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RESEARCH PAPER

Rainfall in Telangana (India): a decadal trend analysis

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Abstract
This study examines rainfall trends and monsoon dynamics over Telangana, India, using high-resolution daily rainfall data from the India Meteorological Department for the period 1991–2020. We focus on the southwest monsoon season (June–September) and analyze variations in total rainfall, rainy days, and rainfall intensity across three decades. Additionally, atmospheric variables such as soil moisture, solar radiation, wind components, and pressure data from the ERA-5 reanalysis dataset were utilized to explore the drivers of these changes. Our findings reveal significant spatial variability in monsoon rainfall, with the northeastern and central regions of Telangana experiencing higher precipitation. There is a noticeable increase in the number of rainy days and the frequency of heavy rainfall events in the most recent decade (2011–2020). This uptick in rainfall intensity is attributed to factors such as enhanced soil moisture, stronger south-westerly monsoon winds, and favourable atmospheric conditions, which have intensified precipitation during the monsoon. Further analysis of wind patterns at 850 hPa and velocity potential at 200 hPa indicates significant shifts in atmospheric circulation. Strengthened monsoon winds and increased upper-level divergence were observed in recent years, suggesting a response to global warming and the influence of climate models like the Indian Ocean Dipole and El Niño-Southern Oscillation. The study concludes that Telangana is witnessing an overall increase in rainfall, particularly in its northern and eastern districts, along with a rise in extreme rainfall events. These changes present challenges for water resource management and agriculture, underscoring the need for adaptive strategies to cope with shifting monsoon patterns in a warming climate.

Keywords Trend · Variability · Southwest monsoon · Mann–Kendall test · Telangana

Introduction

Rainfall is vital for a primarily agrarian country like India. Seasonal rains replenish rivers and irrigation sources, which are crucial during the various phenological stages of crops. Uneven rainfall not only jeopardizes agriculture but also threatens the sustainability of communities (Bhuiyan et al. 2009). In India, the southwest monsoon— the primary rainy season— largely determines water availability, as it accounts for 80% of the total annual rainfall (Sahai et al., 2003; Deshpande et al., 2012; Prabir et al., 2014). Evidence suggests that climatic extremes, such as heavy rainfall, droughts, and tropical cyclones, are increasingly driven and amplified by human activities (IPCC, AR6, 2023). Climate change exacerbates these extremes, causing temporal and spatial variations in rainfall patterns globally (Kumar et al. 2017; Gadgil & Gadgil 2006; New et al., 2001). The unpredictability of the monsoon has widespread impacts across various sectors (Murari et al. 2016; Mishra & Singh 2011; Rohan et al. 2017). Telangana, a landlocked state, relies heavily on rainfall to replenish its water resources. Two-thirds of India's agricultural land is rain-fed (Dore 2005; Kumar et al. 2010), and agriculture contributes 18.3% to the national GDP (https://desagri.gov.in).

Extensive research on India's precipitation trends led (Parthasarathy et al., 1995) to divide the country into five rainfall regions. Building on this, the IMD now categorizes

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India into four main regions for rainfall assessment: Northwest India (NWI), Northeast India (NEI), Central India (CI), and South Peninsular India (SPIN). This classification helps in analyzing and understanding regional climate variations across the country as well as over the meteorological subdivisions of India. The historical data showed no trend in the pre-global warming era. Pramanik et al. (1954), Jagannathan et al. (1973), Parthasarathy (1984), Guhathakurta and Rajeevan (2008), Rupa Kumar et al. (1992), Naidu et al (2015, 2017) and Roxy, M.K., et al. (2017) observed long-term trend variations in All-India rainfall series and on a sub-divisional scale.

Many researchers have studied rainfall variability in the Telangana meteorological subdivision as part of broader pan-India analyses. Kulkarni et al. (2016), Krishnamurthy and Shukla (2000), Mohanty (1994) studies focus on regional climate dynamics, seasonal monsoon variations, and long-term rainfall trends in Telangana and other regions. Before 1980, rainfall increased over Telangana sub-division (Parthasarathy 1984). Using the IITM homogeneous monthly rainfall series for 1901–2003, Guhathakurta and Rajeevan (2008) observed a monotonic increasing or decreasing rainfall trend in various subdivisions. They observed an increasing trend at 95% significance level in August rainfall and a decreasing trend at a 90% significance level in September rainfall over Telangana. The Relative humidity or amount of water vapour in the atmosphere determine the amount of rainfall (Trenberth 2011) and Donat et al (2016). Aruna Jyothy et al. 2021 observed an increase in relative humidity (0.07%/year), vapor pressure (0.058 mbar/year) and a significant increase in annual rainfall (10.92 mm/year) for the period 1969–2008 at Hyderabad of Telangana state.

Besides a similar vulnerability in the Jagtial district in the state, Navatha et al., 2021 using daily rainfall and temperature data of 39 years (1980–2019), analyzed climate variability and change over the northern Telangana Zone. Reddy et al. 2007 observed a decreasing Rainfall trend over Telangana's northern parts, inferring from the rainfall data set of 40 years (1963–2002). Long-term annual and seasonal rainfall pattern in Telangana state from January 1982 to December 2021 was analyzed by Jyostna et al. 2022, who observed a tendency of trend in the rainfall pattern during the pre-monsoon, monsoon, and post-monsoon periods while a significantly increasing trend of rainfall was registered in May.

Researchers mostly focused on the trends in rainfall events considering three decades of data or more, and rainfall over the state and its constituent districts received less attention. Moreover, the impact of rainfall by districts is left out. An analysis of recent data is needed for policy-related decisions to be undertaken by the government because of the climatic variations across the districts of Telangana.

Identifying this lacuna in the earlier studies, the authors of the present study tried to appreciate the variability of rainfall trends in the recent period as there is increasing interest in planners to install pluviometric instruments like Automatic Rain Gauges (ARGs) at various places so that there is a dense network of the rain gauges. The enhanced network of rain gauges will help reduce data collection errors and address the hitherto data-scarce areas. The Indian Meteorological Department (IMD) employs a system of hydrological data collection called 'MK-Rain' to collate and comprehensively collect the data. This data is used in the present study.

Data and methodology

We used gridded daily rainfall data from the IMD at a 0.25-degree resolution, spanning the period from 1991 to 2020 (Pai et al. 2020). The dataset covers the Telangana region, between latitudes 15.5°N to 20°N and longitudes 77.5°E to 81.5°E (Fig. 1). We calculated the climatological mean and the number of rainy days during the southwest monsoon season (June to September) over the 30-year period. This time frame was divided into three decades: 1991–2000, 2001–2010, and 2011–2020. To assess the statistical significance of the differences between these periods, we employed the z-statistic.

Additionally, we obtained monthly data on soil moisture, solar radiation, relative humidity, U and V wind components from the ERA-5 dataset (Hersbach et al. 2020), developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). This state-of-the-art reanalysis dataset provides atmospheric variables at a 30 KM resolution for the same 1991–2020 period. The wind and pressure data cover a broader domain extending from 0° to 40°N in latitude and from 40°E to 120°E in longitude. To understand the spatial distribution of atmospheric circulation in the context of recent global warming, we computed composite anomalies of rotational wind and stream function at the 850 hPa level, along with divergence and velocity potential at 200 hPa. The southwest monsoon season and its associated months were analyzed by dividing the data into the same three 10-year periods. We then computed the spatial distribution of these variables and analyzed their differences and anomalies over the Telangana region.

Results and discussion

According to IMD, heavy rainfall is categorized into – heavy (64.5–115.5 mm), very heavy (115.6–204.4 mm) and extremely heavy (above 204.4 mm). Earlier researchers also carried out rainfall intensity studies (Dhar and Nandargi 1995; Sen Roy and Balling 2004; Dash, 2010) based on

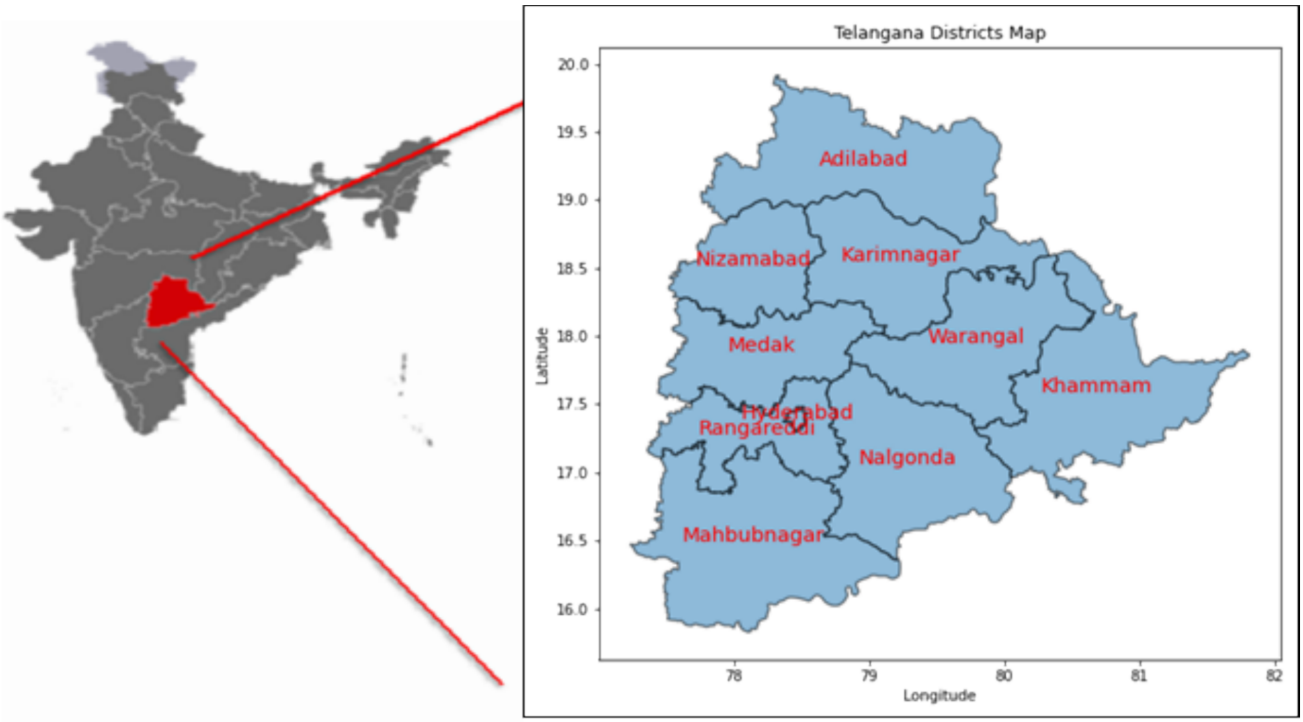


Fig. 1 The Geographical location of the Telangana state (District wise) curved from the India map

