



Challenges of forecasting rainfall associated with tropical cyclones in India

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Abstract

Rainfall associated with landfalling tropical cyclones (TCs) is one of the significant causes of loss of life, property, and crops in India. In the past few decades, the accuracy of track and intensity forecast of tropical cyclones has improved considerably, but the estimation and forecast of associated rainfall is still a challenge. Accurate rainfall estimation at the time of landfall is crucial as it enables disaster management agencies to plan for disaster management strategies in the affected areas. It is known that the rainfall associated with TCs, particularly at the time of landfall, is highly variable and asymmetric due to various factors such as vertical wind shear, translational speed, land surface processes, extratropical transition and moisture. This paper discusses the challenges faced in forecasting rainfall associated with the land falling TCs in the North Indian Ocean and the factors responsible for variable and asymmetric rainfall by considering several TCs of various intensities. Advances in methodology for measuring and estimating precipitation with the help of Satellites and Radars and forecasting it using statistical and numerical weather prediction (NWP) techniques are also discussed here. Rainfall characteristics associated with the landfall of two unique TCs formed in the Bay of Bengal in December 2011 and 2016, based on composites of the frequency distribution of rain rates and quadrant mean rain rates, have been discussed in detail to highlight the challenges involved. It is inferred that rapid intensification or weakening of a TC over or close to the coast during the landfall process may alter the rainfall characteristics overland to a large extent.

1 Introduction

Tropical cyclones (TCs) are major natural disasters affecting the 7516 km long coastline of India. These cyclonic systems occur in the North Indian Ocean (NIO) prominently during the pre-monsoon (March–April–May) and post-monsoon (October–November–December) seasons. On an average,

NIO experiences 1.07 and 2.58 TCs during pre-monsoon and post-monsoon seasons (Mohapatra et al. 2015), respectively. The average number of TCs in the post-monsoon season is more and the associated rainfall contributes almost 60% of the total annual precipitation in various coastal states in India (Singh et al. 2019). The hazards caused by the extreme rainfall associated with TCs are enormous. As per future projections, the hazards will escalate further since there may be a 20% increase in TC induced precipitation (Knutson et al. 2010). Few recent TCs such as Phailin, Hudhud, Vardah, and Gaja caused massive destructions and loss in the economy of Indian coastal states. Accurate rainfall estimation at the time of landfall is crucial as it enables disaster management agencies to prepare strategies in disaster management in the affected areas. Although state-of-the-art models have succeeded in capturing the track and intensity of TCs, the associated rainfall, particularly at the time of landfall, is observed to have significant spatial and temporal variations.

Further, rainfall distribution is highly asymmetric due to various factors such as vertical wind shear, translational speed, nature of the topography, extratropical transition,

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moisture supply etc. (Wu et al. 2002; Ying and Chen 2005; Chen and Li 2004; Larson et al. 2005; Shen et al. 2002). Haggag and Badry (2012) investigated the effect of initialisation time, horizontal grid resolution and terrain elevations on the simulation of cyclone track, intensity and heavy rainfall for the TC named Phet over the Arabian Sea in 2010. Simulation results showed a negligible effect of model initialisation time on cyclone track and intensity. Still, the rainfall results at the time of landfall were highly sensitive to the resolution of the model terrain.

The intensity of TCs may not directly correlate with its rainfall at the time of landfall since other complex interactions may play a dominant role, and thus weak TCs may produce higher rain rates than more potent TCs (Chen et al. 2010; Cheung et al. 2018). Similarly, physical processes, such as moisture transport and latent heat release, may also play essential roles in producing TC rainfall. Generally, a landfalling TC would dissipate due to the cut-off of moisture supply by the ocean and an increase in land surface friction. However, in the presence of a strong vapour transport channel, heavy rainfall with landfalling TC would continue despite its weakening (Chen et al. 2010). Shen et al. (2002) showed that the decay rate of a landfalling TC decreases if the TC passes through a water surface over land. The Kandla cyclone that originated over the southeast Arabian Sea and crossed Gujarat Coast (Western India) as a very severe cyclonic storm on 9 June 1998 near Porbandar maintained its intensity as a Very Severe Cyclonic Storm (VSCS) even after crossing the coast. After making landfall near Porbandar, it did not weaken but re-emerged in the Gulf of Kutch as a Severe Cyclonic Storm (SCS) and caused major devastation over Kandla port due to storm surge and heavy rains, which led to floods (Kalsi and Gupta 2003).

Variability of precipitation is also linked to the variability in raindrop size distribution (RSD). The process of raindrop growth, formation, transformation, and decay occurs on a microphysical scale within a cyclone. Many studies have used disdrometer data to study RSD variations (Janapatia et al. 2017; Maeso et al. 2005; Tokay et al. 2008). Tokay et al. (2008), in their study, found that floods generated by TCs were mainly attributed to the presence of abundant small and medium-size drops in the rainfall and the difference in the characteristics of RSD in the induced rainfall. Janapatia et al. (2017) studied the RSD variability in the TC induced rain before and after landfall of TC Nilam. They found that there was a higher concentration of mid and large drops in the rainfall after the landfall than before the landfall. Further, after-landfall rainfall was relatively more convective than before the landfall. Some of the earlier works indicate that the heaviest rainfall occurs in a narrow band along the track of the cyclone (Lonfat et al. 2004) whereas the distribution of rainfall is guided significantly by the transitional speed of the cyclone (Shapiro 1983). Yu et al. (2017) showed

that the translational speed of landfalling TCs is not responsible for the asymmetric rainfall distribution. However, in a weak vertical wind shear (VWS) environment, the coastline will significantly affect the rainfall distribution (asymmetry) in the landfalling TCs. They emphasised that the environmental VWS associated with the monsoon affects precipitation distribution, while local VWS affects precipitation intensity. Chen et al. (2006) used Tropical Rainfall Measuring Mission (TRMM) data for five global oceans to show the combined effect of storm motion and VWS on the rainfall asymmetry observed in TCs. They concluded that for shear more than 7.5 m/s, the environmental shear is a dominant factor guiding the rainfall asymmetries. When shear is less than 5 m/s, TC's translation speed and direction play a role in rainfall asymmetry. Although environmental VWS typically forces an asymmetric precipitation distribution in TCs, the magnitude of this asymmetry can exhibit considerable variability, even among TCs that experience similar shear magnitudes (Nguyen et al. 2017). Bala et al. (2014) analysed 43 NIO cyclones during 2000–2010 and concluded that among the four quadrants, rain rates in the front quadrants are greater than the rain rates in the rear quadrants. The highest rain rates of 3.5–4.5 mm/h are observed in the Front Left (FL) quadrant during the intensification stages while for recurving cyclones (North/Northeast), the highest rain rate is in the Front Right (FR) quadrant. Recently, Ankur et al. (2020) using data of 71 TCs (1997–2017) over NIO, have shown that TCs in the Bay of Bengal produce higher rain rate (9–10 mm/h) as compared to those due to the TCs over the Arabian Sea (7–8 mm/h). Debnath and Mandal (2012) have shown that the orographic effect further enhances the heavy rainfall associated with the landfalling cyclone. There are few studies to explain the variability and asymmetry of rainfall associated with TCs in India. Nevertheless, recently Singh et al. (2020) have used the enormous dataset available with India Meteorological Department (IMD) to study the rainfall associated with TCs over the NIO and its impact on India's coastal states.

