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Variations in Indian summer monsoon rainfall patterns in changing climate

R. BHATLA, MANAS PANT, SOUMIK GHOSH*, SHRUTI VERMA**,

NISHANT PANDEY*** and SANJAY BIST***#

Department of Geophysics, Institute of Science, Banaras Hindu University, Varanasi, India

**Department of Earth and Planetary Sciences, Weizmann Institute of Science, Revovot, Israel*

***Department of Atmospheric Physics, Faculty of Mathematics Physics, Charles University, Czech Republic*

****IIT (ISM), Dhanbad, India*

*****#India Meteorological Department, MoES, New Delhi, India*

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e mail : rbhatla@bhu.ac.in

सार — **भारतीय ग्रीष्मकालीन मॉनसून एक वृहत मान सिनाऑप्टिक और प्रबल परिसंचरण है जो मुख्य रूप से जून से सितंबर तक गर्मियों के महीनों तक ही सीमित है। वर्षा प्रतिरूप और इसकी प्रवृत्तियों की उचित समझ से जल संसाधन विकास, कृषि क्षेत्र और विकासात्मक गतिविधियों के लिए निर्णय लेने में मदद मिल सकती है। यह अध्ययन जलवायविक अवधि** (1901-2010) **में भारतीय उपमहाद्वीप में भारतीय ग्रीष्मकालीन मॉनसून वर्षा** (ISMR) **में स्थानिक परिवर्तनशीलता का मूल्यांकन करने का एक प्रयास है। मॉनसून (जून-सितंबर) और चरम मॉनसून महीने (जुलाई-अगस्त) के दौरान** 1901-2010 **की अवधि के दीर्घावधि वार्षिक, दशकीय और तीसदशकीय मॉनसून वर्षा विविधताओं पर विचार किया गया है। परिणाम ऊपरी हिमालय, पश्चिमी और प्रायद्वीपीय भारत के प्रमुख क्षेत्रों के लिए मॉनसून और चरम मॉनसून के महीनों के दौरान** 0.2 **से** 1 **मिमी/दिन भिन्नता के साथ वर्षा में सकारात्मक अंतर/वर्षा में वृद्धि हुई है, परिणाम चिंताजनक हैं। साथ ही, पश्चिमी घाट, भारत गांगेय मैदान** (IGP) **और कुछ मध्य भारतीय क्षेत्रों में** -0.6 **से** -1.5 **मिमी/दिन की सीमा में वर्षा में कमी दर्ज की गई है। इसके अलावा, अध्ययन का एक व्यापक अवलोकन पश्चिमी भारत में आईएसएमआर की वृद्धि जबकि पूर्वोत्तर भारतीय क्षेत्रों में पर्याप्त गिरावट दर्शाता है जो बदलती जलवायु में आईएसएमआर के पश्चिम की ओर परिवर्तन के बारे में बताता है।**

ABSTRACT. The Indian summer monsoon is a large scale synoptic and dominant circulation feature which is largely restricted to the summer months from June to September. The proper understanding of rainfall pattern and its trends may help water resources development, agriculture sector and to take decisions for developmental activities. The present study is an attempt to evaluate the spatial variability in Indian summer monsoon rainfall (ISMR) over the Indian subcontinent during the climatological period (1901-2010). The long-term annual, decadal and tricadal monsoon rainfall differences are considered for the period 1901-2010 during the monsoon (June-September) and peak monsoon month (July-August). The results show concern for the major areas of upper Himalaya, Western and peninsular India where positive rainfall difference/increase rainfall with 0.2 to 1 mm/day variation have been reported during the monsoon and peak monsoon months. Also, decrease in rainfall have been reported over Western Ghats, Indo-Gangetic Plain (IGP) and some central Indian regions in the range of -0.6 to -1.5 mm/day. Further, a broad overview of the study shows an enhancement of ISMR over Western India whereas a substantial decline over Northeast Indian regions which suggests the western shift of ISMR in changing climate.

Key words – ISMR, Interannual variability, Decadal, Tricadal.

1. Introduction

The Indian summer monsoon rainfall (ISMR) over India contributes approximately 80% of the annual precipitation during June-September, *i.e.*, Indian Summer Monsoon (ISM) Season. The agriculture, power generation and industrial production activities in India substantially depend on monsoon rainfall. The ISM season with its onset around 1st June extends up to September and is characterized by its epochs such as evolution (onset),

advancement (active/break) and withdrawal over India (Raju *et al.*, 2005; Bhatla *et al.*, 2019). Two remarkable features of the summer monsoon are its regular occurrence every year and the irregular variation in the amount of seasonal mean rainfall that it brings to India from one year to the other. The ISMR is associated with interannual and intraseasonal variation (Gadgil, 2003; Raju *et al.*, 2002) which affects water resources, agriculture, power generation, the economy of the country (Turner and Annamalai, 2012; Bollasina *et al.*, 2014; Singh *et al.*, 2014).

Considering the thought of the country as one unit, many studies are focused on understanding and predicting the seasonal rainfall behavior over India. Practical study of entire regions of India is a very difficult task, so the overall view of the rainfall fluctuations and abnormalities are considered by the planners and scientists in studying general circulation and changes (Parthasarathy *et al.*, 1992; 1993). The variability in the pattern of monsoonal rainfall occasionally leads to extreme hydrological events (large-scale droughts and floods) resulting in a serious reduction in agricultural output and affecting the vast population (over excess of one billion) and the national economy (Kripalani *et al.*, 2003). The warming of SST (mainly in the tropical Pacific) corresponds to increased variability of evaporation which enhances the variability in ISMR (Meehl and Arblaster, 2003). Naidu *et al.* (1999) studied the trends and periodicities of annual rainfall for different subdivisions of India for a period of 124 years (1871-1994). There are considerable variations in the rainfall, both in time and space, within a season. A recent gridded daily rainfall data over continental India for more than 50 yearsrepresents the spatial pattern of anomalies of rainfall in association with different phases of Intra-seasonal variations (Rajeevan *et al*., 2010). The behavior of precipitation during the monsoon season varies regionally, and in several studies, it was found that complex land-atmosphere interaction has a vital impact on monsoonal rainfall characteristics. (Medina *et al.*, 2010; Asharaf *et al.*, 2012; Bhatla *et al.*, 2016, 2019). Further, an increasing trend of future rainfall during the monsoon season was found which is due to global warming (Kumar *et al*., 2010). Several scientists have found facts that our earth has been warmed by around 1°C as compared to the pre-industrial era and it may rise 3-6°C by the end of the 21st century under high emission scenarios (Tollefson, 2020; Pachauri *et al.*, 2014). The ISM circulation is sensitive to the warming climatic conditions and the unprecedented emission (RCP8.5 scenarios) may enhance the monsoon vagaries and complexities which consequently could enhance the frequency and severity of extreme rainfall events over the subcontinent (Kitoh *et al*., 1997; Trenberth *et al*., 2003; Gadgil and Rupa Kumar, 2006); IPCC, 2007, 2012).

