



Spatial and temporal variability in pre-monsoon convective activity over Telangana, India

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सार – यह अध्ययन 1951 से 2024 तक तेलंगाना, भारत में मानसून-पूर्व संवहनी गतिविधि (Pre-monsoon convective activity) की अंतर-वार्षिक परिवर्तनशीलता की जांच करता है, जो वर्षा वितरण, वर्षा के दिनों और संबद्ध वायुमंडलीय प्रक्रियाओं पर इसके प्रभाव पर केंद्रित है। मार्च-मई (MAM) सीजन के दौरान वर्षा के दिनों का सामान्यीकृत विश्लेषण मजबूत संवहनी वर्षा (SCY) (जैसे, 1951, 1990, 2006, 2015, 2023) में औसत से अधिक मानसून-पूर्व वर्षा गतिविधि और कमजोर संवहनी वर्षा (WCY) (जैसे, 1964, 1965, 1966, 1973, 1984) में औसत से कम वर्षा गतिविधि को प्रकट करता है। हाल के वर्षों में संवहनी गतिविधि के कारण मानसून-पूर्व वर्षा में मामूली रूप से बढ़ती प्रवृत्ति देखी गई है। वायुमंडलीय प्रक्रियाओं की भूमिका को समझने के लिए, वर्षा, वर्षा के दिन, संवहनी उपलब्ध स्थितिज ऊर्जा (CAPE), लंबवत एकीकृत नमी अपसरण (VIMD), कुल क्लाउड कवर (TCC), कुल कॉलम क्लाउड लिक्विड वाटर (TCLW), सौर विकिरण और मिट्टी की जल सामग्री सहित प्रमुख मौसम संबंधी चरों के लिए समग्र विसंगति विश्लेषण (Composite anomaly analysis) किया जाता है। स्थानिक विश्लेषण क्षेत्रीय परिवर्तनशीलता को उजागर करते हैं, जो SCY के दौरान बढ़ी हुई मानसून-पूर्व वर्षा गतिविधि और WCY के दौरान दबी हुई वर्षा गतिविधि को दर्शाते हैं। 850 hPa पर हवा के प्रतिरूप प्रायद्वीपीय भारत में एक महत्वपूर्ण विच्छेदन प्रकट करते हैं, जिसमें SCY के दौरान तीव्र परिसंचरण और WCY के दौरान हवाओं में पूर्व की ओर बदलाव देखा गया है, जो संवहनी गतिविधि को संशोधित करने में वायुमंडलीय गतिकी की भूमिका पर जोर देता है। SCY वर्ष बढ़ी हुई वायुमंडलीय अस्थिरता, नमी अभिसरण, बादलों की स्थिति और मिट्टी की जल सामग्री के साथ-साथ कम सौर विकिरण प्रदर्शित करते हैं, जबकि WCY वर्ष विपरीत प्रवृत्तियाँ दिखाते हैं। ये निष्कर्ष संवहनी गतिविधि को चलाने वाली वायुमंडलीय प्रक्रियाओं के जटिल अंतःसंबंध को रेखांकित करते हैं और क्षेत्रीय जल संसाधन प्रबंधन तथा जलवायु अनुकूलन के लिए महत्वपूर्ण अंतर्दृष्टि प्रदान करते हैं। संवहनी गतिविधि को व्यापक जलवायु कारकों से जोड़कर, यह अध्ययन तेलंगाना में मानसून-पूर्व गतिकी की समझ को बढ़ाता है और चरम मौसम के प्रभावों के पूर्वानुमान और शमन के लिए मूल्यवान इनपुट प्रदान करता है।

ABSTRACT. This study examines the interannual variability of pre-monsoon convective activity over Telangana, India, from 1951 to 2024, focusing on its influence on rainfall distribution, rainy days, and associated atmospheric processes. Normalized analysis of rainy days during the March-May (MAM) season reveals above-average pre-monsoon rainfall activity in Strong Convective Years (SCY) (e.g., 1951, 1990, 2006, 2015, 2023) and below-average rainfall activity in Weak Convective Years (WCY) (e.g., 1964, 1965, 1966, 1973, 1984). A marginally increasing trend in pre-monsoon rainfall due to convective activity is observed in recent years. To understand the role of atmospheric processes, composite anomaly analysis is performed for key meteorological variables, including rainfall, rainy days, Convective Available Potential Energy (CAPE), vertically integrated moisture divergence (VIMD), total cloud cover (TCC), total column cloud liquid water (TCLW), solar radiation, and soil water content. Spatial analyses highlight regional variability, showing enhanced pre-monsoon rainfall activity during SCY and suppressed rainfall activity during WCY. Wind patterns at 850 hPa reveal a significant discontinuity over peninsular India, with intensified circulations during SCY and an eastward shift in winds during WCY, emphasizing the role of atmospheric dynamics in modulating convective activity.

SCY years exhibit increased atmospheric instability, moisture convergence, cloudiness, and soil water content, along with reduced solar radiation, whereas WCY years show opposite trends. These findings underscore the complex interplay of atmospheric processes driving convective activity and offer critical insights for regional water resource management and climate adaptation. By linking convective activity to broader climatic factors, this study enhances the understanding of pre-monsoon dynamics in Telangana and provides valuable input for forecasting and mitigating extreme weather impacts.

Key words – Pre-monsoon rainfall, Convective activity, Total cloud cover, Telangana, CAPE.

1. Introduction

The pre-monsoon period in India, from March to May, is crucial to the nation's hydrometeorological system. As per the India Meteorological Department (IMD), this period makes considerable contributions to the total annual precipitation, especially over southern India, with precipitation between 40–50 cm in south Kerala and 10–20 cm in other parts (Bhowmick *et al.* 2023). Even though it is transitional, pre-monsoon experiences intense convective activity fueled by mesoscale and synoptic-scale systems (Dalal *et al.* 2012; Vinay and Naidu 2020). These convective activities from scattered thunderstorms to composite mesoscale convective systems (MCS) account for more than 90% of pre-monsoon rainfall and are frequently followed by dangerous situations in the form of heavy rain, hail, gusty winds, and lightning (Houze 1977; Puranik and Karekar 2004; Singh and Singh 2015; Bhowmick *et al.* 2023).

The impact of pre-monsoon convection is not limited to meteorology. The events often lead to agricultural loss, infrastructural damage, and deaths. Approximately 80% of thunderstorm-related fatalities in India take place during this season (Bhardwaj *et al.* 2017). In the world, it is estimated that 16 million thunderstorms occur per year (Khan and Arsalan 2007), and the significance of knowing convective mechanisms becomes more important. Thermodynamic processes like Convective Available Potential Energy (CAPE), ground moisture, solar irradiance, and vertical moisture fluxes are at the core of initiating as well as maintaining these systems (Moncrieff and Miller 1976; Murugavel *et al.* 2014; Emanuel 1994; Seneviratne *et al.* 2013). CAPE, in turn, is a primary measure for determining atmospheric instability, while vertically integrated moisture divergence (VIMD) is indicative of moisture transport essential for convective rainfall (Ullah and Gao 2012). Cloud-related parameters, including Total Cloud Cover (TCC) and Total Column Cloud Liquid Water (TCLW), also affect radiative processes and energy balances (Stephens 2005; William *et al.* 2009).

