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Some characteristics of southwest monsoon rainfall over urban entres in Andhra Pradesh and Telangana

K. NAGA RATNA and MANORAMA MOHANTY*

Meteorological Centre, Hyderabad, India

**Meteorological Centre, Ahmedabad, India*

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e mail : knratna@gmail.com

सार – इस शोध पत्र में तटीय आंध्र प्रदेश (CAP) के तटीय क्षेत्रों के लिए शहरी स्टेशनों और आसपास के स्टेशनों तथा तेलंगना एवं रायलसीमा के 46 वर्षों (1969-2014) के दैनिक वर्षा आँकड़ों का चयन किया गया है। इन स्टेशनों के समूची अवधि के समाश्रयण, मानक विचलन एवं प्रसरण गुणांक, टी टेस्ट उपयोग करते हुए महत्वपूर्ण परीक्षण, मान-कैन्डेल टेस्ट के आँकड़ों को लिया गया है। इन स्टेशनों का चयन समान अवधि वाले आँकड़ों के आधार पर किया गया है। इस प्रकार सभी स्टेशनों पर किए गए टी-टेस्ट से ऋतुनिष्ठ वर्षा (JJAS) में सभी स्टेशनों पर सार्थक परिणाम ($P < 0.001$) देखने को मिले हैं। इसके अलावा मेन-कैन्डेल टेस्ट का उपयोग करते हुए जेड-आँकड़े प्राप्त किए गए हैं जो आंध्र प्रदेश राज्य के तटीय स्टेशन गन्नावरम, मछलीपट्टनम और विशाखापट्टनम के आँकड़ों की सटीकता में 95 प्रतिशत की सार्थक वृद्धि को दर्शाते हैं। तेलंगना, अंदरूनी स्टेशन हैदराबाद (शहरी केंद्र) में अत्यधिक भारी वर्षा की घटनाओं में 90 प्रतिशत स्तर तक महत्वपूर्ण वृद्धि पाई गई है। इसके बाद प्रत्येक शहरी केंद्र (विशाखापट्टनम, गन्नावरम, मछलीपट्टनम तथा हैदराबाद) के अलग-अलग अध्ययन किए गए और प्राप्त परिणामों से पता चला कि शहरी क्षेत्र के केंद्रों पर आस-पास के अन्य स्टेशनों की तुलना में वर्षा में महत्वपूर्ण वृद्धि पाई गई है। तटीय आंध्र प्रदेश के तटवर्ती स्टेशनों पर तेलंगना एवं रायलसीमा के अंदरूनी स्टेशनों की तुलना में वर्षा की मात्रा में महत्वपूर्ण वृद्धि देखी गई है।

ABSTRACT. In the present study daily rainfall data for 46 years (1969-2014) was selected for the urban stations and surrounding stations for coastal areas of Coastal Andhra Pradesh (CAP) and inland areas of Telanagana (TEL) and Rayalaseema (RSM). The statistics such as regression, standard deviation and coefficient of variance, significance test using *t*-test, Mann-Kandell test were worked out for the entire period for the stations. The stations were selected on the basis where the period of data is same. The *t*-test thus performed for all stations showed significance ($p < 0.001$) in seasonal rainfall (JJAS) for all the stations. Further *z*-statistics using Mann-Kandell test was performed that showed significant increase at 95% confidence level for Gannavaram, Machilipatnam and Visakhapatnam along the coast of Andhra Pradesh state. Over Telengana, Hyderabad (Urban centre) an inland station, showed significant increase at 90% level of confidence for extreme heavy rainfall events. Henceforth, seperate studies for each urban centre (Visakhapatnam, Gannavaram, Machilipatnam and Hyderabad) were done and results showed significant increase in rainfall over urban centres compared to other surrounding stations and the significant increase in rainfall was observed for the coastal stations along Andhra Pradesh coast when compared to inland stations of Telanagana and Rayalaseema.

Key words – Seasonal rainfall, Rainydays, Coastal stations, Inland stations, Man-Kandell test.

1. Introduction

Andhra Pradesh bordered by Telangana in the north lies between 12°41' and 22° N latitude and 77° and 84°40' E longitude with Bay of Bengal in the East. Among the other states, which are situated on the country's coastal area, Andhra Pradesh has got a coastline of around 972 km, which gives it the 2nd longest coastline in the nation. Southwest monsoon during July and continues till September has major role in determining the climate of the state. Andhra Pradesh and Telanagana have three meteorological sub-divisions namely, Coastal Andhra Pradesh (CAP), Rayalaseema (RSM) and Telangana (TEL) as defined by India Meteorological Department (IMD) 1999. CAP consists of nine districts and this again subdivided to North Coastal Andhra Pradesh (NCAP) and South Coastal Andhra Pradesh (SCAP) for easy representation of climate parameters according to their climatic sub-regions, which comprises of Srikakulam, Visakhapatnam, Vizianagaram, East

Godavari, West Godavari (NCAP) and Krishna, Guntur, Prakasam, Nellore (SCAP) respectively. The climate of Andhra Pradesh is generally classified as sub-humid and dry (over NCAP) and wet-wetter and semi-arid (over SCAP), which receive total rainfall about 1128 mm and 996 mm respectively. Rayalaseema is a geographic region in the state of Andhra Pradesh in India. It occupies atleast 42% of the state territory, with TEL to the north and the CAP region of Andhra Pradesh to the east. The region is divided into southern zone (Chittoor and Kadapa) and scarce rainfall zone (Anantapur and Kurnool) which are classified as semi-arid and arid zone. Telangana comprises of North Telangana (Adilabad, Nizamabad, Krimnagar, Warangal and Khammam) and South Telangana (Medak, Nalgonda and Ranga Reddy). South Telanagana (STEL) is semi-arid and arid area and has a predominantly hot and dry climate. North Telangana (NTEL) is semi arid (wetter in some districts).

As a result, the regions are marked by large scale variations in land characteristics, vegetation and lead to complex circulations embedded with large scale monsoon flow. The rainfall extremes during monsoon season leads to unusual floods and drought over the regions. The permanent and semi permanent synoptic features over Indian sub-continent in the large-scale monsoon circulation, causes spatial and temporal variability in the rainfall distribution. The geography and land surface play vital role, influencing convective activity and rainfall intensity of the sub-divisions. The total annual rainfall varies from 566 mm over Anantapur in Rayalaseema (RSM) sub-division to 1135 mm over Kakinada in Coastal Andhra Pradesh (CAP). The total annual rainfall varies from 649 mm over Nalgonda to 1149 mm of rainfall over Ramagundam in Telangana (TEL). Moreover, southwest monsoon comprises nearly 2/3rd of the total annual rainfall. The southwest monsoon advances in first week of June and covers all the three sub-divisions by second week of June. July and August are most rainy months contributing 25%-35% of the annual rainfall play vital role in agriculture production and economy of the two states. The rainfall occurs due to the influence of the synoptic scale systems like monsoon trough/low and depressions that usually develop over Bay over Bengal. These systems bring moisture supply to the coast and some parts of the inland areas. On an average there were 10-12 rainy days and 12-18 rainy days over Andhra Pradesh and Telangana respectively. The withdrawal of monsoon begins during first week of October. During monsoon season, the two states receive heavy (HRF), very heavy (VHRF) and extremely heavy rainfall (EHRF) in association with cyclonic circulations such as monsoon lows/depressions that develop over Bay of Bengal and move westwards/northwestwards/westnorthwards or due to monsoon troughs with predominant westerlies at surface level and easterlies in upper level (100 hPa). Extreme heavy rainfall events cause intense rainfall events that lead to severe floods and landslides causing damage to property and life and influence the economical status of the state. Therefore climatology studies also have importance for understanding the climate changes happening during long term period over a specified location or region for well planned management and growth of the state economy.

In this global warming era, the monsoon variability had been challenging to the scientific community. Many studies have attempted to determine the trend in rainfall on both large and regional scales. Most of these deal with the analysis of annual and seasonal series of rainfall for some individual stations or group of stations. Subbaramayya and Naidu (1997) have examined the trend in rainfall for different sub-divisions and the whole of India were examined for the period 1871-1988. Rajeevan *et al.* (2006) analysed rainfall series using 1476 rainguage stations data for the period 1901-2003. Mohanty *et al.* (2014) analysed the rainfall for different stations of Gujarat for the period 1969-2010 and found that there is significant increase trend of rainfall over coastal areas of Gujarat. Studies of extreme rainfall trends in India showed that increase in frequency of intense rainfall events lead to decrease in number of moderate rainfall events and total seasonal and annual rainfall. Also Rajeevan *et al*. (2008) showed that increased trend of extreme rainfall events could be associated with increased trend in sea surface temperature and surface heat flux. Goswami *et al*. (2006) showed that there was significant increasing trend in the frequency and magnitude of extreme rainfall events and significant decreasing trend of moderate events over central India during monsoon season, leading no significant trend in mean rainfall. Also some studies, particularly over hilly terrain over Kerala indicated decreasing trend in extreme annual rainfall for some stations and non-significant increasing trend for most of the stations. Aim of the study is to understand the concept of urbanization and their impacts on urbanization to help the economic planning and economic developments of the states. Part-2 includes the data and methodology used for the purpose in the present study. Part-3 gives details of the results and further discussion of the climate variables like rainfall, rainydays and extreme rainfall events.

