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Tornado over West Bengal on 25 May, 2021 in association with Very Severe Cyclonic Storm - YAAS over Bay of Bengal

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सार – उष्णकटिबंधीय चक्रवात (टीसी) बवंडर संक्षिप्त और अक्सर अप्रत्याशित घटनाएँ होती हैं जो घातक हो सकती हैं और आर्थिक नुकसान पहुँचा सकती हैं। जलवायु संबंधी अध्ययनों से पता चलता है कि टीसी जनित बवंडर मुख्य रूप से बाहरी वर्षा बैंड में लघु सुपरसेल से उत्पन्न होते हैं। बवंडर की विशेषताओं का पूर्वानुमान और रडार का का पता लगाना विशेष रूप से चुनौतीपूर्ण है। इस शोधपत्र में हमने अवलोकन डेटा का विश्लेषण किया है, जो 25 मई, 2021 को पश्चिम बंगाल के उत्तर 24 परगना और हुगली जिलों में बहुत गंभीर चक्रवाती तूफान (वीएससीएस) "यास" के साथ एक बवंडर की घटना का संकेत देता है, जो 26 मई, 2021 को लगभग 0600 UTC पर ओडिशा तट को पार कर गया था। बवंडर के स्थान 25 मई, 2021 को 0900 UTC पर वीएससीएस "यास" के संवहनी बाहरी बैंड में थे। बवंडर की विशेषताओं का अध्ययन कोलकाता डॉपलर मौसम रडार छवियों, ऊर्ध्वाधर पवन प्रोफ़ाइल और साउंडिंग डेटा के साथ किया गया था। इस बवंडर में हुक इको और मेसोसाइक्लोन जैसे विशिष्ट सुपरसेल तूफानों के समान विशेषताएं प्रदर्शित की गईं। यह अध्ययन वीएससीएस "यास" के सहयोग से पश्चिम बंगाल के उत्तर 24 परगना और हुगली जिलों में टीसी बवंडर की घटना के लिए अनुकूल परिस्थितियों को सामने लाता है।

ABSTRACT. Tropical cyclone (TC) tornadoes are brief and often unpredictable events that can produce fatalities and create economic loss. Climatological studies characterize TC spawned tornadoes as primarily originating from miniature supercells in the outer rainbands. The tornadic features forecasting and radar detection are particularly challenging. In this paper we analyzed the observation data which indicated the occurrence of a tornado over North 24 Parganas and Hooghly districts of West Bengal on 25 May, 2021 in association with Very Severe Cyclonic Storm (VSCS) "YAAS" which crossed Odisha coast around 0600 UTC of 26thMay, 2021. The tornado locations were in the convective outer bands of the VSCS "YAAS" at 0900 UTC of 25thMay, 2021. The characteristics of the tornado were studied with Kolkata doppler weather radar images, vertical wind profile and sounding data. This tornadoexhibited characteristics similar to typical supercell storms such as hook echo and mesocyclone. This study brings out the conditions favourable for the occurrence of a TC tornado over North 24 Parganas and Hooghly districts of West Bengal in association with VSCS "YAAS".

Key words – Tornado, Tropical cyclone, Supercell, Vertical wind shear, Doppler weather radar.

1. Introduction

Landfalling Tropical Cyclone (TCs) are associated with multiple hazards including damaging winds, flooding, storm surge, and tornadoes. TC tornadoes have been documented as early as 1773 (Sadowski 1962). But the steady recording and assessment of tornadoes within land-falling TC were not readily documented prior to 1955. Throughout the years, a variety of research has been published on many aspects of TC tornadoes, including multiple long and short-term climatologies regarding the location, detection, forecasting, and formation of TC tornadoes. Climatology has been a well-studied aspect of TC tornadoes and it is well documented since the 1960s (Hill *et al.*, 1966; Novlan and Gray, 1974; Gentry, 1983; McCaul and Weisman, 1996; Schultz and Cecil, 2009; Edwards *et al.*,2010; Moore and Dixon, 2011), with individual focus placed on particular aspects, such as temporal and spatial distribution, frequency and intensity variations, as well as outbreak potential. TC tornadoes range from several tornadoes to several dozen (Baker *et al.*, 2009). Previous studies have shown that many of the tornadoes either occur along with convective outer bands of TC or well in advance of the tropical storm or hurricane-force winds. Hence, their forecasting becomes a crucial complex problem (Gentry, 1983). Edwards (2012) observed that damaging winds from TC tornadoes mainly occur away from the area of hurricane force winds, in regions where hurricane preparations may not have been performed.

