Precursors of northeast monsoon rainfall variability during extreme epochs of the global warming era

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Abstract
The smoothed time series of northeast monsoon rainfall over south peninsular (SP) India has revealed two extreme active epochs (1877–1887 and 2005–2015) and two extreme weak epochs (1899–1909 and 1980–1990) during 1871–2016. Only the recent two epochs 1980–1990 and 2005–2015 were chosen due to data constraints. For these two epochs, the distribution of zonal wind pattern at the 850 and 200 hPa levels, latent heat flux, vertical shear in the zonal wind between 850 and 200 hPa, sea surface temperature and outgoing long wave radiation (OLR) were studied. The vertical profile of zonal wind over the mean position of the subtropical westerly jet and the maximum wind reversal were also analysed. Further, the frequencies of dry days, little rainfall days (0–20 mm), moderate rainfall days (20–60 mm), heavy rainfall days (60–100 mm) and very heavy rainfall days (>100 mm) were evaluated. SP India has experienced active/weak monsoon conditions every one to two decades alternately. An active monsoon epoch shows a higher north–south temperature gradient over the Bay of Bengal than a weak monsoon epoch. An upper level subtropical westerly jet over north India, strong tropical easterlies in the lower troposphere and low vertical shear in the zonal wind over the Bay of Bengal were observed during the active epoch, which facilitates the transportation of good amounts of moisture to SP India. The low OLR values over SP India in the active monsoon epoch indicate more convective activity over that region. Enhanced rainfall activity over SP India in the active monsoon epoch is due to the enhanced frequency of very heavy, heavy, moderate and little rainfall events and the reduced frequency of dry days.

KEYWORDS
active epoch, latent heat flux, northeast monsoon, weak epoch, zonal wind

1 INTRODUCTION
The northeast monsoon persists over India during October–December; the rainfall during the season contributes about 50% of the annual rainfall over the southeastern tip of peninsular India (Rao Krishna and Jagannathan, 1953; Kumar et al., 2007). South peninsular (SP) India experiences a northeast monsoon in addition to the summer
monsoon. The northeast monsoon influences the rabi crop over SP India as it provides appreciable amounts of rainfall; in particular, in the eastern half comprising coastal Andhra Pradesh, Rayalaseema and Tamil Nadu, the rainfall is reasonably significant. For Tamil Nadu, this is the main rainy season accounting for about 48% of the annual rainfall. Although the principal rainy season for interior Karnataka, Kerala and Lakshadweep is the southwest monsoon season, rainfall continues until December in these subdivisions, amounting to about 20% of the annual total. The increased rainfall activity over the Andhra–Tamil Nadu coast around mid October (around October 20 with a standard deviation of 1 week) is generally associated with the onset of the northeast monsoon (www.imdchennai.gov.in).

Naidu et al. (2012) stated that the cold and dry continental air mass from the Siberian high may not provide copious amounts of rainfall during the northeast monsoon season. However, it influences SP India as it passes through the warm waters of the Bay of Bengal by picking up moisture. Also, this area experiences reasonable amounts of rainfall due to tropical cyclones, depressions, north–south trough activity, coastal convergence, cold surges from high pressure cells, the equatorial trough, the disturbances in the equatorial trough and the adjoining easterlies (Subbaramayya, 1976; Jayanthi and Govindhachari, 1999).

The boreal winter heat source is a combination of both the near equatorial zone and the extra-tropical region (Chan and Li, 2004). Hence, the temperature and density stratification of higher latitudes holds more control in the winter monsoon than in the summer monsoon. The region between 10°S and 10°N undergoes maximum wind reversal and the rainfall happens in pace with this wind change in this area. The latent heat release from the area can be considered as the major planetary heat source that runs the global circulation during boreal winter. This happens mainly due to the blocking of atmospheric circulation in the mid latitude by the Ural Mountains where the northerly surges originate (Chen, 1999; Webster, 1999). The prevailing Indian Ocean circulation in the meantime decides further El Niño Southern Oscillation (ENSO) monsoon coupling. During October, the monsoon trough is positioned over northern parts of India in a northwest–southeast orientation at the surface and the lower troposphere starts a rapid shift southwards (Khole and De, 2003). The low level winds reverse to northeasterlies and the southwest monsoon withdraws from these regions. However, over SP India, the rainfall continues in October also with a sharp increase of rainfall over coastal Tamil Nadu in the second half of October. In response to various oceans, the northeast monsoon has distinguished striking oscillations in its seasonal flow, which are 1–5, 10–20 and 20–60 day oscillations. Only 1–2 and 3–5 day oscillations are apparent in deficit northeast monsoon years while a combination of all three modes of oscillation is evident (with rare occurrence of 20–60 day oscillations) in normal years (Charlotte et al., 2012).