2. Data and methodology

2.1. *Data*

To find out the characteristic features of the south-west monsoon season rainfall over subdivisions of CAP, RSM and TEL (Fig. 1), daily data for the stations over a

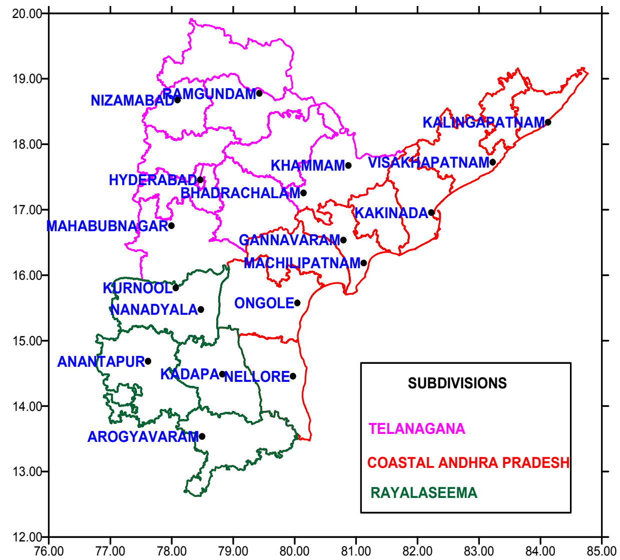


Fig. 1. Locations of sub-divisions and stations of Andhra Pradesh and Telangana state

period of 46 years (1969-2014) was considered for the study. These rainfall data were obtained from National data centre (NDC) Pune, India and Meteorological Centre, Hyderabad, India. The stations considered for the present study are Kalingapatnam (18.33/84.13), Visakhapatnam (17.68/83.3), Kakinada (16.95/82.23), Gannavaram (16.53/80.8), Machilipatnam (16.18/81.13), Ongole (15.57/80.05), Nellore (14.45/79.98), Kunool (15.8/78.07), Nandyala (15.47/78.48), Anantapur (14.68/77.62), Kadapa (14.48/78.83), Arogyavaram (13.53/78.5) situated in Andhra Pradesh state and Hyderabad (17.45/78.47), Nizamabad (18.67/78.1), Ramgundam (18.77/79.43), Mahabubnagar (16.75/78), Bhadrachalam (17.25/80.15) and Khammam (17.67/80.88) situated in Telagana state.

2.2. *Methodology*

The daily rainfall was averaged over the months (June, July, August and September) and (JJAS) monsoon season as a whole. Average rainy days and heavy rainfall events for different monsoon months and season as a whole were also computed and analysed. The month-wise and annual frequency of heavy, very heavy and extremely heavy rainfall events were found out. For the present study, daily 24 hr accumulated rainfall events were considered for the study period of 46 years (1969-2014). As per IMD terminology of IMD heavy (64.5 mm to 124.4 mm), very heavy (124.5 mm to 244.4 mm) and extremely heavy rainfall (>244.4 mm) were considered in this study. The month-wise comparison and interannual variability was analysed. The statistics like regression, standard deviation and coefficient of variance, significance test using Mann-Kandell test were worked out for the entire period (1969-2014) for the stations.

The Mann-Kendall test is a non-parameteric test for identifying trends in time series data. The test was suggested by Mann (1945) and has been extensively used with environmental time series (Hipel and McLeod, 2005).

Let $X_1, X_2, X_3, \ldots, X_n$ represents n data points where X_j represents the data point at time j. Then the Mann-Kendall statistic (S) is given by:

$$S = \sum\sum \text{sign}\left(x_j - x_k\right),\ j = 2,3,4 \ldots n \text{ and } k = 1,2,3,\ldots j-1$$

where,

$$\text{sign}\left(X_j - X_k\right) = 1, \quad \text{if}\left(X_j - X_k\right) > 0$$

$$= 0, \quad \text{if}\left(X_j - X_k\right) = 0$$

$$= \text{-}1, \quad \text{if}\left(X_j - X_k\right) < 0$$

A very high value of S is an indicator of an increasing trend, and a very low negative value indicates a decreasing trend. For the sample size >30, a normal approximations to the Mann-Kendall test may be used. For this variance S is obtained as,

$$V(S) = \frac{\left[n(n-1)(2n+5) - \sum tp(tp-1)(2tp+5)\right]}{18}$$

$$p = 1,2,3,\ldots q$$

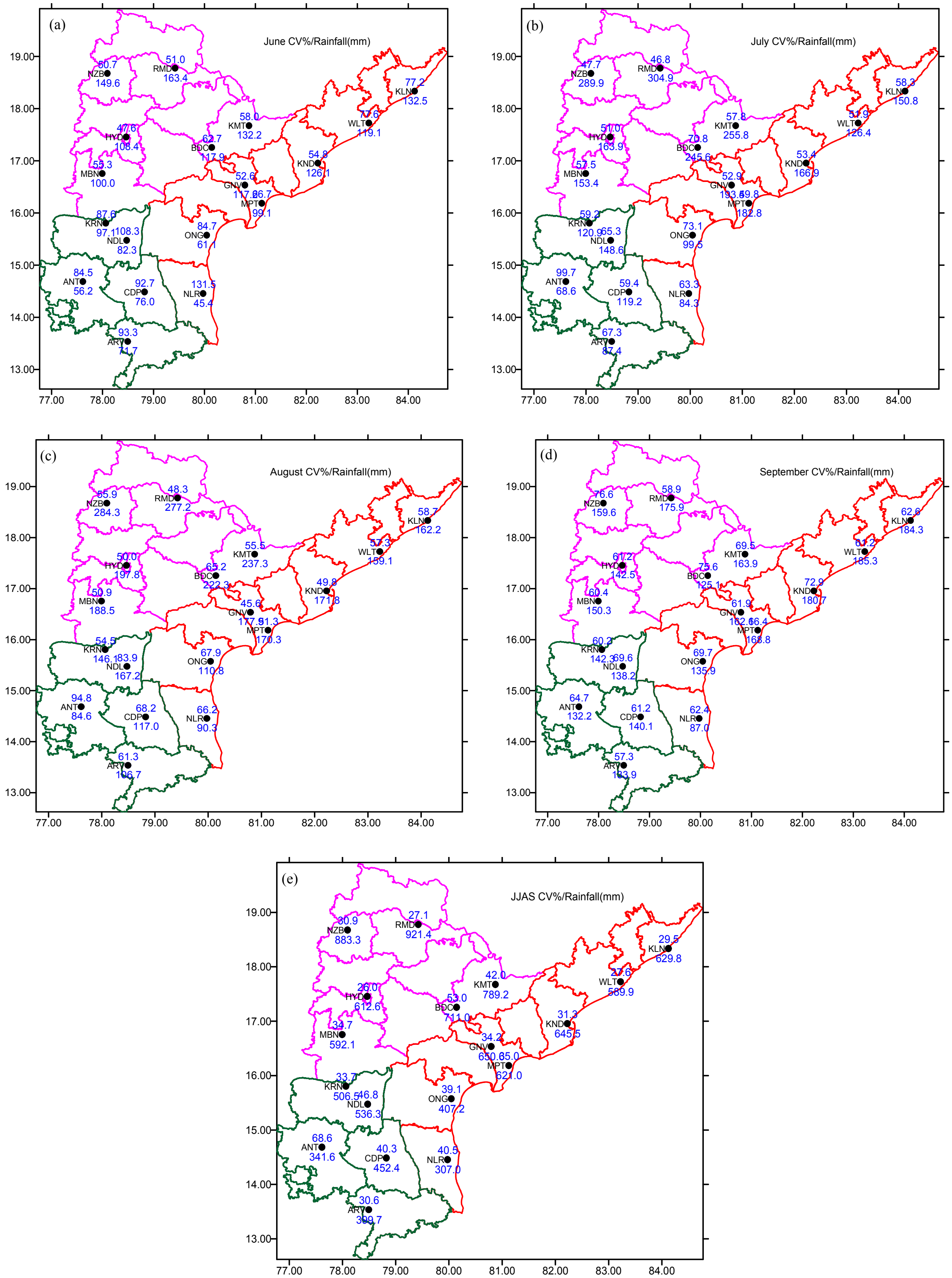
where, tp is the number of ties for the pth value and q is the number of tied values.

