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SPATIOTEMPORAL RAINFALL VARIABILITY IN HUMID SUBTROPICAL ZONE, INDIA

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ABSTRACT

Climate change is profoundly altering rainfall patterns in India, resulting in a surge in extreme weather events, including floods, droughts, and landslides. Unpredictable monsoon seasons feature intense, localized downpours that overwhelm drainage systems and prolonged dry spells that aggravate drought conditions. The humid subtropical zone, as classified in the Koppen climate classification system, is the study area. The humid subtropical regions in India are greatly influenced by the seasonal monsoon rains. The agricultural and water resource systems are directly dependent on rain for sustenance. This study is based on the short-term rainfall variability using a method called the 5-year grouping method. The analysis has been carried out annually and seasonally. The annual maximum rainfall for humid subtropical varies mostly between rather heavy rainfall to extremely heavy rainfall. In January and February, the maximum rainfall for humid subtropical varies between no rain to very heavy rainfall in the study period. In March, April, and May, the maximum rainfall for humid subtropical varies between no rainfall to very heavy rainfall in the study, except in the years 1986 to 1980, where the rainfall is exceptionally heavy. In June, July, August, and September, the maximum rainfall for humid subtropical varies between rather *heavy rainfall to extremely heavy rainfall throughout the study period, except in the years 2006 to 2010, where the maximum rainfall is about 650 mm in Bihar. In October, November, and December, the maximum rainfall for humid subtropical varies mostly between no rain to very heavy rain/ extremely heavy rainfall throughout the study period, except in the years 1956-1960 and 1966-1970, where the rainfall exceeds 300 mm. It is generally observed that recent years are witnessing frequent extreme events when compared to earlier years. Decision makers have to take the necessary measures to combat the recent changes in rainfall during planning and design.*

Keywords: 5-year grouping method, Annual rainfall variability, Seasonal rainfall variability

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1. INTRODUCTION

Rainfall is a significant part of the hydrological cycle, and its temporal and spatial variability is of key importance, as alteration of its pattern directly affects the water resources [1],[2] and [3]. The changing pattern of rainfall in consequence of climate change is now a concern to water resource managers and hydrologists. [4], [5], and [6] reported that the changes of rainfall quantities and frequencies is directly changing the stream flow pattern and its demand, spatiotemporal allocation of run-off, ground water reserves, and soil moisture.

Changing weather patterns, including less predictable seasons, increased frequency of erratic rainfall, and prolonged droughts, pose significant risks to agricultural sustainability and food security [7]. India, being an agricultural nation, relies on timely rainfall for crop cultivation. However, recent years have seen extreme rainfall events that have caused widespread damage and loss of life and property [8], [9],[10], and [11]. The extent of rainfall variation varies by location, necessitating a detailed assessment of rainfall patterns. This paper evaluates rainfall variability in the Humid subtropical zone of India, as classified by the Koppen Climate zones. These climate groups are based on the types of vegetation found in each climate classification region. The variability and trends in rainfall patterns are influenced by climate change, leading to altered intensity, frequency, and spatial distribution of rainfall, which poses challenges for agriculture, water resources, and disaster management in humid subtropical regions of India. [12], [13],[14], and [15].

The present study is carried out to analyse the rainfall variability annually and seasonally, over short periods by classifying India into Koppen climate zones, which was developed based on the empirical relationship between climate and vegetation. The outcome of the study is useful in understanding the rainfall variability in recent years in the Humid Subtropical, Koppen climate zone of India. Rainfall variability studies are crucial for understanding its profound impacts on agriculture, water resources, climate change dynamics, ecological balance, risk management, socio-economic stability, and policy formulation. Variations in rainfall patterns directly affect crop yields, water availability for drinking and irrigation, and energy generation through hydropower. They serve as early indicators of climate change, influencing biodiversity, habitats, and ecosystem health. Moreover, rainfall variability informs disaster preparedness and management strategies, guiding responses to floods, droughts, and other natural disasters. Socio-economically, these studies highlight vulnerabilities in rural communities and sectors like tourism, shaping policies for sustainable development and resilience-building. Ultimately, they underpin informed decision-making and adaptive strategies essential for mitigating risks and promoting long-term sustainability in a changing climate.

The rainfall variability study in the Humid Subtropical Zone of India is carried out by a new method called the 5-year grouping to study the rainfall variability spatiotemporally. Statistical parameters such as mean, maximum, minimum, and standard deviation provide crucial insights into the characteristics and behaviour of rainfall data

2. MATERIALS AND METHODOLOGY

2.1 Study area and data used

The Great Plains of India, extending from Punjab in the west to Assam in the east, predominantly experience a humid subtropical climate according to the Koppen classification. This climate is marked by hot, humid summers with temperatures often exceeding 35°C and relatively mild winters with temperatures ranging from 5°C to 15°C. The location map of the study area is shown in Figure 1.

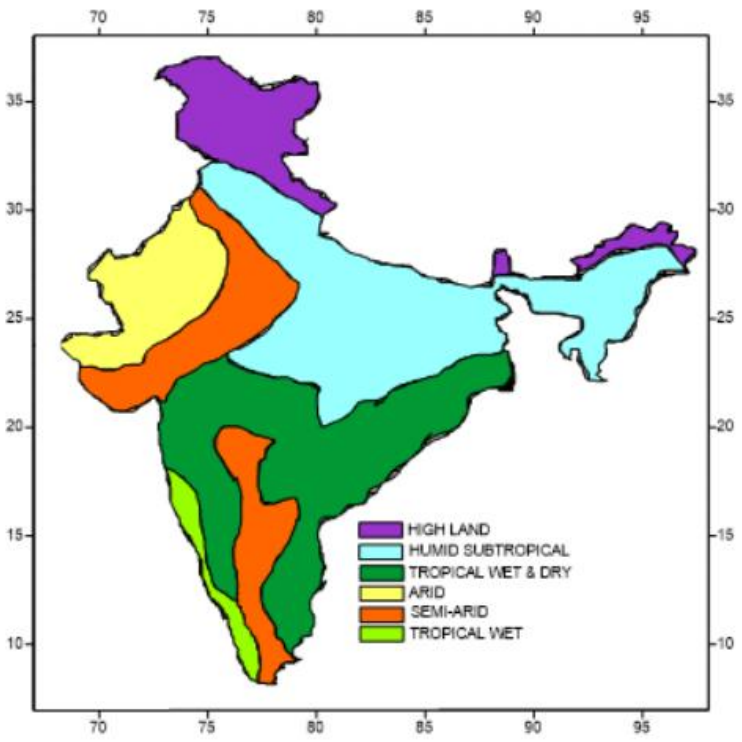

Figure 1. Climatic zones of India – Koppen Climate Classification [16]

The post-processed daily rainfall data for the years 1951 to 2015 (1-degree x 1-degree grid – approximately 111 km x 111 km) were collected from the India Meteorological Department (IMD) for India (excluding Andaman and Nicobar Islands and Lakshadweep). The Humid subtropical zone covers approximately 97 grids, which is about 1195137 sq. km.

2.2 Methodology

The daily rainfall data for the years 1951 to 2015 were collected from IMD for India (excluding Andaman and Nicobar Islands and Lakshadweep). For each year, the maximum rainfall values were extracted both annually and seasonally for all the grids in the Humid Subtropical region. The 65 years of rainfall data are classified into 13 groups of 5 years each. The groups are – 1951-1955, 1956-1960, 1961-1965, 1966-1970, 1971-1975, 1976-1980, 1981-1985, 1986-1990, 1991-1995,1996-2000, 2001-2005, 2006-2010 and 2011-2015. For each of these groups, the maximum and minimum rainfall values were extracted. The basic statistical parameters, such as mean and Standard deviations, were also calculated. The rainfall variability study was conducted for the Humid Subtropical zone, as classified by the Koppen Climate zones. The graphs are plotted, and the rainfall variability study is carried out as shown in Fig. 2.

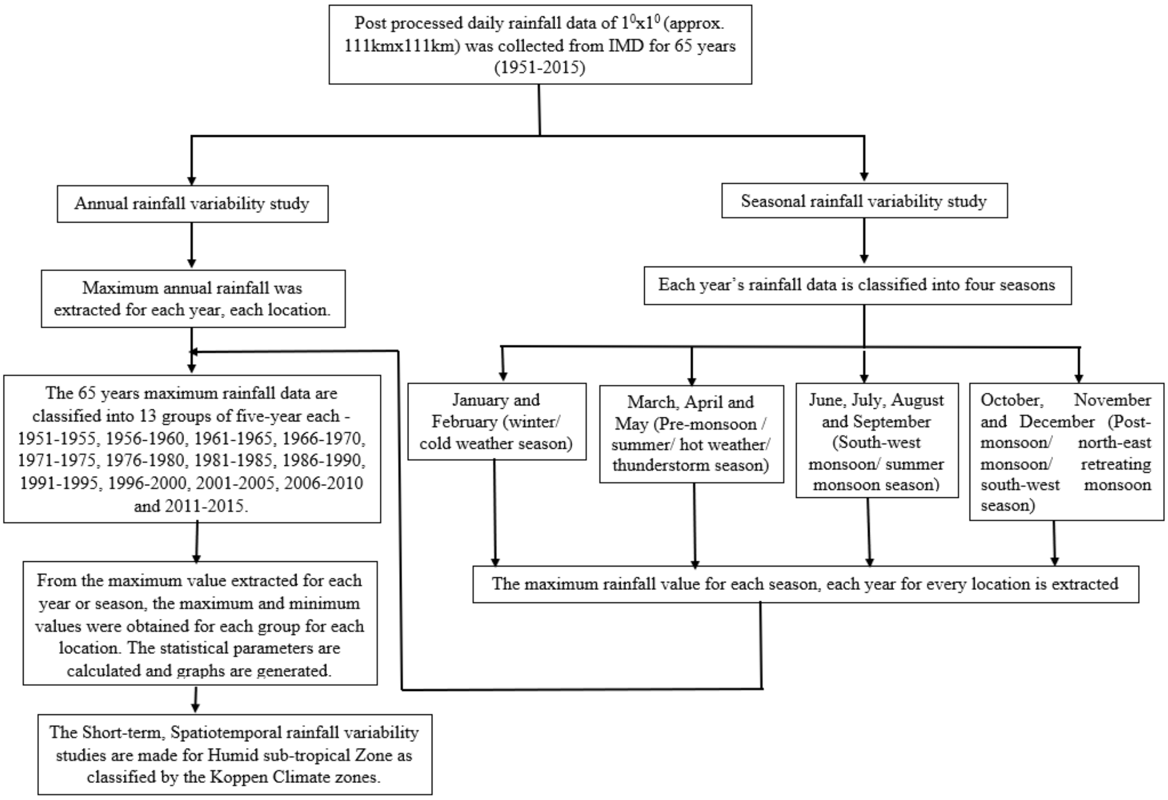

Figure 2. Methodology for the Short-term Rainfall Variability Study of the Humid Subtropical Zone

3. RESULTS

Rainfall patterns are helpful for effectively managing hydrological processes that directly impact ecosystems, agriculture, and the sustainability of water resources. The study of rainfall data is presented through key statistical indicators, which include maximum, minimum, mean, and standard deviation values. These parameters are instrumental in revealing the spatiotemporal distribution and variability of precipitation across the study period. Such an approach not only facilitates the interpretation of prevailing climate characteristics but also contributes to identifying anomalies and informing strategic decisions in water resource planning and climate adaptation efforts.

