srikakulam District of Andhra Pradesh) as a VSCS with a wind speed of 80 knots.

TABLE 1

Overview of HWRF modeling system used in the study

Horizontal Grid Vertical Levels	27 km: 77.76° × 77.76° 9 km: 10.56°× 10.2° 3 km: 6.16° × 5.44° 42 hybrid levels
Vortex Initialization	27-9-3 km: Yes
Cycling	Yes
Microphysics	Ferrier
Short- and Long- Wave Radiation	GFDL
Surface Scheme	GFDL (HR implementation)
PBL Scheme	GFS
Cumulus Parameterization (CP)	Simplified Arakawa-Schubert (27-9 km) No CP (3 km)
Land Surface	GFDL Slab

Phethai : The SCS Phethai originated from a low-pressure area, which formed over the equatorial Indian Ocean and adjoining central parts of south BoB on 9 December. Under favorable atmospheric conditions, it intensified into a cyclonic storm on 15 December evening hours (1200 UTC) and further deepened to SCS during 0500 UTC 16th December. The severe cyclonic storm intensity of the system was about 15 hours of life span only. Continuing to move north-north westwards and then northwards, it crossed Andhra Pradesh coast close to the south of Yanam (Union Territory of Puducherry) and north Amalapuram (East Godavari District of Andhra Pradesh) on 0800-0900 UTC of 17th December, 2018 as a cyclonic storm.

3. Methodology

The initial and boundary conditions for HWRF are derived from the analyses and forecast fields (at 0.25° × 0.25° resolution) of the NCEP Global Forecasting System (GFS) model. Constant SST is used throughout the short-range integration and the lateral boundary conditions are updated every 6 hours. The United States Geological Survey (USGS) data at 2 min horizontal resolution provides permanent land surface fields such as terrain and topography. The storm message (also known as TC Vitals), provided by the IMD New Delhi on real time basis and is used for vortex initialization. It is to be noted that no coupling and no assimilation is employed during the study. The configuration of model setup can be found in Osuri *et al*., 2017; Nadimpalli *et al*., 2019. A summary of the model configuration is presented in Table 1.

Our approach is to assess the HWRF simulation on a large-scale by examining the environmental vertical wind shear. The reason behind considering this parameter is that shear is taken as an unfavorable factor for TC intensification. Vertical wind shear could advect the heat and moisture away from the inner core of the TC necessary for convection (Gray, 1968; Chen and Gopalakrishnan, 2015; Bhalachandran *et al*., 2019), or can tilt the vortex, producing an anomaly that prevents convection (DeMaria, 1996). For this purpose, we have examined the local rate of change of relative vorticity (ζ) in isobaric coordinates, which is given by

$$\frac{\partial \zeta}{\partial t} = -\vec{V}.\nabla(\zeta + f) - \omega \frac{\partial \zeta}{\partial p} - (\zeta + f)\nabla.\vec{V} + \hat{k}.\left(\frac{\partial \vec{V}}{\partial p} \times \nabla \omega\right) \tag{1}$$

