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ORIGINAL PAPER

Regional variabilities of rainfall and convective parameters during the summer monsoon period: their linkage with El Niño Southern Oscillation

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Abstract
The present study explored the influence of different convective parameters such as lower tropospheric stability (LTS), low and medium cloud covers (LCC and MCC), and convective available potential energy (CAPE) on the regional variability of Indian summer monsoon rainfall (ISMR). The variabilities and trends of summer monsoon rainfall over the west coast (WC), central India (CI), northeast (NE) and northwest (NW) regions of India were analyzed during the period 1979–2015. The linkage of convective parameters and ISMR with ENSO were also examined based on spatial and 21-year sliding correlations. The ISMR shows considerable regional variability with maximum (moderate) rainfall in the WC and NE regions (CI) and minimum in the NW regions. The ISMR shows an increasing trend in all four regions, except in the NE region, where the trend is negative. All the convective parameters exhibit significant trends; however, the trend values highly vary from one region to another. A positive correlation is observed between LTS and ISMR in the WC and CI regions. The increase in specific humidity or LTS may cause more moisture to be trapped within the lower levels which increases the low-level clouds and thus rainfall. The rainfall and CAPE are exhibiting an in-phase (out-of-phase) relationship over the WC and NW (WC and CI) regions. The out-of-phase relationship may be due to the high and low orographic influence over the WC and CI regions, respectively. Both the LCC and MCC are positively correlated with ISMR over all regions; however, a robust relationship is observed in the case of LCC. An out-of-phase relationship between Niño 3.4 index with rainfall and LCC is observed over most of the Indian regions during the summer monsoon season. However, an out-of-phase relationship is observed between Niño 3.4 index and LTS over the eastern and southeastern parts of the country. On the other hand, in the case of CAPE, a significant out-of-phase relationship is dominated only over the CI region.

1 Introduction

In India, most of the annual rainfall is contributed by the summer monsoon which is from June to September (Parthasarathy and Pant 1985). The Indian summer monsoon rainfall (ISMR) exhibits significant variabilities in temporal and spatial domains (Mooley and Parthasarathy 1983; Varikoden and Preethi 2013; Hrudya et al. 2020a). On the spatial domain, the rainfall is highly varying from region to region with the maximum amount in the west coast and northeast regions, moderate amount in the central Indian region and the least in the northwest and southeast regions (Rao 1976; Rajeevan et al. 2006; Nair et al. 2018). Several studies have been made in recent decades to understand the variabilities and trends of summer monsoon rainfall on the regional scale over the Indian subcontinent (Goswami et al. 2006; Rajeevan et al. 2008; Guhathakurtha and Rajeevan 2008; Konwar et al. 2012; Guhathakurta et al. 2014; Sinha et al. 2014; Varikoden et al. 2013; Cash et al. 2015; Kishore et al. 2015; Ghosh et al. 2012, 2016; Paul et al. 2018; Fukushima et al. 2019; Varikoden and Revadekar 2019). The spatio-temporal variabilities of ISMR for the period 1901–2007 were studied by Kishore et al. (2015). They found a significant positive (negative) trend in rainfall over northeast and west coastal regions (the western Himalayas and north-central regions). Similarly, the regional variations of monsoon rainfall over the Western Ghats, the Ganges basin, the

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Bay of Bengal and Bangladesh-northeastern India for the period 1979–2009 were analyzed by Cash et al. (2015). They observed that rainfall varies independently in these regions since the correlations were insignificant among the regions. Guhathakurtha and Rajeevan (2008) reported insignificant linear trends for ISMR over the Indian region; however, significant trends are noticed on a regional scale during the period 1901–2003. Similar results were also reported by Varikoden et al. (2013). They also reported the different variabilities and trends in different intensity ranges over different regions of the Indian subcontinent. Guhathakurtha et al. (2014) also examined the linear trends over the northwest, central, northeast and peninsular Indian regions during pre-50 and post-50 periods. They found significant changes in the characteristics of the trends in all the regions. In a study by Ghosh et al. (2016), it was reported that the spatial variability of mean summer monsoon rainfall is decreasing over the Indian regions; however, the variability of extreme rainfall events is increasing during the period 1951–2004. The duration and spatial coverage of ISMR was found to be decreasing during the period 1951–2003 (Ramesh and Goswami 2007).

It is known that the ISMR is associated with mesoscale convective systems having high spatio-temporal variability (Revadekar et al. 2016; Jayakumar et al. 2017). Therefore, identifying the influence of convective systems on the variability of ISMR, especially on a regional scale is important. The convective parameters that are mainly contributing to the rainfall variations over the Indian region include the cloud cover, lower-tropospheric stability (LTS), and convective available potential energy (CAPE). The total cloud cover is classified as low, medium and high cloud covers depends upon their vertical extend. Pokhrel and Sikka (2013) reported that about 99% of the total rainfall during the summer monsoon season is contributed by the stratiform and convective clouds. However, Sreekanth et al. (2019) classified the clouds as stratiform, convective, transition and mixed clouds and they reported that the stratiform and convective rainfall together contributes only about 65% and the remaining rainfall is contributed by the transition and mixed rains during the summer monsoon period.