According to Naidu et al. (2010; 2012), a weak Southern Oscillation Index, intensified lower troposphere easterlies over the major part of the northeast monsoon region, an increase in the north–south temperature gradient and the strengthening of the subtropical westerly jet over north India are responsible for the enhancement of northeast monsoon rainfall over SP India in the global warming period. Surplus rainfall in active monsoon epochs releases abundant amounts of latent heat energy into the atmospheric system. This enhances the north–south temperature gradient, which facilitates an intensified subtropical westerly jet over India. During the global warming era, an unequal warming takes place over the northern and southern latitudes. The high meridional temperature gradient on the sea surface is due to the high warming rates over the lower latitudes and less warming rates over higher latitudes. This strengthens the northeast monsoon flow and facilitates more moisture transport from northern latitudes to southern latitudes. An increase in low rainfall events as well as extreme rainfall events and a decrease in no rainfall events as well as moderate rainfall events are associated with active rainfall events. The influence of all these type of events results in a net increase of rainfall activity over SP India (Naidu et al., 2012).

Positive/negative phases of the Indian Ocean dipole mode result in enhanced/reduced northeast monsoon rainfall activity (Kripalani and Kumar, 2004). Kumar et al. (2007) stated that the ENSO significantly influences the interannual variability of northeast monsoon rainfall. Unlike the southwest monsoon, the northeast monsoon rainfall is enhanced during warm ENSO events, and vice versa. The positive relationship between ENSO and northeast monsoon rainfall over South Asia is robust over recent years. According to Kumar et al. (2007), this secular variation of the relationship is due to epochal changes in the tropospheric circulation associated with ENSO over this region. In south India, the Southern Oscillation Index (Niño-3.4 SST) is negatively (positively) correlated with northeast monsoon rainfall (Ropelewski and Halpert, 1987; Singh and Chattopadhyaya, 1998; Nageswara Rao, 1999; Jayanthi and Govindhachari, 1999). Observations of recent trends in the rainfall amounts in some years over different parts of India demonstrate that two or three extreme events can provide the rainfall which
equals the seasonal rainfall. De *et al.* (1992) stated that spells of above normal rainfall occurred over SP India only in 2 or 3 weeks during the northeast monsoon season even in both normal and/or above normal rainfall seasons.

More attention has been paid by researchers to studies of various aspects of the Indian summer monsoon as it provides 70% of the annual total rainfall. Very few studies have been made on the northeast monsoon over India. The rainfall activity during the northeast monsoon season is crucial for the rabi crop over SP India. In view of the importance of northeast monsoon rainfall, the epochal changes in the northeast monsoon rainfall over SP India with respect to changes in the circulation patterns, outgoing long wave radiation (OLR), sea surface temperature (SST), vertical shear in the zonal wind and latent heat flux were examined. Apart from this, the vertical profiles of zonal wind and frequencies of different rainfall events were studied. Most studies related to epochal changes were made on the summer monsoon and no studies are related to epochal changes of the northeast monsoon. Therefore, an attempt was made to investigate the possible causes of the epochal variability of the northeast monsoon rainfall.

**FIGURE 1**  
(a) Meteorological subdivisions of India (adapted from Aggarwal *et al.*, 2008). (b) Time series of northeast monsoon rainfall anomaly over south peninsular India. (c) Eleven year moving averages of normalized values of northeast monsoon rainfall. (d) Graphical representation of the study region
2 | DATA AND METHODOLOGY

2.1 | Datasets utilized

The area-weighted subdivisional rainfall data for five meteorological subdivisions (coastal Andhra Pradesh, Rayalaseema, Tamil Nadu, Kerala and south interior Karnataka) (Khole and De, 2003; Naidu et al., 2012; Rajeevan et al., 2012) (Figure 1a, adapted from Aggarwal et al., 2008) in the northeast monsoon season (October through December) during 1871–2016 were taken from the website of the Indian Institute of Tropical Meteorology (IITM), Pune, India (www.tropmet.res.in). The high resolution gridded daily rainfall data (Rajeevan et al., 2006) of India Meteorological Department (IMD) with 0.25° × 0.25° resolution were also used. The monthly averaged datasets of latent heat flux, zonal wind at 850 and 200 hPa (Kalnay et al., 1996) and OLR (Liebmann and Smith, 1996) from the National Centers for Atmospheric Prediction and National Center for Atmospheric Research reanalysis datasets were considered. The Extended Reconstructed Sea Surface Temperature version 5 SST data (Huang et al., 2017) with 2° × 2° resolution for the period 1948–2016 were obtained from the National Oceanic and Atmospheric Administration.