Based on the discussion on the observed features of landfalling TCs, in this paper, we intend to analyse the following aspects related to the estimation and forecasting of rainfall associated with TCs in India. First of all, Sect. 2 discusses ongoing QPE and QPF efforts in India. Section 3 deals with the data used and methods adopted in this study. In Sect. 4.1, major challenges in the TC rainfall forecasting in the NIO basin, rapid intensification/weakening, and change in the movement of the system close to the coast, and stationary/slow movement off the coast are discussed based on some of the prominent TCs of various intensities in India. Section 5 deals with the case study of two unique VSCSSs, Thane and Vardah, observed in the same month of December but in two different years, 2011 and 2016, respectively, using the very popular TCRAIN analytics.

Section 6 summarises the critical results and briefly states the conclusions of this study.

2 Quantitative precipitation estimates (QPE) and quantitative precipitation forecast efforts in India

2.1 QPE

Forecasters have used surface rain-gauge records to measure rainfall over a location and estimate area-weighted rainfall values over a larger area using this data. Based on these archived surface data, IMD developed a high spatial resolution ($0.25^\circ \times 0.25^\circ$) long period (1901–2010) daily gridded rainfall data set over the India Region (Pai et al. 2015) for validation of numerical models. Due to the large spatial and temporal variability of rainfall across the Indian region and lack of data over the oceans, the forecasters started using Kalpana-1 Satellite (INSAT-1D) data to obtain precipitation estimates. Since the Tropical Rainfall Measuring Mission (TRMM) satellite with Precipitation Radar onboard was launched in 1997, data from the active sensors have been widely used to estimate TC rainfall. Mitra et al. (2009) developed a daily cumulative rainfall dataset for India and adjoining NIO regions using TRMM and surface rain-gauge data. The precipitation analysis formed from the merge of IMD rain-gauge data with the TRMM TMPA satellite-derived rainfall estimates showed that the heaviest rainfall (≥ 800 mm) due to the TC called Phailin occurred over the open waters of east-central Bay of Bengal (Fig. 1). Phailin gave maximum cumulative rainfall of about 740 mm in the southwest sector of the track over east-central Bay of Bengal near the Andaman Islands, when it intensified from a Deep Depression (DD) into a Cyclonic Storm (CS) (Ray et al. 2017). Panda et al. (2015) have also calculated QPE during Phet using satellite data and the WRF model. Panda and Giri (2012) used integrated precipitable water vapour to calculate QPE during Phyan. Prakash et al. (2013) evaluated the qualitative and quantitative surface rain rate from three different data products, namely TMI-2A12, TMPA-3B42, and GSMaP. They compared it with PR-2A25 to assess the performance of satellite-retrieved precipitation estimates during cyclonic events. TMPA-3B42 product showed better understanding than the other two precipitation products during low to moderate rainfall regimes. The GSMaP precipitation product showed better compliance than the TMPA-3B42 product with PR rain rate under extreme (more than 10 mm h^{-1}) rain events. Mitra et al. (2018) have utilised Indian Satellite INSAT-3D data to derive rainfall estimates like Hydro-Estimator Precipitation (HEM), INSAT Multispectral Rainfall (IMR), and

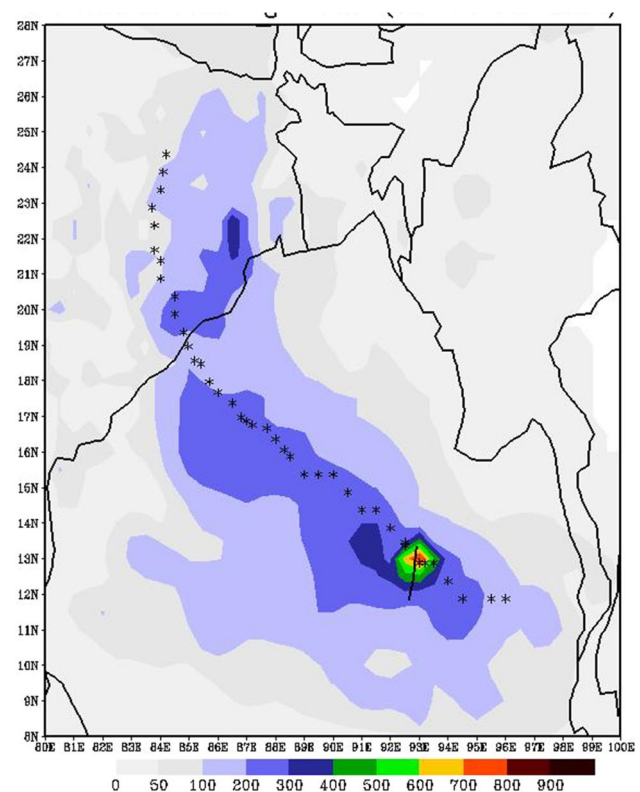


Fig. 1 Rainfall map showing the total accumulated rainfall triggered by Cyclone Phailin from 8 to 14 October 2013. The dots indicate the best track of IMD

QPE for heavy rainfall episodes over the Indian region, and they have validated with surface rainfall observations. They found HEM showed a higher correlation with heavy rainfall episodes as compared to IMR and QPE. HEM also captured the intensity of rainfall in the initial stages of Raonu. The geostationary satellite products are more useful for operational forecasting than the Polar satellites due to data availability every 30 min. Gairola and Krishnamurti (1992) have integrated data from both geostationary satellites and polar-orbiting satellites for obtaining rainfall estimates.

2.2 QPF

Rain rate estimates from Radar reflectivity data are now-a-days widely used for obtaining QPF. IMD has a network of 27 Doppler Weather Radars (DWRs) all over India, and rainfall estimates are also obtained from these radars. Ray et al. (2018) have used radar data to examine and substantiate the cloud burst in association with low-pressure systems that led to torrential rains over Chennai during 8–9 November and 30 November–2 December 2015. The variation in the maximum rain rate in every hour and mean hourly rain rate based on DWR, from 30 November to 2 December in the

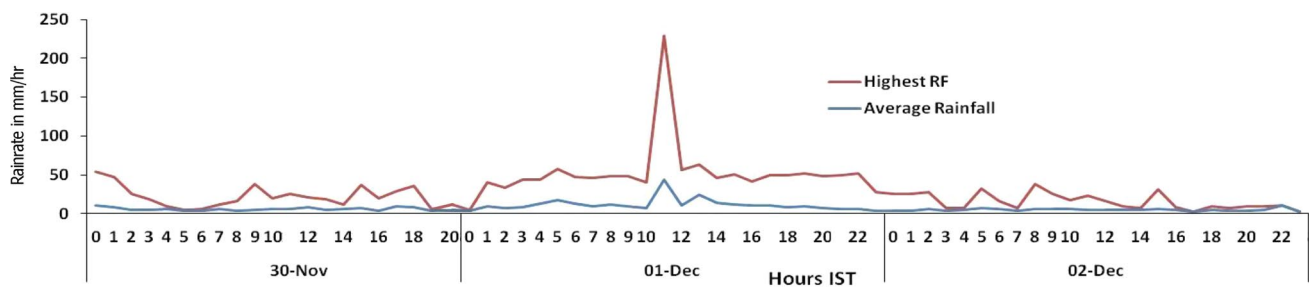


Fig. 2 Hourly variation of maximum and average rainfall rates over Chennai District from 30 November to 2 December 2015 based on DWR

Chennai district show that the peak rain rate of > 200 mm/h was reached between 1000 and 1500 UTC leading to flooding and devastation in Chennai city (Fig. 2).