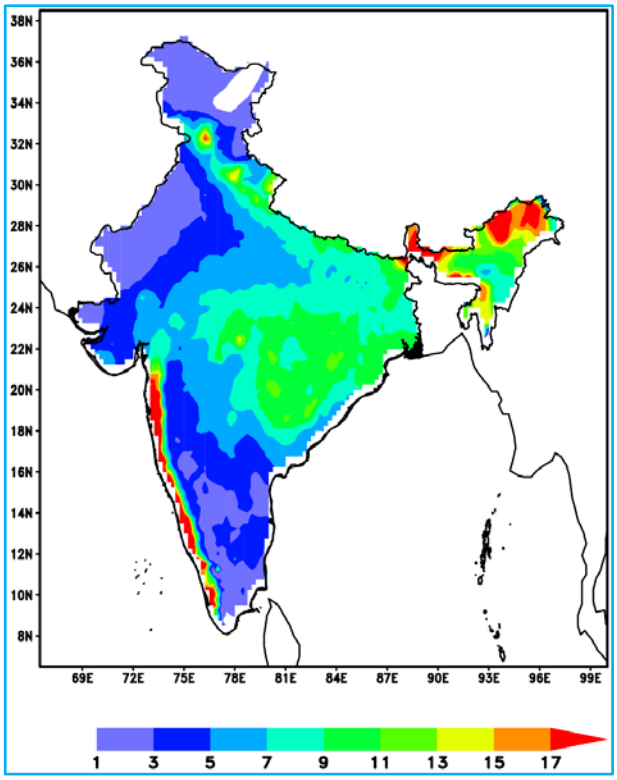
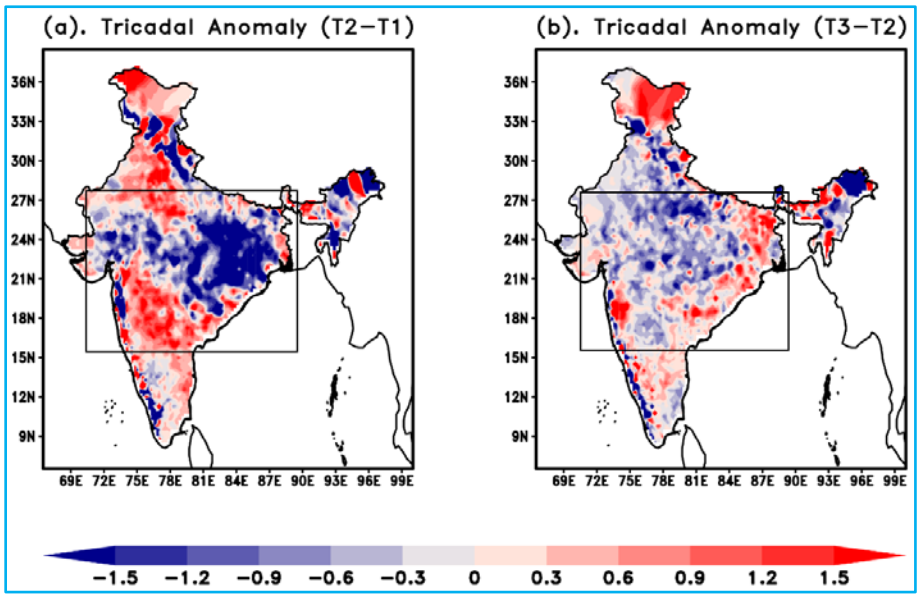


Fig. 1. The rainfall climatology pattern (mm/day) from 1901 to 2013 during JJAS

In this study, an investigation of the ISMR pattern during June to September and the peak monsoon months of July-August over the Indian region was carried out for the period 1901-2013. Differences in the pattern of monsoonal rainfall were studied for the decadal and tricadal time scale combined for the ISM season (June to September) and also for peak monsoon months (July-August). This study may help in understanding the evolution of the summer monsoonrainfall and associated variability over India and its region. It might help various researchers and policymakers to enhance their understanding and decision-making capabilities in order to develop mitigating approaches in changing climate. Also, it may provide a way to assess the reliability of any model validation.

2. Data and methodology

The high resolution (0.25°×0.25°) datasets were obtained from the India Meteorological Department (IMD) for all the regions of India (Pai *et al.*, 2014). Separate analysis have been done for different time periods, which include combined study of patterns from June to September (JJAS) and July to August (JA) during 1901-2013. The study of tricadal patterns has been done by taking out the differences averaging the 30 years data,