Then, standard statistical is computed by:

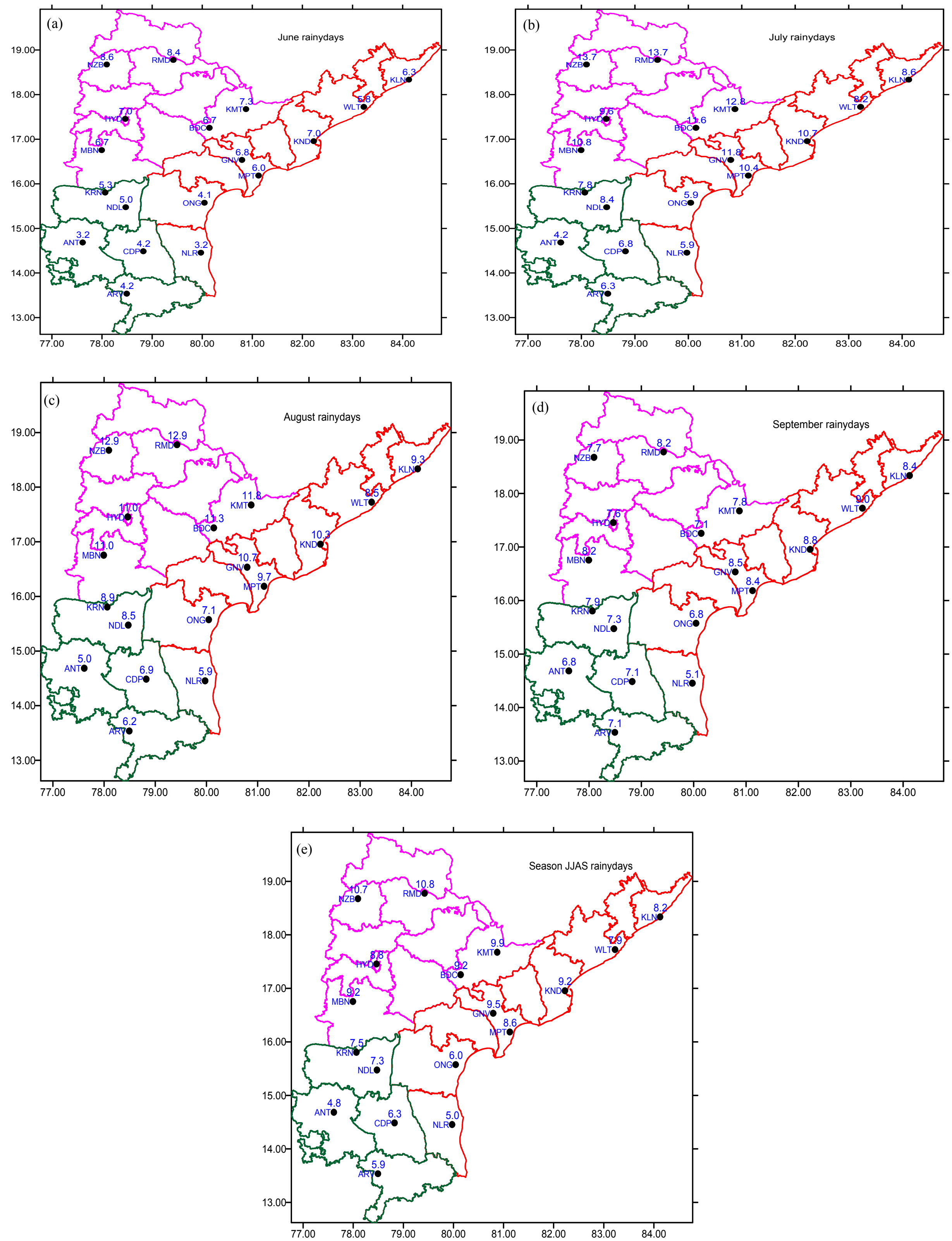
$$Z = S-1 \Big/ \sqrt{V(S)} \quad \text{if } S > 0$$

$$= S+1 \Big/ \sqrt{V(S)} \quad \text{if } S < 0$$

If the 'z' score is positive or negative value indicates increasing or decreasing trend of the total population respectively. If calculated value is equal to or greater than the table value (1.65, 1.96 and 2.58), the trend is significant at a particular level of significance (10%, 5% and 1% respectively).



Figs. 2(a-e). Average rainfall (mm) and coefficient of variation(%) during June, July, August and September months and season for 46 years (1969-2014). CV is mentioned above and Rainfall below



Figs. 3(a-e). Average rainydays during June, July, August and September months and season for 46 years (1969-2014)

The standard deviation is calculated by using the formula given below:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2}$$

σ = standard deviation

x_i = each value of dataset

$\bar{x}$ = the arithmetic mean of the data (This symbol will be indicated as mean from now)

N = the total number of data points

$\sum \left(x_i - \bar{x}\right)^2$ = The sum of $\left(x_i - \bar{x}\right)^2$ for all data points

The population CV can be estimated using the ratio of the sample standard deviation σ to the sample mean $\bar{x}$:

$$\text{CV} = \frac{\sigma}{\bar{x}}$$

3. Results and discussion

The *t*-test performed for the selected stations showed significance ($p < 0.01$) in seasonal rainfall (JJAS) for all the stations. The analysis for coefficient of variance, average rainfall, rainydays (>2.5 mm) and extreme rainfall events (> 64.5 mm) was presented in section 3.1, 3.2 and 3.3 respectively. Interannual variability and trend analysis of the climate parameters rainfall, rainydays and extreme rainfall events was discussed in section 3.4.

