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Satellite-based analysis of rapid intensification of Super Cyclone Amphan

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सार – उष्णकटिबंधीय चक्रवात (टीसी) उष्णकटिबंधीय बेल्ट के साथ जीवन और संपत्ति पर विनाशकारी प्रभाव वाले दुर्जेय प्राकृतिक खतरे हैं। उष्णकटिबंधीय चक्रवात नदी और शहरी बाढ़, अत्यधिक हवाओं और बिजली, तूफानी उछाल जैसे कई खतरों के लिए जिम्मेदार हैं, जो उनके द्वारा उत्पन्न खतरों को काफी हद तक बढ़ा देते हैं। तीव्र तीव्रता (आरआई), जिसे अधिकतम निरंतर हवाओं (एमएसडब्ल्यू) में 24 घंटे में 30 kt या उससे अधिक की अचानक वृद्धि के रूप में परिभाषित किया जाता है, एक बढ़ती हुई चिंता का विषय रहा है। एमएसडब्ल्यू में तेजी से वृद्धि की विशेषता वाली ये घटनाएं पूर्वानुमान लगाने वालों के लिए चुनौतीपूर्ण हैं और तटीय समुदायों के लिए जोखिम को बढ़ाते हुए एक बड़ी परिचालन चुनौती बनी हुई हैं। संख्यात्मक मॉडलिंग भी आरआई की पूर्वानुमान करने के लिए संघर्ष करती है वर्तमान अध्ययन में हम सुपर साइक्लोनिक स्टॉर्म (SuCS) अम्फान, इस सदी के पहले सुपर साइक्लोन की जांच करते हैं, जो 2020 में बंगाल की खाड़ी के ऊपर बना था, जो RI के शुरुआती संकेतों की निगरानी और पहचान करने के लिए उपग्रह इमेजरी और लगभग वास्तविक समय में उपलब्ध व्युत्पन्न उत्पादों का उपयोग करता है। यह देखा गया है कि तीव्रता RI से पहले इसकी सममितता के साथ-साथ बाहरी और आंतरिक दोनों कोर आकारों में पर्याप्त विस्तार से जटिल रूप से जुड़ी हुई है। विशेष रूप से, बहुत गंभीर चक्रवाती तूफान (VSCS) और SuCS चरणों के बीच आकार में कोई महत्वपूर्ण परिवर्तन नहीं देखा गया है। TC की संवहन विशेषताएँ उनकी तीव्रता के महत्वपूर्ण मार्कर प्रदान करने के लिए पाई गई हैं, जिसमें अंतर्निहित संवहन और प्रारंभिक आंखों का पता लगाने के विश्लेषण के लिए ध्रुवीय उपग्रह-आधारित निष्क्रिय माइक्रोवेव इमेजरी पर विशेष जोर दिया गया है इसके साथ ही, मध्य-जीवन काल के दौरान देखा गया बाहरी वलय पैटर्न, प्रणाली की और अधिक गहनता की अनुमति देता है।

ABSTRACT. Tropical Cyclones (TCs) are formidable natural hazards with destructive impacts on life and property along the tropical belt. TCs are responsible for multiple hazards, such as riverine and urban floods, extreme winds, and lightning, storm surge, significantly amplifying the threats they pose. Rapid Intensification (RI), defined as a sudden increase in Maximum Sustained Winds (MSWs) by 30 kt or more in 24 hrs, has been a growing concern. These events, characterized by a swift escalation in MSW are challenging to the forecasters and remain a considerable operational challenge, amplifying risks for coastal communities. Numerical modelling also struggles to predict RI, with limitations in describing inner core convective scale processes cited as a significant limitation. Monitoring and assessing TCs heavily rely on satellite-based observations due to the absence of adequate in-situ measurements over the ocean. In the present study we examine Super Cyclonic Storm (SuCS) Amphan, the first Super Cyclone of this century, that formed over Bay of Bengal in 2020 using satellite imagery and derived products available in near-real time to monitor and identify the early signatures for the RI. It is observed that the intensification is intricately tied to substantial expansions in both the outer and inner core sizes along with its symmetricity before the RI. Notably, no significant alterations in size are observed between the very severe cyclonic storm (VSCS) and SuCS stages. The convection characteristics of TCs are found to provide crucial markers of their intensification, with a particular emphasis on polar satellite-based passive microwave imagery for analysing embedded convection and early eye detection. Key observations indicate that inner convective ring patterns, identified through 37Ghz microwave imagery in lower-level convection, act as precursors to rapid intensification. Concurrently, the outer ring pattern observed during the mid-life course is found to permit further intensification of the system.

