Journal of Basic & Applied Sciences, 2023, *19*, 1-19

Published by SET Publisher

Journal of Basic & Applied Sciences

ISSN (online): 1927-5129

District-Level Seasonal Rainfall Characteristics over Andhra Pradesh and its Global Teleconnections in Changing Climate

M.M. Nageswararao[1,2,*], M.C. Sannan[3], A.K. Sahai[1], K.R. Baswanth Kumar[4], Susmitha Joseph[1] and M. Anji Reddy[4]

[1]Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Govt. of India, Dr. Homi Bhaba Road, Pashan, Pune, Maharashtra, India; [2]CPAESS, University Corporation for Atmospheric Research at NOAA/NWS/NCEP/EMC, College Park, Maryland, USA; [3]School of Earth, Ocean and Climate Sciences, Indian Institute of Technology (IIT) Bhubaneswar, Argul, Jatni, Odisha, India; [4]Center for Environment, Jawaharlal Nehru Technology University, Hyderabad, Telangana, India

Article Info:

Keywords:
Seasonal rainfall,
Climate change,
Andhra Pradesh,
District-level rainfall,
ENSO,
Global warming.

Timeline:
Received: December 15, 2022
Accepted: January 15, 2023
Published: February 01, 2023

Citation: Nageswararao MM, Sannan MC, Sahai AK, Baswanth Kumar KR, Joseph S, Anji Reddy M. District-level seasonal rainfall characteristics over andhra pradesh and its global teleconnections in changing climate. J Basic Appl Sci 2023; 19: 1-19.

Abstract:

Investigating the trends and changes in rainfall over vulnerable regions is of huge importance in this global warming era. The present study intensively investigates the rainfall over the Indian state, Andhra Pradesh (AP), and its 13 districts using a high-resolution (0.25°×0.25°) gridded rainfall analysis dataset from India Meteorological Department (IMD) for the study period of 118 years (1901-2018). For this, normality, homogeneity, persistence, and change-point tests are performed and changes in the district-level rainfall in the present global warming period (1991-2018) as compared to the pre-global warming period (1901-1990) is also analyzed.

The results suggest that the long-term average annual rainfall over AP is 882 mm and most of the rainfall is contributed by the monsoon (55.7%) and the post-monsoon rainfall (32.8%). The coefficient of variation is low (high) during monsoon (winter). The coastal region receives more rainfall than the inland districts. The post-monsoon rainfall over AP is more consistent than in other seasons, and the persistence is only during the southwest monsoon season. The southwest monsoon and post-monsoon rainfall have increased (by about 10%) over most of the districts in the recent period. The Nino3.4 region SST (South Oscillation Index; SOI) has a significant negative (positive) relationship with southwest summer monsoon rainfall in most of the districts. The relationship of Nino 3.4 SST and DMI is strikingly similar for post-monsoon and has significantly weakened in recent decades. This study is useful for proper planning and mitigation measures for the agricultural and water resources sector at the district level over AP in this global warming era.

DOI: https://doi.org/10.29169/1927-5129.2023.19.01

*Corresponding Author
E-mail: muralinagesh.ocean@gmail.com

1. INTRODUCTION

Global warming-induced climate change, accompanied by a rise in temperature, can pose a serious threat to mankind in numerous ways [1]. One of which arises due to the increase in the water-holding capacity of the atmosphere that may lead to changes in the precipitation frequencies and patterns all around the world, which impacts various sectors such as agriculture, and hydropower generation, which are highly dependent on rainfall [2-3]. So, the analysis of rainfall changes at the regional/local level in the present global warming era is highly important to explore the impacts of climate change on water resource management and to control, adapt and mitigate with proper planning and management strategies [4]. Various studies shows that an increasing trend an increasing trend in extreme precipitation events globally and in India [5-8]. During the last few decades, India has experienced a subtle decrease in rainfall, frequency of rainy days, and increased relative humidity [9-11]. A recent study of Indian River basins reveals that the annual rainfall and the number of rainy days have remarkably decreased in 15 out of 22 basins [12]. There is conclusive evidence from recent studies that rainfall is decreasing in Asia [10-11, 13-16]. These significant changes in variability and trends in climate over South Asia are mostly caused due to anthropogenic influence, which is high over regions with a population of about 2 billion; South Asia is one of the regions most vulnerable to global warming [17-21]. Even though plenty of global and continental-scale studies related to global warming are available, they are rarely useful in local or regional scale planning [22-23]. Hence, there is a need to study the changes in rainfall at a regional/ local level, especially in regions where agriculture is highly dependent on it. In the present study, an effort has been made to unravel the climatological patterns, trends, and recent changes in the rainfall over the Indian state, Andhra Pradesh (AP) at a district level in the past century. A year is divided into four seasons viz. winter (Jan-Feb), Pre-monsoon (March-May), Monsoon (June- September), and Post-monsoon (October-December), and the study is carried out for the period 1901-2018 (118 years).

Apart from the apparent reasons, such as global warming, that have an increasing effect on the rainfall, Ocean-atmosphere phenomena such as the Indian Ocean Dipole (IOD) and the El Niño Southern Oscillation (ENSO) are also known to affect the regional rainfall over the Indian region [20-21, 24-33]. The inter-annual variability of post-monsoon rainfall over India has a strong positive relationship with ENSO, while the relationship is inverse for the monsoon rainfall [26-27, 29-30, 34-36]. These same studies also point out that the relationship between monsoon rainfall and ENSO has weakened in the previous decade, while the relationship of post-monsoon rainfall has strengthened [19-21]. There is a significant positive relationship between the Indian Ocean Dipole mode (IODM) and Northeast monsoon over South Peninsular India (SPI) [25], which has weakened in recent periods as compared to that of ENSO [37]. In the decades, the southern oscillation index (SOI) has been negatively correlated with the post-monsoon rainfall over AP [38]. The relationship between these global climate indices and local scale rainfall in AP needs to be evaluated to explore the global climate indices' influences for a better understanding of recent changes in seasonal rainfall at the regional level in AP [19-21, 39-40]. For better planning and implementation of adaptation strategies in agriculture, water resources, and hydro energy sectors, rainfall information at higher spatial resolution at specific district levels are highly necessary. A few studies found that there is a significant increasing trend of southwest summer-monsoon and post-monsoon rainfall over AP, and it was confirmed that the increase is mostly due to the increase in the high-intensity rainfall events [20, 41-42]. But these studies only focus on AP as a whole and do not address this at a district level, which is critical for proper planning and management of water resources in a rain-dependent seasonal agriculture-based locality. Therefore, this study attempts to investigate rainfall characteristics during four distinctive seasons at a district level over the state of AP using long-term high-resolution gridded analysis datasets from India Meteorological Department (IMD). This study will be beneficial for a retrospective understanding of the behavior of district-level rainfall in AP and its global teleconnections, which would help prepare better water resource management strategies and catastrophe preparedness, such as flood control at the district level. In this paper, a brief description of the study domain, data and analysis methodologies are provided in section 2. The results are presented in section 3, and the broad conclusions are summarized in section 4.

2. STUDY DOMAIN, DATA, AND METHODOLOGY

2.1. Study Area

AP is a state located at the southeast coast of India between the latitudes 12°41'N and 19°07'N and longitudes 77°E and 84°40'E and shares about 974 km of coastline with the Bay of Bengal (Figure **1**). It is known as the "Rice Bowl of India" and its economy is mainly based on agriculture where about 60% of the population is engaged in agriculture and related activities, and it contributes 34% to the state's Gross Domestic Product. Hence, there is a huge economic dependency on rainfall which is now highly vulnerable to variability under the influence of climate change. The detailed analysis of rainfall characteristics and trends of the seasonal rainfall for all four seasons, at each of the 13 districts and AP as a whole is carried out, which is very crucial for local-scale planning and proper analysis-based implementation of newer technologies for sustainable development in the present global warming era. The 13 districts are shown in Figure **1** and abbreviated in Table **1**.

2.2. Data used and Methodology

The IMD daily gridded rainfall analysis dataset which is available at a high-resolution of 0.25° × 0.25° for the study period (1901-2018) has been obtained from the National Data Centre, IMD Pune archives, and utilized to perform this study. This high-resolution daily gridded dataset is prepared using 6955 rain gauge station records in India available at different periods; more details about the preparation of this dataset are available in [43], and evidence of its superiority compared to existing datasets can be found in [44]. To study the district-level seasonal rainfall over AP, a year is divided into four seasons namely winter (January-February, JF), pre-monsoon (March-May, MAM), southwest monsoon (June–September, JJAS), and post-monsoon (October– December, OND). The analysis of long-term time series of seasonal rainfall for 13 districts is carried out. To have an overwied understanding of the general characteristic of rainfall over AP, the climatological mean, inter-annual variability (IAV), and coefficient of variation (CV) are computed for the study period (1901-2018) of 118 years.

Various statistical tests such as the Shapiro–Wilk normality test (SWNT), Hurst exponent (H), Pettit's test (PTT), Buishand range test (BRT), Buishand U test (BUT), and standard normal homogeneity test (SNHT) were performed to quantify the homogeneity, normality, persistence and sudden changes of seasonal rainfall over the 13 districts of AP for the study period. The Shapiro–Wilk normality test is done to know whether the seasonal time series of rainfall for the 13 districts of AP are normally distributed at a 95% confidence level [45-46]. The other four tests, i.e., PTT, BRT, BUT and SNHT are performed to test the homogeneity of the