Convective activity is extremely sensitive to local and regional causes. Land surface heating, topography, and wind regimes on a larger scale interact with each other to define the nature, frequency, and magnitude of convective systems (Schneider *et al.* 2018; Riehl and

Malkus 1958). In the Indian subcontinent, the South Peninsular region, particularly Telangana, has heterogeneous terrain and meteorological conditions favouring the generation of convection (Stella and Agnihotri 2015; Agnihotri and Dimri 2018). Disturbances in easterly winds and Pacific typhoon remnants sometimes intensify convection and even lead to tropical cyclones over the Bay of Bengal (Srinivasan *et al.* 1973). Although there are studies on convective variability over the global tropical and subtropical regions like South Asia, Africa, and South America (Houze *et al.* 2015; Romatschke *et al.* 2010; Zuluaga and Houze 2015). Indian studies have primarily been focused on the northeastern states in terms of short-term thunderstorm instances or extreme events (Pramanik 1939; Roy and Chatterji 1929; Sahu *et al.* 2020). As a result, there is a significant lack of long-term climatological studies of pre-monsoon convection, especially over Telangana.

To address this gap, the present study conducts a comprehensive 74-year (1951–2024) climatological assessment of pre-monsoon convective activity over Telangana. Using long-term rainfall and rainy-day datasets, the study classifies years with above-average rainfall as Strong Convective Years (SCY) and those with below-average rainfall as Weak Convective Years (WCY). Composite anomaly analysis is employed to examine key atmospheric and surface variables such as CAPE, VIMD, TCC, TCLW, solar radiation, and soil moisture to understand the mechanisms that drive convective variability. Furthermore, the study explores the role of large-scale atmospheric circulation, including 850 hPa wind patterns, and examines potential teleconnections with global climate drivers such as El Niño–Southern Oscillation (ENSO). By analyzing spatial and temporal patterns, this research enhances our understanding of the long-term trends and variability of pre-monsoon convection in Telangana.

This research delivers new insights on the dynamics of convective systems within a climatically exposed area. The results hold significant implications for disaster risk reduction, agricultural planning, water resource management, and regional climate adaptation planning. This contribution to the current literature incorporates the longer-term observational evidence with dynamic and thermodynamic variables, which aids the expanding research base in monsoon transition stages and facilitates

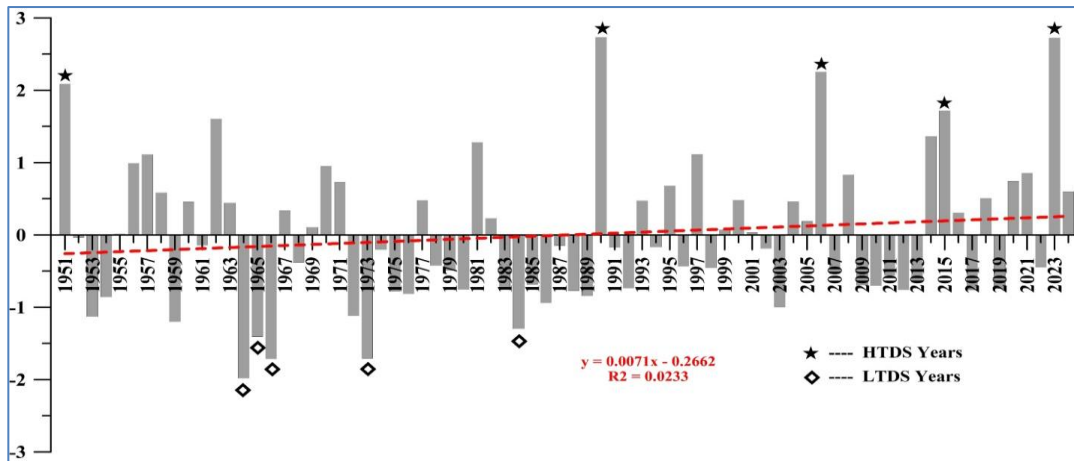


Fig. 1. The Normalized value performance of the Mean Rainy days for the MAM (1951-2024) over the Telangana region

enhanced forecasting of extreme weather conditions within the Indian subcontinent.

2. Data and methodology

We utilized gridded daily rainfall data from the India Meteorological Department (IMD) at a resolution of 0.25 degrees, covering the period from 1951 to 2024. This dataset spans the geographical extent of Telangana, ranging from 15.5° N to 20° N latitude and 77.5° E to 81.5° E longitude. The climatological mean of rainfall and rainy days for the pre-monsoon season (March-April-May, MAM) is calculated. Strong Convective Years (SCY), with more than a normal number of rainy days, five years have been identified as 1951, 1990, 2006, 2015 and 2023 when the normalized mean rainy days are more than 1.5 (Fig. 1). Weak Convective Years (WCY), indicating below-normal rainfall days, are noted in 1964, 1965, 1966, 1973, and 1984 when the normalized mean rainy days are less than 1.5. Composite anomalies for every SCY and WCY year are calculated to analyze the contrasting rainfall and convective activity patterns during these seasons and to look into their climatic and meteorological causes.

The ERA-5 dataset by the European Centre for Medium-Range Weather Forecasts (ECMWF) is the newest European reanalysis dataset generation, providing high-resolution information at a 0.25-degree grid level (Hersbach *et al.* 2020). The all-encompassing dataset was inspected for the pre-monsoon period (March–May, MAM) between 1951 and 2024 to examine fundamental climatic factors that affect weather patterns in Telangana. The research emphasized a variety of atmospheric and surface parameters such as mean 850 hPa winds, Convective Available Potential Energy (CAPE), Vertically Integrated Moisture Divergence (VIMD), Total

Cloud Cover (TCC), Total Column of Cloud Liquid Water (TCLW), solar radiation, average volumetric soil water layer (SWVL), average surface temperature, and total column of vertically integrated water vapour (TCWV). The examination included the spatial distribution and composite anomalies Strong Convective Years (SCY) and Weak Convective Years (WCY) of these variables. This detailed analysis offers critical information regarding the atmospheric instability and land surface processes that generate convective activity and regional climate dynamics over Telangana and aids in appreciating the relationship between climate variability and extreme weather conditions.

3. Results and discussion

The interannual variation of mean rainy days during pre-monsoon from 1951 to 2024 provides insights into fluctuations in rainfall, identifying anomalously wet and dry seasons. This analysis helps to identifying the SCY and WCY and continuing the further analysis. It helps in identifying long-term trends whether the mean rainy days is increasing, decreasing, or fluctuating due to climate variability hence reflect the convective activity. It is essential to understand long-term changes in rainfall patterns, especially for regions like Telangana, where convective systems play a significant role. It is also crucial for agriculture, water resource management, and disaster preparedness by identifying anomalies in pre-monsoon rainfall, which directly affect soil moisture and reservoir levels. Normalization allows for better comparisons across different years and regions, enhancing climate variability assessments.

Fig. 1 presents the normalized mean number of rainy days per year during the pre-monsoon season (March–April–May, MAM) over Telangana from 1951 to 2024.

