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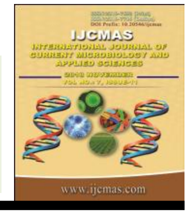

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Variability and Trends of Rainfall Events in the Brahmaputra Valley of Assam, India

Bikash Jyoti Gharphalia[1*], Rajib Lochan Deka[1], Athar Nishat Islam[1], Pranjal Dutta[1] and Kuldip Medhi[2]

[1]*Department of Agrometeorology, Assam Agricultural University, Jorhat-785013, India*
[2]*Regional Agricultural Research Station, Gossaigaon, AAU, India*

**Corresponding author*

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A B S T R A C T

The present study intended to determine potential trends in monthly, seasonal and annual rainfall in the Brahmaputra valley of Assam during 1986-2015, based on observed daily rainfall data from 10 locations. The magnitude of the trends was estimated using Theil-Sen's slope method, while statistical significance of the trends was tested using Mann-Kendall rank statistics. Analysis revealed that mean annual rainfall varied from 1653.5 mm in Golaghat to 3676.9 mm in Gossaigaon, with variability in order of 13-32 per cent at different locations. Annual rainfall was found to decrease in all the 10 stations, with a significant decrease in Golaghat, Dhubri, Kamrup and Tezpur. On seasonal basis, pre-monsoon rainfall indicated increasing trends at Jorhat, Golaghat, Lilabari, Mohanbari, Beki and Tezpur during the study period. Conversely, rainfall during the monsoon season exhibited significant decreasing trends at Beki, Dhubri, Shillongoni and Tezpur, due to the corresponding significant decrease in July and September rainfall in the locations. Similar decreasing rainfall trends were also observed during post-monsoon season in all the stations. During winter, due to significant decrease in February rainfall, all the stations showed decreasing rainfall trends, with statistically significant values for Golaghat, Lilabari, Mohanbari, Kamrup, Shillongoni and Tezpur, as per Mann-Kendall rank statistics.

Introduction

Investigating historical changes in the climatic system is recognized as one of the basic necessities of climate change research. The aspect of climate, which most interests the layman and the scientists, is predominantly uncertain, regarding its possible trends (Barry and Chorley, 1987). Climate change studies mostly rely on detecting significant trends in the records of hydro-meteorological variables *viz.* relative humidity, rainfall and air temperature (IPCC, 2014). In this context, rainfall is of prime interest, owing to its manifestation as a deficient resource or a catastrophic agent. It plays a crucial role as its variations in seasonal and monthly values, coupled with changes in extreme events, can impact on water resources, on natural environments, as well as on human health and safety (Oguntunde *et al.*, 2006, IPCC, 2007). However, there is a large variation in the amount of rainfall received at different locations (Attri and Tyagi, 2010). These changes in rainfall pattern exert a significant impact on human's socio-economic activities. Thus, a detailed study regarding the amount, variability and changes in rainfall, along with a complete and accurate description at different spatial and temporal scales has got special attention worldwide in recent years (Markham, 1996). However, reliable weather records have only been kept during the last hundred years or so, and therefore, it is only the recent climatic fluctuations, which can be investigated adequately (IPCC, 1996). At present, the spatial and temporal characteristics of changes in rainfall amounts and concentration have become principal research objects for climate change (Huang *et al.,* 2013). Many researchers have conducted extensive studies on rainfall analysis on seasonal as well as annual scales (Hulme *et al.,* 1998; Parthasarathy *et al.,* 1993; Alexander *et al.,* 2006; Guhathakurta and Rajeevan, 2008; Choudhury *et al.,* 2012; Jain *et al.,* 2013; Patle and Libang, 2014; Asikoglu and Ciftlik, 2015).