TC tornadoes are short and often unpredictable events that can produce fatalities. However, most of these tornadoes are associated with light-to-moderate damage (*i.e.*, EF-0 or EF-1; McCaul 1991; Schultz and Cecil 2009). Most tornadoes occur during the afternoon within 100–500 km of the TC center during the 48 h period before and after landfall (Novlan and Gray 1974; Schultz and Cecil 2009). Compared to their non-TC counterparts, TC tornadoes are typically less damaging (Edwards, 2010; Edwards, 2012); produced by "miniature" supercells (Spratt *et al.* 1997; Edwards *et al.* 2012); occur in strong vertical wind shear (VWS) and have sufficient thermodynamic instability concentrated over a shallow lower-tropospheric layer (McCaul 1991; McCaul and Weisman 1996). These favourable kinematic conditions are due to the TC warm-core structure and surface friction (Novlan and Gray 1974; Gentry 1983), while favourable thermodynamic environments are associated with weak convective inhibition and CAPE typical of the tropics (McCaul 1991; Molinari *et al.* 2012). Research also suggests that strong VWS through deeper layers tends to increase the number and intensity of TC spawned tornadoes. Moreover, faster moving TC tends to produce more tornadoes (Schenkel *et al.* 2020).

Several climatological studies of non-TC tornadoes for the Indian subcontinent have been carried out. The most comprehensive works were by Petersen and Mehta (1981), which documented 51 possible tornadoes across Bengal, 18 of which killed 10 people or more. Twelve of these occurred from 1838 to 1963 and 24 occurred after 1968. Between 1972 and 1978, 13 tornado events occurred. Goldar *et al.* (2001) documented 36 possible spring tornadoes between 1890 and 2000 over West Bengal, 14 of which killed 10 people or more. In a detailed study of east India and Bangladesh tornadoes, Finch and Dewan (2003) (http://bangladeshtornadoes.org) observed that 76% of nor'westers and tornadoes occurred during the pre-monsoon period; and 38.3% of them occurred in April. Bhan *et al.* (2016) indicated that there have been 15 tornadoes during the last 110 years (1903-2012) in the northwest India and Pakistan region. Reports of 12 tornadoes in recent 36 years (1975 to 2010) make it one tornado every three years. Litta *et al.* (2009, 2012) successfully simulated severe thunderstorms, which produced tornadoes close to Ludhiana Airport (Punjab), the north-west region of India, on 15 August, 2007 and over Odisha on 31 March 2009 using WRF-NMM model.

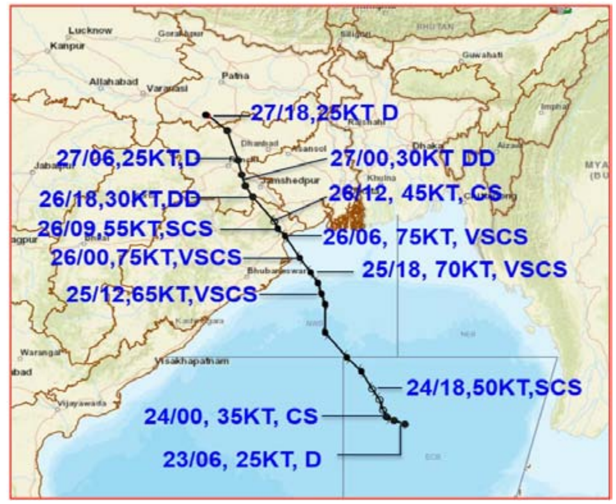

Fig. 1. Observed track of VSCS "YAAS" during 23rd-27th May, 2021

In this paper, we examine the tornado that occurred over West Bengal on May 25, 2021, in connection with the Very Severe Cyclonic Storm (VSCS) - YAAS over the Bay of Bengal (BoB). Section 2 provides a brief overview of VSCS YAAS and the tornado event. In Section 3, we present an analysis of the tornado, including the favourable conditions that contributed to its formation, as well as the observational datasets used in the study. Finally, Section 4 summarizes the key conclusions of the research.