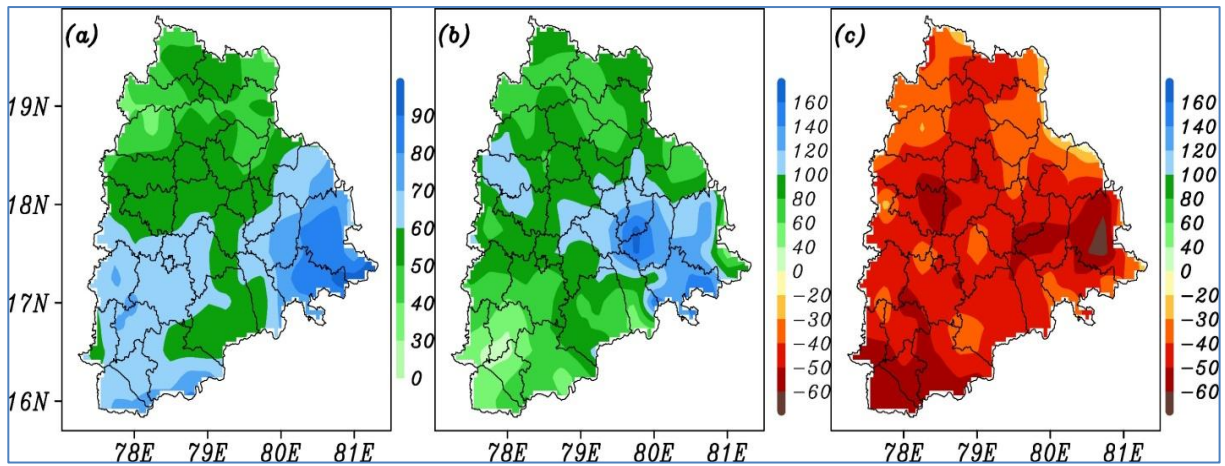


Fig. 2(a-c). The spatial distribution of rainfall (mm) for (a) Mean, (b) Composite anomaly of Strong Convective years and (c) Composite anomaly of Weak Convective years during pre-monsoon from 1951 to 2024

Positive bars indicate years with above-average rainy days, while negative bars represent below-average values.

A red trendline illustrates a marginal increasing trend in recent years. Black stars denote Strong Convective Years (SCY) periods associated with above-average rainfall and rainy days identified in 1951, 1990, 2006, 2015, and 2023. Diamonds indicate Weak Convective Years (WCY) characterized by below-average rainfall and rainy days occurring in 1964, 1965, 1966, 1973, and 1984. These classifications help reveal the interannual variability of convective activity and its influence on rainfall distribution across the region.

The data indicates significant decadal oscillation in pre-monsoon rainfall, indicating variability controlled by larger climatic parameters. Significantly, SCY years are found to have become more frequent since the recent global warming times, which is more likely attributable to climate change. Interestingly, SCY years are found to also overlap primarily with El Niño years, pointing towards a potential teleconnection. For further exploration of spatial variability, the top five SCY and WCY years were analyzed in some detail. This includes spatial patterns of mean rainfall, mean rainy days, and their respective anomalies, offering key insights into the localized impact of convective systems. These findings are essential for understanding pre-monsoon rainfall dynamics in Telangana, especially in the context of climate variability and changing convective behaviour.

3.1. Spatial distribution of rainfall (mm) and rainy days (days/year)

Fig. 2 illustrates the spatial distribution of pre-monsoon rainfall (in mm) across Telangana region for the

period 1951–2024, showcasing three figures. Fig. 2a represents the mean pre-monsoon rainfall, where dark blue areas having rainfall 60 mm to 90 mm indicate regions with higher average rainfall. In comparison, green shades up to 60 mm signify areas with lower rainfall, highlighting spatial variability over the decades. Fig. 2b shows the composite anomaly of SCY years indicating positive anomalies (above-average rainfall), suggesting enhanced rainfall in specific zones during these years over Telangana. Fig. 2c depicts the composite anomaly during low TDS years, dominated by red and orange shades, representing significant negative anomalies and reduced rainfall, which indicate vulnerability to dry conditions. These spatial patterns provide insights into how TDS levels and atmospheric processes influence rainfall variability, which is critical for regional water resource management and understanding climate impacts.

Fig. 3 illustrates the spatial distribution of pre-monsoon rainy days (in days per year) across a region from 1951 to 2024, with three figures representing the mean and composite anomalies during SCY and WCY years. Fig. 3a shows the mean pre-monsoon rainy days, with regions having rainy days 6.5 to 9.5 darker blue shades indicating areas experiencing a higher frequency of rainy days. In contrast, lighter blue and green regions, 0 to 6.5 rainy days signify fewer rainy days, reflecting significant spatial variability. Fig. 3b displays the composite anomaly during SCY years, where blue shades of 4 to 6 rainy days represent strong positive anomalies (more rainy days), and green shades of 1 to 4 rainy days indicate weak positive anomalies (fewer rainy days), suggesting localized increases in rainy day frequency. Fig. 3c depicts the composite anomaly during WCY years, dominated by red and orange shades of the negative magnitude of rainy days, highlighting widespread

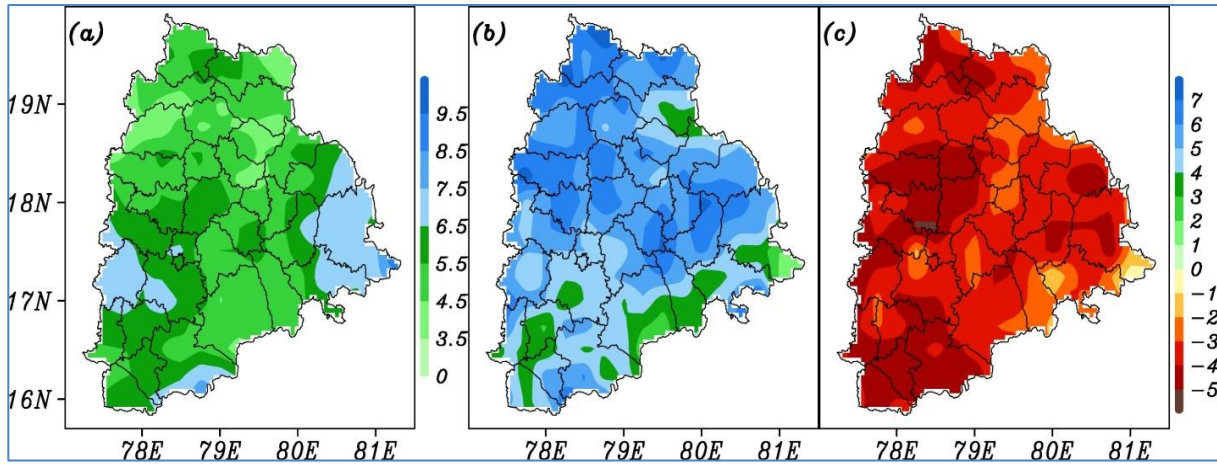


Fig. 3(a-c). The spatial distribution of rainy days (days/year) for (a) Mean, (b) Composite anomaly of High Convective years and (c) Composite anomaly of Weak Convective years during pre-monsoon from 1951 to 2024

