



Spatial Distribution of Extreme Rainfall Events During 2017 Southwest Monsoon over Indian Subcontinent

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Abstract—The extreme rainfall events over India during 2017 southwest monsoon and associated mechanisms are investigated using daily rainfall, winds and SST data sets. Extreme events occurred over mainly four locations according to the designed criteria, which are westcentral India (WC), central India (CI), northeast (NE) India and northwest coastal region (NWC). The events are identified mostly in the active phase of monsoon except in the northeast India, there the extremes are during break monsoon situation. As observed over the northwest coastal region and central India, most of the rainfall events are clustered during the peak monsoon (in the month of July). The seasonal frequencies of extreme events are significantly high in the west central and central India region. On the other hand, the relative contributions of these events are exceptionally high. In the northeast India, extreme events are followed the criterion of low-level wind regimes, where westerly regime induces a positive feed-back to enhance the extreme event. The temporal distribution and relative contribution of rainfall towards seasonal total in the northeast and northwest regions differ from other two selected regions. Global circulation pattern and local updraft contribute largely towards the seasonal rainfall in the west central and central India. A positive Indian Ocean Dipole mode together with the presence of a weak La Niña eventually favoured the rainfall in the northern parts during the month of July.

Key words: Extreme events, central India, circulation, sea surface temperature.

1. Introduction

Present climate models predict an increase in extreme precipitation events in the future based on the International Panel for Climate Change (IPCC) third assessment report (Houghton et al. 2001). The

observed amplification of rainfall extremes is found larger in intensity and frequency than predicted (Allan and Soden 2008). Since the climate models underestimate the frequency and strength of extreme rainfall events, there remains an ambiguity to form risk management policies. Herein, 2017 monsoon is a perfect paradigm for disassociation of noticed overall weakening of the monsoon circulation over India (Joseph and Simon 2005; Roxy et al. 2017) with the strength of the extreme precipitation events even during the below normal monsoon condition (IMD 2017). The increasing trend of extreme rainfall events over India has been reported in previous literatures (e.g. Goswami et al. 2006; Krishnamurthy et al. 2009; Guhathakurta et al. 2011; Varikoden et al. 2013), which are primarily associated with the increase of greenhouse gas emissions alongside a warming atmosphere (Ramanathan et al. 2005; Ramanathan and Carmichael 2008; Singh et al. 2019). Observational investigations indicated an enhancement in the atmospheric surface temperature about 1.1 °C which consecutively increases the water holding capacity of atmosphere, in addition to increasing sea surface temperature (SST) of the Arabian Sea and Bay of Bengal, which correlates with the occurrence of extreme rainfall events (Dash et al. 2007). Overall increase in the SST stimulates cyclonic disturbances, which play a vital role in the enhancement of rainfall activities over Indian region. A large part of the country shows a positive relationship between the indices of precipitation extremes and frequency of cyclonic disturbances (Revadekar et al. 2016).

In the last few decades, the numbers of low and moderate rain days averaged over the whole of India have significantly decreased during the summer monsoon season (Dash et al. 2011). However, the

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number of heavy rain days showed an insignificant increasing trend (Krishnamurthy and Shukla 2007; De et al. 2005; Sen Roy and Balling 2004; Roxy et al. 2017; Dash et al. 2011). On investigating the duration of these severe rainfall events, Dhar and Nandargi (1995) found that the majority of severe rainstorms are of 3-day duration. Dash et al. (2009, 2011) also suggested that long (short) spells show a decreasing (increasing) trend over India. Roxy et al. (2017) also highlighted that extreme rainfall events occurred from the rain spells having at least 3 days of length in central Indian region. Main causes of floods due to heavy rainfall and associated natural calamities are attributed to the inadequate capacity of rivers to carry the high flood discharge in addition to the lack of proper drainage systems to carry the rainwater (Sikka et al. 2016).

Extreme rain events over windward side of Western Ghats were analysed by Francis and Gadgil (2006) and they found that the chance of getting heavy rainfall is relatively high in mid-June to early-August compared to the withdrawal month September. They also found the spatial probability of occurrence of the heavy rainfall events between 14°N–16°N and near 19°N and the basic reason they attributed is the orography. Also, there are always regional changes in the mean and extreme rainfall trends over Indian subcontinent (Parthasarathy and Dhar 1974; Subbaramayya and Naidu 1992; Ghosh et al. 2016; Varikoden et al. 2019). Sen Roy and Balling (2004) found an increasing trend in extreme events over the region extending from Northwestern Himalaya through most of the Deccan Plateau in the southern peninsular region of India, however a decrease in these events is found in the eastern part of the Gangetic Plain and parts of Uttaranchal.

Global general circulation has far-reaching impacts on Indian summer monsoon rainfall (ISMR) which in turn influences the livelihood of global population. Past observations indicate delayed/early onset and relative advancing time influence the development of extreme precipitation events. Southwest monsoon of 2017 hits Kerala coast on 30 May, which is 2 days prior to the climatological date of onset and it swayed the entire Indian domain with a delay of 4 days indicating a slow northward propagation. The present study focuses only 2017

southwest monsoon to examine the recent behaviour of extreme events spatially and temporally in the light of the previous research findings. There are different criteria formulated for identifying the extreme events to understand the variability and their trends (Goswami et al. 2006; Pattanaik and Rajeevan 2010; Dash et al. 2009), however, in the present study we used the criteria of standard deviation and threshold value.

In this study we try to explain the spatial and temporal distribution of extreme rainfall. A comparison with the seasonal anomaly, seasonal frequency of the events and the relative contributions towards the seasonal total depicted solely the major rain swept areas. After identifying the areas, we have located one prominent event in each location and tried to identify the dynamic drivers behind each one of them. Section 2 describes the data and methods of research analysis. Section 3 discusses the distribution of extreme rainfall events and the drivers of these extreme events and the paper is concluded with major findings in Sect. 4.