2.2 | Methodology

The area comprising the five subdivisions (mentioned above) is considered as SP India. The area-weighted average rainfall for each subdivision of SP India was computed using the IITM subdivisional data. The time series of the northeast monsoon rainfall anomaly (deviation from the mean) is presented in Figure 1b. It shows high fluctuations. In order to smooth the time series, the normalized values were subjected to 11 year moving averages (Figure 1c), which revealed two extreme active epochs (1877–1887 and 2005–2015) and two extreme weak epochs (1899–1909 and 1980–1990). For this study, only the two recent epochs 1980–1990 (weak) and 2005–2015 (active) were chosen. The composite zonal wind circulation patterns during the northeast monsoon season at two pressure levels, 850 hPa (lower troposphere) and 200 hPa (upper troposphere), the latent heat flux and the distribution of OLR in the domain 60° E–100° E, 10° S–40° N were evaluated. Further, the composite of the vertical shear in the zonal wind component between 850 and 200 hPa over the domain 5° N–14° N, 80° E–98° E and the SST for two blocks, 8° N–16° N, 80° E–92° E and 16° N–22° N, 80° E–92° E, over the Bay of Bengal were studied. Further, the composite

![Figure 1](https://example.com/figure1.png)
vertical profiles of zonal wind over the two blocks (5° N–10° N, 80° E–95° E and 27° N–30° N, 50° E–100° E) for the two epochs were analysed. The various regions chosen for different purposes are given in Figure 1d. In addition, the frequencies of rainfall days with different rainfall limits were calculated using high resolution IMD rainfall data (Naidu et al., 2012): (a) zero rain (dry day), (b) 0–20 mm (little rainfall), (c) 20–60 mm (moderate rainfall), (d) 60–100 mm (heavy rainfall) and (e) >100 mm (very heavy rainfall).

3 | RESULTS AND DISCUSSION

3.1 | Rainfall variations

The time series of the northeast monsoon rainfall anomaly over SP India during 1871–2016 shows fluctuations (Figure 1b). The short period oscillations mask long period oscillations. The 11 year running averages of the normalized values reveal epochal changes (Figure 1c). The alternating active and weak monsoon epochs are clearly perceptible. Above the mean monsoon rainfall activity is perceived during 1880–1891, 1914–1945 and 1971–1982, and has been continuing since 1991. Below the mean monsoon rainfall activity is exhibited during 1892–1913, 1946–1970 and 1983–1989. This pinpoints the existence of active/weak monsoon conditions for one to two decades. In the recent past, SP India has experienced an active epoch (2005–2015) and a weak epoch (1980–1990).

The northeast monsoon rainfall in an active monsoon epoch and a weak monsoon epoch, and the mean and differences between these two epochs (rainfall in active epoch minus rainfall in weak epoch) are shown in Figure 2. The five meteorological subdivisions showed an abnormal increase in northeast monsoon rainfall in the active epoch compared to the weak epoch. The differences in rainfall activity between active and weak epochs are high, about 149 mm over Tamil Nadu, 128 mm over Kerala and 60 mm over coastal Andhra Pradesh, Rayalaseema and south interior Karnataka.

3.2 | Sea surface temperature

The Indian Ocean surrounds the southern parts of India. Since a considerable amount of moisture comes from the oceans, it is reasonable to assume that SST anomalies and wind over the oceanic area would have a marked influence on the weather and climate of India and Sri Lanka (Suppiah, 1988). The north–south temperature gradient over the Bay of Bengal from where the mean northeasterlies travel towards the south Indian continent