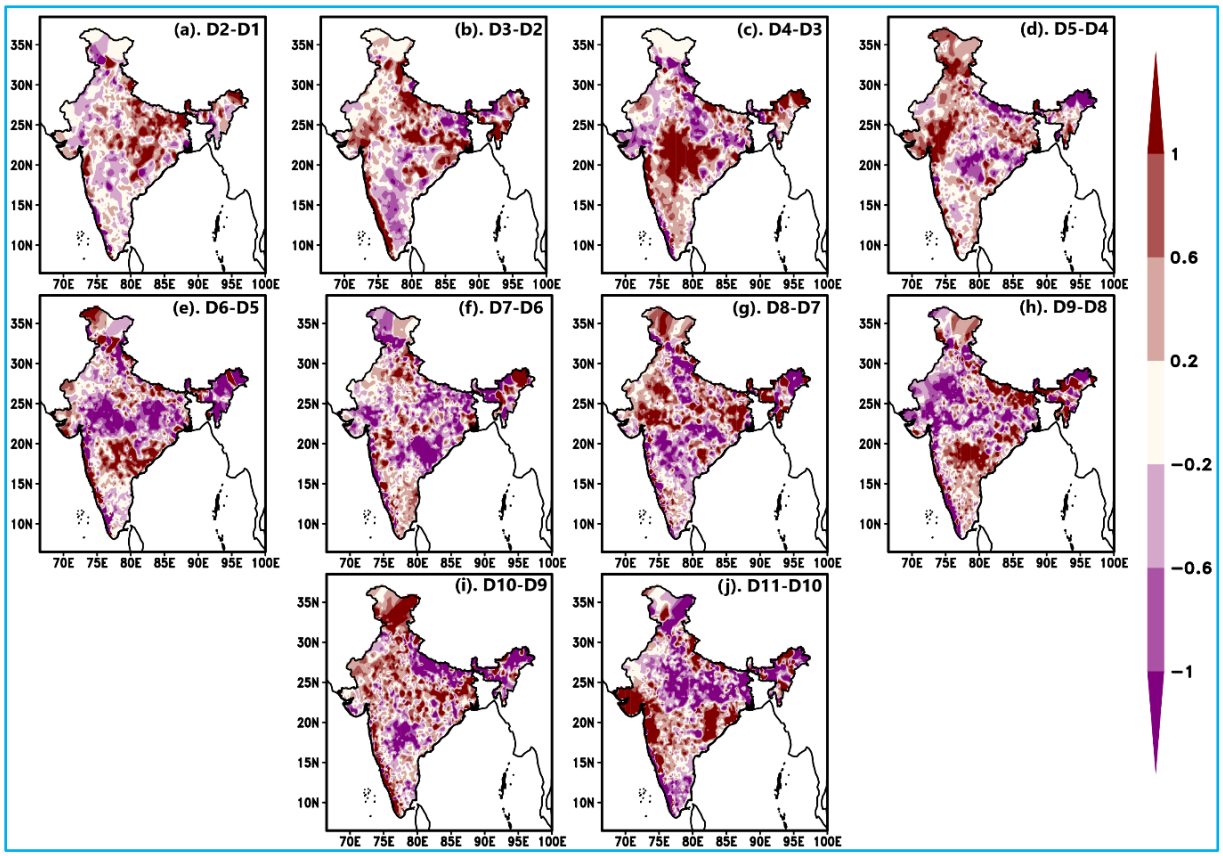


Figs. 2(a&b). The tricadal difference of JJAS rainfall pattern (mm/day) during the tricades: 1921-1950 (T1), 1951-1980 (T2), 1981-2010 (T3)

i.e., 1921-1950 (T1), 1951-1980 (T2), 1981-2010 (T3) for which two tricadal differences, T2-T1 and T3-T2 have been considered over India. Further, the decadal difference patterns have been studied by taking the difference of 10 year's averages. For that purpose, eleven decades have been taken into consideration, *viz.*, 1901-1910(D1), 1911-1920 (D2), 1921-1930 (D3), 1931-1940 (D4), 1941-1950 (D5), 1951-1960 (D6), 1961-1970 (D7), 1971-1980 (D8), 1981-1990 (D9), 1991-2000 (D10) and 2001-2010 (D11) for which decadal differences, namely D2-D1, D3-D2, D4-D3, D5-D4, D6-D5, D7-D6, D8-D7, D9-D8, D10-D9 and D11-D10 have been computed.

3. Results and analysis

The average ISMR (June to September) pattern over 113 years from 1901 to 2013 has been depicted in Fig. 1. The monsoon rainfall distribution is not uniform as the Western Ghats and a few regions of northeast India reported the highest amount of rainfall (15 to 17mm/day or more), while western Indian, upper Himalayan regions and the Lower Peninsula have received less rainfall with a variation of 1 to 3 mm/day. The central regions of Rajasthan, some upper portion of Gujarat and Deccan regions have rainfall variation of 3 to 5 mm/day. The Indo - Gangetic plain (IGP) and a major portion of Central India have received rainfall which lies in the range of 5 to 11 mm/day or more, while lower central Indian regions show rainfall in the range of 5 to 9 mm/day. Regions of central north east India have received a moderate amount of rainfall with a variation of 9 to 11 mm/day. The tricadal difference (T2-T1) which is the difference of two tricades (1921-1950) and (1951-1980) represents the variation in the precipitation pattern during ISM season over India [Fig. 2(a)]. Adecrease in the amount of rainfall occurred in the major regions of central India, central northeast, northeast and some parts of the western Ghats with a variation of -0.6 to -1.5 mm/day. Various studies have also reported the decrease in rainfall during the summer monsoon season in India (Guhatakurta and Rajeevan, 2008; Sontakke *et al.*,2008). Some regions of the upper Himalaya, Western Ghats and northeast India have shown an increase in the amount of rainfall with 0.6 to 1.5 mm/day variation. The positive and negative differences occur in different regions of central India, Rajasthan, Gujarat and the lower peninsula, with variation which lies in the range of -0.6 to 0.3 mm/day. Major areas of upper Himalaya, Rajasthan and peninsular India show a positive difference in precipitation pattern with 0.2 to 1.2 mm/day variation. Further, the tricadal difference (T3-T2) shown in Fig. 2(b) depicts a negative difference in rainfall over major regions of the Western Ghats. Northeast India and some parts of IGP with variation of -0.9 to -1.5 mm/day. Positive differences arise in certain regions of upper Himalaya, northeast India and some parts of the Western Ghats and central northeast India with variation in the range of 1.2 to 1.5 mm/day. The decrease in rainfall occurs in the major areas of central India, IGP and Lower Peninsula by -0.9 to -1.2 mm/day. The different regions of upper Himalaya, Rajasthan, Gujarat, central India and peninsular India show an increase in the



Figs. 3(a-j). The decadal difference of mean ISM rainfall in mm/day during JJAS. The considered eleven decades are 1901-1910(D1), 1911-1920(D2), 1921-1930(D3), 1931-1940(D4), 1941-1950(D5), 1951-1960(D6), 1961-1970(D7), 1971-1980(D8), 1981-1990(D9), 1991-2000(D10) and 2001-2010(D11)

pattern of rainfall with a variation of 0.3 to 1.2 mm/day. The rectangular box in Figs. 2(a&b) represents the highly affected area with negative and positive differences during the different tricades. The rainfall over central India, lower IGP and a few Eastern coastal regions was reduced during T2 as T2-T1 is highly negative. However, the situation improved during T3 as T3-T1 shows fewer negative values as compared to T2-T1. Further, lower IGP regions have received excess rainfall during the recent tricade while the rainfall over upper and central IGP regions has been reduced during the same period. Fig. 3(a) illustrates the decadal difference (D2-D1) which is the difference of two decades (1901-10) and (1911-20). This clearly represents the decrease and increase in the amount of rainfall over different regions of India during JJAS. The regions of central India and the eastern part of north-east India have shown an increase in precipitation by 0.6 to1 mm/day, while major regions of the Western Ghats and some lower areas of north east India have shown a decrease in rainfall which falls in the range of -0.6 to -1 mm/day. The middle and lower parts of Rajasthan show negative difference in the range of about -0.2 to -0.6 mm/day. The upper Himalayan regions, some parts of eastern Rajasthan and mid areas of peninsular regions show both negative and positive differences with variation of -0.2 to 0.2 mm/day. Some upper regions of Gujarat, middle and lower parts of central India and the lower Peninsula have shown precipitation variation of 0.2 to 1 mm/day. Fig. 3(b) represents decadal difference (D3-D2) which is the difference between two decades D3(1921-30) and D2(1911-20). The upper and lower regions of central India, eastern coastal regions, eastern part of northeast India and Western Ghats reported positive differences with rainfall variation of more than 1 mm/day. A significant decrease in the amount of rainfall over the middle central India, peninsular India and some lower IGP regions in the range of -0.2 to -1 mm/day can be noticed, while central and upper IGP regions depicted enhance rainfall. Further, the northern Himalayan regions showed rainfall difference in the range -0.2 to 1 mm/day. The decadal difference D4-D3 [Fig. 3(c)] depicts an opposite situation in comparison to that of D3-D2 as the major regions of the Western Ghats, western and upper central Indian regions, upper IGP and northern India along with Himalayan regions reported a decrease in rainfall (-0.2 to 1 mm/day). Most of the northeast and central