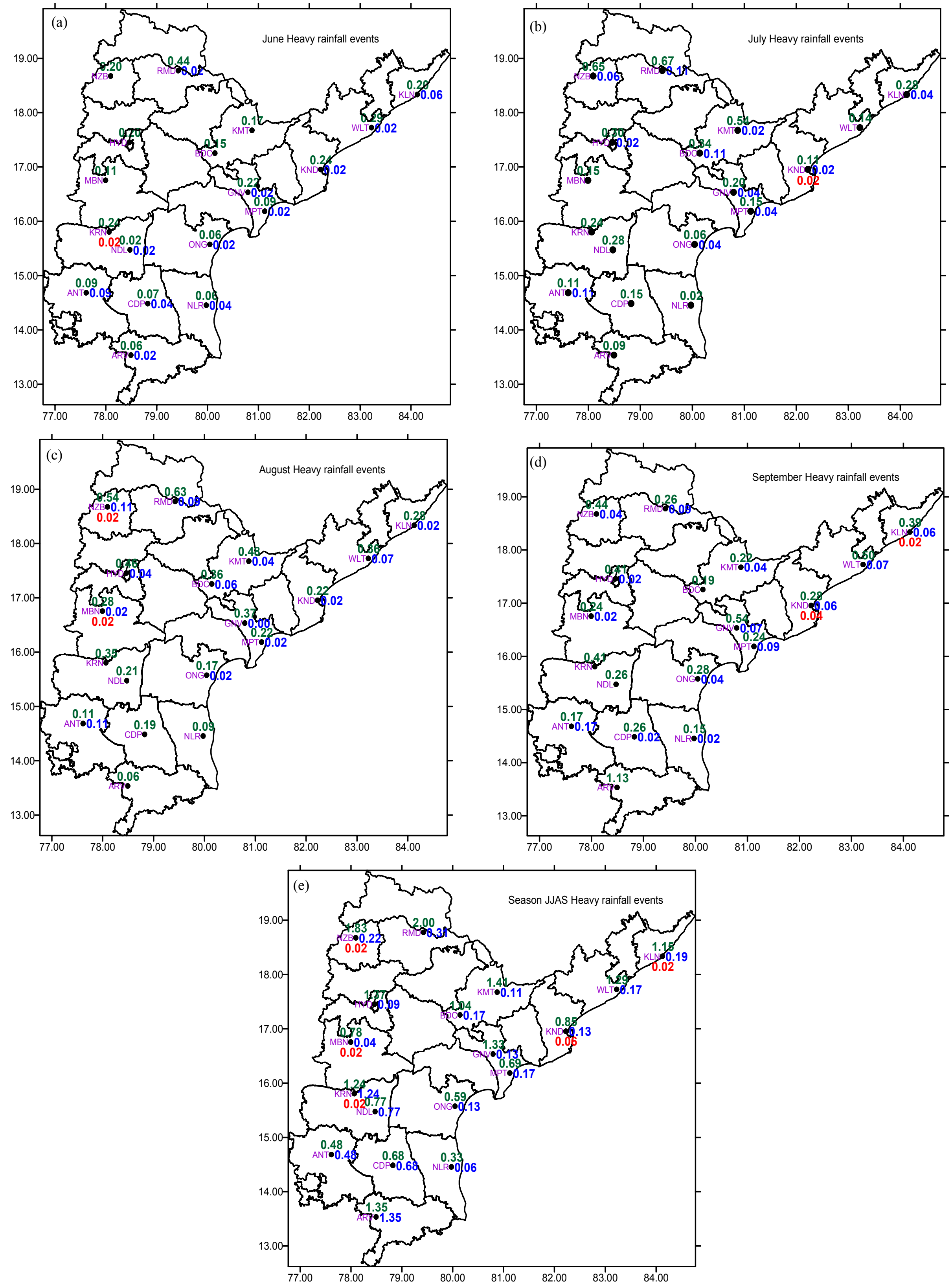
3.1. *Rainfall variability*

The average monthly and seasonal rainfall and their coefficients of variance (CV) of the stations of Andhra Pradesh and Telangana state were shown in Figs. 2(a-e). The average rainfall was found to be high during July, August and September when compared to June. The analysis of coefficient of variance for each station indicated rainfall variability is more during June as compared to July, August and September. The rainfall vaiariability is noticed to be more over RSM when compared to CAP and TEL. This showed as moving north to south the rainfall variability increased. The rainfall intensity was found to decrease from north to south over Andhra Pradesh and also Telangana states. The average rainfall over Telangana (TEL) was found be maximum during July with Ramgundam (304.9 mm) and Nizamabad (289.9 mm); August with Nizamabad (284.8 mm) and Ramagundam (277.2 mm). It was also noted that Coastal Andhra Pradesh received higher rainfall in July with Gannavaram (193.1 mm) and Machilipatnam (182.8 mm); August with Gannavaram (177.1 mm) and Machilipatnam (170.8 mm). The rainfall over Rayalaseema was least as compared to the other sub-divisions. Nandyala received maximum rainfall during July and August with 148.6 mm and 167.2 mm respectively. Rayalaseema received more rainfall during July, August and less during September and June respectively. Anantapur is the supposed to be station that receives scarce rainfall than any other station. Average rainfall recorded was 56.2 mm, 68.6 mm, 84.6 mm and 132.2 mm respectively in the months of June, July, August and September. However minimum rainfall was received over Nellore, Anantapur and Ongole during June. As such, it is noticed that there was considerable increase in rainfall in all the regions with well establishment of monsoon circulation as season progress from July, August and September.

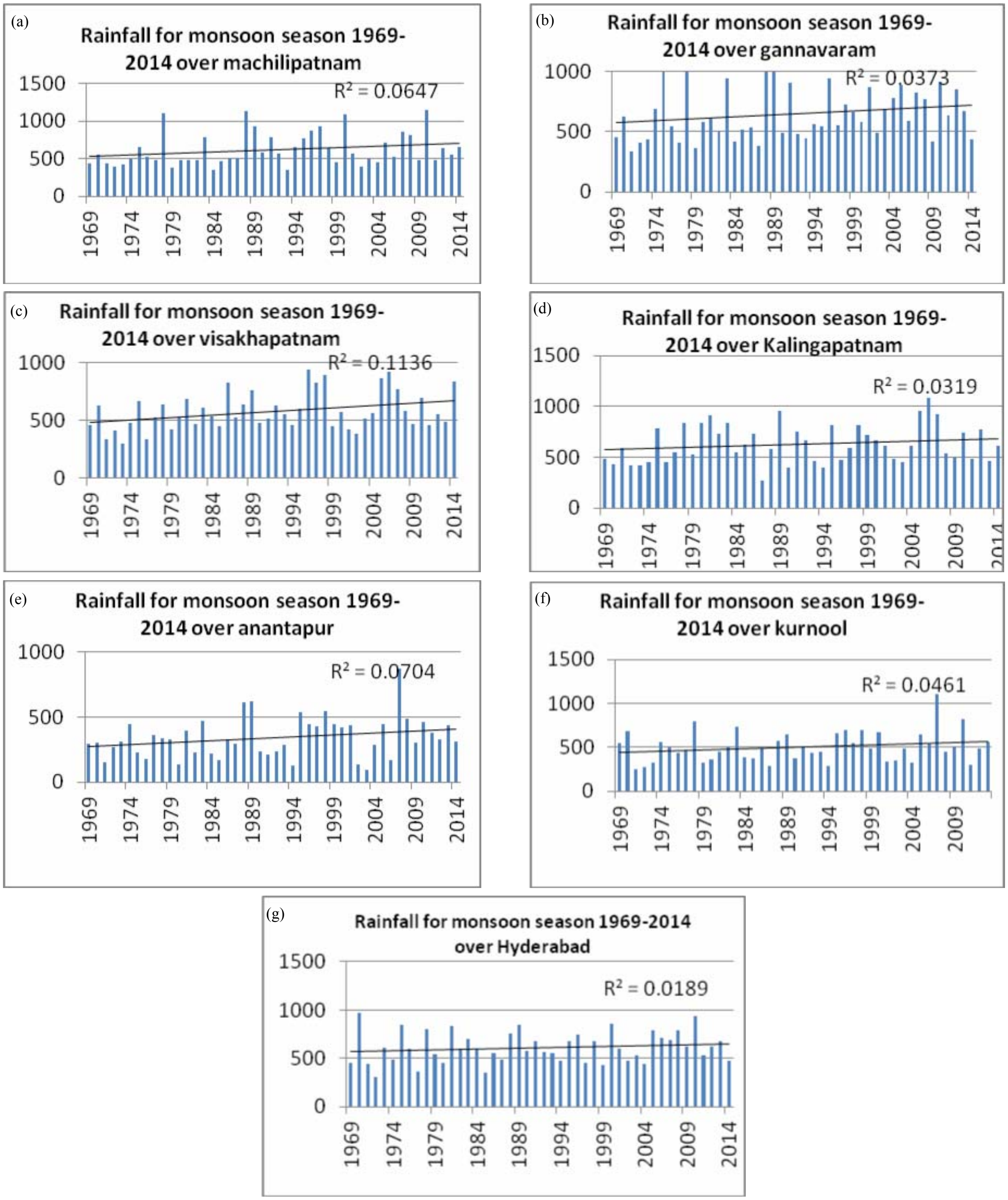
CAP recorded higher rainfall as compared to RSM and North Telangana (NTEL) recorded higher rainfall as compared to South Telangana (STEL). Season as a whole very high rainfall was recorded over Gannavaram (650 mm) in Andhra Pradesh and Ramagundam (921.4 mm) in Telanagana. Very less rainfall was recorded over Nellore (307 mm) in Andhra Pradesh and Hyderabad (612.6 mm) in Telangana.

3.2. *Rainy days (rainfall events greater than 2.5 mm)*

The number of rainy days (days with 24 hours cumulative rainfall (>2.5 mm) for June, July, August, September and season as a whole are presented in Figs. 3(a-e). The rainy days are found to be maximum in number (15-25 mm/day) during the peak months July and August months followed by September and June. TEL recorded maximum number of rainy days during July and August as compared to June and September. The rainy days are more in number during July, August and September for the CAP and RSM, whereas less number in June. Further, TEL was found to have more rainy days than CAP and RSM. The frequency of rainy days and the rainfall amounts during monsoon season showed the progression and intensity of the monsoon season over the region. However, this represented the magnitude of convective activity over Andhra Pradesh and Telangana states. The time series of the subdivisions were presented in Fig. 7. This showed rainfall increased and rainy days decreased over a period of time, which revealed the intensity of rainfall increased over the three sub-divisions.



