

Assessing climatic trends of extreme rainfall indices over northeast Bangladesh

Md. Abul Basher¹ · Mathew Alexander Stiller-Reeve² · A. K. M. Saiful Islam¹ · Scott Bremer²

Received: 16 January 2017 / Accepted: 2 October 2017 / Published online: 7 October 2017
© Springer-Verlag GmbH Austria 2017

Abstract This study analyzes the trends of extreme rainfall indices over northeast Bangladesh for the period of 1984 to 2016 for the pre-monsoon and monsoon seasons. The research was framed as part of a project co-producing knowledge of climate variability and impacts through collaboration between scientific and local communities in northeast Bangladesh, which found pre-monsoon and monsoon rainfall to be most important. With access to a greater number of rainfall stations than previous work in northeast Bangladesh, we investigated trends in extreme rainfall events using the Mann–Kendall trend test and Sen’s slope estimator. To appraise the quality of the data, we used the Standard Normal Homogeneity and the Pettitt tests to check its homogeneity. Among the seven stations, only Sunamganj was found inhomogeneous, and was not considered for trend analysis. All indices of rainfall

extremes showed a decreasing trend in both seasons, with the most significant decrease during the monsoon. Importantly, we saw a decreasing trend in the seasonal total rainfall and consecutive wet days, whereas there was an increasing trend in consecutive dry days. Moreover, we saw a decreasing trend in 1-day maximum rainfall, 5-day maximum rainfall, the intensity of the daily rainfall over 25 mm during the pre-monsoon and 50 mm during monsoon, which together may indicate a future decrease in the magnitude and intensity of flash floods and monsoon floods. If this trend continues, the northeast Bangladesh may suffer from water stress, which could affect the lives and livelihoods of communities living there.

1 Introduction

Global climate change is arguably changing rainfall patterns in different regions of the world, with far-reaching environmental, social, and economic impacts for local communities. One important change can be to the frequency and severity of extreme rainfall events, which can exacerbate risks of climate-related damages in a region. Insofar as rainfall patterns are specific to different regions, any changes to rainfall brought by global climatic change will be similarly specific (Visbeck 2008). For this reason, communities need high-quality scientific information on the particular historic rainfall trends for their region, including rainfall extremes, which they can use to support adaptation to changes in the rainfall; both relative to current climate variability, and future climatic change (Moss et al. 2013). To this end, it is important that scientific investigations are based in local observations of historical climate, rather than global or continental understandings. It is also important that these investigations of rainfall are integrated with local adaptation efforts, to be salient, legitimate, and

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s00704-017-2285-4>) contains supplementary material, which is available to authorized users.

✉ Md. Abul Basher
mbashar725@gmail.com

Mathew Alexander Stiller-Reeve
mathew.reeve@uni.no

A. K. M. Saiful Islam
akmsaifulislam@iwfm.buet.ac.bd

Scott Bremer
Scott.Bremer@uib.no

¹ Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh

² Uni Research Climate, Bjerknes Centre for Climate Research, Bergen, Norway

credible in a particular region (Cash et al. 2003, 2006; Dilling and Lemos 2011).

This study investigates trends of extreme rainfall indices for the period 1984–2016 of northeast Bangladesh. It is motivated by recent research by Stiller-Reeve et al. (2015) that highlights the unique and important pre-monsoon and monsoon rainfall patterns distinguishing northeast Bangladesh, and discusses how local adaptation might be hindered by significant uncertainty about the causes and timing the monsoon onset, in relation to scientific and local understandings. Our study was undertaken as part of the wider Norwegian Research Council-funded TRACKS project (*TRAnsforming Climate Knowledge with and for Society*), which attempts to “co-produce” an improved understanding of climate variability more generally in northeast Bangladesh through active collaboration between scientific and local communities (see, e.g., Bartels et al. 2013; Hegger and Dieperrink 2014 and Meadow et al. 2015). This study of extreme rainfall is novel and important for two main reasons: (i) it is framed by the adaptation priorities of communities in northeast Bangladesh; and (ii) it goes beyond previous studies of Sylhet rainfall by drawing on a greater number of rainfall stations for a more comprehensive understanding of regional rainfall patterns.