**FIGURE 2** Northeast monsoon rainfall (mm) over south peninsular India for (a) the active epoch and (b) the weak epoch, (c) the mean rainfall of the northeast monsoon and (d) the difference in the northeast monsoon rainfall (a) minus (b).
has a prominent role in the supply of moisture to the south peninsula during the northeast monsoon season. Hence, the evolution of SSTs from 1948 to 2016 were analysed by considering the Bay of Bengal region as two blocks, 8° N–16° N, 80° E–92° E and 16° N–22° N, 80° E–92° E. Figure 3a (Figure 3b) shows the time series of the southern (northern) block temperatures. The rate of warming over the southern region is 1.6°C per century, while it is relatively less over the northern region, about 1.4°C per century. The north–south temperature gradient
was evaluated by subtracting the SST of the northern region from that of the southern region (Figure 3c). The general tendency of this north–south temperature gradient is positive. The presence of positive SST anomalies over the north Indian Ocean could be responsible for the persistence of the intertropical convergence zone over the south peninsula (Rajeevan et al., 2012). An active monsoon epoch shows a higher north–south temperature gradient (0.521°C) than a weak monsoon epoch (0.4056°C). This analysis depicts that the extra warming over the southern block of the Bay of Bengal increases the SST gradient. A greater north–south temperature gradient results in a high pressure difference and then strong winds. As the northeast monsoon is primarily associated with northeasterlies coming from the Siberian high, the SST gradient over the Bay of Bengal enhances the monsoon strength and leads to transportation of greater amounts of moisture towards the northeast monsoon region. This in turn helps in the enrichment of northeast monsoon rainfall during active epochs.

### 3.3 | Zonal wind vertical profile

During the boreal winter in the Northern Hemisphere, a northeasterly wind persists with predominant zonal wind in the upper troposphere between the western Pacific and the Indian Ocean. Hence, the composite vertical profile of zonal wind for the active and weak monsoon epochs over the domain 27° N–30° N, 50° E–100° E was studied, where the mean winter subtropical westerly jet is present (Figure 4a). In the lower levels, the strength of the zonal wind is more or less the same for both active and weak monsoon epochs. In the layer 800–700 hPa, the westerlies are stronger for the weak monsoon epoch. After that, in the layer 600–400 hPa the zonal wind is more or less the same for both cases. However, in the layer 400–150 hPa the westerlies are dominant in the active monsoon epoch. The subtropical westerly jet in the active monsoon epoch is more intense than in the weak monsoon epoch. This is closely connected with rainfall activity. Generally, high rainfall amounts lead to the liberation of excess latent heat into the atmosphere. This results in a greater north–south temperature gradient and hence an intensified subtropical westerly jet stream. It seems that the variations of the northeast monsoon rainfall induce the strengthening of the subtropical westerly jet stream in the upper troposphere.

The maximum wind reversal and the rainfall happen apace with this wind change over 10° S–10° N during winter (Chan and Li, 2004). The composite vertical structures of the zonal wind were analysed for the averaged domain 5° N–10° N, 80° E–95° E during the active and weak monsoon epochs (Figure 4b). From the surface to the 300 hPa level, the easterlies are prominent in the active epoch compared to the weak epoch. From 300 to 150 hPa, the easterlies in the active monsoon are relatively weak. This figure clearly indicates that the vertical wind shear between the 850 and 200 hPa levels in the active epoch is less than in the weak epoch. According to Gouda and Goswami (2016), over the Indian summer monsoon domain, area-averaged shear drops sharply, creating an environment conducive for cloud formation (low ventilation) over the Indian summer monsoon domain. In a similar way, the low vertical wind shear over SP India during the active epoch creates more cloud
formation than the weak epoch. This is consistent with low OLR values over the northeast monsoon region during the active epoch.

### 3.4 | Zonal wind distribution

The composite zonal wind distributions for both active and weak monsoon epochs at two pressure levels, 850 and 200 hPa, and their differences (active minus weak) are presented in Figures 5 and 6. During the active monsoon epoch, easterlies are prominent at the 850 hPa level over Tamil Nadu compared to the weak monsoon epoch. At the 200 hPa level, the subtropical westerly jet over north India is predominant in the active monsoon epoch. The enhancement of northeast monsoon rainfall over SP India in the global warming period is associated with intensification of the easterly belt in the lower troposphere over the major part of the northeast monsoon region of India and the strengthening of the subtropical westerly jet over India (according to Naidu et al. 2010; 2012). In the active monsoon epoch, the highly intensified easterly wind in the lower troposphere and the subtropical westerly jet in the upper troposphere are associated with surplus rainfall. The reverse condition is true for the weak monsoon epoch.