where,

p = pressure

$\vec{V}$ = horizontal wind velocity vector

f = absolute vorticity or Coriolis parameter

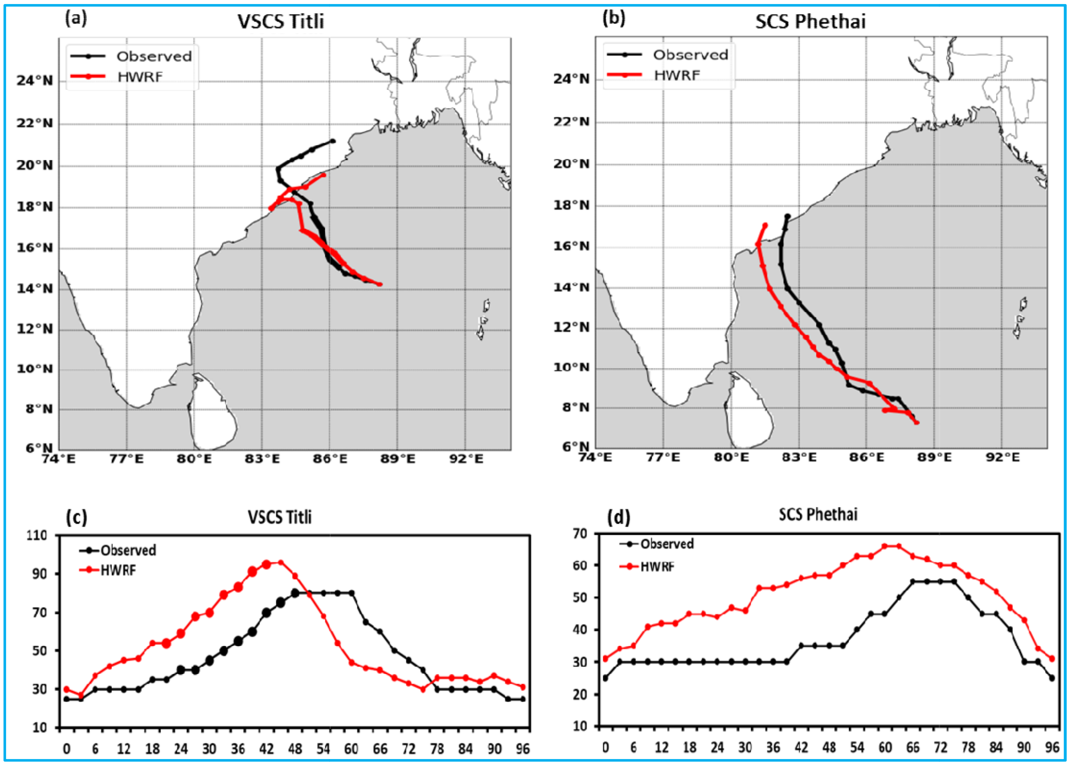
ω = vertical wind velocity in pressure coordinates $(\partial p / \partial t)$.

The area-average of the relative vorticity is defined as the circulation of the storm. Thus, we have examined the vorticity equation (1) to identify the processes by which the successful simulation of the TCs developed a stronger circulation. Further environmental and inner-core characteristics of Titli and Phethai were examined by calculating area-averages of the quantities over four different radii (*r*) from the center of the storm (200, 300, 400 and 500 km). This was done to verify that the differences between the simulations were consistent at multiple scales.

The environmental vertical wind shear impact was analyzed by computing the area average of the wind vector difference between the two pressure levels. The calculation of the standard deep-layer wind shear (850-200 hPa) was followed by the calculation of the mid-layer wind shear (850-500 hPa). As the circulation may not extend to 200 hPa level, the mid-layer wind shear might be more pertinent at the early stages of TC development.

Titli's inner structure is studied by analyzing the stretching (divergence) term of the vorticity equation (1), given by

$$-\vec{V}.\nabla(\zeta + f)$$



Figs. 1(a-d). (a) Tracks of TC Titli along with IMD best estimations, (b) same as (a) but for Phethai. The RI period of TC Titli is bolded. (c) 10m maximum sustained wind speed (knots) for TC Titli and (d) same as (c) but for TC Phethai, The RI period marks are made bold

The stretching term could modify the relative vorticity in the model in two ways:

(*i*) The model run that initialized with higher relative vorticity (stronger cyclonic circulation) near the surface will endure having higher relative vorticity at similar divergence.

(*ii*) At similar initial vorticity, the divergence or convergence of air could play a vital role in modulating the local rate of change of the relative vorticity.