The TRACKS project adopts an extended mode of scientific enquiry that facilitates interaction between scientists and Sylhet communities at different phases of the research process, including in (a) framing the research problem, (b) mobilizing and appraising different knowledge systems salient to the problem, and (c) communicating and applying the co-produced research (see a similar approach by Lang et al. 2012). In the framing phase, the project completed 234 qualitative interviews with people from communities in Jamalganj, Sunamganj, Hakaluki Haor, and Barlekha, in November 2014; with these interviews helping to identify the weather phenomena that have the most important impact on communities, and the information they need to adapt to these phenomena. The interviews voiced communities’ need for information on rainfall, storms, and associated flooding as a priority, particularly in the pre-monsoon season. During this time, the region receives more than 900 mm rainfall, which is three times higher than the average rainfall of the whole country (Kripalani et al. 1996). The pre-monsoon rainfall is also characterized by severe local storms known as nor’westers or Kalbaishaki. These storms bring heavy rain, hail, gusty wind, lightning, and sometimes tornadoes (Karmakar and Alam 2006; Yamane et al. 2010; Murata et al. 2011). This severe weather can kill people and livestock, destroy houses, infrastructure, and the Boro rice crops, which is the year’s main harvest in this region (Alam et al. 2010). This research focuses on the pre-monsoon and monsoon rainfall, which has been subsequently validated through further discussions with these communities, most recently in workshops in May 2017. It is this research framing work that has motivated and steered this

study of extreme rainfall indices. It also marks the study as unique, because our focus on the pre-monsoon rainfall is truly guided by our interactions with the local communities in northeast Bangladesh.

Northeast Bangladesh is located in the downstream part of the Meghna river basin. The total catchment area of the Meghna basin is roughly 6500 km² of which only 33% lies in northeast Bangladesh and remaining 67% is within India (Masood and Takeuchi 2016). Previous studies have either considered Bangladesh (Ahmed and Karmakar 1993; Karmakar and Khatun 1995; Rahman et al. 1997) or India (Mirza et al. 1998; Jain et al. 2013; Oza and Kishitawal 2014) separately. These studies often consider trends in seasonal (including pre-monsoon and monsoon) or annual rainfall. The trends vary between positive (Deka et al. 2013; Kumar and Jain 2011) and negative (Das et al. 2015; Kumar et al. 2010; Mirza et al. 1998), depending on the region and the time period analyzed, but none have been statistically significant. Common to these studies covered in Bangladesh, they only use the Sylhet station for analysis. These studies have shown increasing trends for pre-monsoon and decreasing trend for monsoon (Shahid 2011; Kripalani et al. 1996), which is similar to most studies over India. However, total seasonal or annual rainfall is just one rainfall characteristic that can change. Fewer studies have looked at changes of other characteristics. For example, Shahid (2011) found insignificant increase of 1-day maximum rainfall while decrease of 5-day maximum rainfall, consecutive wet day, and consecutive dry day for Sylhet station for the last 60 years (1958–2007). Over the border in India, Prokop and Walanus (2015) found that low-intensity rainfall has decreased and high-intensity rainfall had increased in Cherrapunji, but only during the pre-monsoon. These results imply less, but more intense rainy days over the region. By comparison, the Barak Basin further east seems to have experienced an increase in the number of pre-monsoon rainy days (Kumar and Jain 2011).

Much of the Meghna basin is within India, which make observational data challenging to obtain. This study therefore extends on previous studies of rainfall in northeast Bangladesh. Many of the previous studies on rainfall in northeast Bangladesh have been limited to a single rainfall station: Sylhet. A single rainfall station might not represent the surrounding climate (Wu et al. 2015), as it may be influenced by a particular local climate (Janis and Robeson 2004). This study therefore draws on a wider data observational dataset from the Bangladesh Water Development Board (BWDB) and Bangladesh Meteorological Department (BMD). We analyze the rainfall records from seven stations located across the northeast Bangladesh. We identify trends in seasonal totals as well as seven other rainfall indices depicting different rainfall characteristics. We consider trends in the pre-monsoon and monsoon seasons separately. Rainfall in these seasons can have different convective triggering mechanisms, but

can also impact the lives of the local communities in very different ways.