3.1 Spatial Rainfall Variability

3.1.1 Annual Spatial Rainfall Variability

The maximum rainfall for humid subtropical varies mostly between rather heavy rainfall to extremely heavy rainfall throughout the period considered for study in the range of 40 to 440 mm, except for the years 2006 to 2010, where the rainfall is about 640mm. The minimum rainfall varies between moderate rainfall to very heavy rainfall for most of the years considered in the study. The rainfall details are as recorded in Table 1. The isohyets of the maximum and minimum rainfall are shown in Fig. 3a and 3b. The isohyets for both maximum and minimum rainfall indicate that there is significant spatial variation, and temporal variability is almost the same, except in some years, such as 2006-2010.

Table 1: Rainfall range for humid subtropical for the years 1951-2015

<table>
<tr><th>Year</th><th>1951-1955</th><th>1956-1960</th><th>1961-1965</th><th>1966-1970</th><th>1971-1975</th><th>1976-1980</th><th>1981-1985</th></tr>
<tr><td rowspan="2">Rainfall range (mm) - maximum</td><td>40-280</td><td>40-400</td><td>80-320</td><td>40-360</td><td>40-280</td><td>40-280</td><td>40-400</td></tr>
<tr><td colspan="2">Rather heavy to extremely heavy rain</td><td>Heavy to extremely heavy rain</td><td colspan="4">Rather heavy to extremely heavy rain</td></tr>
<tr><td rowspan="2">Rainfall range (mm) - minimum</td><td>30-170</td><td>40-160</td><td>40-140</td><td>10-160</td><td>10-140</td><td>10-110</td><td>10-150</td></tr>
<tr><td>Moderate to very heavy rain</td><td colspan="2">Rather heavy to very heavy rain</td><td colspan="2">Moderate to very heavy rain</td><td>Moderate to heavy rain</td><td>Moderate to very heavy rain</td></tr>
<tr><th>Year</th><th>1986-1990</th><th>1991-1995</th><th>1996-2000</th><th>2001-2005</th><th>2006-2010</th><th>2011-2015</th><th></th></tr>
<tr><td rowspan="2">Rainfall range (mm) - maximum</td><td>40-320</td><td>40-360</td><td>40-360</td><td>40-440</td><td>40-640</td><td>40-360</td><td rowspan="2"></td></tr>
<tr><td colspan="6">Rather heavy to extremely heavy rain</td></tr>
<tr><td rowspan="2">Rainfall range (mm) - minimum</td><td>20-140</td><td>10-150</td><td>10-190</td><td>20-210</td><td>0-140</td><td>20-160</td><td rowspan="2"></td></tr>
<tr><td colspan="4">Moderate to very heavy rain</td><td>No rain to very heavy rain</td><td>Moderate to very heavy rain</td></tr>
</table>

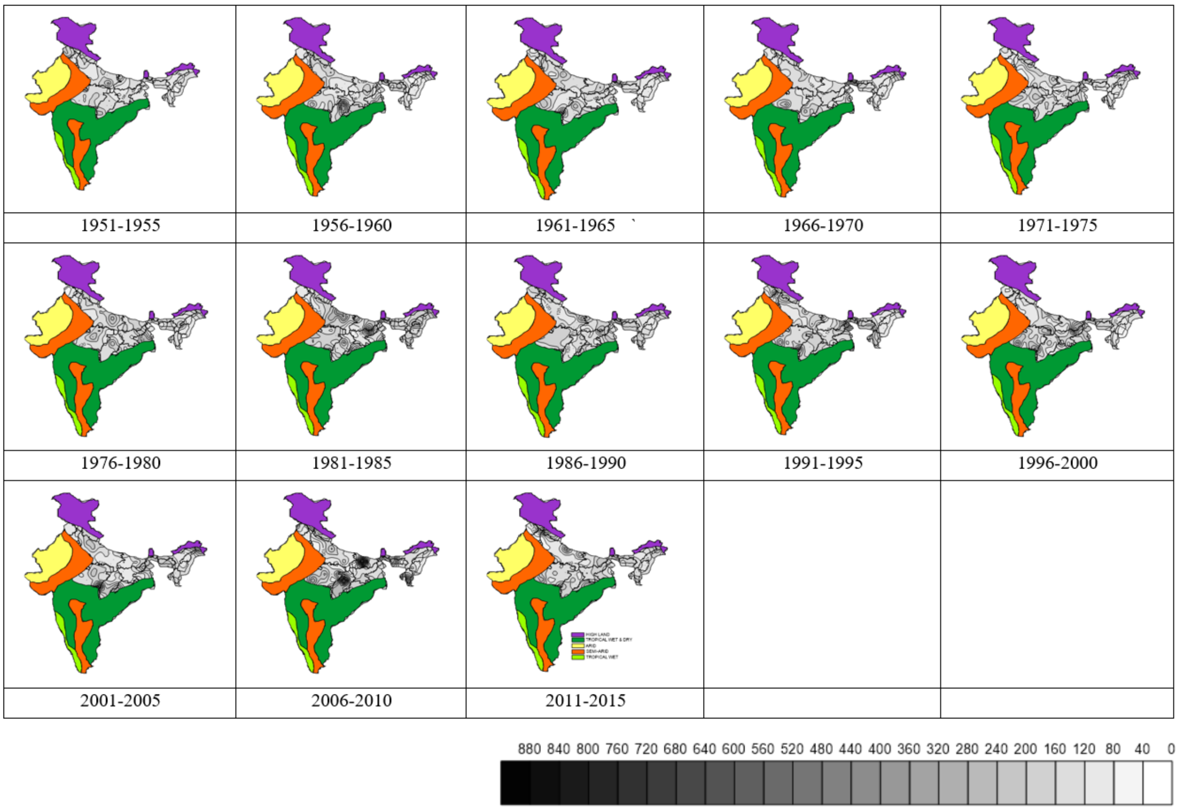

Figure 3(a): Humid subtropical - Annual rainfall variability (maximum values)

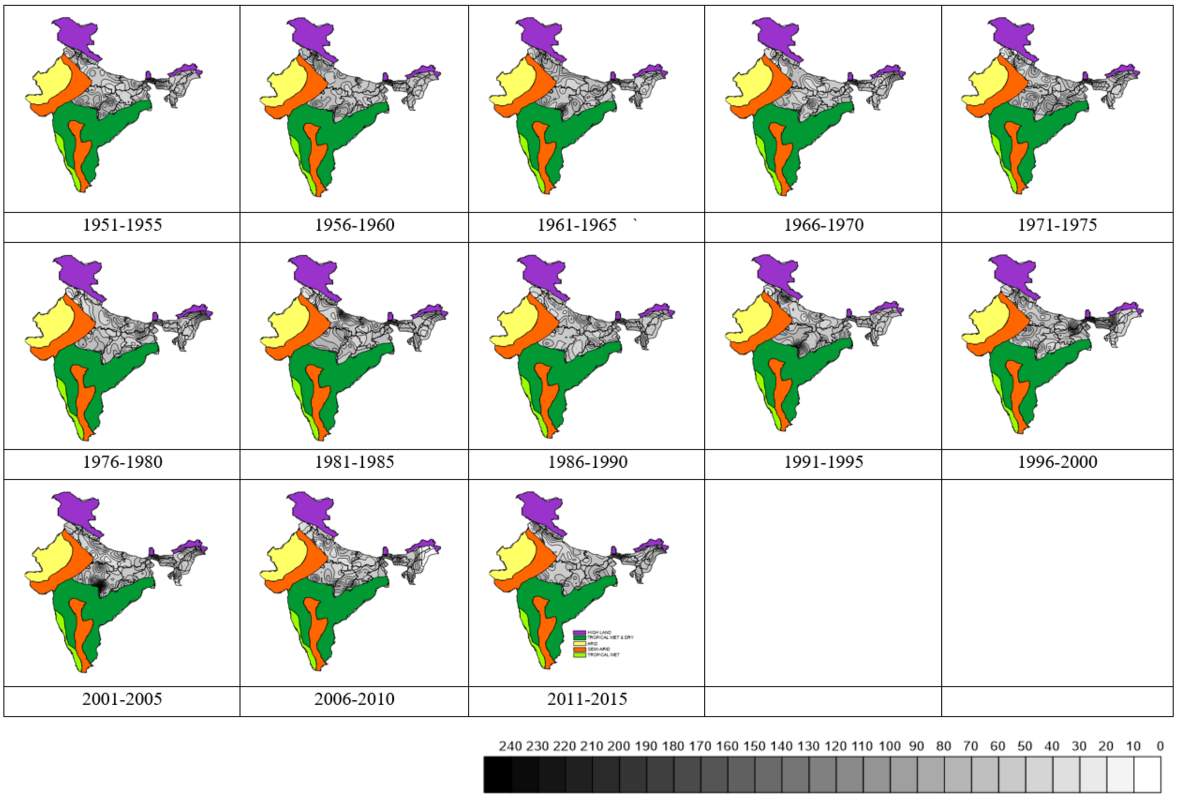

Figure 3(b): Humid subtropical - Annual rainfall variability (minimum values)

3.1.2 Seasonal Spatial Rainfall Variability

January and February (winter/cold weather season)

The maximum rainfall for humid subtropical varies between no rain to very heavy rainfall throughout the period considered for the study in the range of 0 to 140 mm. The minimum rainfall varies between no rain to moderate rain, except in the years 1996-2000, where the rainfall varies between light rain to heavy rain. The rainfall details throughout the study are as shown in Table 2. The isohyets of the maximum and minimum rainfall are shown in Fig. 4(a) and 4(b). A similar spatial and temporal variability is noticed for the entire period considered in the study.