IMD has been using quantitative precipitation estimates and forecasts (QPE and QPF) obtained not only from satellites, radars and numerical weather models but also from synoptic analogue models. The method of selecting analogues from the past data was employed to obtain a cumulative QPF statistical model over the river basins. Ray and Patel (2000) used ten years of synoptic analysis to formulate a synoptic analogue model for the Narmada river, which forecasters efficiently used for the issue of daily cumulative QPF. Similar work for various river basins and their catchments has helped issue QPF for many years (Ray and Sahu 1998; Singh et al. 2010). Another climatological model for QPF during typhoon periods was developed by Lee et al. (2006). Zhong et al. (2009) developed a dynamic similarity scheme for QPF in the case of TCs. This model statistically considered the dynamic evolution of TC features and associated environmental fields, particularly considering the corresponding similarity after forecast time.

The National Oceanic and Atmospheric Administration (NOAA) Satellite Data and Information Service (NESDIS) have been producing operational areal Tropical Rainfall Potential (TRaP) forecasts for landfalling TCs since the early 2000s. TRaP forecasts are essentially 24 h extrapolation forecasts of satellite-estimated rain rates that give the expected location and intensity of the maximum rain and the spatial rainfall pattern (Kidder et al. 2005).

Despite recent advances in numerical weather prediction techniques, QPF is still a challenge (Hense & Wulfmeyer 2008). Osuri et al. (2020) have used the Advanced Research Weather Research and Forecasting (ARW) model for rainfall prediction of 42 TCs over the NIO basin from 2007 to 2018, and they found that the 24 h forecast is more skillful than the 48–72 h forecast when the model is initialized at any stage of the TC.

Indian Institute of Tropical Meteorology (IITM), Pune, India, implemented National Centre for Environmental Prediction Global Forecast System (GFS) model, which is now

operationally used by IMD to issue a short-range forecast for rainfall.

IMD uses a satellite-based diagnostic tool such as Tropical Cyclone Rainfall Analysis (TCRAIN) for NIO. It depicts rainfall characteristics with respect to TC center and direction of movement for all TCs over the NIO during 2000–2010 based on 3-hourly $0.25^\circ \times 0.25^\circ$ TRMM rainfall data (Balachandran et al. 2014). This tool is helpful for the validation of NWP model products. The results suggest that the most frequently occurring rain rate during all the five intensity stages of TCs of NIO is in the range 1–2.5 mm/h, which occur over an area of about 10–14% (6%) within 5° radial distance from the TC center during the intensification stages (weakening stages). The frequency of rain rates greater than 5 mm/h is about 10–15% during intensification stages, but during weakening stages, such higher rain rates are less frequent at about 5% only. Regarding the asymmetric rainfall structure, among the four quadrants [Front Left (FL), Front Right (FR), Rear Left (RL), and Rear Right (RR)] around TCs of NIO, rain rates in the front quadrants are higher than the rain rates in the rear quadrants. The highest rain rates of 3.5–4.5 mm/h were observed in the FL quadrant during the intensification stages. In the case of a westward (recurving northward) moving TC, the highest rain rate has been observed in the FL (Front Right) quadrant.

3 Data used and methods adopted

The low-pressure systems over the Indian region are classified based on the maximum sustained winds speed associated with the system and the pressure deficit/ number of closed isobars associated with the system. The pressure criterion is used when the system is over land, and wind criteria are used when it is over the sea. Table 1 gives a detailed classification based on wind criteria. As per the wind criteria, the system with a wind speed of 17–27 knots is called a depression and the low-pressure system with a maximum sustained three minutes surface winds between 28 and 33 knots is called a DD. The system with a maximum sustained 3 min surface winds of 34 knots or more is called

Table 1 Classification of cyclonic systems of various intensities in India

System	Associated wind speed in knots (Kmph)
Low-pressure area (LPA)	< 17 (< 31)
Depression (D)	17–27 (31–49)
Deep depression (DD)	28–33 (50–61)
Cyclonic storm (CS)	34–47 (62–88)
Severe cyclonic storm (SCS)	48–63 (89–117)
Very severe cyclonic storm (VSCS)	64–89 (118–166)
Extremely severe cyclonic storm (ESCS)	90–119 (167–221)
Super cyclonic storm	≥ 120 (≥ 222)

a CS. The study has utilised archived data measured during TCs formed in the recent past, such as Nisha (2008), Thane (2011), Vardah (2016), Ockhi (2017), and Gaja (2018), as per the requirement of the analysis. TRMM, INSAT-3D, DWR, and IMD gridded rainfall data are utilised based on the study context.

We have carried out a detailed analysis of rainfall associated with TCs Thane landfall (2011) and Vardah (2016) using a satellite-based 3-hourly TRMM 3B42 dataset. For all 3-hourly positions of the TC (taken from IMD best track data), (i) frequency distribution of rain rates within 5° radial distance from the TC centre, (ii) azimuthally averaged rain rates within every 0.1° annulus around the TC centre, determined up to 5° (50 annuli) radial distance from the centre, and (iii) quadrant-wise mean rain rates within 2° radial distance from the centre and with respect to the direction of motion of the TC are determined and analysed for all observations from 24 h before landfall time to 12 h after landfall at 6-hourly/3-hourly intervals.

4 Results and discussion

4.1 Major challenges in TCs rainfall forecasting in the NIO basin

It has been found based on the past observed cases that forecasting rainfall over the land areas arising out of TCs is difficult since there can be rapid intensification or rapid weakening over or close to the coast just before the landfall. Further, close to the coast, the movement of the system may change. Sometimes the TC remains stationary, or its movement becomes slow off the coastline. These crucial aspects are briefly discussed below.