2. Data and Methodology

Our analysis is focused on Indian southwest monsoon season (June–September) of 2017 to explore the regional extreme event analysis. We used the India Meteorological Department (IMD) gridded daily rainfall with a spatial resolution of $0.25^\circ \times 0.25^\circ$ latitude–longitude grid from 1981 to 2016 (Pai et al. 2014), which is used to calculate the daily climatology and standard deviation. For 2017 monsoon period daily Merged Satellite Gauge Rainfall (GPM) data (Mitra et al. 2009) is used, which is obtained from <http://www.imdpune.gov.in>, National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP-NCAR) Reanalysis wind data sets with a spatial resolution of $2.5^\circ \times 2.5^\circ$ latitude–longitude grid (Kalnay et al. 1996) in different pressure levels with a temporal resolution of a day used for the analysis of circulation pattern. In addition to the wind data, interpolated outgoing long wave radiation (OLR) from National Oceanic and Atmospheric Administration (NOAA) with the same spatial resolution (Liebmann and Smith 1996) was also used to study the organized

convection. The SST data from Hadley Centre sea Ice and Sea Surface Temperature dataset (HadISST: Rayner et al. 2003) with $1^\circ \times 1^\circ$ resolution is used to understand the oceanic features.

The present analysis is focused on rainfall events from June to September, the daily climatology and standard deviation were calculated over 30 years for entire available grids (66.5°E – 100°E and 6.5°N – 38.5°N). According to IMD criteria rainfall is classified into six different categories starting from very light (0.1 – 2.4 mm day^{-1}) to extremely heavy rainfall ($> 244.4 \text{ mm day}^{-1}$). Based on IMD's criteria, the heavy rainfall is when the rainfall amount is more than 64.5 mm day^{-1} , however, in the present analysis the extreme event is considered when the rainfall over the grid point exceeds 3σ (where σ is the standard deviation) from the daily climatology with a threshold rainfall of 100 mm day^{-1} . The number of extreme events, their relative contribution towards seasonal rainfall in terms of magnitude and percentage were analyzed. The monthly variation of extreme events was also studied and the anomalous behaviour in the rainfall and circulation patterns was also studied.

With the help of spatial distribution of events, we identified the locations which are significantly over-driven by extreme rainfall events. The date of extreme rainfall events were selected from the daily March of rainfall for each region. Circulation features at 850 hPa and vertical velocity at 500 hPa were analysed in addition to the convection and rainfall features for the identified extreme events to explore the evolution and dissipation characteristics. Moreover, the large scale features based on Indo-Pacific SSTs and east–west circulation patterns were also explored to understand the drivers of the extreme events.

3. Results and Discussion

3.1. Spatial and Temporal Distribution

The daily averaged southwest monsoon rainfall shows higher values over the northwest coastal belt and northeastern regions with subdued rainfall over southeast and northwest of India (Fig. 1a). Rainfall

anomaly during southwest monsoon period of 2017 is given in Fig. 1b. From the figure, it is clear that negative anomalies are seen over the south Konkan coast, parts of Arunachal Pradesh, eastern regions of central India. The positive anomalies are registered over westcentral, central, northeast regions and north Konkan coast. In general, the negative anomalies are widely spread over Indian region; however, the positive anomalies are more intense and regionally confined. The westcentral region shows abnormally high rainfall (with a departure of more than 10 mm day^{-1} from the climatology) during 2017 southwest monsoon period.

The locations of extreme rainfall based on the criteria suggested in previous section is identified and given in Fig. 1c. There are multiple places of extreme events spread all over India; however, certain regions are prone to extreme events over relatively larger domain. Those domains are considered for further analysis. The details of the domain and rainfall characteristics are given in Table 1. The regions are selected on the basis of high intensity over a wide region with higher number of events. In the WC and CI regions, more than seven extreme events are occurred in certain grid points. In the case of NWC and NE regions, the maximum number of extreme events registered is with more than ten events in certain grid points. In the case of relative contribution from the extreme events, CI and WC areas are contributing more towards seasonal rainfall (Fig. 1d). There the percentage of contribution towards total monsoon rainfall is found more than 60%. However, NE and NWC regions are climatologically rain fed areas and therefore the rainfall from the extreme events is contributed only up to 30% to the seasonal rainfall. The increasing trend of extreme events over the Central Indian belt was also reported by Roxy et al. (2017).

The monthly distribution of extreme rainfall events in the southwest monsoon season are shown in Fig. 2. The distribution of the heavy rainfall events of WC and CI are mainly concentrated in the month of July, thus for further analysis we have mainly concentrated in July month. But the NE and NWC regions behave differently from the other two regions. The NE region is vulnerable to extreme events in the month of August. In addition to this it is