Table 2: Rainfall range for humid subtropical for the years 1951-2015

Year	**1951-1955**	**1956-1960**	**1961-1965**	**1966-1970**	**1971-1975**	**1976-1980**	**1981-1985**
Rainfall range (mm) - maximum	0-60	0-80	0-140	0-100	0-120	0-140	0-100
	No rain to rather heavy rain	No rain to heavy rain	No rain to very heavy rain	No rain to heavy rain		No rain to very heavy rain	No rain to heavy rain
Rainfall range (mm) - minimum	0-20	0-20	0-25	0-20	0-20	0-20	0-20
	No rain to moderate rain						
Year	**1986-1990**	**1991-1995**	**1996-2000**	**2001-2005**	**2006-2010**	**2011-2015**	
Rainfall range (mm) - maximum	0-120	0-140	0-80	0-100	0-100	0-100	
	No rain to heavy rain	No rain to very heavy rain	No rain to heavy rain				
Rainfall range (mm) - minimum	0-20	0-35	5-65	0-20	0-20	0-25	
	No rain to moderate rain		Light rain to heavy rain	No rain to moderate rain			

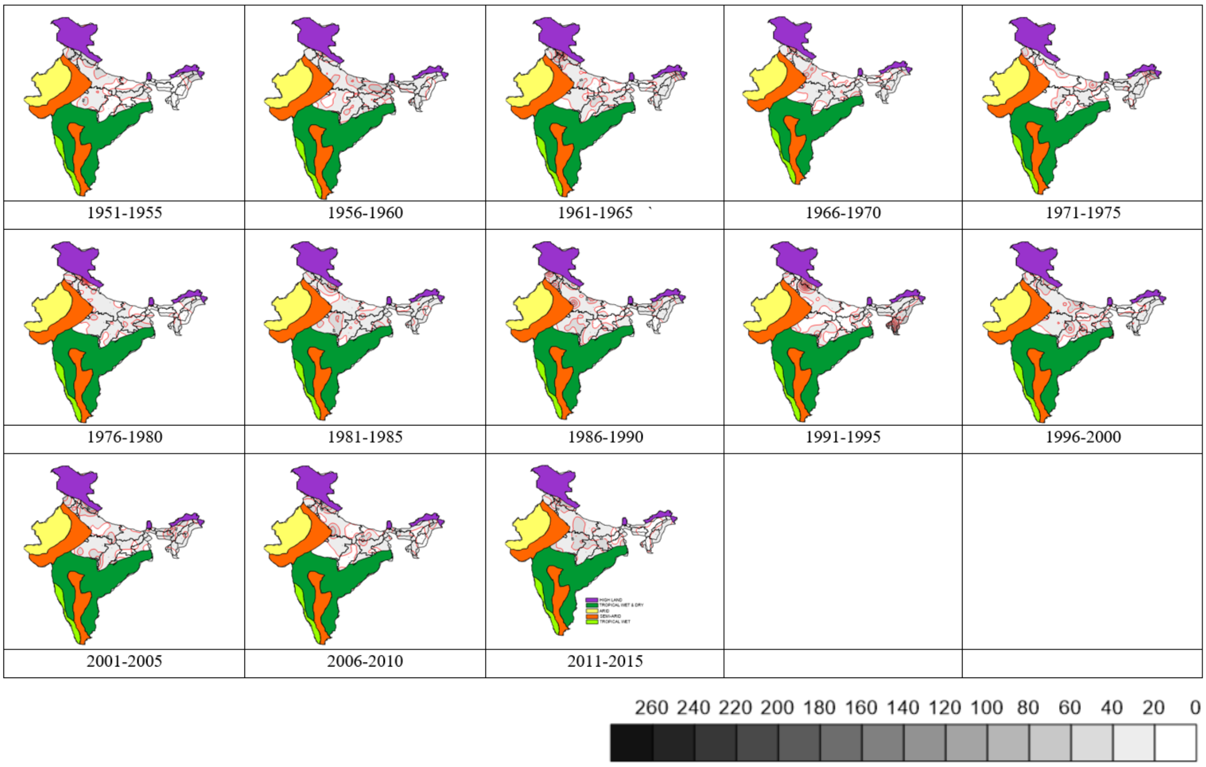

Figure 4(a): Humid subtropical - Seasonal rainfall variability (maximum values – January and February)

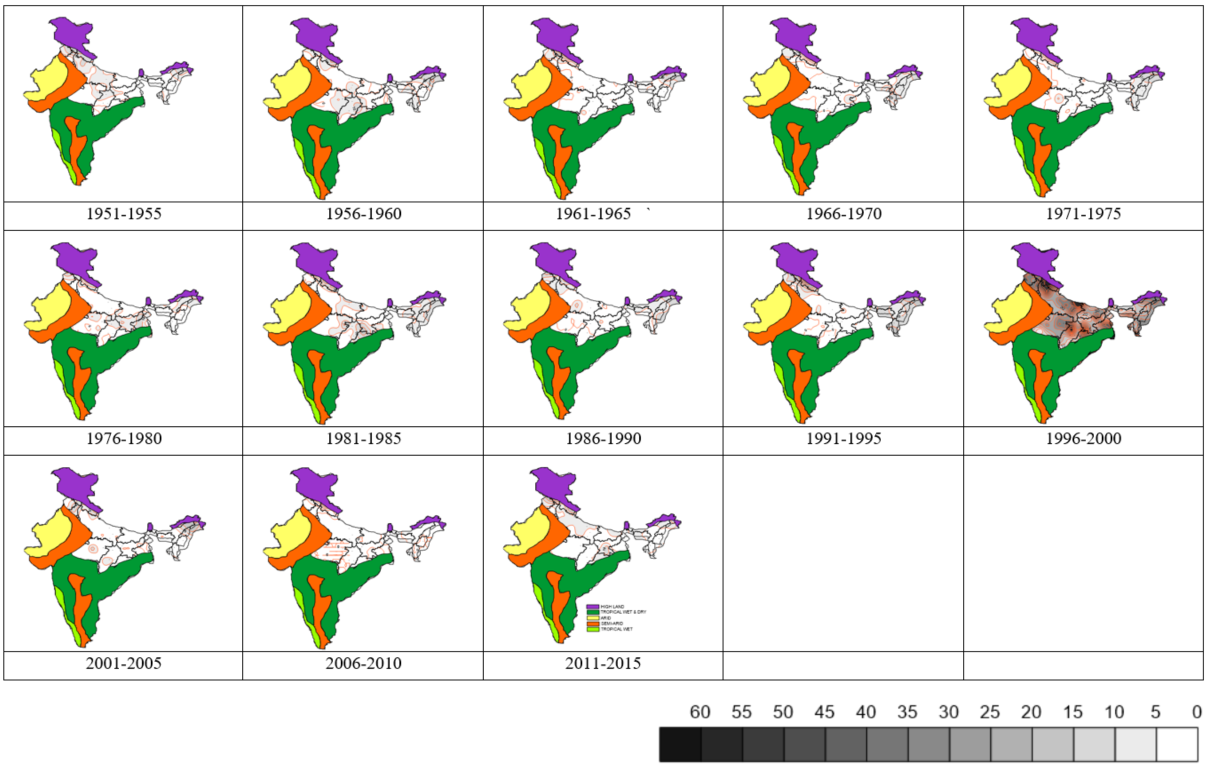

Figure 4(b): Humid subtropical - Seasonal rainfall variability (minimum values – January and February)

March, April, and May (Pre-monsoon/summer/hot weather/thunderstorm season)

The maximum rainfall for humid subtropical varies between no rainfall to very heavy rainfall throughout the period considered for the study, except in the years 1986 to 1980, where the rainfall is exceptionally heavy. The heavy rainfall is mostly noticed in the north-eastern part of India, except in the years 1996 – 2000, where a very heavy rainfall is noticed in Uttar Pradesh. The minimum rainfall varies between no rain to rather heavy/ very heavy in the years considered in the study. The rainfall details are as shown in Table 3. The isohyets of the maximum and minimum rainfall are shown in Fig. 5(a) and 5(b).

Table 3: Rainfall range for humid subtropical for the years 1951-2015

Year	**1951-1955**	**1956-1960**	**1961-1965**	**1966-1970**	**1971-1975**	**1976-1980**	**1981-1985**
Rainfall range (mm) - maximum	0-175	0-175	0-125	0-175	0-150	0-150	0-225
	No rain to very heavy rain						
Rainfall range (mm) - minimum	0-60	0-70	0-70	0-60	0-60	0-70	0-70
	No rain to rather heavy rain	No rain to heavy rain		No rain to rather heavy rain		No rain to heavy rain	
Year	**1986-1990**	**1991-1995**	**1996-2000**	**2001-2005**	**2006-2010**	**2011-2015**	
Rainfall range (mm) - maximum	0-325	0-200	0-225	0-175	0-200	0-150	
	No rain to extremely heavy rain	No rain to very heavy rain					
Rainfall range (mm) - minimum	0-80	0-70	0-50	0-60	0-70	0-70	
	No rain to heavy rain		No rain to rather heavy rain		No rain to heavy rain		

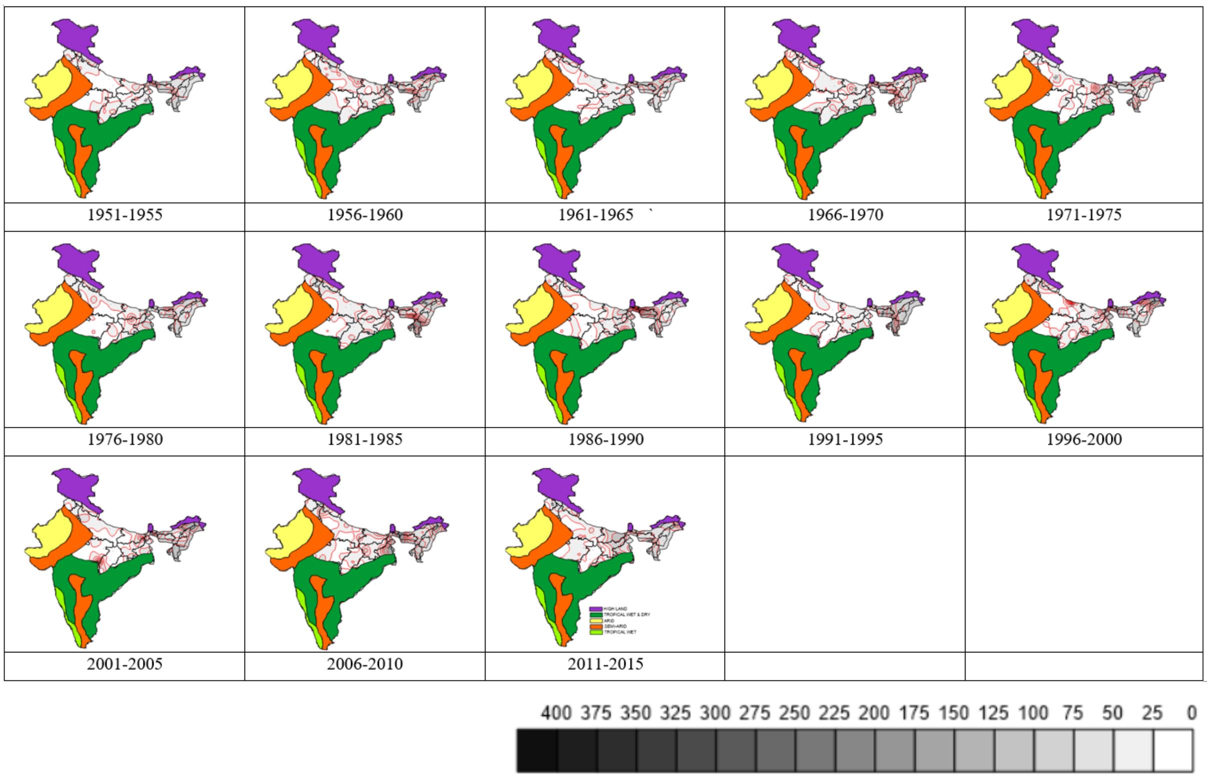

Figure 5(a): Humid subtropical - Seasonal rainfall variability (maximum values – March, April and May)