4.1.1 Rapid intensification close to the coast just before landfall

On some occasions, contrary to the numerical prediction guidance, TCs undergo rapid intensification close to the coast before landfall. Under such situations, forecasting the rainfall associated with the landfall and further movement of the system poses tremendous challenges. Severe Cyclonic Storm (SCS) Gaja (10–19 November 2018) was initially formed as a depression over the southeast Bay of Bengal on 10 November 2018 and intensified into a CS at about 0000 UTC of 11 November. Subsequently, it moved westwards without much intensification for the next 3 days. After that, moving west-south-westwards towards Tamil Nadu–Puducherry coast, the system intensified into SCS on the 15th morning. Most numerical models predicted a weakening of the system to a CS before landfall by the 15th night. However, when the system approached the coast, it rapidly intensified into a VSCS by the 15th night. It crossed the Tamil Nadu coast close to Vedaranniyam around 19–21 UTC of 15 November. After crossing the coast, it moved across the orographic terrain in Tamil Nadu and Kerala's interior. Gradually the system weakened into a depression and emerged into the Arabian Sea by 1700 UTC of 16 November. Tamil Nadu recorded widespread rainfall activity on 16th and 17th November with reports of isolated but very heavy to extremely heavy rainfall (12–28 cm/day) even in Tamil Nadu and Kerala's interior districts on 17th under the orographic influence. The entire sub-division of Tamil Nadu received 10% of the northeast monsoon seasonal rainfall during these 2 days, with Thanjavur, Sivaganga, Dindigul, and Theni districts receiving more than 20% of their seasonal rainfall during this period.

4.1.2 Rapid weakening over or near the coast

In many TCs, contrary to the expectation, a rapid weakening during its landfall may occur. The SCS called Jal (4–7 November, 2010) crossed the north Tamil Nadu–south Andhra Pradesh coast close to the north of Chennai on 7 November. It underwent rapid weakening from the intensity of 60 knots on 7th at 0000 UTC to 30 knots at 1200 UTC on the same day just before its landfall around 1600 UTC of 7 November. Although the 24 h accumulated rainfall at 0300 UTC of 8 November over Chennai recorded only 5 cm/day, the rainfall recorded at Palasa, in the Srikakulam district in extreme north Coastal Andhra Pradesh (about 600 km from the TC centre) was 27 cm/day (IMD 2011). Based on TRMM 3B42 rainfall data, Balachandran et al. (2014) have observed a significant asymmetry in rainfall distribution within a 5° radial distance from Jal's centre. The system was generally moving with a translational speed of about 5–10 m/s in a strong shear environment (22–30 m/s). When

the system entered its weakening stage, its mean translational speed almost doubled from about 4.4 m/s to 7.6 m/s. The rainfall asymmetry maximum shifted from down shear left to down shear right. The percentage of non-raining bins, about 25–50% during the intensification stages, increased to 68–86% during the weakening stages just before the landfall. Such an increase in non-raining areas enhances the asymmetric rainfall distribution during the weakening stages and poses significant challenges to forecasting the location of heavy rainfall events.

4.1.3 Change in the movement of the system close to the coast

When a TC is forming or intensifying close to the coast, even a slight change in its speed and direction of movement might change the location and time of heavy rainfall occurrences. For example, one can discuss the VSCS called Ockhi (29 Nov–6 Dec, 2017), which was initially formed as a depression over the southwest Bay of Bengal off Sri Lanka coast on 29 November 2017. In general, numerical models predicted westward movement and intensification of the system on 30 November over the Lakshadweep area in the southeast Arabian Sea. As expected, the system moved westwards across Sri Lanka and emerged into the Comorin area by the 29th evening. However, on the 29th night, it moved northwestwards with double the average speed of movement (30 km/h against the normal rate of 15 km/h) and came close to the extreme southern coastal areas of peninsular India. By 30th at 0300 UTC, it intensified into a CS over the Comorin area with the TC centre at about 60 km south of Kanyakumari, India's southernmost location. Under the influence of convective bursts during the intensification of the system very close to land, Papanasam, Manimutharu (both in Tirunelveli districts of south Tamil Nadu) and Kollam (in Kerala) recorded extremely heavy rainfall of 45 cm/day, 38 cm/day, and 23 cm/day, respectively, for a 24 h period ending at 0300 UTC of 1 December 2017.

4.1.4 Stationary/slow movement off the coast

Balachandran et al. (2014) have analysed the rainfall associated with the TC called Nisha (25–27 Nov, 2008) that formed over Sri Lanka on 25 November, 2008 (tracked northward over Sri Lankan land and thence off the coast of the Tamil Nadu) and made landfall over Tamil Nadu to the north of Karaikal. Throughout its life period, it was over/close to the land. Further, it remained quasi-stationary close to the coast for about one day and caused extremely heavy rainfall over Cauvery delta areas. Rain amounting to 25–33 cm/day was recorded consecutively for 2 days on 26th and 27th November at Orathanaadu, Vedaranniyam, and Thanjavur of the Cauvery delta region that led to extensive

flooding over these areas and destruction of crops. Nisha was in a low-moderate vertical shear environment (9–14 m/s), slow-moving (translational speed < 5 m/s), and was under the influence of land throughout its life. During the period when the system was off the coast of Tamil Nadu, the most frequently occurring rain rate within 5° radial distance from the TC centre was 1–2.5 mm/h, which was about 10.5% and 12.3% during the depression and CS stages followed by 2.5–5 mm/h which was about 8.7% and 9.3% during the depression and CS stages, respectively. However, after landfall, the system gradually weakened into a depression, and under the terrain influence, the most frequent rain rate shifted to higher rain rates of 2.5–5 mm/h (13.4%), followed by the range 1–2.5 mm/h (11.8%).

5 Study based on VSCSs named Thane and Vardah

This section deals with TCRAIN analytics in two VSCSs Thane and Vardah, which occurred in December. Figure 3 presents the tracks of the two cyclones. It is interesting to see that these two VSCSs had an identical time of origin and path. The frequency of SCS formation during the post-monsoon season is generally higher. Thus, more rainfall is observed during this period than in the pre-monsoon months, with a higher contribution of rainfall over Andhra Pradesh and Northeast Tamil Nadu (Singh et al. 2019). Usually, the frequency of occurrence of TCs in December in the Bay of Bengal is very low. In the last 10 years, only two VSCSs named Thane and Vardah crossed Tamil Nadu coast in December, leading to good rainfall over Tamil Nadu and adjoining states. In the present analysis, we have used the TCRAIN analytical tool developed by Balachandran et al. (2014) to evaluate rainfall characteristics associated with these two westward-moving VSCSs that crossed Tamil Nadu coast during December during various instances of TRMM observations from 24 h before landfall to 6–12 h after landfall.

