Towards the understanding of controlling factors on sub daily scale variability of extreme rainfall intensity over west coast in India

**Introduction**

Climate change has profound effect on water cycle, as warming atmosphere holds more moisture. Consequently, the nature of rainfall events has been modulated though its intensity, frequency and duration. Extreme rainfall events (EREs) are severe weather phenomena which brings substantially excess of rainfall than normal on different temporal scales. In recent decades, EREs are turned out to be socially concerned natural hazards as the climate change due to global warming remarkably is reflected in the high frequency of occurrence of EREs [Sunil Kumar et al., 2021;]. In India, EREs are often associated with flash floods, prominently in urban regions, river basins, and landslides along hilly regions. EREs occur due to various synoptic and meso-scale weather systems such as Mesoscale convective systems, atmospheric rivers, tropical cyclones, and cloud burst over the tropical region. Several disaster reports and previous studies claim that, EREs cause substantial societal and economic loss in various regions including India []. Floods caused by EREs are one of the natural disasters that cause maximum mortality in India []. Nevertheless, the quantification and predictability of EREs have become challenging owing to a lack of detailed understanding on the physical process that governs the nature of EREs.

As EREs are becoming a rising concern for many countries, numerous studies were attempted to understand EREs evolution, possible physical mechanisms, and trends subjected to different climate change scenarios []. Both modelling and observational approaches have been employed to investigate the evolution of EREs on regional and continental scales []. From these studies, it is learnt that the nature of EREs is primarily influenced by the amount of water vapour transported during the event evolution. Increasing in the water vapour content as result of global warming according to Clausius -Clapeyron equation turns out the rainfall events much intensified and short duration. However, the relationship between EREs variability and water vapour content tends to be modified by the other important dynamical/thermodynamical attributes such as temperature, vertical updrafts and adiabatic lapse rate as evidenced by the observations and global models. Moreover, the global model simulations are not able to follow such thermodynamic relationship between water vapour and EREs mostly over tropical regions due to their incapability of resolving convective processes (westra et al., 2014; o groimann 2009). Hence, further understanding of the EREs in the light of their association with other attributes certainly improves our understanding these systems and hence the model simulations. Increasing in the water vapour due to trends in EREs concerning different geographical regions and spatiotemporal scales are inconclusive, as insignificant increasing/decreasing trends were reported. The possible physical and dynamic attributes for such mixed trends, unlike other parameters such as temperature, are still a subject for open dissuasion.

As India is concerned, the frequency of occurrence of EREs, in general, is predominant during the Indian Summer Monsoon season from June to September. The seasonal (JJAS) rainfall exhibits a relatively heterogeneous regional distribution in India (Sunil Kumar et al., 2021; Ghosh et al., 2009). For instance, West Coast India and North East India regions receive copious seasonal rainfall than the other regions. Though the EREs in the summer season are reported annually in India, the West Coast region is much more vulnerable to such EREs owing to various physical, dynamic, and geographical reasons [ Rupa Kumar et al., 2006; ]. Among the others, the most influencing factor is the series of mountains along the west coast. These mountain barriers act as a catalyst to enhance precipitation along the west coast region. When large-scale monsoonal wind flow enriched with moisture from the Arabian Sea interacts with these sloppy mountains, wind flow encounters an orography lift. Hence clouds formation becomes more feasible. Thus, the land regions along the windward side of the Western Ghats receive copious amounts of rainfall, possibly with few extreme spells. Such extreme spells often cause flash floods and havoc along the west coast region [].