Indian regions, lower IGP and some of the western coastal regions have shown increased rainfall with differences 0.6 to 1 mm/day or more. It also indicates that Jammu & Kashmir, some western regions of Rajasthan and eastern areas of the lower peninsula reflect positive and negative differences which lie in the range of -0.2 to 0.2 mm/day. Fig. 3(d) illustrates the decadal difference (D5-D4) which is the difference of two decades D5 (1941-50) and D4 (1931-40). The major areas of western India,*i.e.*, Rajasthan, Gujarat and north western India along with most of the northern regions such as Jammu & Kashmir, Punjab and Uttarakhand reported an increase in rainfall with differences in the range 0.6 to 1 mm/day. A study by Naidu *et al.* (2009) has also reported the wet monsoon conditions during the 1950s However, situation over most of the IGP, upper northeast India and central Indian regions has reversed as suppression of rainfall (-0-2 to -1 mm/day) has been faced by these regions. Some parts of eastern and middle peninsular India depicted a decrease in rainfall with a difference in the range -0.2 to 1 or more, whereas most of the western and eastern coastal peninsular India showed a positive difference of 0.2 to 0.6 or more.

The decadal difference (D6-D5) depicts a negative difference in the rainfall pattern over almost entire central and northeast India along with some areas of the Western Ghats with variation of -0.6 to -1 mm/day or more [Fig. 3(e)]. The vast region of IGP except a few lower and upper regions, upper parts of the southern peninsula along with western and eastern coastal regions depicted enhanced rainfall with variation of 0.6 to 1 mm/day while lower peninsular regions reported rainfall differences in the range -0.6 to 0.2 mm/day. Some areas of western India, such as the upper part of Rajasthan along with Gujarat and western Jammu & Kashmir, showed increased rainfall (0.2 to 0.6 mm/day however, the difference of decades D7 and D6 showed a negative difference ranging from -0.6 to -1 mm/day over these regions [Fig. 3(f)]. Further, situation over a few regions of central India, southern peninsula and northeast India have reversed and enhancement in rainfall has been reported as the rainfall difference during D7-D6 depicts values in the range 0.2 to -1 mm/day. The central and lower IGP regions along with southeastern coastal regions (such as Andhra Pradesh) have shown a significant decrease in rainfall (-0.6 to -1 mm/day or more) during D7-D6. The decadal difference D8-D7 [Fig. 3(g)] depicts rainfall excess (difference being 0.6-1 mm/day) over western India (Rajasthan and few regions of Gujarat), Northern India (entire Jammu & Kashmir) and upper central India along with lower IGP regions. However, negative rainfall difference (-0.2 to -1 mm/day), *i.e.*, decrease in rainfall have been reported over the upper peninsula, lower central India and upper IGP regions. Fig. 3(h), which shows the

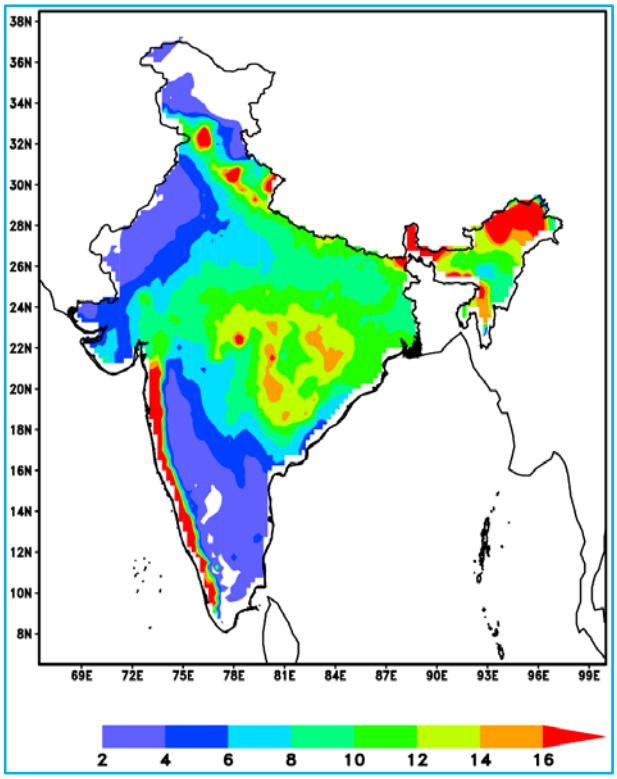
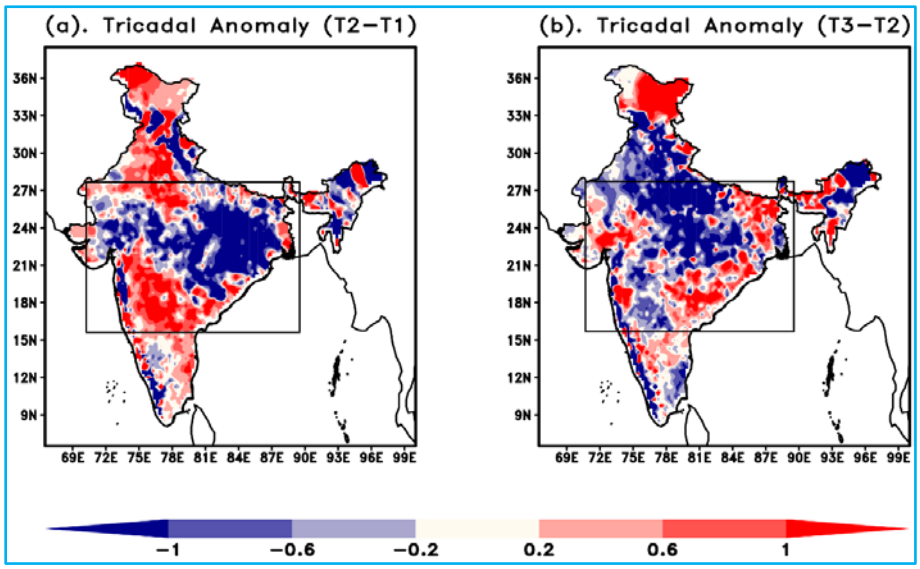