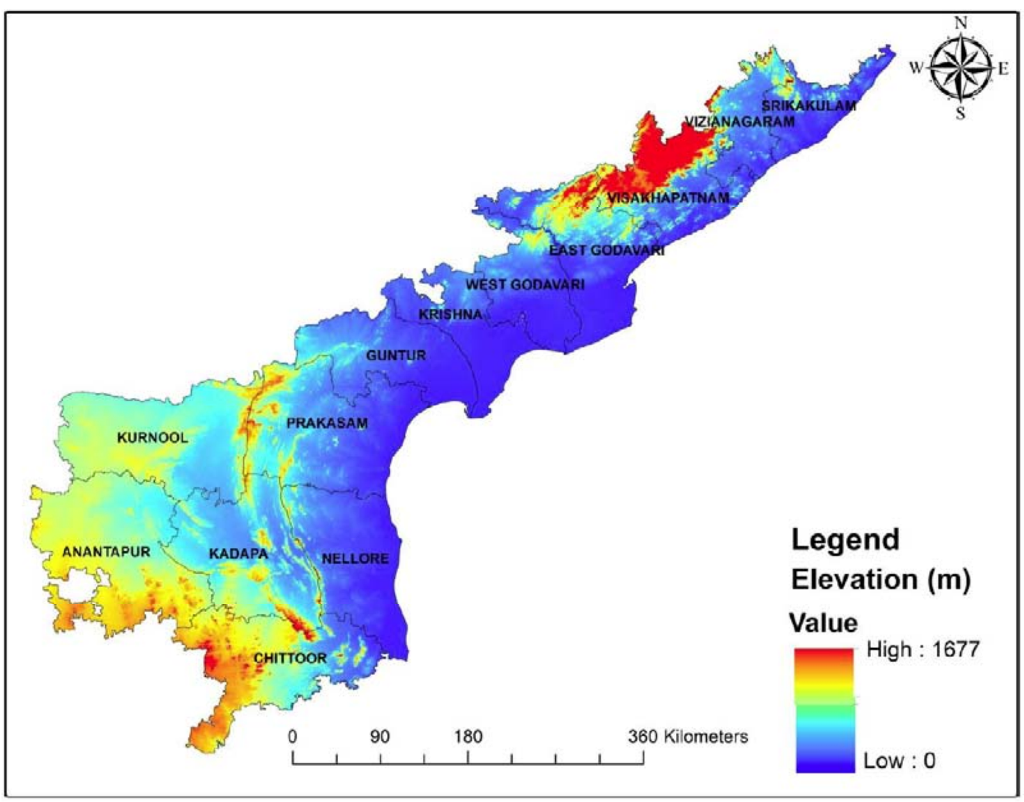


Figure 1: Districts and Elevation of Andhra Pradesh.

Table 1: Short Forms used in this Study

Short forms	Full form
ANT	Anantapur
CHT	Chittoor
CV	Coefficient of Variation
DMI	Dipole Mode Index
EG	East Godavari
GNT	Guntur
IAV	Interannual variability
IMD	India Meteorological Department
JF	January-February
JJAS	June-July-August-Sep
KDP	Kadapa
KRI	Krishna
KRN	Kurnool
MAM	March-April-May
NINO 3.4 SST index	NINO3.4 region sea surface Temperature index
NLR	Nellore
OND	October-November-December
PRK	Prakasam
SOI	South Oscillation Index
SRK	Srikakulam
VSP	Visakhapatnam
VZM	Vizianagaram
WG	West Godavari

same [47]. However, it is necessary to mention that the BRT, BUT, and PTT are more convenient in detecting the discontinuities in the middle of the time series, while the SNHT is more sensitive in detecting the same near the beginning and end of the series [47]. The Hurst-exponent (H) test is used to quantify the persistence of a time series and also determines whether the series is completely random or has a long-term memory. In order to compute the Hurst exponent, the estimation of the dependence of the rescaled range on the timeline of observations is required. Out of the various ways to calculate the Hurst exponent [47-49], the most used method is the R/S analysis [50-51]. The value of H ranges from 0 to 1. Depending on the value of H, the time series is categorized as random (if $H = 0.5$), an anti-persistent, i.e., having negative autocorrelation (if $0 < H < 0.5$), and persistent, i.e., having positive correlation (if $0.5 < H < 1$), all at 95% confidence level [52]. The persistence of a series indicates that the next value is more likely to follow the same direction of the current value, and in the opposite direction for an anti-persistent series.

In order to determine the concurrent relationships of district-level rainfall with ENSO and IOD for all the seasons, the SOI, Nino3.4 region SST and Indian Ocean Dipole Mode Index (DMI) for the period 1901-2018 is obtained from the Climate Research Unit (CRU), University of East Anglia (http://www.cgd.ucar.edu/cas/–catalog/climind), while the time series of the seasonal rainfall is prepared using the IMD high-resolution gridded dataset itself. The secular variations of the relationship between seasonal rainfall over AP and the climate indices are analyzed by calculating the sliding correlations between them for a 31-year moving window during the study period. To determine the significance of the correlation coefficients, Student's t-test is performed for 3 different confidence levels, i.e., 90%, 95%, and 99%.

3. RESULTS AND DISCUSSION:

3.1. Monthly Rainfall Distribution over AP

Figure **2** illustrates the climatological mean, inter-annual variability (IAV), and coefficient of variation (CV) of monthly scale rainfall over AP for the study period (1901-2018). AP receives most of its rainfall during the retreating phase of the summer monsoon and during the post-monsoon season [8, 29-31, 53] which can be well perceived from the Figure **2a**. AP receives its maximum rainfall during October (163 mm) specifically when the post-monsoon season onsets over south peninsular India (SPI) [20]. The peak is however followed by 149 mm which is during September and adequate rainfall during June (126 mm) and July (131 mm). The least rainfall is received during February (8 mm), followed by 9 mm during January and March. About 55.7 % (492 mm) of the annual rainfall over AP is received during the monsoon season and 32.8 % (290 mm) during the post-monsoon months, whereas the rest of the rainfall is received during pre-monsoon (10.6 %) and winter months (1.9 %). During southwest summer monsoon and post-monsoon months, the monthly IAV is similar to that of its climatological mean (Figure **2a**). However, the IAV during May (42 mm) is more than that of IAV during June (36 mm), which is the other way around for climatological mean (Figure **2a**). The CV is a little more interpretable when it comes to the extent of variability, The CV is large during January (147 %), February (165 %), and March (159 %), which is high because it rarely rains during these months (Figure **2b**). However, the CV is high (105 %) during December as most of the rainfall contribution comes from the cyclonic disturbances over the Bay of Bengal, which is highly inconsistent [20]. The variability of monsoon rainfall over AP is considerably less than that of the rainfall received during the post-monsoon season [54].

3.2. Characteristics of District-Level Seasonal Rainfall over AP

The statistical characteristics of seasonal rainfall such as climatological mean, IAV, and CV for four respective seasons at district-level over AP during the study period of 118 years (1901-2018) have been computed. The analysis of rainfall distribution patterns during four distinctive seasons reveals that the seasonal rainfall over AP is highly heterogeneous in both spatial and temporal scales (Figure **3**). As stated earlier, it can be seen that the rainfall is lowest during winter (18.4 mm)

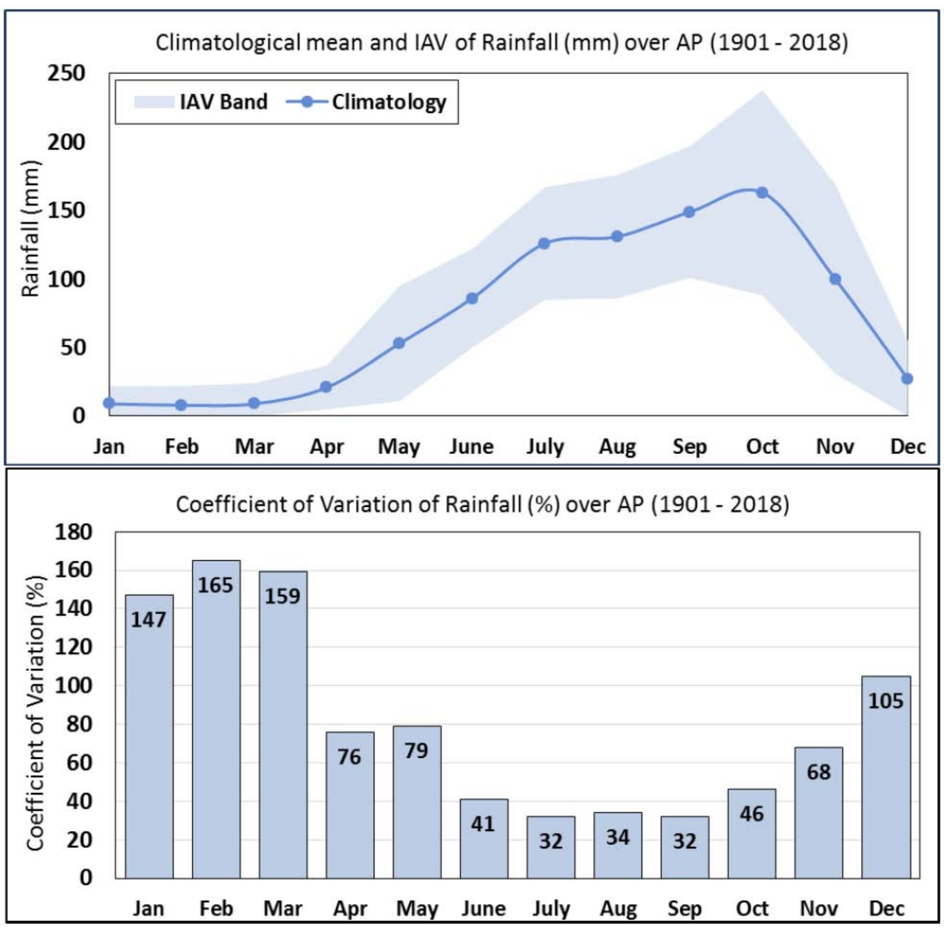


Figure 2: Statistical analysis of Andhra Pradesh rainfall (mm) at monthly scale (**a**) climatological mean and Inter-annual variability and (**b**) Coefficient of variation for the study period 1901-2018.