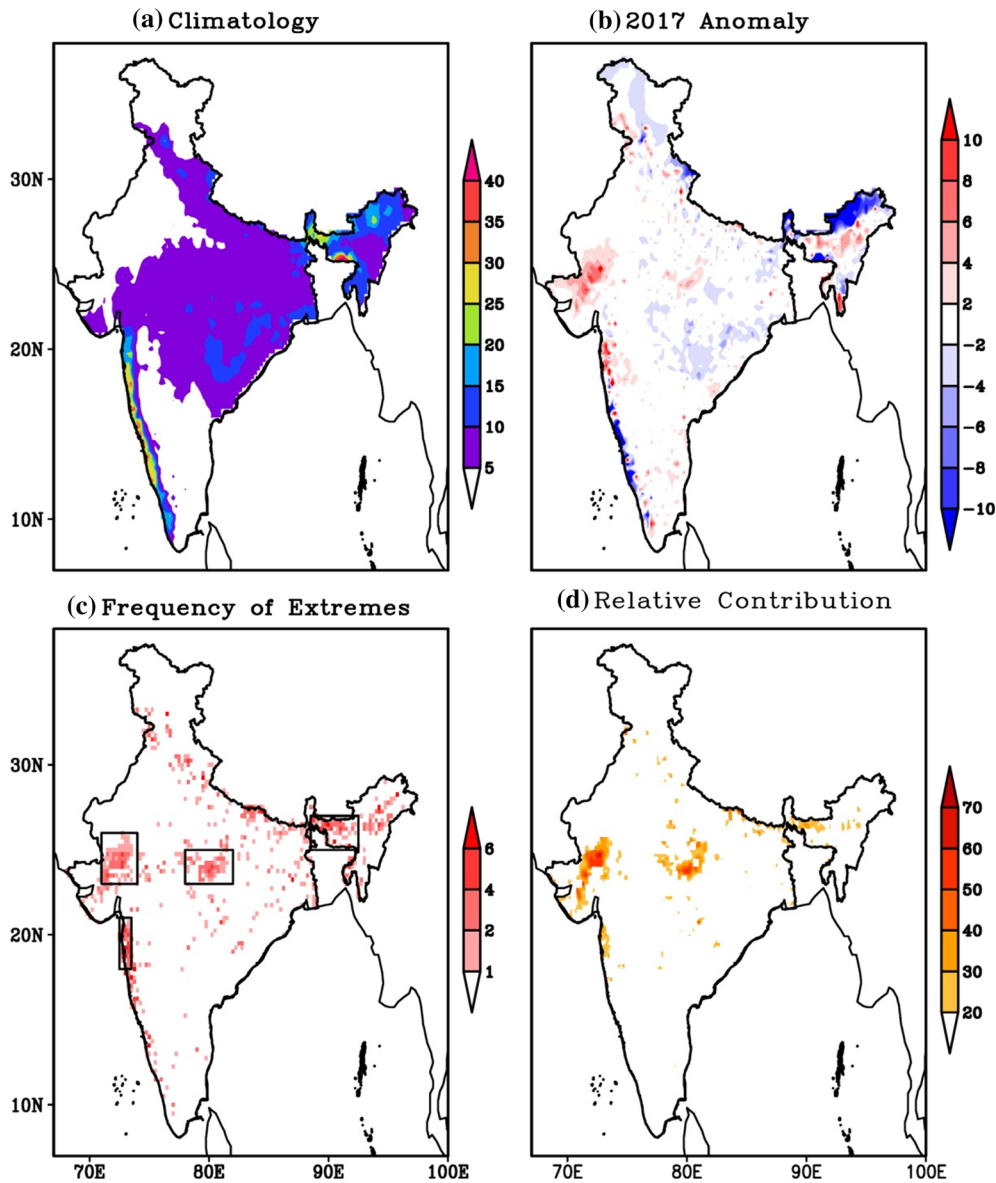


Figure 1

a Daily rainfall climatology (mm day^{-1}) of JJAS season for the base period 1981–2016 over India, **b** rainfall anomaly of the JJAS period in the year 2017, **c** frequency of extreme events according to the designed criteria in the southwest monsoon season for each grid, the selected regions are marked as latitudinal longitudinal boxes and **d** the percentage of contribution of the extreme rainfall events towards the seasonal total

found that July month was the only contributor of extreme rain events in the CI and WC regions and no events were reported during other months over these regions. In the case NWC, the extreme events are distributed in all monsoon months with peak occurrence in the month of July. In the NE region, the

extreme events are more during the month of August in contrast to other regions. There lower number of extremes was also observed in other monsoon months too. During the southwest monsoon season of 2017, northwest, southeast and southern regions of

Table 1

Area selected for the study and rainfall features and their relative contribution to seasonal rainfall for all the selected regions

Region	Area	Climatology (mm day ⁻¹)	Seasonal rainfall (mm day ⁻¹)	Contribution from the extremes (in percentage)
Westcentral India (WC)	71°E–74°E; 23°N–26°N	5.08	8.68	5.02 (57)
Central India (CI)	78°E–82°E; 23°N–25°N	8.03	8.7	4.1 (47)
Northeast India (NE)	88.5°E–92.5°E; 25°N–27°N	17.21	14.56	3.59 (24)
Northwest coastal region (NWC)	72.5°E–73.5°E; 18°N–21°N	19.36	20.31	5.3 (26)

peninsular India have not registered any extreme events based on the present criteria.

3.2. Analysis of Extreme Rainfall Events

In the present study, we selected four regions (marked in Fig. 1c) based on criteria discussed in the methodology section. Normally extreme events occur in the active phase of monsoon (Krishnamurthy and Shukla 2007). Figure 3 gives the day to day variations of area average rainfall over the four selected regions. The number of grids in which the threshold extreme rainfall events in the area is a few cases and hence daily rainfall values are small in the region due to area averaging. The 5 days running mean of rainfall in the monsoon core zone (75°E–84°E; 18°N–26°N) is overlaid in Fig. 3a to identify the influence of active-break conditions. Here, we considered the active cycle, when the rainfall is at least 5 mm for more than five consecutive days and a feeble spell of rainfall less than 5 mm for more than five days is categorised as break condition. Observed extreme events are occurred in the active phase of monsoon in the NWC and CI, however, it is occurred during the break phase in the NE region. The extreme events considered in the WC region are during transition period from active to break. The daily rainfall in the WC region shows abnormally high values in the month of July (> 120 mm day⁻¹), especially from 23 to 25 July. All other spells associated with active monsoon condition are comparatively less intense during other months. For CI, the events started from 11 to 13 July with an average rainfall of about 100 mm day⁻¹ as part of the active phase (Fig. 3b). First two weeks of August recorded heavy rainfall events over NE especially from 10 to 12 August. These regions behave out-of-phase relationship with monsoon core zone (Pant and Kumar

1997; Guhathakurta and Rajeevan 2008; Varikoden and Babu 2015). Therefore, the extreme events are mostly reported during break monsoon condition. Moreover, the active rainfall conditions in the regions (Fig. 3c) are mostly associated with the break monsoon conditions (Fig. 3a line graph). NWC region is known for its high climatological rainfall values as evidenced from Fig. 1a (as reported by Francis and Gadgil 2006) and this region is showing multiple peaks associated with active monsoon condition. For further analysis, we considered the event starting from 17 to 19 July.