the quantum of monsoon rainfall by standard thresholds. Extreme rainfall events showed noticeably different patterns in 2000 compared to the period 1951–2000, with an increase in extreme rainfall events and a decrease in the frequency of moderate ones, according to Malik et al., (2011), Dash et al., (2009), Roxy et al. (2017) and Goswami et al. 2007.

Inter-decadal variations

The Fig. 2 presents the spatial distribution of JJAS rainfall across the Telangana region, with each figures highlighting a different analysis period. Figure 2a displays the mean rainfall from 1991 to 2020, showing distinct regional variations, with higher rainfall concentrated in the northern and eastern parts of Telangana, and lower amounts in the south parts of Telangana. Figures 2b–d illustrate the differences in rainfall for the periods 1991–2000, 2001–2010, and 2011–2020, compared to the overall mean. These difference figures reveal clear shifts in rainfall patterns over time, with some regions experiencing increased rainfall, especially in the most recent decade (2011–2020), while others have seen a decline. This visualization highlights the dynamic nature of rainfall distribution in Telangana, offering valuable insights for managing water resources and planning for agricultural resilience in the face of changing climate conditions.

The summer monsoon rainfall (June–September) over Telangana shows a positive tendency for 1991–2020 (Fig. 3a). The time series shows inter-annual variations. The overall trend is 7.8 mm/year, and it is statistically significant at 95% Level. To identify wet and dry periods in the rainfall time series, a normalized plot with an 11-year running average is shown (Fig. 3b). The 11-year running average remains below the zero line until 2007, after which positive anomalies become more frequent. From 2008 to 2022, only 5 out of 15 years had below-normal rainfall, indicating that 66.7% of the years experienced positive anomalies. This reflects inter-decadal variations in rainfall amounts over Telangana State, suggesting an increase in wetter years in the recent decade amidst a warming environment. The rise in rainfall is attributable to higher soil moisture, intensified southwesterly winds, a stronger upper-level easterly jet, and further leads to reduced solar radiation.

Mean rainy days

The Fig. 4i showing analysis of mean rainy days (≥ 2.5 mm) in Telangana from 1991 to 2020 indicates distinct regional variations. The northeastern districts, including Adilabad, Nizamabad, and Karimnagar, recorded the highest frequency of rainy days, with 36 to 38 days during the 122-day monsoon season. Eastern districts such as Warangal and Khammam,

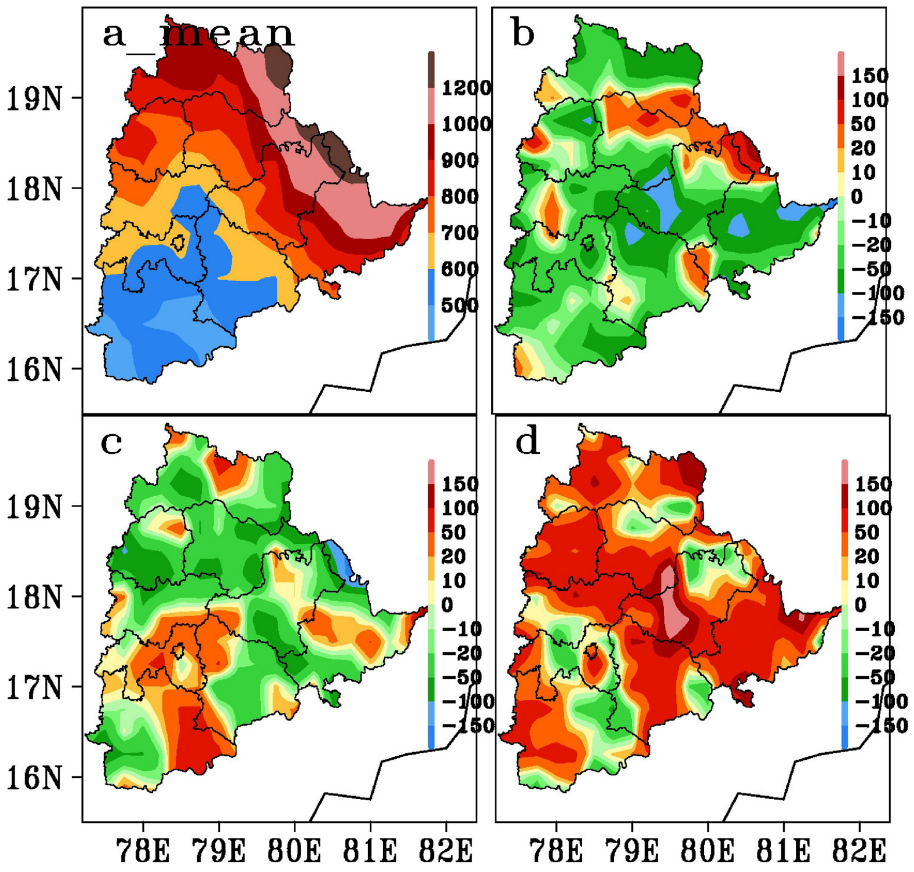


Fig. 2 Spatial distribution of rainfall in mm/year **a** Mean from 1991 to 2020 **b** differences from 1991 to 2000, **c** differences from 2001 to 2010 and **d** differences from 2011 to 2020 for Telangana region

and western areas like Medak and parts of Rangareddi, followed closely. A gradual decline in rainy days is evident as one moves southward, with a conservative difference of about 2 days. The east-to-west variation is more pronounced, with a difference of about 6 days. Southern Telangana experienced notably drier conditions throughout this period.

In the most recent decade (2011–2020), southern districts like Mahbubnagar and Nalgonda showed an increase in the number of rainy days, with an additional 6 to 10 rainy days compared to earlier decades (1991–2000 and 2001–2010). This shift in rainfall distribution suggests changing monsoon patterns, likely influenced by the presence of major rivers such as the Godavari and Krishna, which supply atmospheric moisture. Favorable atmospheric conditions, including wind shear and monsoon dynamics, play a role in driving this convection, leading to increased rainfall in certain areas. These observations are consistent with studies by Bosilovich et al. (2005) and Singh and Kumar (2015), which highlight the influence of water cycle processes and regional climate shifts.

Moderate rainfall days

Figure 4ii. represents the mean Moderate rainfall days (15.6 mm). Mean moderate rainfall days of 16 to 20 are observed over north and eastern districts from Adilabad to a few parts of Karimnagar and Warangal and extended to Khammam district, with areas recording 16 to 20 days. There are four quantified zones with a gradual decrease from northeast to south in respect of mean moderate rainfall 16–20 days, 12–16 days, 10–12 days, and 6–8 days, as observed in the Mahbubnagar district of mean moderate rainfall days during the climatological period 1991–2020. Surprisingly significant spatial spread positive differences were observed in the recent decade (2011–2020) with 2–4 days over the central parts of Medak, Karimnagar, western parts of the Warangal, and northern parts of the Nalgonda while the remaining parts of the Telangana showed positive anomalies up to 0.5 days during the decade when observed with that of the first decade (1991–2000) and second decade (2001–2010).