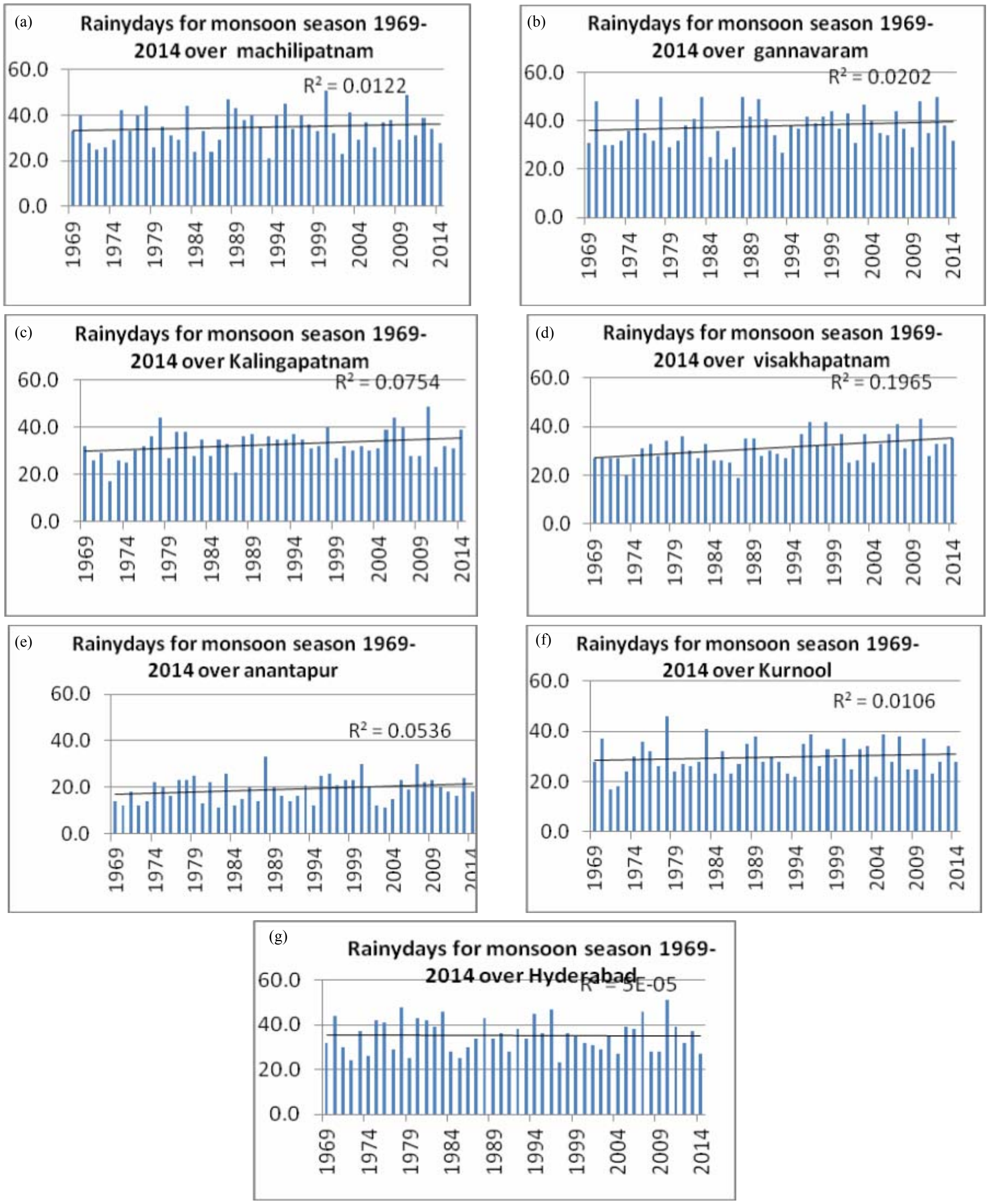
Figs. 4(a-e). The monthly and seasonal frequencies of daily 24 hr cumulative heavy, very heavy, extremely heavy rainfall during 46 years (1969-2014) over the stations of Andhra Pradesh and Telangana



Figs. 5(a-g). The time series of the seasonal rainfall over urban centres Machilipatnam, Gannavaram, Kalingapatnam, Visakhapatnam, Anantapur, Kunool and Hyderabad stations

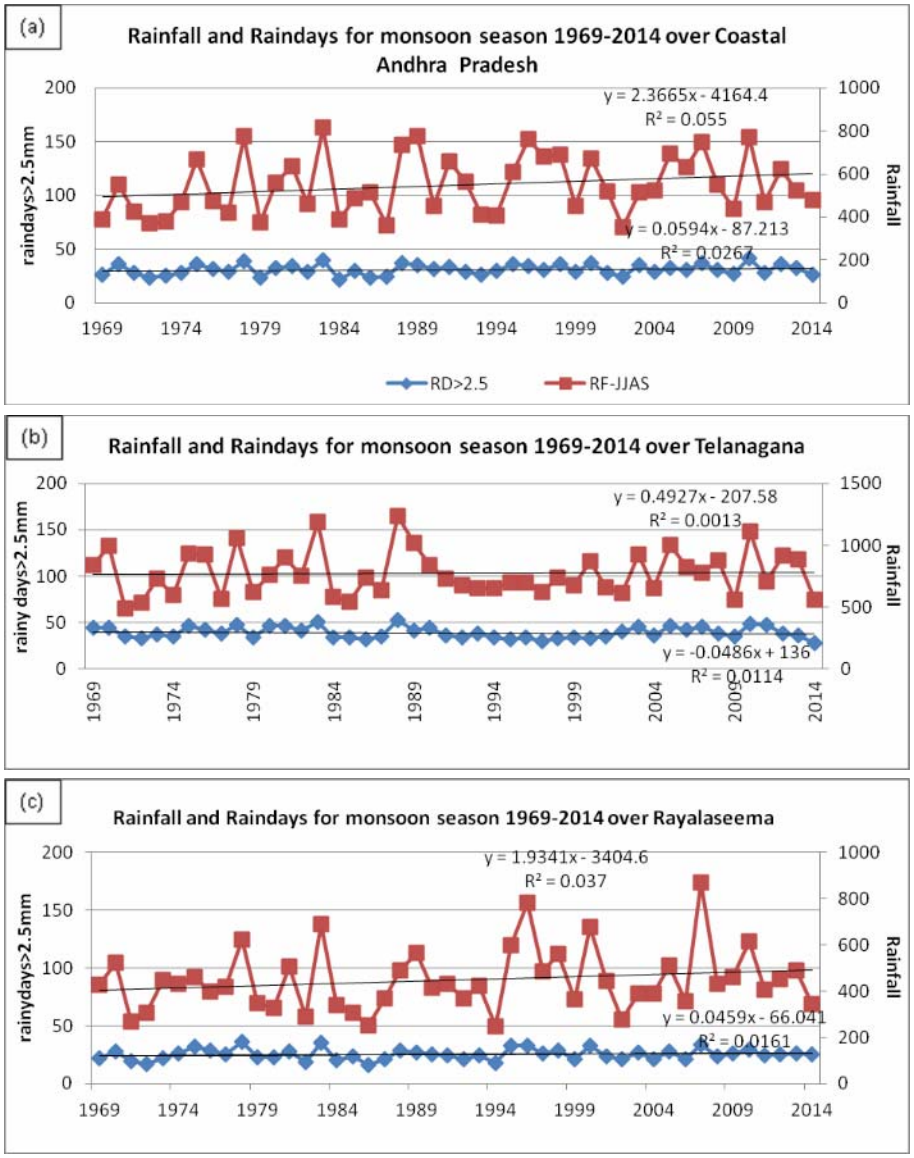
3.3. *Heavy rainfall events (greater than 64.5 mm)*

The monthly and seasonal frequencies of daily 24 hr cumulative heavy, very heavy, extremely heavy rainfall during past 46 years (1969-2014) over the stations of Andhra Pradesh and Telangana states were analysed and presented in Figs. 4(a-e). It is observed that the frequency of heavy rainfall events (HRF) is very high during July, August, September and followed by June. The frequency of very heavy rainfall (VHRF), extreme heavy rainfall events (EHRF) is high during the months of July, August, September and followed by June. The frequency of HRF,



Figs. 6(a-g). The time series of the seasonal rainydays over urban centres Machilipatnam, Gannavaram, Kalingapatnam, Visakhapatnam, Anantapur, Kurnool and Hyderabad stations

VHRF and EHRF is more during the months of July, August and September as compared to June month. It may be due to the impact of monsoon lows/depressions that form over Bay of Bengal and move westwards or northwestwards. It was also observed that the frequency of HRF and VHRF is less and EHRF are found only in a few occasions during all the monsoon months, over a few stations except September where the EHRF was received along coast line. This may be due to the reason that monsoon lows/depression frequency cross the



Figs. 7(a-c). The time series of the seasonal rainfall and rainydays over (a) Coastal Andhra Pradesh, (b) Telangana and (c) Rayalaseema

Andhra Pradesh coast. The time series of the seasonal rainydays over urban centres Machilipatnam, Gannavaram, Kalingapatnam, Visakhapatnam, Anantapur, Kurnool and Hyderabad stations of Andhra Pradesh and Telangana as given in Figs. 6(a-g) were analysed. It was seen that the frequency of heavy rains was high over Nizamabad (2.1/year), Ramagundam (2.3/year), Khammam (1.5/year) and Hyderabad (1.4/year) in Telangana. It was recorded for Gannavaram (1.5/year), Visakhapatnam (1.5/year), Machilipatnam (0.9/year) and Kalingapatnam (1.4/year) in Andhra Pradesh. It was found that EHRF events found to be more in NTEL followed by CAP. However in STEL, EHRF was more over Hyderabad (1.4/year) as compared to its surrounding stations.