In Section 2, we describe our methodology, including the indices, homogeneity test, and trend analysis methods. We present and discuss the results in Section 3, before we conclude the paper in Section 4.

2 Materials and method

2.1 Study area

The northeast Bangladesh is located between 24° N to 25° N and 90.62° E to 92.50° E (Fig. 1) which is part of the Meghna river basin. It is situated on the flatlands to the south of the southern slopes of the Meghalaya Plateau, where this plateau is thought to act as a barrier against the southwesterly monsoon (Kataoka and Satomura 2005). This region receives

heavy rainfall during pre-monsoon and monsoon caused by topographic lifting by the Meghalaya Plateau and other mechanisms (e.g., Murata et al. 2008; Terao et al. 2008; Murata et al. 2011; Reeve 2015). The region's climate is characterized by sub-tropical humid conditions with wide seasonal variations (Hasan et al. 2012). From a climatic perspective, the predominant seasons are dry winter (December to February), pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October to November) (Rafiuddin et al. 2010). Because of the large seasonal variations, the weather plays an important role in the socio-economic development and livelihoods of local people, as well as the ecological balance of the region.

This region is known as the “haor region” due to the expansive lakes (or haors) that materialize during the pre-monsoon and into the monsoon season. The biodiversity of the haor region makes it a unique wetland ecosystem. The local geography is mainly low-lying flat land, but is also