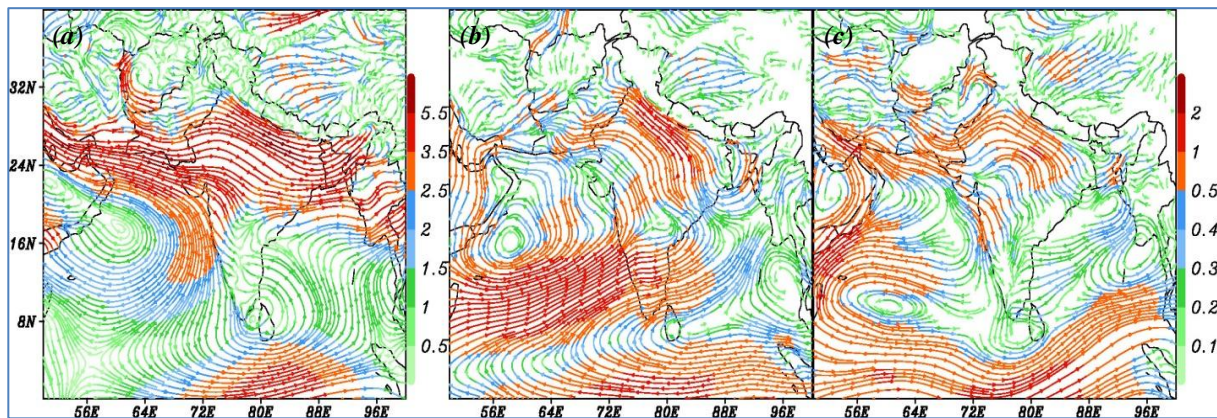


Fig. 4(a-c). The spatial distribution of wind (m s^{-1}) at 850hPa for (a) Mean, (b) Composite anomaly of Strong Convective and (c) Composite anomaly of Weak Convective years, during the pre-monsoon season for the period 1951 to 2024

negative anomalies and significant reductions in rainy days, pointing to drought-prone conditions. This analysis underscores the influence of TDS levels on the frequency of rainy days and its implications for regional water availability and climate adaptation strategies.

3.2. The performance of wind at the lower troposphere (850hPa)

Fig. 4 illustrates the spatial distribution of wind patterns at the 850 hPa level during the pre-monsoon season from 1951 to 2024. Fig. 4a depicts the mean wind field, highlighting a prominent wind discontinuity over peninsular India, influenced by two anticyclonic circulations, one over the Arabian Sea and the other over the Bay of Bengal. This discontinuity forms a distinct V-shaped pattern characterized by

northwesterly/northerly winds converging with southeasterly/southerly winds. The quasi-stationary north-south-oriented trough over the peninsula is a key feature contributing to convective systems, lightning, showers, hail, and squalls in the region. Fig. 4b shows the composite anomaly during Strong Convective Years (SCY), indicating a strengthening of northeasterly winds over northwestern India and an intensified Arabian Sea circulation, with wind speeds increasing by 1.5 to 2 m/s over Telangana. In contrast, Fig. 4c displays the composite anomaly during Weak Convective Years (WCY), revealing enhanced northwesterly winds shifting eastward and intensifying the Bay of Bengal circulation, with wind speeds increasing by 1.5 to 3 m/s. These patterns underscore the dynamic role of wind circulation in influencing convective activity over peninsular India.

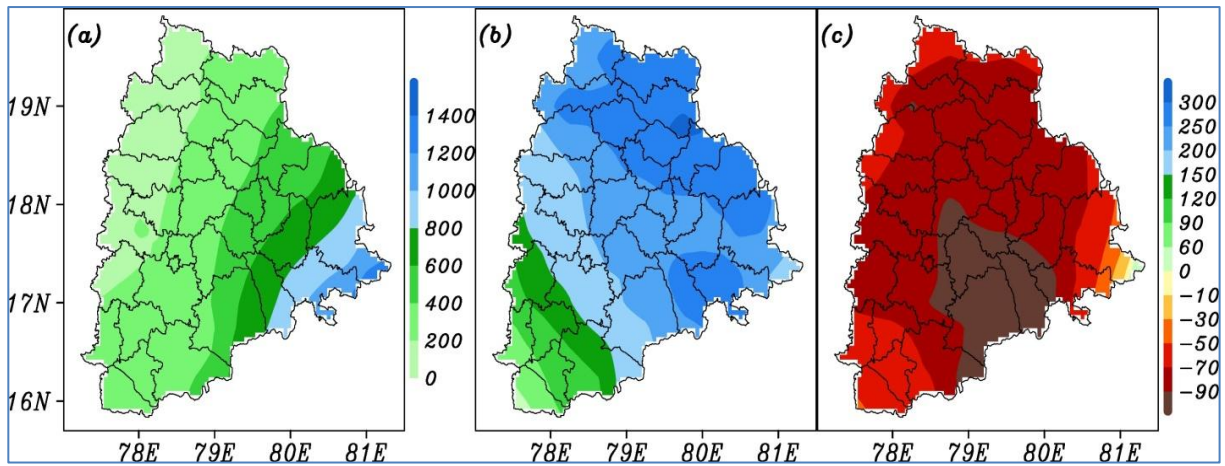


Fig. 5(a-c). The spatial distribution of Convective Available Potential Energy (CAPE; J/Kg) (a) Mean, (b) Composite anomaly of Strong Convective and (c) Composite anomaly of Weak Convective years during pre-monsoon season from 1951 to 2024

3.3. The spatial distribution of convective available potential energy (CAPE; J/Kg)

By considering and computing the possible, conditional, latent, and convective instability, the thermodynamic indices, which address the physical and dynamical developments of the atmosphere, give knowledge regarding the circumstances which have the potential to result in a convective activity occurrence. (Sahu *et al.*, 2020). These have been regularly used to enhance the prediction of convective systems and consequent rainfall events (Schultz, 1989; Haklander and Van Delden, 2003; Madhulatha *et al.*, 2013; Viceto, Marta-Almeida and Rocha 2017). The most widely used indices to interpret convective development in an area are convective available potential energy (CAPE) (Murugavel *et al.*, 2014; Westermayer *et al.*, 2017).

Fig. 5 depicts the geographical distribution of Convective Available Potential Energy (CAPE, in J/kg) from the pre-monsoon period of 1951 to 2024, emphasizing mean values and anomalies of high and low convective activity Years. Fig. 5a is the mean distribution of CAPE, with higher values (dark blue) in magnitude 1200 to 1400 J/Kg representing areas with higher atmospheric instability and greater capacity for the formation of convective activity, while lower values 200 to 800 J/Kg (green) represent relatively stable atmospheric conditions. Fig. 5b presents the composite anomaly during years with a high frequency of convective activity, with high positive anomalies (blue shades) highlighting areas of increased instability conducive to convective activity development and low positive anomalies (green) indicating weak instability. Fig. 5c displays the composite anomaly during years

with a low frequency of convective activity days, where widespread negative anomalies (red and orange) dominate, reflecting significantly reduced atmospheric instability and decreased potential for convective activity. This analysis emphasizes the relationship between CAPE and convective activity occurrences, identifying regions prone to extreme weather during the pre-monsoon season.

3.4. Mean volumetric soil water layer (SWVL)

There is positive feedback between the influence of soil moisture on the initiation of convective activity and the formation of precipitation. In Fig. 5 there is a good agreement between convective activity and CAPE as the anomaly of strong/weak convective years shows positive/negative magnitude. The theory of soil moisture–precipitation feedback suggests that higher soil moisture increases planetary boundary layer (PBL) humidity and consequently enhances the total energy available within the PBL (Pal and Eltahir 2001). This increase will augment convective available potential energy (CAPE) which is beneficial for convective triggering. Hence further analysis is done to signify the relation between soil moisture and convective activity.