The low-level stratiform cloud frequency has a significant positive correlation with LTS during the Indian summer monsoon (Varikoden et al. 2011). LTS was defined as the difference in potential temperature between 700 h Pa and the surface (1000 h Pa, Slingo 1987; Klien and Hartmann 1993; Wood and Hartmann 2006; Varikoden et al. 2011). LTS is considered as a measure of the strength of inversion that caps the planetary boundary layer (Wood and Bretherton 2006) and its variations have a major impact on stratiform low cloud fraction and thus the regional rainfall (Zhang et al. 2009). The variations in monsoon rainfall are also influenced by CAPE, which is considered as the positive buoyancy to be available for an air parcel to rise. The consumption of CAPE is associated with convective activity (Jain et al. 2019) and is essential for the formation of convective clouds. The association between CAPE and summer monsoon rainfall over central India and the Bay of Bengal (BoB) on a diurnal scale was studied by Jain et al. (2019). They found that the maximum CAPE occurs six hours prior to the precipitation over land (i.e., central India) and 3 h prior to the precipitation over the BoB. Mani et al. (2009) reported a significant increase in CAPE during the summer monsoon over central India during the period 1901–2004 and they attributed this to the increase in convective instability of the atmosphere.

Even though many studies have been carried out to study the regional variability of ISMR, the influence from different convective parameters on the regional rainfall variations has not been fully explored. In this context, the present study aims to explore the regional variability of summer monsoon rainfall over the west coast, northeast, central and northwest regions of India during the period 1979–2015, by identifying its relationship with LTS, cloud cover at different heights and CAPE. Here we are trying to study the variability and trends of the summer monsoon and convective parameters over different Indian regions as well as to establish a linkage between these convective parameters and regional rainfall. The study also aims to examine the association between ISMR and convective parameters with El Niño Southern Oscillation (ENSO). The paper is organized as follows. Data and methodology of the study are described in Sect. 2. Results and discussions are presented in Sect. 3 and the main conclusions are summarized in Sect. 4.

2 Data and methodology

For the present study, we have utilized the monthly reanalysis data for potential temperature from the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) with a spatial resolution of 2.5° latitude × 2.5° longitude grid (Kalnay et al. 1996) for the period 1979–2015. The NCEP/NCAR reanalysis project is using a data assimilation system using past data from 1948 to the present in which the potential temperature data is available over 17 atmospheric pressure levels. Following the previous studies (Slingo 1987; Klien and Hartmann 1993; Wood and Hartmann 2006), the lower tropospheric stability (LTS) was calculated as the difference in potential temperature between 700 h Pa and the surface (1000 h Pa). i.e., $\mathrm{LTS} = \Theta_{700} – \Theta_{1000}$, where Θ is the potential temperature.

Monthly rainfall data from climate research unit (CRU, Harris et al. 2014) with 0.5° × 0.5° grid spatial resolution for the same period was also used in this study. The CRU monthly datasets of rainfall were formed by interpolating the rainfall anomalies (base period: 1961–1990) observed at different meteorological stations across the world's land areas into a 0.5° × 0.5° grid cells and combined with the existing climatology. The resulted precipitation data set is found to be well correlated with the existing observational datasets (Harris et al. 2014).

We have also utilized the ERA-Interim monthly reanalysis data with 0.75° × 0.75° grid spatial resolution (Dee et al. 2011) for cloud cover (low cloud cover (LCC), medium cloud cover (MCC), and high cloud cover (HCC)), and convective available potential energy (CAPE) for the period 1979–2015. The data were accessed from the European Centre for Medium-Range Weather Forecast (ECMWF). The Niño 3.4 index (sea surface temperature anomaly over the Niño 3.4 region, i. e, 5° N–5° S, 170°–120° W) was obtained from the climate prediction centre, NOAA (http://www.cpc.ncep.noaa.gov). For better accuracy, all the datasets were interpolated to a common spatial resolution of 0.25° × 0.25° latitude–longitude grid resolution.