2. VSCS "YAAS" and associated tornado

2.1. *TC track, intensity, structure, and evolution*

On May 22, 2021, a low-pressure area formed over eastcentral BoB at 0300 UTC under the influence of a cyclonic circulation over Andaman Sea and adjoining east central BoB. It lay as a well-marked low-pressure area at 0900 UTC of the same day over eastcentral BoB. Under favourable environmental conditions, it concentrated into a depression over eastcentral BoB at 0600 UTC of 23rd May, 2021. It moved north-westwards and intensified into a deep depression (DD) over east central BoB at 1800 UTC of 23rd May and into the cyclonic storm (CS) "YAAS" at 0000 UTC of 24th May over the same region. It moved nearly north-northwestwards and intensified into a severe cyclonic storm (SCS) at 1800 UTC of 24th May over eastcentral BoB. It then recurved and started moving northwards from 0300 UTC of the 25th May and intensified into a VSCS at 1200 UTC over northwest BoB. Thereafter, it moved north-northwestwards reaching peak intensity of 75 knots (kts) and lay centred over northwest BoB close to Odisha coast at 0000 UTC of 26th May. Continuing to move north-northwestwards, it crossed

Fig. 2. Locations of Chinsurah and Halisahar in West Bengal map

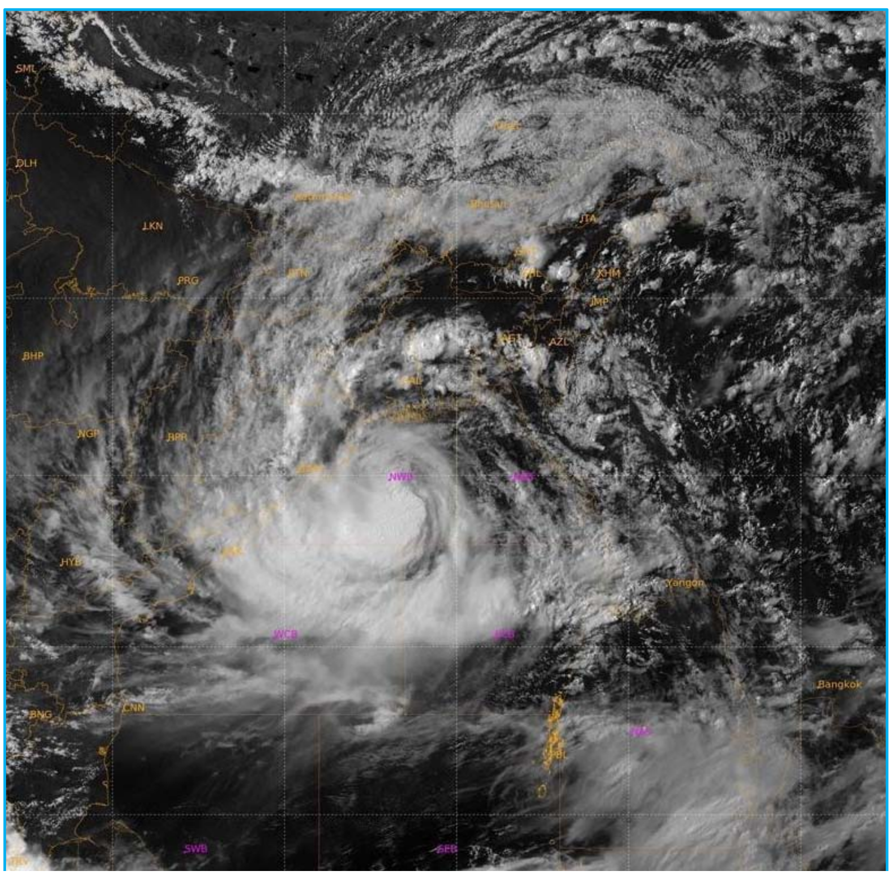

Fig. 3. INSAT-3DVisible satellite image of 0900 UTC 25 May, 2021 ((IMD 2021)