3.4. *Trend analysis of rainfall*

The Mann-Kandell trend test (*z*-statistics) was done for the period of 46 years (1969-2014) for the rainfall tendency over all the stations for the season as a whole and each month of the season. Thus the *z*-scores computed for the seasonal means of rainfall for inland stations of TEL/RSM and coastal stations in CAP are presented in Table 1. Among these stations, three stations noted to be robust, that indicated significant increasing trend of 95% level of significance with z score of 1.97* for Gannavaram, 2.12* for Machilipatnam and 1.97* for Visakhapatnam. All the three stations located were in Coastal Andhra Pradesh along the coast. Gannavaram and Machilipatnam located in SCAP (Krishna District) and

TABLE 1

***Z*-statistics of seasonal rainfall for selected stations during the years 1969-2014**

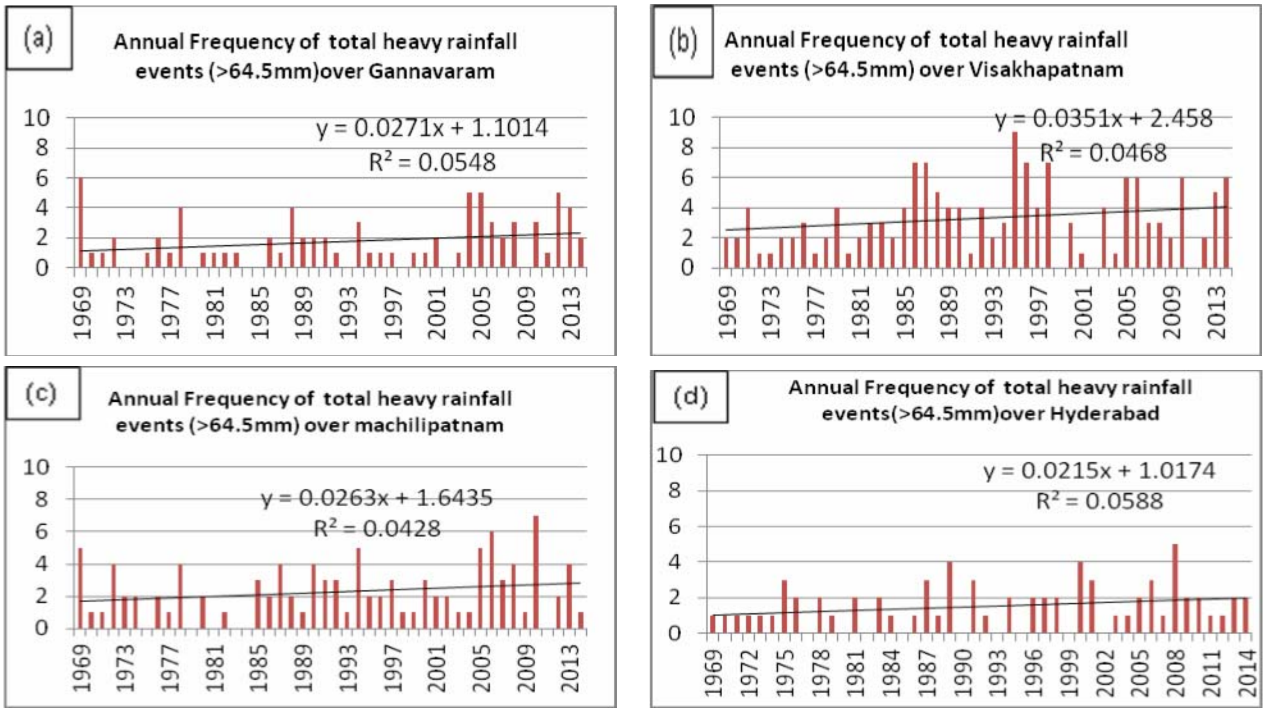
Time series	Rainfall	Rainy days	Rainfall > 64.5 mm
	Test *Z*	Test *Z*	Test *Z*
JJASknd	0.64	0.41	-0.31
JJASkln	1.17	1.46	0.09
JJASmpt	**2.12***	0.54	1.00
JJASnlr	0.68	-0.13	0.06
JJASong	0.18	-0.78	-0.67
JJASgnv	**1.97***	1.13	1.29
JJASwlt	**1.97***	**2.88***	0.31
JJASCAP	**1.69+**	1.08	0.26
JJASant	1.53	1.53	0.52
JJASarv	0.55	0.23	0.56
JJAScdp	0.48	0.66	-0.03
JJASkrn	1.44	0.70	1.14
JJASndl	0.26	0.30	-1.34
JJASRSM	1.02	0.86	0.28
JJASbdc	0.68	-1.41	-0.41
JJAShyd	0.89	-0.13	**1.71+**
JJASkmt	1.22	0.37	1.26
JJASmbn	-0.05	0.26	-1.28
JJASnzb	-0.15	0.33	-0.84
JJASrmd	-0.42	0.26	-1.42
JJASTEL	0.44	-0.49	-1.09

Visakhapatnam located in NCAP (Visakhapatnam district). The time series of the three sub-divisions are presented in Figs. 7(a-c). It is also noted that CAP showed significant increasing trend in rainfall at 90% level of confidence (with z-score of 1.69^{+}). Rainfall significantly increased at the rate of 2.37 mm/year (CAP), 1.93 mm/year (RSM), 0.492 mm/year (TEL) and inversely proportional as rainydays decreased for all the three subdivisions at the rate of 0.059/year (CAP), 0.045/year (RSM) and -0.048/year (TEL) respectively.

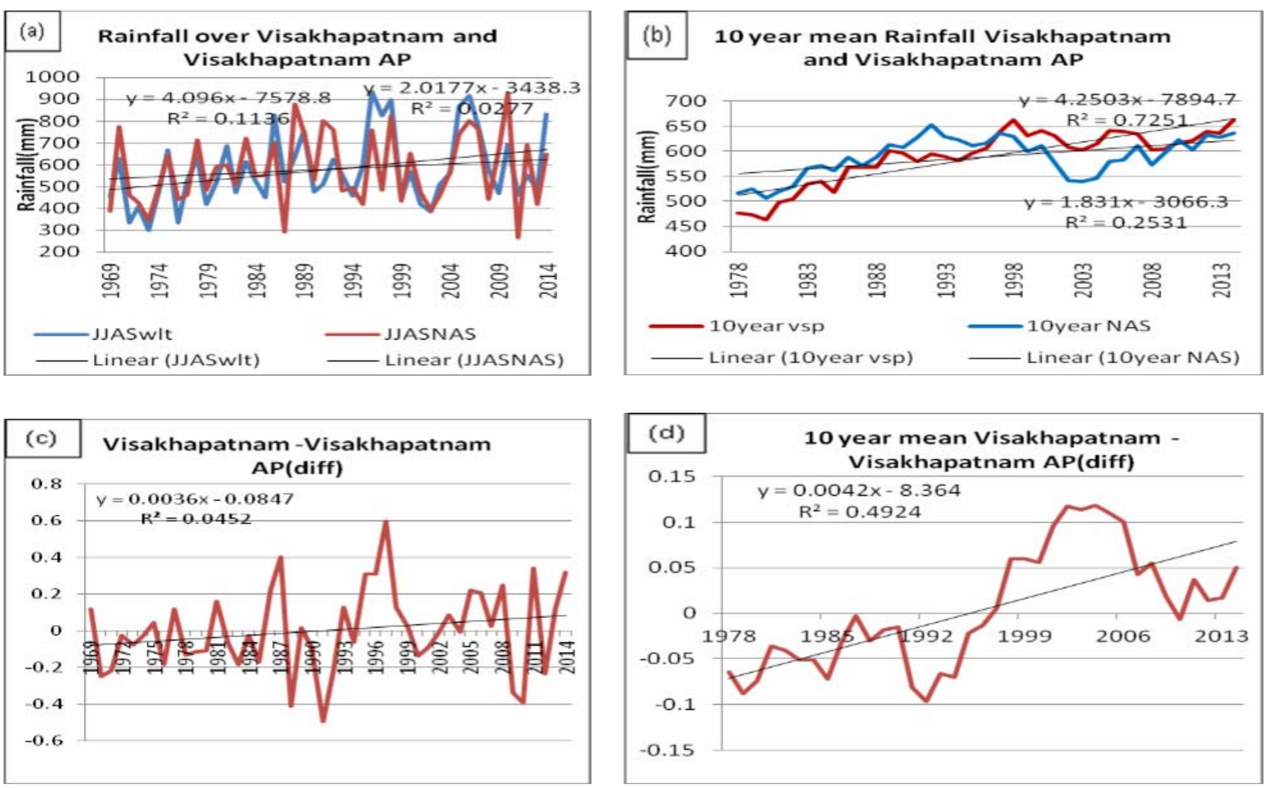
However, Hyderabad also exhibited insignificant increasing trend (*z*-score = 0.89) located in Telanagana. Kurnool and Anantapur which is local urban centre in Rayalaseema also exhibited insignificant increasing trend in rainfall as compared to other cities near to its location. Rest of the stations were selected, in order to test the urbanization impact showed mixed trend with insignificant decreasing or increasing trend in rainfall (Please refer to *z*-score values in Table 1. The time series of the seasonal rainfall and rainydays of the urban cities were presented in Figs. 4(a-e) and 5(a-g). Henceforth, it may be clearly noted that increased trend in seasonal rainfall over major cities (Hyderabad) and developing cities (Visakhapatnam, Gannavaram, Machilipatnam) may be due to the impact of urbanization. Thus, the data is considered separately and study was done for understanding the urbanization. The present work is to aim for the impacts of urbanization of the cities as compared to the surrounding locations. However, only the stations that showed significant increasing trend (above 90% level of confidence) of rainfall and extreme heavy rainfall events were considered for detailed study. Further the trend analyses also revealed that the data analysis performed for 1969-2014 for extremely heavy rainfall (EHRF) events found to be well marked for Hyderabad with significant increase at 95% level of confidence at *z* value of 1.71* during the monsoon season as whole during the 46 years (1969-2014) period (Table 1). One of the reasons that such a phenomenon of increase rainfall could occur may be because an increase in temperature (heat islands) that increases the capacity of the atmosphere to hold water which in turn increases the amount of precipitation. Also Mohapatra *et al.* (2009 and 2010) revealed that the increased rainfall may be due to the impact of urbanization as found for other major cities like Bangalore and Mumbai. The annual frequency of the extreme heavy rainfall events showing significant increase for Machilipatnam, Gannavaram, Visakhapatnam and Hyderabad were shown in Figs. 8(a-d).