Mean heavy rainfall days

Figure 4iii represents the mean heavy rainfall days (64.5 mm) from 1991 to 2020. Notably, Northern (Adilabad, Eastern parts of the Karimnagar) and eastern (Warangal and Khammam) parts recorded mean heavy rainfall days of 1 to 3 days. A few parts of Nizamabad, Medak, Sanga Reddi, and Ranga Reddi in the west of Telangana and significant parts of Nalgonda, and a few parts

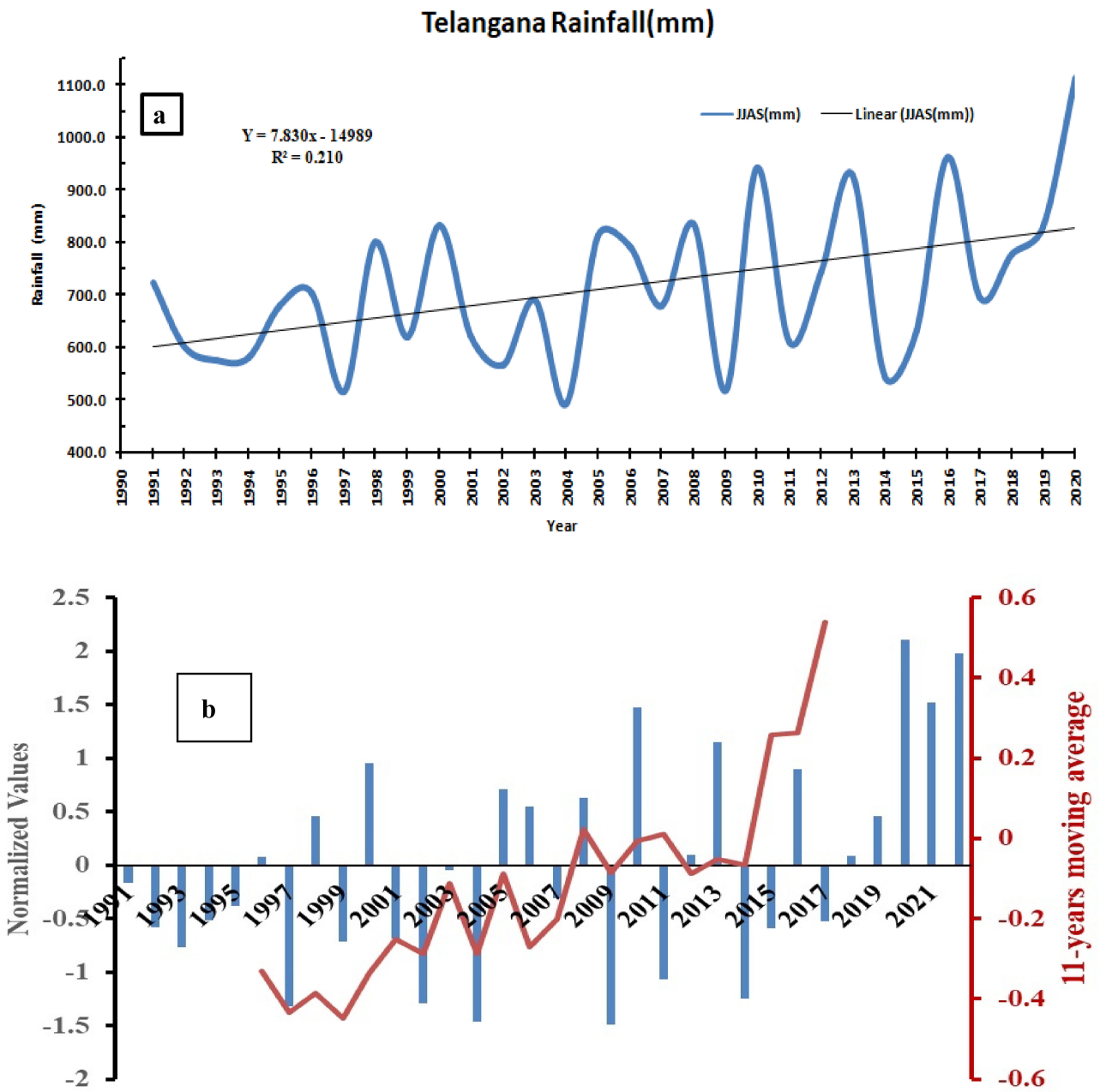


Fig. 3 The Time series of **a** Normalized values Telangana (1991–2020) and their 11 years moving averages **b** Telangana rainfall (mm) for the study period

of Mahbubnagar reported mean heavy rainfall days ranging from 0.5 to 1 during the period 1991–2020. Surprisingly a notable spread of mean heavy rainfall days during the decade 2011–2020 is in most parts of Adilabad (northwestern parts), Warangal, and Khammam, with Eastern parts recording 0.5 to 1.0 days of mean heavy rainfall. Significant parts of Mahbubnagar, Rangareddi, and smaller portions of northern Karimnagar and Warangal districts recorded negative anomalies of 0.5 days of mean heavy rainfall during 2011- 2020.

Mean very heavy rainfall days

The mean very heavy rainfall days (115.6 mm) from 1991 to 2020 are shown in Fig. 4iv. A few parts of Northern Telangana (Adilabad, Eastern parts of the Karimnagar) and eastern Telangana (Warangal and Khammam) recorded mean very heavy rainfall days of 0.5 to 1 days, and major parts of Telangana reported mean very heavy rainfall days 0.1–0.5 days during the period 1991–2020. While observing the differences of the recent decade, there is a considerable

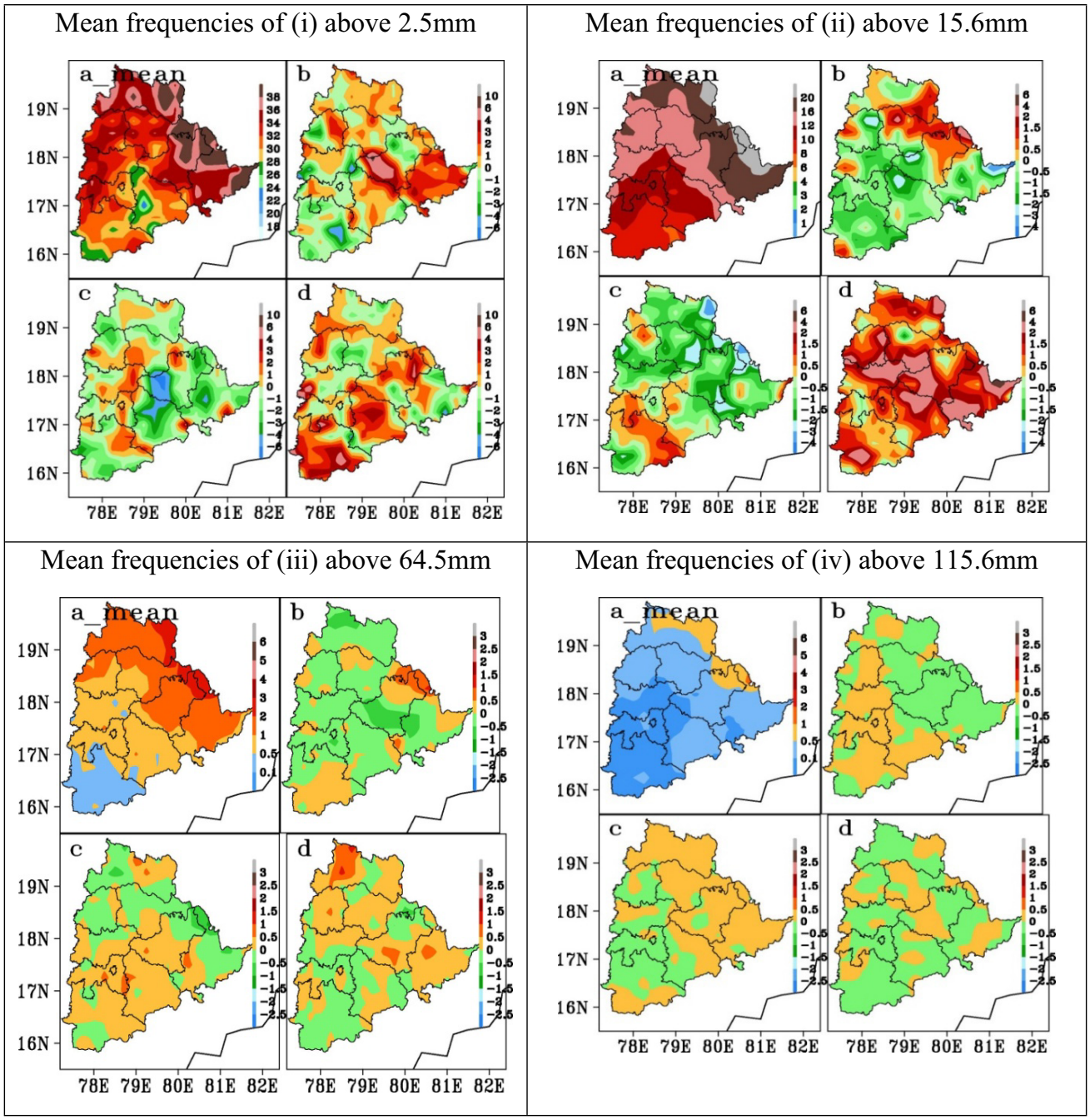


Fig. 4 Spatial distribution of mean frequencies of (i) above 2.5 mm, (ii) above 15.6 mm, (iii) above 64.5 mm and (iv) above 115.6 mm rainfall days/year for Telangana **a** Mean for the entire study period **b** differences (1991–2000), **c** differences (2001–2010) and **d** differences (2011–2020)

variation of monsoon rainfall from year to year, interannual as well as interdecadal, which agrees with the previous studies carried out by Parthasarathy and Mooley (1975), Mooley and Shukla (1987), and Goswami et al. (2007).

Telangana has experienced above-normal rainfall in the recent decade. Table 1 compares rainfall distribution (in mm) across all ten districts of Telangana for the climatological period 1991–2020 (A) and the recent decade 2011–2020 (B). The data shows a clear increase in rainfall across all districts during the recent decade compared to the climatological period. The most significant increases are observed in Warangal (117.9 mm) and Medak (100.2 mm), while smaller increments are noted in Mahbubnagar (42.9 mm) and Adilabad (38.0 mm). These positive anomalies align with trends identified in spatial and intensity analyses, reaffirming the increase in rainfall.