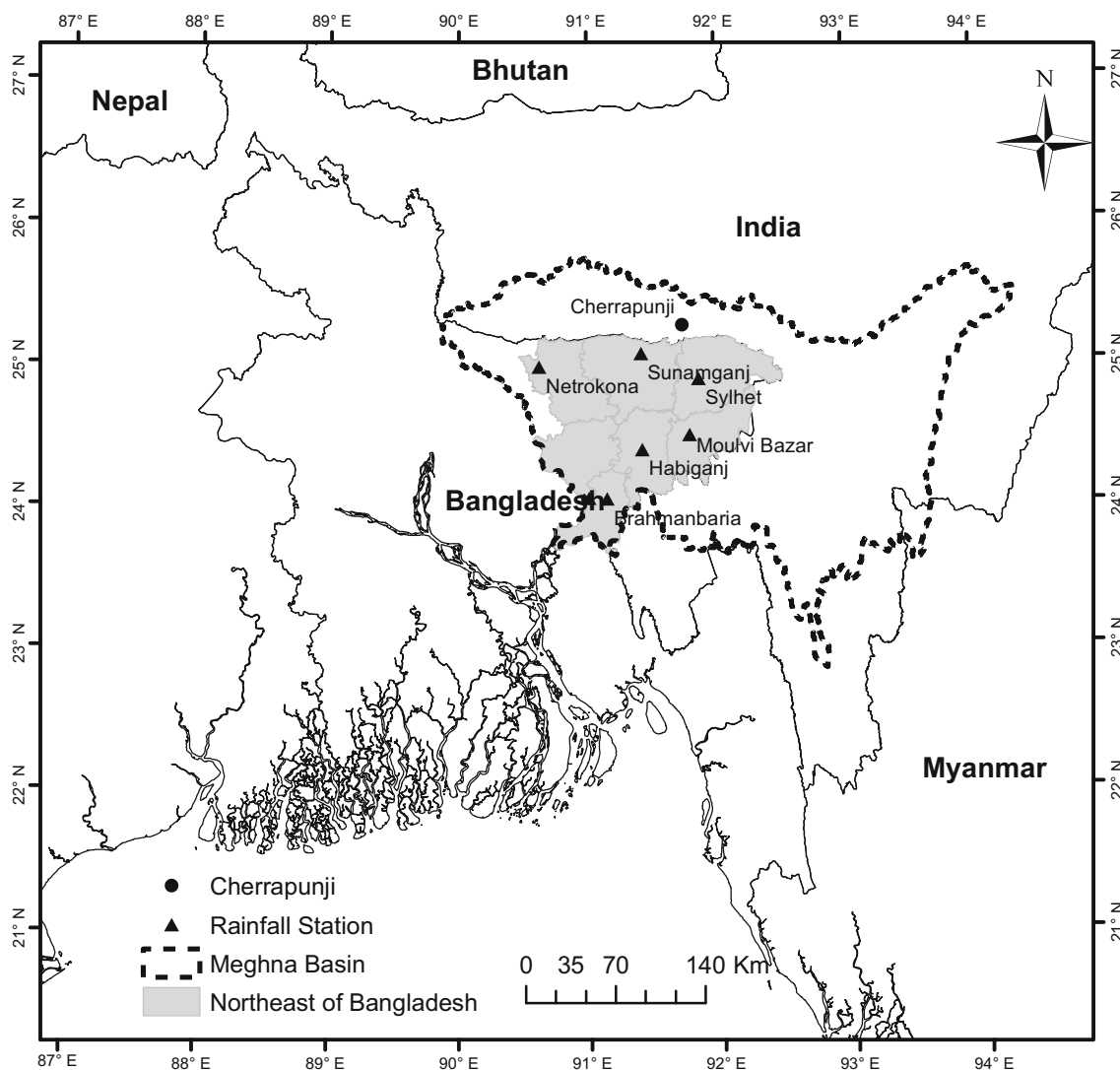


Fig. 1 Location of northeast Bangladesh with rainfall stations

characterized by a number of special topographical features like hills, hillocks, and haors, with vast reserve forests, large tea gardens, and growing rubber gardens. The Boro rice during pre-monsoon accounts for the majority of agricultural output (Alam et al. 2010) which contributes significantly to total rice production of the country. Since this Boro rice is harvested before the large-scale monsoon begins, it is easy to understand why the pre-monsoon rains are so important in the Sylhet Division. We have heard from the locals that if flooding happens early, then the Boro crop can be damaged or destroyed.

The rivers in this region originate from the hills of Shillong and Meghalaya, India. Cherrapunji, widely known as the wettest place on Earth, is situated very close to the study area (Fig. 1). To illustrate the rainfall patterns over this Meghna basin, we present seasonal rainfall totals in Fig. 2 using WFDI (WATCH Forcing Data methodology applied to ERA-Interim) data. It is a meteorological forcing dataset which is produced using land surface and hydrological models based on ERA-Interim data. The mean pre-monsoon and monsoon rainfall of Cherrapunji is about 1700 and 7400 mm. From this figure, we can see that the rainfall pattern over the Indian hills can greatly influence flooding over the low-lying region of northeast Bangladesh. Flash floods resulting from heavy rainfall in the hills can be disastrous this region where crops and property can easily be damaged. We need to keep these impacts in mind since, in this study, we only concentrate on weather stations situated within this low-lying region.

2.2 Data

Our main dataset is comprised of daily rainfall observations from seven weather stations in northeast Bangladesh. Among

the stations, only the Sylhet station is maintained by Bangladesh Meteorological Department (BMD) and others are maintained by Bangladesh Water Development Board (BWDB). In this study, we analyze the observations from the period 1984–2016. Supp. Table 1 shows a list of the observation stations, their names, and their locations (also shown in Fig. 1). As we do not have the access to observed daily rainfall data over Indian weather stations, we used WFDEI for preparing spatial distribution mean seasonal rainfall of the Meghna basin.