The divergence of a fluid can be written from the mass continuity equation and expressed as:

$$\nabla.\vec{V} = -\frac{\partial \omega}{\partial p}$$

Under hydrostatic balance,

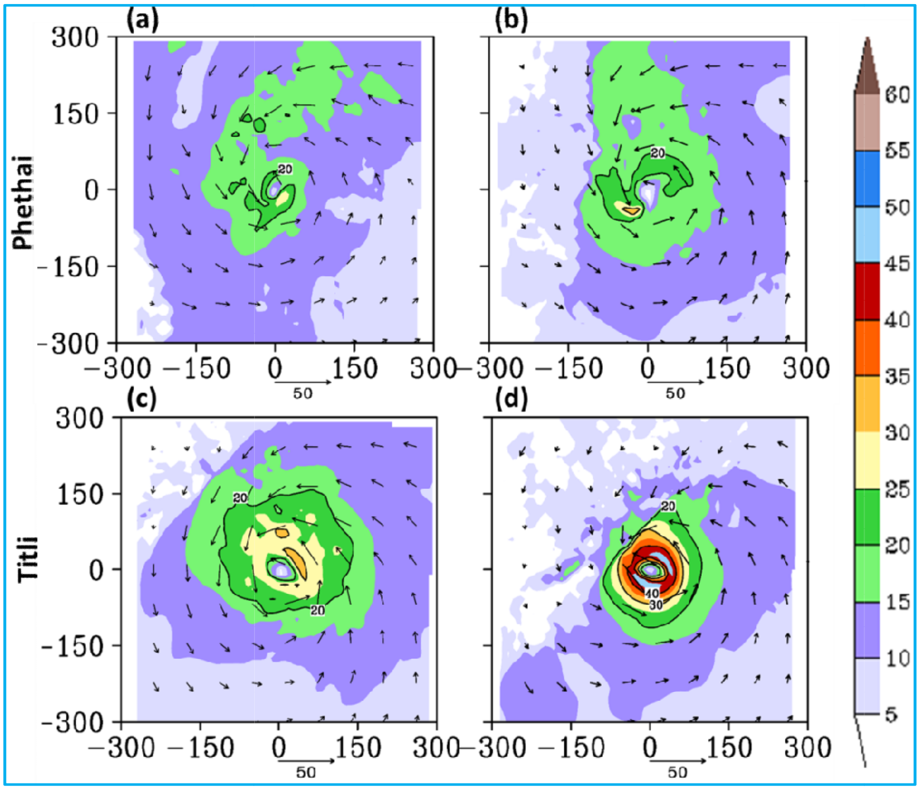
$$\nabla.\vec{V} = -\frac{\partial \omega}{\partial p} \approx -\frac{\partial w}{\partial z}$$

where, w is the vertical wind velocity in height coordinates (dz/dt). The downward (upward) motion is associated with (divergence) convergence near the surface.

The mass flux (σ), or area-average vertical transport of mass, represents whether upward or downward motion is taking place in the atmosphere and is given by:

$$\sigma = \rho \omega A$$

where, ρ is the air density and A is the averaging area. To identify the convergence or divergence of air, vertical profiles of the mass flux are compared. The water vapor content near the clouds could affect the mass flux. The downdrafts and divergence of air near the surface could be formed by entrainment of dry air into the inner core of the mid-troposphere (Bhalachandran *et al*., 2019; Tang and Emmanuel, 2010). Therefore, vertical profiles of the average relative humidity were also presented. The environmental impacts of the relative humidity are examined by using an averaging radius of 400 km at the initial time. The TC evolution strongly influences the humidity profile near the storm's inner core (at an average radius of 200 km). It is to be noted that the first and second terms in equation 1 (advection terms) are not considered in the present study and will be documented in



Figs. 2(a-d). Horizontal wind field of TC Phethai (a) CS stage and (b) after 24 hours of CS stage, (c) and (d) are the same as (a) and (b) but for the Titli case. The Titli developed the typical hurricane structure, including the eye and the highest winds in the eyewall

a future article. The environmental vertical wind shear could be related to the horizontal advection term of absolute vorticity. Further, the fourth term in equation 1 (influence of tilting) is not considered in this study as it is characteristically less significant on horizontal scales of 100 km or more.