For the Indian region, the earliest study was made by Walker (1910), which indicated no significant trend in rainfall in the monsoon season during the second half of the 19th century. Thereafter, studies have been limited to trends and periodicities over specific regions of India by using different data period (Naidu *et al.,* 1999). There are several studies in India on the variability of rainfall and its long term trends (Parthasarathy and Dhar, 1975; Mooley and Parthasarathy, 1984; Sarkar and Thapliyal, 1988; Thapliyal and Kulshresthra, 1991; Guhathakurta and Rajeevan, 2008; Krishnakumar *et al.,* 2009; Kumar *et al.,* 2010; Jain and Kumar, 2012; Bhatla and Tripathi, 2014; Das *et al.,* 2015; Deka *et al.,* 2016; Kothawale and Rajeevan, 2017; Sharma and Singh, 2017). Similarly, there are several studies which focused mainly on the intensity and trends of extreme rainfall events over India, Rakhecha and Soman (1994), Sen Roy and Balling (2004), Joshi and Rajeevan (2006), Rajeevan *et al.,* (2008), Guhathakurta *et al.,* (2010), Gill *et al.,* (2013), Satyanarayana and Kar (2016) and Talchabhadel *et al.,* (2018), to name a few. However, there are only a few studies available on the rainfall variability and trends over northeast India (Das and Goswami, 2003; Das *et al.,* 2011; Deka *et al.,* 2013; Jain *et al.,* 2013; Das *et al.,* 2015; Deka *et al.,* 2016). Since rainfall is having high spatial variability, study of long-term trends of rainfall in smaller spatial scale on daily, weekly, monthly and seasonal time scale is found to be more relevant. For the Brahmaputra valley, where flood is a regular feature, especially during the rainy season, analysis of rainfall trends for the region is of even greater significance.

Climatic characteristics of the study area

The Brahmaputra valley of Assam is a part of NE India which, in turn, is an integral part of the sub-tropical South-East Asia (Barthakur, 2004). It extends from 26°30′ N latitude and 92°45′ E longitude, covering an area of 56,194 km^2 (DES, 2016). Being a part of the sub-tropical belt, the climate of the Brahmaputra valley is akin to the South-East Asiatic monsoon climate (Barthakur, 2004). Climate of the valley is characterized by hot summers and mild to moderately cool winters. The mean annual rainfall of the Brahmaputra valley is 2293 mm with large spatial variations (Deka *et al.,* 2013), which is generally influenced by orography of the region (Pant *et al.,* 1970; Goswami *et al.,* 2010). The southwest monsoon is responsible for causing the bulk of rainfall, which is about 65 per cent of the annual rainfall over the valley, followed by pre-monsoon rainfall (25%), post-monsoon rainfall (7-8%) and winter rainfall (2-3%) (Deka *et al.,* 2013). Variability of annual rainfall over the valley is low, in the order of

10-18 per cent (Deka *et al.,* 2016). Before the onset of monsoon, there is substantial thunderstorm activity over the region during April and May, as moisture thrusts into the region from the neighbouring Bay of Bengal (Dhar and Nandargi, 2000). Heavy rainfall mostly occurred when the eastern end of the monsoon trough shifts northwards to the valley, or during the periods when 'Break' monsoon situations set in over the country with a northward shift of the monsoon trough to the foot of the Himalayas. These two particular meteorological situations are responsible for causing heavy rainfall on about 65% of the occasions (Dhar and Changrani, 1966; Dhar and Nandargi, 2003). Cyclonic circulations progress through the Orissa-Bengal Coast and move in a northwesterly or northerly direction, or re-curve in a northerly or northeasterly direction, thus causing heavy rainfall over the Brahmaputra valley (Ramaswamy and Rao, 1979; Rajeevan *et al.*, 2012).

With 23 per cent of the net cultivated area (28.27 lakh hectares) being flood or drought prone, Brahmaputra valley represents one of the most intense hazard-prone regions in India (Das *et al.*, 2015, DES, 2016). Therefore, the present investigation is carried out, using 10 stations, having quality rainfall data and representing the distinctive features of the river basin, with an objective to strengthen a vivid idea on the recent trend of rainfall in the Brahmaputra valley of Assam.