Fig. 4. The rainfall climatology pattern (mm/day) from 1901 to 2013 during JA

decadal difference D9-D8, depicts a reduction in rainfall over almost entire western India and the Western Ghats along with some upper regions of central India extending towards the eastern coasts (-0.2 to -1 mm/day). Further, D9-D8 reported enhancement in rainfall over IGP, lower central India and peninsular regions with a rainfall difference 0.2 to 1 mm/day. The decadal difference D10-D9 represents a reversed situation over almost the entire country as compared with last decade [Fig. 3(i)]. A significant increase in rainfall (difference being 0.2 to 1 mm/day) has been reported over northern India with the Himalayan regions, upper central India and western India (most of the regions of Rajasthan and Gujarat) along with the Western Ghats. Conversely, lower central India, northeast India and central-lower IGP regions have shown a decrease in rainfall as D10-D9 ranges -0.6 to -1 mm/day or more. Fig. 3(j) represents the decadal difference of decades D11 and D10 and suggests a significant increase in rainfall (0.6 to 1 mm/day or more) over lower central India, eastern coasts and Gujarat along with adjoining western coastal regions. However, a decrease in rainfall over upper central India, northern Indian Himalayan regions and southern peninsular regions can be observed as the D11-D10 has shown values in the range -0.6 to -1 mm/day or more.

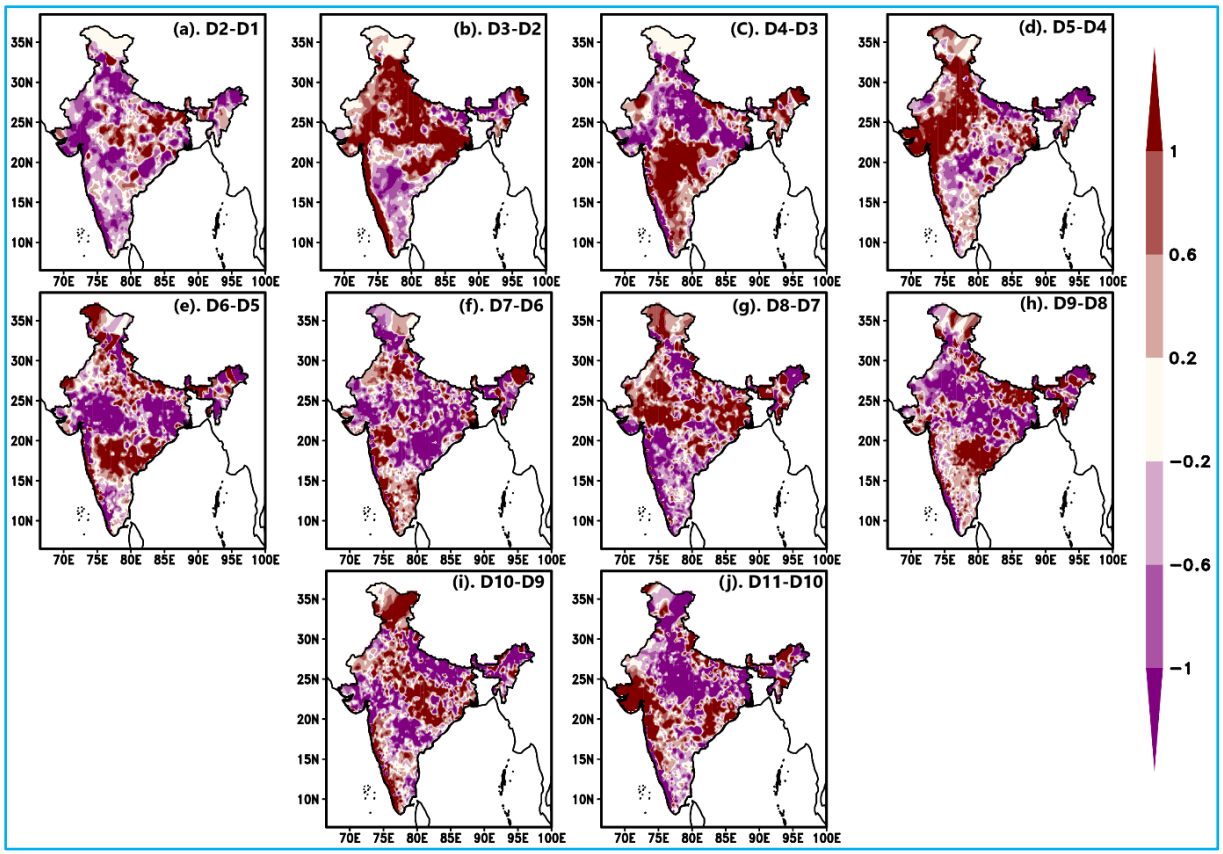


Figs. 5(a&b). The tricadal difference of JA rainfall pattern (mm/day) during the tricades: 1921-1950(T1), 1951-1980(T2), 1981-2010(T3)

The average peak ISMR (July to August) pattern or peak monsoon rainfall climatology over 113 years from 1901 to 2013 has been shown in Fig. 4. The precipitation pattern is not uniform and has certain variations. The major parts of the Western Ghats and some regions of the northeast have received high amounts of rainfall (14 to 16 mm/day or more). The peninsular region, some parts of Rajasthan and upper Himalaya have received less rainfall with a variation of 2 to 4 mm/day. About 4 to 8 mm/day variation in the precipitation pattern arises in certain parts of Rajasthan, Gujarat and regions of lower central India. Moderate rainfall occurs in major parts of IGP, central northeast and some areas of the northeast with variation which lies in the range of 8 to 12 mm/day. Some parts of central India and northeast also received a good amount of rainfall with 12 to 16 mm/day variation.

The tricadal difference (T2-T1) of two tricades (1921-1950) and (1951-1980) for the peak monsoon months (July to August) has been shown in Fig. 5(a). The negative difference in monsoonal precipitation pattern occurs in regions of northern India, central India, central northeast and parts of the Western Ghats with variation in the range of about -0.6 to -1 mm/day. There is an increase in the amount of rainfall occurring in regions of upper Himalaya, Rajasthan, some parts of Gujarat and major parts of the peninsular region with a variation of 0.2 to 1.5 mm/day. The monsoonal precipitation pattern with positive and negative differences occurs in some parts of Gujarat, Rajasthan, central India, IGP and the lower part of Indian peninsula with -0.6 to -1 mm/day of variation.