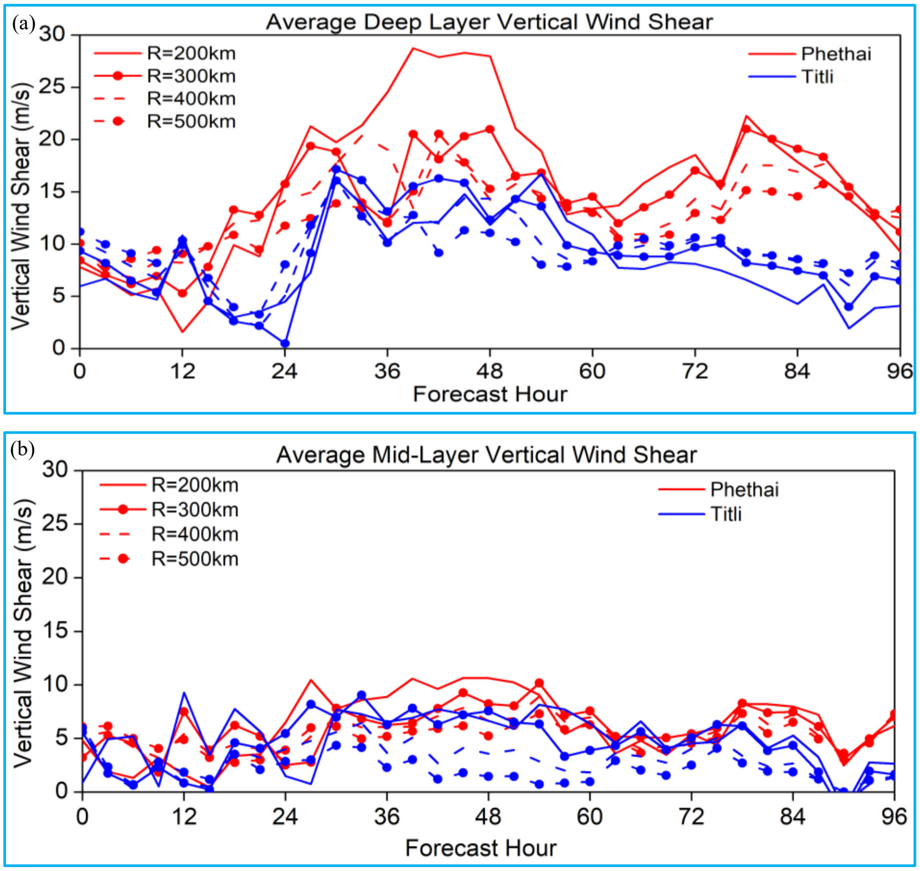
4. Results and discussion

Both track and intensity analyses of the two cyclones, Titli and Phethai, are discussed in the present section. As discussed in the previous section, the possible reasons behind the rapid intensification of Titli as compared to Phethai are reported in terms of environmental and inner-core characteristics in the following subsections.

4.1. *Prediction of track and intensity of TCs*

The track and Intensity of TCs, Titli and Phethai simulated with the HWRF model and IMD best estimation (available at www.rsmcnewdelhi.imd.gov.in) are illustrated in Figs. 1(a&b). Both the cyclones are simulated well by the model. The simulated tracks follow the IMD best track as the TCs recurve. However, for TC Titli, the recurvture in the north-eastward direction starts near the coast for the simulated one, unlikely the observed one for which the recurvature takes place more inland. The average track errors are 93 km and 122 km for Titli and Phethai, respectively. For the TCs, 24-hour track error is nearly 70 km, increasing with time up to 96 hours of simulation. The intensity evolution in 10m maximum sustained wind is provided in Figs. 1(c&d) for Titli and Phethai. The intensity changes pattern is well captured, showing the RI from 21 h to 42 hours in Titli. However, there is a considerable bias observed in the intensity changes for both the cyclones. The average biases present in these simulations are 6 knots and 15 knots for Titli and Phethai. As the paper aims to address the RI related analysis of the storm, the bias is neglected.