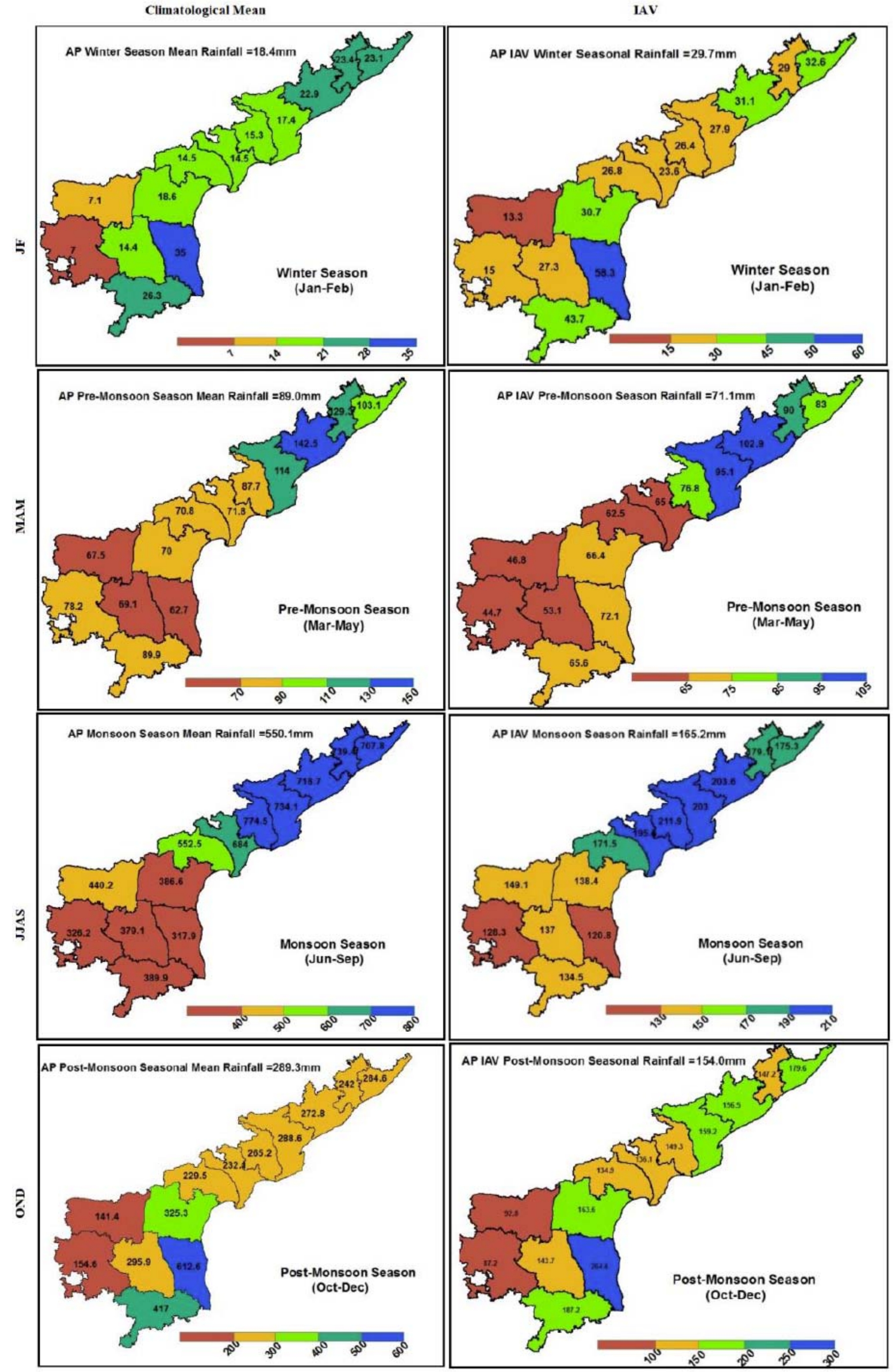


Figure 3: Climatological mean and IAV of district-level seasonal rainfall over Andhra Pradesh during four distinctive seasons for the study period 1901-2018.

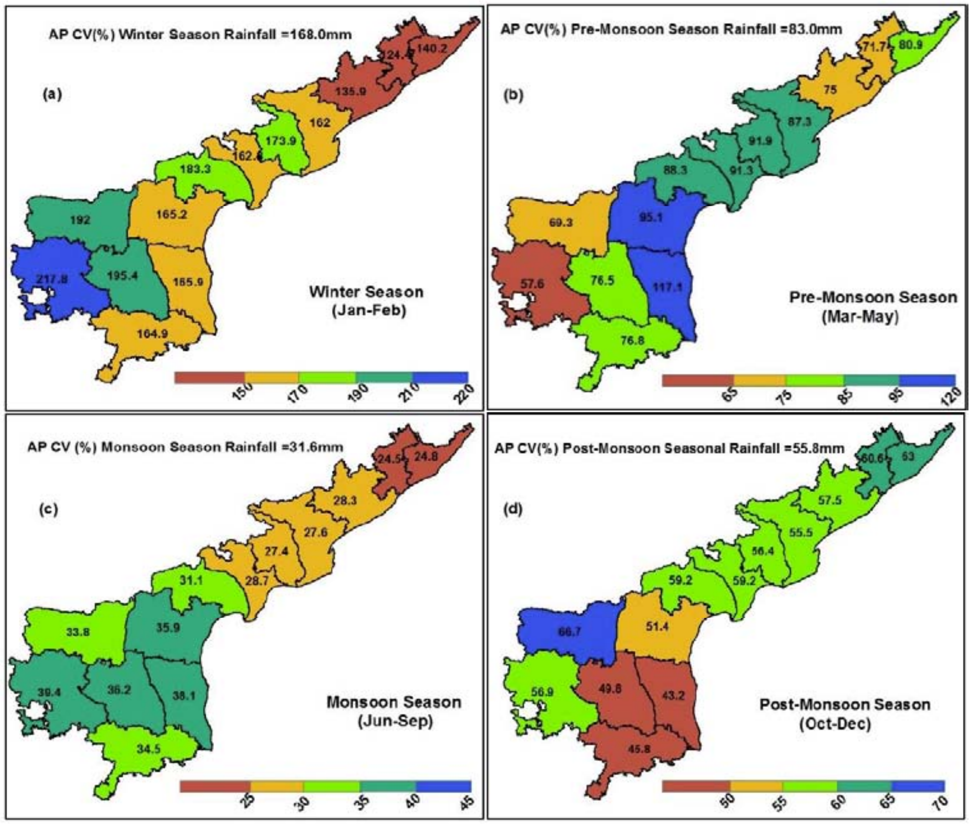


Figure 4: Coefficient of variation (CV in %) of district-level seasonal rainfall over Andhra Pradesh during four distinctive seasons (**a**) JF (**b**) MAM (**c**) JJAS and (**d**) OND for the study period 1901-2018.

and maximum during the monsoon season (550 mm), followed by post- (289 mm) and pre-monsoon (89 mm) seasons. During the monsoon season, the seven northern districts of AP above 16°N receive above 500 mm rainfall, which is particularly concentrated over five northern parts at above 700 mm. It is evident that the coastal districts receive more rainfall during all four seasons, which contributes to the entire state's rainfall, i.e. the rainfall amounts decrease spatially as we move away from the coast. The coastal region receives more rainfall than the interior parts of AP, especially during the post-monsoon season due to the influence of cyclonic disturbances over the Bay of Bengal as it decreases towards interior parts of the AP. The north-south gradient almost reflects a mirror image during the southwest monsoon and the post-monsoon seasons, where the rainfall is higher in the northern part districts during the southwest monsoon season and in the southern part districts during the post-monsoon season and vice versa. The climatological rainfall occurring in the northern part districts of AP is due to the monsoon convective systems over the southern Bay of Bengal, which propagates to the land and hence precipitates in the coastal districts, which is anomalous to when the convection takes place over the northern Bay of Bengal and is transmitted towards northwestern India normally during monsoons [55]. The interior districts of AP seem to receive the least rainfall during all seasons. The rainfall over the northern region districts of AP during the post-monsoon is due to the retreating monsoon circulation bringing convective systems to peninsular India and the cyclonic formations in the Bay of Bengal [53]. The pattern of IAV is identical to the climatological mean, although it is noticed that the IAV value of pre-monsoon and winter season rainfall over a few districts is almost similar and more as that of their respective climatological mean, which supports the fact that most of the rainfall occurring during this season is of high intensity and brought in by the westward propagating cyclones from the Bay of Bengal. The magnitude of CV exhibits an opposite characteristic than that of the climatological rainfall during the southwest monsoon and post-monsoon seasons (Figure **4**). During the monsoon season, the CV is higher in the southern part of AP as it rarely rains in the region during normal monsoon seasons [56]. The CV during the post-monsoon season is high over the regions where the magnitude is low, as seen in the case of regions where monsoon rainfall is low as well. In terms of the inter-seasonal facet, the CV is highest during the winter season overall followed by the pre-monsoon season, as the ratio of climatological rainfall and the variability is very low, which is just another indication of rare, but heavy rains during these seasons.

To understand the statistical characteristics of district-level rainfall over AP with more lucidity, statistical tests such as Shapiro–Wilk normality test (SWNT), Hurst exponent (H), Pettit's test (PTT), Buishand range test (BRT), Buishand U test (BUT) and standard normal homogeneity test (SNHT) are conducted on the time series of seasonal rainfall. These tests help us to comprehend the normality, homogeneity, persistence, and abrupt changes in the district-level seasonal rainfall over AP. The SWNT, which signifies the normality at the 95 % confidence level (where the p-value is greater than 0.05) is computed for p-values and displayed in Table **2**. It is evident that the rainfall during the winter and the pre-monsoon season does not follow a normal distribution, although interestingly during monsoon, rainfall only over EG and WG follow a normal distribution. During post-monsoon, the rainfall follows a normal distribution over WG, NLR, KDP, and ANT. In the case of annual rainfall, the normal distribution of rainfall is only over WG, KDP, and ANT. Over AP as a whole, the normal distribution of rainfall is only during the post-monsoon season, which is the normal rainfall season and explicable, as the post-monsoon rainfall is more consistent over AP as a whole in comparison with the rainfall in the other seasons.

The persistence test of the district-level rainfall over AP is done by computing the Hurst exponent (H) and shown in Figure **5**. If H > 0.5, it indicates that the series is persistent, anti-persistent if H < 0.5 and random if H = 0.5. It is observed that the monsoon rainfall over AP and all its districts is persistent, which is attributed to the low variability during this season. Although the same is not observed for other seasons. Over AP, the rainfall is persistent over SRK, KRI, GNT, PRK, NLR, CHT, KDP, and KRN during the pre-monsoon season and over VZM, VSP, EG, WG, PRK, NRK, CHT, KDP, KRN during the post-monsoon season (The expansion of the abbreviations used can be found in Table **1**). The annual and winter rainfall over AP is persistent over all the districts except for WG.

The change point years with 90%, 95%, and 99% confidence levels in the time series of district-level seasonal rainfall over AP is analyzed by carrying out the PTT, BRT, BUT, and SNHT. The season-wise change point years for individual districts are given in Table **3**. From the PTT, it is perceived that there are 7 change point years for 13 districts (1938, 1939-3, 1944, 1977, 1982-2, 1983, 2005-2 during the winter season, the BRT and BUT suggests 8 change point years

Table 2: Shapiro-Wilk normality test (SWNT) for testing the normality of district-level seasonal rainfall over Andhra Pradesh during the four distinctive seasons for the period of 118 years (1901-2018). The p-value is > 0.05 (< 0.05) with bold (without bold) indicates that the associated district-level seasonal rainfall is following (not following) the normal distribution.