Fig. 4. Images of tornado outbreak in West Bengal on 25 May in association with VSCS "YAAS" (Cyclone YAAS, Wikipedia 2021)

north Odisha coast near latitude 21.35°N and longitude 86.95°E, about 20 km to the south of Balasore as a VSCS with maximum sustained wind speed of 75 kts gusting to 85 kts (130 -140 kmph gusting to 155 kmph) during 0500 and 0600 UTC of 26th. The observed track of VSCS "YAAS" is presented in Fig. 1. The VSCS "YAAS" was a relatively strong and very damaging TC that brought wide-spread impacts on coastal areas, with high-intensity wind, rainfall, and, most significantly, inundation in Odisha and West Bengal coastal region (IMD 2021).

2.2. *Tornado over West Bengal*

On May 25, 2021, heavy rains and strong winds started to brush the coastal and inland areas of West Bengal.Before VSCS "YAAS hit the coast, a tornado outbreak was reported in the North 24 Parganas and Hooghly districts of West Bengal. One tornado was reported in Halisahar (a city of North 24 Parganas) and another was reported in Chinsurah (a city of Hooghly). Two people died, five were injured and 80 houses were damaged in this incident. In North 24 Parganas district's Halisahar, the tornado lasted for a little over a minute, impacting 40 houses and injuring five people. Fig. 2 shows the locations of Halisahar and Chinsurah in West Bengal map. The INSAT 3D satellite visible image of 0900 UTC 25May, 2021 shows that the location of North 24 Parganas and Hooghly districts of West Bengal was in the convective outer bands of VSCS "YAAS" (Fig. 3). The hair-raising visuals (Fig. 4) showed an extremely fast-moving tornado that sent huge water spouts twirling high up into the sky with a gush of strong winds. The visuals were captured by residents across Chinsurah and Halisahar on their mobile phones (Akter and Rafiuddin, 2023; Cyclone YAAS, Wikipedia 2021). Studies of Novlan and Gray 1974 and McCaul 1991 pointed out that the intensity of a TC is an important factor for the ability to produce tornadoes. The mean intensities of 21.9, 28.7, and 47.1 m/s were found for hurricanes that produced no tornado, one tornado, and more than eight tornadoes, respectively (McCaul 1991). The intensity of the VSCS "YAAS" was around 33 m/s at the time of the tornado, which is consistent with his result. The tornado occurred in the afternoon around 0900 UTC (1430 hrs IST) of 25th May when the intensity of VSCS "YAAS" was 65 kt (33m/s) and was located over the northwest BoB away from Odisha-West Bengal coasts. The VSCS "YAAS" moved with a speed of 30-40 kmph during 0000 UTC to 1200 UTC of 25th May which was favourable for generation of tornadoes. According to Schenkel *et al.* (2020), faster moving TC tend to produce more tornadoes.

3. Observation data analysis

3.1. *Radar image analysis*

Forecasting the typically short-lived tornadoes associated with TCs is a major concern for forecasters because TC supercells tend to be shallower, narrower and less resolvable at similar distances from radars (McCaul and Weisman 1996; McCaul *et al.* 2004) compared to their mid-latitude counterparts. For these reasons, TC tornado warnings typically have higher false-alarm rates than their midlatitude counterparts in the United States (Martinaitis 2017; Nowotarski *et al.* 2021). Multiple "climatologies" have been constructed over the