In India, numerous attempts were made to investigate EREs possible trends and spatiotemporal variability using both observational and modelling approaches [Ajaymohan and Rao., 2008]. Rajeevan et al., 2008 explored the link between EREs and the SST and concluded that the SST modulates the possible trends and variability of EREs over the tropical ocean. Using IMD-generated rain gauge-based gridded product, the trends and spatiotemporal variability of EREs are attempted by Patnaik et al., 2010; Goswami e al., 2006; vital et al., 2013; Srivastava et al., 2016; Jain et al., 2012; Guhathakurta et al., 2011]. The important conclusion from these studies highlights the recent increase in EREs, significantly post-1980 in India. It is also stated that the increasing tendency in EREs is comparatively more significant than the mean seasonal rainfall in India []. On average, the detected trends showed a possible increase in 24 hr rainfall and wetting trend in India [Sen Roy and Balling, 2004]. However, on the regional level, the trends show an increasing signal in peninsular, east, and northeast India and decreasing tendency in central India and north India [].

Despite the substantial progress in understanding the day-to-day, decadal variability, and long-term trends in EREs in India, previous studies focussed on EREs on daily scales. Further extension of such attempts on the evolution of EREs on sub-daily scales is limited to fewer studies due to the unavailability of reliable rainfall data on the sub-daily scale. Though, few recent literatures investigated the sub-daily scale variability of rainfall, they addressed characteristics of mean rainfall rather than extreme rainfall events over selected regions [KAMALJIT Ray et al., 2016]. However, when it comes to EREs, the key features of daily EREs are not necessarily applicable to the sub-daily extremes in several respects []. The inapplicability of empirical relations between rainfall water vapour and temperature on sub-daily scales and the set of physical processes that govern the rapidly intensified sub daily EREs are significant attributes that eventually furcate sub-daily EREs from daily EREs. Sub-daily precipitation extremes may intensify more than anticipated based on currently available modelling and theory [Lenderink and van Meijgaard, [2008](https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL071917#grl55414-bib-0042); Hardwick-Jones et al., [2010](https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL071917#grl55414-bib-0028)]. This seems to be a property of convective precipitation and may be explained by the latent heat released within storms invigorating vertical motion. This mechanism is thought to generate greater increases in hourly rainfall intensities [Lenderink and van Meijgaard, [2008](https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL071917#grl55414-bib-0042); Berg et al., [2009](https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL071917#grl55414-bib-0007); Hardwick-Jones et al., [2010](https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL071917#grl55414-bib-0028); Westra et al., [2014](https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL071917#grl55414-bib-0076); Blenkinsop et al., [2015](https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL071917#grl55414-bib-0009); Lepore et al., [2015](https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL071917#grl55414-bib-0045)], with a stronger response in convective systems than in stratiform systems [Berg et al., [2013](https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL071917#grl55414-bib-0008)]. This suggests that hourly extremes will probably intensify more with global warming than daily extremes [Utsumi et al., [2011](https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL071917#grl55414-bib-0068); Westra et al., [2014](https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016GL071917#grl55414-bib-0076)]. The results from daily-scale observational or modeling studies therefore are unlikely to be directly transferrable to sub daily time scales. On comparing the possible projections, the potential of increasing the intensity of sub daily extremes is elucidated in recent articles []. As a result, the uneven temporal distribution of EREs magnitude on sub-daily scales is responsible for the fast hydro-meteorological process, such as flash floods and cloud bursts which are more hazardous than slower onset floods because of very limited response time. Parameterization of such fast hydrological processes certainly needs the better understanding of EREs evolution on sub-daily scales. Hence, understanding the potential drivers responsible for sub daily scale variability of EREs on regional scale provides basis for impact based risk assessments.

 The evolution of EREs is documented in previous studies over the Indian West coast [Deshpande et al., 2012; Xavier et al., 2018; Kottayil., 2021; Sunil Kumar et al., 2022; Francis et al., 2006; Ray et al., 2016]. These studies addressed the evolution of EREs and possible physical attributes and associated systems. Deshpande et al., 2012 observed that many stations recorded more than 10 cm within span of 1 hr and 80% total daily rainfall is accumulated within 12 hours. Kottayil et al., 2021 concluded that the EREs over west coast are well associated with the behaviour of LLJ and mid-troposphere humidity levels. Francis et al., investigated the possible synoptic systems related to heavy rainfall events on a daily scale. However, studies on the sub-daily variability of EREs and their association with different controlling elements are still lacking over the West coast. In the present article, we subjectively diagnosed the variability of EREs on sub-daily scales and its controlling factors using a suit of observational approaches such as high-resolution satellite, reanalysis, rain gauge network, and cloud radar data.