2.3 Quality control of data

Before performing trend analysis, the quality of the data must be checked for possible errors. Homogeneity and autocorrelation tests were performed to check the data quality. The reliability of the data series is tested using homogeneity test. This test is used to check if there is any error in data series due to several reason such as station relocations, equipment changes, equipment drifts, and changes in the method of data collection. If the data series is subjected to any kind of error other than climatic factors, the data series is called inhomogeneous. This inhomogeneous data series need to be either adjusted or discarded from further analysis. The homogeneity test can be classified as absolute homogeneity and relative homogeneity (Firat et al. 2010). Data series from different stations are tested individually in absolute homogeneity tests, while they are compared with neighboring reference stations in relative homogeneity tests. But in practice, it is very difficult to find a reference station with a high correlation and a homogeneous structure. Hence, in this study, we applied the absolute homogeneity test to check for reliability of the data series. Within this test category, we chose to use the

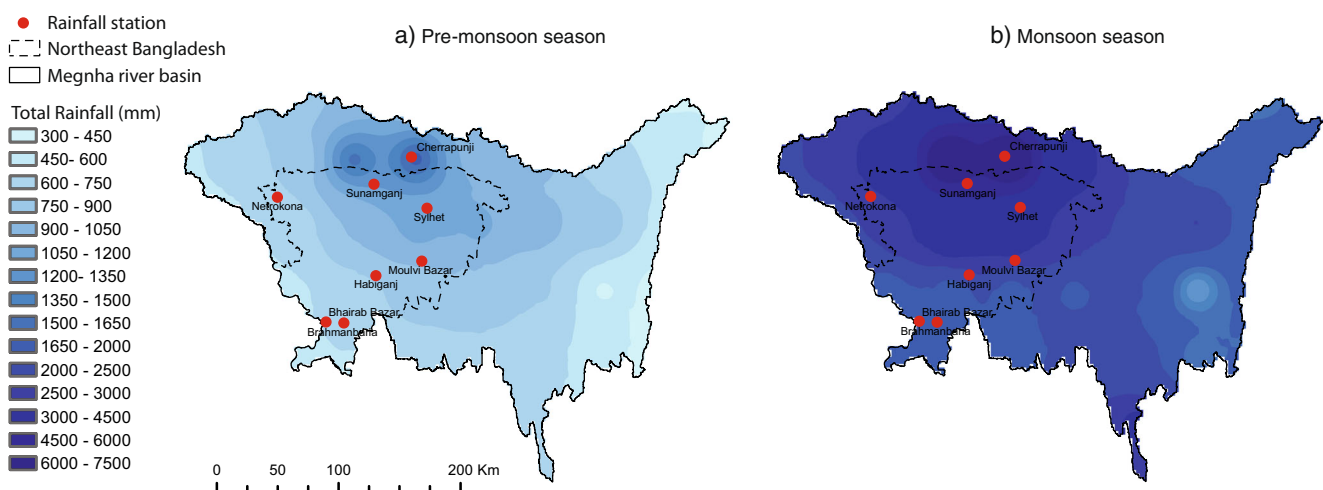


Fig. 2 Distribution of mean rainfall over the Meghna basin using WFDI data. The figure shows the locations of the stations analyzed in this study as well as Cherrapunji across the border in India. Panel **a** shows the mean

rainfall for the pre-monsoon season, whereas panel **b** shows the same for the monsoon season

Standard Normal Homogeneity (Alexandersson 1986) and the Pettitt (1979) tests.

The indices of rainfall extreme obtained from observed data series must be a series of random events in order to get reliable trends from the trend analysis. The autocorrelation is generally performed to check randomness of the data series. If the data series is positively autocorrelated, then it is not a random event and the resulting trend may be not realistic (Mondal et al. 2012). In this study, we performed first-order autocorrelation. The theory of the above mentioned statistical tests is discussed in supplementary materials.