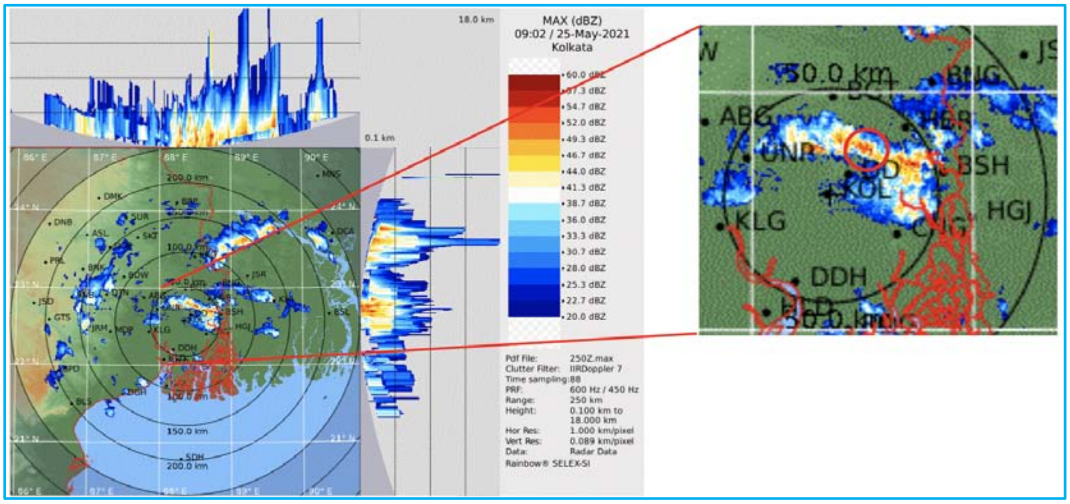

Fig. 5. Kolkata radar based reflectivity image of 25th May at 0902 UTC

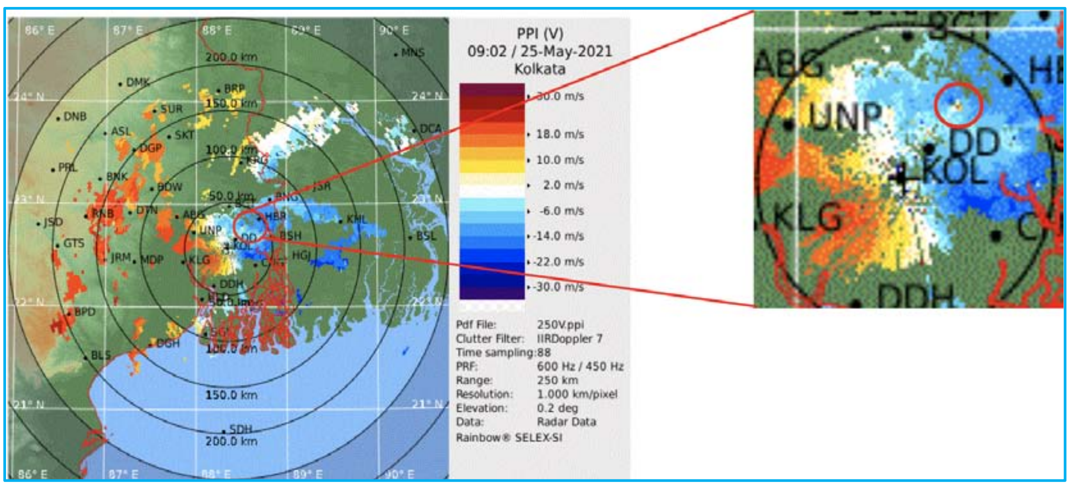

Fig. 6. Kolkata radial based velocity image of 25th May at 0902 UTC

years to document the time of occurrence, locations, and environmental conditions under which TC tornadoes occur (Sadowski 1962; Smith 1965; Pearson and Sadowski 1965; Hill *et al.* 1966; Novlan and Gray 1974; Gentry 1983; McCaul 1991; Verbout *et al.* 2007). These have shown a strong preference for tornado occurrence in the right-front quadrant with respect to TC motion, or the northeast quadrant with more of the tornadoes occurring during the afternoon. The Kolkata radar reflectivity images of 25th May between 0852 UTC and 0922 UTC in a 10 minutes interval are shown in Fig. 5. The radar reflectivity images show that the location of Tornado is in the northeast quadrant of TC and occurred in the afternoon (around 0900 UTC).