Materials and Methods

Data

Climate change studies require a long period of data in order to identify long- term trends (WMO, 1996). The daily rainfall data cover the period 1986-2015 (30 years) and were recorded at 10 climatological weather stations, representing the Brahmaputra valley of Assam (Table 1 and Fig. 1). Data for the 10 stations were collected from the Department of Agrometeorology, Assam Agricultural University, Jorhat, India Meteorological Department (IMD), Pune and Regional Meteorological Centre (RMC), Guwahati. From the daily rainfall data, monthly, seasonal and annual rainfall series were calculated for each station. For seasonal analysis, each year has been divided in to four seasons, *viz.* winter (December-February), pre-monsoon (March-May), monsoon (June-September) and post-monsoon (October-November) (Deka and Nath, 2000).

Trend analysis

Sen's slope

The magnitude of trend in hydro-meteorological time series can be determined using Sen's slope method (Yue *et al.*, 2002). Since the Sen's slope is insensitive to outliers or missing data, it is more rigorous than the usual regression slopes, and thus provides us a realistic measure of the trends in the data series. The approach involves computing slopes for all the pairs of ordinal time points using the median of these slopes as an estimate of the overall slope (Sen, 1968).

The slope estimates Q_i of N pairs of data are calculated by

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

For i = 1, 2,......., N

Where x_j and x_k are data values at times j and k ($j > k$) respectively. The median of these N values of Q_i is Sen's estimator of slope. If there is only one datum in each time period, then N= n(n-1)/2, where n corresponds to the number of time periods. The N values of slopes are ranked from the smallest to largest and if N is odd, Sen's estimator of slope is calculated as

$$Q_{median} = Q(N+1)/2$$

If N is even, then Sen's estimator becomes

$$Q_{median} = \left[Q_{N/2} + Q_{(N+2)/2}\right]/2$$

A positive value of *Q* indicates an upward (increasing) trend and a negative value indicates a downward (decreasing) trend in the time series.

Mann-Kendall rank test

Mann-Kendall rank test (Mann, 1945 and Kendall, 1975) was used to statistically assess the presence of significant trend in the series of rainfall data (Partal and Kahya, 2006), streamflow data (Liu and Zheng, 2004) and water quality data (Donohue *et al.*, 2001). It is a distribution free method, more resistant to outliers, can deal with missing data unlike the parametric method (Wilcox, 1998) and mainly focuses on pair-wise slopes (Alexander *et al.*, 2006).

The MK test statistic (S) is given by

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}\left(x_j - x_k\right)$$

Where n is the number of data, x is the data point at times j and k (k>j) and the sign function is given as

$$\operatorname{sgn}\left(x_j - x_k\right) = \begin{cases} +1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases}$$

The S statistic, in cases where the sample size n is larger than 10, is assumed to be asymptotically normal, with E(S) = 0 and the variance of S is computed by

$$\operatorname{Var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)\right]$$

Where t refers to the extent of any given tie and Σt states the summation over all ties. The standard normal deviate Z is computed by

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S < 0 \end{cases}$$

The presence of statistically significant trend is evaluated using the Z value. In a two-sided test for trend, the null hypothesis H_0 should be accepted if $[Z] > Z_{\alpha/2}$, at the level of significance. In this analysis, the null hypothesis was tested at both 90 and 95 per cent confidence level.

Results and Discussion

Rainfall statistics in the Brahmaputra valley

Important statistical characteristics (Mean (M), Standard Deviation (SD) and Coefficient of Variation (CV) of monthly and seasonal rainfall series of 30 subdivisions, 5 homogeneous regions and all-India for the period 1901-2013 have been computed. The mean annual rainfall in the Brahmaputra valley varied from 1653.5 mm in Golaghat to 3676.9 mm in Gossaigaon, with coefficient of variation (CV) ranging between 13 to 32 per cent at different locations. Maximum amount of rainfall was received during monsoon, followed by pre-monsoon, post-monsoon and winter season at all the selected locations (Table 2). Rainfall during the monsoon season ranged from 1045.4 mm in Golaghat to 2784.0

mm in Gossaigaon. Among all the seasons, CV was found to be highest in winter season, ranging from 46 per cent in Mohanbari to 94 per cent in Gossaigaon.