The surrounding stations showed different trends for EHRF events in TEL state. These stations were Ramagundam well known for its mordernisation and industrialization (Thermal power stations and coal mines) and Nizamabad that were surrounded with hills, forest and river showed insignificant decrease in Seasonal rainfall and EHRF events. In RSM, Nandyala which surrounded by Nallamala Hills, dense forest to east and granite mines towards south and river to its west showed insignificant decrease in EHRF events. If this trend continues in the future then it could have repercussions in the sustainability of surface water resources and groundwater recharge.

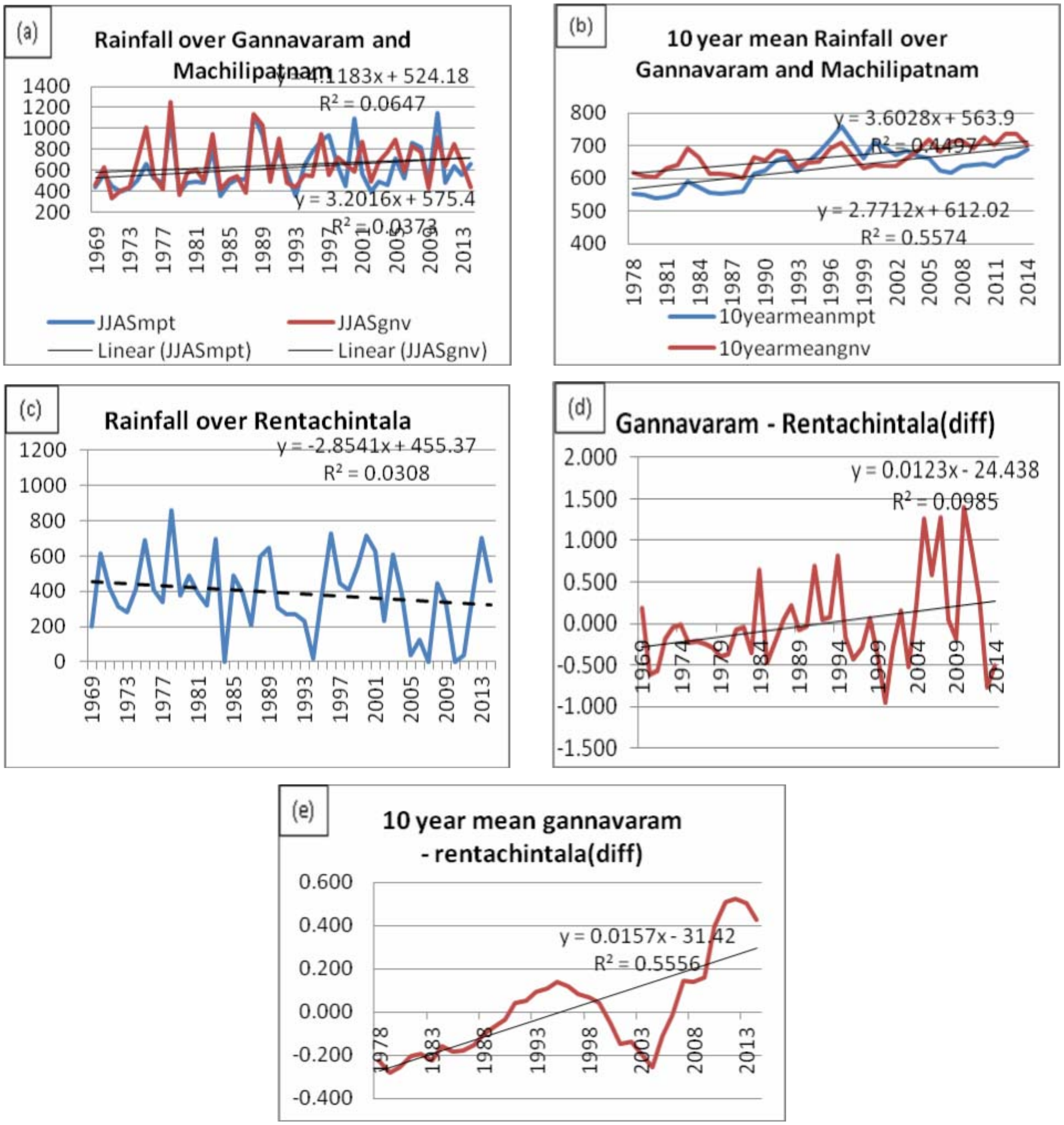
It was also seen that during 1969-2014, there were 7 monsoon depressions that formed over BOB and crossed from sea to land between 12° N to 18° N latitude over Andhra Pradesh coast. Out of these 7 monsoon depressions (1969-2007); 5 crossed near to Machilipatnam and Gannavaram and moved over land towards NTEL. While the other two monsoon depressions crossed above 17° N latitude near to Visakhapatnam. After monsoon season of 2007 no such systems were observed to cross the coast (IMD, 2008). This may be reason that impacts of decreased trend of extreme heavy rainfall events over NTEL which is located inland. This would also be the



Figs. 8(a-d). The time series of the annual frequency of total heavy rainfall events (> 64.5 mm) showing significant increase over urban cities (a) Gannavaram, (b) Visakhapatnam, (c) Machilipatnam and (d) Hyderabad



Figs. 9(a-d). The time series of the seasonal rainfall events showing significant increase over (a) actual rainfall of Visakhapatnam and Visakhapatnam AP (b) decadal mean of actual rainfall of Visakhapatnam and Visakhapatnam AP (c) difference of actual rainfall of Visakhapatnam and Visakhapatnam AP and (d) difference of decadal mean of actual rainfall of Visakhapatnam and Visakhapatnam AP at 90% significance level



Figs. 10(a-e). The time series of the Seasonal rainfall events showing significant increase over (a) actual rainfall of Machilipatnam and Gannavaram (b) decadal mean of actual rainfall of Machilipatnam and Gannavaram (c) actual rainfall of Rentachintala (d) difference of actual rainfall of Machilipatnam and Gannavaram and (e) difference of decadal mean of actual rainfall of Machilipatnam and Gannavaram at 90% significance level

reason for occurrence of more moderate rainfall events (2.5 mm to 64.4 mm) than extreme heavy rainfall events over Visakhapatnam (in NCAP) during the study period. The reason for this may be convection becomes weaker over Bay of Bengal and its surrounding stations during the recent years in this global warming era. Since 1965, satellites have been monitoring the weather systems for the areas of formation of monsoon depressions continuously and during this period the vertical shear of the horizontal wind between the lower and upper troposphere is found to decrease. Naidu *et al.* (2011) showed the prominent weakening of upper level easterlies in this global warming era and significant decrease in southwest monsoon rainfall. Some results indicate that