The manuscript is organized as follow. With a brief background literature review, datasets and methodology used in the present study are discussed in section 2. Results and discussions are described in section 3. Essential conclusions from the current study are mentioned in section 4.

2. Datasets and Methodology.

 2.1 GPM-IMERG

Global Precipitation Measurement (GPM) mission Integrated Multi-satellitE Retrievals for GPM (IMERG) is A multi-satellite based merged precipitation estimate. GPM-IMERG is derived using the combined observations of GPM and its counterpart in other international satellites. GPM Combined Ku Radar –Radiometer algorithm (CORRA) is served as an inter-calibrator for GPM-IMERG product. The precipitation estimates are computed from various microwave measurements obtained from passive microwave sensors by 2017 version of the Goddard Profiling algorithm (GPROF 2017). Half an hourly precipitation estimates are further recalibrated with CMORPH Kalman Filter (CMORPH -KF) and PERSIANN Cloud Classification System methods (PERSIANN-CCS). Finally, IMERG research product is bias adjusted to the monthly Global Precipitation Climatology Project (GPCP) Satellite-Guage (SG) PRODUCT (Huffman et al., 2017). IMERG product is available with various latency periods, namely IMERG-Early, Late, and Final, with a latency period of 3 hr., 12 hr., and 3.5 months. IMERG-Early and Late products are targeted for various real-time applications such as flood monitoring, water management, and crop forecasting (Hou et al., 2014). IMERG product is currently available with 0.1-degree spatial resolution and half an hour temporal resolution.

2.2. ERA5

The fifth generation ECMWF reanalysis (ERA5) provides gridded data with a horizontal resolution of 0.25 X 0.25º and vertical coverage from 1000 to 1 hPa, consisting of 37 pressure levels. This study uses hourly data on all pressure levels of temperature, specific humidity, and vertical velocity for the extreme day events for a grid size of 2º X 2º. The vertical velocity sign in pressure coordinates of ERA5 has been reversed for convenience of interpretation, where positive denotes upward motion and negative downwards. Temperature and specific humidity were utilized for calculating moist static energy (MSE). MSE remains a conserved quantity with different phase changes of water in adiabatic descent or ascend. MSE is computed using

MSE=C\_pd T+gz+Lv q

Where T denotes absolute temperature, z is height, q is specific humidity, and the constant g is the acceleration due to gravity, Lv is the latent heat of vaporization, C\_pd is the specific heat at constant air pressure. The first two terms denote dry, static energy

2.3. KaSPR

Further, the vertical profile of reflectivity-factor (VPR) measurements of ground-based Ka-band scanning polarimetric radar (KaSPR) operating at 35.29 GHz are used to investigate two cases of extreme events through their cloud vertical structure. It is to be noted that despite having issues with attenuation, KaSPR is the only option available to understand the cloud properties of those rainy cases. KaSPR provides high-resolution (25 m and 1 s) measurements of cloud and precipitation over Mandhardev (18.04° N, 73.87° E, and ~1.3 km AMSL), Western Ghats region of India from a mobile platform since June 2013. KaSPR operates under a hybrid scan strategy (cyclic volume scan, Range Height Indicator scan, and vertical looking) to study 3-D cloud structures, and vertical pointing observations for 5 minutes duration at every 15 minutes intervals are available. KaSPR possesses a sensitivity of ~ -45 dBZe at 5 km and is, therefore, sensitive to the cloud droplet. Cloud radar measurements could be contaminated by the presence of airborne biological targets called biota. An indigenously developed quality control TEST algorithm (Kalapureddy et al., 2018) is used to segregate the biota contribution from the radar reflectivity (Ze) factor measurements and infers genuine cloud information. The necessary gaseous correction to VPR is also done, and the radar calibration and validation aspect has been taken care of using CloudSat comparison (Sukanya and Kalapureddy, 2019). Half-hourly rain accumulation data is taken from GIOVANI multi-satellite-based precipitation estimates from gauge calibration to capture the highest accumulation hour for each case. Then at those hour VSC is obtained from KaSPR’s vertical-looking measurements, and contoured frequency by altitude diagram (CFAD) of Ze and velocity are studied. Further, the mass-weighted mean diameter is estimated from the co-located drop size distribution of JW Disdrometer using the following equation.