District	P values of Shapiro-Wilk normality test				
	JF	MAM	JJAS	OND	Annual
SRK	0.000	0.000	0.029	0.000	0.002
VZM	0.000	0.000	0.025	0.000	0.001
VSP	0.000	0.000	0.000	0.001	0.004
EG	0.000	0.000	**0.173**	0.027	0.028
WG	0.000	0.000	**0.576**	**0.085**	**0.060**
KRI	0.000	0.000	0.010	0.002	0.001
GNT	0.000	0.000	0.004	0.003	0.006
PRK	0.000	0.000	0.001	0.027	0.007
NLR	0.000	0.000	0.000	**0.546**	0.010
CHT	0.000	0.000	0.001	0.004	0.004
KDP	0.000	0.000	0.000	**0.120**	**0.112**
ANT	0.000	0.042	0.001	0.107	0.054
KRN	0.000	0.000	0.000	0.000	0.000
AP	0.000	0.000	0.039	**0.184**	0.014

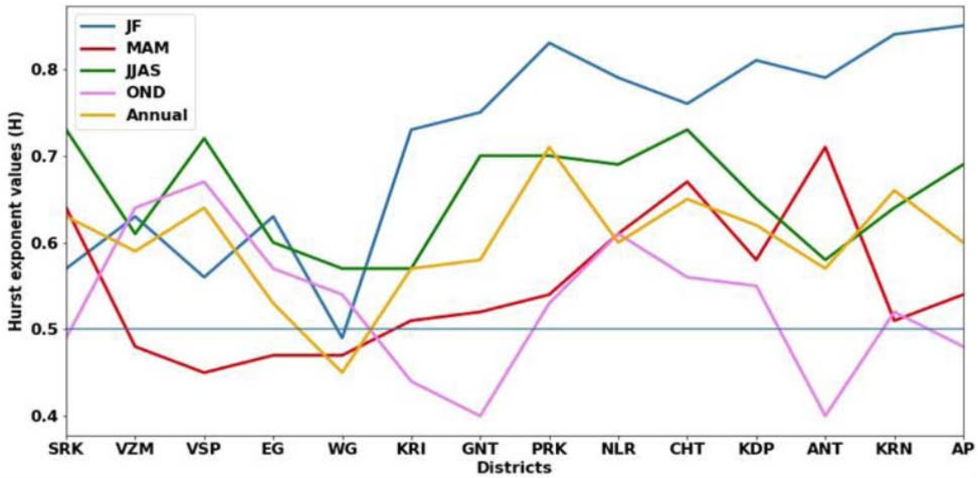


Figure 5: Hurst exponent (H) of district-level seasonal rainfall time series over Andhra Pradesh during four distinctive seasons for the long-term of 118 years (1901-2018). The Hurst-exponent values on the figure H>0.5, H<0.5, and H=0.5 values indicate that the time series of district-level seasonal rainfall is persistent (positive autocorrelation), anti-persistent (negative autocorrelation) and random (no memory of previous values) time series, respectively.

(1929, 1932, 1936-2, 1937-2, 1938-3,1977, 1984-2 and 2000) exactly same for all districts, while the SNHT suggests 6 change point years (1901-6, 1929, 1932-3, 1938, 2000 and 2008). The change point years for rainfall over AP during the winter season is 1938 (for PTT, BUT, and BRT) and 1937 (for SNHT). These change point years are at a 99% confidence interval over 2 (PTT), 3 (BRT), 2 (BUT) and 5 (SNHT) districts respectively and at a 95% confidence interval over 3 (BRT), 1 (BUT) and 5 (SNHT) districts and 90% confidence interval over 1 (PTT), 2 (BRT), 1 (BUT) and 1 (SNHT) districts respectively. During the pre-monsoon, season rainfall, there are about 12 (PTT), 7 (BRT, BUT, and SNHT) change point years for different districts and it is at 90% confidence level for 3 districts and 95% for 1 of them. Over AP as a whole, the change point year as computed by PTT is 1992, and 1989 computed by BRT, BUT, and SNHT. During monsoon season, the change point years are the same for all 4 tests over 6 districts and AP as a whole (the year 1952). It is noticeable that BRT and BUT tests however show the same change point years for all the districts for all rainfall seasons. There are about 7 (PTT), 6 (BRT, BUT, and SNHT) change point years for the rainfall during the post-monsoon season. The change point year over AP as a whole is 1914 (based on PTT, BRT, and BUT) and 2015 (based on SNHT). Most of the change point years during the winter season are from 1932 to 1939 and pre-monsoon season from 1985 to 1989. From this analysis, it is concluded that the changes in district-level regional rainfall for all four seasons range from 1930 to 1990 for most of the districts as well as AP as a whole. The inter-comparison between the four tests, however, for the sudden changes clearly establishes the sensitivity in detecting these changes at the beginning and end of the time series is higher for SNHT than the other three tests.

3.3. Comprehensive Analysis of Seasonal Rainfall over AP

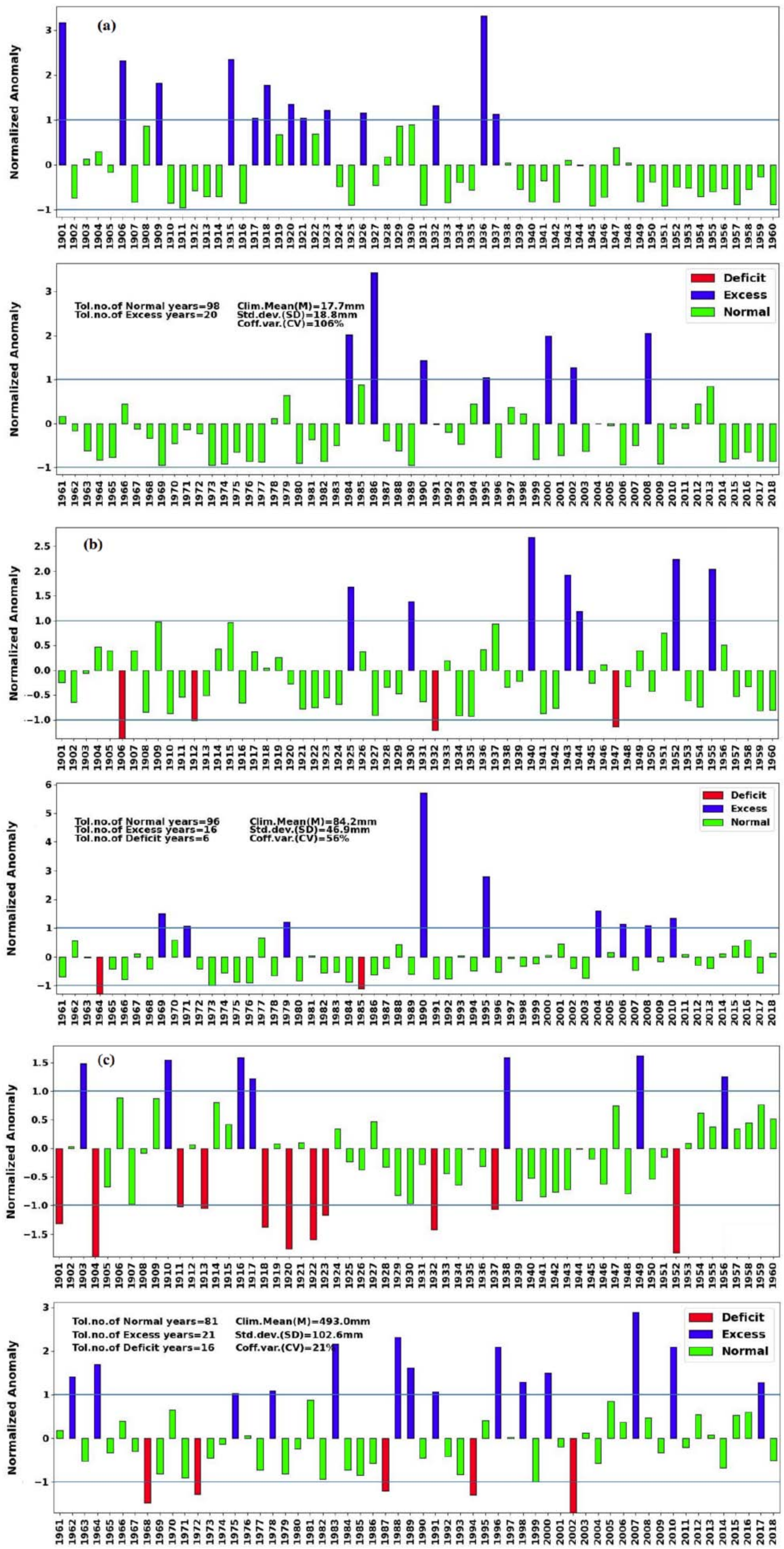
The normalized time series of rainfall over AP for four distinctive seasons JF, MAM, JJAS, and OND from 1901 to 2018 (118 years) has been prepared. Here, a particular year is categorized as normal if the standardized rainfall anomaly (SDR) is ± 1, as excess, if SDR > 1, and as a deficit, if SDR < -1. The normalized time series indicates a notable year-to-year variation in seasonal rainfall over AP for all the seasons (Figure **6**). It is observed that 20 years (1901, 1906, 1909, 1915, 1917, 1918, 1920, 1921, 1923, 1926, 1932, 1936, 1937, 1984, 1986, 1990, 1995, 2000, 2002, and 2008) have received excess rainfall and there has been no year with deficit rainfall during the winter season (JF), but most of the years usually receive below normal rainfall over AP during winter (Figure **6a**). It is interesting to notice that there is no excess rainfall year for consecutively 45 years from 1938 to 1983 during the winter season over AP (Figure **6a**). During the pre-monsoon season (MAM), AP has experienced about 16 years (1925, 1930, 1940, 1943, 1944, 1952, 1955, 1969, 1971, 1979, 1990, 1995, 2004, 2006, 2008, and 2010) of excess rainfall and 6 years (1906, 1912, 1932, 1947, 1964, and 1985) of deficit rainfall (Figure **6b**). Although it is needed to mention that rainfall during the pre-monsoon season for most of the years is below the mean just like the