Table 1 Distribution of JJAS rainfall (in mm) across Telangana districts for the climatological period 1991–2020 (A), the recent decade 2011–2020 (B), and their differences (B–A)

S.No	Districts	A(1991–2020)	B(2011–2020)	B–A
1	Hyderabad	610.9	661.2	50.3
2	Warangal	781.3	899.2	117.9
3	Khammam	782.0	844.7	62.7
4	Nalgonda	608.9	680.5	71.6
5	Adilabad	937.7	975.6	38.0
6	Medak	680.2	780.3	100.2
7	Nizamabad	795.8	856.8	61.0
8	Mahbubnagar	562.0	605.0	42.9
9	Karimnagar	767.5	830.1	62.6
10	Ranga Reddy	621.5	714.6	93.1

Table 2 Mean and CV for monsoon season and months

	June	July	August	September	Season
Mean	136.53	213.91	202.67	174.52	727.63
CV	54.20	41.17	46.71	45.85	18.96

Table 3 Highest rainfall recorded for southwest monsoon months

Month	Highest rainfall received (mm)	Year
June	715	2015
July	1084.6	2013
August	1312.6	2020
September	789.4	2016

The present analysis highlights the performance and distribution characteristics of rainfall over Telangana. Table 2 shows the mean rainfall and coefficient of variation (CV) for the southwest monsoon season and individual monsoon months during the study period. July contributes the most to the total rainfall (29.41%), followed by August (27.85%), September (23.98%), and June (18.76%). The overall CV for the monsoon season is 18.96%.

Trend analysis indicates that while monthly rainfall does not show any significant trend, seasonal rainfall exhibits a statistically significant upward trend. Table 3 displays the highest rainfall recorded during the monsoon months for the study period. In August 2020, Warangal district recorded the highest rainfall at 1312.6 mm, while Khammam received 715 mm in June 2015 and 1084.6 mm in July 2013. The highest rainfall in September, 789.4 mm, was recorded in Nizamabad district in 2016.

Trend in district-wise rainfall

District/month-wise, the rainfall mean, and coefficient of variance are represented in Table 4. The northern districts of Telangana viz. Adilabad, Nizamabad, and Karimnagar received mean rainfall in the range of 147.96–187.25 mm in June, 260.56–302.84 mm in July, 232.09–268.52 mm in August, and 194.81–201.18 mm in September, while the districts of central region viz. Medak, Warangal, and Khammam received mean rainfall ranges of 116.39–175.29 mm in June, 180.59–281.57 mm in July, 156.24–295.82 mm in August, and 167.91–199.56 mm in September. The southern districts viz. Hyderabad, Ranga Reddy, Nalgonda, and Mahabubnagar received mean rainfall in the ranges of 86.43–110.54 mm in June, 126.01–156.10 mm in July, 127.30–145.73 mm in August, and 136.93–173.10 mm in September. During the monsoon season, Adilabad received the highest mean rainfall, 238.35 mm, while Mahbubnagar received the lowest (121.54 mm).

Figure 5 depicts varying mean rainfall trends for monsoon months. Mahbubnagar registered an increasing trend in mean rainfall days at a 95.7% significant level, while the rest of the districts showed no significant trends. There was no significant trend in Telangana during July except in Hyderabad and Nizamabad, which exhibited stable

Table 4 Mean rainfall and coefficient of variance (district/month-wise) for the study period

District	June		July		August		September	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Adilabad	187.251	46.1605	302.841	38.8774	268.524	36.6656	194.818	39.1144
Hyderabad	110.545	39.8542	156.104	25.5428	141.76	36.7601	173.108	27.6506
Karimnagar	147.965	52.1751	272.076	30.0991	232.098	40.8444	201.185	43.6707
Khammam	172.902	53	281.573	43	295.821	40.5233	199.566	41.8136
Mahbubnagar	86.4368	61.249	135.497	43	127.309	50.6039	136.933	49.103
Medak	116.394	71.0525	180.597	50.1032	156.242	56.49	167.916	61.7354
Nalgonda	100.675	66.5594	126.011	53.9976	145.732	59.0473	147.852	50.7873
Nizamabad	164.4	41.3065	260.564	30.9431	239.36	33.4556	195.087	44.6627
Rangareddy	103.444	65.998	143.348	53.5054	140.709	64.5025	139.671	57.0506
Warangal	175.291	44.6245	280.512	43.0154	279.171	48.2139	189.021	42.8807

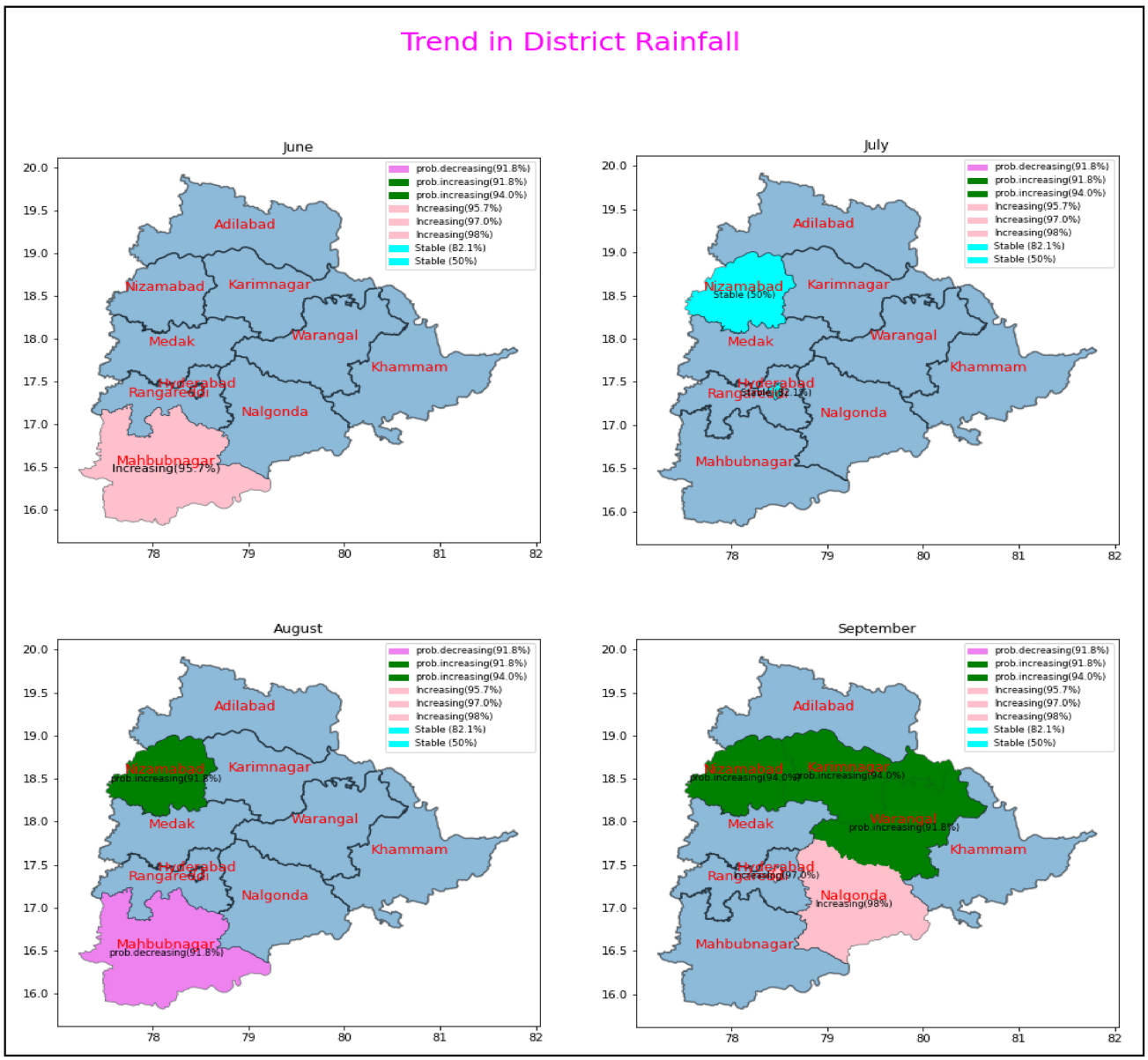


Fig. 5 Trend in district rainfall for the study period

trends at 82.1% and 50% significance levels, respectively. Only Nizamabad showed a probability of increasing, while Mahbubnagar had decreasing trends in August. However, in September, the districts of Nizamabad, Karimnagar, and Warangal showed a probability of an increasing trend, while Nalgonda exhibited a rising trend at a 98% significant level.

Frequency of rainfall by intensity

Figure 6 depicts the trend in the average frequency of rainy days across Telangana. In northern Telangana, the average rainy days range from 2.08 to 14.81 in June, 4 to 20.54 in July, 2.08 to 18.2 in August, and 5.55 to 17.21 in September. The central region records 1.83 to 15.61 days in June, 2.81 to 21.9 in July, 6.37 to 19.8 in August, and 3.72 to 17.58 days in September. Southern Telangana shows 1.65 to 13.88 days in June, 3.13 to 18 in July, 5.58 to 18.66 in August, and 2.85 to 16.5 days in September. Notably, the central districts recorded more rainy days than the northern and southern regions.