2.4 Selection of extreme rainfall indices

The decision to focus on extreme rainfall indices was guided by the collaborative research-framing phase, as part of the TRACKS project approach to co-produce knowledge of climate variability for adaptation, with communities in northeast Bangladesh. This framing, or co-design, of the research sought to identify those weather phenomena most important to local people, and emerged over several rounds of interaction between scientific project partners and different actors in communities in northeast Bangladesh. This began with a broad scoping meeting in Sylhet city September 2014, bringing together local government officials, representatives of non-governmental organizations, scientists at local universities and research institutes, and other groups such as teachers and journalists. This scoping meeting identified local Sylhet communities that are vulnerable to climate variability and change and led to a second round of interaction; conducting 234 interviews in Sunamganj Sadar, Jamalganj, Barlekha, and Hakaluki Haor in December 2014, with diverse “grassroots” actors. A third round of interaction brought together a subset of those people interviewed in workshops in Sunamganj Sadar and Barlekha in March 2016. Through this interaction, communities were able to make clear the weather information that was most important to support local adaptation efforts, and scientists were in turn able to make clear limitations of the science, and what information it is possible to provide. This interaction also allowed for discussion across different knowledge systems, with climate and meteorological information discussed relative to other local and traditional ways of knowing the weather and seasons, using traditional calendars and natural signs for instance. Framing of this research also drew on the published literature.

These interactions showed us that the local communities are particularly concerned about the pre-monsoon rainfall, particularly its amount and distribution. For instance, heavy rain at this time can cause flash floods that can damage or destroy the year’s main Boro rice crop. This can have a huge economic impact on the local society. Once we understood the importance of rainfall in the pre-monsoon season, we had to split our analysis between both the pre-monsoon and monsoon

seasons. We understand that the onset of the monsoon changes from year-to-year (Stiller-Reeve et al. 2014); however, we apply a static definition of the monsoon and pre-monsoon seasons in order to facilitate comparison with previous studies (e.g., Rahman et al. 1997 and Shahid 2011). In this study, we define the pre-monsoon as the months of March–May and the monsoon as June–September. Next, we had to identify appropriate rainfall indices to analyze. We chose indices (Table 1) that reflect rapid flash floods, wet and dry periods, and seasonal totals. The selection of indices is therefore meant to reflect some of the challenges the local people told us about, but also be comparable to previous and future climate studies.

Through considerable discussion, we selected eight indices of rainfall extremes as also proposed by Frich et al. (2002) and Alexander et al. (2006). These indices are presented in Table 2 with their respective definitions. Both the RX1DAY and RX5DAY represent extremely heavy rainfall; RX1DAY causes flash flooding while RX5DAY is more likely to cause long-term riverine flooding. We learnt through our discussions with the locals that the amount and distribution of PRCPTOT especially during pre-monsoon is very important for Boro rice production, since it influences the water levels in the seasonal haor lakes.

2.5 Trend analysis

The trend of indices of rainfall extremes listed in Table 2 was performed using Mann–Kendall test (Mann 1945; Kendall 1975) and the slope of the trend was determined by Sen’s slope estimator (Sen 1968). The Mann–Kendall test is widely used for trend analysis of rainfall and other climatologic events (Yang et al. 2012; Fu et al. 2013; Zarenistanak et al. 2014; Wu et al. 2015). It is a non-parametric test and is less sensitive to non-homogeneous time series. It can be applied for non-normally distributed data and for the data which contain outliers and non-linear trends (Birsan et al. 2005). According to this test, the null hypothesis H_0 indicates that there is no trend and alternative hypothesis H_1 indicates that there is a trend (Onoz and Bayazit 2012).

Sen’s slope method (Sen 1968) is then applied to estimate the magnitude of the trend. A time series of equally spaced data is required for this method and is not influenced by missing values or gaps in the input data. Supp. Table 1 in the supplementary materials showed location of the rainfall stations and their respective percentage of missing daily rainfall values. Among the rainfall station considered, Sylhet station has less missing values (0.5%) and Netrokona has more missing values (3.9%). There are several methods used for filling missing values of daily rainfall values. The most common methods generally used in filling of the missing data include closest station, simple arithmetic averaging, inverse distance weighting,

Table 1 List of indices of rainfall extremes used for trend analysis and their definition