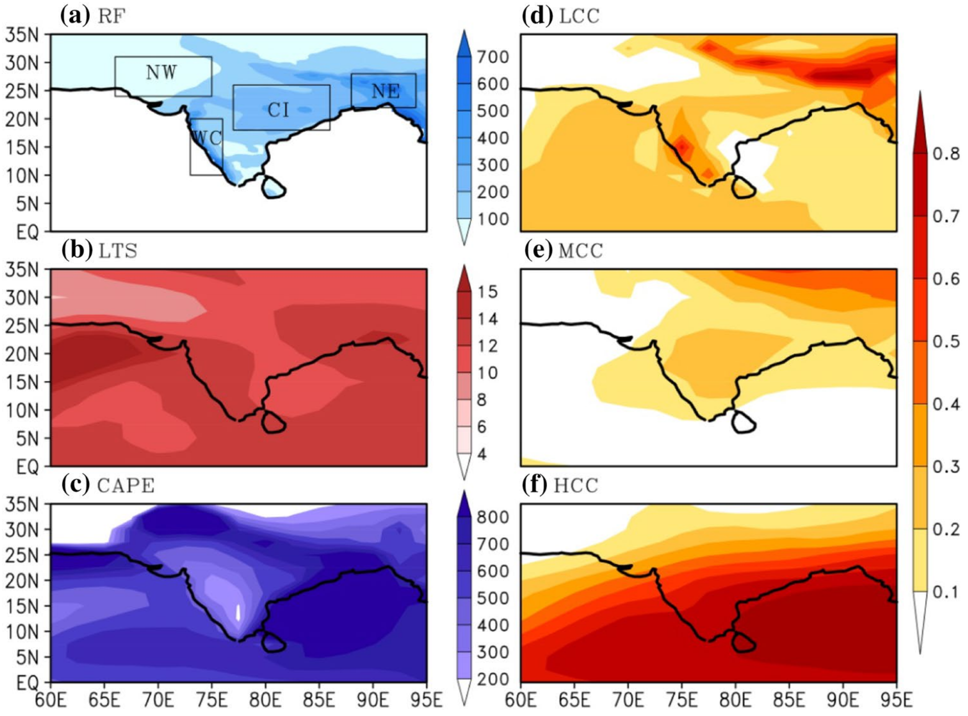
Based on the difference in rainfall characteristics, we have considered four different regions of India; west coast (WC: 73°–76° E, 10°–20° N), central India (CI: 77°–86° E, 18°–26° N), northeast (NE: 88°–94° E, 22°–28° N), and northwest (NW: 66°–75° E, 24°–31° N) for the study. The four rainfall regions selected are highlighted as rectangular boxes in Fig. 1a. Since the analysis based on the entire country does not reveal the regional characteristics (Dash et al. 2009), we have carried out the entire analysis separately for each regions. The spatio-temporal variabilities of rainfall, LTS, cloud cover and CAPE along with their trends and correlations were analyzed for each region during the summer monsoon season (June–September) for the period 1979–2015. The statistical significance of trends and correlations were found out using the F test and students's *t*-test, respectively.

3 Results and discussion

3.1 Climatology of rainfall and convective parameters

Figure 1 shows the climatology of rainfall, LTS, CAPE, LCC, MCC and HCC during the summer monsoon season for the period 1979–2015. From the rainfall climatology (Fig. 1a), it is found that northeast and west coastal regions receive maximum rainfall, the foothills of Himalayas and central India receive moderate rainfall whereas northwest and southeast regions receive the least amount of rainfall during the summer monsoon. It is consistent with the results of previous studies (Rajeevan et al. 2006; Kishore et al. 2015; Nair et al. 2018; Suthinkumar et al. 2019). High values of LTS are observed over most of the Indian region during the summer monsoon season, with a noticeable increase of about 14–15 K over the northeast and peninsular regions (Fig. 1b). The northwest region is associated with relatively low LTS values. The distribution of LTS over the northeast, northwest and west coastal regions is similar to that of the rainfall, which indicates the direct relationship between LTS and rainfall over these regions. Most of the Indian regions including the northeast, northwest and central Indian regions

Fig. 1 Climatology of **a** rainfall (mm), **b** LTS (K), **c** CAPE (J kg^{-1}), **d** LCC (Okta), **e** MCC (Okta), and **f** HCC (Okta) during the summer monsoon (June–September) for the period 1979–2015



associated with high values of CAPE (about 700–800 J kg^{-1}) (Fig. 1c). Usually, the convection is likely to occur in the regions with a high value of CAPE (Jain et al. 2019). This is evident from Fig. 1c, that the regions with high values of CAPE (mainly the northeast, central India and foothills of Himalayas) are associated with a high amount of rainfall as shown in Fig. 1a. This association does not hold good in the case of the west coast region, in which relatively low values of CAPE and high values of LTS and rainfall are observed. This contradictory characteristic may be due to the stratiform nature of rainfall over the western Ghats regions (Sreekanth et al. 2019) and convective nature in other regions due to the less influence of orography (Jayakumar et al. 2017). The spatial distribution of LCC (Fig. 1d) shows a good association with rainfall since the high (low) values of LCC is related to the excess (deficit) rainfall. It is also related to the spatial pattern of CAPE, except over the west coast region. The regions of high and low values of LCC are coherent with the regions of high and low values of LTS, respectively, and hence with the rainfall too.

In contrast to LCC, the values of MCC are not dominant over most of the Indian regions; however, considerable variability is observed over the monsoon core zone (Fig. 1e). In general, the analysis shows a good relationship between low and medium cloud covers, LTS and CAPE with regional variability of summer monsoon rainfall. But these relationships can be validated only after analyzing the interannual and regional trends of these parameters and the correlations between them. Since the HCC does not show any relationship with spatial variation of rainfall and does not contribute to the regional rainfall characteristics (Fig. 1f), therefore, we have excluded the HCC for further analysis.