Figure 4 presents the circulation features at 850 hPa along with OLR during the extreme events in all the selected regions. The triads (three day average) are presented with one triad prior (– 1 T) to the event and one triad after (+ 1 T) the event in addition to the extreme event triad (0 T). In the case of WC event (Fig. 4: – 1 T), there is a thick convective cloud system which covers central India and western coast including Gujarat in the – 1 and 0 triads and the winds are converging in nature during this period. After the extreme event, the convection started to weaken and corresponding changes are observed in the low level circulation features. For the CI, the extreme event is part of large scale organised convection starting from – 1 T to 0 T, however, the strength of convection is gradually dissipating by + 1 T and shifting to the Bay of Bengal. The circulation at lower levels shows more convergence during 0 T and therefore one can infer that this convergence attributed to the occurrence of extreme event.

Normally northeastern region receives rainfall when the wind pattern is in westerly regime and moisture inflow from the Bay region is favourable. During the break monsoon period the winds over northeastern region becomes southwesterly and hence the regional orographic barrier present in the location

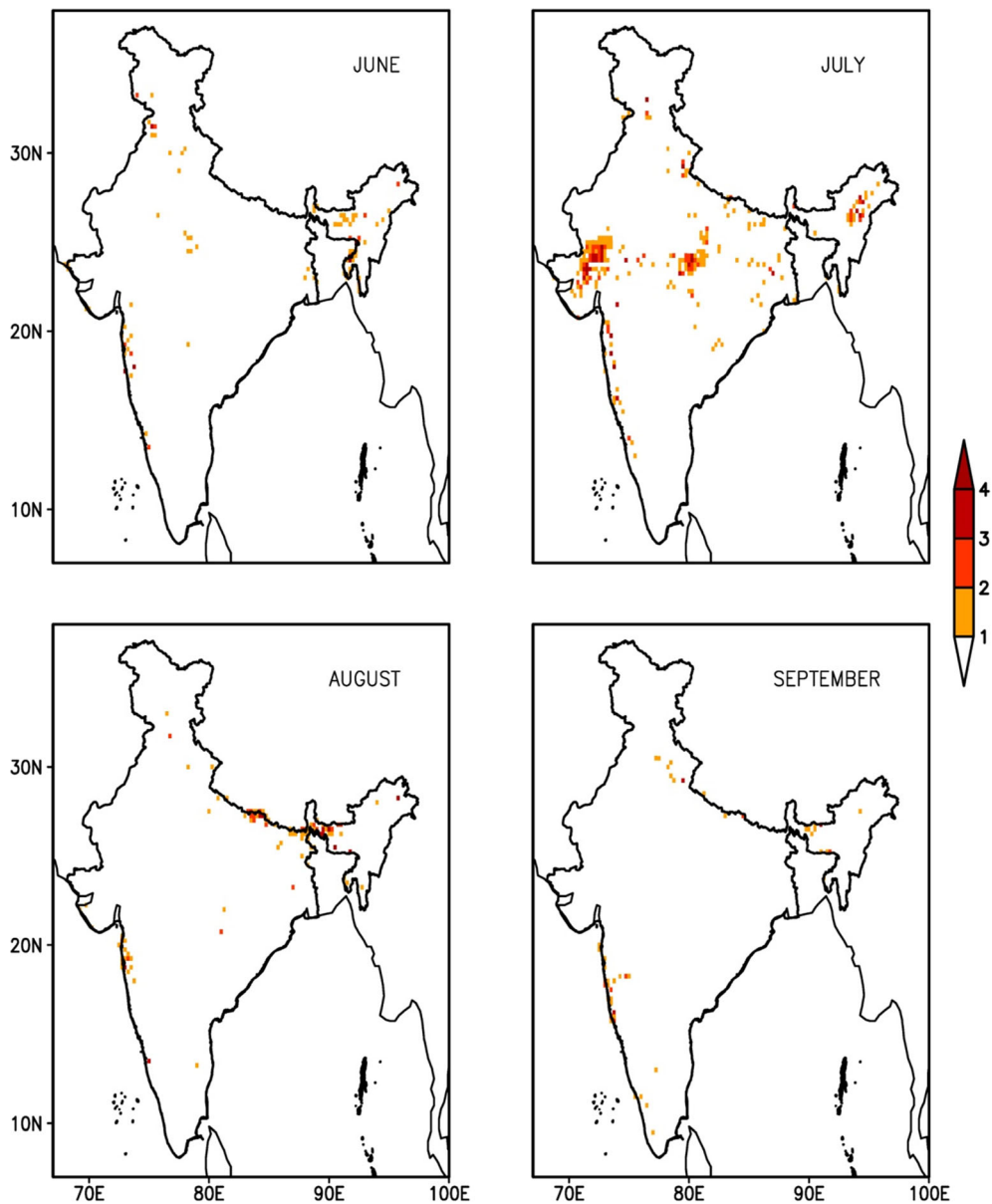


Figure 2

Monthly distribution of the extreme rainfall events during 2017 southwest monsoon period. The shaded regions indicates the number of rainfall events observed in that region

induces updraft and subsequent heavy rainfall in the southern slopes of the mountains. In the case of NE region, the extreme events are occurred mainly during the westerly regime (WR): low level wind oriented with more westerly component at Meghalaya plateau as explained by Fujinami et al. (2017). Under

the WR, strong low level southwesterlies bring humid air from the Bay of Bengal, which favours the extreme precipitation over northeast India. The winds are southwesterlies during – 1 T and the situation is favourable for further developments of the convection bands over the eastern end of NE region.