Throughout the monsoon season, Hyderabad displayed a stable trend in the frequency of rainy days. A similar trend was observed in Adilabad, Nizamabad, Karimnagar, and Khammam during July and August, as well as in Ranga Reddy and Nalgonda in July, and Medak in August. Ranga Reddy and Mahbubnagar showed a significant increasing

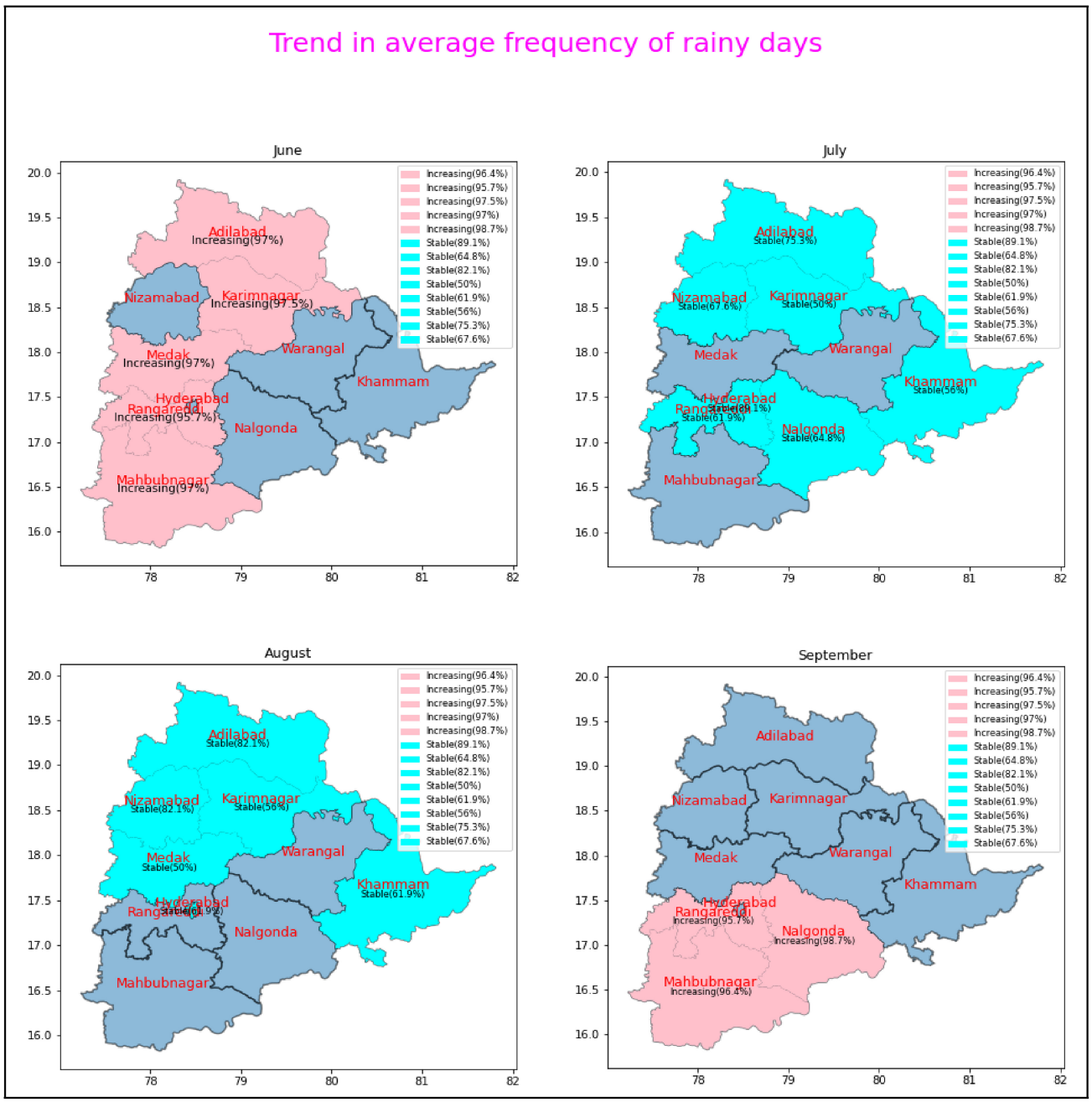


Fig. 6 Trend in average frequency of rainy days

trend in rainy days during June and September, while Adilabad, Karimnagar, and Medak showed similar trends in June, and Nalgonda in September. These trends were statistically significant at or above the 95.7% confidence level.

Figure 7 illustrates the trend in the frequency of heavy rainfall days. In the central districts, the average number of heavy rainfall days during the monsoon months is 0.08 to 0.42 in June, 0.16 to 0.40 in July, 0.07 to 0.55 in August, and 0.23 to 0.33 in September. Northern districts recorded slightly different ranges: 0.2–0.27 in June, 0.31 to 0.39 in July, 0.26–0.48 in August, and 0.25–0.46 in September, while southern districts ranged from 0.06 to 0.13 in June, 0.09 to 0.24 in July, 0.07 to 0.24 in August, and 0.12–0.22 in September.

A statistically significant increase in heavy rainfall days was found in Warangal throughout the monsoon season, with Medak and Karimnagar showing similar trends in June and August. Khammam exhibited increases in July and August. All districts, except Adilabad and Ranga Reddy, showed an increasing trend in September.

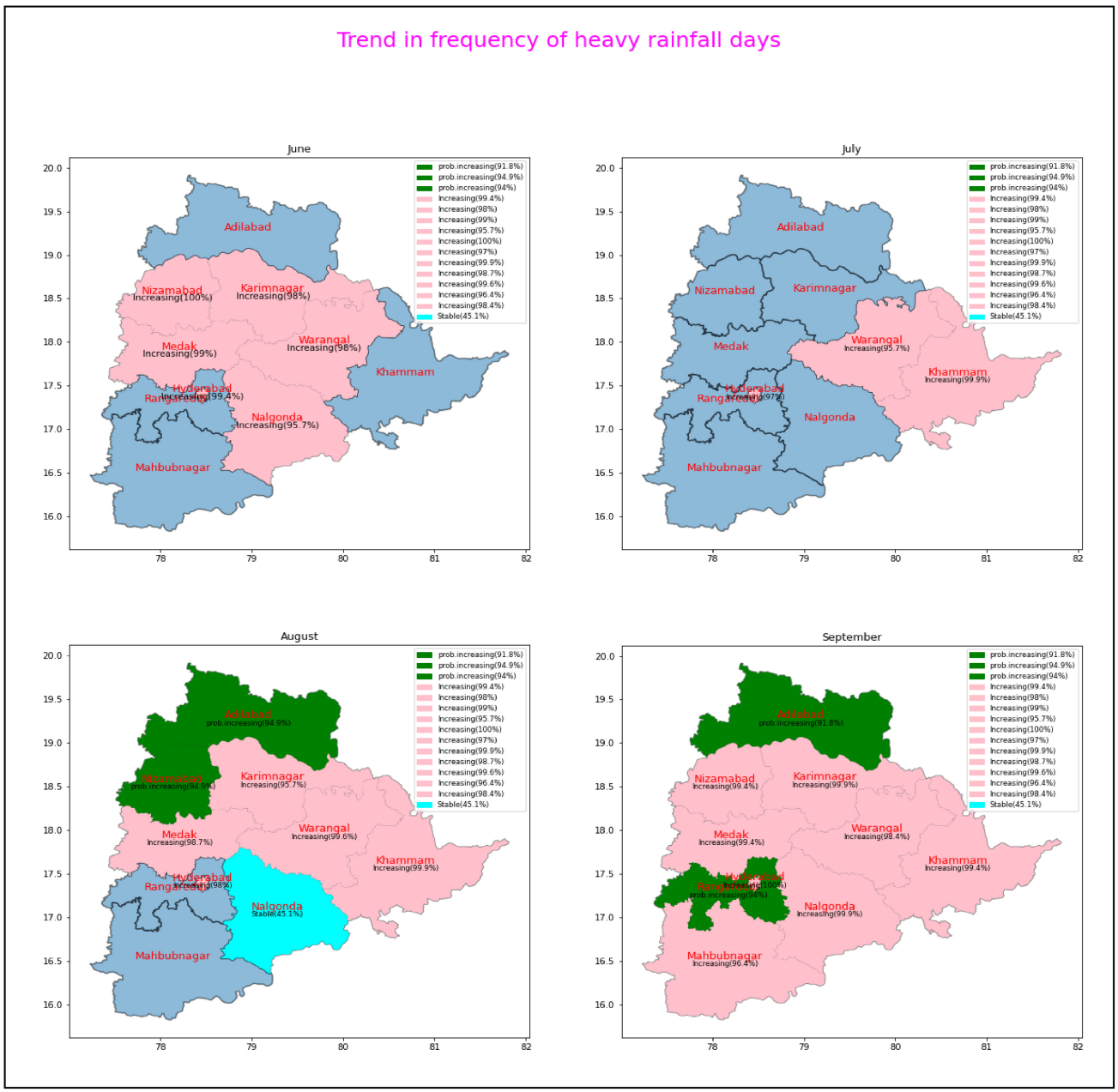


Fig. 7 Trend in average frequency of heavy rainfall days

Nizamabad showed a possible increasing trend in August, and Ranga Reddy showed the same in September. Adilabad exhibited increasing trends in both months. Except for September, Mahbubnagar showed no trend in heavy rainfall days, while Nalgonda remained stable in August.

Overall, most of the state exhibited no significant trend in very high rainfall days. However, Adilabad and Mahbubnagar showed a potential increasing trend in July, and Warangal in September. Warangal also showed a significant increase in August at the 97% confidence level (Fig. 8).