Trend analysis

Monthly rainfall trends

The trend analysis of monthly rainfall for 10 locations of the Brahmaputra valley during the period 1986-2015 revealed that rainfall is decreasing significantly during the month of February at Golaghat (8.8 mm decade^{-1}), Lilabari (14.4 mm decade^{-1}), Mohanbari (16.1 mm decade^{-1}), Kamrup (5.3 mm decade^{-1}), Shillongoni (9.3 mm decade^{-1}) and Tezpur (7.7 mm decade^{-1}) (Table 3).

Similar significant decreasing trends were also observed at Mohanbari (38.4 mm decade^{-1}), Dhubri (235.5 mm decade^{-1}), Kamrup (42.4 mm decade^{-1}), and Tezpur (31.8 mm decade^{-1}) during the month of July, at Mohanbari (66.1 mm decade^{-1}) and Dhubri (110.2 mm decade^{-1}) during September, at Mohanbari (20.3 mm decade^{-1}), Beki (33.8 mm decade^{-1}) and Tezpur (23.5 mm decade^{-1}) during October, and at Jorhat (4.5 mm decade^{-1}) and Golaghat (5.0 mm decade^{-1}) during the month of November (Table 3). On the contrary, positive trends were also observed at different locations, mostly during the months of April and May. However, these values were statistically non-significant.

Seasonal rainfall trends

Rainfall during pre-monsoon season indicated increasing trends at Jorhat, Golaghat, Lilabari, Mohanbari, Beki and Tezpur (Table 3). However, during monsoon season, all the stations, except Jorhat, showed decreasing trend of rainfall, with statistically significant values for Beki (115.7 mm decade^{-1}), Dhubri (570.6 mm decade^{-1}), Shillongoni (129.3 mm decade^{-1}) and Tezpur (92.2 mm decade^{-1}) (Table 3). This decrease was mainly attributed to the significant decreasing trends in July and September rainfall in these locations. During the post-monsoon season, rainfall exhibited decreasing trends at all locations, with significant values for Jorhat (23.7 mm decade^{-1}), Beki (32.9 mm decade^{-1}), and Dhubri (40.9 mm decade^{-1}) (Table 3).

Similar decreasing trends were also exhibited by winter rainfall in all the stations, with significant values for Lilabari (30.8 mm decade^{-1}), Mohanbari (21.5 mm decade^{-1}) and Shillongoni (14.4 mm decade^{-1}) (Table 3). This decrease was mainly attributed by the significant decrease of rainfall during the month of February in these stations (Table 3).

Annual rainfall trends

Table 3 indicated strong decreasing trends of annual rainfall in all the locations. However, the decrease was found to be statistically significant at Golaghat (105.1 mm decade^{-1}), Dhubri (637.5 mm decade^{-1}), Kamrup (100.0 mm decade^{-1}) and Tezpur (122.2 mm decade^{-1}) (Table 3).

This was mainly corresponded by the significant decrease of monsoon and post-monsoon rainfall at Dhubri and Kamrup.

From the above study, a decrease in the annual as well as seasonal rainfall was observed in the selected stations of the Brahmaputra valley during the period of study (1986-2015). Mooley *et al.*, (1985) studied the inter-annual variability of all-India summer monsoon rainfall and its association with southern oscillation and sea-surface temperature (SST) for the period of 1871-1978. They reported a significant weakening of the Southern Oscillation and relaxation of the meridional temperature gradient over the Indian Ocean. These were the major factors which inhibited summer monsoon rainfall activity over India.