The seasonal rainfall variability affects the variability in soil moisture, which influences the wetness/dryness of monsoon season (Douville 2002). Soil moisture influences pre-monsoon convective activity by regulating surface heating and moisture availability. Wet soil enhances evapotranspiration, increasing low-level humidity and aiding convection, while dry soils heat up faster, intensifying boundary layer turbulence and CAPE, which can trigger stronger storms. However, excessively

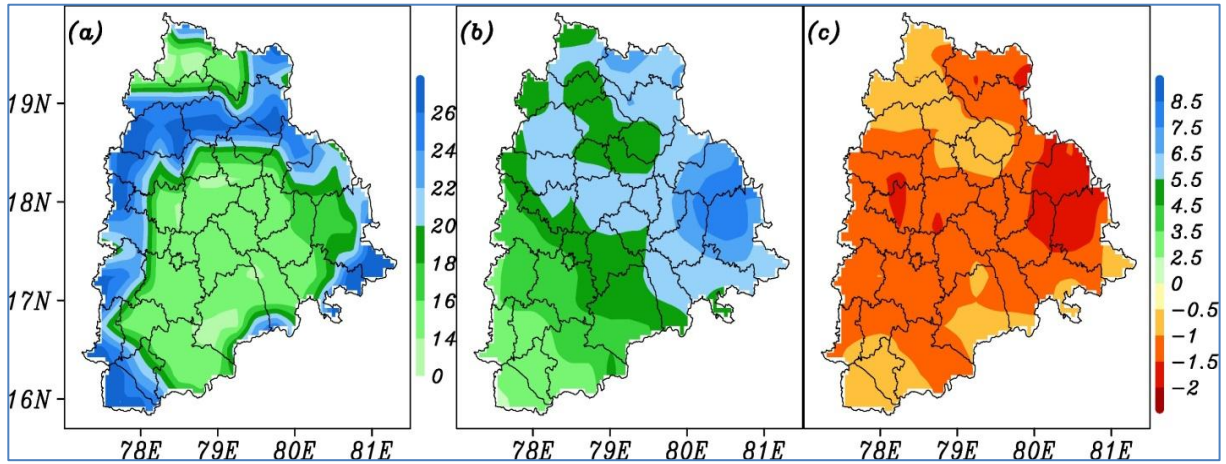


Fig. 6(a-c). The spatial distribution of Volumetric Soil water layer (SWVL; 10^{-2}) (a) Mean (b) Composite anomaly of Strong convective years and (c) Weak convective years during pre-monsoon season from 1951 to 2024

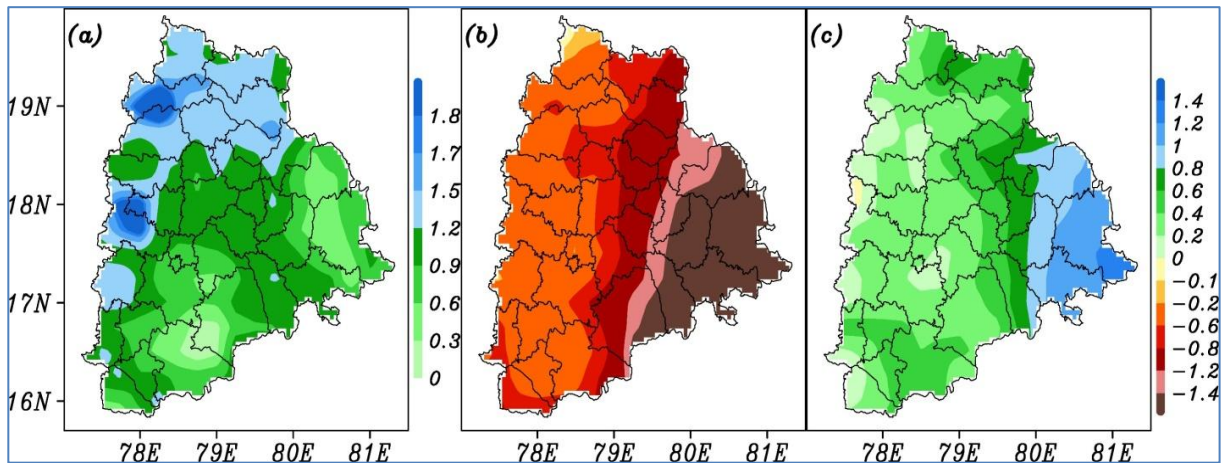


Fig. 7(a-c). The spatial distribution of vertically integrated moisture divergence (VIMD) (a) Mean, (b) Composite anomaly of Strong Convective years and (c) Composite anomaly of Weak Convective years during pre-monsoon season from 1951 to 2024

wet or dry conditions may suppress convection by altering surface energy fluxes. Optimal soil moisture supports localized convective systems and pre-monsoon rainfall.

Fig. 6 illustrates the spatial distribution of Volumetric Soil Water Layer (SWVL; 10^{-2}) during the pre-monsoon season (1951–2024), highlighting mean values and composite anomalies for years with high and low convective activity. Fig. 6a presents the mean SWVL, with northern and western regions showing higher soil moisture content (blue shades), which enhances evapotranspiration rates, contributing to atmospheric moisture and supporting convection. In contrast, central and southern regions exhibit lower values (green shades),

reflecting drier soil conditions with limited moisture availability for atmospheric processes. Fig. 6b shows SWVL anomalies during years with frequent convective systems, where positive anomalies of higher values (blue shades) align well with CAPE (Fig. 5b). The value dominates in central eastern and some regions of northern areas. Some research studies reported positive soil moisture rainfall feedback through evaporation (Pal and Eltahir 2001; Meehl 1994; Froidevaux *et al.* 2014). Increased soil moisture in these regions is likely attributed to higher rainfall from convective systems, amplifying surface moisture and promoting convective activity. Fig. 6c depicts anomalies during years with low convective activity, with widespread negative anomalies (orange to red shades)

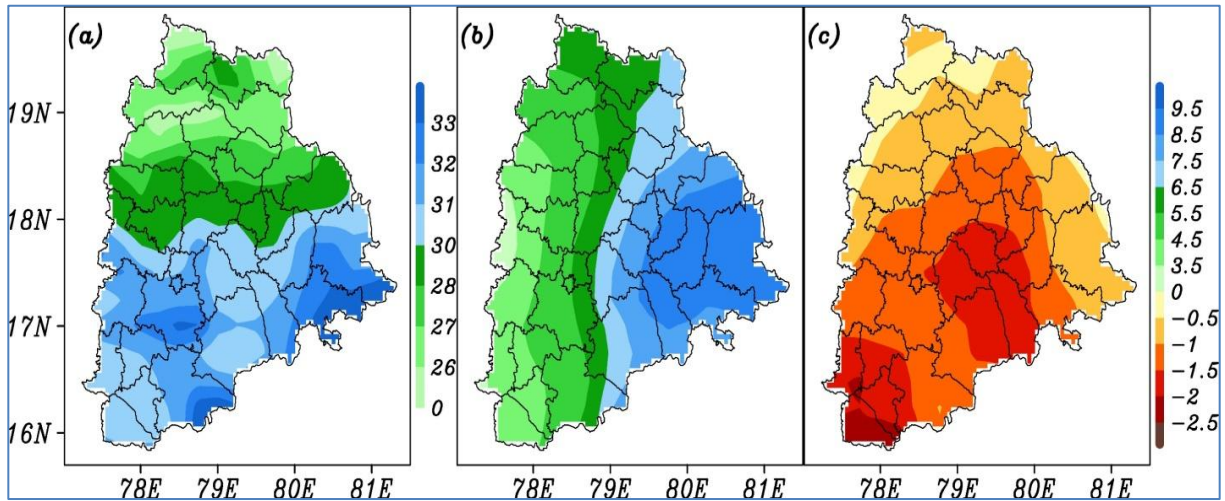


Fig. 8(a-c). The spatial distribution of Total Cloud Cover (TCC; 10^2 dimensionless) (a) Mean, (b) Composite anomaly of Strong Convective and (c) Weak Convective years during pre-monsoon season from 1951 to 2024