Kinematics of the monsoon flow through stream function (velocity potential), rotational (divergent) wind perspectives

The stream wind flow and rotational wind patterns at 850 hPa

The variability of precipitation over Telangana is influenced by complex interactions between regional wind patterns and larger-scale monsoon dynamics. Telangana, being a semi-arid region, is highly dependent on the southwest

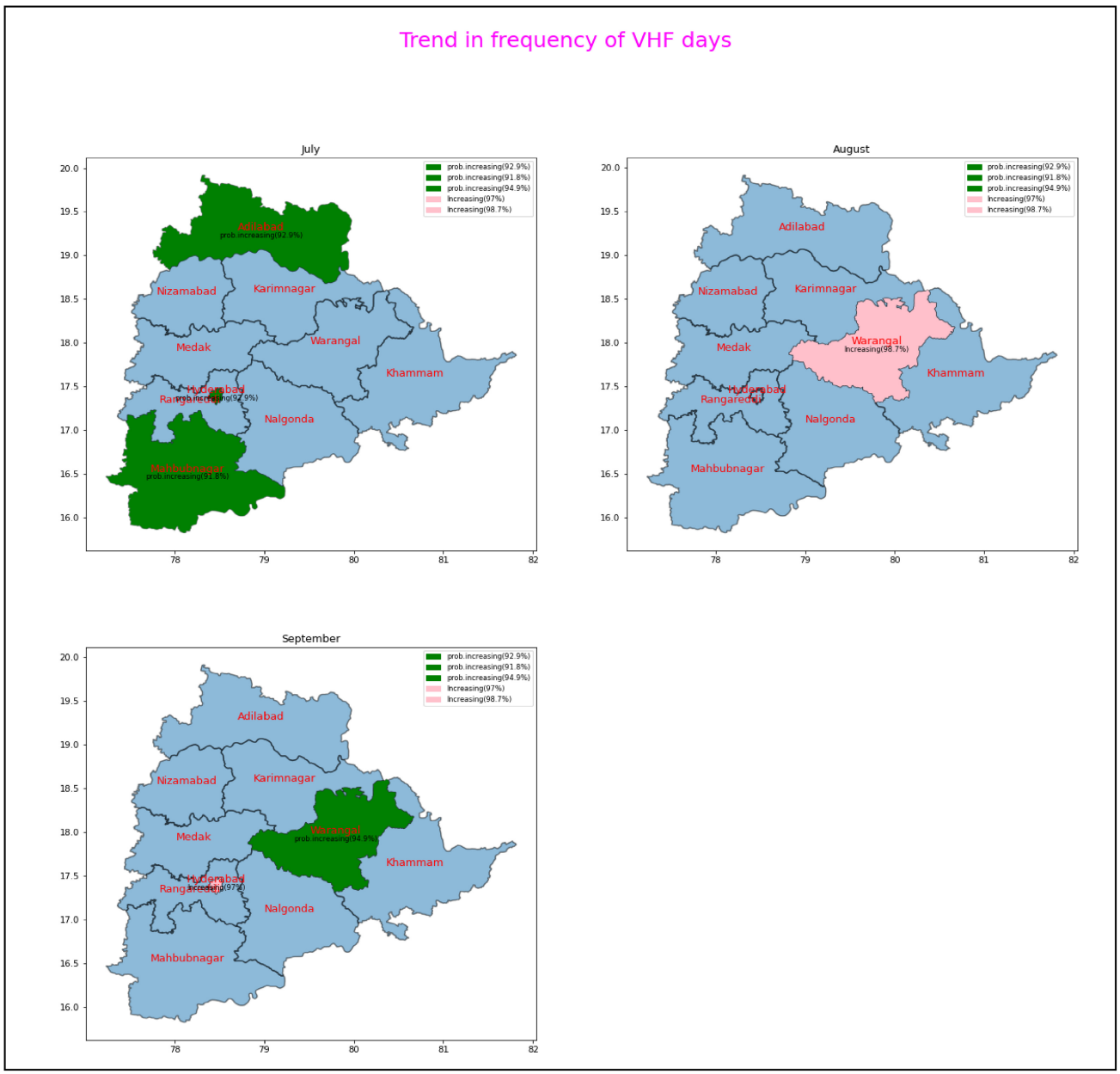


Fig. 8 Trend in average frequency of very heavy rainfall days

monsoon for the majority of its annual rainfall. Understanding the shifts in wind flow and monsoon intensity is crucial to explaining variations in precipitation patterns across the region.

Figure 9 illustrates the stream wind flow and rotational wind patterns at 850 hPa during the summer monsoon season. The figure compares the mean wind flow over the entire study period with decadal differences, providing insights into evolving monsoon behavior. Figure 8a depicts the average stream flow and rotational winds, highlighting the predominant monsoon wind patterns across the Indian subcontinent and surrounding seas. These patterns are vital for the onset and distribution of rainfall, particularly in regions like Telangana, which lies inland and depends on the movement of moist air masses from the Bay of Bengal (BoB) and the Arabian Sea (AS). Figures 9b–d focus on decadal changes in wind flow for the periods 1991–2000, 2001–2010, and 2011–2020, respectively. These figures illustrate significant shifts in wind intensity and direction, particularly over the BoB and AS. Such shifts have direct implications for the strength and trajectory of monsoon winds that transport moisture into the interior of the Indian subcontinent, including Telangana.

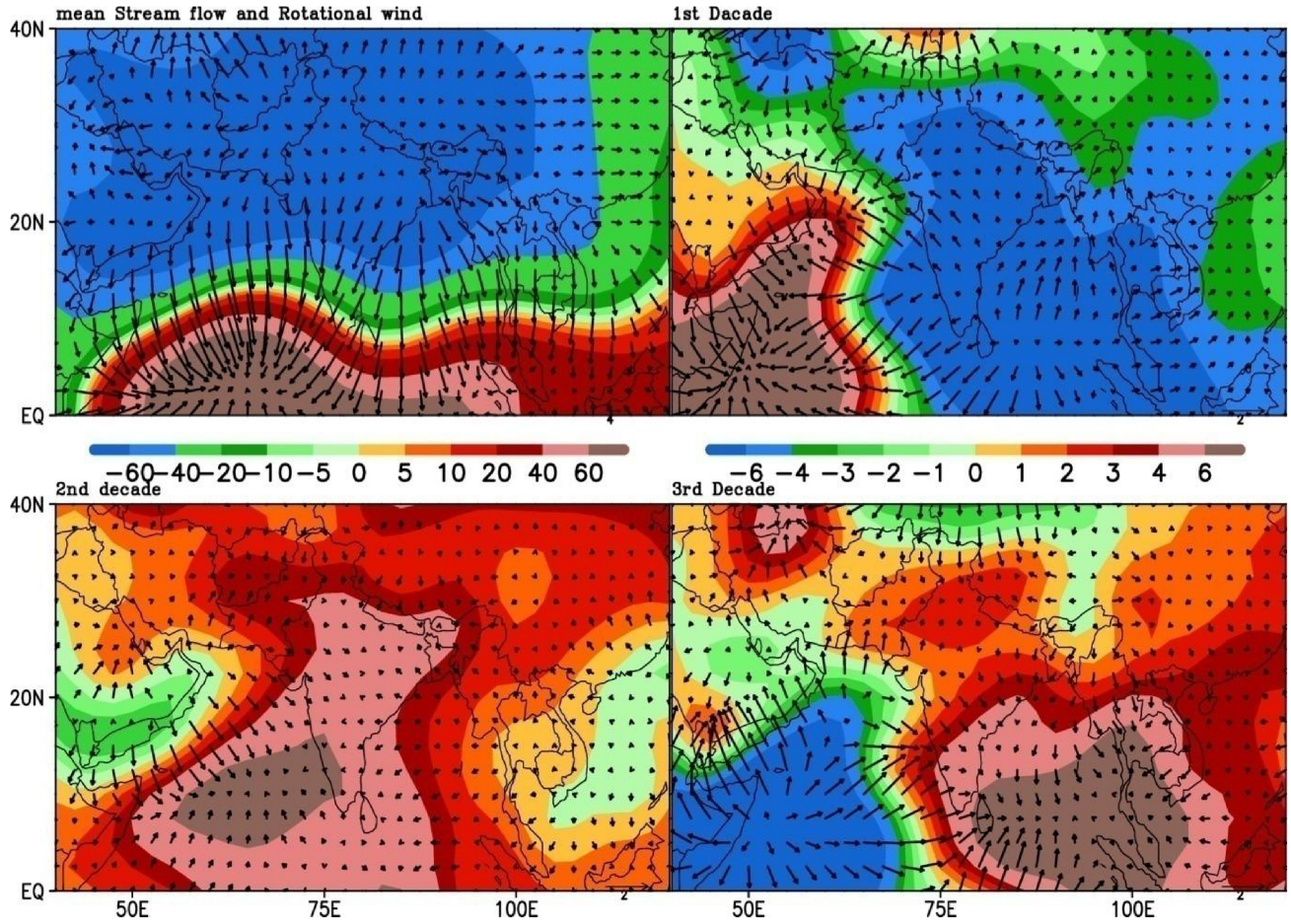


Fig. 9 Stream wind flow and rotational wind at 850 hPa for summer monsoon season **a** Mean for the entire study period **b** differences (1991–2000), **c** differences (2001–2010) and **d** differences (2011–2020)

The decadal changes in wind patterns reflected in Fig. 9 suggest that variations in monsoon strength could lead to fluctuations in rainfall distribution and intensity across Telangana. For instance, a strengthening of the monsoon winds from the BoB may result in increased rainfall in the eastern parts of Telangana, while a weakening could lead to reduced precipitation and prolonged dry spells. This variability in rainfall, in turn, affects agricultural productivity and water resources, both of which are critical to the state's economy and livelihood. The observed decadal shifts in wind flow patterns may also be linked to broader climate change phenomena, such as warming sea surface temperatures or changes in the Indian Ocean Dipole. These changes can alter the monsoon system, making it more unpredictable. For Telangana, this could mean a greater incidence of extreme weather events, such as heavy downpours or droughts, posing challenges for water management and agricultural planning.