### 3.5 | Latent heat flux

The latent heat release from this area can be considered as the major planetary heat source that runs the global
circulation during boreal winter. Hence, the latent heat exchange at the ocean surface is an important mechanism for transferring heat from ocean to atmosphere. To assess the influence of the latent heat flux upon the northeast monsoon rainfall variations during active and weak epochs, the latent heat flux over the Bay of Bengal was analysed. The composite latent heat flux distributions over the Bay of Bengal in the active and weak monsoons and their differences (active minus weak) are shown in Figure 7. Latent heat flux values are dominant in the active monsoon epoch over the major part of the north Bay of Bengal and southeastern parts of the Arabian Sea. They are high particularly over the eastern part of the Bay of Bengal. The major part of the western Bay of Bengal shows less magnitude in the active monsoon epoch. In active monsoons, a good amount of moisture is available for transportation towards SP India. Strong anomalies in the zonal winds particularly in the southern latitudes of India facilitate the transportation of good amounts of moisture from the Bay of Bengal towards the northeast monsoon regime of India.

3.6 | Outgoing long wave radiation (OLR)

The composite OLR distributions for the two epochs 1980–1990 and 2005–2015 and their differences (active minus weak) are presented in Figure 8. In the active epoch, the OLR values are lower by about 10 W·m$^{-2}$
than in the weak epoch over the SP region. The OLR values are 235 W·m⁻² over the southeastern parts of Tamil Nadu in the weak epoch but 225 W·m⁻² in the active epoch. In the epoch 1980–1990, OLR values over Tamil Nadu and Kerala range from 235 to 250 W·m⁻², whereas in the epoch 2005–2015 these values are reduced to 225–240 W·m⁻². The OLR values in the weak monsoon epoch are 255–270 W·m⁻² over south interior Karnataka and 250–265 W·m⁻² over Rayalaseema and coastal Andhra Pradesh; in the active epoch, the values are decreased to 245–265 W·m⁻² over south interior Karnataka, Rayalaseema, and coastal Andhra Pradesh. The difference in the OLR values between the active and weak epochs is −14 W·m⁻² over the southern tip of Tamil Nadu and −10 W·m⁻² over Kerala, Tamil Nadu (except the northeastern parts) and southwestern parts of Rayalaseema. The difference is −8 to −4 W·m⁻² over northeastern parts of Tamil Nadu, southern parts of coastal Andhra Pradesh, southern parts of south interior Karnataka and northern parts of Rayalaseema. A high magnitude difference (about −6 to −14 W·m⁻²) between the active and weak epochs is noticed over the northeast monsoon regime. The physically consistent decrease in OLR over the equatorial Indian Ocean and peninsular India suggests that the increase in the NEMR over these regions is realistic (Prakash et al., 2013). Overall, the low OLR values over SP India in the active monsoons indicate more convective activity over this region and suggest a positive rainfall anomaly.
3.7 Wind shear

The time series of the zonal wind at 850 hPa for the domain 5° N–14° N, 80° E–98° E is presented in Figure 9a. The magnitude of the easterlies at this level increases at a rate of 0.019 m·s⁻¹ per year. The time series of the zonal wind at 200 hPa for the domain 5° N–14° N, 80° E–98° E is presented in Figure 9b. The magnitude of the easterlies decreases at a rate of 0.022 m·s⁻¹ per year. Figure 9c represents the time series of the vertical shear in the zonal wind for the above domain. The magnitude of the shear decreases with time in the global warming period. The active monsoon epoch has low vertical wind shear (−5.27 m·s⁻¹), while the weak monsoon epoch has comparatively high wind shear (−5.67 m·s⁻¹). From Figures 1c and 9c, it is clear that the decreased vertical wind shear is associated with increased rainfall amounts. As discussed by Gray (1979), observational evidence clearly shows that tropical cyclones form under conditions of very small vertical wind shear of horizontal wind between the lower and upper troposphere. During the active epoch, low vertical shear over the Bay of Bengal is more favourable for the formation of more tropical cyclonic systems. The increase in cyclone frequency in the Bay of Bengal and steady warming of the Indian Ocean may be the cause behind the rainfall increase (Prakash et al., 2013).
3.8 Mean frequencies of different rainfall limits in active and weak northeast monsoon epochs

3.8.1 Frequency of dry days

The mean frequencies of dry days over SP India in the active and weak northeast monsoon epochs are depicted in Figure 10. In the active monsoon epoch, the mean frequency is very high over the north and northeastern parts of south interior Karnataka (72–76 days per season) and very low frequencies of 40 days are observed over the southern parts of Kerala; moderate frequencies are seen over north and northwestern parts of Rayalaseema and the northern parts of coastal Andhra Pradesh, and the second lowest frequencies are observed over central coastal parts of Tamil Nadu (44–48 days per season). However, in the case of the weak epoch, the frequency of no rain days increases to 80 days per season over the northeastern parts of south interior Karnataka and the north and northwestern parts of Rayalaseema, and the frequencies over Kerala, Tamil Nadu and northern parts of coastal Andhra Pradesh are also increased. The frequency of dry days is increased by 9 days per season from the active epoch to the weak epoch over southern and southeastern parts of south interior Karnataka, southwest and northwestern parts of Rayalaseema and some parts of the central and northern Tamil Nadu region. The differences in the frequencies (active minus weak) are negative particularly over the major part of SP India. This indicates an increase in rainfall days over SP India in the active monsoon epoch.