The tricadal difference (T3-T2) shows the precipitation pattern is not uniform over the Indian region during July to August [Fig. 5(b)]. An increase in the amount of rainfall was in major parts of Jammu & Kashmir and some parts of Gujarat, northeast and peninsular region with a variation of about 0.2 to 1.5 mm/day. The decrease in precipitation occurs in major regions of IGPs and some parts of central India, Western Ghats and northeast, which varies in range of -0.6 to -1 mm/day. About -0.6 to 0.2 of variation occurs in parts of the lower peninsula, Gujarat and Rajasthan. The box in Figs. 5(a&b) represents the highly affected area with negative and positive differences. The central Indian region is continuously facing negative differences and average rainfall is decreased. The difference T2-T1 is negative while T3-T2 shows positive values over Eastern coastal regions, which indicates that these regions have received sufficient rainfall during recent tricade. The Western Ghats have shown an increase in rainfall during recent tricades whereas a decrease in rainfall has been observed over the Ahmadabad and Nagpur regions. These results are in accordance with the study of Alvi and Koteswaram (1985). The lower central India depicts large values of positive differences when T2-T1 is calculated, while rainfall has getting reduced during recent decades as T3-T2 shows negative values over that region. Further, it can be noticed that rainfall over Northern India and Some regions of upper and central IGP is getting suppressed as T3-T2 is more negative than T2-T1. An overall perspective depicts western shift in ISMR in recent times which resembles to the study of Maharana *et al*. (2021).



Figs. 6(a-j). The decadal difference of mean ISM rainfall in mm/day during JA. The considered eleven decades are 1901-1910(D1), 1911-1920(D2), 1921-1930(D3), 1931-1940(D4), 1941-1950(D5), 1951-1960(D6), 1961-1970(D7), 1971-1980(D8), 1981-1990(D9), 1991-2000(D10) and 2001-2010(D11)

The decadal difference (D2-D1) which is the difference of two decades, *i.e.*, 1911-1920 and 1901-1910 during July to August (*i.e.*, peak monsoon months) has been shown in Fig. 6(a). The major regions of the Western Ghats, Gujarat and some parts of Rajasthan, central India, northeast and IGP show negative difference in precipitation pattern which lies in the range of -0.2 to -1 mm/day or less. An increase in the amount of rainfall occurs in some parts of IGP and central India with a variation of 0.6 to 1 mm/day or more. The major regions of the upper Himalaya represent a combination of both negative and positive differences with slight variations lying in the range -0.2 to 0.2 mm/day. Some regions of central and northeast India show a positive difference in precipitation pattern with 0.2 to 1 mm/day variations. Further, the decadal difference (D3-D2) shows the increase in the amount of rainfall occurs in major regions of the Western Ghats, central India, IGP and central northeast with variation of 0.6 to 1 mm/day and more than that [Fig. 6(b)]. The regions of lower central India, peninsular region and some parts of the northeast show a decrease in the amount of precipitation by -0.2 to -1 mm/day. The major portion of the upper Himalaya western parts of Rajasthan and some of the areas of the eastern peninsular region show a combination of both positive and negative differences in the pattern of rainfall which lies in the range of -0.2 to 0.2 mm/day. About 0.2 to 1 mm/day increase in rainfall occurs in the western parts of Rajasthan. Fig. 6(c) represents decadal difference (D4-D3) which depicts the reduction in the amount of rainfall over major areas of IGP, Gujarat and some parts of Rajasthan with variation of -0.6 to -1 mm/day. Positive and negative differences arise over almost the entire Jammu & Kashmir and eastern lower Peninsula region with variation in the range of -0.2 to 0.2 mm/day. A moderate to high increase in the amount of rainfall can be observed over central India, some northeast and lower peninsular regions with a variation 0.2 to 1 mm/day.

The decadal difference (D5-D4) shows that the precipitation pattern is not uniform over various Indian regions [Fig. 6(d)]. The northern regions, major parts of Gujarat, Rajasthan and some areas of central India and western Ghats show a high increase in the amount of