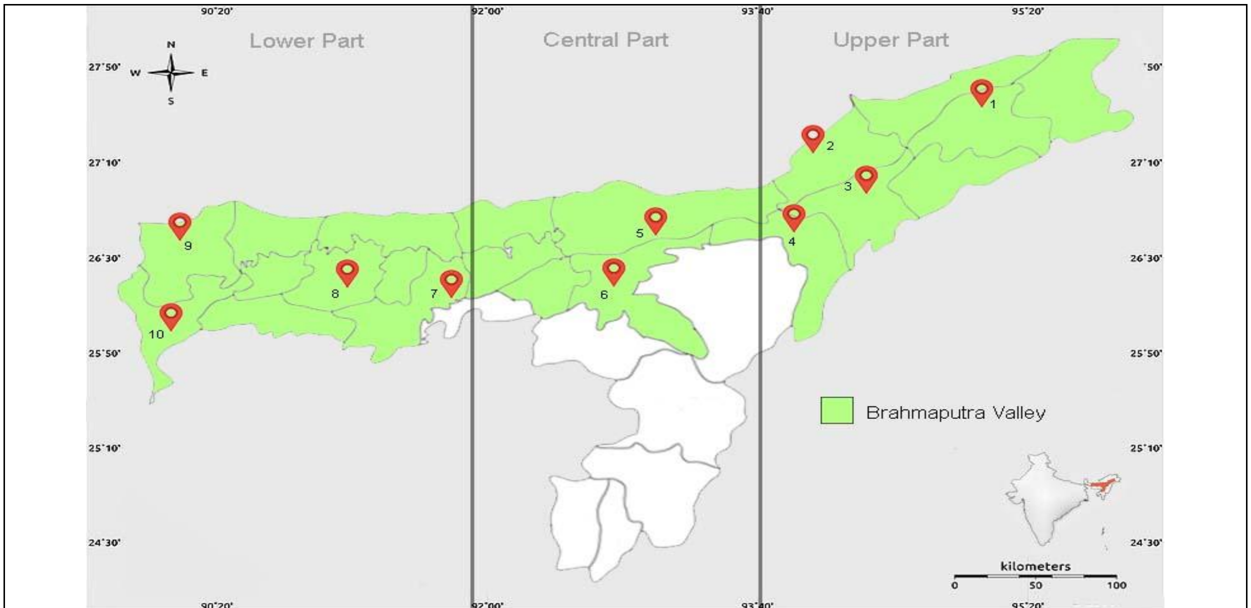

Fig.1 Study area and spatial distribution of selected meteorological stations

Table.1 List of stations considered for the study

Sl no	*Station*	*Location*	*Sl no*	*Station*	*Location*
1	Mohanbari	Upper	6	Shillongoni	Central
2	Lilabari	Upper	7	Kamrup	Lower
3	Jorhat	Upper	8	Beki Rly Bridge	Lower
4	Golaghat	Upper	9	Gossaigaon	Lower
5	Tezpur	Central	10	Dhubri	Lower

Table.2 Station-wise basic statistical characteristics of seasonal and annual rainfall during 1986-2015

Stations	**Pre-monsoon (MAM)**		**Monsoon (JJAS)**		**Post-monsoon (ON)**		**Winter (DJF)**		**Annual**	
	Mean (mm)	CV (%)	Mean (mm)	CV (%)	Mean (mm)	CV (%)	Mean (mm)	CV (%)	Mean (mm)	CV (%)
Jorhat	484.7	27	1151.4	14	133.3	58	63	60	1832.5	14
Golaghat	420.5	25	1045.4	19	134.0	62	53.5	67	1653.5	14
Lilabari	674.5	32	2208.3	16	178.9	60	104.4	53	3166.1	13
Mohanbari	668.1	30	1684.3	17	149.0	46	96.4	46	2597.8	13
Beki	671.2	28	1909.7	17	160.9	53	41.1	89	2782.9	15
Dhubri	597.2	33	1962.8	41	178.6	78	29.3	82	2767.9	32
Kamrup	487.9	31	1072.6	21	140.5	59	36.5	80	1737.5	15
Gossaigaon	692.3	31	2784.0	27	170.2	72	30.4	94	3676.9	22
Shillongoni	394.5	22	1224.5	22	126.8	65	38.5	90	1784.3	19
Tezpur	491.6	23	1142.6	22	123.5	52	41.5	89	1799.2	17

Table.3 Sen's estimator of slope (mm decade^{-1}) of monthly, seasonal and annual rainfall in the Brahmaputra valley during the period 1986-2015