The surface wind distribution around the eye of the storm is analyzed for both the cyclones at the initial stage (CS) and the subsequent 24 hours after and presented in Figs. 2(a-d). The simulation of Phethai exhibited a maximum wind increase of 20 knots during 24 hours [Figs. 2(a&b)], where RI has not occurred. The simulation



Figs. 3(a&b). Average (a) 850-200 hPa vertical wind shear and (b) 850-500 hPa vertical wind shear for TC Phethai (red lines) and TC Titli (blue lines)

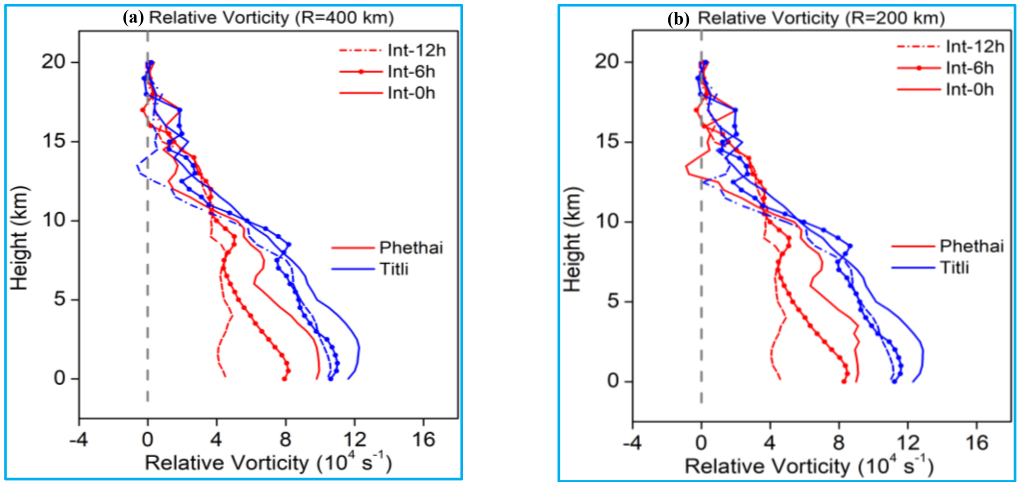
of Titli produced a maximum increasing wind rate of 45 knots during the 24 hours of the span. The development of a well-organized cyclonic wind structure is built at the end of RI time for Titli, which is not present for the Phethai case.

4.2. *Environmental characteristics*

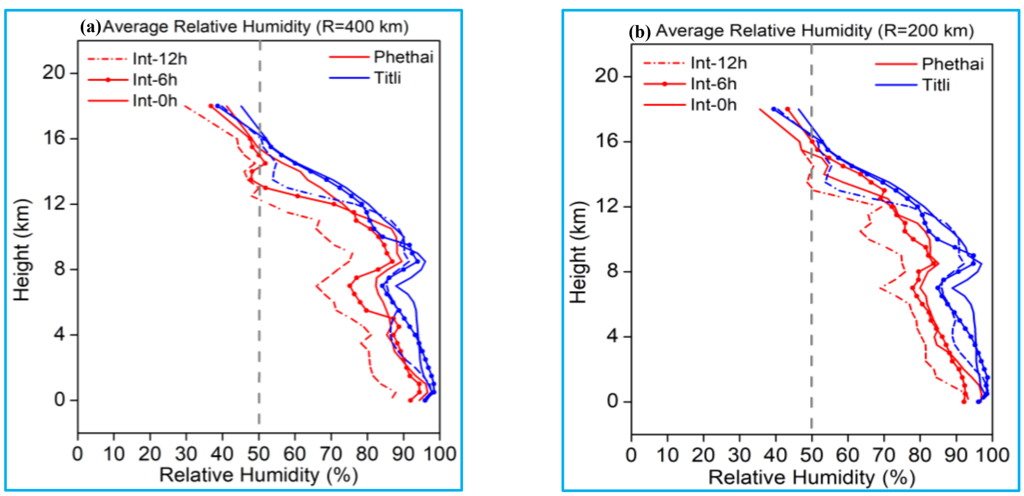
Under a favourable environment and a vortex structure development, TCs are anticipated to intensify unless they are influenced by vertical wind shear, dry air, or relatively low sea surface temperatures (Kaplan and Demaria, 2003). Time series of the average deep-layer vertical wind shear (850-200 hPa) are presented in Fig. 3(a). For all four averaging radii and for both simulations, the initial vertical wind shear was low (less than 10 m/s) compared to what is commonly considered unfavorable for TC intensification (about 10 m/s). While the Phethai simulation experienced stronger deep-layer wind shear, it didn't do as such until after the intensities in the two simulations began diverging from one another. These results put forward that the wind shear does not impact the intensification of Titli. The time series of the mean 850-500 hPa (shallow-layer) vertical wind shear [Fig. 3(b)] also confirming the result. For all four averaging radii, the shallow-layer wind shear is comparable for both simulations at the beginning. After the first 12 hours into the Titli and Phethai simulations, the shallow-layer wind shear became stronger in the Titli than in the Phethai simulation. Deep layer shear is considerably low for Titli. Prior to RI, Titli exerted sharp lowering in shear during the onset of RI.