Key words – Tropical cyclones, Rapid intensification, Satellite meteorology.

1. Introduction

Tropical Cyclones (TCs) are amongst the deadliest natural hazards that significantly affect the life and property around the tropical belt. It includes several associated hazards like storm surge, flooding, extreme winds and lightning that substantially increases its potential to threaten life and property. TCs have proved catastrophic to the coastal regions around the world. TCs are the synoptic scale, ocean-atmosphere coupled phenomena that originate over the deep oceans, which is a data sparse region. Due to lack of in-situ measurements, the monitoring and assessment of TCs depend on the satellite-based observations. Rapid intensification (RI) is defined as a sudden increase in Maximum Sustained Winds (MSWs) by 30 kts or more in 24 hrs (Kaplan and De Maria, 2003). For Satellite based analysis it considered to be increase in T no by 1.5 in 24 hrs (Dvorak, 1984). In recent decades multiple studies have reported the sudden increase in the intensity of TCs in relatively shorter duration (De Maria, 2003; Nadimpalli *et al*., 2021). This sudden increase of MSW within a short time span is very much hazardous to the coastal population and industrial installations.

RI cases are responsible for exceptionally severe losses to the lives and property. Forecasting the RI cases is very challenging and thus it further increases the risks for coastal communities (Emanuel, 2017). There are several studies that bring out difficulties in forecasting of RI and how it poses significant challenges to the operational forecasts (Elsberry, 2014; Emanuel, 2017a; Rappaport *et al*., 2012; Knaff *et al*., 2018). In a recent study, (Nadimpalli *et al.,* 2021) carried out the trend analysis over NIO using International Best Track Archive for Climate Stewardship (IBTrACS) data. It indicates that there is a significant trend observed in the RI cases over NIO since 2000 with one among three intensifying cyclones undergoing RI in its lifetime, mostly in the initial stages. They also found that the TCs over NIO are sensitive to seasons as a greater number of RI cases are observed in the post monsoon season and they are also basin dependent with higher number of TCs undergoing RI over BoB than the AS. The cases of TCs undergoing rapid decay were also found to be higher over BoB with 90% contribution.

Numerical modelling - based forecasts finds prediction of RI challenging. A study carried out at National Hurricane Centre (NHC; Rappaport *et al.*, 2009) brings out lack of description of inner core convective scale processes inducing intensity changes as one of the reasons for this limited success in TC intensity prediction. It also opines that the skill of human forecaster is much more than the objective intensity guidance based on models. Limited understanding of TC intensity change in general is primarily responsible for the inability to forecast RI (Kaplan and De Maria, 2003). Forecasting the RI cases is very challenging and thus it further increases the risks for coastal communities (Emanuel, 2017).

The necessary environmental conditions for TC have long been studied and established like warmer sea surface temperatures, enhanced moisture availability in lower atmosphere and lower vertical wind shear (Merrill, 1988; Kaplan *et al*., 2010). Convective indices based on cloud top temperature measurements using GEO satellite-based infrared channels (Gentry, 1980) and latent heat release associated with it using satellite-based microwave channels (Adler and Rodgers, 1977) were found to be strongly associated with the maximum TC winds. Geostationary brightness temperature dataset (Tierra & Bagtasa, 2022) shows an optimal combination of convection parameters like cloud top temperature, overshooting tops and are of occurrence for RI. Using there are several studies that bring out the role of convective structure within the inner core of the TCs (Steranka, 1986, Alvey *et al.*, 2015, Fischer *et al.*, 2018). Based on the Infrared brightness temperatures, RI episodes were found to be associated with more symmetric convection (Kaplan *et al.,* 2015). However, a recent study by Donglei *et al.* (2023) using Satellite based precipitation estimates shows that RI is not necessarily preceded by rainfall axi symmetrization. A study by Willoughby *et al.* (1982) shows that concentric eyewall cycles is linked to the changes in TC intensity. A recent study by Lin and Qian (2019) using AMSU satellite dataset found strong warming rate above eye-wall cloud top. The ability of microwave wavelengths to penetrate through the clouds brings out some important observations related to the TC core structure. Harnos and Nesbitt (2011) carried out RI specific study using microwave observations and found that the convective ring is seen from the 37-GHz imagery for TCs undergoing RI. They also observed that this convective ring and favorable environmental conditions together could be sufficient condition of RI. A study by Kieper and Jiang (2012) using passive microwave imagery shows the structural differences in RI TCs and TCs with lesser intensification rates. They observed a moderately intense convective ring surrounding the storm centre forming prior to the onset of RI. Also, along with this convective ring the precipitative ring around the TC centre was also found to be a good predictor of RI. Using Hurricane Weather research and Forecasting (HWRF) model simulations Gopalakrishnan *et al.* (2013) show how collocated vertical vorticity fields and convective bursts and their propagation from down shear to up shear region play a role in triggering the RI.