Table 3: Years identified as change points by four change-point detection tests (Pettit's test (PTT), Buishand range (BRT), Buishand U test (BUT), and standard normal homogeneity test (SNHT) in seasonal rainfall at district level over Andhra Pradesh during JF, MAM, JJAS, OND seasons for the period of 118 years(1901-2018). *, **, ***Indicates that the abrupt changes in the seasonal rainfall is significant at 90, 95, and 99% confidence levels, respectively

District	JF				MAM			
	PPT	BRT	BUT	SNHT	PPT	BRT	BUT	SNHT
SRK	2005	2000	2000	2000	1980**	1985	1985*	1985
VZM	1944	1938	1938	1938	1985	1989	1989	1989
VSP	2005	1938	1938	2008	1935	1968	1968	1935
EG	2008	1938	1938	1901***	1985	1987	1987	1989
WG	1982	1937	1937	1901*	1920	1987	1987	1987
KRI	1982	1984*	1984	1901**	1998	1989	1989	1989
GNT	1983	1984*	1984	1901***	1956	1989	1989	1989
PRK	1977	1977**	1977	1901**	1986	1989	1989	1989
NLR	1939**	1936**	1936	1932**	1994	1938	1938	1938
CHT	1939***	1936**	1936***	1932***	1989*	1989	1989	1989
KDP	1939***	1932***	1932***	1932***	1987	1938	1938	1924
ANT	1944	1929***	1929*	1929**	2003	2003	2003	2003*
KRN	1938*	1937***	1937**	1901***	1987	1935	1935	2003
AP	1938*	1938***	1938**	1937**	1992	1989	1989	1989

District	JJAS				OND			
	PPT	BRT	BUT	SNHT	PPT	BRT	BUT	SNHT
SRK	1952***	1952**	1952***	1952**	1914**	1914	1914	1914
VZM	1946	1946	1946	2005	1914	1963	1963	1914
VSP	1995	2002***	2002*	2004***	1914	1914	1914	1914
EG	1987	1987	1987	1987	1977	1914	1914	2013
WG	1946	1946	1946	2014	1914	1914	1914	2013
KRI	1987	1987	1987	2009	1914	1914	1914	1914
GNT	1953**	1953**	1953***	1953**	1914	1914	1914	2014
PRK	1952***	1952**	1952***	1952**	1971	1971	1971	2015
NLR	1953*	1948*	1948**	1948*	1946	1946	1946	2015
CHT	1960*	1972*	1972**	1972*	1974*	1965	1965	1903
KDP	1953	1953	1953	1953	1965	1965	1965	2015
ANT	1919	1919	1919	1919	1989	1989	1989	1903
KRN	1952*	1946	1946	1946	1989	1970	1970	1992
AP	1952	1952	1952**	1952	1914	1914	1914	2015

other seasons (Figure **6b**). The high excess rainfall (having more than 5-SDR) that occurred during the year 1990 due to the super cyclonic storm over the Bay of Bengal, which caused a lot of damage to AP [57] is evident from the figure. During the monsoon season (JJAS), there are 21 years (1903, 1910,1916,1917, 1938, 1949, 1962, 1964, 1975, 1978, 1983, 1988, 1989, 1991, 1996, 1998, 2000, 2007, 2010, 2017) with excess rainfall and 16 years (1901, 1904, 1911, 1914, 1918, 1920, 1922, 1923, 1932, 1937, 1952, 1968,


(a)
Normalized Anomaly
Tol.no.of Normal years=98
Tol.no.of Excess years=20
Clim.Mean(M)=17.7mm
Std.dev.(SD)=18.8mm
Coff.var.(CV)=106%
Deficit
Excess
Normal
(b)
Tol.no.of Normal years=96
Tol.no.of Excess years=16
Tol.no.of Deficit years=6
Clim.Mean(M)=84.2mm
Std.dev.(SD)=46.9mm
Coff.var.(CV)=56%
(c)
Tol.no.of Normal years=81
Tol.no.of Excess years=21
Tol.no.of Deficit years=16
Clim.Mean(M)=493.0mm
Std.dev.(SD)=102.6mm
Coff.var.(CV)=21%

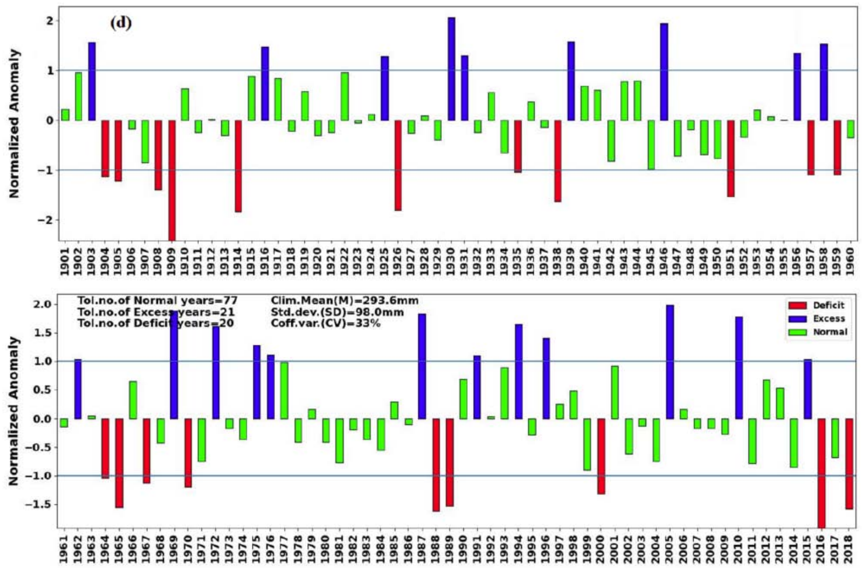


Figure 6: The normalized time series of (**a**) winter (JF), (**b**) Pre-monsoon (MAM), (**c**) Southwest summer monsoon (JJAS), and (**d**) Post-monsoon (OND) seasonal rainfall of Andhra Pradesh from 1901 to 2018.

1972, 1987, 1994, 2002) with deficit rainfall (Figure **6c**). It is noticed that there have been more excess monsoon years in the recent half of the study period (1961-2018) than in the earlier half (1901-1960), which is the opposite in terms of deficit monsoon years (Figure **6c**). During the post-monsoon season (OND), there are 21 years with excess rainfall and 20 years with deficit rainfall (Figure **6d**). There are no interrelationships with the excess, the deficit, and normal rainfall years between the monsoon and post-monsoon seasonal rainfall over AP, contrary to what is observed in an all-India rainfall.

To identify the extent of the impact of intense global warming on rainfall over AP in the recent decades, the mean difference of the district-level rainfall in the pre-global warming period (1901-1990) and the global warming period (1991-2018) for the respective seasons is computed and illustrated in Table **4**. This recent period is selected as there has been an intense rise in the Earth's temperature since before the cessation of the 20th Century [3]. The magnitude of monsoon rainfall has drastically increased in the recent period, and the increase is even more than 10% in a few districts. This increase is statistically significant at the 90 % confidence level over GNT, NLR, CHT, and AP as a whole and the 95% confidence interval at SRK, VSP, and PRK (Table **4**). It is interesting to notice that the post-monsoon rainfall has increased over all of the districts except for the 4 northern coastal districts of AP, where it has decreased notably over VZM, VSP, and EG and no change over SRK (Table **4**). Although not significant, there is an increase in the overall magnitude of rainfall over the majority of the districts in the most recent period for the pre-, and post-monsoon seasons (Table **4**), which could be mainly due to the increase in the frequency of cyclones over the Bay of Bengal in the recent times [58]. No significant decrease of rainfall is noticed in any of the districts during any season over AP (Table **4**) except CHT, whereas a significant decrease is observed during winter. Changes that have occurred in the Annual rainfall over AP are mostly due to the changes in the post-monsoon and monsoon rainfall for most of the districts (Table **4**). The significance of the increase in annual rainfall is of 90% confidence level over SRK, KRI, and AP as a whole and at a 95% confidence interval over KRN and PRK.

3.4. Empirical Relationships of Seasonal Rainfall over AP with ENSO and IOD

The secular variations in the simultaneous relationship between the rainfall over AP with Nino 3.4 SST, SOI, and DMI are analyzed by computing the sliding correlation between them on a 31-year moving window, the same is illustrated in Figure **7**. Any year mentioned here would mean the central year of the window of 31 years, for instance, the year 1916 defines the years from 1901 to 1931 and so on. The relationship of rainfall over AP with SOI and Nino 3.4 SST has an opposite pattern, although not exact (Figure **7a-d**). It can be inferred that the relationship of DMI with winter rainfall has weakened significantly in the last century (Figure **7a**). The relationship with SOI and Nino 3.4 SST was positive in the beginning years of the century

Table 4: Mean difference in the district-level seasonal rainfall between the global warming period (1991-2018) and pre-global warming (1901-1990) periods over Andhra Pradesh during four distinctive seasons. *,, ***Indicates that the recent changes in the monthly rainfall are significant at 90, 95, and 99% confidence levels, respectively**

District	Mean difference in the district-level rainfall				
	JF	MAM	JJAS	OND	Annual
SRK	-5.9	26.9	77.8**	0.0	95.5*
VZM	-5.9	8.6	3.2	-30.1	-24.3
VSP	-5.1	-7.4	88.7**	-17.7	58.6
EG	-2.3	0.3	49.8	-13.4	34.4
WG	-2.7	-3.6	17.1	2.2	13.0
KRI	3.9	7.1	58.3	20.1	89.4*
GNT	5.7	3.4	59.8*	2.7	71.5
PRK	9.9*	15.3	56.7**	25.8	107.8**
NLR	-3.7	6.7	40.4*	34.3	77.7
CHT	-14.2*	17.8	38.9*	19.5	62.0
KDP	-7.9	11.4	12.9	17.6	34.1
ANT	2.0	8.0	12.8	12.5	35.4
KRN	1.3	12.5	36.3	21.9	71.9**
AP	-1.4	8.5	40.7*	11.2	59.1*

which has weakened with SOI and has become negative for Nino 3.4 SST. It is observed that the relationship of DMI with pre-monsoon rainfall was statistically significant at 95 % confidence from 1956 to 1975, although it has drastically weakened as well (Figure **7b**). The SOI depicts a weak relationship with the pre-monsoon rainfall throughout the past century. The monsoon rainfall over AP has a significant relationship with Nino3.4 SST and SOI, and the relationship with DMI is not as strong (Figure **7c**). However, it is interesting to notice that the DMI and the Nino 3.4 SST have the same relationship with the rainfall over AP during the post-monsoon season (Figure **7d**). It is also intriguing to see a periodic pattern in the running relationship between these indices and the post-monsoon rainfall, which has a period of approximately 60 years for all three indices. Overall, this suggests that the Indian Ocean Dipole and the ENSO have an opposite influence on the monsoon and the post-monsoon rainfall. However, the relationship between monsoon and DMI has decreased in recent decades, and the relationship of post-monsoon rainfall with DMI and Nino 3.4 SST has weakened as well.