Thane intensified despite relatively colder sea (SST of 26–27 °C, low ocean thermal energy (< 50 kJ/cm²) over southwest Bay of Bengal near north Tamil Nadu coast. Most NWP models could not pick up the continuous intensification and slight weakening before landfall. The track was also rare, as no analogue was available in December based on the recorded historical data of IMD during 1891–2010 (IMD 2012). Thane crossed the coast south of Cuddalore, Tamil Nadu, between 0100 and 0200 UTC of 30 December 2011 with MSW of 75 knots. Vardah struck the coast over Chennai, Tamil Nadu, between 0930 and 1130 UTC of 12 December 2016 with MSW of about 60 knots (based on IMD best track data). The total precipitable water imageries during 6th to 13th December indicated

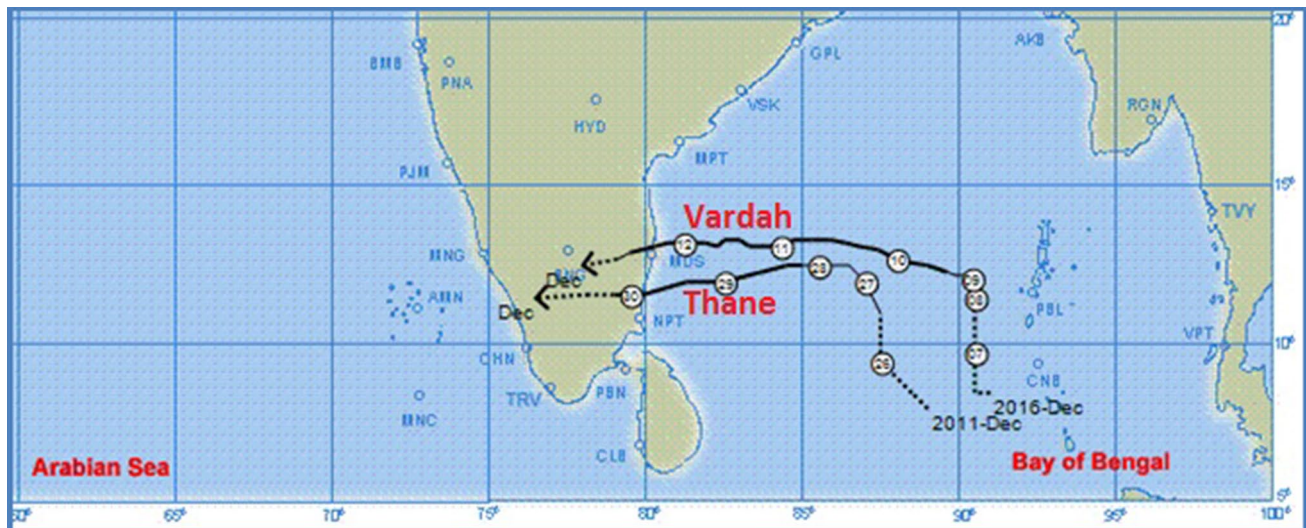


Fig. 3 Tracks of the VSCSs named Thane (Dec 2011) and Vardah (Dec 2016). Numbers in the open circles indicate the dates on which the systems were at the respective locations at 03:00 UTC. Dotted portions of the tracks indicate that the intensity was in the depression

a gradual incursion of cold, dry air from the northwest into the system, cutting off the supply of cross-equatorial moist air to the system on 12th completely. It led to the rapid weakening of the system after landfall. The HWRF model could predict rainfall over the Andaman & Nicobar Islands based on initial conditions of 8 December but could not capture rainfall over north Tamil Nadu. The occurrence of heavy to very heavy rainfall over the Andhra Pradesh coast was also over-predicted. However, it could capture heavy rain over south interior Karnataka and the emergence of a system in the east-central Arabian Sea (IMD 2017).

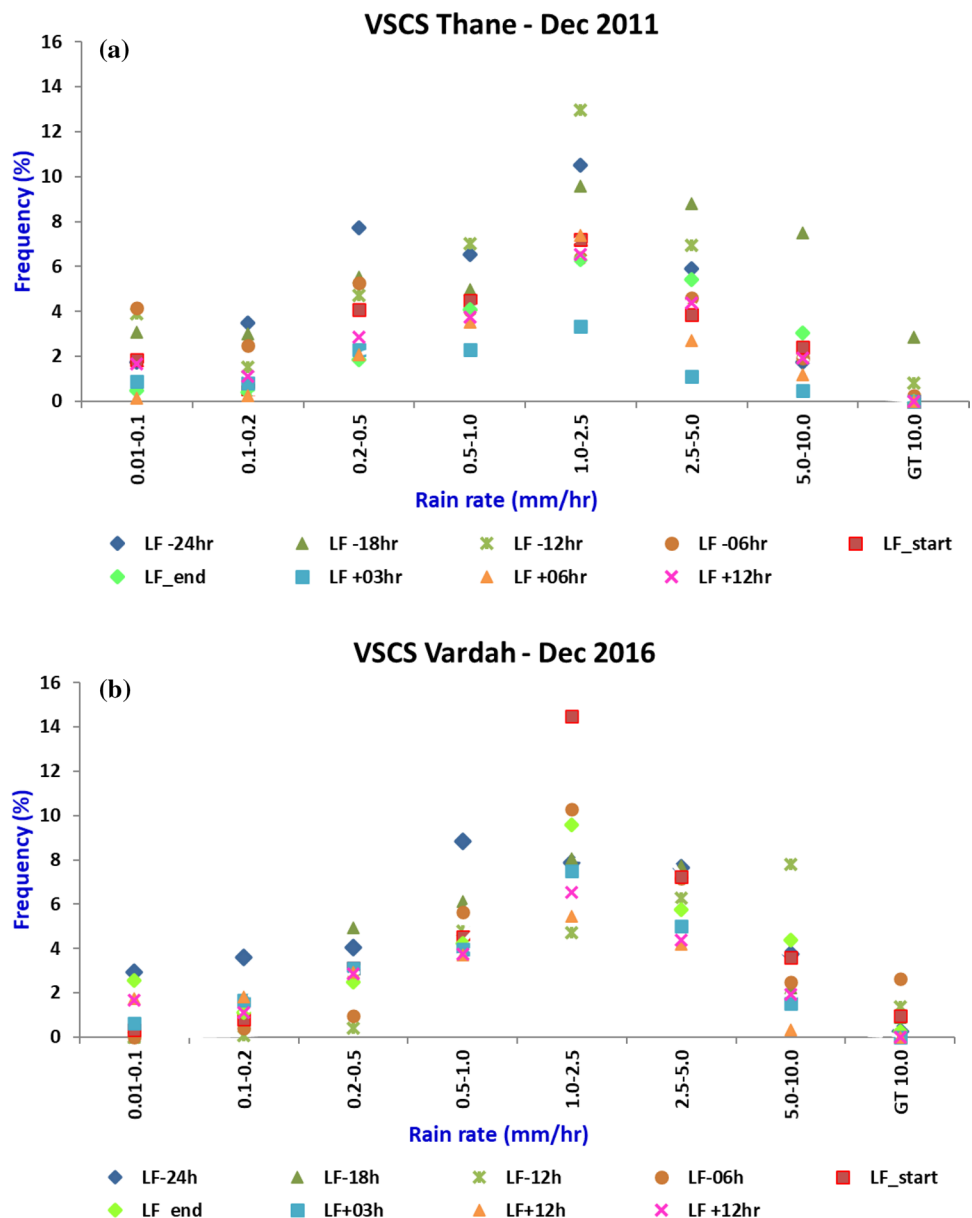
Figure 4a and b gives the frequency distribution of rain rates associated with both the VSCSs at various instances of time with respect to the landfall (LF; 1 h window for considering TRMM observation time for LF_start and LF_end). These figures present the percentage frequency of various rain rate categories at different instances of time with respect to landfalls, such as LF – 24 h, LF – 18 h, LF – 12 h, LF – 06 h, LF_start, LF_end, LF + 03 h, LF + 06 h, and LF + 12 h in cases of Thane and Vardah, respectively. 1 h window is considered for denoting TRMM observation times for LF_start and LF_end. It is found that in both the cases of Thane and Vardah, the most frequent rain rate happens in the range of 1–2.5 mm/h. However, the timings are not the same in the two cases. In Thane (Fig. 4a), the most frequent rain rate of 1.0–2.5 mm/h occurs at LF – 12 h, whereas in Vardah (Fig. 4b) it occurs at LF_start. Figure 4a indicates that the rain rates between LF_start and LF_end are not very much different in Thane and the maximum frequency is low, being not more than 7%. On the other hand, in