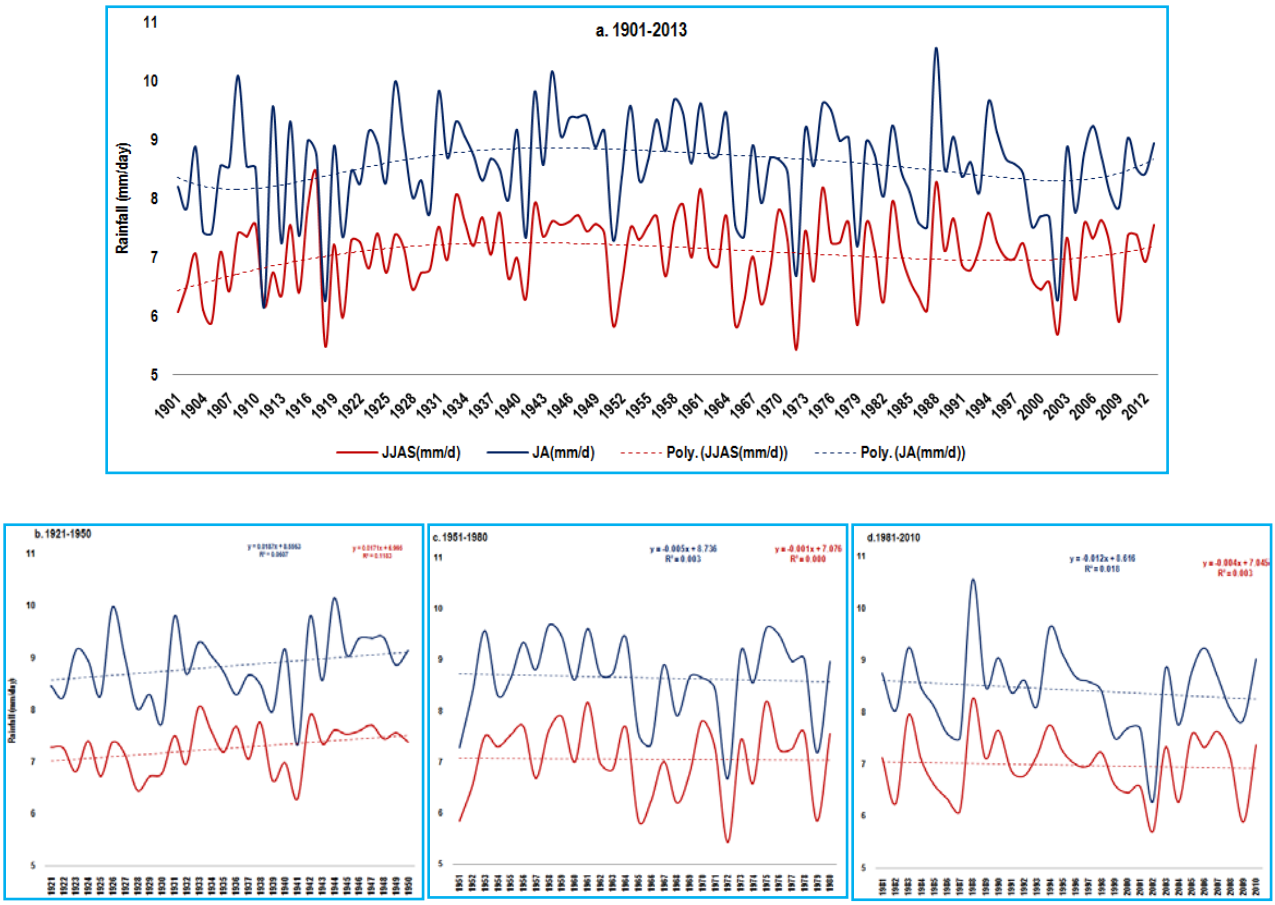
TABLE 1

The standard deviation (SD) and coefficient of variation (CV) of summer monsoon rainfall (JJAS and JA) over All India during the period 1901-2010 and its tricades and decades

Time Period	Mean(mm/day)		Standard Deviation (mm/day)		CV (%)	
	JJAS	JA	JJAS	JA	JJAS	JA
1901-2010	7.04	8.56	0.64	0.83	9.16	9.74
T1 (1921-1950)	7.26	8.85	0.38	0.62	5.28	6.96
T2 (1951-1980)	7.05	8.65	0.71	0.77	10.02	9.29
T3 (1981-2010)	6.98	8.42	0.6	0.77	8.27	9.02
D1 (1901-1910)	6.74	8.4	0.59	0.74	8.71	8.79
D2 (1911-1920)	6.81	7.98	0.87	1.2	12.7	14.99
D3 (1921-1930)	7	8.61	0.32	0.62	4.54	7.19
D4 (1931-1940)	7.34	8.82	0.42	0.5	5.75	5.7
D5 (1941-1950)	7.44	9.11	0.41	0.73	5.55	8.01
D6 (1951-1960)	7.16	8.8	0.61	0.7	8.45	7.91
D7 (1961-1970)	6.96	8.55	0.71	0.71	10.26	8.28
D8 (1971-1980)	7.04	8.61	0.8	0.91	11.34	10.58
D9 (1981-1990)	7.04	8.58	0.7	0.85	9.93	9.92
D10 (1991-2000)	7.01	8.48	0.35	0.59	5.04	6.98
D11 (2001-2010)	6.88	8.22	0.68	0.84	9.84	10.17

rainfall with a variation of 1 mm/day or more. Some parts of northeast, central India and regions close to the foothills of the Himalaya showed a decrease in rainfall pattern with variation in the range of -0.6 to -1 or less mm/day. The variation in the upper Himalayan region and lower peninsular region occurs with a combination of negative and positive differences in the range of -0.2 to 0.2 mm/day. Positive differences occurred in the areas of the upper Himalaya, some parts of Rajasthan and the eastern part of the lower Peninsula with a variation of 0.2 to 1mm/day. However, the decadal difference (D6-D5) reported decreased rainfall over the regions of Gujarat, central India, central northeast, lower Peninsula and northeast with a variation of -0.6 to -1 mm/day [Fig. 6(e)]. The regions of the eastern parts of upper Himalaya, Rajasthan and some part of the Western Ghats and peninsular region show an increase in rainfall by more than 1 mm/day. The positive and negative difference pattern of precipitation arises in the eastern part of the upper Himalayas, western regions of Rajasthan and eastern regions of the lower Peninsula with variation in the range of -0.2 to0.2 mm/day. The moderate pattern of rainfall was seen in some selected regions of northern India, peninsular India and northeast with 0.2 to 1 mm/day variation. Parthasarathy and Dhar (1974) found a gradual increasing trend in annual rainfall over central India, Punjab, Himachal Pradesh and north Assam, whereas a decreasing trend over south Assam has been noticed for the period 1901-1960.

Further, in Fig. 6(f) the decadal difference (D7-D6) suggests an increase in the rainfall amount over northeast, Western Ghats and some regions of northern India with variation of more than 1 mm/day. The decrease in the amount of rainfall arises in areas of the upper Himalaya, some parts of Gujarat, central India, northeast and a major portion of central northeast with variation in the range of -0.6 to -1 mm/day. The combination of both positive and negative differences occurs in the eastern part of Jammu & Kashmir and the peninsular region with a variation of -0.2 to 0.2 mm/day. An increase in the amount of rainfall occurs in some parts of Jammu & Kashmir, Rajasthan and the lower peninsular region by 0.2 to 1 mm/day. The decadal difference (D8-D7) shows an increase in the amount of rainfall over different regions of Rajasthan, Gujarat, central India, IGP and northeast by 0.6 to 1 mm/day or more [Fig. 6(g)]. The major parts of the Western Ghats and some regions of northeast, northern India, Gujarat and the peninsular region show a decrease in the rainfall pattern with a variation of -0.6 to -1 mm/day. The positive and negative difference in the pattern of rainfall occurs in the western part of Rajasthan



Figs. 7(a-d). The yearly variation of mean rainfall for the period 1901-2013 and for the respective tricade 1921-1950, 1951-1980 and 1981-2010

with variation in the range of -0.2 to 0.2 mm/day. The eastern parts of Jammu & Kashmir and Rajasthan show a moderate increase in the rainfall pattern with a variation of about 0.2 to 1 mm/day.

The decadal difference (D9-D8) reported a significant decline of monsoonal precipitation with variation of -0.6 to -1 mm/day or more over the regions of Rajasthan, central India, Northeast, western Ghats and major parts of IGP [Fig. 6(h)]. An increase in the rainfall occurs in some parts of Jammu & Kashmir, IGP, northeast and in lower areas of central India with a variation of more than 1 mm/day. The eastern regions of the upper Himalaya and the eastern part of the lower Peninsula show a combination of both positive and negative differences in the pattern of monsoonal rainfall with variation of -0.2 to -0.2 mm/day. A positive difference in precipitation pattern also occurs in some parts of Gujarat and the peninsular region with 0.2 to 1 mm/day variation. Fig. 6(i) represents decadal difference (D10-D9) which illustrates the high increase in the amount of rainfall over the major parts of Jammu & Kashmir, western Ghats and some regions of central India by 0.6 to 1 mm/day. The decrease in monsoonal rainfall occurs in major regions of IGP, Northeast and some parts of lower central India and Gujarat with a variation of -0.6 to -1 mm/day and more. About 0.2 to 1 mm/day increase in precipitation occurs in some parts of northern India, Western Ghats and the lower Peninsula. Positive and negative differences in the pattern of rainfall arise in the western part of Jammu & Kashmir, Rajasthan and lower areas of the peninsular region with a variation of about -0.2 to 0.2 mm/day. Further, Fig. 6(j) represents decadal difference (D11-D10) which is of two decades (2001-2010) and (1991-2000). The entire part of Gujarat and some parts of the Western Ghats, lower central India, northeast, central northeast and selected areas near the foothills of Himalaya show an increase in precipitation pattern with a variation of 0.2 to 1 mm/day. A decrease in the monsoonal rainfall occurs in parts of the upper Himalaya, central India, IGP and some regions of the northeast with variation in the range of -0.6 to -1 mm/day or more. The western parts of Rajasthan and

the lower eastern peninsular region show a combination of negative and positive differences in precipitation pattern with variation of about -0.2 to 0.2 mm/day.