D is the mean diameter, and Dm is the mass-weighted mean diameter (mm). ND(D) dD is the number concentration of raindrops per cubic meter of air in the diameter range D to D + dD.

**3. Results**

**3.1. Rainfall characteristics**

The spatial distribution of seasonal rainfall during JJAS months suggests inhomogeneity in seasonal accumulation [Sunilkumar et al., 2016]. West Coast, one of the country's wettest regions, receives ~300 cm to 400 cm of rainfall during JJAS. Figure 1 depicts the seasonal rainfall accumulation over the west coast region in 2019. The coastal area receives relatively more seasonal rainfall than the leeward side of the mountains. The strong interaction of monsoon winds with orography phenomenally results in copious amount of rain over the west coast region. In general, several long-duration good spells over the west coast region contribute to the seasonal rainfall accumulation. However, numerous literatures reported that the duration of such active spells has decreased in recent decades [Vinay kumar et al., 2021; Sunil kumar et al., 2022]. In recent decades, it is also observed that the west coast region encountered a significant change in the distribution of active and break spells during the summer monsoon. Thus, despite a significant difference in mean seasonal accumulation, the number of heavy to extreme rainfall events has been increasing []. Figure 1b shows the fraction of rainfall contributed by the heavy to extreme rainfall events to total seasonal rainfall in 2019. From the Figure 1b, it is clear that more than 40 % of seasonal rainfall is contributed by heavy to extreme rainfall events over a significant number of grids over the west coast region. It is interesting to note that such rainfall contribution from EREs is much more prominent around the Mumbai metropolitan region in 2019. To further explore the sub-daily scale variability of EREs rainfall on sub-daily scale, the variability of mean rainfall of extreme nature is presented in Figure 2. Figure 2 also illustrates the number of mini cloud bursts (accumulated rain>50 mm in two consecutive hours) that occurred at sub-daily hours over the study region. The sub-daily scale variability of mean rainfall suggests a uniform distribution of rainfall on sub daily scales except during evening to late evening hours. However, the peak in the occurrence of mini-cloud bursts at midnight and afternoon hours infers the possible occurrence of sub-daily extremes. Such events last only for a few hours and result in an ample amount of rainfall that leads to flooding, particularly in urban regions. It is imperative to understand the possible dynamical and thermo dynamical process that regulates the variability of extreme rainfall intensity on sub-daily scale.