The velocity potential (VP) and divergent wind patterns at 200 hPa

Figure 10 illustrates the velocity potential (VP) and divergent wind patterns at 200 hPa for the summer monsoon season, presenting the climatological mean from 1991 to 2020 (Fig. 10a) alongside the decadal anomalies for 1991–2000 (Fig. 10b), 2001–2010 (Fig. 10c), and 2011–2020 (Fig. 10d). These figures help visualize the changes in upper-tropospheric circulation and the associated large-scale monsoon dynamics over the Indian subcontinent.

Figure 10a: The climatological mean (1991–2020) depicts the typical large-scale monsoonal circulation at the upper troposphere. The blue regions, indicating negative VP, correspond to areas of strong convergence, particularly over the Indian subcontinent, a characteristic feature of monsoon activity. Conversely, the warmer colors (reds and yellows) represent regions of divergence, especially to the west of the subcontinent, marking subsidence zones. This configuration is consistent with the expected large-scale tropical Walker

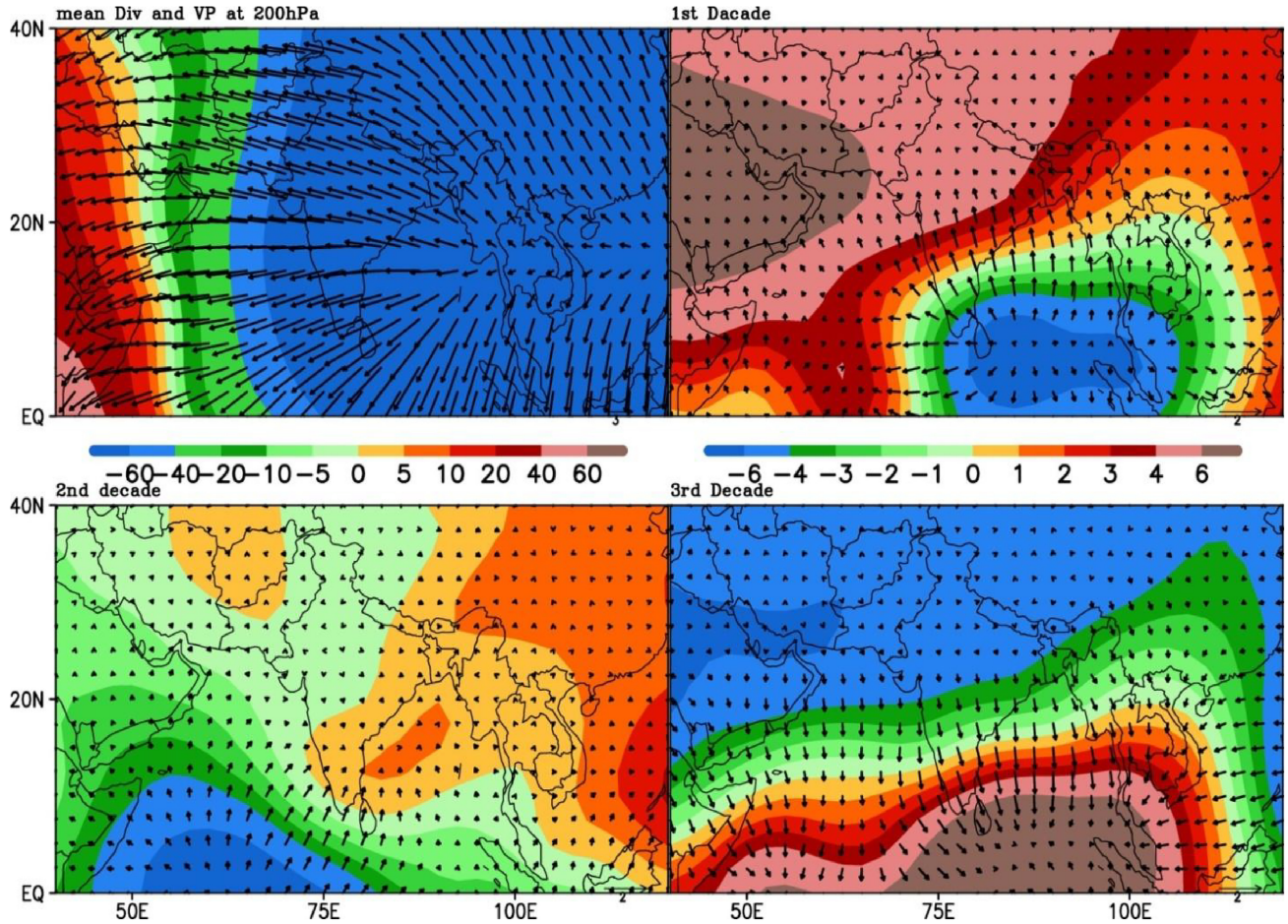


Fig. 10 Velocity potential and divergence wind at 200 hPa for the summer monsoon season **a** Mean (1991–2020), **b** differences (1991–2000), **c** differences (2001–2010) and **d** differences (2011–2020)

circulation during the monsoon season, with upper-level divergence over the eastern Indian Ocean and convergence over continental Asia.

Figure 10b: The anomaly for 1991–2000 shows positive divergence anomalies (reds and pinks) concentrated over northwestern India, parts of Central Asia, and extending into the AS. These features suggest weakened upper-level convergence during this decade, potentially indicative of suppressed convective activity over India. This weakened circulation could correspond to a weaker-than-average monsoon, possibly linked to variability in factors like the Pacific Decadal Oscillation (PDO) or the influence of El Niño episodes that tend to weaken the monsoon.

Figure 10c: The differences for 2001–2010 reveal enhanced divergence over western India and the northern BoB, pointing to stronger monsoonal circulation during this period. The increased divergence anomalies suggest more vigorous upper-level outflow, which typically corresponds to stronger convective activity and increased rainfall. This period may also be linked to enhanced convective activity over the Indian Ocean, driven by favorable phases of the IOD or La Niña episodes, which often lead to stronger monsoon circulations.

Figure 10d: The 2011–2020 anomalies show an intensification of divergence over western and southern India, alongside increased convergence over Southeast Asia and parts of the central Indian Ocean. This reflects notable shifts in the large-scale monsoon dynamics, potentially driven by the increasing frequency of climate modes such as the positive IOD and strong El Niño events. These anomalies suggest a redistribution of monsoon convection, with enhanced upper-level divergence over the AS and parts of the Indian subcontinent and a strengthening of convergence zones over Southeast Asia. Such patterns are often associated with more erratic monsoon behavior, influencing regional rainfall distribution and contributing to extremes like droughts and heat waves.

These decadal changes in upper-tropospheric divergence and velocity potential reflect the evolving monsoon circulation over the Indian subcontinent, influenced by interannual

and decadal climate variability. The shifting patterns in VP and divergent winds have significant implications for regional rainfall distribution, drought frequency, and the occurrence of extreme weather events, with potential impacts on agriculture, water resources, and socioeconomic conditions across the region.

Solar radiation (W/m^2)

Mean values of solar radiation (w/m^2) for the entire climatology period are plotted. The decadal anomalies with respect to these mean values are also visualised in Fig. 11.

The solar output over a large area of the state ranges between 12.6 × 10^2 and 13.2 × 10^2 W/m^2.The eastern and southwest fringes of the state received between 12.2 × 10^2 and 12.6 × 10^2 W/m^2 while the smaller patches of south and west received isolation between 13.2 × 10^2 and 13.8 × 10^2 W/m^2. Over the entire state there were positive anomalies ranging between 3–4 and 4–6 with clear spatial demarcations during the decade 1991–2000. There were more normal values of solar radiation over the state during 2001–2010 with positive anomaly (1–2 W/m^2) spotted over only miniscule portion of North Telangana and a diminutively little negative anomaly (− 1 W/m^2) observed over extreme eastern edge of the state. In the recent decade 2011–2020, there were wide swathes of negative anomalies (− 4 to − 6 W/m^2) and a small fraction of the northwestern part of the state showed negative anomaly of − 3 to − 4 W/m^2.

The positive anomalies indicate increased solar input indicating diabatic heating and little cloudiness while the negative anomalies of insulation imply cloudiness and condensation and hence the possibility of precipitation (Hodges and Loughran 2000; Koster and Milly 1997).

Soil moisture

Soil moisture plays a crucial role in influencing rainfall patterns, particularly during the monsoon season. Dry, parched lands during the pre-monsoon period can trigger feedback mechanisms that impact the boundary layer of the atmosphere. The process of evapotranspiration transfers soil moisture from the surface to the boundary layer, which in turn sustains monsoon circulations both locally and remotely. Shukla et al. (1982) demonstrated through simulations that dry soils can initiate water–vapor transport from nearby oceans, enhancing the land–ocean temperature contrast that drives the monsoon system.