category (17–33 kts). Similarly, thin continuous lines denote the then intensity in the CS category (34–47 kts) and thick continuous lines represent intensity in the VSCSs category (≥ 48 kts)

Vardah (Fig. 4b) the rain rates during the landfall process are high with a value of 15% at the start to 9% at the end, with a variation of about 5% in the most frequent rate of intensity 1.0–2.5 mm/h. So far as the rain rates > 2.5 are concerned, rates of 2.5–10 mm/h are consistently more frequent at LF – 18 h in Thane (Fig. 4a). In Vardah (Fig. 4b), rain rates > 2.5 mm/h occurred at different instances of time, i.e. 2.5–5.0 mm/h at LF – 24 h, 5.0–10.0 mm/h at LF – 12 h and > 10.0 mm/h at LF – 06 h.

Figure 5a and b shows the percentage frequency of rain rate ranges of 0.01–1 mm/h, 1–2.5 mm/h, 2.5–5 mm/h, 5–10 mm/h, and > 10 mm/h at 3-hourly intervals from 24 h before LF_start to 12 h after LF_end in Thane and Vardah, respectively. We have noted that within 5° radial distance from the TC centre, in the case of both the VSCSs, the percentage of no rainfall bins during the period 24 h before landfall to the landfall time is about 60–70% which increases to about 90% in 12 h after landfall (shown as 'No rain frequency' in Fig. 5a and b). Hence, when the TC approaches the coast, rainfall occurs only in 30–40% of the area, within 5° radial distance and the area decreases further to 10%, 12 h after landfall. These curves in both the cases of Thane and Vardah also show similar paths. Comparison of frequencies of rain rates < 1 mm/h, 5–10.0 mm/h, and > 10.0 mm/h does not show any notable differences in their patterns before and after landfall of Thane and Vardah. In Thane, the frequency of 1–2.5 mm/h rain rate was the highest at LF – 24 h which systematically decreases till 3 h before the landfall started and remained almost the same until the end of landfall. Similarly, in Vardah, the frequency of rain rate 2.5–5 mm/h did not

Fig. 4 Percentage frequency of various rain rate categories at various instances of time with respect to landfall (LF) such as at LF–24 h, LF–18 h, LF–12 h, LF–06 h, LF_start, LF_end, LF+03 h, LF+06 h, and LF+12 h of VSCSs named **a** Thane (Dec 2011) and **b** Vardah (Dec 2016)



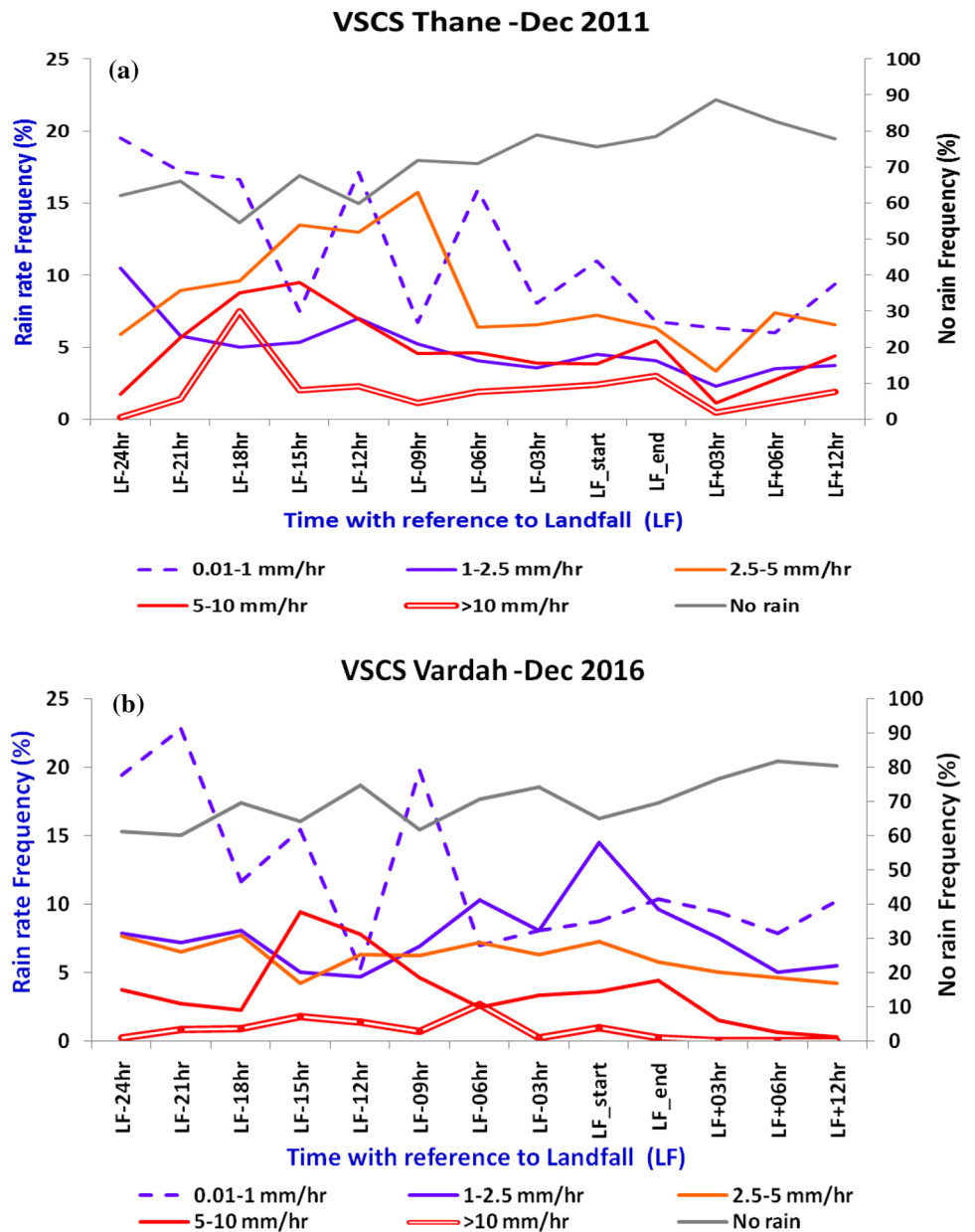
have much variation. However, the frequency of rain rate 1–2.5 mm/h in Vardah and that of 2.5–5 mm/h in Thane exhibited remarkable variations during the evolution of the respective systems. The frequency of rain rate 2.5–5 mm/h increased to about 16% till LF–9 h, then dropped about 6% till LF–06 h and underwent almost no variation till LF_end in Thane. The frequency of rain rate 1–2.5 mm/h had a significant increase till LF_start (up to 14% or so) and then a consistent decrease through LF_end in Vardah. In both cases, it occurs over 6–14% of the area within 5° radial distance from the TC centre.