We have considered one case study of a heavy rainfall event spell that occurred from 26th Jun to 30th Jun, 2019 over the study region. Figure 3a depicts the average areal rainfall recorded on different days during that spell. The event commenced on 26th Jun with light rainfall magnitude ~13 mm, and the daily rainfall subsequently increased on next two days and then started dissipating on 29th Jun 2019. The study region received the highest rainfall (~117 mm) in 28-06-2019. Figure 3b shows the sub-daily scale variability of average areal rainfall on 28-06-2019. The rainfall activity is intensified during midnight hours compared to other sub-daily hours. The predominant occurrence of such enhanced rainfall activity is also shown in figure 2 and discussed in Sunilkumar et al., 2022. Thus, we have considered several possible attributes, such as moisture convergence, offshore trough, wind gradients and etc, to quantify the influence of such attributes on sub-daily scale variability of extreme rainfall over study region. We have considered several such extreme rainfall events based on average rainfall recorded during the last decade (2010-2020). Table 1 shows the list of extreme precipitation events that occurred along the west coast. The seasonal distribution of such extreme events is shown in figure 4a. Six of 11 events occurred in July and August, which are active monsoon months. The basis for defining an extreme rainfall event is relaxed to 80 mm/day to evaluate the seasonal distribution of such extreme rainfall events. The seasonal distribution of such events are shown in figure 4b. The seasonal distribution suggests that the frequency of EREs is higher in July and August than in the June and September months. It can be stated that extreme events are well associated with the active phase of monsoon (July and August) and are less observed during the onset and withdrawal phase of monsoon (June and September).

**3.2. Case Study on 28-06-2019**

The sub-daily scale variability of extreme rainfall events depicts bimodal distribution within 24 hours, as shown in figure 2b. The bimodal distribution of rainfall magnitude may associate with several dynamical attributes. Figure 5 illustrates the spatial variability of rainfall over the west coast on 28-06-2019 at 4 AM, along with several possible attributes such as wind pattern, vertical velocity, cloud liquid water content, cloud ice water content, cloud fraction, and relative vortices. All the associate parameters are taken at two pressure levels: 850 and 500 hPa, to look at the co-variability of rainfall and other parameters at the lower troposphere and mid-troposphere. The spatial distribution of rains suggests intense rainfall activity over the coastal region north of Mumbai. The spatial wind pattern at the lower/mid-troposphere represents wind heading towards the west coast region and cyclonic vortex at the mid-tropospheric level. Low-level convergence of monsoon winds results in upper-level divergence, leading to cyclonic vortex at upper levels. Total cloud fraction at mid-tropospheric levels also depicts cloud activity along the west coast region. The spatial mismatch between maximum cloudiness and rainfall over grid points is attributed to the lead-lag relation of cloud activity and rainfall at the surface. However, the cloud fraction at mid-tropospheric levels is well connected with strong convection (positive omega) along west coast regions. The phenomenal relation between strong convection and cloud fraction at mid-troposphere is also demonstrated in a 3D pattern, as shown figure 5. Interestingly, the spatial distribution maximum rainfall intensity is well associated with strong convection at the surface level. To understand the controlling factors that are responsible for rainfall intensity variability at shorter temporal scales, figure 6 illustrates the regional average rainfall intensity variability with possible controlling factors for an extreme rainfall events case that occurred on 26-30, Jun, 2019. The rainfall event began on 26-06-2019 with light rainfall intensity (~2mm), and intensity doubled on the subsequent day and reached its peak on 28-06-2019. Later, the event is dissipated on the next day. It is interesting to note that possible attributes also suggests a remarkable change in their magnitudes on peak event day (28-06-2019). The pressure difference (PD) that accounts for the presence of the off-shore trough indicates a dip in magnitudes just before rainfall intensifies at 36th, 52nd and 70th hours. However, the dip in the PD does not show one-to-one correspondence with rainfall magnitude. The wind gradient effect (WG) seems to be negatively correlated with rainfall intensity. The wind magnitude over region B becomes less than its counterpart region A and leads to form low-pressure zone over region A and turns out to be potentially influencing the moisture convergence over the study region. The influence of moisture convergence on the distribution of rainfall intensity is clearly shown in figure 6. The vertically integrated moisture convergence magnitude becomes strong enough to enhance the rainfall intensity during peak rainfall intensity hours (36th, 52nd, and 70th) on 28-06-2019. The sharp fall in rainfall intensity post-peak event day is well associated with a lack of moisture convergence over the study region. Hence the role of moisture availability becomes significant and strongly influences the variability of rainfall intensity on shorter scales. The signature of rainfall variability on the sub-daily scale is clearly reflected in relative vorticity at mid-troposphere levels. The potential vorticity magnitude increases during peak rain hours on 28-06-2019. However, the signature of such extreme rainfall events on mid-tropospheric circulation continues to persist even after the dissipation of the event.