Months/ Seasons	Jorhat	Golaghat	Lilabari	Mohanbari	Beki	Dhubri	Kamrup	Gossaigaon	Shillongoni	Tezpur
January	-2.8	-1.0	-6.3**	-1.0	-1.8	-0.1	-1.3	0	-5.3*	-2.2
February	-5.1	-8.8*	-14.4**	-16.1**	-6.2	-4.0	-5.3**	-0.4	-9.3*	-7.7*
March	0.2	2.0	-7.8	-9.0	-0.3	5.1	-7.0	8.6	0.6	0
April	10.6	2.5	2.7	6.7	30.0	-24.6	-7.4	-7.5	14.4	11.0
May	24.5	3.3	30.9	21.8	7.2	-48.9	2.1	-42.7	-26.9*	-0.1
June	18.0	-19.6	24.8	6.8	-43.3	-69.8	18.5	3.7	-47.0**	-13.8
July	-9.7	-5.9	-55.7	-38.4*	-79.2	-235.5*	-42.4**	-112.1	-51.5	-31.8**
August	23.0**	-10.9	25.5	7.9	-6.0	-83.3	-21.3	-41.6	-25.8**	-34.5
September	-27.7	-23.1	-40.8	-66.1*	-14.0	-110.2*	-17.7	-41.3	-26.4	-20.6
October	-14.6	-23.8	-27.2	-20.3**	-33.8**	-37.4	-9.7	-15.4	-28	-23.5**
November	-4.5**	-5.0**	1.7	-0.4	-0.5	-1.9	-1.4	0	-3.1	-1.6
December	-0.3	0	0.2	-1.0	0.0	0	0	0	0	0.01
Pre monsoon	24.7	4.5	24.3	24.3	34.0	-45.3	-4.3	-52.6	-19.2	16.5
Monsoon	13.4	-87.0	-24.6	-71.1	-115.7**	-570.6*	-37.5	-87.8	-129.3*	-92.2**
Post monsoon	- 23.7**	-25.4	-27.6	-18.0	-32.9**	-40.9**	-11.1	-16.9	-25.6	-23.0
Winter	-9.8	-10.3	-30.8*	-21.5*	-9.8	-6.2	-6.7	-2.0	-14.4*	-8.5
Annual	-9.8	-105.1*	-110.3	-104.6	-138.6	-637.5*	-100.0**	-213.4	-212.1*	-122.2**

* indicates 5% level and ** indicates 10% level of significance as per the M-K rank test

Mooley *et al.,* (1985) also reported that the meridional sea surface temperature (SST) gradient showed a decreasing trend, which ultimately lead to the weakening of the monsoon circulation. Kripalani *et al.,* (2003) reported that the El Niño Southern Oscillation (ENSO) and the Himalayan/Eurasian Snow were two of the external factors which cause extreme events. The warm phase (El Niño) is associated with weakening of the Indian monsoon with overall reduction in rainfall while the cold phase (La Nina) is associated with the strengthening of the Indian monsoon with enhancement of rainfall (Kripalani *et al.,* 2003).

However, during the recent times, it was observed that the relationship of ENSO and Indian monsoon rainfall was weakening, which might be the possible reasons of decreasing frequency of rainfall events in the study area. Sikka (2006) also reported a decrease in the frequency of rain-producing events in the recent decades over the Bay of Bengal. These decreases in monsoon depressions over the Bay of Bengal might play a major role in the decrease in the amount of monsoon rainfall in the Brahmaputra valley during the period of study (1986-2015).

In this study, long term rainfall data of 10 stations over the Brahmaputra valley was analyzed for spatial and temporal trends at monthly, seasonal and annual basis during the period 1986-2015. From the analysis, it was observed that annual rainfall was decreasing for all the locations during the study period. Seasonal analysis showed that pre-monsoon rainfall increased over 6 out of 10 stations.

On the contrary, monsoon, post-monsoon and winter rainfall exhibited decreasing trends over all the stations. These trends and fluctuation of rainfall pattern are not anticipated to create an alarming situation in the study area. However, the amplification of these trends will very likely aggravate the occurrence of frequent and extreme climate events, thus provoking a major threat to agriculture and allied sectors in the near future.

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