red shades) indicating reduced soil moisture align well with CAPE (Fig. 5c). These dry conditions suppress evapotranspiration and atmospheric instability, reducing the likelihood of convective activity development. Overall, the analysis highlights the strong connection between soil moisture and convective activity, with wetter conditions enhancing convection during high convective activity years and drier conditions suppressing convection during low convective activity years. This underscores the critical role of land-atmosphere feedback in shaping pre-monsoon convective activity dynamics.

3.5. Vertically integrated moisture divergence (VIMD)

Fig. 7 illustrates the spatial distribution of vertically integrated moisture divergence (VIMD) during the pre-monsoon season from 1951 to 2024, highlighting mean values and composite anomalies during years with SCY and WCY. Fig. 7a shows the mean VIMD, where green and blue shades represent positive magnitude, regions of moisture divergence is not favourable for, conducive to cloud formation and precipitation.

Fig. 7b presents the composite anomaly of VIMD during years with a SCY. Here, red and brown shades signify negative magnitude as decrease in moisture divergence i.e convergence, which is favourable for the precipitation intensification, high atmospheric instability or wind dynamics. Fig. 7c shows the composite anomaly of VIMD during years with WCY. During WCY years the magnitude of VIMD is positive which represents moisture that is spreading out, or diverging, which is quite unfavourable for convective activity and precipitation,

which likely suppress convective activity having good alignment with Fig. 1.

Overall, the analysis highlights the interplay between moisture dynamics and convective activity, showing that while moisture convergence generally supports convective systems, other factors such as atmospheric instability and wind patterns may counteract the influence of moisture divergence. This insight is valuable for understanding the atmospheric conditions that drive convective activity variability during the pre-monsoon season.

3.6. Total Cloud Cover (TCC)

With convective precipitation driven by the surface heating in the pre-monsoon period giving way to an increase in cloud cover and surface rainfall during the monsoon season (Ananthkrishnan and Soman, 1988). Total Cloud Cover (TCC) and convective activities during the pre-monsoon season are closely linked, as deep convection significantly contributes to cloud formation. Strong surface heating and high Convective Available Potential Energy (CAPE) lead to the development of cumulonimbus clouds, increasing TCC. Moisture influx from the Bay of Bengal enhances convection, resulting in localized convective systems and cloud buildup. High TCC often indicates intense convective activity, though rapid dissipation of clouds occurs post-storm. In contrast, suppressed convection leads to lower TCC, with only scattered cumulus clouds present. This relationship is crucial for understanding rainfall patterns and total cloud cover during SCY and WCY.

Fig. 8 depicts the spatial distribution of Total Cloud Cover (TCC; dimensionless $\times 10^2$) during the pre-monsoon

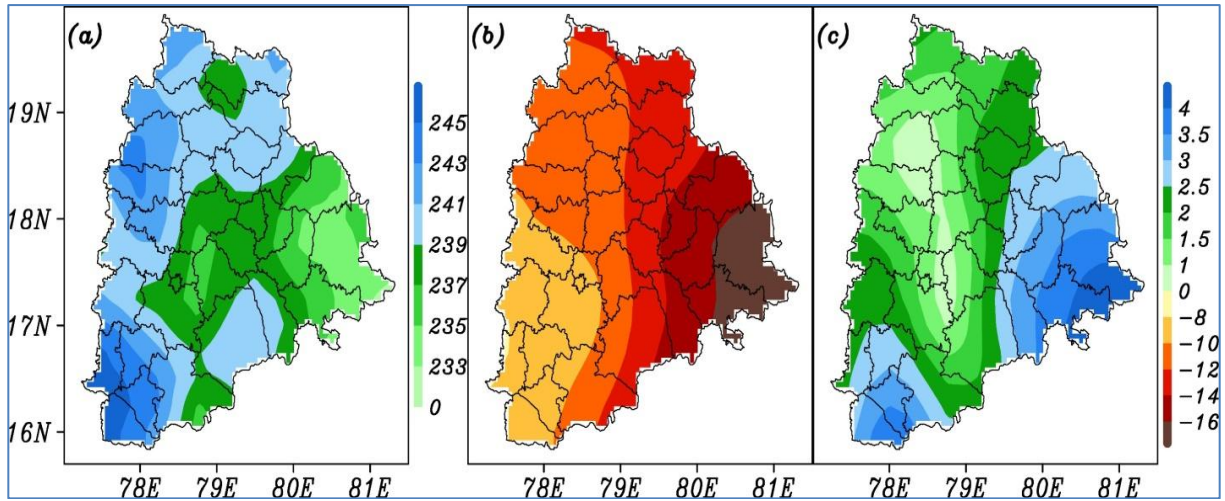


Fig. 9(a-c). The spatial distribution of Solar Radiation (10^{-5} W/m^2) (a) Mean, (b) Composite anomaly of Strong Convective and (c) Weak Convective years during pre-monsoon season from 1951 to 2024

season (1951–2024), highlighting mean values, as well as composite anomalies for years with high and low convective activity days. Fig. 8a shows the mean TCC distribution, with blue-shaded regions indicating higher cloud cover associated with enhanced moisture availability and favorable conditions for convection and precipitation. In contrast, green-shaded areas reflect lower cloud cover, signifying reduced moisture retention and potentially weaker convective activity. Fig. 8b illustrates the composite TCC anomalies for years with frequent convective systems, where positive anomalies (blue) indicate increased cloud cover that supports convective activity development through enhanced atmospheric instability and moisture availability. Meanwhile, some areas exhibit lower values of TCC (green), indicating localized reductions in cloud cover, though convective systems may still occur due to other factors such as wind shear or temperature gradients. Fig. 8c highlights the composite anomalies for years with fewer convective systems, with red and orange shades dominating the map, signifying widespread reductions in cloud cover. This diminished cloudiness corresponds to drier atmospheric conditions and limited convection, leading to less favorable conditions for convective activity formation. Collectively, the analysis emphasizes the critical role of TCC in shaping convective activity variability during the pre-monsoon season, where increased cloudiness supports convective activity years, while reduced cloudiness suppresses convective systems occurrence in low convective activity years. These findings underline the importance of monitoring TCC as a predictor of convective activity variability and regional weather patterns. Thick, low-level clouds can reduce solar radiation by 80–90%. In some

cases, tall convective clouds may actually increase solar radiation by 10–15% compared to clear skies (Monteith and Unsworth 1990). Reynolds *et al.* (1975) and Liou (1976) found that Cumulonimbus clouds, when the sky is fully overcast, allow only 3% of radiation to pass through. Matuszko (2011) noted that clouds generally reduce the intensity of solar radiation by weakening it. Hence for analyzing more about the relationship between TCC and solar radiation we did same approach for solar radiation.