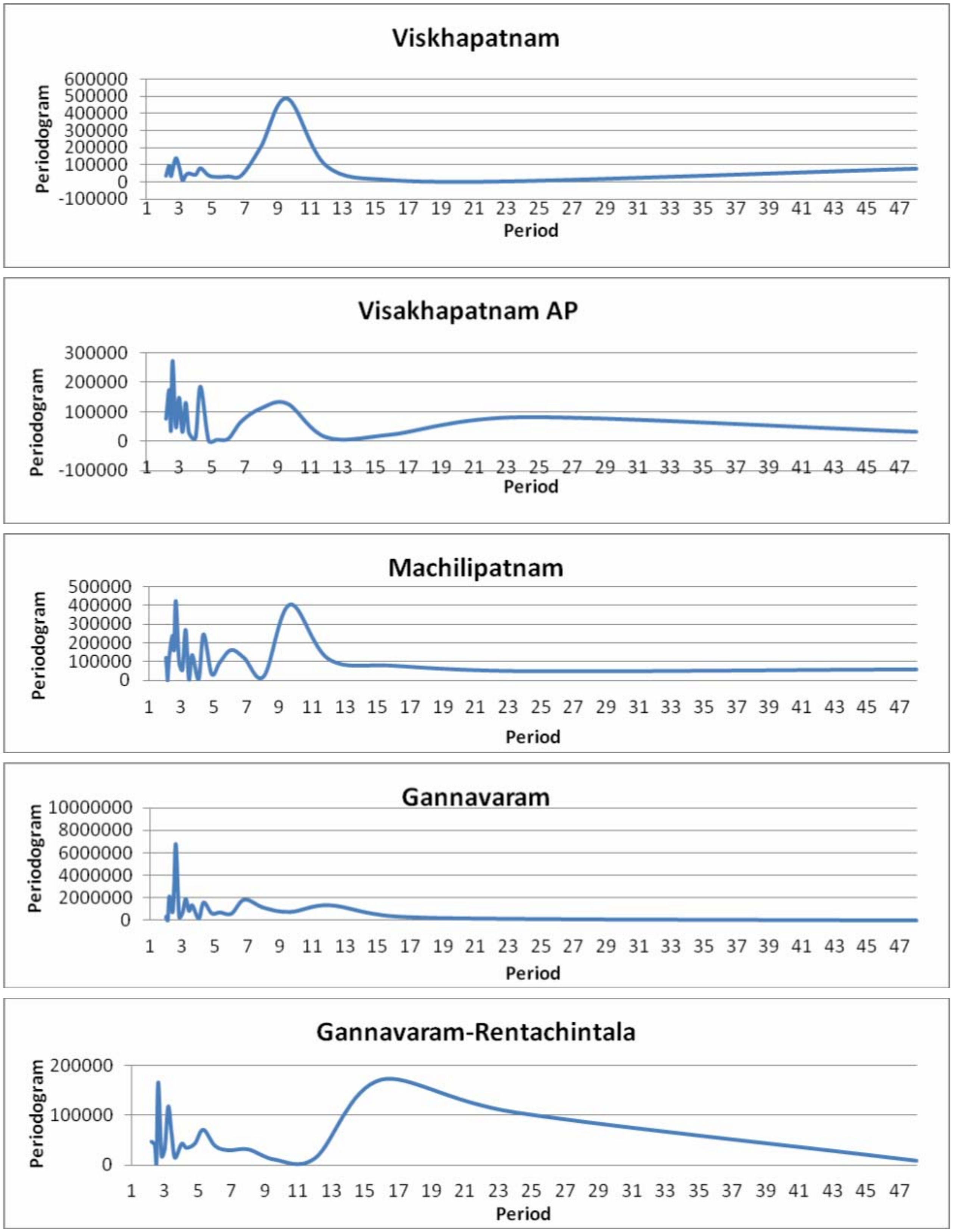


Fig. 11. Periodicities of urban centres of coastal Andhra Pradesh

although the number of low pressures has been increasing during the past decades, the dynamic conditions such as wind shears, moisture, mean sea level pressure were not favourable for the intensification to depressions and cyclonic systems (Dash *et al*., 2004).

Separate studies were done for examining the impact of urbanization and rainfall over Visakhapatnam and Gannavaram, which exhibited significant increasing trend in rainfall. Inorder to understand the urbanization of Visakhapatnam, the rainfall was compared to the local Airport station located in the outskirts of the city, 15 kms away from the current station. The rainfall trend of the two stations is shown in Figs. 6(a-g). The rainfall showed gradual raise in rainfall after 1991. It continued to increase at the rate of 4.09 mm/year, while airport reported 2.01 mm/year. The difference in rainfall was found to significantly increase at 90% level of confidence (*z*-score = 1.86*). The actual, 10 year mean rainfall and difference rainfall of Visakhapatnam and Airport were presented in Figs. 9(a-d). The rate of increase was faster for Visakhapatnam city until 2010. After 2010, the Airport station also recorded the almost same rainfall values, which thus revealed that impact of extension of urbanization into the outskirts of the city. Surprisingly, over the Visakhapatnam city the rainfall and rainy days increased significantly with z-score of 2.88* (95% level of confidence) which showed increase in convective activity was very prominent during the monsoon with lower rainfall amounts (2.5 mm to <64.5 mm). This may be due to maritime air near to the coast causing rainfall due to land and sea breeze effect.

Gannavaram and Machilipatnam recorded significant increase trend in rainfall as compared to the surrounding stations in Coastal Andhra Pradesh. This may be also due to the impact of urbanization. The rainfall data was compared with Rentachintala located in remote area near to Gannavaram. Rentachintala recorded decreasing tendency in rainfall. The difference of rainfall with Gannavaram was well marked that showed significant increasing trend in rainfall with *z*-score of 1.87^{+} (90% level of confidence) and 2.06* (95% level of confidence) respectively. The actual, 10 year mean rainfall and difference rainfall of Gannavaram, Machilipatnam and Rentachintala are presented in Figs. 10(a-e). It was understood due to urbanization, rainfall was increasing over years. The reason may be due to unusual heat of the surface, the hot surface can hold more water vapour and hence precipitation takes place. To examine, whether the increasing trend of the rainfall over city centres was inherent natural periodicity in rainfall, the power spectrum analyses of the rainfall data (1969-2014) was carried out. It indicates that there were periodicities of 3 years and 9 years in case of all the stations except Gannavaram (Fig. 11). Considering the periodicity in difference of rainfall for Gannavaram and Rentachintala, no such natural periodicity was seen. This shows that the increase in rainfall over the city centres was not a part of natural variability, but due to urbanization impact.

4. Conclusions

The analysis of rainfall over the urban centres and its surrounding locations during monsoon season (June through September) based on 46 years data revealed.

(*i*) The average rainfall was found to be maximum in July and August for stations of Telangana followed by Coastal Andhra Pradesh and Rayalaseema. The rainfall variability was found to be maximum during July and August followed September and June.

(*ii*) The frequency of heavy rainfall events was found to be high as compared to very heavy rainfall and extreme heavy rainfall events and frequency was more during July, August and September. Extreme heavy rainfall events were few in number.

(*iii*) The time series of seasonal rainfall indicated significant increase (95% level of significance) in seasonal rainfall for the stations of Gannavaram, Machilipatnam and Visakhapatnam located along the coastline in CAP. The seasonal rainfall found to be significant increase for coastal area stations when compared to inland area stations.

(*iv*) It was revealed that the CAP rainfall increased significantly (90% level of confidence) and rainy days (>2.5 mm) decreased. Also, Telangana and Rayalaseema showed increasing and decreasing trend for seasonal rainfall and rainy days respectively. The number of rainy days less as compared to rainfall amounts indicates rainfall intensity increased and more over coastal stations as compared to inland stations.

(*v*) Over Visakhapatnam city (Coastal station) the rainfall and rainydays increased significantly (95% level of confidence) which showed increase in convective activity was very prominent during the monsoon with high lower rainfall events and less extreme rainfall events.

(*vi*) Over Hyderabad city (Inland station), the extreme rainfall events significantly increased (90% level of confidence), but the lower rainfall events are very less.

(*vii*) It was also observed that significant increasing (decreasing) of contribution of extreme rainfall events may be balanced by significant decreasing (increasing) of lower rainfall events.

(*viii*) However, density of station observations would be necessary to understand the chief features of the variability of climate for specified region or location.

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