The relationship of seasonal rainfall over AP at a district level with global climate indices has not been explored before, which is a huge gap in the study area and needs to be investigated to have a proper insight into the various factors that influence local rainfall. In this analysis, the correlation of district-wise rainfall during the respective seasons with Nino 3.4 SST, SOI, and DMI for the study period of 118 years and illustrated in Figure **8**. It is noticed that there is an insignificant positive relationship of the district-level seasonal rainfall with Nino 3.4 SST during all the seasons except for the monsoon. The monsoon rainfall has a negative relationship with the Nino 3.4 SST over all the districts, and it is significant at the 99 % confidence level over most districts except for SRK, VZM, and VSP (90% confidence level). A similar inference can be derived from analyzing the relationships of district-level rainfall over AP with the Southern Oscillation Index (SOI). The monsoon season rainfall has a significant positive relationship over most of the districts (Figure **8**) and an insignificant negative relationship over most of the districts during the other seasons (Figure **8**). There is a significant positive relationship between SOI and monsoon rainfall over the entire state except for the three northern districts, which have a positive but insignificant relationship (Figure **8**). The Indian Ocean Dipole mode has a significant impact on the rainfall over the Indian region, and it has been well discussed in various studies [25,31, 59-60], whereas its implications on local rainfall are yet to be reviewed thoroughly. There is no significant relationship between DMI and seasonal

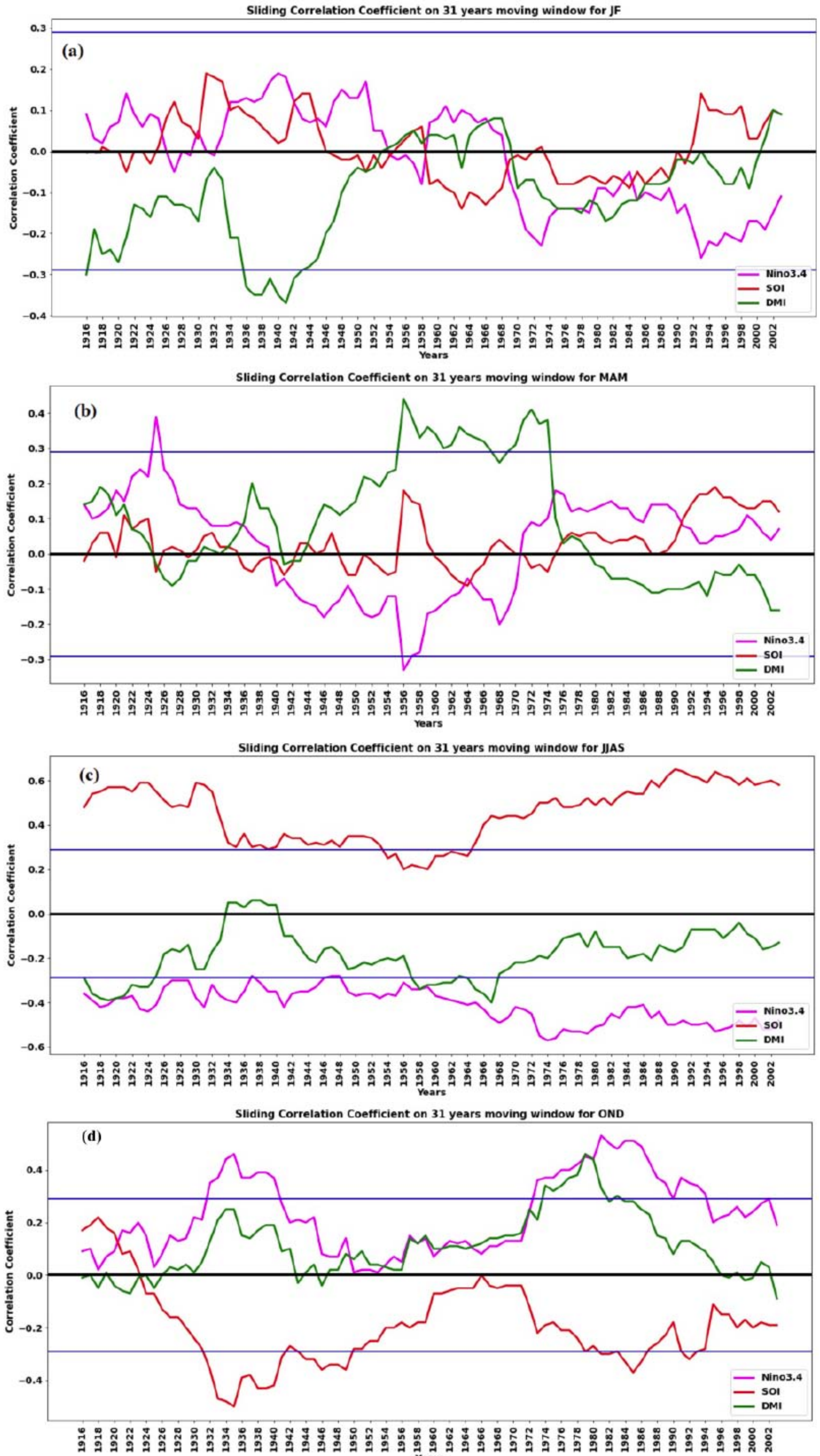


Figure 7: The sliding relationships on a 31–year moving window of climate indices such Nino3.4 region SST, SOI and DMI with Andhra Pradesh seasonal rainfall during four distinctive seasons (**a**) JF (**b**) MAM (**c**) JJAS and (**d**) OND for the period 1901–2018. The 95% significance level of 31-year period correlation value is ± 0.29.

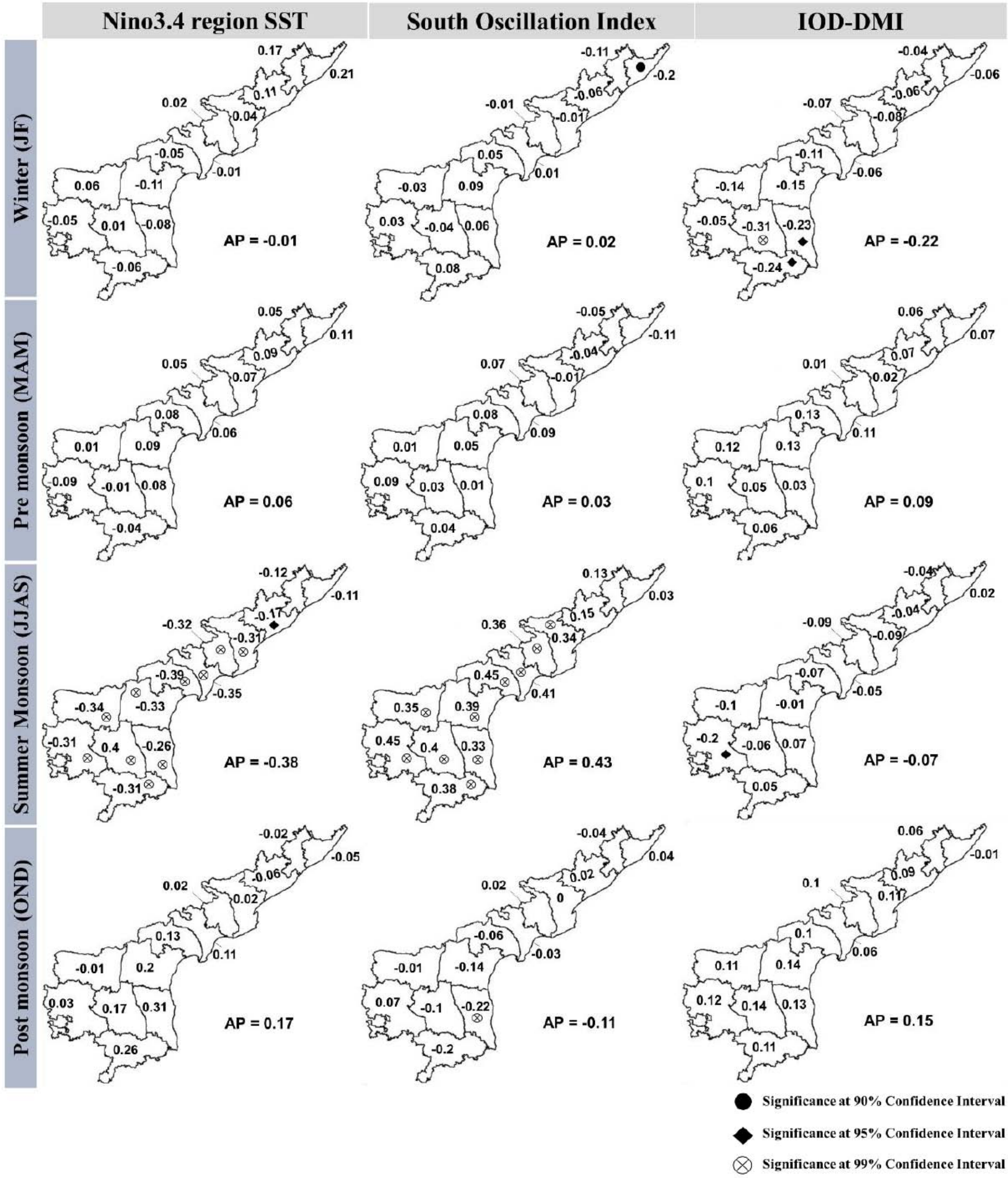


Figure 8: The relationship (correlation coefficient) of JF (Row-1), MAM (Row-2), JJAS (Row-3) and OND (Row-4) seasonal rainfall at district level over Andhra Pradesh with climate indicies such as Nino3.4 Region SST (Column-1), Southern Oscillation Index (Column-2) and IOD-DMI (Column-3) for the period 1901–2018. The different symbols on the figures indicate the relationship's significance.

rainfall in most of the districts over AP (Figure **8**). The pre-monsoon and post-monsoon rainfall are positively correlated for most of the districts over AP (Figure **8**). The winter rainfall has a significant inverse relationship with DMI over NLR, CHT at 90%, and KDP at a 99% confidence level. In summary, the DMI has no significant relationship with the rainfall in any season over the northern districts of AP; however, there is a significant relationship in a few southern districts during winter and monsoon seasons.