In the previous section, the sub-daily scale variability of extreme rainfall is quantified in terms of various dynamical/physical attributes such as moisture convergence, wind gradient, etc. Since the low-level convergence of winds significantly alters the vertical distribution of water vapor, the latent heating profile, and the moist static energy (MSE), are excellent proxy to investigate the air parcel’s internal energy accounted by its enthalpy, potential energy and latent energy due to presence of water vapour. Since the first two quantities are conserved for a given air parcel above the surface, it is water vapour that modifies the air parcel's nature in terms of MSE with respect to height. Figure 7 demonstrates the sub-daily scale variability of MSE with respect to event time and pressure level. The overlaid vertical arrows represent the strength of the updraft during the total event period. Though the magnitude of the MSE does nothave much variation below 800 hPa, the footprint of MSE shows contrasting features above 800 hPa pressure level before/after the peak rainfall intensity hours (48-72). During peak rainfall intensity hours, MSE magnitude substantially increased to the 340-346 K range, predominantly between 300 hPa and 600 hPa. The increase in MSE magnitude suggests the moistening in the mid-level and hence the conversion of cloud liquid water content into surface rainfall. On comparing the mean vertical profile of MSE on event day (28-06-2019) with respect to the pre/post event spell, the parcel possesses a relatively higher magnitude of MSE on event day below/above 550 hPa, which closely equals zero degree isothermal level. The pre-event (post-event) days represent a anomalously high MSE above (below) the melting layer. The enhancement of MSE above the melting layer suggests the presence of water vapor in supercooled water drops or mixed phases. As the ice microphysics greatly influences the surface rain rate distribution (reference?), Figure 8 explains the variation of surface rainfall intensity due to the possible dynamical process. The Figure 8 shows the two-dimensional distribution of liquid water content (LWC) and ice water content (IWC) during the extreme rainfall event case on 28-06-2019. Interestingly, the temporal variation in surface rainfall intensity is well connected with the intensity and presence of LWC andIWC, respectively. The peak in surface rainfall intensity around the 36th, 52nd, and 70th hrs is associated with a higher magnitude of LWC/IWC and MSE above 550 hPa. Moreover, the strong vertical updrafts also create a favorable environment at the surface to lift more moisture to upper-pressure levels. For example, the strong updraft around 30-42 hrs, 54-66 hours possibly raises the air parcel to higher pressure levels, leads to the formation of more IWC, and subsequently enhances the surface rain rate with a lag period. One important conclusion is that the intense surface rain rate results from the formation of a significant amount of IWC at higher pressure levels due to strong surface updrafts and moisture convergence.

**3.3 Cloud vertical structure during extreme rain events: ground based radar perspective**

This section is dedicated to explore two extreme rain events; 01 to 05 August 2019 and 28 June to 2 July 2019. Each having 5 days of 2019 using ground based vertical looking measurements of Ka-band radar data over Mandhardev, Western Ghats. The extreme precipitation is captured by half hourly GIOVANI rain gauge data. KaSPR data is analysed at three instances; (i) at the initiation phase, (ii) intense phase, and (iii) just before dissipation phase of the extreme events. The hourly rain accumulation and hence, the cloud structure at these three phases is different between the one case study.