3.8.2 Frequencies of little rainfall days

The mean frequencies of little rainfall days over SP India in the active and weak northeast monsoon epochs are depicted in Figure 11. The frequency of little rainfall days is greater over southern parts of Kerala, i.e. 38–44 days per season in the active monsoon epoch and 40 days in the weak monsoon epoch. It is 30–36 days in the active epoch and 26–34 days in the weak epoch over Tamil Nadu and 20–28 days in the active epoch and 14–20 days in the weak epoch over southern parts of south interior Karnataka. In the active epoch, the frequency is 14–18 days over...
northern parts of south interior Karnataka. It is 30 days over southeastern parts of Rayalaseema and decreases towards northern parts. It is 26–22 days over the southernmost parts of coastal Andhra Pradesh and becomes low towards northern regions.

The differences in frequency (active minus weak) are positive over SP India. The differences are high over interior parts of SP India. The frequency of little rainfall days is markedly high in active monsoons compared to weak monsoons.

### 3.8.3 Frequencies of moderate rainfall days

The mean frequencies of moderate rainfall days over SP India in the active and weak northeast monsoon epochs are depicted in Figure 12. In the active epoch, the moderate rainfall days are very high (more than 10 days) over southernmost parts of Kerala compared with the weak epoch. Over Tamil Nadu, the frequencies range from 8 to 10 days across the coastal regions and are reduced to 4 days away from the coast. There are only 2–3 moderate rainfall days over south interior Karnataka and Rayalaseema excluding southeastern parts of Rayalaseema (reaches 5–8 days) and southwestern parts of south interior Karnataka (reaches 4.5 days). The frequency over Andhra Pradesh decreases from southern coastal regions to northern coastal regions from 8.5 to 3 days per season. In the weak monsoon epoch, the moderate rainy days are comparatively lower than in the active epoch. Over southernmost parts of Kerala they are about 7 days and over coastal parts of Tamil Nadu they reduce to 7.5 days except for the central part of the Tamil Nadu coast.
The differences in frequency (active minus weak) are positive over the northeast monsoon region. The differences are high (about 2 days) over the coastal regions of SP India. The frequency of the moderate rainfall days is reasonably high in active monsoons compared to weak monsoons.

3.8.4 Frequencies of heavy rainfall days

The mean frequencies of heavy rainfall days over SP India in the active and weak epochs are depicted in Figure 13. The distribution of the differences in the frequency (active minus weak) is positive over the northeast monsoon region. The differences are high over the interior parts of SP India. The frequency of heavy rainfall days is markedly high in active monsoons compared to weak monsoons.

In the active monsoon epoch, heavy rainfall events are more over coastal regions, in particular over the eastern coast. The frequency of heavy rainfall is up to 2.7 days per season over Tamil Nadu, especially over northern parts of the Tamil Nadu coast and southernmost parts of coastal Andhra Pradesh. It is 2 days per season over northern parts of coastal Andhra Pradesh and Kerala. The frequency of heavy rainfall days is 1.1–1.2 days over south interior Karnataka and Rayalaseema excluding eastern parts. In the weak epoch, the frequencies reach 2.6 days per season over the grid points 77 °E, 10 °N, 79.5 °E, 10.5 °N and 82.5 °E, 18.5 °N only. The frequencies of heavy rain are 2–2.5 days per season over northern and southern parts of coastal Andhra Pradesh. The frequency is 1.1–1.2 days over Kerala, south interior Karnataka, Rayalaseema and central parts of Tamil Nadu. Heavy rainfall events are 1.7–2 days per season.
over western parts of Tamil Nadu, the southern tip of SP India and southwestern parts of south interior Karnataka. The frequencies are lower over all subdivisions of SP India. In the weak monsoon epoch, heavy rainfall days are less over coastal regions. The frequency difference between active and weak is more (up to 1.4 days per season) over northern parts of the Tamil Nadu coast. It is 0.3–0.9 days over northern parts of coastal Andhra Pradesh and Kerala and 0.9 days over southern parts of coastal Andhra Pradesh. It is 0.2–0.7 days over southern and western parts of Tamil Nadu.