3.2 Annual cycle of rainfall and convective parameters

The monthly time series of rainfall, LTS, CAPE, LCC, and MCC over the four homogenous regions (WC, CI, NE and NW) are shown in Fig. 2. For all four regions, the monthly variations of rainfall have a common trend even though the precipitation amounts vary from one region to another (Fig. 2a). As far as the WC region is considered, the least values of rainfall are observed during winter (January–February) and pre-monsoon (March–April–May) seasons. However, high values are observed during the summer monsoon months, with the peak value of precipitation in July (~ 325 mm). The rainfall decreases after September through the post-monsoon (October–November–December) season. The similar annual cycle is seen in CI region with slightly reduced magnitude, and the peak in rainfall is observed in the month of August (~ 290 mm). The variation of rainfall over NE region is almost similar to that of WC. But an increase in the precipitation amount (peak value of ~ 460 mm during July) is observed throughout the year, except in November and December. Considerable values of precipitation are observed in this region from March to October. In the case of NW region, the amount of precipitation is less while comparing with the other three regions with more rainfall only during the summer monsoon period. In other seasons, the rainfall is observed to be negligible.

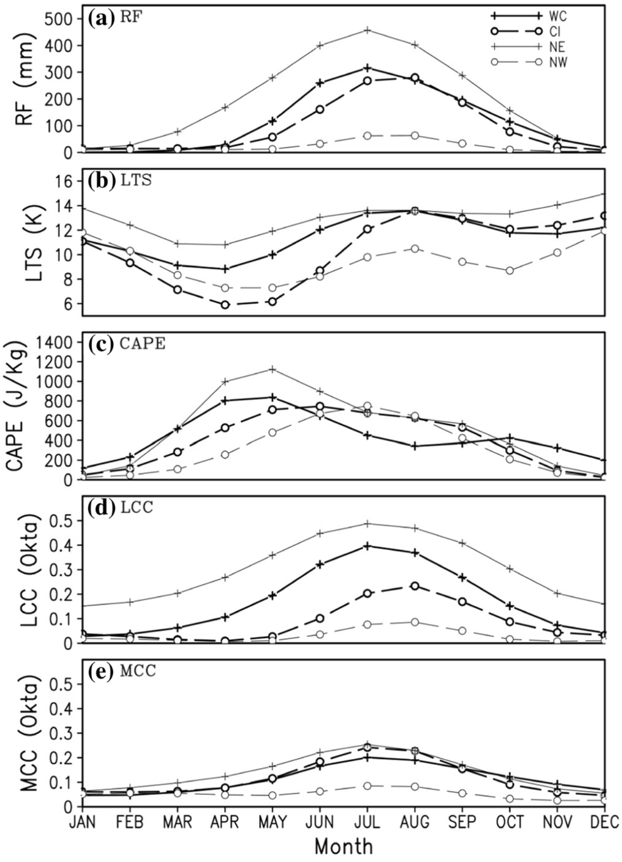


Fig. 2 Annual cycle of **a** rainfall (mm), **b** LTS (K), **c** CAPE (J kg^{-1}), **d** LCC (Okta), and **e** MCC (Okta) over WC, CI, NE, and NW regions for the period 1979–2015

In the case of LTS (Fig. 2b), a common trend in the distribution is observed over all the regions. As in the case of rainfall, LTS is also registered low values over the NW region while comparing with the other three regions. Even though the peak values of LTS are observed during the months of summer monsoon in all the regions, it shows a relative increase in the last two months of the year (November–December). It may be due to the enhancement of moisture content in the lower troposphere during these months as explained by Wood and Bretherton (2006). The variation in LTS during JJAS season is almost similar to that of rainfall for all the regions, but, it is different over other seasons as observed in Fig. 2a.

Figure 2c gives the annual cycle of CAPE (a measure of convection) over different regions of the Indian subcontinent. CAPE is observed to be more prominent over WC and NE during the pre-monsoon period. It may be due to the local convective systems developed by the convective instability of the atmosphere during the season (Murugavel et al. 2012). Over the CI region, CAPE is prominent during May–June and that over the NW region is during July. The annual cycle of CAPE follows the pattern of rainfall in the NW region, which indicates a dominance of convective rainfall over the region. Siingh et al. (2014) has also obtained a significant association between CAPE and convective rainfall over the NW region. The dominance of the convective nature of rainfall over the NW region has also been reported by Narayanan et al. (2013). It is noticed that the variation of CAPE over the WC region during the summer monsoon period is almost opposite to that of rainfall. Therefore, the rainfall in this region may be contributed more from the stratiform type.

In the case of LCC (Fig. 2d), it shows a similar trend in the annual cycle as that of rainfall over all the regions. During the summer monsoon, high values of LCC are observed over WC (peak value of ~ 0.4 Okta in July) and NE (peak value of ~ 0.5 Okta in July) regions. However, moderate values are observed over CI region (peak value of ~ 0.24 Okta in August) and the least values over NW (peak value of ~ 0.1 Okta in August) region. These observed variations during the summer monsoon are directly related to the annual cycle of rainfall (Fig. 2a) and thus the rainfall climatology (Fig. 1a). The monthly variations of MCC (Fig. 2e) show a similar trend as that of LCC over all the regions but with a decrease in their magnitudes. During the summer monsoon, the MCC values are high over the NE and CI regions, slightly decreases in the WC region and becomes the minimum in the NW region. It is also coherent with the climatology of MCC depicted in Fig. 1e. For all the four regions, the peak values of MCC are observed during the month of July (~ 0.2, 0.24, 0.25, and 0.09 Okta for WC, CI, NE and NW regions, respectively). The annual cycle of MCC over all the regions is in good agreement with the observed annual cycle and the spatial patterns of rainfall, especially during the summer monsoon period. Such relationships between convective parameters and ISMR can be further explored by studying their interannual variations and correlations among them.