4.3. *Inner structure characteristics*

The vertical profiles of the area-averaged parameters at different times are analyzed. The time of RI onset in Titli simulation and the peak intensity of Phethai simulation are considered as in the profile figures presented in the paper. The area-averaged profiles are calculated during the peak intensity (for Phethai), RI (for Titli) and subsequently 6 and 12 h before that for both the simulations. The vertical profile of relative vorticity (circulation) for both the simulations are shown in Figs. 4(a&b). It is seen that the Titli had a stronger circulation than the Phethai throughout the troposphere.



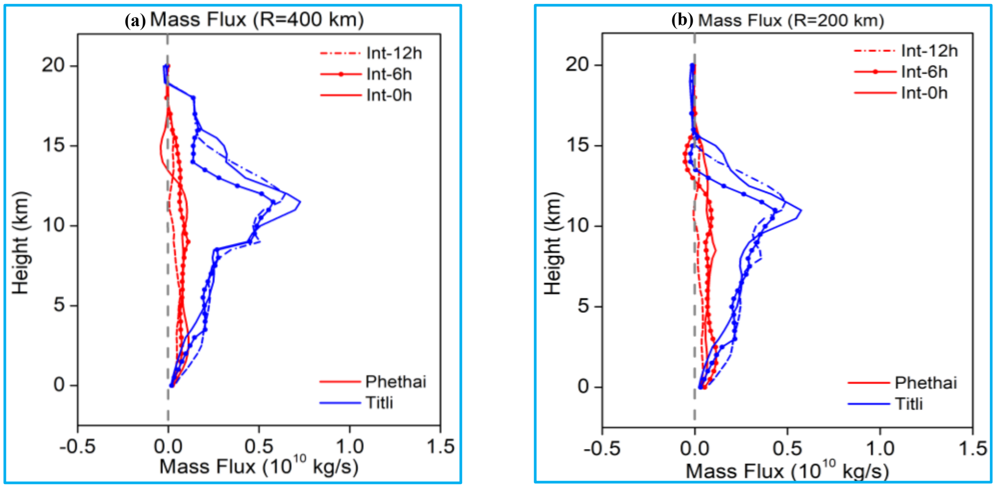
Figs. 4(a&b). Area area-average of the relative vorticity (circulation) for TC Phethai (red lines) and TC Titli (blue lines) with an averaging radius of (a) 200 km and (b) 400 km



Figs. 5(a&b). Same as Fig. 4 but for average relative humidity

By analyzing the stretching (divergence) term in equation 1, we could say that the successful simulation would develop a much stronger circulation since the initial circulation is stronger. Wang, 2012 suggested the relative vorticity maximum averaged over the 200 km box (the meso-β scale) is primarily located between 600 and 700 hPa, accompanying the antecedent easterly wave cresting at the level of the easterly jet [Fig. 4(a)]. During 24-48 h, there is an apparent downward growth of the cyclonic circulation as vorticity increases near the surface (not shown). However, the reduction of the mid-level vorticity at the same time proposes that the spin up of the surface rotation is not due to the mid-level vortex increase (Wang *et al*., 2010). The vorticity budget analysis in Wang *et al*. (2010) revealed that the rise in vorticity near the surface is majorly due to the low-level convergence.