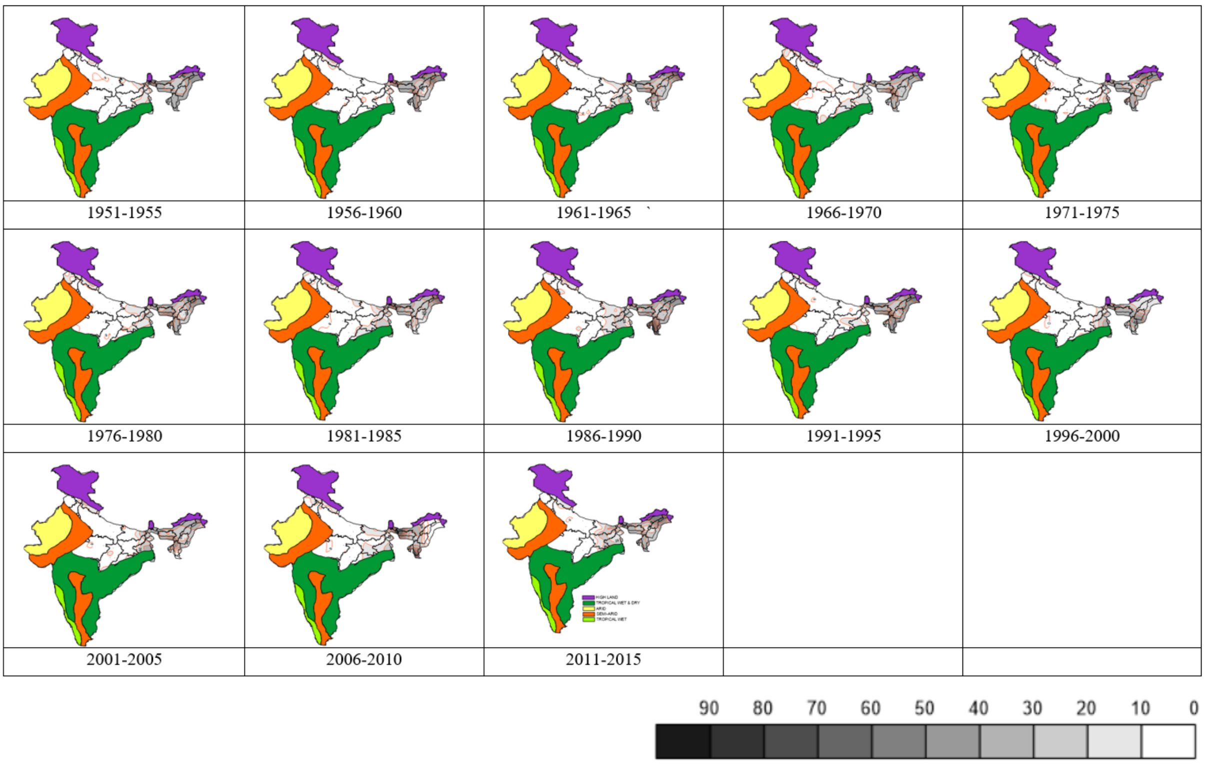

Figure 5(b): Humid subtropical - Seasonal rainfall variability (minimum values – March, April, and May)

June, July, August, and September (South-west monsoon/summer monsoon season)

The maximum rainfall for humid subtropical varies between rather heavy rainfall to extremely heavy rainfall throughout the period considered for study in the range of 50 to 450 except in the years 2006 to 2010, where the maximum rainfall is about 650mm, noticed in Bihar. The minimum rainfall varies mostly between no rain/ moderate rainfall to very heavy rainfall. The maximum rainfall is noticed in the northeast India and the northern part of West Bengal. The rainfall details are as shown in Table 4. The isohyets of the maximum and minimum rainfall are shown in Fig. 6(a) and 6(b). The isohyets for maximum rainfall indicate a temporal variation which is concentrated in two small locations in Chhattisgarh and Bihar, and the minimum rainfall indicates minimum variations in spatial and temporal variability, except in the northern part of West Bengal.

Table 4: Rainfall range for humid subtropical for the years 1951-2015

<table>
<tr><th>Year</th><th>1951-1955</th><th>1956-1960</th><th>1961-1965</th><th>1966-1970</th><th>1971-1975</th><th>1976-1980</th><th>1981-1985</th></tr>
<tr><td rowspan="2">Rainfall range (mm) - maximum</td><td>50-250</td><td>0-350</td><td>50-300</td><td>50-400</td><td>50-250</td><td>50-300</td><td>50-450</td></tr>
<tr><td>Rather heavy to extremely heavy rain</td><td>No rain to extremely heavy rain</td><td colspan="5">Rather heavy to extremely heavy rain</td></tr>
<tr><td rowspan="2">Rainfall range (mm) - minimum</td><td>0-140</td><td>20-180</td><td>20-160</td><td>0-160</td><td>0-160</td><td>0-120</td><td>0-200</td></tr>
<tr><td>No rain to very heavy rain</td><td colspan="2">Moderate rain to very heavy rain</td><td colspan="2">No rain to very heavy rain</td><td>No rain to heavy rain</td><td>No rain to very heavy rain</td></tr>
<tr><td>Year</td><td>1986-1990</td><td>1991-1995</td><td>1996-2000</td><td>2001-2005</td><td>2006-2010</td><td>2011-2015</td><td></td></tr>
<tr><td rowspan="2">Rainfall range (mm) - maximum</td><td>50-250</td><td>50-400</td><td>50-350</td><td>50-450</td><td>50-650</td><td>50-350</td><td></td></tr>
<tr><td colspan="6">Rather heavy to extremely heavy rain</td><td></td></tr>
<tr><td rowspan="2">Rainfall range (mm) - minimum</td><td>0-140</td><td>0-160</td><td>0-200</td><td>0-220</td><td>0-140</td><td>20-160</td><td></td></tr>
<tr><td colspan="5">No rain to very heavy rain</td><td>Moderate rain to very heavy rain</td><td></td></tr>
</table>

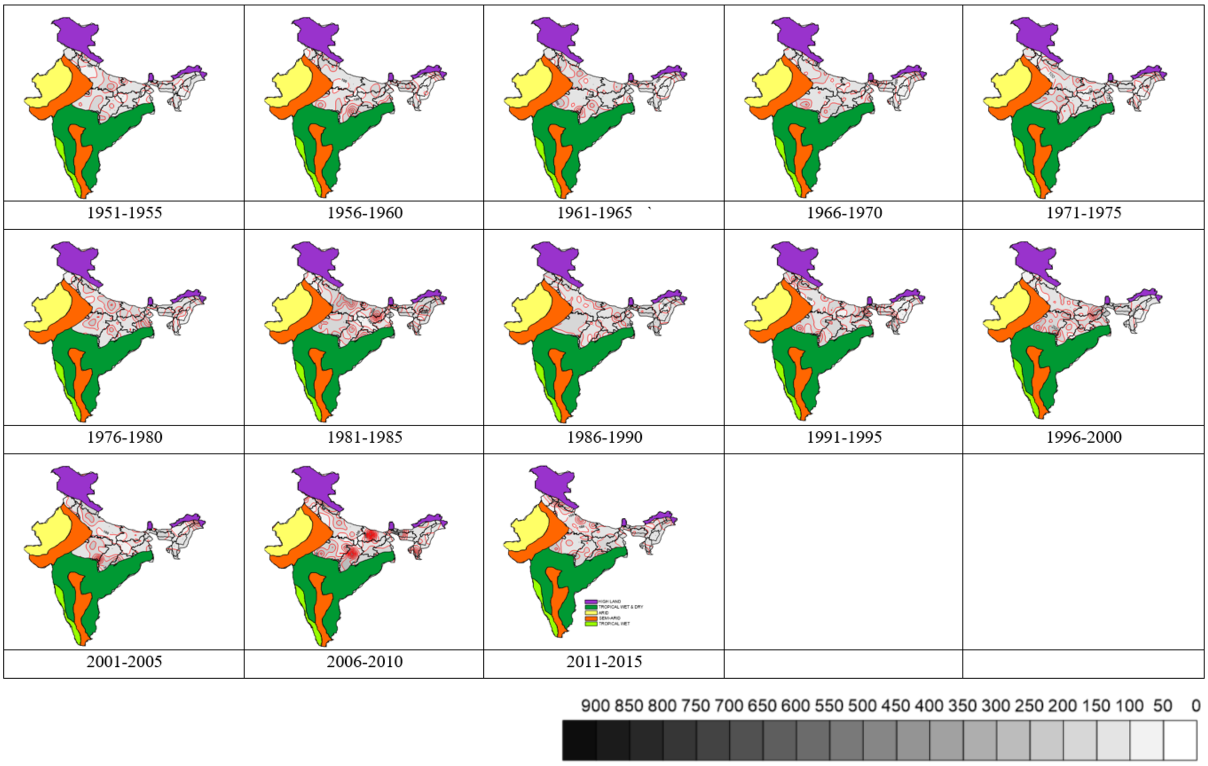

Figure 6(a): Humid subtropical Seasonal rainfall variability (maximum values – June, July, August and September)

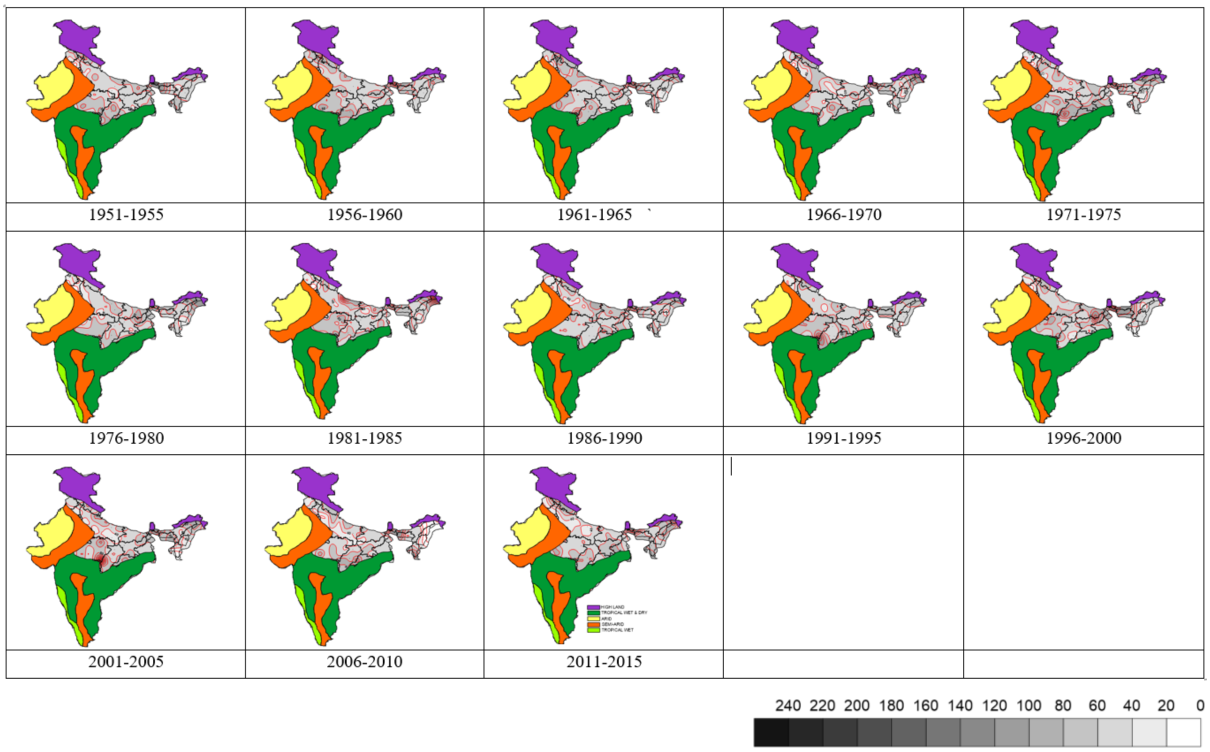

Figure 6(b): Humid subtropical Seasonal rainfall variability (minimum values – June, July, August and September)

October, November and December (Post-monsoon/north-east monsoon /retreating south-west monsoon season)

The maximum rainfall for humid subtropical varies mostly between no rain to very heavy rain/ extremely heavy rainfall throughout the period considered for study in the range of 0 to 250 mm, except in the years 1956-1960 and 1966-1970, where the rainfall exceeds 300mm. The minimum rainfall is almost consistent between no rain to rather heavy rainfall throughout the study period. The rainfall values recorded are as shown in Table 5. The isohyets of the maximum and minimum rainfall are as shown in Fig. 7(a) and 7(b).