3.3 Interannual variations of rainfall and convective parameters

The year-to-year variations of rainfall, LTS, CAPE, LCC and MCC over WC, CI, NE and NW regions during the summer monsoon season are shown in Fig. 3 and their trend values (per decade) are given in Table 1. The summer monsoon rainfall shows high interannual variability during the period of study over all the four regions with standard deviations of 64.6, 29.4, 59.1 and 15.6 mm over the WC, CI, NE and NW regions (Fig. 3a). These values of standard deviations were obtained by calculating the differences in the precipitation amount from the mean value for each region. The summer monsoon rainfall shows a decreasing trend in NE regions, whereas increasing trends are observed in other three

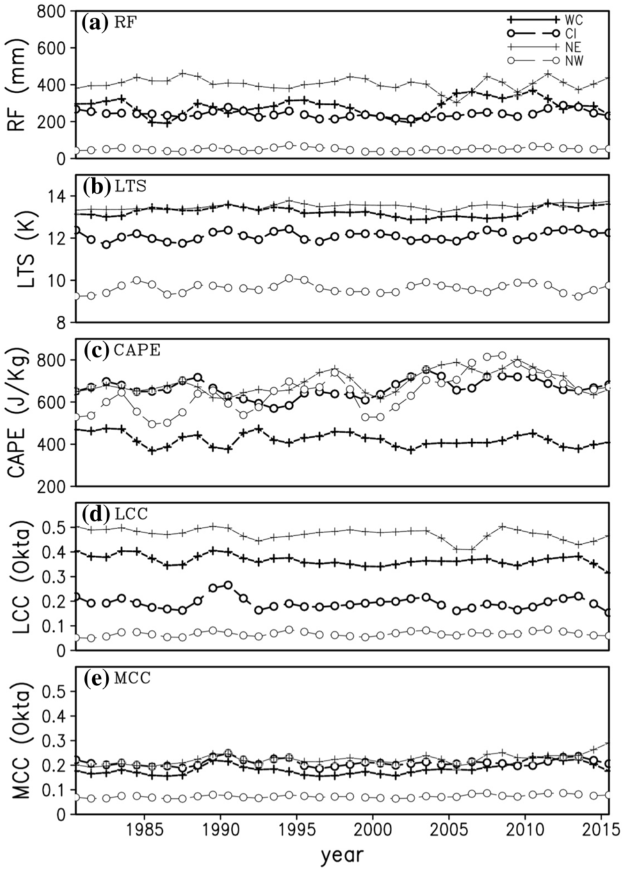


Fig. 3 Interannual variability of **a** rainfall (mm), **b** LTS (K), **c** CAPE (J kg^{-1}), **d** LCC (Okta), and **e** MCC (Okta) over WC, CI, NE, and NW regions during the summer monsoon (June–September) for the period 1979–2015

Table 1 The trend values (per decade) of rainfall, LTS, CAPE, LCC and MCC over WC, CI, NE and NW regions during the summer monsoon (June–September) for the period 1979–2015

Variable	WC	CI	NE	NW
RF (mm) LTS (K)	10.24	0.472	− 3.66	1.58
CAPE (J kg^{-1})	0.01	0.063	0.071*	0.019
LCC (Okta)	− 14.78	6.11	16.10**	51.78*
MCC (Okta)	− 0.007**	− 0.001	− 0.007**	0.003**
RF (mm) LTS (K)	0.01*	0.003	0.014*	0.004*

* and ** represent the trend values confident at 95% and 90% levels, respectively

regions. However, the trends are insignificant in all regions considered. The decreasing trend of summer monsoon rainfall in the NE region was also reported by Guhathakurtha et al. (2014) based on the data of post 1950s. However, Varikoden et al. (2013) and Varikoden and Revedekar (2019) found an increasing trend in the NE region and that may be due to the different temporal period they considered. An increasing trend in LTS is observed over all the four regions with a significant trend in the NE region (Fig. 3b).

In the case of CAPE, an increasing trend is noticed in all the regions except in the WC (Fig. 3c), where the trend is negative with a value of -15 J kg^{-1} decade^{-1}. Significant positive trends are observed in the NE and NW regions, whereas the other regions show insignificant trend values. The increasing trend of CAPE over most parts of the Indian regions during post-1980s has been reported by Murugavel et al (2012). They attributed it to the increase in moisture content in the lower troposphere and increasing temperature in the upper troposphere. Significant trends in LCC and MCC are observed over all the regions except over the CI region (Fig. 3d,e). These observed trends in turn reveal the linkage between the rainfall and convective parameters during the summer monsoon. Therefore, it can be further explored by analyzing the correlations between them. The correlation coefficients between summer monsoon rainfall and convective parameters over the WC, CI, NE and NW regions are given in Table 2.