Figure 8 shows the hourly rain accumulation in (a) and contoured frequency by altitude diagram (CFAD) of Ze in (b-d) in the three phases (11 hr on 01/08, 09 hr on 02/08, 07 hr on 04/08,23hr on 04/08) as previously mentioned with exception that middle phase has 2 rain accumulation maxima which is explained. The primary and secondary maxima of the intense spells show RA of 44/hr mm and 32 mm/hr respectively but, interestingly the RA near the secondary maxima is also comparatively high than the primary maxima. The three phases have rain accumulation of 6 mm, 44 mm, and 32 mm, and 10 mm, respectively. All the CFAD shows complete cloud vertical structure (VSC) exceeding warm level cloud regime (above 0 ºC). Few similar characteristics of CFADs are observed between the initiation phase and just before the dissipation phase in terms of contour structure, maximum cloud top height, and 100% (50%) occurrence of Ze around 20 dBZe below (above) 3 km. In these two phases, almost 30% cloud frequency in the warm cloud region shows reflectivity above 0 dBZe (vertical line) indicating dominance of raindrops inside the whole warm cloud region as shown in Fig. 8 b and e. Intense phase CFADs in Fig. 8c and d have very unique structure with narrow frequency distribution throughout the vertical structure. The one with highest RA, though have similar cloud top height with other two phases but the frequency distribution in mixed phase region is unlikely high. The high frequency ~100% cloud occurrence in the bright band is another feature limited to the middle phase. The active middle phase contribution causes the difference between the RA in the middle phase than the other two phases. This contribution is again higher in the secondary peak of the middle phase (Fig. 8d) where 40% of contours shows Ze > 0 dBZe. Another contrasting feature during the initial phase is two different contours centred around -5 dBZe and 15 dBZe with almost same frequency between 5.5 to 7 km (pink box in Fig. 8b). The existence of two different dBZe contours represents two different mixed-phased cloud growth processes governing at that altitude. Both the contours connect mixed phase region to warm phase region. Another two dominating processes are also observed above 7.25 and 6.75 km (grey circle in 8 b and d) in the initial phase, and prior to the dissipation phase, respectively. The occurrence of two different Ze contours at the same altitude is first of its kind in the radar observations.

Figure 9 shows the vertical profile of mode Ze during different phases of the extreme rainfall event on 01-05 August 2019. This high dBZe value up to 8 km is prominent in the mode values of Ze profiles (grey curve). The slower rate of change of Ze above 6 km and profoundly extended up to 10 km is due to the active participation of bigger ice particles compared to other phases in making rain. Stiffer curve depicts rate of cloud growth remains same with increasing height which further hints rapid growth of cloud droplets with altitude than usual at 5 km. On the other hand, curves in the mixed phase cloud region at the primary peak of the intense phase gradually decreases with increasing height depicting steady growth of cloud droplets. The initial and prior to dissipation phase (green and blue curves, respectively) have almost similar feature with dBZe > 10 in the warm phase region. But the higher dBZe at the mixed phase region is only limited to initial phase again establishing the critical role of mixed phase cloud region even before the main event. During the primary peak in the intense spells, the larger Ze values from surface to 0º isotherm leads to the maximum RA than the other understudied hours. So it can be concluded that higher dBZe (< 15) in the warm cloud region leads to the maximum RA whereas in the mixed phase region higher dBZe results in high RA for a longer time.Maximum cloud occurrence at the initial phase centred at 20 dBZe is due to the presence of bright band unlike the other two phases.

The same as Figure 8 but for velocity is shown in Figure 10. Again the initial and prior to the dissipation phase match on some features as evident in Fig. 10b and d; (i) fall velocity magnitude more than 3 ms-1 (grey vertical lines) throughout the warm cloud region, (ii) maximum frequency at -6 ms-1 below 3 km (grey curve), (iii) 4-5 km, frequency contour of 25% with higher velocity (magnitude > 11 ms-1). More than 11 ms-1 magnitudes in velocity specify the presence of bigger raindrops just below the bright band during both the initial and prior to dissipation phases. This higher velocity extended from 5 km up to 2 km during the both the peaks of the intense spells further confirms bigger drops reaching the surface. Above 7 km, 100% cloud occurrence with a fall velocity of 2 ms-1 is the sole characteristic of the secondary peak in the intense spell which has a sustained higher RA for duration of ~ 5 hours. The narrow structured contour in the intense spell especially above 50% repeats for velocity distribution as well. Therefore, unlike the initial and prior to the dissipation phases, during the intense spells, mixed phase process have significant contribution in making rain causing more than 3 times higher rain accumulation.