Table 5: Rainfall range for humid subtropical for the years 1951-2015

<table>
<tr><th>Year</th><th>1951-1955</th><th>1956-1960</th><th>1961-1965</th><th>1966-1970</th><th>1971-1975</th><th>1976-1980</th><th>1981-1985</th></tr>
<tr><td rowspan="2">Rainfall range (mm) - maximum</td><td>0-225</td><td>25-375</td><td>0-175</td><td>0-300</td><td>0-250</td><td>0-225</td><td>0-175</td></tr>
<tr><td>No rain to very heavy rain</td><td>Moderate to extremely Heavy rain</td><td>No rain to very heavy rain</td><td colspan="2">No rain to extremely heavy rain</td><td colspan="2">No rain to very heavy rain</td></tr>
<tr><td rowspan="2">Rainfall range (mm) - minimum</td><td>0-50</td><td>0-70</td><td>0-40</td><td>0-40</td><td>0-40</td><td>0-40</td><td>0-50</td></tr>
<tr><td>No rain to rather heavy rain</td><td>No rain to very heavy rain</td><td colspan="5">No rain to rather heavy rain</td></tr>
<tr><td>Year</td><td>1986-1990</td><td>1991-1995</td><td>1996-2000</td><td>2001-2005</td><td>2006-2010</td><td>2011-2015</td><td></td></tr>
<tr><td rowspan="2">Rainfall range (mm) - maximum</td><td>0-200</td><td>0-200</td><td>0-250</td><td>0-250</td><td>0-225</td><td>0-225</td><td></td></tr>
<tr><td colspan="2">No rain to very heavy rain</td><td colspan="2">No rain to extremely heavy rain</td><td colspan="2">No rain to very heavy rain</td><td></td></tr>
<tr><td rowspan="2">Rainfall range (mm) - minimum</td><td>0-50</td><td>0-50</td><td>0-50</td><td>0-50</td><td>0-40</td><td>0-40</td><td></td></tr>
<tr><td colspan="6">No rain to rather heavy rain</td><td></td></tr>
</table>

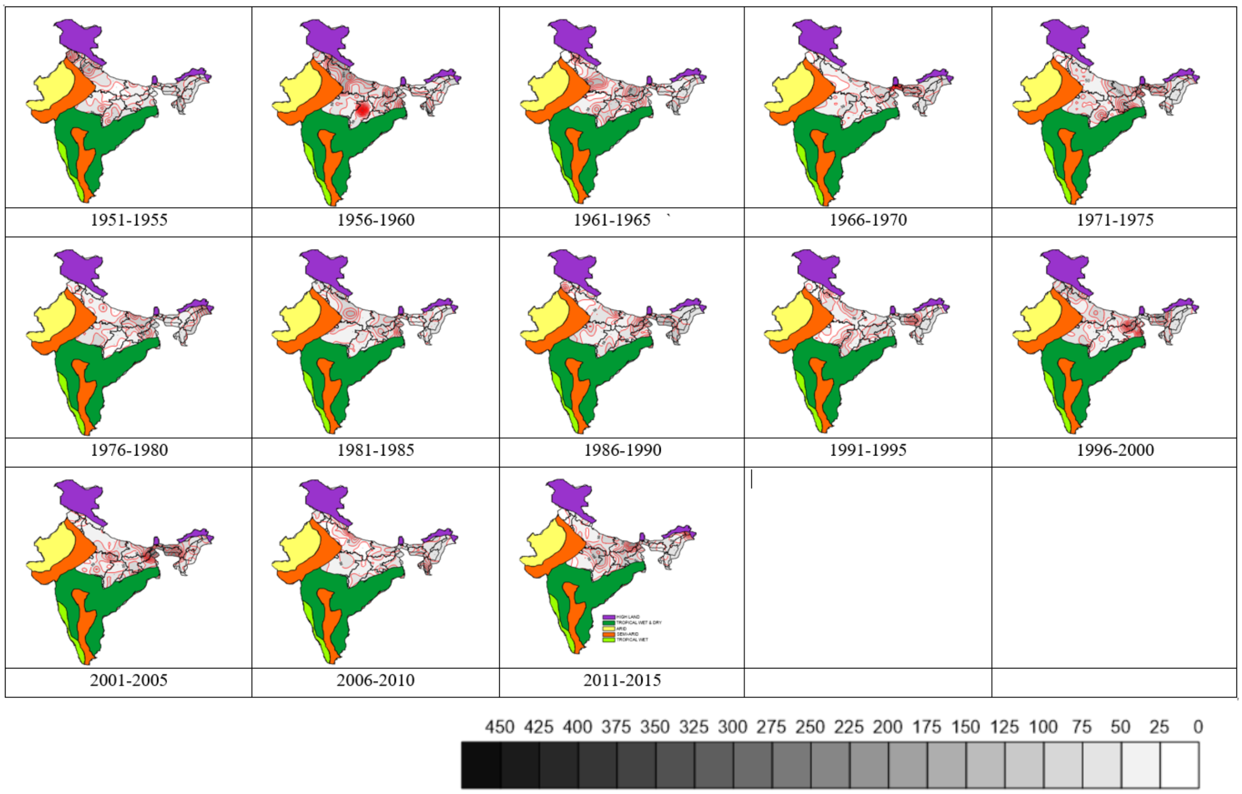

Figure 7(a): Humid subtropical – Seasonal rainfall variability (maximum values – October, November and December)

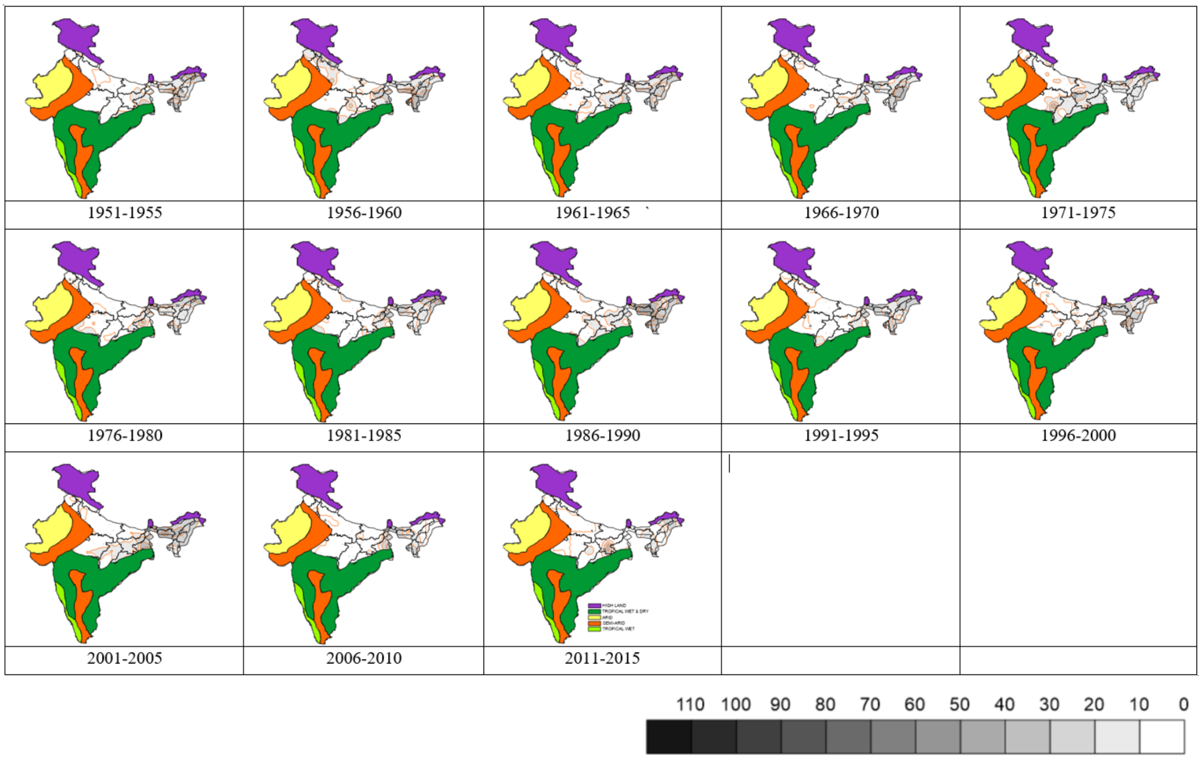

Figure 7(b): Humid subtropical – Seasonal rainfall variability (minimum values – October, November and December)

3.2 Temporal Rainfall Variability

3.2.1 Annual Temporal Rainfall Variability

The annual rainfall studies provide valuable insights into climate change trends and patterns. By analysing historical rainfall data spanning decades or centuries, scientists can identify long-term climate trends, including changes in precipitation patterns, shifts in rainfall seasons, and variations in extreme weather events. The rainfall trend in annual rainfall is as shown in Fig. 8(a), and further, the percentage variations of the maximum rainfall and standard deviations from the mean are also projected in Fig. 8(b).

Minimum Rainfall

The minimum rainfall from 1951 to 2015 exhibits notable variability without a consistent upward or downward trend. Between 1951 and 1980, the minimum rainfall generally ranged between 10 mm and 13 mm, except for a spike to 22.7 mm during 1956–1960. A further rise occurred in the 1981–1985 period, reaching 23.3 mm. However, this was followed by a sharp decline in the subsequent two periods, where the minimum dropped to approximately 6 mm. In 1996–2000, a moderate increase brought it back up to 12.5 mm, aligning more closely with earlier mid-range values. From 2001 to 2015, another decrease was observed, with figures falling to around 3 to 6 mm. Overall, the data highlights short-term fluctuations in minimum rainfall, potentially influenced by shifting climate patterns or seasonal variations, rather than indicating any long-term trend.