LTS is positively correlated with summer monsoon rainfall over the WC and CI regions, while a negative correlation is observed over the other two regions. However, the correlation values are insignificant in all regions. The increase in specific humidity or inversion strength in the lower troposphere during the summer monsoon causes more moisture within the lower troposphere. It enhances the formation of low-level clouds and thus the rainfall (Varikoden et al. 2011). Such an association between LTS and the cloud cover and thus the rainfall has been extended to the global monsoon domain also. An in-phase relationship between the seasonal cycle of LCC and LTS over different global monsoon domains other than the Indian region was reported in various studies (e.g., Wood and Bretherton 2006; Sun et al. 2011; Naud et al. 2016; Ceppi and Gregory 2017).

Table 2 Correlation coefficients between LTS, CAPE, LCC, and MCC with rainfall over the WC, CI, NE and NW regions during the summer monsoon (June–September) for the period 1979–2015

Variable	WC	CI	NE	NW
LTS (K)	0.234	0.150	-0.039	-0.181
CAPE (J kg^{-1})	0.471*	-0.246	-0.148	0.665
LCC (Okta)	0.313**	0.647	0.362*	0.814
MCC (Okta)	0.424*	0.739	0.330**	0.809

* and ** represent the trend values confident at 95% and 90% levels, respectively

In the case CAPE, the relationship with rainfall is significant only over the WC region. An in-phase relationship is observed over WC and NW regions and this relationship is out-of-phase in other regions. The contrasting nature of correlations between CAPE and rainfall over the WC and CI may be due to the high and low orographic influences over the regions, respectively, as explained in the climatology section. The variations in CAPE are driven by the low-level moisture and inversion strength, which can favour an enhanced cloud cover and rainfall (Murugavel et al. 2012). This relationship is well holding in the case of WC and NW regions. Even though the increase in CAPE is associated with increase in convective activity, the regions of high CAPE need not be always coincide with the regions of high precipitation since the convective inhibition energy (CINE) plays an important role (Jain et al. 2019). This may be attributed as the reason for the out-of-phase relationship between CAPE and rainfall observed over the NE and CI regions. CAPE is significantly correlated with the rainfall characteristics over different regions across the world. However, while some studies show in-phase relationship between CAPE and precipitation (Zawadzki et al. 1981; Monkam 2002), others show an out-of-phase relationship (McBride and Frank 1999). We also found that the LCC during the summer monsoon season is positively correlated with rainfall over all the four regions with a significant correlation over the WC and NE regions. A similar positive correlation is also observed for MCC, with significant values over the WC and NE regions.

3.4 Teleconnections with ENSO

It is well known that the ENSO is a coupled ocean–atmosphere phenomenon in the tropical Pacific Ocean and one of the strongest drivers of ISMR variability (Feba et al. 2018; Seetha et al. 2020). The positive and negative phases of ENSO, namely El Niño and La Niña provide reduced and enhanced rainfall, respectively, to the Indian region (Sikka 1980; Rassmussen and Carpenter 1983; Varikoden and Preethi 2013; Hrudya et al. 2020a, b). It affects global climate and weather events (Guilyardi et al. 2009) and has a significant impact on the monsoon systems of other countries apart from the Indian region (e.g., Nazemosadat and Cordery 2000; Pavia et al. 2006; Cai et al. 2011; Cao et al. 2017).

In this section, we explore the associations between rainfall, LTS, CAPE and cloud cover with ENSO during the summer monsoon season for the period 1979–2015. It is in addition to the regional variability of summer monsoon rainfall and its influence from convective parameters described in the prior sections. Figure 4 shows the spatial