### 3.8.5 Frequencies of very heavy rainfall days

The mean frequencies of very heavy rainfall days over SP India in the active and weak epochs are depicted in Figure 14. In the active monsoon epoch, very heavy rainfall events are concentrated with a frequency up to 1.6 days per season over northern parts of the Tamil Nadu coast and 0.9–1.35 days over southernmost parts of coastal Andhra Pradesh. Extreme rainfall events range from 0.1 to 0.95 over central parts of coastal Andhra Pradesh, southern parts of Kerala, southeastern parts of Rayalaseema and western parts of Tamil Nadu. In the weak monsoon epoch, the frequency of extreme rainfall days is reduced and is 1.5 days per season over the Chennai region, 0.1–0.7 days over northern and central parts of coastal Andhra Pradesh and 1.35 over southernmost parts of coastal Andhra Pradesh. The frequency difference between active and weak monsoon epochs is 0.05–1 over northern parts of the Tamil Nadu coast, southeastern parts of Rayalaseema and central and southernmost parts of coastal Andhra Pradesh. It is 0.05–0.5 over northern parts of coastal Andhra Pradesh.
The differences in the frequency (active minus weak) are positive particularly over the northern coast of Tamil Nadu and over coastal Andhra Pradesh. The enhanced rainfall activity in the active monsoon epoch over SP India is due to the enhanced frequency of very heavy rainfall events.

4 | CONCLUSIONS

The present study reveals two extreme active epochs (1877–1887 and 2005–2015) and two extreme weak epochs (1899–1909 and 1980–1990). Of these, the most recent epochs 2005–2015 (active) and 1980–1990 (weak) were used to examine the factors responsible for the northeast monsoon rainfall variability.

The analysis of long-term rainfall over south peninsular (SP) India pinpoints the existence of active/weak monsoon conditions for every one to two decades. The five meteorological subdivisions showed an abnormal increase (decrease) in the northeast monsoon rainfall during the active (weak) epoch.

The general tendency of the north–south temperature gradient over the Bay of Bengal is positive during 1948–2016. A higher north–south temperature gradient during the active monsoon epoch (0.521°C) than the weak monsoon epoch (0.406°C) was found. The analysis shows that the extra warming over the southern block of the Bay of Bengal increases the north–south temperature gradient which helps to increase the moisture transport from northern latitudes to southern latitudes and enhances monsoon activity over SP India.
An intensified subtropical westerly jet is observed during the active monsoon epoch compared to the weak monsoon epoch. It seems that the variations of the northeast monsoon rainfall induce a strengthening of the subtropical westerly jet stream in the global warming period. During the active monsoon epoch, easterlies are prominent at the 850 hPa level over the southern tip of Tamil Nadu compared to the weak monsoon epoch.

In the active monsoon epoch, a good amount of moisture is available for transportation towards SP India. Strong easterlies in the southern tip of India facilitate the transportation of good amounts of moisture from the Bay of Bengal towards the northeast monsoon regime of India. Also low outgoing long wave radiation values over SP India in the active monsoon epoch indicate more convective activity over this region. This further supports rainfall activity.

The active monsoon epoch has a low vertical wind shear ($-5.27$ m s$^{-1}$), while the weak monsoon epoch has comparatively high shear ($-5.67$ m s$^{-1}$) over the SP region. Low vertical shear in the zonal component is a favourable condition for the formation of intensified tropical cyclonic systems, which in turn suggests active monsoon conditions. The enhanced rainfall activity in the active monsoon epoch over SP India is also associated with the rainfall frequencies.