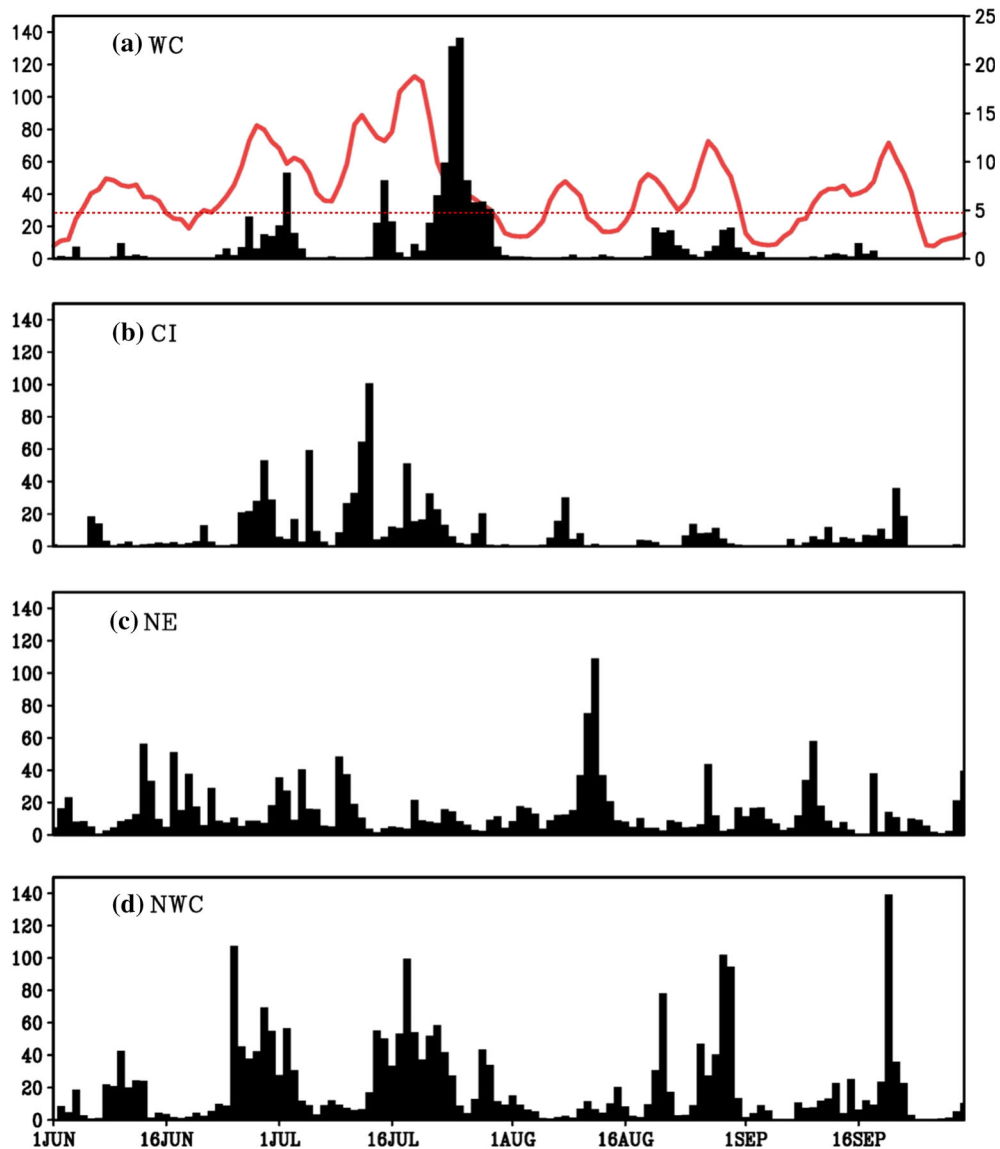


Figure 3

The daily March of rainfall (mm day^{-1}) averaged over the **a** Westcentral (WC), **b** central India (CI), **c** Northeast India (NE) and **d** Northwest costal (NWC) regions. Red line in (a) is the 5-day running mean of rainfall in the monsoon core region (75°E – 84°E ; 18°N – 26°N)

Thereafter, it progresses towards the study regions with organised convection (Fig. 4: 0 T), which is responsible for the heavy shower leading to the occurrence of the extreme events. The weakening of the cloud bands and formation of another convective system in the equatorial Indian Ocean is found during +1 T as an indication of the break monsoon condition. Similarly in NWC region, as part of the active monsoon condition, deep and organised

convective cloud bands are present in the southern peninsular India (Fig. 4: –1 T) extending from the southern Bay of Bengal to the northwest Arabian Sea, in addition to low level circulation passing through the peninsular India. These cloud bands advance towards north and get further intensified to form the extreme event (Fig. 4: 0 T) after which it moves further northward (Fig. 4: +1 T) as manifested by Sikka and Gadgil (1980). As an overall picture, we