The current investigation aims to analyze alterations in convection and wind structure related to the recent rapid intensification of Super Cyclone Amphan using satellite imagery and derived products. Super Cyclone Amphan originated from a residual circulation of a Low-Pressure Area that formed near the Equatorial Easterly wave over the South Andaman Sea and adjacent southeast Bay of Bengal (BoB) on the morning of May 13th (0300 UTC). Under favorable environmental conditions, it evolved into a depression (D) over the southeast BoB in the early morning of May 16th (0000 UTC) and further intensified into a deep depression (DD) later that afternoon (0900 UTC). Progressing nearly northwards, it reached Severe Cyclonic Storm (SCS) status over the southeast BoB on the morning of May 17th (0300 UTC). In the subsequent 24 hours, it underwent rapid intensification, reaching Very Severe Cyclonic Storm (VSCS) category by the afternoon of May 17th (0900 UTC), Extremely Severe Cyclonic Storm (ESCS) status in the early hours of May 18th (2100 UTC of May 17th) and eventually Super Cyclonic Storm (SuCS) status around noon on May 18th, 2020 (0600 UTC). Maintaining SuCS intensity over west-central BoB for nearly 24 hours, it eventually weakened into an ESCS over the same region around noon on May 19th (0600 UTC). Subsequently, it slightly weakened further and crossed the coasts of West Bengal – Bangladesh as a VSCS, traversing the Sundarbans (https://rsmcnewdelhi.imd.gov.in/download.php?path=uploads/report/26/26_936e63_amphan.pdf).
The observed track of the system from May 16th to 21st is depicted in Fig. 1.

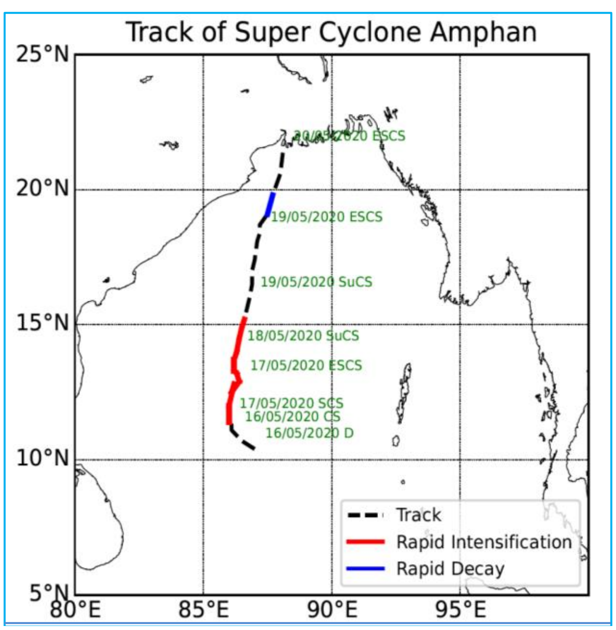


Fig. 1. Observed track and intensity of SuCS Amphan.

TABLE 1

Intensity based nomenclature and equivalent T no used by RSMC New Delhi

Nomenclature	T no	Maximum Sustained Winds (knots)
Well-Marked Low (WML)	1	< 17
Depression (D)	1.5	17-27
Deep Depression (DD)	2.0	28-33
Cyclonic Storm (CS)	2.5, 3.0	34-47
Severe Cyclonic Storm (SCS)	3.5	48-63
Very Severe Cyclonic Storm (VSCS)	4.0, 4.5	64-90
Extremely Severe Cyclonic Storm (ESCS)	5.0 - 6.0	91-119
Super Cyclonic Storm (SuCS)	≥ 6.5	≥ 120