Maximum Rainfall

Maximum rainfall over the period from 1951 to 2015 shows considerable fluctuations, marked by alternating periods of increase and decrease. The most prominent spike occurs during 1956–1960, where maximum rainfall surges from 317.3 mm to 426.8 mm. This is followed by a sharp drop to 185.7 mm in 1961–1965, before rising again to 343.7 mm in the subsequent period. From 1971 to 1995, a gradual decline is observed, with values decreasing from 251.5 mm to 198.8 mm. Between 1996 and 2015, there was a partial recovery, with maximum rainfall generally stabilizing between 230 mm and 250 mm, except for a notable dip to 120.12 mm in 2001–2005. The period from 2006–2015 sees some improvement, though it doesn't reach the high levels recorded in earlier decades. These patterns reflect the high variability of maximum rainfall over time, potentially influenced by changing climatic conditions or natural shifts in weather dynamics.

Mean Rainfall

Mean rainfall from 1951 to 2015 displays noticeable fluctuations, with alternating periods of increase and decrease. The most significant rise is observed during 1956–1960, where the mean rainfall reached 89.57 mm. However, several subsequent periods, such as 1966–1970 (63 mm), 1976–1980 (60 mm), and 2006–2010 (58 mm), indicate a steady decline, pointing to drier conditions during those years. Between 1996 and 2015, the mean rainfall shows a mixed pattern, with values ranging moderately between 60 mm and 75 mm. This variability suggests that mean rainfall is influenced by periodic shifts, likely driven by changing climate trends, atmospheric dynamics, or regional weather patterns, rather than exhibiting a consistent long-term trend.

Standard Deviation of Rainfall

The standard deviation of rainfall from 1951 to 2015 reflects varying levels of rainfall variability over time. Between 1951 and 1975, the standard deviation ranged from 40 mm to 57 mm, indicating relatively higher variability during this early period. A notable decline follows from 1976 to 1995, with values dropping to between 33 mm and 38 mm, suggesting more stable rainfall patterns during these years. From 1996 onward, the standard deviation rises again to fall between 42 mm and 54 mm, except for the 2006–2010 period, which shows a temporary dip to 36.72 mm. Overall, there is no consistent upward or downward trend in rainfall variability across the entire timeframe. Instead, these fluctuations likely reflect the influence of broader climate cycles such as El Niño and La Niña or other regional weather systems that intermittently impact rainfall patterns.

Variability in Percentage Standard Deviation from the Mean

The percentage standard deviation from the mean rainfall between 1951 and 2015 highlights significant fluctuations in rainfall consistency over the decades. From 1951 to 1965, values range between 58% and 68%, with a sharp peak in 1966–1970 reaching 85.41%, indicating a period of heightened rainfall variability. This is followed by a general decline in variability from 1971 to 2000, where the percentage standard deviation typically falls between 50% and 60%, suggesting a phase of relatively more stable rainfall patterns. However, in the more recent decades from 2001 to 2015, variability once again shows an upward trend, fluctuating between 63% and 72%. Although not as extreme as the peak in the 1960s, these values still reflect considerable changes in rainfall behaviour, likely influenced by shifting climatic conditions and regional weather dynamics.

Variability in Percentage Maximum Value from the Mean

The percentage maximum value from the mean rainfall provides insight into the extent of extreme rainfall events over the decades. In the periods 1951–1955 and 1956–1960, the maximum rainfall reached 378.2% and 376.47% of the mean, respectively, indicating that rainfall extremes were nearly four times the average during those years. Although the 1961–

1965 period showed a decrease to 170.2%, it still represented substantial deviation from the mean. The most dramatic spike occurs in 1966–1970, where the maximum value surged to 443.1%—the highest in the entire dataset—signalling an exceptional extreme event. The following periods, 1971–1975 (235.7%) and 1976–1980 (238.4%), reflect a continued presence of high extremes, albeit less severe. A gradual decline is noted in 1981–1985 (183.6%) and 1986–1990 (192.1%), though still above average. The 1991–1995 period sees a slight resurgence with 243.06%, while the 2001–2005 period stands out for its notably low maximum value of 60.51%, indicating a brief phase of reduced extreme events. However, this is followed by an uptick in 2006–2010 (301.83%) and 2011–2015 (237.68%), showing that while recent extremes are not as intense as those in earlier decades, significant variability persists. These trends suggest that extreme rainfall events continue to be a feature of the climate, albeit with changing intensity over time.

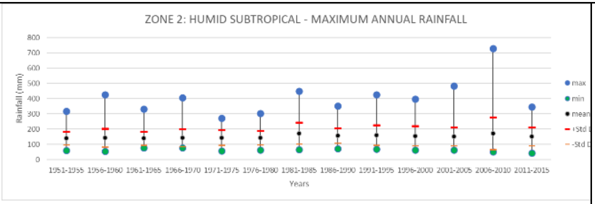

Figure 8(a): Short-term Annual Rainfall statistics for Humid Subtropical: Mean, Maximum, Minimum, and Standard deviation

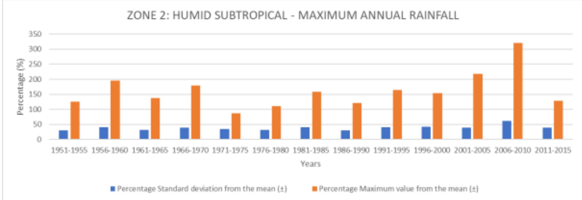

Figure 8(b): Short-term Relative Rainfall Variability for Humid Subtropical: Percentage Standard Deviation and Maximum Rainfall Value from Mean

3.2.2 Seasonal Spatial Rainfall Variability

January and February (winter/cold weather season)

Minimum Rainfall

The minimum rainfall values from 1951 to 2015 reveal a pattern of fluctuating dryness over the decades. In the initial three periods (1951–1965), the minimum rainfall ranged between 8 mm and 13 mm, indicating relatively moderate dry spells. However, during the following three periods (1966–1980), there was a notable decline, with minimum values dropping sharply to between 1 mm and 4 mm, suggesting increasingly arid conditions. A slight improvement occurred in the next three periods (1981–1995), where minimum rainfall increased to between 5 mm and 10 mm. This upward trend did not last, as values once again dropped to around 1–2 mm during 1996–2010, indicating a return to more extreme dry conditions. The most recent period, 2011–2015, shows signs of recovery, with the minimum rainfall rising to 10.1 mm, suggesting a reduction in drought intensity compared to earlier decades. This cyclical variation highlights the shifting nature of dry spells, potentially driven by broader climatic and environmental factors.

Maximum Rainfall

Maximum rainfall values from 1951 to 2015 demonstrate a pattern of significant fluctuations across the decades. The period 1951–1955 began with relatively low maximum rainfall at 55.9 mm, followed by a sharp increase in 1961–1965, reaching 143.4 mm. This was immediately followed by a notable drop to 84 mm in 1966–1970. The most remarkable peak occurred during 1976–1980, with a maximum rainfall of 189.2 mm—the highest recorded in the entire study period. A decline followed in the next period, dropping to 99.4 mm, before gradually rising again to 178.4 mm in 1991–1995. This was followed by another dip to 99.3 mm, but rainfall rose steadily in the subsequent years, reaching 108 mm in the 2006–2010 period. However, the most recent period, 2011–2015, experienced another drop to 94 mm. These alternating highs and lows suggest that while extreme rainfall events have occurred intermittently, there is no consistent trend, reflecting the variability and unpredictability of maximum rainfall over time.

Mean Rainfall

Throughout the study period from 1951 to 2015, the fluctuations in mean rainfall are relatively minor, indicating a general consistency in average rainfall levels over the decades. The mean rainfall varied within a narrow range of 24 mm to 36 mm, showing no significant long-term increases or decreases. This stability suggests that, despite periodic extremes in maximum or minimum rainfall, the overall average remained fairly steady, likely reflecting a balance between wetter and drier years within each period.

Standard Deviation of Rainfall

The standard deviation of rainfall over the period from 1951 to 2015 shows generally minor fluctuations, indicating a relatively consistent spread of rainfall values around the mean. Across most decades, the standard deviation ranged between 13 mm and 20 mm, suggesting stable variability in rainfall distribution. An exception to this trend is observed during the 1991–1995 period, where the standard deviation spiked to 26.9 mm, pointing to a brief phase of heightened variability. Despite this outlier, the overall trend suggests limited deviation from the norm, reflecting consistent rainfall patterns in terms of distribution over time.

Variability in Percentage Standard Deviation from the Mean

The percentage standard deviation from the mean rainfall over the decades reveals notable shifts in rainfall variability. From 1951 to 1980, the percentage standard deviation gradually increased from 51% to 71%, indicating a rise in rainfall variability. This trend was followed by a decline in the next two periods, with values dropping to between 50% and 58%, suggesting a reduction in variability. However, the period from 1991 to 1995 saw a sharp rise in the percentage standard deviation to 83%, reflecting extreme fluctuations in rainfall during that time. From 1996 to 2015, the percentage standard deviation returned to more moderate levels, ranging from 47% to 61%, which is lower compared to the more variable decades. These fluctuations in percentage standard deviation highlight significant changes in rainfall patterns, with occasional periods of heightened variability.

Variability in Percentage Maximum Value from the Mean

The variability in maximum rainfall as a percentage of the mean over the decades shows significant fluctuations, with extreme values observed in several periods. From 1951 to 1955, the maximum rainfall was 115.1% above the mean, and in 1956–1960, it was 21.9% higher than the mean. A sharp increase occurred in 1961–1965, where the maximum value was more than 3.6 times the mean. In 1966–1970, the maximum rainfall was nearly double the mean at 197.8%, and in 1971–1975, it exceeded three times the mean. The 1976–1980 period stands out with the largest extreme, where the maximum rainfall was almost six times the mean (584%), reflecting highly erratic weather patterns. The next two periods saw the maximum rainfall at 2.15 and 2.6 times the mean, while 1996–2000 again saw a significant spike, with the maximum rainfall reaching 453.38% of the mean, more than 4.5 times the average. In the subsequent periods, the maximum values were 2.15 and 1.9 times the mean. The 2006–2010 period experienced a 279.36% increase, nearly 2.8 times the mean, and by 2011–2015, the maximum rainfall was about 182.81% of the mean, approximately 1.8 times the average. While these extremes were notably higher in the earlier decades, recent years have seen a decrease in the intensity of these extremes, suggesting a shift toward more moderate rainfall fluctuations in recent times.