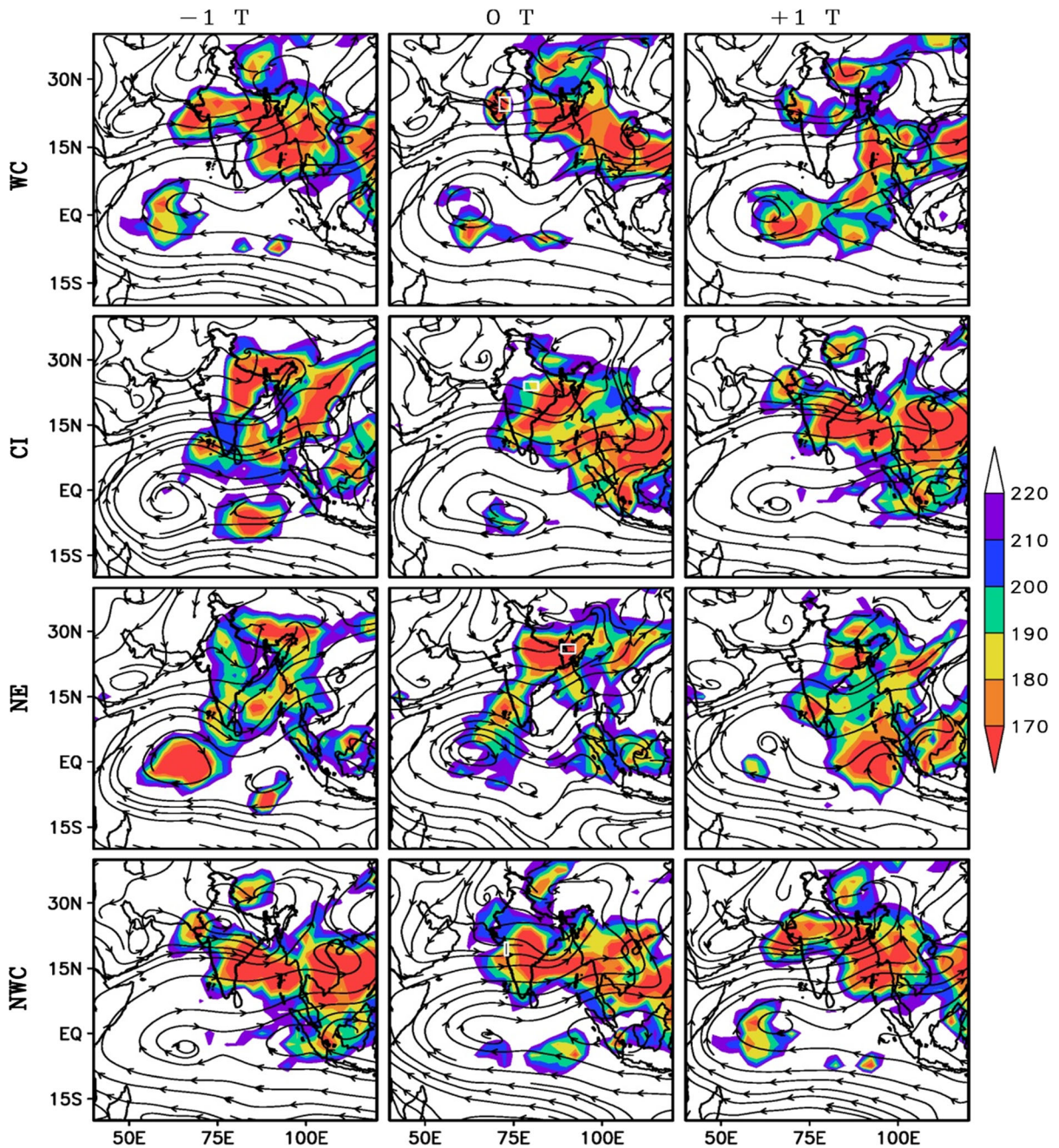


Figure 4

OLR ($W m^{-2}$) patterns (shaded) along with the 850 hPa wind ($m s^{-1}$) patterns (stream line) for the selected dates are represented in triads. Here - 1 T represent triad before the occurrence of the extreme events, 0 T represent the triad at the time of the event and + 1 T is the triad after the occurrence for all for the selected locations (WC,CI,NE and NWC). The selected locations are drawn in the 0 T panels

can observe the movement of the organised convection band associated with these events slowly moving northward. On 10 July thick convection caused heavy

rains in Central Indian region and moves further Northward, eventually, after that, another convection hits the west coast on 16 July with heavy downpour

over Northwestern coastal zone. This convection moves further northward with heavy showers over mostly dry regions of Westcentral India.

Relative vorticity at 850 hPa and ascending motion at 500 hPa patterns result in heavy rainfall events as given in Fig. 5. The WC regions show a strong updraft before and during the event (Fig. 5:

– 1 T and 0 T) associated with low level convergence focused over the regions of extreme event and thereafter the updraft and convergence show a weakening (Fig. 5: + 1 T). In the CI region, the extreme event is associated with strong updraft at 500 hPa (Fig. 5: 0 T). However, these values are negligibly small prior to the event and feeble after the