Radial profiles of azimuthally averaged rain rate up to 5° radial distance from the centres of Thane and Vardah at various instances of time (LF–24 h, LF–12 h, LF–06 h, LF_start, LF_end, LF+06 h) are depicted in Fig. 6a&b,

respectively. It is found that in both the VSCSs, within the 2° radial distance from the respective centres, the dominant rain rates happen. Rainfall rates beyond 2° radial distance are insignificant in both the cases of Thane and Vardah. It is also estimated that about 7% (2–3%) of the rain rates within 5° radial distance from the TC centre are higher than 10 mm/h before LF_start in the case of TC Thane (Vardah).

Figure 7 depicts the asymmetry in the rainfall distribution within 2° radial distance from the respective centres of VSCSs, for both the cases of Thane and Vardah in the form of mean rain rates in the four quadrants such as Front Left (FL), Front Right (FR), Rear Left (RL) and Rear Right (RR) for different instances of time LF–24 h, LF–12 h, LF–06 h, LF_start, LF_end, LF+06 h. In both VSCS, we can see a prominent front-back asymmetry before LF. In

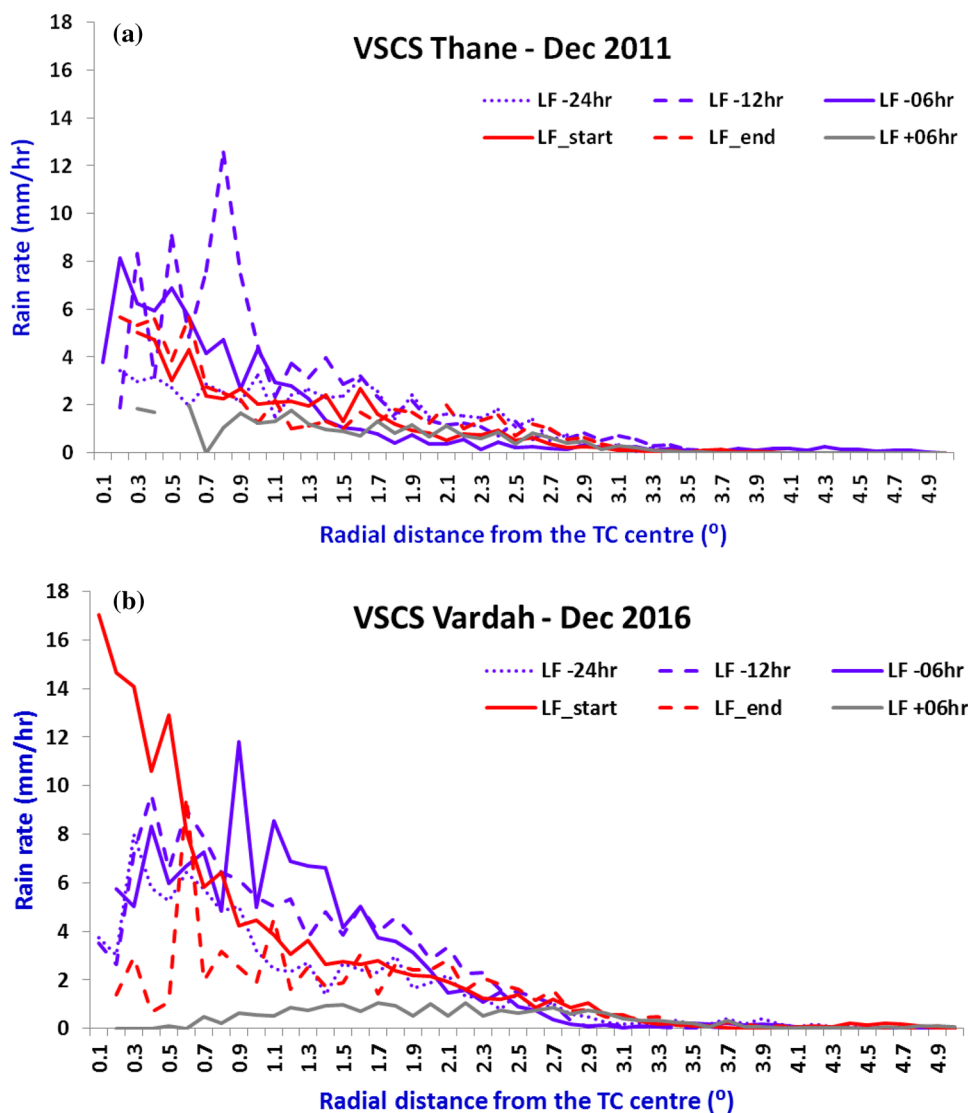
Fig. 5 Percentage frequency of rain rate ranges of 0.01–1 mm/h, 1–2.5 mm/h, 2.5–5 mm/h, 5–10 mm/h and > 10 mm/h at 3-hourly intervals from 24 h prior to LF_start to 12 h after LF_end in respect of VSCSs **a** Thane (Dec 2011) and **b** Vardah (Dec 2016). No rain frequency indicates the bins with no rainfall



Thane it increased from 1.7 mm/h at LF – 24 h to 3.8 mm/h at LF – 12 h, followed by a sharp decrease. On the other hand, in Vardah, the FR rain rate of 4.9 mm/h at LF – 24 h (4.9 mm/h) increased to 6.7 mm/h at LF – 12 h and the rate increased further to 10.5 mm/h at LF – 6 h. After LF_start, rainfall is mainly confined to only one sector, i.e. RR in Thane and FR, in case of Vardah. The variations in the rain rates observed in the RL quadrant are almost similar in both systems. In the RR quadrant after LF – 6 h, there was a sharp decrease in the mean rain rate for Vardah in the next 6 h and an increase in Thane. In the FL quadrant, Thane showed a sharp reduction in the mean rain rate after LF – 6 h and a slow consistent decrease in Vardah. In the FR quadrant, the variations are most conspicuous. Although the patterns are

somewhat similar with peak mean rates at – 6 h, the sharpness is remarkable at a high intensity of 10 mm/h in Vardah as against only 3 mm/h in Thane. In both the systems, there was a fall in the rain rates through the landfall process. The two most prominent examples of front-back asymmetry during the landfall processes are stated here. In the RR sector, Thane underwent almost no rain rate variation during the landfall process, whereas Vardah experienced a sharp decline during LF_start and LF_end. In the FR quadrant, in both the VSCSs, there was hardly any variation in rain rate during the landfall process, but during LF – 6 h, there was a sharp rise and fall in Vardah.