2. Data and methodology

Dvorak technique (Dvorak 1984, 1995) is used to determine the intensity of TCs. The categorization used by Regional Specialized Meteorological Centre (RSMC), New Delhi is given in Table 1. This technique uses Vis and IR channel imagery. For this analysis INSAT-3D geostationary satellite imagery is used. Apart from this, multiple Satellites imagery and products were used to analyze the convection pattern, wind structure and size of the TC. Passive Microwave imagery from Defense Meteorological Satellite Program series of satellites available at https://www.nrlmry.navy.mil/tc_pages/tc_home.html is used. The 37 Ghz channel is sensitive to the lower-level convection, while the 89Ghz channel is sensitive to the higher-level convection. The imagery from these channels was used to identify the convective patterns observed at different stages of the TC.

The Multi-Platform Tropical Cyclone Surface Wind Analysis is another data source used in this research paper to analyze the wind structure associated with intensification of tropical cyclones. The data were obtained from the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University, and were available through https://rammb-data.cira.colostate.edu/tc_realtime.

The best track dataset from RSMC, New Delhi, (available at - https://rsmcnewdelhi.imd.gov.in/) is used in this study. RSMC is a World Meteorological Organization (WMO) recognised nodal agency responsible for monitoring and forecasting of TCs in the North Indian Ocean region. The RSMC New Delhi best track dataset provides detailed information on the location

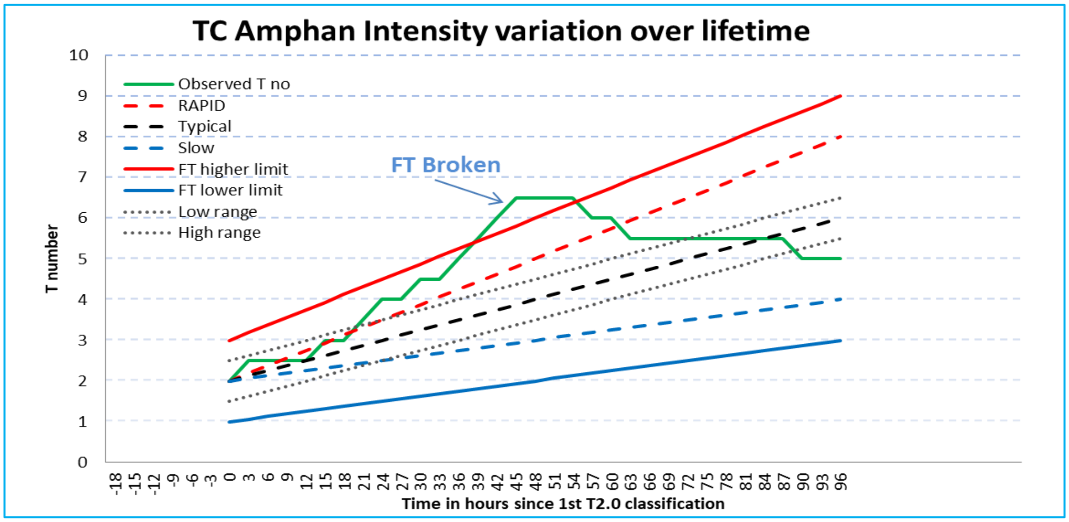


Fig. 2. Intensity variation over lifetime along with Trend, constraints, and threshold for Final T no.

and intensity of TCs in the region. The dataset is based upon rigorous scrutiny using a combination of all the available observations including Satellite, Radar and Surface based in-situ observations.

3. Results and discussion

Amphan was the first SuCS over the BoB, after the Odisha SuCS of 1999. It showed a clockwise recurving track as it moved initially north-northwestwards and north-northeastwards thereafter. The total track length of the system was 1765 km. It was mainly steered by an anticyclonic circulation in middle & upper tropospheric levels to the northeast of the system centre. It underwent intensification during 17th noon (0600 UTC) to 19th May early morning hours (2100 UTC of 18th) over west central BoB mainly due to low vertical wind shear (10-15 knots), very warm sea surface temperatures (SSTs – 30-31 °C), high tropical cyclone heat potential (100 - 120 KJ /cm^2) and increased cross equatorial wind surge. During this period, the system experienced an increase in MSW from 50 knots at 0600 UTC on the 17th to 130 knots at 2100 UTC of 18th May. The system maintained the cyclonic storm intensity for almost 15 hours even after landfall.