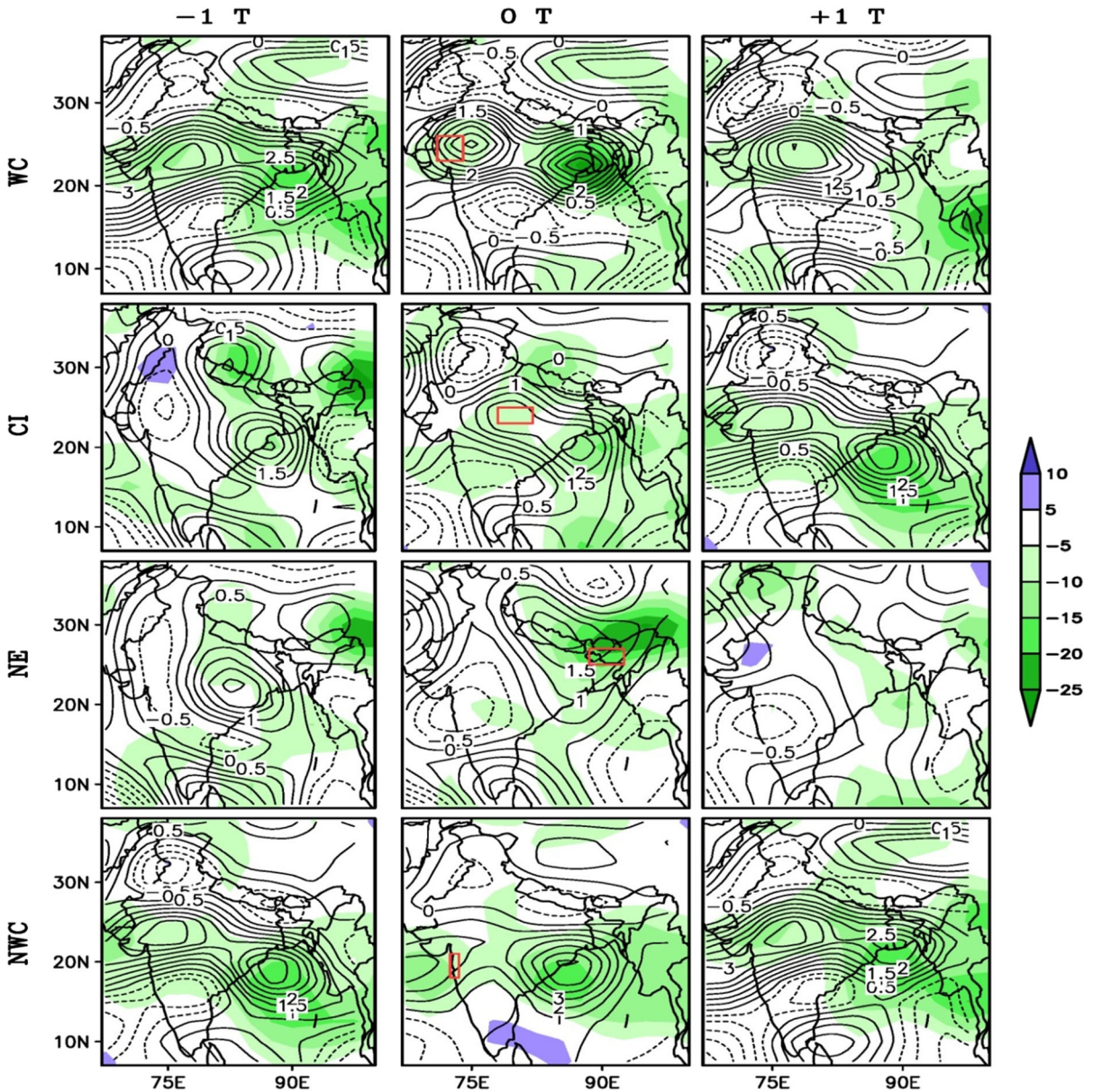


Figure 5
500 hPa omega ($\times 10^{-2} \text{ Pa s}^{-1}$) patterns (shaded) along with the 850 hPa relative vorticity ($\times 10^{-5} \text{ s}^{-1}$) patterns (contour) for the selected dates are represented in Triads

event, which indicates that the extreme event developed within a short time interval. Particularly in NE event, the convergence and vertical component of wind is comparatively very high than all other locations during the 0 T and it indicates a rapid progress and dissipation of the extreme rainfall events (Fig. 5: -1 T and $+1$ T). The presence of strong low level convergence zone extending from the north Bay of Bengal was one of the main features of NWC event (Fig. 5: 0 T), which is also prominent in the -1 T and $+1$ T, however, the vertical wind is relatively small. Generally, vertical ascent with suitable low level convergence intensified the extreme events in all four selected regions. Active phase of monsoon induces more moisture flux in the western and central parts of the subcontinent. The significance of narrow mountain ranges in the western coastal belt helps to modulate the organization of monsoon convective systems in the windward side (Grossman and Durran 1984; Xie et al. 2006) to generate heavy precipitation events.

The large scale features associated with extreme events were also studied based on the sea surface temperature and zonal circulation over the vertical plain in the northern tropics. The SST anomaly pattern shows a mild La Niña (Fig. 6a) in the eastern Pacific Ocean, however, other regions of Pacific in the tropical belt is abnormally warm and this influences the atmospheric circulation in both vertical and horizontal plain. Mujumdar et al. (2012) reported that the La Niña events cause to extreme events over the north central parts of India. SST pattern of the Indian Ocean shows a positive Indian Ocean Dipole (IOD) like structure, which causes to surplus rainfall over Indian subcontinent (Ashok et al. 2004; Ashok and Saji 2007). The negative anomaly of SST in the east Pacific and cold SSTs in the southern Indian Ocean leads to formation of extreme events in central and northern regions of Indian subcontinent. Ajayamohan and Rao (2008) also reported a similar finding that an anomalous cooling in the southern Indian Ocean modulates extreme rainfall events in the central India. The meridional temperature gradient in the equatorial Pacific also influences the rainfall patterns in the subtropics (Mujumdar et al. 2017) as we see in 2017 July, the meridional temperature gradient in the central Pacific is high,

which causes to subdued rainfall in the south Asian monsoon domain, however, it causes anomalous extreme events in the central Indian regions. In line with SST pattern, the east–west circulation in the vertical plain over the latitudinal belt of 20°N – 30°N also supports the anomalous ascending motion over central Indian region (Fig. 6b). This rising limb of east–west circulation along the longitudes 60°E to 100°E during July month leads to increased rainfall activity over the central Indian regions, which leads to frequent flood from the extreme rainfall events.