4. SUMMARY AND CONCLUSIONS

In the present study, a detailed retrospective analysis of the patterns and statistical features of the district-level seasonal rainfall over AP for 13 districts has been carried out for the period 1901 to 2018 using the high-resolution (0.25° × 0.25°) gridded rainfall dataset from IMD. Further, the relationships of the seasonal rainfall over AP with climate indices (Niño–3.4 region SST, SOI, DMI) during the study period is deliberated, and the key findings of this study are given below:

- The long-term average annual rainfall over AP is 882 mm, and its coefficient of variation is about 82 % for the annual rainfall; nevertheless, the variation is low during the monsoon season (34 %) and mostly during the winter season (56 %) when the rainfall is low.

- An estimated 55.7 % (492 mm) of the annual rainfall over AP is received during the monsoon season and 32.8 % (290 mm) during the post-monsoon months, whereas the rest of the rainfall is received during pre-monsoon (10.6 %) and winter months (1.9 %).

- The climatological mean and IAV of monthly rainfall pose a similar intra-year pattern, but judging by the extent of variability, it is inferred that the variability is highest during the winter and the pre-monsoon season, followed by post-monsoon and lastly, the monsoon season.

- The coastal districts receive more rainfall than the inland districts, especially during the post-monsoon season, due to the influence of cyclonic disturbances over the Bay of Bengal, assisting the northeast monsoon circulation. Another notable pattern shows that the rainfall is higher (lower) in the northern (southern) parts of AP during the southwest monsoon. This pattern reverses during the post-monsoon season.

- The CV of rainfall is highest during the winter season as the ratio of climatological rainfall, and variability is very low. Spatially, the CV is highest over the regions where the rainfall is lowest and vice versa.

- The Shapiro–Wilk normality test confirmed that the rainfall follows a normal distribution, i.e., more consistent only during the post-monsoon season over AP as a whole, but rainfall over EG and WG during the monsoon and over WG, NLR, KDP, and ANT during the post-monsoon season does follow a normal distribution.

- The Hurst exponent test revealed that the rainfall is persistent over SRK, KRI, GNT, PRK, NLR, CHT, KDP, and KRN during the pre-monsoon season and over VZM, VSP, EG, WG, PRK, NRK, CHT, KDP, KRN during the post-monsoon season. The annual and winter rainfall over AP is persistent over all the districts except for WG. However, the monsoon rainfall is persistent in all the districts.

- The change point years for abrupt changes in the district level rainfall during all four seasons are within the time range from 1930 to 1990 for most of the districts and AP as a whole (as confirmed by the four tests PTT, BRT, BUT, and SNHT).

- The total number of excess rainfall years is more than that of the deficit rainfall years during all four seasons. There are 21 years of excess rainfall during the monsoon and the post-monsoon rainfall, whereas there are 16 years with deficit monsoon rainfall and 20 years with deficit post-monsoon rainfall, although these years are entirely different and have no interrelationship with one another.

- The magnitude of monsoon rainfall has drastically increased in the recent period (1991-2018), and the increase is even more than 10% in a few districts. This increase is statistically significant at the 90 % confidence level over GNT, NLR, CHT, and AP as a whole and a 95% confidence interval at SRK, VSP, and PRK. The post-monsoon rainfall has also increased in all the districts over AP except for 4 northern districts.

- It was found that the monsoon rainfall over AP has a significant negative relationship with the Nino 3.4 SST at the 99 % confidence level over most of the districts except over SRK, VZM, and VSP (90% confidence level). A similar relationship is found with the SOI but in the opposite direction; the relationship during the other season, however, is insignificant.

- Although there is no significant relationship of the seasonal rainfall over AP with that of the Indian Ocean Dipole Index for most of the districts, there is some positive correlation with the pre and post-monsoon rainfall in some. The DMI has no significant relationship with the rainfall over the northern districts, whereas there is a significant relationship in a few southern districts during the winter and monsoon seasons.

- The relationship of ENSO and Indian Ocean dipole is opposite to the monsoon and post-monsoon seasons, the relationship of Nino 3.4 SST and DMI is strikingly similar to the post-monsoon season and has weakened in recent decades.

This study will be beneficial for a detailed understanding of the behavior of the district-level rainfall in AP and its relationship with respective global teleconnections, which would help in preparing better strategies for water resource management, catastrophe preparedness, such as for flood control to plan for a sustainable future in the present global warming era.

ACKNOWLEDGEMENT

The authors thank the Indian Institute of Tropical Meteorology (IITM), Pune, Ministry of Earth Sciences, Govt. of India, New Delhi. The authors duly acknowledge the India Meteorological Department (IMD) for providing observed gridded rainfall datasets, and the authors would also like to thank the University Corporation for Atmospheric Research (UCAR), USA, for the climate indices data (http://www.cgd.ucar.edu/cas/–catalog/climind). The authors are glad to appreciate the anonymous reviewers for providing valuable suggestions and comments that helped improve the manuscript's quality.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

FUNDING

Not applicable.

AVAILABILITY OF DATA AND MATERIAL

Observed rainfall and temperature datasets are obtained from India Meteorological Department (IMD), Pune, and available at https://imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html. The climate indices data from UCAR at http://www.cgd.ucar.edu/cas/–catalog/climind.

CODE AVAILABILITY

On request.

AUTHORS' CONTRIBUTIONS

MMN designed the study, whereas MCS and KRBK performed the delineation. MCS had drafted the first version of the manuscript. MMN, AKS, SJ, and MAR conceptualized and restructured it, MMN prepared the final version of the manuscript with significant contributions. AKS and SJ in editing and reviewing the manuscript. All the authors analyzed the results and provided scientific inputs to prepare the final version of the manuscript. The entire research was supervised by AKS.

ETHICS APPROVAL

All the procedures performed in this study are in accordance with the ethical standards of the institute. The manuscript has not been submitted to more than one journal for simultaneous consideration. The manuscript has not been published elsewhere previously.

CONSENT TO PARTICIPATE

Not applicable.

CONSENT FOR PUBLICATION

The authors give consent to the publication of all details of the manuscript, including texts, figures, and tables.

REFERENCES

[1] Parry M, Parry ML, Canziani O, Palutikof J, Van der Linden P, Hanson C, (Eds.) Climate change 2007-impacts, adaptation and vulnerability: Working group II contribution to the fourth assessment report of the IPCC. Cambridge University Press 2007; Vol. 4.

[2] Dore MHI. Climate change and changes in global precipitation patterns: what do we know? Environ Int 2005; 31: 1167-1181. https://doi.org/10.1016/j.envint.2005.03.004

[3] Trenberth KE. Changes in precipitation with climate change. Clim Res 2011; 47: 123-138. https://doi.org/10.3354/cr00953

[4] Olmstead SM. Climate change adaptation and water resource management: A review of the literature. Energy Economics 2014; 46: 500-509. https://doi.org/10.1016/j.eneco.2013.09.005

[5] Roy SS, Balling RC. Trends in extreme daily precipitation indices in India. International Journal of Climatology 2004; 24(4): 457-466. https://doi.org/10.1002/joc.995

[6] Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL. Global observed changes in daily climate extremes of temperature and precipitation. Journal of Geophysical Research: Atmospheres 2006; 111(D5). https://doi.org/10.1029/2005JD006290

[7] Klein Tank AMG, Peterson TC, QuadirDA, Dorji S, Zou X, Tang H, Santhosh K, Joshi UR, Jaswal AK, Kolli K, Sikder AB, Deshpande NR, Revadekar JV, Yeleuova K,

Vandasheva S, Faleyeva M, Gomboluudev PK, Budhathoki P, Hussain A, Afzaal M, Chandrapala L, Anvar H, Amanmurad D, Asanova VS, Jones PD, New MG, Spektorman T. Changes in daily temperature and precipitation extremes in central and south Asia. Journal of Geophysical Research: Atmospheres 2006; 111(D16). https://doi.org/10.1029/2005JD006316

[8] Guhathakurta P, Rajeevan M. Trends in the rainfall pattern over India. International Journal of Climatology: A Journal of the Royal Meteorological Society 2008; 28(11): 1453-1469. https://doi.org/10.1002/joc.1640

[9] Kumar KR, Sahai AK, Kumar KK, Patwardhan SK, Mishra PK, Revadekar JV, Kamala K, Pant GB. High-resolution climate change scenarios for India for the 21st century. Current Science 2006; 90(3): 334-345.

[10] Goswami BN, Venugopal V, Sengupta D, Madhusoodanan MS, Xavier PK. Increasing trend of extreme rain events over India in a warming environment. Science 2006; 314(5804): 1442-1445. https://doi.org/10.1126/science.1132027

[11] Dash SK, Jenamani RK, Kalsi SR, Panda SK. Some evidence of climate change in twentieth-century India. Climatic Change 2007; 85(3-4): 299-321. https://doi.org/10.1007/s10584-007-9305-9

[12] Kumar V, Jain SK. Trends in rainfall amount and number of rainy days in river basins of India (1951–2004). Hydrol Res 2011; 42(4): 290-306. https://doi.org/10.2166/nh.2011.067

[13] Shrestha AB, Wake CP, Dibb JE, Mayewski PA. Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. International Journal of Climatology: A Journal of the Royal Meteorological Society 2000; 20(3): 317-327. https://doi.org/10.1002/(SICI)1097-0088(20000315)20:3<317::AID-JOC476>3.0.CO;2-G

[14] Mirza MMQ. Global warming and changes in the probability of occurrence of floods in Bangladesh and implications. Global Environmental Change 2002; 12(2): 127-138. https://doi.org/10.1016/S0959-3780(02)00002-X

[15] Lal M. Global climate change: India's monsoon and its variability. Journal of Environmental Studies and Policy 2003; 6(1): 1-34.