An enhanced frequency of very heavy, heavy, moderate and little rainfall events and a reduction in the number of no rainfall days are also responsible for high rainfall in the active monsoon epoch.
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REFERENCES
Aggarwal, P.K., Hebbar, K.B., Venugopalan, M.V., Rani, S., Bala, A., Biswal, A. and Wani, S.P. (2008) Quantification of yield gaps in rain-fed rice, wheat, cotton and mustard in India. Global Theme on Agro Ecosystems, Report no. 43. Patancheru, India: International Crops Research Institute for the Semi-Arid Tropics. 36 p.
Chan, J.C.L. and Li, C. (2004) The East Asia winter monsoon. In: Chang, C.P. (Ed.) Eastern Asian Monsoon. Singapore: World Science, pp. 54–106.
Charlotte, B.V., Simon, E.K., George, G., Yesodharan, S. and Ruchith, R.D. (2012) Intra-seasonal oscillation of northeast monsoon over southern peninsular India – an investigation. International Journal of Science, 2(8), 1–22.
Chen, T. and Weng, S. (1999) Inter-annual and intra-seasonal variations in monsoon depressions and their westward-propagating predecessors. Monthly Weather Review, 127, 1005–1020.
De, U.S., Joshi, K.S. and Lele, R.R. (1992) Intra-seasonal variation in circulation and rainfall during northeast monsoon. Vayu Mandal, 22, 103–108.
Gouda, K.C. and Goswami, P. (2016) Organization of vertical shear of wind and daily variability of monsoon rainfall. Meteorology and Atmospheric Physics, 128(5), 565–577.
Gray, W.M. (1979) Hurricanes: their formation structure and likely role in the tropical circulation. In: Shaw, D.B. (Ed.), Meteorology over the Tropical Oceans, Royal Meteorological Society. Grenville Place, Bracknell: James Glashier House. 155–218.
Huang, B., Thorne, P.W., Banzon, V.F., Boyer, T., Chepurin, G., Lawrimore, J.H., Menne, M.J., Smith, T.M., Vose, R.S. and Zhang, H.-M. (2017) Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5), upgrades, validations, and inter-comparisons. Journal of Climate, 30, 8179–8205.
Jayanthi, N. and Govindhachari, S. (1999) El-Nino and northeast monsoon rainfall over Tamil Nadu. Mausam, 50, 2–217.
Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R. and Joseph, D. (1996) The NCEP/NCAR 40 years reanalysis project. Bulletin of the American Meteorological Society, 77, 437–447.
Khole, M. and De, U.S. (2003) A study on northeast monsoon rainfall over India. Mausam, 54(2), 419–426.
Kripalani, R.H. and Kumar, P. (2004) Northeast monsoon rainfall variability over south peninsular India vis-a-vis Indian Ocean dipole mode. International Journal of Climatology, 24, 1267–1282.
Kumar, P., Rupa Kumar, K., Rajeevan, M. and Sahai, A.K. (2007) On the recent strengthening of the relationship between ENSO and northeast monsoon rainfall over South Asia. Climate Dynamics, 28, 649–660.
Liebmann, B. and Smith, C.A. (1996) Description of a complete (interpolated) outgoing longwave radiation dataset. Bulletin of the American Meteorological Society, 77, 1275–1277.
Nageswara Rao, G. (1999) Variations of the SO relationship with summer and winter monsoon rainfall over India. 1872–1993. Journal of Climate, 12, 3486–3495.
Naidu, C.V., Satyanarayana, G.C., Durgalakshmi, K., MalleswaraRao, L., Jeevannounika, G. and Dharma Raju, A. (2012) Changes in the frequencies of northeast monsoon rainy days in the global warming. Global and Planetary Change, 72, 69–72.
Prakash, S., Mahesh, C., Sathiyaamoorthy, V. and Gairola, R.M. (2013) Increasing trend of northeast monsoon rainfall over the equatorial Indian Ocean and peninsular India. Theoretical and Applied Climatology, 112, 185–191.
Rajeevan, M., Bhave, J., Kale, J.D. and Lal, B. (2006) High resolution daily gridded rainfall data for the Indian region: analysis of break and active monsoon spells. Current Science, 91(3), 296–306.
Rajeevan, M., Unnikrishnan, C., Bhave, J., Niranjan, K.K. and Sreekala, P. (2012) Northeast monsoon over India: variability and prediction. Meteorological Applications, 19, 226–236.
Rao Krishna, P.R. and Jagnnathan, P. (1953) A study of the northeast monsoon rainfall of Tamilnadu. Indian Journal of Meteorology and Geophysics, 4, 22–43.
Ropelewski, C.F. and Halpert, M.S. (1987) Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. Monthly Weather Review, 115, 1606–1626.
Singh, G.P. and Chattopadyaya, J. (1998) Influence of some circulation anomalies on Indian northeast monsoon. Mausam, 49, 4–443.
Subbaramayya, I. (1976) The northeast monsoon and the causes of the winter rains of southeast India. The Meteorological Magazine, 105, 153–159.
Suppiah, R. (1988) Relationships between Indian Ocean sea surface temperature and the rainfall of Sri Lanka. Journal of Meteorological Society of Japan, 66, 103–112.
Webster, P.J. (1999) Coupled ocean atmosphere dynamics in Indian Ocean during 1997-98. Nature, 401, 356–360.

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