The vertical profiles of the relative humidity are shown in Figs. 5(a&b). The Phethai simulation started with a drier profile in the troposphere. Dry air in the mid-troposphere makes the atmosphere susceptible to downdrafts (downward air motion). These downdrafts produce divergence in the lower troposphere, a negative factor for increasing cyclone intensity. Relative humidity above the boundary layer in the immediate environment (*r* = 600 km) usually rise with TC intensification rate. Rapidly intensifying TCs are associated with higher relative humidity than weakening and neutral TCs (Wu *et al.*, 2012). Also, prior to 12 h of RI, the moisture present both in the storm's inner and outer core is less than the time of RI onset. The relative humidity profiles strongly support the fact that there is anomalously high moisture present in the TC environment to actuate RI onset.



Figs. 6(a&b). Same as Fig. 4 but for Area average of the vertical mass transport (mass flux)

The vertical profiles of the mass flux, which were computed to examine the divergence in the vorticity equation's stretching term are shown in Figs. 6(a&b). Considering the relation between the mid-tropospheric vorticity and precipitation, a possible reason for the increasing lower-tropospheric vorticity is a variation in the vertical mass flux profile. The vertical mass flux profile relays to vorticity tendencies *via* the divergence term, proportional to divergence or the vertical gradient of the vertical mass flux. An unstable profile favours vorticity spinup over a deep layer, whereas a stable profile favours vorticity spinup near the surface. A shift from an unstable to a stable profile ensues throughout tropical cyclogenesis when a lower-tropospheric center of circulation forms from a disturbance with a mid-tropospheric vorticity maximum (Raymond and López Carrillo, 2011; Gjorgjievska and Raymond, 2014; Davis, 2015; Tang *et al*., 2016).

In the Titli simulation, the mass flux increased rapidly in the mid-troposphere (strong mid-tropospheric convergence developed) within the first 24 hours in the successful forecast. This occurred before any significant change in the circulation occurred near the surface [Figs. 4(a&b)]. So, it is hypothesized that the rapid increase in the mass flux at the mid-troposphere is related to the initial higher moisture content in the successful simulation. Simultaneously, a rapid rise in the relative humidity at mid-levels was associated with this rapid increase in the Titli simulation's mass flux. The convergence of air at the surface is necessary for convection to occur. The convection itself moistens the air at mid-upper levels. Although the Phethai simulation experienced some moistening, the air was still dry compared to the Titli simulation.

The rapid growth of the relative vorticity at the mid-troposphere also occurred during the first 24 hours in the Titli forecast. After establishing a deep vortex, mass flux (and lower tropospheric convergence) sustained to increase. After 48 hours, the Titli simulation developed a mature hurricane's typical mass flux profile, with convergence in the lower and middle troposphere (positive slope) and divergence aloft (negative slope). This lead to VSCS Titli's RI, where Phethai didn't exhibit similar higher profiles.

5. Conclusions

The purpose of this study has been to identify the environmental and storm structure characteristics associated with RI of TCs in the Bay of Bengal using the HWRF modeling system. For this purpose, two TC cases from the 2018 post-monsoon season [VSCS Titli (RI case) and SCS Phethai (Non-RI)] are considered. We have assessed both the simulations by examining the environmental vertical wind shear and the vorticity equation. The present study has attempted to understand how the HWRF model produced Titli's RI about the observed RI that occurred. Therefore, it is expected to provide insight into RI occurrence.

On a large scale, the results propose that the environmental vertical wind shear did not significantly influence the RI of the Titli simulation. However, low shear exhibited at the mid-level before RI in Titli, which could set a conducive situation for triggering RI. The relative humidity and relative vorticity (circulation) are initially stronger for the Titli simulation than for the Phethai simulation on the storm scale. So, the high moisture availability in the mid-troposphere in the Titli simulation helped increase the mass flux over these levels. As a result, the humidity and circulation also increased rapidly at the mid-troposphere; thus, the RI at the lower troposphere was observed.

Though there is still more to analyze, the current study provides a basis for future research to understand RI development better. Future research would include the analysis of other thermo-dynamic structural aspects of TC. In addition, a similar kind of study should be carried out for a large number of RI TCs to establish a well-proven mechanism behind RI changes of TCs.

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