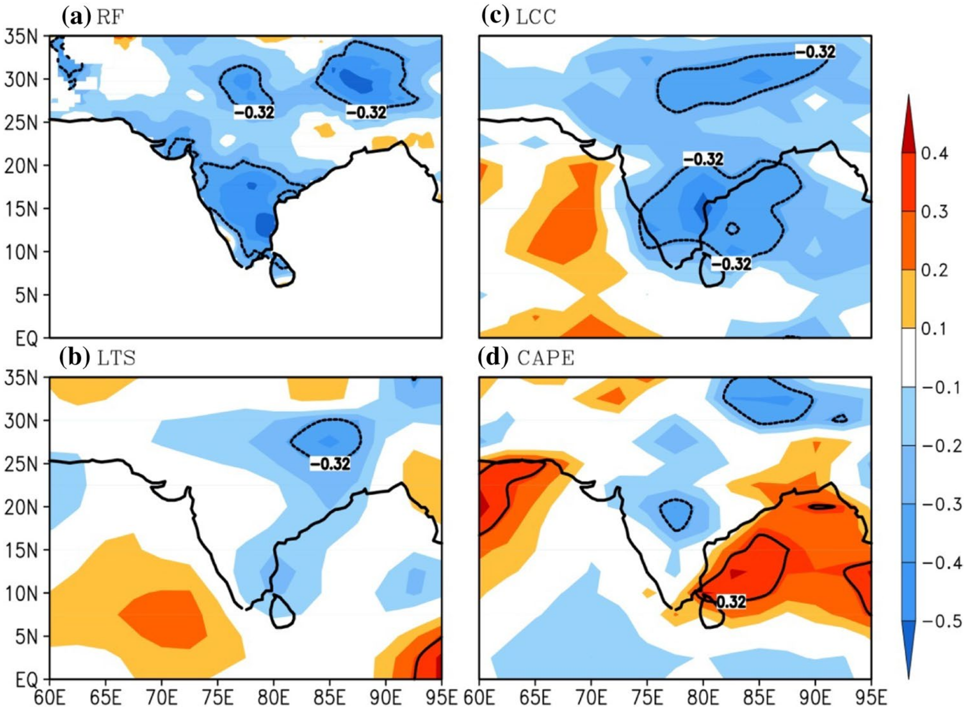


Fig. 4 Spatial correlation between **a** rainfall, **b** LTS, **c** LCC, and **d** CAPE with Niño 3.4 index during the summer monsoon season (June–September) for the period 1979–2015. The contours represent 5% significant level

correlation between rainfall, LTS, LCC and CAPE with Niño 3.4 index during the summer monsoon season. The contours in the figure represent 5% significant level. Since the relationship between LCC and ISMR is more robust than that with MCC, the analysis of MCC was excluded. The ISMR is negatively correlated with Niño 3.4 index over most of the Indian regions with significant correlations over the peninsular and northern regions (Fig. 4a). It is consistent with the previous studies (Mooley and Shukla 1987; Varikoden and Babu 2015; Varikoden and Revadekar 2019) which found a negative ENSO-monsoon correlation over most of the Indian subcontinent during the summer monsoon season. A negative correlation is observed between LTS and Niño 3.4 index over the eastern and southeastern parts of the country, with significant values over some areas of the central-east. However, the western parts of the country do not exhibit any noticeable correlations (Fig. 4b). The negative correlation is dominated over most of the Indian regions for LCC also (Fig. 4c) with significant values over the peninsular and northern regions. However, a relatively weak correlation is observed over the NE region. The correlation between Niño 3.4 index and CAPE shows a different spatial pattern (Fig. 4d), where the CI and NE regions are associated with negative and positive correlations, respectively. Significant negative correlation is observed over some areas of the CI region, whereas the Bay of Bengal and the southeast regions of India show positive correlations. So the analysis altogether indicates a negative correlation between ENSO with rainfall, and LCC during the summer monsoon period over most of the Indian regions. In the case of LTS, the eastern and southeastern parts of the country are associated with an out-of-phase LTS-ENSO relationship and in the case of CAPE, a significant out-of-phase relationship is dominated only in some areas of central India.

To check the consistency of the correlation analysis, we have analysed a 21-year sliding correlation between rainfall, LTS, LCC, and CAPE with Niño 3.4 index during the summer monsoon period (Fig. 5). The spatial correlations described in the earlier section between rainfall, LTS, LCC, and CAPE with Niño 3.4 index is well depicted in the present analysis also. The observed out-of-phase relationship between Niño 3.4 index with rainfall over most of the Indian regions is clearly noticed in Fig. 5a, with some temporal fluctuations. Even though the negative correlation is dominated in all the regions considered, it is relatively weak in the NE region. The out-of-phase relationship is almost consistent since the 1990s up to 2005 in all regions with less significance. This sliding correlation is also found true in the case of LTS (Fig. 5b). The negative relationship between LCC and Niño 3.4 index is dominated over all four regions. It shows an out-of-phase relationship up to 1995; thereafter it turns to in-phase relationship over the WC and NW regions. However, it remains unchanged in the other two regions (Fig. 5c). A different correlation pattern is observed in the case of CAPE (Fig. 5d), in which an out-of-phase relationship is dominated only over the CI region (as observed in Fig. 4d). An in-phase relationship is observed over the NE and NW regions. However, a change from in-phase to out-of-phase relationship after 1995 is observed in the WC region. The different patterns of CAPE-ENSO correlation