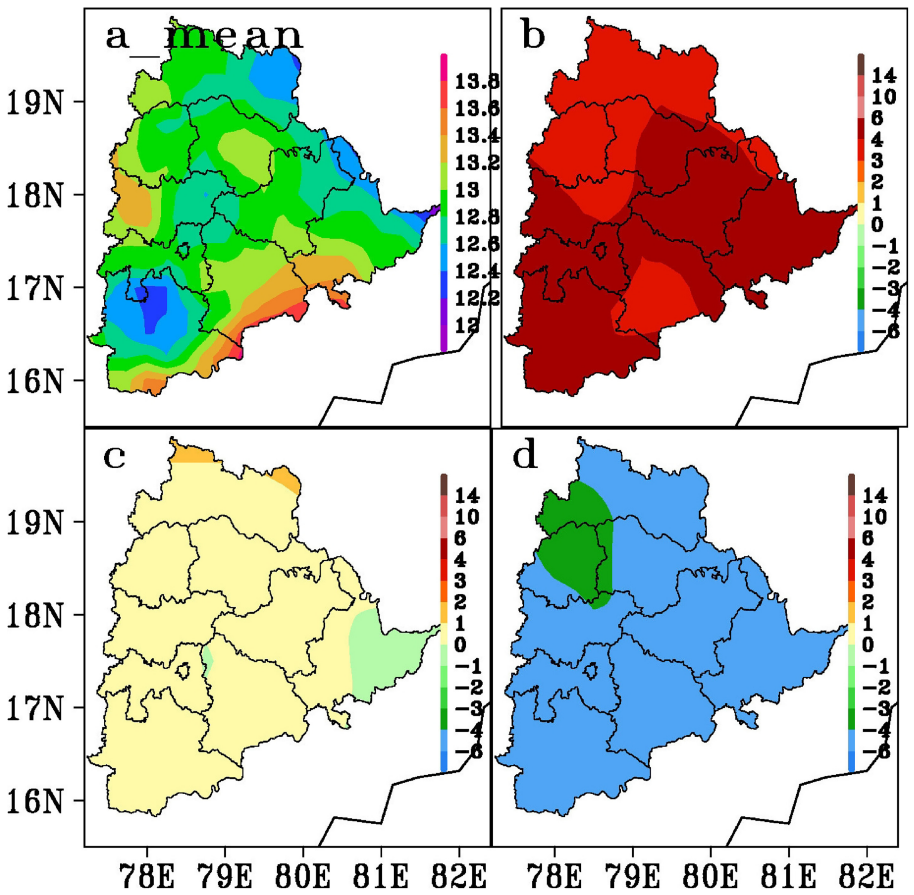


Fig. 11 Solar radiation (W/m.^{2}) for summer monsoon season **a** Mean for the entire study period **b** differences (1991–2000), **c** differences (2001–2010) and **d** differences (2011–2020)

In the latest decade (2011–2022), positive soil moisture anomalies have been observed, coinciding with increased rainfall during this period. The rise in soil moisture promotes convection by enhancing latent heat flux and accumulating moist static energy, as noted by Pal et al. (2001). Figure 12 illustrates these changes by showing the mean soil moisture levels (1991–2020) and the deviations for each decade in Telangana. Except for a small area in the southern districts (parts of east Rangareddi, south and west Nalgonda, and east Mahbubnagar), most of Telangana shows soil moisture levels ranging from 320 to 380 m3/m3. This increase in soil moisture is linked to the higher frequency of rainfall during the monsoon season.

Bounoua and Krishnamurti (1993) highlight that storing water in the soil for extended periods and managing water resources effectively such as diverting water from surplus to deficit areas can significantly enhance the soil's water-holding capacity. Recent studies by Naidu et al. (2017), Baisya et al. (2017), and Nanaji et al. (2022) support this view. Interestingly, the spatial distribution of soil moisture has expanded in the most recent decade compared to the first (1991–2000) and second (2001–2010) decades. Notably, the northernmost and western districts of Telangana, as well as parts of the east, have shown significant increases in soil moisture (by 14 m3/m3 and 6 to 10 m3/m3 in some areas). This rise is attributed to more frequent rainfall, improved water harvesting methods, and state government policies aimed at rainwater storage and conservation.

Summary and conclusions

This study analysed the summer monsoon (June–September) rainfall trends across Telangana from 1991 to 2020, with special emphasis on the last decade (2011–2020). Key findings are:

- Telangana experienced an upward trend in monsoon rainfall, averaging an annual increase of 7.8 mm over the study period, a trend statistically significant at the 95% confidence level. Notably, the last decade saw frequent positive rainfall anomalies, with the northern and eastern districts like Warangal and Medak experiencing the most substantial rainfall increases. Southern districts, such as Mahbubnagar and Nalgonda, also recorded significant rainfall growth during 2011–2020.
- Distinct shifts in rainfall patterns were observed over three decades: 1991–2000, 2001–2010, and 2011–2020. In the recent decade, southern Telangana saw marked

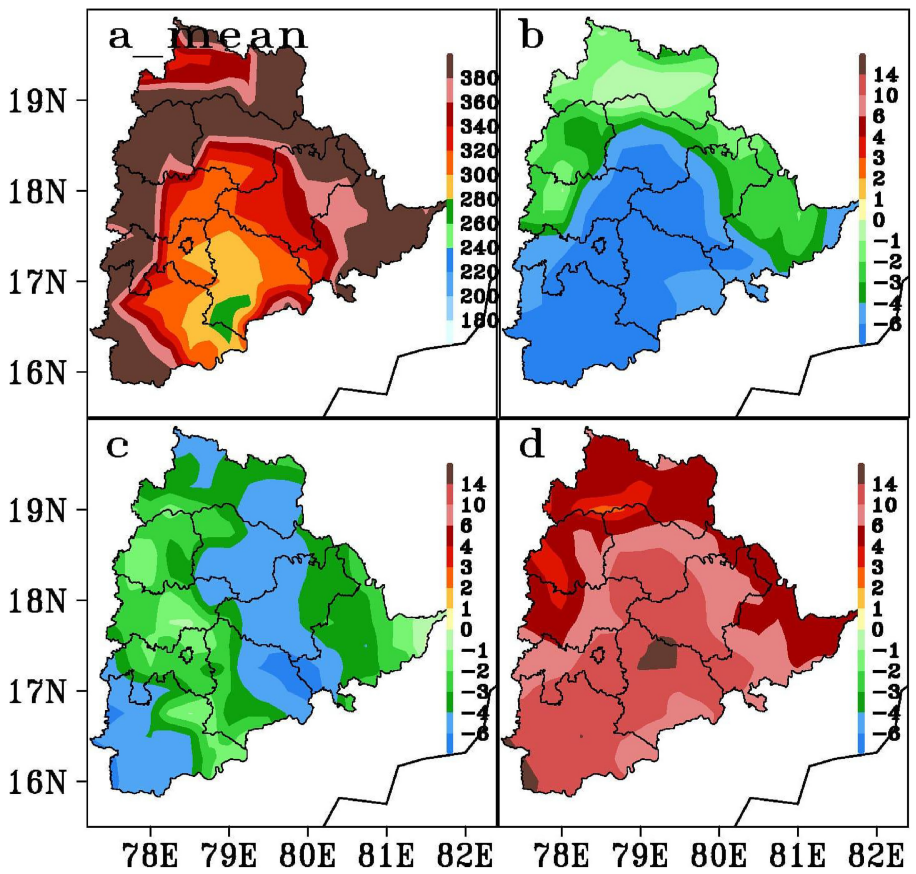


Fig. 12 Spatial distribution of soil moisture (m3/m3) Telangana for the summer monsoon season **a** Mean for the study period, **b** differences (1991–2000), **c** differences (2001–2010), and **d** differences (2011–2020)

increases in rainfall, possibly linked to changing atmospheric patterns and the influence of nearby river systems.
- There has been a noticeable rise in the number of rainy days ($\geq$2.5 mm) and moderate-to-heavy rainfall events over the past decade. Central Telangana showed the highest increase in the frequency of rainy days, while heavy rainfall events became more widely distributed across the region.
- Variations in the monsoon flow at lower (850 hPa) and upper (200 hPa) atmospheric levels were found to contribute to changing rainfall patterns. Decadal shifts in wind circulation over the BoB and AS were influential in these changes. Large-scale climate phenomena, such as the Indian Ocean Dipole (IOD) and El Niño events, further impacted the monsoon's behavior in Telangana.

The rise in monsoon rainfall, while beneficial for agriculture, also poses risks such as flash floods and soil erosion due to more intense rain events. These findings highlight the increasing unpredictability of monsoon patterns in the region, driven by climate change and global atmospheric variability. The monsoon rainfall in Telangana has undergone significant shifts in the past few decades, especially in the last ten years. Increased rainfall frequency and intensity indicate that monsoon patterns are becoming more erratic due to changes in regional and global climate systems. These changes underscore the need for adaptive strategies in agriculture, water management, and disaster preparedness to address the emerging challenges posed by these evolving monsoon patterns in Telangana.

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Data availability Rainfall dataset was obtained from https://imdpune.gov.in/lrfindex.php and the rest of the data used in the study were sourced from ERA5 data as accessed from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5 and The ERA5 Global Reanalysis Hersbach, H. et al. May 2020. QJRMS, https://doi:10.1002/qj.3803.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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