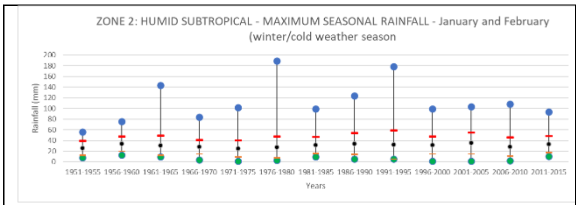

Figure 9 (a): Short-term Rainfall statistics for Humid Subtropical January and February (winter/cold weather season): Mean, Maximum, Minimum, and Standard deviation

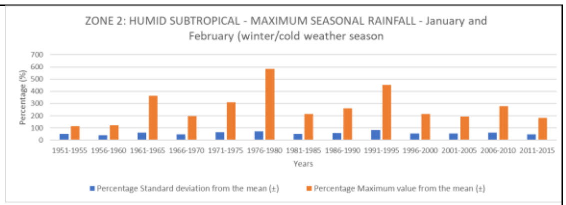

Figure 9(b): Short-term Rainfall Variability for Humid Subtropical January and February (winter/cold weather season): Percentage Standard Deviation and Maximum Rainfall Value from Mean

March, April, and May (Pre-monsoon/summer/hot weather/thunderstorm season)

Minimum Rainfall

The minimum rainfall values throughout the study period from 1951 to 2015 generally ranged between 0.2 mm and 11 mm, reflecting significant variability in dry conditions. In the earlier periods, the minimum rainfall often fell to much lower values, indicating drier spells. However, in the most recent periods, specifically 2006–2010 and 2011–2015, the minimum rainfall increased slightly, reaching 10.3 mm and 11 mm, respectively. This rise suggests wetter conditions compared to previous decades, where minimum values were typically much lower. The increase in minimum rainfall could potentially reflect changes in climatic conditions or shifts in precipitation patterns, indicating a possible trend toward more consistent or increased rainfall in recent years.

Maximum Rainfall

The maximum rainfall values over the study period from 1951 to 2015 exhibit considerable fluctuation, with alternating periods of increase and decrease. From 1951 to 1980, the maximum rainfall ranged between 155 mm and 200 mm, except for the 1961–1965 period, where it dropped to 134.3 mm. A more significant increase occurred in 1981–1985, with the maximum rainfall reaching 226.7 mm, followed by a dramatic rise to 351.6 mm in 1986–1990. However, in 1991–1995, the maximum rainfall dropped to 183.8 mm, returning to levels similar to those seen in 1976–1980. The following period, 1996–2000, saw another increase to 305.1 mm, before the maximum rainfall decreased to 187.8 mm in 2001–2005, reflecting a return to mid-1970s and early 1980s levels. A slight increase followed in 2006–2010, reaching 190.6 mm, but by 2011–2015, the maximum rainfall had decreased again to 160.2 mm, lower than the previous period. These fluctuations highlight the variability in rainfall intensity, with no consistent upward or downward trend over time.

Mean Rainfall

Throughout the study period from 1951 to 2015, the mean rainfall ranged between 42 mm and 61 mm. The data suggests an overall increase in average rainfall from the 1950s to the late 1990s, reflecting wetter conditions in those decades. However, in the 2000s and 2010s, there were periods of fluctuation, with some stabilization or slight decrease in the mean rainfall, particularly from 2006 to 2015. This more recent trend may be indicative of regional shifts in climate or weather patterns and could potentially be linked to broader global climatic changes, such as increased moisture in the atmosphere or the ongoing effects of global warming. These changes highlight the complexity of rainfall patterns, which may be influenced by a combination of local and global climatic factors.

Standard Deviation of Rainfall

The standard deviation of rainfall over the study period shows variability in the spread of rainfall values around the mean. From 1951 to 1980, the standard deviation ranged between 30 mm and 40 mm, indicating moderate variability in rainfall. From 1981 to 2010, the standard deviation increased to between 40 mm and 53 mm, suggesting higher rainfall variability during this period. However, in the most recent period, 2011–2015, the standard deviation dropped to 33.60 mm, reflecting a decrease in rainfall variability compared to the previous decades. This shift may indicate more consistent rainfall patterns in recent years, possibly influenced by changes in climate or weather systems.

Variability in Percentage Standard Deviation from the Mean

The percentage standard deviation from the mean rainfall shows significant fluctuations over the study period. From 1951 to 1985, the percentage standard deviation ranged between 65% and 75%, indicating a moderate level of variability in rainfall. However, starting in 1986, there was a notable increase in the percentage standard deviation, rising to between 75% and 98%, reflecting a period of heightened rainfall variability. The most recent period, 2011–2015, saw a sharp drop to 53%, suggesting a decrease in variability compared to the previous decades. This decrease may signal a period of more stable rainfall, possibly linked to regional or broader climatic shifts that have influenced precipitation patterns.

Variability in Percentage Maximum Value from the Mean

From 1951 to 1985, the percentage maximum value from the mean rainfall typically ranged from 2 to 3 times the mean, indicating a moderate level of rainfall extremes. However, the period 1986–1990 saw an exceptional spike, with the maximum rainfall reaching 351.6 mm, over five times the mean rainfall of 55.03 mm. This period experienced extremely intense rainfall events, far more extreme than any other period in the dataset. The following two periods also displayed high variability, with maximum rainfall reaching 3 to 4 times the mean. Since 2001, the percentage maximum value has decreased to between 2 to 3 times the mean, reflecting a trend towards less extreme rainfall events. This shift, particularly from the 2000s onwards, suggests that rainfall patterns have become more stable and predictable, likely influenced by broader climatic changes, regional weather patterns, and long-term atmospheric shifts.

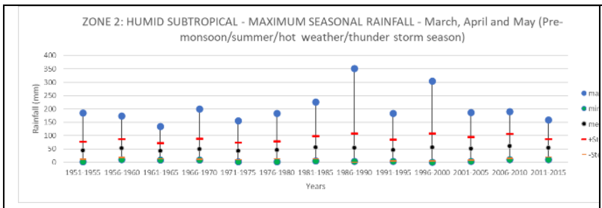

Figure 10 (a): Short-term Rainfall statistics for Humid Subtropical March, April, and May (Pre-monsoon/summer/hot weather/thunderstorm season): Mean, Maximum, Minimum, and Standard deviation

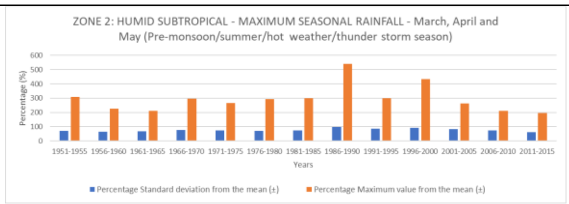

Figure 10 (b): Short-term Rainfall Variability for Humid Subtropical March, April, and May (Pre-monsoon/summer/hot weather/thunderstorm season): Percentage Standard Deviation and Maximum Rainfall Value from Mean

June, July, August, and September (South-west monsoon/summer monsoon season)

Minimum Rainfall

From 1951 to 1981, the minimum rainfall fluctuated between 57 mm and 66 mm, except the 1956–1960 period, where it dropped to around 41 mm. In 1986–1990, the minimum rainfall increased significantly to 72.9 mm, reaching the highest point during this period. The minimum rainfall from 1991 to 2010 fluctuated between 52 mm and 65 mm, reflecting moderate variability. However, from 1996 onwards, a downward trend emerged, with significant drops in the 2006–2010 period (52.3 mm) and the 2011–2015 period (44.3 mm). This decline suggests that rainfall events during these periods may have been influenced by extreme weather events, such as heavy storms or unusual seasonal patterns, leading to both the spikes and eventual reductions in minimum rainfall observed in the most recent years.

Maximum Rainfall

The maximum rainfall exhibited a general upward trend from 277.2 mm in 1951 to 405.6 mm in 1970, although there were notable decreases, particularly in 1971–1975, when it dropped sharply to 271.5 mm. In 1976–1980, the maximum rainfall increased to 302.9 mm, followed by a significant rise in 1981–1985 to 448.8 mm. However, in 1986–1990, the rainfall decreased again to 312.5 mm, suggesting variability and potential impacts from extreme weather events. The next three periods saw higher rainfall levels, ranging from 397 mm to 483 mm. The most significant increase occurred in 2006–2010, with a peak of 729.3 mm, the highest value observed in the study period. After this extreme peak, rainfall dropped to 348.2 mm in 2011–2015, returning to levels similar to those seen earlier, indicating a shift back toward more typical rainfall conditions following an unusually high event.

Mean Rainfall

The mean rainfall gradually increased from 134.51 mm in 1951–1955 to 141.92 mm in 1975–1980, indicating a slow rise in average rainfall during these years. A more substantial increase occurred in 1981–1985, with the mean reaching 168.51 mm, marking a significant rise. From 1986 to 2005, the rainfall fluctuated between 142 mm and 159 mm, showing moderate variability. The mean rainfall then increased again to 171.30 mm in 2006–2010, which was the highest value recorded in the dataset. However, by 2011–2015, the mean rainfall dropped to 148.22 mm, suggesting a return to lower rainfall levels after the peak observed in the previous period.

Standard Deviation of Rainfall

From 1951 to 1980, the standard deviation generally ranged between 40 mm and 54 mm, suggesting relatively moderate variability in rainfall during these periods. Although there were slight fluctuations, overall, the rainfall was fairly consistent. A significant increase in variability occurred in 1981–1985, with the standard deviation reaching 72.61 mm, indicating a period of much higher rainfall variability. Afterward, the variability decreased, with the standard deviation dropping to 45.97 mm in 1986–1990. From 1991 to 2005, the standard deviation fluctuated between 58 mm and 67 mm, showing moderate changes. The period from 2006–2010 saw a sharp increase in the standard deviation to 107.29 mm, the highest level recorded in the dataset, suggesting highly variable rainfall events, possibly due to extreme weather patterns. However, by 2011–2015, the standard deviation decreased to 60.69 mm, indicating a return to more moderate rainfall variability.

Variability in Percentage Standard Deviation from the Mean

The percentage standard deviation reveals a clear pattern of fluctuating rainfall variability across the periods, typically ranging from 30% to 43%, except in the 2006–2010 period, where the deviation spiked to 62.63%. From 1991 onward, there is a notable increase in variability, especially during 1991–1995, indicating more erratic rainfall patterns. The sharp rise in the 2006–2010 period suggests extreme rainfall variability, likely due to significant weather events or shifts in climate conditions. After 2010, the variability remains high, although not as extreme as in the previous decade, suggesting some stabilization in rainfall patterns.

Variability in Percentage Maximum Value from the Mean

The extreme rainfall events (maximum rainfall) were generally about 1 to 2 times the mean rainfall from 1951 to 2000. However, there is a significant increase in the percentage maximum value during the 2001-2005 and 2006-2010 periods, with values reaching 238.42% and 325.76%, respectively. These figures indicate that extreme rainfall events in these periods were more than 2 to 3 times the mean, with the 2006-2010 period marking the highest extreme, over 3 times the mean. After 2010, the percentage drops to 134.92% in 2011-2015, though it remains notably higher than the values observed in earlier periods. Overall, the variability in the maximum rainfall values reflects a trend of increasing extreme weather events, suggesting potential shifts in climate patterns, including more frequent or intense storms and greater unpredictability in rainfall.