The mean, Standard deviation (SD) and Coefficient of variation (CV) for all India rainfall during JJAS and JA for the period 1901-2010 has been shown in the Table 1. The mentioned values have been examined for the yearly variation during the period 1901-2010, for 11 different decades and for three tricadal periods. Analysis suggested that the mean JJAS and JA rainfall amount 7.04 mm/day and 8.54 mm/day respectively reported during the period 1901-2010. The calculated SD and CV values during JJAS (JA) are 0.64 mm/day (0.83 mm/day) and 9.16% (9.74%) respectively. The variation of average rainfall during JJAS and JA shows very little value of a positive trend which is not significant and can be considered as random in nature over a long period of time, which is in accordance with the study of Mooley and Parthasarathy (1984) [Fig. 7(a)]. The decadal analysis shows that the average rainfall during JJAS and JA increases from D1 to D5 with maximum values 7.44mm/day and 9.11mm/day respectively (Table 1). A significant drop can be observed during D6 and further fluctuations up to D11. The variation of SD shows fluctuating patterns for decades, D1 to D11 during JJAS and JA. A sudden increase in SD was observed in decade D2 during JJAS and JA with values 0.87 mm/day and 1.2 mm/day respectively, while for both scenarios, a significant decrease could be observed during D3 and D10. The CV shows similar patterns as that of SD.The maximum values 12.7% and 14.9% are observed in decade D2 during JJAS and JA respectively, while a sharp decrease is observed during D3 and D10.

The tricadal temporal variations of monsoon rainfall over all India have revealed some significant results from Figs. 7(b&c). During the first tricade (T1) it could be seen that there exists a slightly increasing trend in mean rainfall during seasonal JJAS and JA monsoon rainfall. Fig. 7(c) depicts a low decrease in the trend of monsoon and July-August peak rainfall during the second tricade, *i.e.*, 1951-1980. During the third tricade significant decrease in the average monsoon and JA rainfall has been observed [Fig. 7(d)]. Therefore, it is crucial to observe the changes in the recent decade. The variation of SD and it can be seen that there is a sudden increase from T1(0.38 mm/day) to T2(0.71 mm/day) for the monsoon season JJAS, while thereis a slight increase from T1(0.62 mm/day) to T2(0.7 mm/day) during peak monsoon season (Table 1). Further, a slight decrease is observed from T2 to T3 during the both seasonal periods JJAS and JA (Table 1). Here also, the CV has shown a sudden increase in value from T1(5.28%) to T2(10.02%) and T1(6.96%) to T2(9.29%) can be seen during the seasonal periods JJAS and JA respectively, while a slight decrease in the value could be observed from tricade T2 to T3 during the both seasonal periods. The overall observation shows that there is a significantly increasing trend in CV.

4. Conclusions

The long term ISMR is dynamic under the climatic variability over the Indian region. So, considering the thought of a country as one-unit, present study has examined the changing pattern of ISMR during June to September over throughout for 1901-2013. This study is focused on understanding or predicting the seasonal rainfall behavior over India and its different region. The different patterns of monsoonal rainfall were studied on the decadal and the tricadal time scale combined for the month of JJAS and July to August. The average overall pattern of 113 years of monsoon rainfall during JJAS clearly represents a changing pattern in rainfall which might be linked with the increasing global warming scenario (Kumar *et al*., 2010). The climatology of ISMR showsthe maximum amount of rainfall, *i.e*., 16 to 18 mm/day in the northeast and windward side of the Western Ghats while the low amount of rainfall occurred in major regions of upper Himalaya, Rajasthan, Gujrat and the leeward side of western Ghats with a variation of 2 to 4 mm/day.

The tricadal difference of the first two tricades shows a significant decrease in the amount of rainfall in the central and northeast parts of India. While the recent tricadal difference represents increased monsoonal rainfall in the area of low or decreased rainfall which extends towards the northern and peninsular India. The decadal difference pattern during JJAS shows a shift in the rainfall pattern. Before the 1950s, decadal differences clearly represented major part of Indian regions which had received moderate to high amounts of rainfall, especially regions of central India and northern India. After 1950s, there was a constant decrease in the amount of rainfall over these specific regions. The possible reasons for this decrease may be rapid industrialization and urbanization, which results in the increasing load of pollutants and aerosol particles in the atmosphere (Lohmann and Feichter, 2005; Manoj *et al*., 2012). The aerosols decrease the wind speeds near the surface; hence the slower winds and cooler temperatures decrease the evaporation which may cause a reduction in rainfall amount (Jacobson and Kaufmann, 2006). Other reasons might be the occurrence of moderate to severe drought years in these periods, *viz*., 1951, 1965, 1966, 1968 and 1972.

The period from July to August represents the duration of peak rainfall during the monsoon season. Major parts, of central India, East India, Western Ghats and northeast showed an occurrence of high rainfall which

varied in the range of 8 to 14 mm/day. Other regions including Northern, Western and the lower Peninsula India received low amount of rainfall of about 2 to 4 mm/day. The regions of central India and northern India represented an increase in the rainfall during the second decadal difference and a decrease in the amount of precipitation in the third decadal difference. A high decrease in the amount of rainfall in July-August occurs during decadal differences (D2-D1), (D7-D6), (D10-D9) and recent decadal differences over different Indian regions such as the upper Himalayas, central India and the eastern part of India. The tricadal difference pattern showed a high decrease in the amount of precipitation during recent tricadal difference over upper and central IGP, while the pattern in tricadal difference of the first two tricades showed the occurrence of good rainfall in the same area. However, the lower IGP received enough rainfall during the recent tricade but the central and upper IGP depicted a reduction in rainfall. An overall view suggests a substantial decline in ISMR over some central and northeast Indian regions whereas an enhancement over Western Indian regions. The peninsular region also received a low amount of rainfall during the period of 1981-2010.The concentration of rainfall in the upper Himalayan region increased from 1950 to 1980.

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