3.7. Mean solar radiation (w/m^2)

Fig. 9 illustrates the spatial distribution of solar radiation (10^{-5} W/m^2) during the pre-monsoon season from 1951 to 2024, focusing on mean values and composite anomalies for high and low convective activity years. Fig. 9a shows the average solar radiation, where higher values (blue shades) are concentrated in northern regions, in contrast, central and southern areas exhibit lower radiation values (blue shades), corresponding to relatively stable conditions with reduced surface heating.

Fig. 9b highlights composite anomalies during years with high convective activity. Negative anomalies (red to dark brown shades) dominate, reflecting reduced solar radiation compared to the mean. This reduction is attributed to increased cloud cover during active convective activity periods (Fig. 8b), which blocks incoming solar energy. Despite limited surface heating, the enhanced moisture and convection associated with cloud cover drive frequent convective activity. Fig. 9c depicts anomalies for years with low convective activity, showing widespread positive anomalies (blue and green shades). These indicate higher – than - average solar radiation due to reduced cloud cover (Fig. 8c),

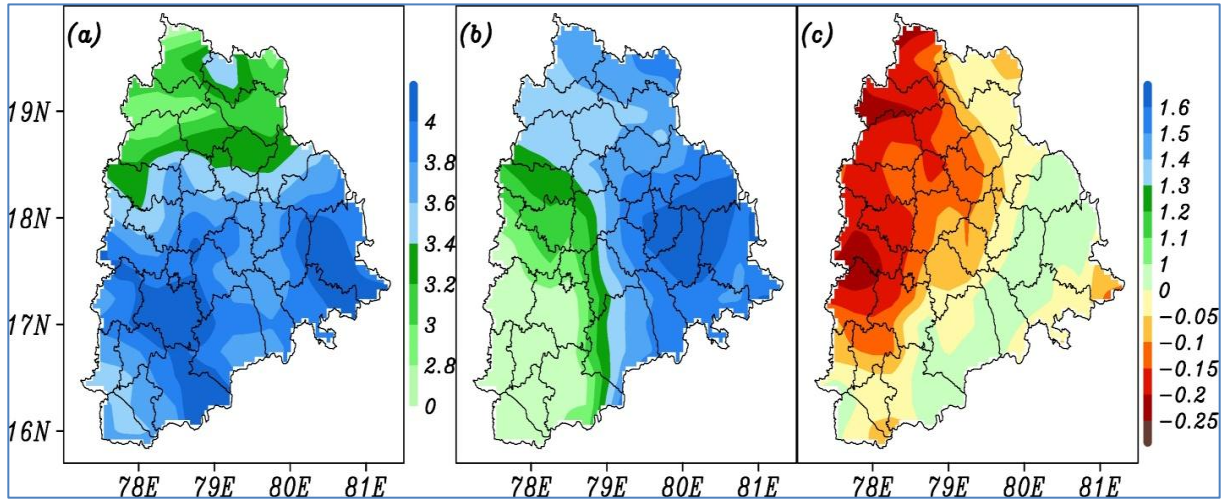


Fig. 10(a-c). The spatial distribution of Total column of cloud liquid water (TCLW; 10^2) (a) Mean, (b) Composite anomaly of Strong Convective and (c) Weak Convective years during pre-monsoon season from 1951 to 2024

leading to increased surface heating but diminished convection, suppressing convective activity development.

The analysis reveals a clear inverse relationship between solar radiation and convective activity frequency. High convective activity coincide with reduced solar radiation due to extensive Total cloud cover, while low activity is associated with enhanced solar radiation under clearer skies. These dynamics underscore the pivotal role of solar energy, cloud cover, and surface heating in driving pre-monsoon convective activity variability across the region.

3.8. Total column of cloud liquid water (TCLW)

The Total Column of Cloud Liquid Water (TCLW) is closely linked to pre-monsoon convective activity, as deep convection enhances cloud liquid water content. Strong updrafts in convective storms lift moisture, leading to increased TCLW, especially in cumulonimbus clouds. High CAPE and moisture availability further amplify TCLW, contributing to heavy rainfall and convective activity intensity. Regions experiencing intense convection during the pre-monsoon season typically show higher TCLW values, making it a key indicator for storm development and cloud microphysics.

Fig. 10 illustrates the spatial distribution of the Total Column of Cloud Liquid Water (TCLW; dimensionless $\times 10^2$) during the pre-monsoon season (1951–2024), providing insights into the mean values and composite anomalies for years with high and low convective activity. Fig. 10a presents the mean TCLW distribution across the region, highlighting higher values (blue shades) in the

southern areas, corresponding to abundant atmospheric moisture conducive to cloud formation and precipitation processes. In contrast, lower values (green shades) dominate the northern parts, indicating relatively drier atmospheric conditions with limited cloud water availability. Fig. 10b showcases the composite anomalies of TCLW during years with high convective activity, where positive anomalies (blue shades) reveal regions with increased cloud liquid water, facilitating enhanced convection and precipitation align good with TCC (Fig. 8b). The presence of lower anomalies (green shades) suggests that most regions with high convective systems experience favorable moisture conditions. Conversely, Fig. 10c depicts the TCLW anomalies during years with low convective systems, with red and orange shades signifying widespread reductions in cloud liquid water align good with TCC (Fig. 8c). These reductions indicate drier atmospheric conditions that suppress cloud formation and convection, thereby inhibiting convective activity.

This analysis underscores the critical role of TCLW in influencing convective activity dynamics during the pre-monsoon season. Regions with increased TCLW exhibit a greater frequency of convective systems, while reductions in TCLW are strongly associated with suppressed storm activity. These findings emphasize the importance of monitoring TCLW as a key parameter for understanding and forecasting convective activity variability across the region.

3.9. Mean surface temperature ($^{\circ}\text{C}$)

Fig. 11 shows the spatial distribution of SAT at 2 meters during the pre-monsoon season (1951–2024),

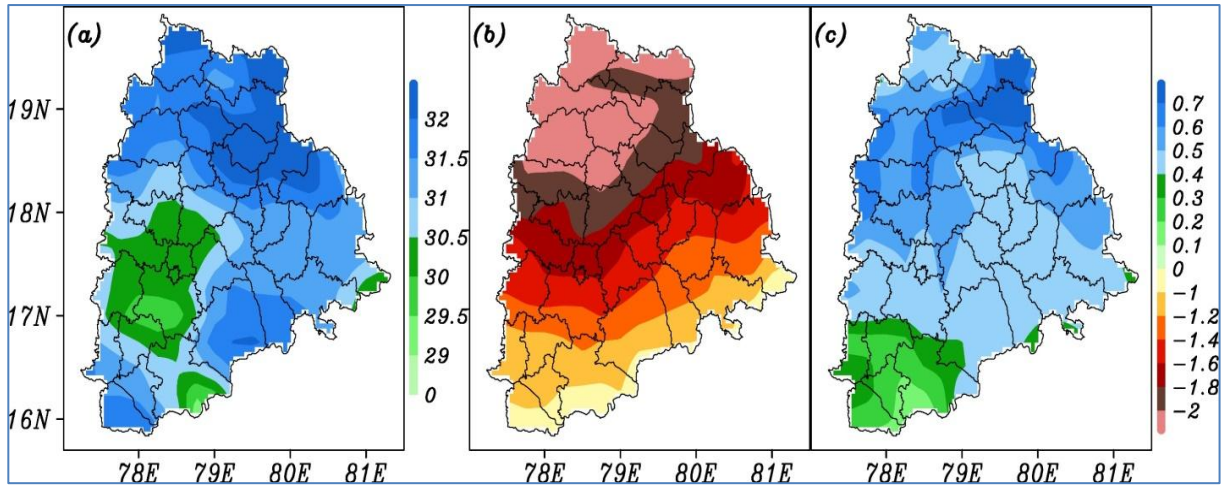


Fig. 11(a-c). The spatial distribution of surface temperature at 2m (a) Mean, (b) Composite anomaly of Strong Convective and (c) Weak Convective years during pre-monsoon season from 1951 to 2024