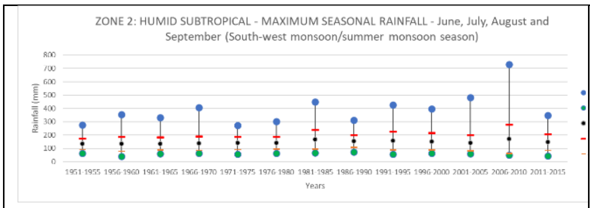

Figure 11(a): Short-term Rainfall statistics for Humid Subtropical June, July, August and September (South-west monsoon/summer monsoon season): Mean, Maximum, Minimum, and Standard deviation

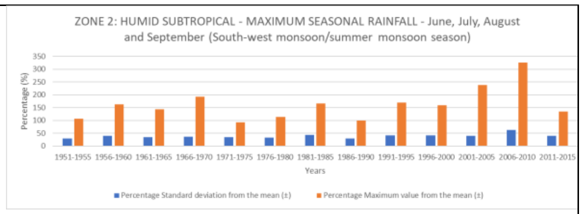

Figure 11(b): Short-term Rainfall Variability for Humid Subtropical June, July, August and September (South-west monsoon/summer monsoon season): Percentage Standard Deviation and Maximum Rainfall Value from Mean

October, November and December (Post-monsoon/north-east monsoon/retreating south-west monsoon season)

Minimum Rainfall

In the early periods (1951-1960), the minimum rainfall remains relatively stable, ranging between 10 to 22 mm. From 1971 to 1985, there is a noticeable increase in the minimum rainfall, reaching up to 23.3 mm in 1981-1985. However, this trend is followed by a drop in minimum rainfall levels in the 1991-2015 period, with values generally around 6 mm, except in certain years. Notably, during the 1996-2000 period, the minimum rainfall rises to 12.5 mm, and in 2006-2010, it drops even further to 3.8 mm, marking some of the lowest levels in the dataset. These fluctuations suggest varying climatic conditions and weather patterns impacting rainfall over the decades.

Maximum Rainfall

The maximum rainfall values show significant fluctuations over the years. From 1951 to 1960, the maximum rainfall increased from 317.3 mm in 1951-1955 to 426.8 mm in 1956-1960. However, there was a notable decrease in 1961-1965, with the maximum rainfall dropping to 185.7 mm. The subsequent period, 1966-1970, saw an increase to 343.7 mm, indicating a return to more intense rainfall. From 1971-1985, the maximum rainfall fluctuated further, with a decrease to 251.5 mm in 1971-1975, and a drop to 205.4 mm in 1976-1980. The period 1981-1985 had relatively low extremes, with a maximum rainfall of 186.6 mm. In 1991-1995, the maximum rainfall rose slightly to 198.8 mm and continued to rise to 249.8 mm in 1996-2000, signalling a return to moderate-to-high extreme rainfall. A sharp decline occurred in 2001-2005, with a maximum of just 120.12 mm, before rising again in 2006-2010 to 233.8 mm and 239.6 mm in 2011-2015. These changes reflect a pattern of fluctuating extremes over the decades.

Mean Rainfall

The mean rainfall ranged from 60 to 68 mm between 1951 and 1990, with the exception of two periods: 1956-1960, which saw a significant increase to 89.6 mm, and 1971-1975, with a mean of 74.9 mm. In 1991-1995, however, the mean rainfall dropped to 57.9 mm, marking a notable decrease. From 1991 to 2015, the mean rainfall fluctuated between 71 and 75 mm, although the period from 2006-2010 saw a dip to 58 mm. Overall, the data suggests a pattern of declining rainfall from the 1960s to the 1990s, followed by a moderate recovery in the 2000s to 2015, indicating a shift in rainfall patterns over the decades.

Standard Deviation of Rainfall

The standard deviation of rainfall varied between 40 and 57 mm from 1951 to 1975, reflecting moderate variability in rainfall during this period. From 1976 to 1995, the standard deviation decreased slightly, ranging from 33 to 38 mm, indicating a period of reduced variability. However, from 1996 to 2015, the standard deviation increased again, fluctuating between 42 and 54 mm, with the exception of the 2006-2010 period, where it dropped to 36.72 mm. This pattern suggests a return to more consistent variability in recent decades, with a brief period of lower fluctuations in the mid-2000s.

Variability in Percentage Standard Deviation from the Mean

The percentage standard deviation from the mean generally ranged between 57% and 67%, reflecting moderate rainfall variability across most of the study period. However, in the years 1966-1970 and 2001-2005, the percentage standard deviation was relatively high, reaching values of 85.4% and 72%, respectively, indicating periods of more extreme rainfall variability. Notably, in 1981-1985, the percentage dropped significantly to 50.19%, suggesting a phase of more stable and consistent rainfall. Overall, the variability in rainfall, as measured by the percentage standard deviation, fluctuated considerably across the decades, with shifts in climate and weather patterns likely contributing to periods of both higher and lower variability.

Variability in Percentage Maximum Value from the Mean

The percentage maximum value of rainfall showed significant fluctuations across the decades. In the early periods of 1951-1955 and 1956-1960, the percentage maximum values were extremely high, at 378.2% and 376.5%, respectively, indicating exceptionally intense rainfall events compared to the mean. This was followed by a significant drop in 1961-1965 to 170.2%. However, the most dramatic spike occurred in 1966-1970, with the percentage maximum value reaching 443.1%, the highest recorded in the dataset. There were also periods of high rainfall variability in 1971-1975 and 1976-1980, with percentage values of 235.7% and 238.4%. By 1981-1985, this trend decreased to 183.6%, and it remained relatively stable with slight increases in 1986-1990 (192.1%), indicating a reduction in extreme rainfall events. In the following years, the percentage maximum values increased again, peaking at 243.06% in 1991-1995 and 236% in 1996-2000. However, there was a sharp decline in 2001-2005 to 60.51%, the lowest in the dataset. A resurgence occurred in 2006-2010 with 301.83%, the second-highest value, followed by 237.68% in 2011-2015, indicating a return to moderate extreme rainfall events. Overall, recent years have experienced a return to sporadic but intense rainfall events, though not as extreme as in earlier decades, indicating moderate variability in rainfall patterns.

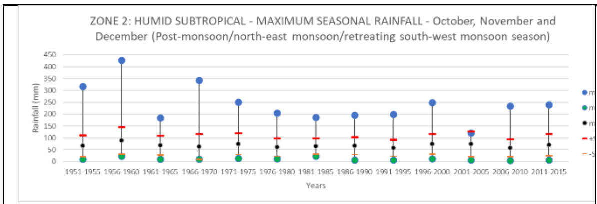

Figure 12(a): Short-term Rainfall statistics for Humid Subtropical October, November and December (Post-monsoon/north-east monsoon/retreating south-west monsoon season)

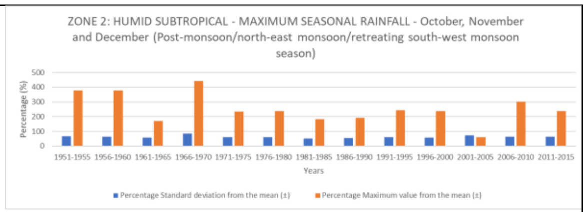

Figure 12(b): Short-term Rainfall Variability for Humid Subtropical October, November and December (Post-monsoon/north-east monsoon/retreating south-west monsoon season)

4. CONCLUSIONS

This study was undertaken to understand the spatiotemporal variability of rainfall in the humid subtropical zone of India, classified as one of the six Koppen climate zones, on both annual and seasonal scales. The study employs a 5-year grouping approach to facilitate short-term variability assessments using daily rainfall data from 1951 to 2015.

Annual rainfall in the humid subtropical region shows significant spatial variability, with maximum values typically between 40–440 mm, peaking at ~640 mm during 2006–2010. Isohyets confirm consistent spatial variation during that period. The temporal annual rainfall (1951–2015) shows no consistent trend but fluctuates notably. Minimum and mean values vary cyclically, while extremes (max rainfall and standard deviation) peak in 1956–60 and 1966–70. Variability in both standard deviation and extremes reflects changing climate dynamics without a clear directional shift.

The rainfall in January and February varies from 0–140 mm, with minimal to moderate spatial variability. Anomalies occurred during 1996–2000, with increased minimum rainfall. Isohyets show overall consistent spatial-temporal patterns. The temporal rainfall (1951–2015) shows cyclic variability in minimum and maximum values, with peaks in 1976–80 and 1996–2000. Mean and standard deviation remained relatively stable, though variability peaked in 1991–95. Recent decades show reduced extremes, indicating a possible moderation of seasonal fluctuations.

The March, April, and May rainfall ranges from 0 to very heavy, with exceptionally heavy rainfall noted in 1986–1990, especially in NE India. Atypical intensity appeared in Uttar Pradesh (1996–2000). Isohyets show marked spatial variation across seasons. The temporal rainfall (1951–2015) shows fluctuating extremes, with peak max rainfall in 1986–90 and reduced extremes post-2000. Mean rainfall rose until the late 1990s, then stabilized or declined. Variability (standard deviation percentages) peaked in the late 20th century, but declined in recent decades, suggesting more stable patterns.

The June, July, August, and September rainfall ranges from 50–450 mm, peaking at ~650 mm in Bihar (2006–2010). Maxima are concentrated in NE India and northern West Bengal. Isohyets reveal localized temporal variation (Chhattisgarh, Bihar), with minimal spatial change in minimum rainfall. The temporal rainfall (1951–2015) reveals significant fluctuations in minimum and maximum rainfall, with notable peaks in 2006–2010. The minimum rainfall has dropped in recent decades, reflecting increased dryness. Maximum rainfall showed a general increase, especially in the late 20th century, culminating in an extreme peak in 2006–

2010. However, the following period (2011–2015) returned to lower levels. Variability in rainfall, as seen through standard deviation and percentage changes, spiked during extreme weather events, indicating shifts in climate patterns and greater unpredictability in recent decades.

October, November, and December rainfall vary from 0–250 mm, exceeding 300 mm in 1956–60 and 1966–70. Minimum rainfall remains largely consistent (0 to rather heavy). Isohyets indicate stable spatial-temporal patterns across the period. The temporal rainfall (1951–2015) reveals significant fluctuations in both minimum and maximum rainfall, with trends suggesting varying climatic conditions over the decades. Minimum rainfall declined from the 1970s to the 2010s, reaching some of the lowest levels in 2006–2010. Maximum rainfall also displayed sharp fluctuations, with notable extremes in the 1960s and early 2000s. The mean rainfall varied moderately, showing a general decrease from the 1960s to 1990s, followed by a partial recovery in the 2000s. Rainfall variability, indicated by standard deviation and percentage shifts, peaked in certain periods like 1966–1970 and 2001–2005, reflecting extreme weather events. Despite these fluctuations, recent years (2006–2015) show a trend toward more moderate rainfall extremes, suggesting some stabilization in rainfall patterns.

As climate change continues to alter rainfall patterns, variability studies provide a valuable baseline for understanding these changes. This information is critical for developing adaptation strategies, such as modifying agricultural practices and adjusting water management policies. By anticipating shifts in rainfall, stakeholders can better prepare for and respond to the impacts of climate change, ensuring more resilient systems and practices.

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