Based on the intensity classification as per Dvorak technique, the system did undergo rapid intensification from the initial classification of T1.0 (Well marked Low). This RI continued for the following 54 hours, and it was observed even at a relatively higher intensity of T 4.5 (Very Severe Cyclonic Storm). Maximum intensity change (shown in Table 2) of T 3.0 in the span of 24 hours was observed from 0300 UTC of 17th May when the system underwent explosive intensification from T 3.0 (Cyclonic Storm) to T 6.0 (Extremely Severe CS) and again from 0600 UTC of the same day when it intensified from T 3.5 (Very Cyclonic Storm) to T 6.5 (Super CS). During this phase, the system also broke the constraints put up on Final T number classification by the Dvorak Technique as shown in Fig. 2.

TABLE 2

Rate of change of observed intensity over following 24 hrs

Sl. NO.	Date	Time (In UTC)	Observed T no change over following 24 hrs
1	15-05-2020	1200	1.5
2	15-05-2020	1500	1.5
3	15-05-2020	1800	1.5
4	15-05-2020	2100	1.5
5	16-05-2020	0000	1.5
6	16-05-2020	0300	1.5
7	16-05-2020	0600	2
8	16-05-2020	0900	2
9	16-05-2020	1200	1.5
10	16-05-2020	1500	2
11	16-05-2020	1800	2
12	16-05-2020	2100	2.5
13	17-05-2020	0000	2.5
14	17-05-2020	0300	3
15	17-05-2020	0600	3
16	17-05-2020	0900	2.5
17	17-05-2020	1200	2.5
18	17-05-2020	1500	2.0
19	17-05-2020	1800	1.5