[16] Min SK, Kwon WT, Park EH, Choi Y. Spatial and temporal comparisons of droughts over Korea with East Asia. International Journal of Climatology: A Journal of the Royal Meteorological Society 2003; 23(2): 223-233. https://doi.org/10.1002/joc.872

[17] Cayan DR, Peterson DH. The influence of north Pacific atmospheric circulation on stream flows in the west. Geophys. Monogram Ser 1989; 55: 375-397. https://doi.org/10.1029/GM055p0375

[18] Lins HF, Slack JR. Stream flow trends in the United States. Geophys Res Lett 1999; 26: 227-230. https://doi.org/10.1029/1998GL900291

[19] Sinha P, Nageswararao MM, Dash GP, Nair A, Mohanty UC. Pre-monsoon rainfall and surface air temperature trends over India and its global linkages. Atmos Phys, Meteorol 2018; 31: 1005-1018. https://doi.org/10.1007/s00703-018-0621-6

[20] Nageswararao MM, Sannan MC, Mohanty UC. Characteristics of various rainfall events over South Peninsular India during northeast monsoon using high-resolution gridded dataset (1901-2016). Theor Appl Climatol 2019a; 132(1-2): 181-207. https://doi.org/10.1007/s00704-018-02755-y

[21] Nageswararao MM, Sinha P, Mohanty UC, Panda RK, Dash GP. Evaluation of district-level rainfall characteristics over Odisha using high-resolution gridded dataset (1901-2013). SN Applied Sciences 2019b; 1: 1211. https://doi.org/10.1007/s42452-019-1234-5

[22] Barsugli J, Anderson C, Smith JB, Vogel JM. Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change. White Paper, Water Utility Climate Alliance 2009.

[23] Raucher RS. The Future of Research on Climate Change Impacts on Water: A Workshop Focused on Adaption Strategies and Information Needs. Water Research Foundation 2011. ⟨http://www.waterrf.org/projectsreports/publicreportlibrary/4340.pdf⟩

[24] De US, Mukhopadhyay RK. The effect of ENSO/anti ENSO on northeast monsoon rainfall. Mausam 1999; 50(4): 343-354. https://doi.org/10.54302/mausam.v50i4.1947

[25] Kripalani RH, Kumar P. Northeast monsoon rainfall variability over south peninsular India vis–à–vis the Indian Ocean dipole mode. Int J Climatol 2004; 24(10): 1267-1282. https://doi.org/10.1002/joc.1071

[26] Gadgil S, Rajeevan M, Francis PA. Monsoon variability: links to major oscillations over the equatorial Pacific and Indian Ocean. Curr Sci 2007; 93(2): 182-194. https://doi.org/10.1029/2004GL019733

[27] Gadgil S, Vinayachandran PN, Francis PA, Gadgil S. Extremes of Indian summer monsoon rainfall, ENSO, equatorial Indian Ocean oscillation. Geophys Res Lett 2004; 31(12): L12213–1–4.

[28] Zubair L, Ropelewski CF. The strengthening relationship between ENSO and northeast monsoon rainfall over Sri Lanka and southern India. J Clim 2006; 19: 1567-1575. https://doi.org/10.1175/JCLI3670.1

[29] Kumar P, Kumar KR, Rajeevan M, Sahai AK On the recent strengthening of the relationship between ENSO and northeast monsoon rainfall over South Asia. Clim Dyn 2007; 28(6): 649-660. https://doi.org/10.1007/s00382-006-0210-0

[30] Sreekala PP, Vijaya Bhaskara Rao S, Rajeevan M. Northeast monsoon rainfall variability over south peninsular India and its teleconnections. Theor Appl Climatol 2012; 108(1-2): 73-83. https://doi.org/10.1007/s00704-011-0513-x

[31] Rajeevan M, Unnikrishnan CK, Jyoti B, Kumar Niranjan K, Sreekala PP. Northeast monsoon over India: variability and prediction. Meteorol Appl 2012; 19(2): 226-236. https://doi.org/10.1002/met.1322

[32] Nageswararao MM, Mohanty UC, Ramakrishna SSVS, Nair A, Prasad SK. Characteristics of winter precipitation over Northwest India using high–resolution gridded dataset (1901 2013). Glob Planet Chang 2016; 147: 67-85. https://doi.org/10.1016/j.gloplacha.2016.10.017

[33] Sannan MC, Nageswararao MM, Mohanty UC. Performance Evaluation of CORDEX-South Asia simulations and Future projections of Northeast Monsoon Rainfall over South Peninsular India. Meteorology and Atmospheric Physics 2020. https://doi.org/10.1007/s00703-019-00716-2

[34] Selvaraj RS, Aditya R. Study of correlation between southwest and northeast monsoon rainfall over Tamil Nadu. Univers J Environ Res Technol 2011; 1(4): 578-581.

[35] Yadav RK Why is ENSO influencing Indian northeast monsoon in the recent decades? J Clim 2012; 23: 1979-1993. https://doi.org/10.1175/2009JCLI3202.1

[36] Yadav RK. Emerging role of Indian Ocean on Indian northeast monsoon. Clim Dyn 2013; 41: 105-116. https://doi.org/10.1007/s00382-012-1637-0

[37] Geethalakshmi V, Yatagai A, Palanisamy K, Umetsu C. Impact of ENSO and the Indian Ocean dipole on the northeast monsoon rainfall of Tamil Nadu state in India. Hydrol Process 2009; 23(4): 633-647. https://doi.org/10.1002/hyp.7191

[38] Bhanu Kumar OSRU, Naidu CV, Rao SRL. Influence of southern oscillation and SSTs over Nino-3.4 region on the winter monsoon rainfall over coastal. Andhra Pradesh Journal of Earth System Science 2004; 113: 313-319. https://doi.org/10.1007/BF02716728

[39] Barde V, Nageswararao MM, Mohanty UC, Panda RK, Ramadas M. Characteristics of southwest summer monsoon rainfall events over East India. Theor Appl Climatol 2020; 141: 1511-1528. https://doi.org/10.1007/s00704-020-03251-y

[40] Swain M, Sinha P, Pattanayak S, Guhathakurta P, Mohanty UC. Characteristics of observed rainfall over Odisha: An extreme vulnerable zone in the east coast of India. Theor Appl Climatol 2020; 139: 517-531. https://doi.org/10.1007/s00704-019-02983-w

[41] Parthasarathy B, Dhar ON. Secular variations of regional rainfall over India. Quarterly Journal of the Royal Meteorological Society 1974; 100(424): 245-257. https://doi.org/10.1002/qj.49710042411

[42] Kumar KR, Pant GB, Parthasarathy B, Sontakke NA. Spatial and sub-seasonal patterns of the long-term trends of Indian summer monsoon rainfall. International Journal of Climatology 1992; 12(3): 257-268. https://doi.org/10.1002/joc.3370120303

[43] Pai DS, Latha Sridhar, Rajeevan M, Sreejith OP, Satbhai NS, Mukhopadhyay B. Development of a new high spatial resolution (0.25° × 0.25°) long period (1901–2010) daily gridded rainfall dataset over India and its comparison with existing datasets over the region. Mausam 2014; 65(1): 1-18. https://doi.org/10.54302/mausam.v65i1.851

[44] Nageswararao MM, Mohanty UC, Ramakrishna SSVS, Dimri AP. An intercomparison of observational precipitation datasets over Northwest India during winter. Theor Appl Climatol 2018; 132(1-2): 181-207. https://doi.org/10.1007/s00704-017-2083-z

[45] Oztuna D, Elhan AH, Tuccar E. Investigation of four different normality tests in terms of type 1 error rate and power under different distributions. Turk J Med Sci 2006; 36(3): 171-176.

[46] Peat J, Barton B. Medical Statistics: A guide to data analysis and critical appraisal. Blackwell Publishing, Hoboken 2005. https://doi.org/10.1002/9780470755945

[47] Wijngaard JB, Klein Tank AMG, KoNnen GP. Homogeneity of 20th century European daily temperature and precipitation series. Int J Climatol 2003; 23: 679-692. https://doi.org/10.1002/joc.906

[48] DeGrauwe P, Dewachter H, Embrechts M. Exchange rate theory chaotic models of foreign exchange markets. Blackwell Publishers, London 1993.

[49] Peitgen HO, Saupe D. The science of fractal images. Springer, New York 1988.

[50] Hurst H. Long-term storage capacity of reservoirs. Trans Am Soc Civ Eng 1951; 6: 770-799. https://doi.org/10.1061/TACEAT.0006518

[51] Mandelbrot B, Wallis JR. Robustness of the rescaled range R/S in the measurement of noncyclic long-run statistical dependence. Water Resour Res 1969; 5: 967-988. https://doi.org/10.1029/WR005i005p00967

[52] Barbulescu A, Cristina S, Carmen M. Evaluation of Hurst exponent for precipitation time-series. Latest Trends Comput 2007; 2: 590-595.

[53] Krishna Rao PR, Jagannathan P. A study of the northeast monsoon rainfall of Tamil Nadu. Indian J Meteorol Geophys 1953; 4: 22. https://doi.org/10.54302/mausam.v4i1.4775

[54] Nageswara Rao G. Variations of the SO relationship with summer and winter monsoon rainfall over India: 1872–1993. J Climate 1999; 12: 3486-3495. https://doi.org/10.1175/1520-0442(1999)012<3486:VOTSRW>2.0.CO;2

[55] Gadgil S. Monsoon-ocean coupling. Curr Sci 2000; 78: 309-23.

[56] Gadgil S. The Indian monsoon and its variability. Annual Review of Earth and Planetary Sciences 2003; 31(1): 429-467. https://doi.org/10.1146/annurev.earth.31.100901.141251

[57] Raghavan S, Rajesh S. Trends in Tropical Cyclone Impact: A Study in Andhra Pradesh, India: A Study in Andhra Pradesh, India. Bulletin of the American Meteorological Society 2003; 84(5): 635-644. https://doi.org/10.1175/BAMS-84-5-635

[58] Singh OP, Khan TA, Rahman MS. Changes in the frequency of tropical cyclones over the North Indian Ocean. Meteorology and Atmospheric Physics 2000; 75(1-2): 11-20. https://doi.org/10.1007/s007030070011

[59] Vinayachandran PN, Pavanathara Francis, Rao S. Indian Ocean dipole: processes and impacts. Current Trends in Science 2010; 569-589.

[60] Ashok K, Saji NH. On the impacts of ENSO and Indian Ocean dipole events on sub-regional Indian summer monsoon rainfall. Natural Hazards 2007; 42(2): 273-285. https://doi.org/10.1007/s11069-006-9091-0