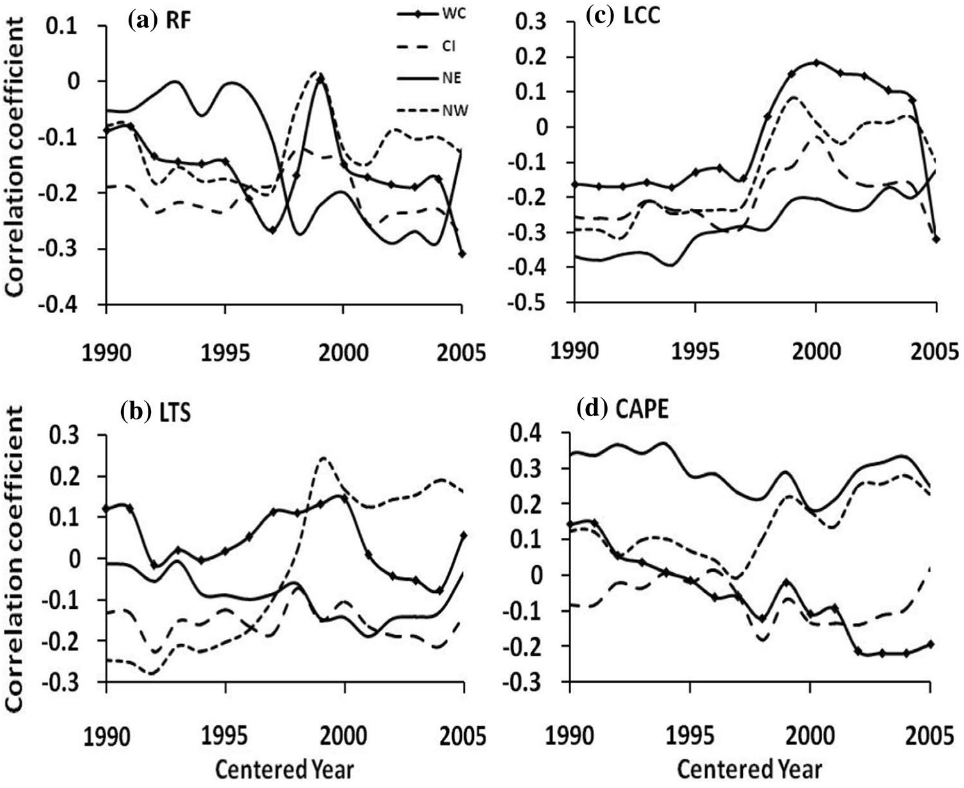


Fig. 5. 21-year sliding correlation between **a** rainfall, **b** LTS, **c** LCC, and **d** CAPE with Niño 3.4 index over WC, CI, NE, and NW regions during summer monsoon season (June–September) for the period 1979–2015

may be due to the influence of other atmospheric and oceanic factors on CAPE, apart from the ENSO. The influence from ocean–atmosphere interactions in the other tropical oceans may also influence the characteristics of CAPE in the atmosphere over the Indian domain.

4 Conclusions

In this study, we have tried to explore the regional variability of ISMR over the WC, CI, NE and NW regions of India during the period 1979–2015 by identifying its relationship with LTS, cloud cover (low and medium) and CAPE. The summer monsoon rainfall exhibits high spatio-temporal variability over all four regions during the period of study. The annual cycle of LTS, LCC and MCC are almost similar to that of rainfall during the summer monsoon season, whereas it is different for the other seasons. But the monthly variations of CAPE over the NW region only show a similar pattern with that of rainfall. CAPE is more prominent over WC and NE regions during the pre-monsoon period and it may be due to the enhanced convective instability of the atmosphere during the season. In the post-monsoon season, the CAPE shows a secondary peak only over the WC region.

The summer monsoon rainfall shows an increasing trend in all the regions, except in the NE, where the trend is negative. LTS shows an increasing trend in all regions, with significant values in the NE region. In the case of CAPE, significant increasing trends are observed in the NE and NW regions, whereas insignificant positive and negative trends are observed in the CI and WC regions, respectively. In the case of LCC and MCC, significant interannual trends are observed in all regions except the CI region. Among all the regions considered, LTS is positively correlated with summer monsoon rainfall in the WC and CI regions. The increase in inversion strength in the lower troposphere during the summer monsoon causes the distribution of more moisture within the lower troposphere. It enhances the low-level clouds and thus the rainfall. An in-phase relationship between CAPE and summer monsoon rainfall is observed over the WC and NW regions, whereas the correlation is out-of-phase over the other regions. Since the increase in CAPE causes an increase in low-level moisture and inversion strength, it can produce an enhanced cloud cover and rainfall. On the other hand, the regions of high CAPE need not be always associated with the regions of high rainfall since the convective inhibition energy (CINE) plays an important role. It can be attributed as the reason for the out-of-phase relationship between CAPE and rainfall observed over the NE and CI regions. A contrasting nature of correlation is observed over the WC and CI regions which may be due to the high and low orographic influences over the WC and CI regions, respectively. Both the LCC and MCC are positively correlated with summer monsoon rainfall over all the regions.

To establish a link between convective parameters and the tropical Pacific, spatial correlation between Niño 3.4 index and convective parameters were analyzed along with that of rainfall. We found a negative correlation between Niño 3.4 index with rainfall, and LCC during summer monsoon over most of the Indian regions; but with a relatively weaker correlation over the NE region. An out-of-phase relationship between LTS and Niño 3.4 index is dominated over the eastern and southeastern parts of the country. The correlation patterns are different in the case of CAPE where a significant in-phase relationship is observed over the Bay of Bengal and southeast regions of the country and an out-of-phase relationship over some areas of the CI region. This different pattern may be due to the influence from other atmospheric and oceanic factors apart from the ENSO. The patterns of sliding correlations between these parameters with Niño 3.4 index have also revealed similar results. A consistent relationship between Niño 3.4 index with rainfall and LTS is observed after 1990s in all regions. In the case of LCC, the out-of-phase relationship with Niño 3.4 index changes to in-phase relationship over the WC and NW regions after 1995. On the other hand, as different from the other parameters, an out-of-phase relationship is dominated only in the CI region in the case of CAPE. However, a change from in-phase to out-of-phase relationship is observed in the WC region after 1995.

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