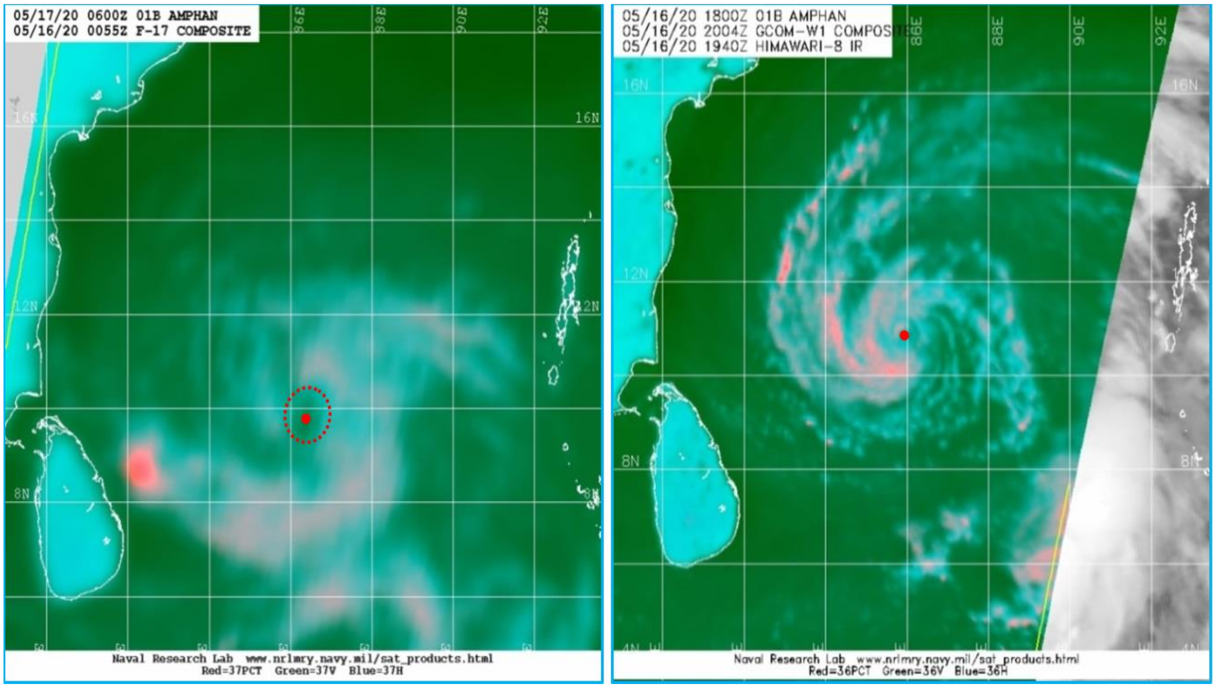
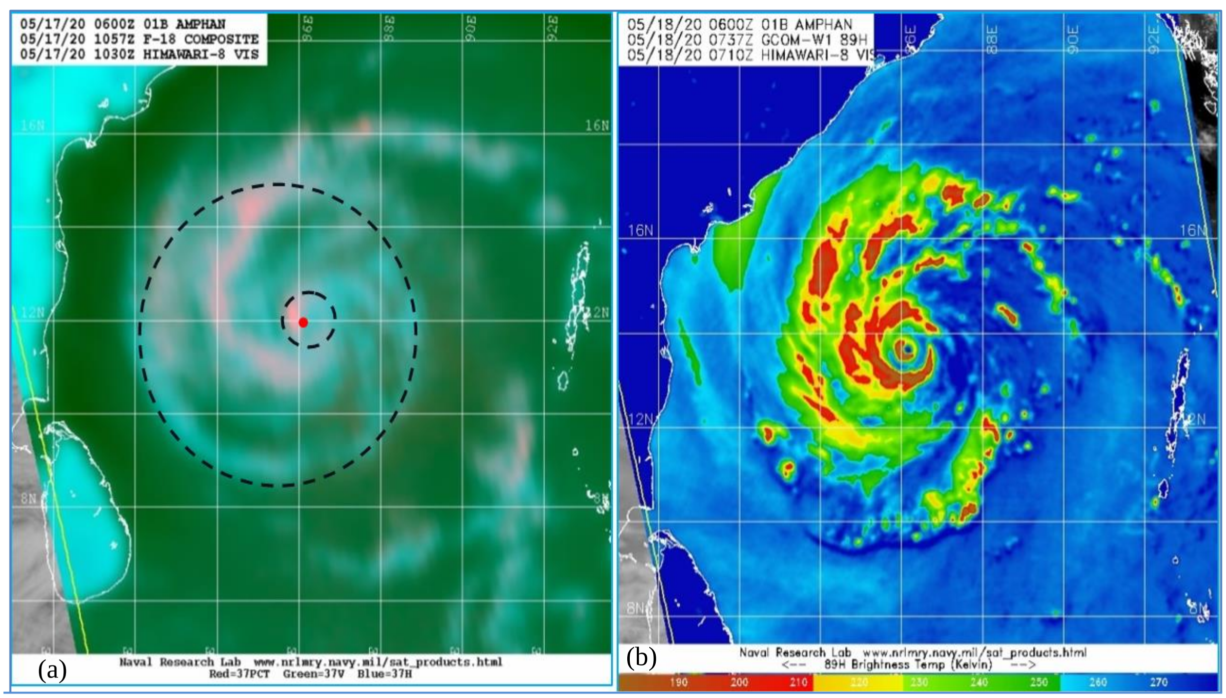
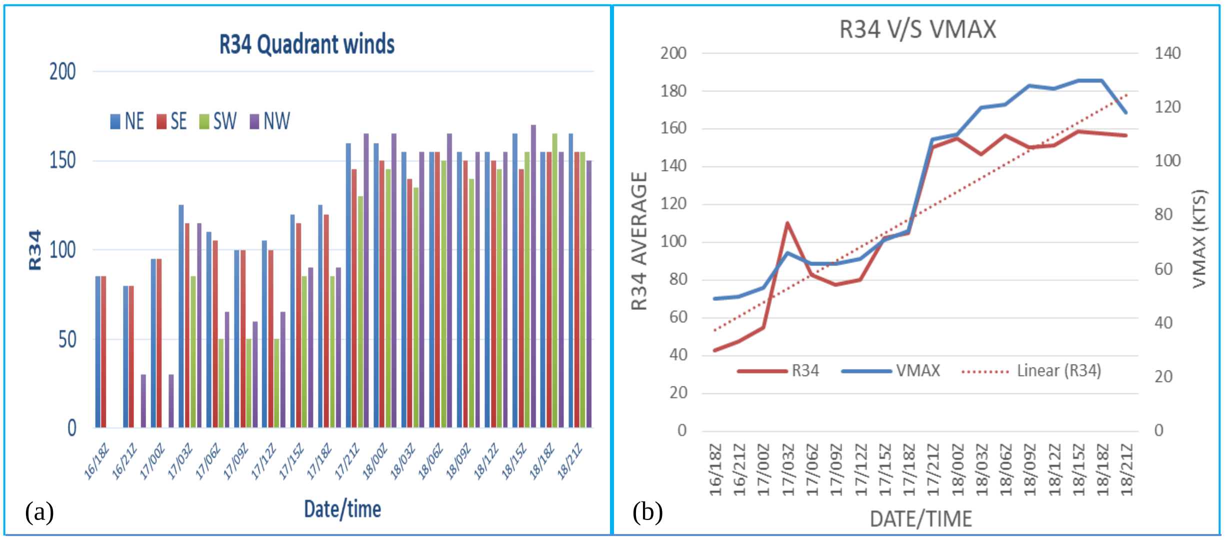