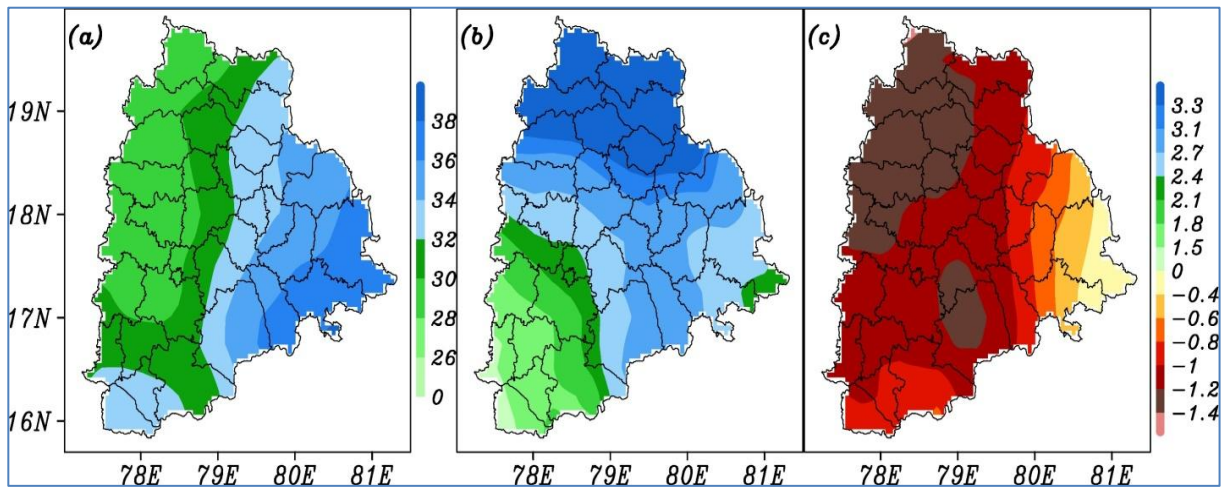


Fig. 12(a-c). The Spatial distribution of Total column of vertically integrated water vapour (kg/m^2) (a) Mean, (b) Composite anomaly of Strong Convective and (c) Weak Convective years during pre-monsoon season from 1951 to 2024

highlighting mean values and composite anomalies for high and low convective activity years. Fig. 11a depicts the mean surface temperature, with higher values concentrated in all regions except western and some part of southern regions, promoting atmospheric instability and favoring convective activity formation. In contrast, the remaining regions show lower temperatures, reflecting more stable conditions. Fig. 11b presents anomalies for high convective activity years, where negative anomalies dominate, particularly in northern and central areas. These cooler-than-average temperatures are due to increased cloud cover and rainfall, which reduce surface heating while still supporting convective systems through enhanced moisture and instability. Fig. 11c displays anomalies for years with low convective activity, showing

positive anomalies over all regions of Telangana. Higher-than-average temperatures result from reduced cloud cover, leading to increased surface heating but suppressed convection due to limited moisture and instability. This analysis highlights the critical role of surface temperature, cloud cover, and atmospheric conditions in regulating convective activity during the pre-monsoon season.

3.10. Total column of vertically integrated water vapor (TCWV; kg/m^2)

Fig. 12 illustrates the spatial distribution of the total column of vertically integrated water vapor (kg/m^2) during the pre-monsoon season from 1951 to 2024, focusing on mean values and composite anomalies for years with high

and low convective activity. Fig. 12a shows the mean distribution, with higher water vapor concentrations (blue shades) in the eastern and central regions, providing favorable moisture conditions for atmospheric convection and convective activity formation. In contrast, lower values (green shades) in the northern and western regions indicate reduced moisture availability, limiting convection. Fig. 12b presents composite anomalies during years with frequent convective activity, showing localized positive anomalies over major regions (blue shades) where increased water vapor supports convective activity development. The rest of the region exhibits near-neutral anomalies, highlighting variability in moisture distribution even during high convective activity years. Fig. 12c depicts anomalies for years with low convective activity, dominated by widespread negative anomalies (red to dark brown shades) across central and eastern regions, indicating significant reductions in water vapor. This suppression of moisture inhibits convection and leads to decreased convective activity frequency. Overall, the analysis underscores the critical role of water vapor in modulating convective activity, with increased moisture promoting convective systems and its absence suppressing them.

4. Conclusions

This study provides a comprehensive analysis of pre-monsoon convective activity variability over Telangana from 1951 to 2024, revealing critical insights into its spatial and temporal characteristics, associated with atmospheric dynamics, and implications for regional hydrometeorology. A marginally increasing trend in convective activity in recent years underscores the growing influence of atmospheric instability and changing climatic conditions. The distinction between Strong Convective Years (SCY) and Weak Convective Years (WCY) highlights the stark variability in rainfall distribution, rainy days, and atmospheric processes during the pre-monsoon season.

The study identifies key drivers of convective activity variability, including Convective Available Potential Energy (CAPE), vertically integrated moisture divergence (VIMD), total cloud cover (TCC), and solar radiation. Enhanced atmospheric instability, moisture convergence, and cloudiness during SCY years facilitate robust convective activity development, while contrasting conditions during WCY years inhibit such activity. Additionally, the analysis of wind patterns at 850 hPa reveals critical shifts in circulation over peninsular India, further emphasizing the role of mesoscale and synoptic dynamics in modulating convective activity. These findings have important implications for water resource management, agricultural planning, and disaster

preparedness in Telangana, particularly in the face of climate variability and increasing frequency of extreme weather events. By linking convective systems to broader atmospheric processes, this study enhances our understanding of pre-monsoon dynamics and provides valuable input for improving weather forecasts and risk mitigation strategies.

Future research should focus on integrating high-resolution climate models and AI-based ensemble systems to further refine convective activity prediction and assess their impacts under various climate scenarios. This will aid in developing adaptive measures to better manage the risks associated with extreme weather events, ensuring sustainable development and resilience in the region.

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Data Availability

The IMD observational dataset was used in this analysis and is available at <https://www.imdpune.gov.in/lrfindex.php>. Also, we used ERA5 data in this present work. It is accessible at <https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>. The data utilized in this study will be made accessible upon reasonable request to the corresponding author.

Conflict of interest

The authors declare no conflict of interest as regards the publication of this manuscript.

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