Fig. 6 Radial profiles of rain rates up to 5° radial distance from the TC centre at various instances from the landfall (LF) time (LF-24 h, LF-12 h, LF-06 h, LF_start, LF_end, LF+06 h) in the case of **a** TC Thane (Dec 2011) and **b** TC Vardah (Dec 2016)



6 Summary and conclusions

The prediction of heavy rainfall events and mesoscale activities from a short-range forecast perspective is of utmost importance to the society, mainly from the disaster management perspective. Although studies indicate a decrease in the frequency of TCs by the end of the twenty-first century, cyclone intensity and precipitation rates may increase. Future projections suggest that the rainfall associated with TCs is likely to increase by 20% with the changing climate (Knutson et al. 2010, 2015). Despite advances in numerical weather prediction techniques, the forecast of rainfall associated with a TC is still a challenge. The present work provides a synoptic view of the possible physical and dynamical interactions that may affect the rainfall characteristics during the landfall of TCs. This paper has discussed the major challenges faced by forecasters in the NIO basin for various TCs. It discusses different methods used to evaluate

QPE and QPF and how these efforts have evolved in India. TCRAIN, a TC centric rainfall analytics that depicts rainfall characteristics in relation to the TC centre and direction of movement over the NIO has been used for the case study of two VSCSs named Thane and Vardah, which formed in the Bay of Bengal in the same month of December but in different years. These two cases were unique in the sense that no analogues were available. In the case of Vardah, the highest rain rate of 4.9 mm/h was observed in the Front Right sector 24 h before the landfall, and this rate increased to 10.5 mm/h, 6 h before the landfall started. On the other hand, in the case of Thane, the rainfall rate was the highest at 3.8 mm/h in the Rear Right quadrant at LF_end. These two VSCSs had an identical time of origin and path. Our analysis partially explains the variable and asymmetric rainfall at the time of landfall due to the rapid intensification of Thane and rapid weakening of Vardah during the landfall process, i.e. between LF_start and LF_end.

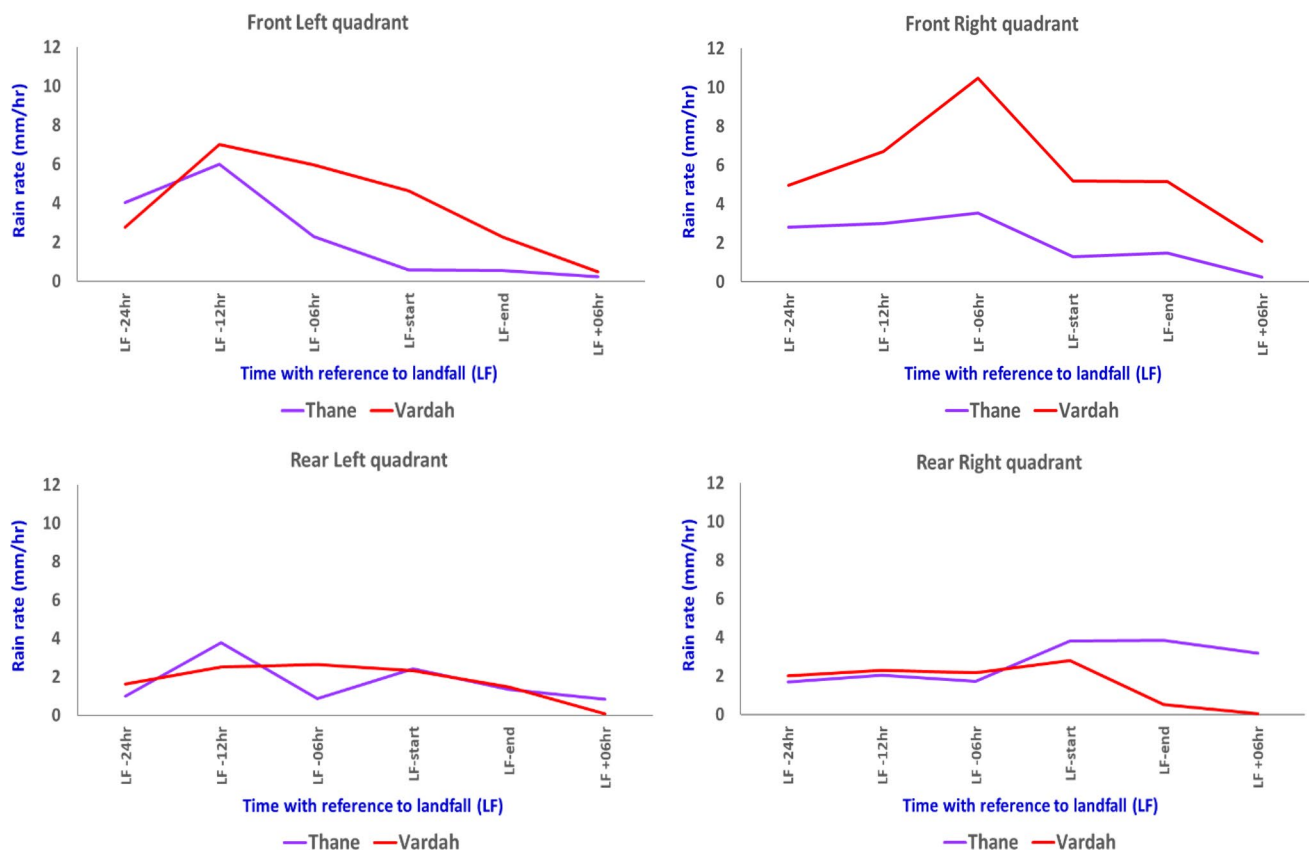


Fig. 7 Quadrant mean rain rates (in mm/h) within 2° radial distance from the TC centre at various instances with respect to Landfall (LF) time: LF – 24 h, LF – 12 h, LF – 06 h, LF_start, LF_end, LF + 06 h in the case of TCs Thane (Dec 2011) and Vardah (Dec 2016)

NWP models have improved considerably and accurate advance estimates of rainfall at the time of landfall would undoubtedly reduce the fatalities and other hazards associated with TCs. Nevertheless, the synoptic analysis based on the climatology and the experience of the forecasters is valuable addition to the final forecast. Currently, some major forecasting centres use advanced techniques for quantitative precipitation estimation (QPE) and quantitative precipitation forecasting (QPF) using satellite and radar observations. However, there is a need for further improvements in QPF based on a better understanding of the physical processes giving rise to TC rainfall.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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