Fig. 3. Passive Microwave 37 GHz imagery of 16th May 2020 (left) 0055 UTC (right) 2004UTC (Source: NRL Tropical Cyclone Page - https://www.nrlmry.navy.mil/tc_pages/tc_home.html)



Figs. 4. (a&b). (a) 37GHzPassive microwave imagery showing the Inner and outer ring structure, (b) Secondary eye wall and eye wall replacement cycle captured in 89Ghz imagery. (Source: NRL Tropical Cyclone Page - https://www.nrlmry.navy.mil/tc_pages/tc_home.html).



Figs. 5 (a&b). (a) Multiplatform satellite wind showing quadrant wise radius of 34 kts winds (b) Maximum sustained winds and radius of 34 kts winds.

Passive microwave imagery of 35-37 GHZ shows the convective structure at the lower levels of the storm as it can penetrate the deep convection with little attenuation. This imagery indicates the formation of a cyan coloured ring-like structure around the system centre (Fig. 3, left panel) about 11 hrs prior to the system reaching the threshold Tropical cyclone intensity of T2.5. This is consistent with the earlier study by Harnos and Nesbitt (2011). This cyan ring surrounding the warmer green-coloured centre further organized and became stronger, as seen in Fig. 3 (right panel) at 2000 UTC of 16th May when the system was classified as Tropical Cyclone, and it continued to undergo RI in the following 24 hrs. This convective ring structure surrounding the system centre can act as a precursor to the RI occurring multiple times during the lifetime of a TC.

Another important feature observed is the formation of outer convective ring apart from the inner ring studied earlier. The curved bands associated with systems themselves surrounded the system completely giving rise to this outer ring like structure. This structure was observed (Fig. 4 (a)) when the system was classified as T 4.0 (VSCS). Even at this higher category the TC continued to intensify rapidly and showed an increase in T no by T2.5, much higher than the prescribed RI threshold of T1.5. This encircling of TC by the curved cloud bands might have acted as an insulator that suppressed the effects of environmental parameters over the TC, for example, reduction in the dry air entrainment which in turn reduces the further growth of system. After about 20hrs of this outer ring formation, 89 GHz microwave imagery (Fig. 4(b)) that characterizes the intense convection associated with the system shows the formation of intense convective ring surrounding the centre. Another secondary intense convective eyewall surrounding the inner eye wall is also observed after which the eye wall replacement cycles occurred at the peak intensity of T 6.5.

Quadrant winds based on the multi-platform wind product categorize the wind structure as radius of 34 kts winds (R34), 50 kts winds (R50) and 64 kts winds (R64) in 4 quadrants around the TC centre. It shows that R34 increased (Fig. 5 (b)) and was also observed in all the quadrants (Fig. 5 (a)) making TC more symmetric and organized before it underwent an explosive intensification of +T3.0/24 hrs from 17/03z to 18/03z. More symmetric structure was observed post VSCS (T4.0) intensity and maximum R34, R50 and R64 were observed in NE quadrant throughout the storm's lifetime. Rapid increase in the R34 size was also observed along with Rapid intensification of the TC. No significant change in TC size was observed from VSCS to SuCS stage.

4. Conclusion

The intensification of TCs is linked to significant increases in the size of the outer and inner core, with no significant change observed between the very severe cyclonic storm (VSCS) and severe cyclonic storm (SuCS) stages. The convection characteristics of TCs offer some signature of their intensification, and the use of polar satellite-based passive microwave imagery is vital in understanding embedded convection and early eye detection. Inner convective ring patterns observed in lower-level convection using 37 Ghz microwave imagery serve as precursors to rapid intensification, while outer ring patterns observed during mid-life course allow the system to intensify even further vigorously. Satellite based products and imagery which are available in near real time is useful and holds the potential for early identification of RI cases. More such studies are required to explore the possibility of formulating a Satellite based RI Index using these satellite-based parameters available in near-real time.

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