4. Conclusions

In the present study, we have analysed extreme rainfalls events during southwest monsoon of the year 2017 over the Indian subcontinent. For the identification of extreme events we have developed a new criteria based on standard deviation of rainfall (3σ) and a threshold value of 100 mm day^{-1} in a grid point. According to the criteria we have observed spatial variabilities in the frequency of occurrence of the extreme rainfall events. We have selected four regions namely westcentral India, central India, northeast India and northwest coastal regions of the country, in which the spatial spread and frequency of extremes are relatively high. Moreover, we observed the monthly distribution of these events and found that they are more frequent in the month of July (active monsoon phase) for west central and central India. The relative contribution of rainfall in both these regions is contributed more than 60% of the total seasonal rainfall. For Northeast India, high intensity events are found more in the month of August (in the break monsoon phase). In the northwest coastal regions, the extreme events are distributed more or less similar manner in all the monsoon months with slightly higher in the month of July. From each region, three triads were selected, one during the extreme event and one before and one after the event to understand the drivers of the extreme event. In the analysis, it was found that the presence of deep convective cloud bands and low level cyclonic disturbances were prominent in the westcentral and central India. The western regimes in the low level circulation during break monsoon

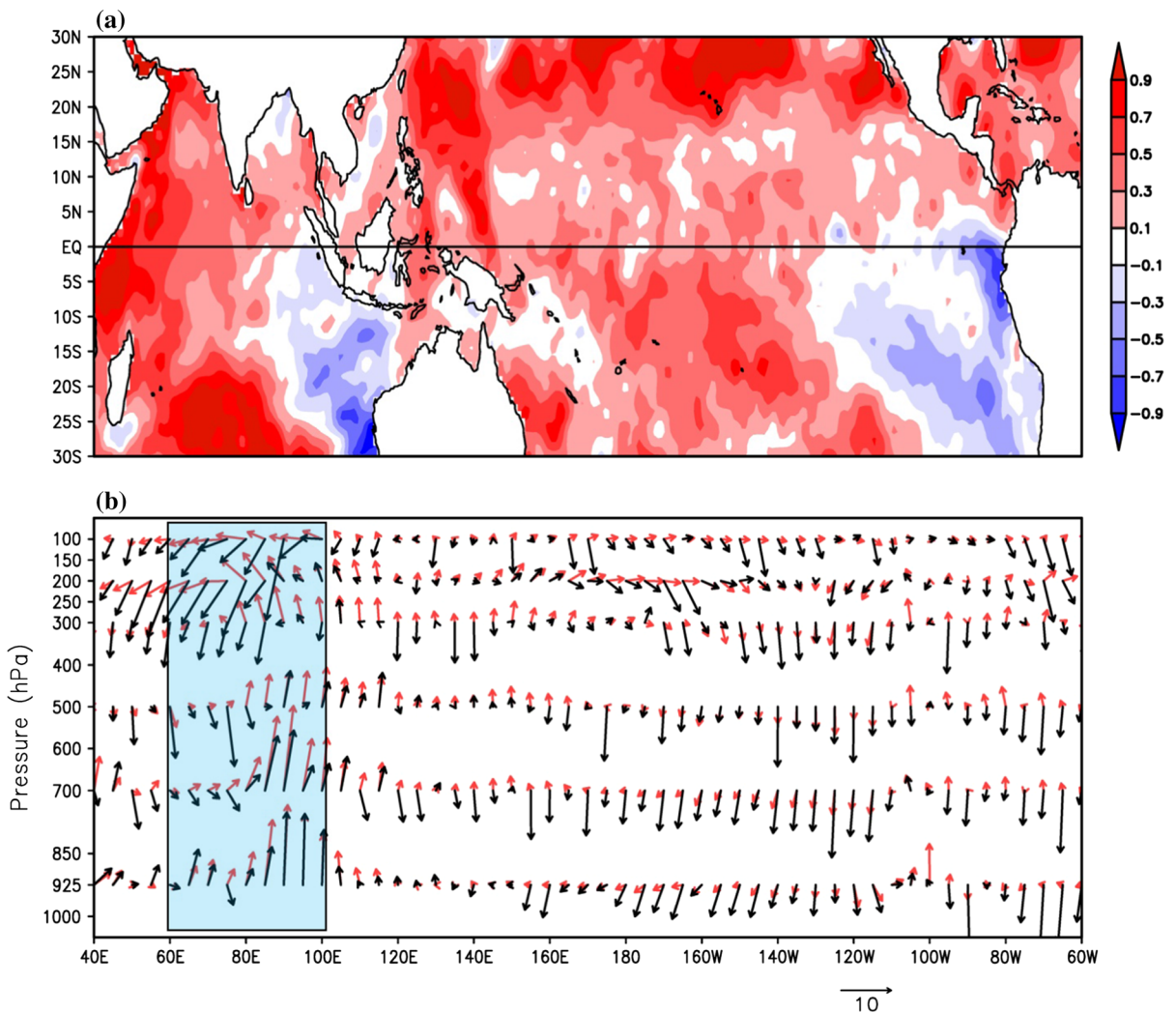


Figure 6

a SST anomaly of 2017 July and **b** climatology (1980–2016) and actual (red line) patterns of east–west zonal circulation in the vertical plane for July month averaged over 20°N–30°N

condition along with high organised convection bands in the vicinity of the Bay of Bengal enhanced the rainfall events in the northeast India. For each location the low level convergence and updraft velocities are favourable for development of the deep and intense convection. In the large scale, a weak La Niña phase in the east Pacific and the positive IOD phase in the Indian Ocean modulates the circulation patterns, which in turn drives the extreme events. The ascending limb of the zonal circulation intensified over central Indian domain and ultimately it led to the

formation of more number of extreme events over the region.

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