Spratt *et al.* (1997) and Hagemeyer (1997) used the WSR-88D radar observations to discuss the structures of tornadic mesocyclones in TCs. Radar reflectivity presentations for tornadic TC supercells span a large spectrum, from those with hook echoes upshear from forward-flank cores to quite messy and indistinct (Spratt *et al.* 1997; Schneider and Sharp 2007; Edwards and Picca 2016). Snell and McCaul (1993) succeeded in Doppler radar observation of tornado-producing storms in hurricane Andrew in 1992, detecting mesocyclones in the storms. They identified at least nine separate mesocyclones in Doppler radar data. The mesocyclones exhibited several features similar to those observed in typical supercell storms. From the Kolkata radar image (Fig. 5), severe mesoscale convective cell echoes (above 40 dBZ) are observed along Hooghly and North 24 Parganas districts where tornadoes were reported. The relatively intense reflectivity on the storm's northeast flank has been long identified as characteristic features

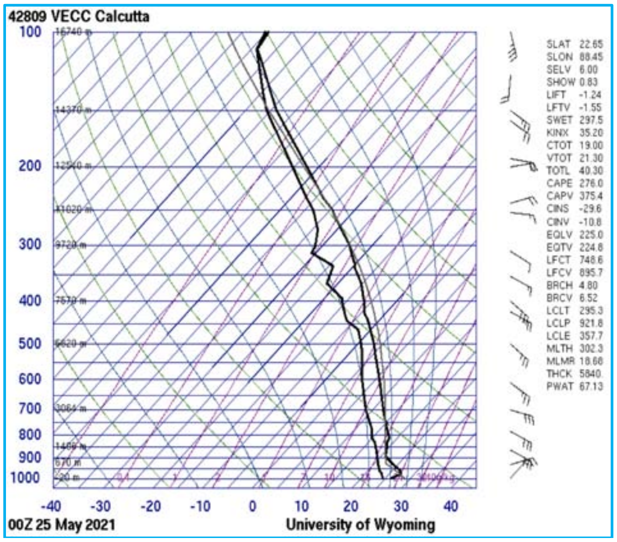

Fig. 7. Skew-T diagram and associated derived parameters over Kolkata of 0000 UTC, 25 May, 2021

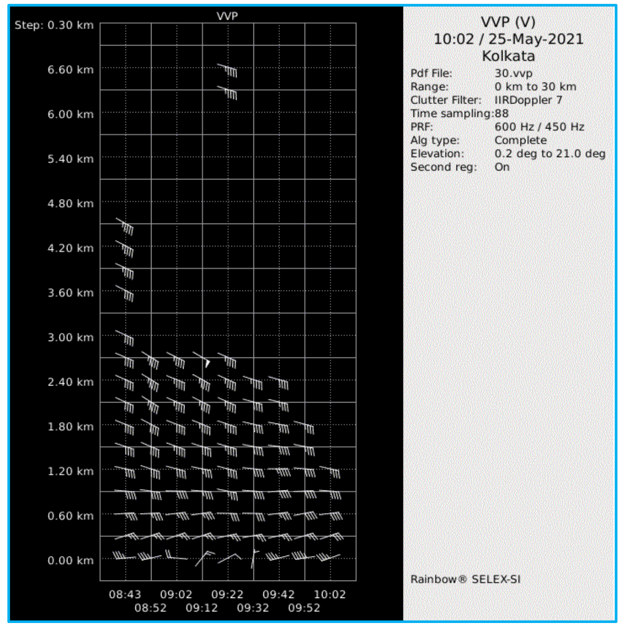

Fig. 8. Doppler Weather radar, Kolkata based vertical wind profile between 0843 UTC and 1002 UTC, 25 May, 2021

among TC supercells as well (Lemon and Doswell 1979). The enlarged Kolkata radar reflectivity image of 25th May at 0902 UTC (Fig. 5) clearly shows the hook echo around the location of Halisahar in West Bengal. A doppler velocity through this supercell (Fig. 6) illustrated the appearance of the associated tornadic mesocyclone with the most intense velocities (30 m/s) and minimum velocities (-30 m/s) located at the same location of hook echoes.