The estimated drop size from velocity in Figure 11 reveals the similar Gaussian distribution during initial and prior to the dissipation phase having peak at 1.6 mm. Bimodal distribution can be observed during the primary maxima of the in the intense phase. The first peak at 1.6 mm matches with the other two phases while the second peak at 2.4 mm explains the intense rainfall events limited to only that hour. Contrastingly the secondary maxima during intense spells only contain one peak around 2-2.2 mm depicting the presence of further larger drops required for a continuous extreme rainfall event even after the understudied hour. More than 75% occurrence of raindrops; 1–1.8 mm (1.4-1.8 mm) can be found in the initial phase (prior to dissipation phase). Interestingly, the presence of drops size <=1.2 mm and >= 2 mm are comparatively more in the initial and prior to the dissipation phase, respectively. Though the dominating drop size is same (1.6 mm) in the initial and prior to the dissipation phase, the difference in secondary dominant drop sizes (<=1.2 mm and >= 2 mm) results in different RA in that two understudied hour.

3.4. Composite analysis

The previous sections discuss the temporal evolution of extreme rainfall events and the possible association of ERE intensity of EREs with several physical/dynamical parameters. Results based on the case study suggest that rainfall intensity becomes vigorous when the winds along the coastal region form a low-pressure zone along the coast and lead to offshore trough. Thus, wind driven moisture convergence due to such low pressure zones acts like a catalyst to intensify the precipitating systems with additional dynamical attributes such as orography effect and low level convergence. The moisture convergence importantly at mid tropospheric levels plays a decisive role in enhancing the amount of cloud water converting in to rain water content. Thus, the strong uplift of air parcel owing to orography and/or low-level convergence increases the amount of LWC reaching to higher pressure levels and converting into ice water content through various microphysical processes, as shown in the Figure 8. The enhancement in surface rainfall intensity is well connected to the amount of IWC present in the upper troposphere levels. In the current section, the composite analysis of all the extreme precipitation events is discussed to validate the observed variation of extreme precipitation intensity on sub-daily scales with possible physical/dynamic attributes for all extreme events. Figure 12 illustrates the composite picture of sub-daily scale variability of rainfall intensity and its resemblance with other physical/dynamical attributes. The peak intensity of rainfall observed on event day (48-72 hrs) is well correlated with the low-pressure zone along the coast and surplus total integrated moisture availability. However, the fingerprint of extreme rainfall events on upper tropospheric levels is observed during post-event hours (later 72 hrs.). Interestingly, the increase in rainfall intensity on event day is almost four times greater than pre-event hours. Such abrupt change is only observed in the availability of moisture content and brightness temperature during peak intensity hours on the event day. It suggests that the availability of moisture content in the atmospheric column and ice water content play a pivotal role during peak rain intensity hours.

3.5. Principal Component analysis

The intrinsic character of sub-daily variability of extreme precipitation and its associated attributes are further explained with the help of the principal component analysis method (PCA). The first four principal components explained 96.4 percent of the total variance in data. The first loading factor (F1) explained 40.7% of the total variance having the highest loading factors by integrated moisture convergence and cloud-top brightness temperature. The common trend of mutual variability of integrated moisture convergence and brightness temperature with rainfall intensity on a sub-daily scale over the study region is highlighted with the higher factor scores of moisture availability (0.86) and brightness temperature (0.75) in the first principal component. The effect of wind gradient on sub-daily scale variability of rainfall intensity is seen in the second principal component that explains 22.28% total variance, and it was the only principal constituent in F2 that settled down with a loading score of 0.70.