3.2. *Vertical Structure*

A landfalling TC is typified by large wind shear and high moisture content while thermodynamic instability is limited primarily due to evaporative cooling and decreased solar radiation induced by cloud cover. The area of large convective available potential energy (CAPE) has been long shown to not well collocate with the locations of TC tornadoes (McCaul 1991). McCaul (1991) found that the average CAPE is 253 Jkg^{-1} for TC tornado environments in the US, substantially lower than the average CAPE for non-TC tornado environments. Regardless, TC tornado occurrence maximizes in the mid to late afternoon, suggesting that instability is still an important ingredient for tornadogenesis (McCaul 1991; Schultz and Cecil 2009). Many previous studies have emphasized the importance of the entrainment of dry air in the mid-troposphere on the outbreak of TC tornadoes (Hill *et al.* 1966; Novlan and Gray 1974; McCaul 1987). The extremely high shear (and helicity) and low-buoyancy environment, with a relatively lower equilibrium level, is conducive for low-topped “miniature” supercells, the predominant convective storm type for TC tornadoes (McCaul and Weisman 1996; Edwards *et al.* 2012).

In this section the outputs of sounding at Kolkata and radar wind profile are analyzed to find the Tornado evidence. The Skew-T plot and instability indices at Kolkata from the University of Wyoming site (https://weather.uwyo.edu/upperair/sounding.html) are provided in Fig 7. The 0000 UTC 25 May Kolkata sounding (Fig. 7) shows high moisture levels around 600 hPa, indicating a more unstable atmosphere conducive to severe weather. The surface-based CAPE value from this sounding (Fig. 7) is 276 Jkg^{-1} which is comparable with the average CAPE (253 Jkg^{-1}) for the TC tornado environment in the United States (McCaul 1991). The sounding shows a marginal CIN value, 29 Jkg^{-1} during this event. The necessary condition for the supercell formation is a strongVWS of the environment in addition to a conditionally unstable atmosphere (Weisman and Klemp 1982). Environments with a large VWS in the lower troposphere have been found to increase the risk of occurrence of TC tornadoes (Novlan and Gray 1974; McCaul 1991). The radar vertical wind profile at Kolkata on 25 May, 2021, between 0843 UTC and 1002 UTC, is shown in Fig. 8. As illustrated in the diagram at 0912 UTC, the wind at the surface is 15 kt while the wind at the 6km aloft is 50 kt. This represents a wind speed change of 35 kt, indicating a highVWS, which is a strong indicator of tornado potential. Recent studies have demonstrated thatVWS in the lowest hundreds of meters, especially within the lowest 500 m, is an even more skillful predictor of tornadoes (Coffer and Parker, 2017; Coffer *et al.*, 2019). The radar vertical wind profile at Kolkata (Fig. 8) showed strong low-level wind shear around the time tornadoes were reported, specifically between 0902 UTC and 0932 UTC.

4. Summary and conclusions

Landfalling TCs are associated with multiple hazards including damaging winds, flooding, storm surge and tornadoes. Of these hazards, tornadoes are brief and often unpredictable events that can produce fatalities and create economic loss.In this paper we analyzed the observation data and the results indicated the occurrence of a Tornado associated with VSCS “YAAS”. The characteristics of the tornado were studied with Kolkata Doppler Weather radar images. This supercell storm exhibited characteristics similar to typical supercell storms such as hook echo and mesocyclone. According to the previous studies TC convective-scale environments are typically more favourable for tornadoes in the following conditions: during the afternoon, especially in the outer rainbands (Novlan and Gray 1974; Edwards and Thompson 2012), during the 48 h before and after landfall typically within 100 km of the coast (Hill *et al.* 1966; Schultz and Cecil 2009), and in TCs within environments characterized by strong deep-tropospheric (*i.e*., 850-200 hPa) VWS (Verbout *et al.* 2007; Schenkel *et al.* 2020). This TC tornado occurred in the afternoon (0900 UTC) of 25th May, 2021 in the outer rainband of VSCS “YAAS" and it was during the 24 hr prior to the TC landfall (0600 UTC of 26th May). The radar vertical wind profile also showed a strong VWS at that time. This study showed all the above conditions to be true for the occurrence of a TC tornado over North 24 Parganas and Hooghly districts of West Bengal in association with VSCS `"YAAS".

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