Index	Descriptive name	Definition	Unit
RX1DAY	Daily maximum rainfall	Seasonal maximum 1-day rainfall	mm
RX5DAY	5-day maximum rainfall	Seasonal maximum 5-day rainfall	mm
R25mm	Frequencies in days	Number of extremely heavy rainfall days ($RR \geq 25$ mm) during pre-monsoon	days
R50mm	Frequencies in days	Number of extremely heavy rainfall days ($RR \geq 100$ mm) during monsoon	days
PRCPTOT	Seasonal total wet day precipitation	Seasonal total precipitation in wet days ($RR \geq 1$ mm)	mm
CWD	Consecutive wet days	Maximum number of consecutive wet days in a season with $RR \geq 1$ mm	days
CDD	Consecutive dry days	Maximum number of consecutive dry days in a season with $RR < 1$ mm	days
SDII	Simple daily intensity index	Seasonal total precipitation divided by the number of wet days in the season	mm/day

multiple regression, and normal ratio (Makhuvha et al. 1997; Xia et al. 2001; Moeletsi et al. 2016). In this study, inverse distance weighting (IDW) method for filling the missing values has been applied as this widely used method is suitable for rainfall stations that are closely spaced and the orographic features of the stations are almost similar to each other (Bennett et al. 2007; Moeletsi et al. 2016). For more information about the theory, please see the supplementary material.

3 Result and discussion

In this section, we firstly describe the rainfall climatology of the northeast Bangladesh according to the new data that we use. Thereafter, we move on to the results from the homogeneity and the autocorrelation tests. We will also discuss how we dealt with the data from one station that proved to be inhomogeneous. In the final sub-section, we present the results from the trend analysis.

3.1 Spatial distribution of annual and seasonal rainfall

For the seven stations combined, the mean annual, monsoon, and pre-monsoon rainfall of the study area was 3232, 1765, and 780 mm respectively. The spatial distribution of annual mean rainfall (Fig. 3) shows that the north receives higher rainfall than the south. The same pattern emerges throughout the year, where the mean annual rainfall ranges from 6000 mm along in the north to 2000 mm in the south (Fig. 3c). The mean monsoon and pre-monsoon rainfall increases respectively from 1000 to 3700 mm, and from 590 to 950 mm between the north and south of the northeast Bangladesh (Fig. 3a, b). The mean annual, monsoon, and pre-monsoon rainfall of Sunamganj was higher than other stations. This is understandable due to the station's close proximity to the Meghalaya foothills and Cherrapunji, India the wettest weather station in the world.

The long-term variation of annual, pre-monsoon, and monsoon rainfall for each station is presented as a Box-and-Whisker plot in Fig. 4. The variability of rainfall is high in Sunamganj for the pre-monsoon as well as monsoon seasons.

Table 2 The first-order autocorrelation coefficient for the indices of rainfall extreme for seven stations of north-east region of Bangladesh for the period of 1984 to 2016

	Station	RX1	RX5	R25	PRCPTOT	CWD	CDD	SDII
Pre- monsoon	Sylhet	-0.02	-0.10	-0.15	-0.30	-0.08	-0.05	0.06
	Habiganj	0.10	0.03	-0.19	0.00	-0.13	-0.19	-0.01
	Moulvi Bazar	0.18	0.15	-0.10	0.05	-0.06	-0.28	0.10
	Netrokona	0.17	0.21	0.05	0.15	-0.13	0.17	0.24
	Brahmanbaria	-0.17	-0.09	-0.17	-0.13	-0.11	0.00	-0.30
	Bhairab Bazar	-0.01	-0.01	0.06	0.00	-0.10	-0.33	0.14
Monsoon	Sylhet	-0.02	0.00	-0.27	-0.19	0.22	-0.17	-0.02
	Habiganj	-0.14	0.16	-0.32	-0.29	-0.03	-0.07	-0.21
	Moulvi Bazar	-0.10	-0.27	-0.10	-0.11	-0.22	-0.22	0.01
	Netrokona	0.22	-0.07	0.18	0.09	0.16	0.10	0.03
	Brahmanbaria	-0.09	-0.17	-0.24	-0.23	0.10	0.14	-0.15
	Bhairab Bazar	-0.11	0.10	0.03	0.08	0.04	-0.24	-0.06

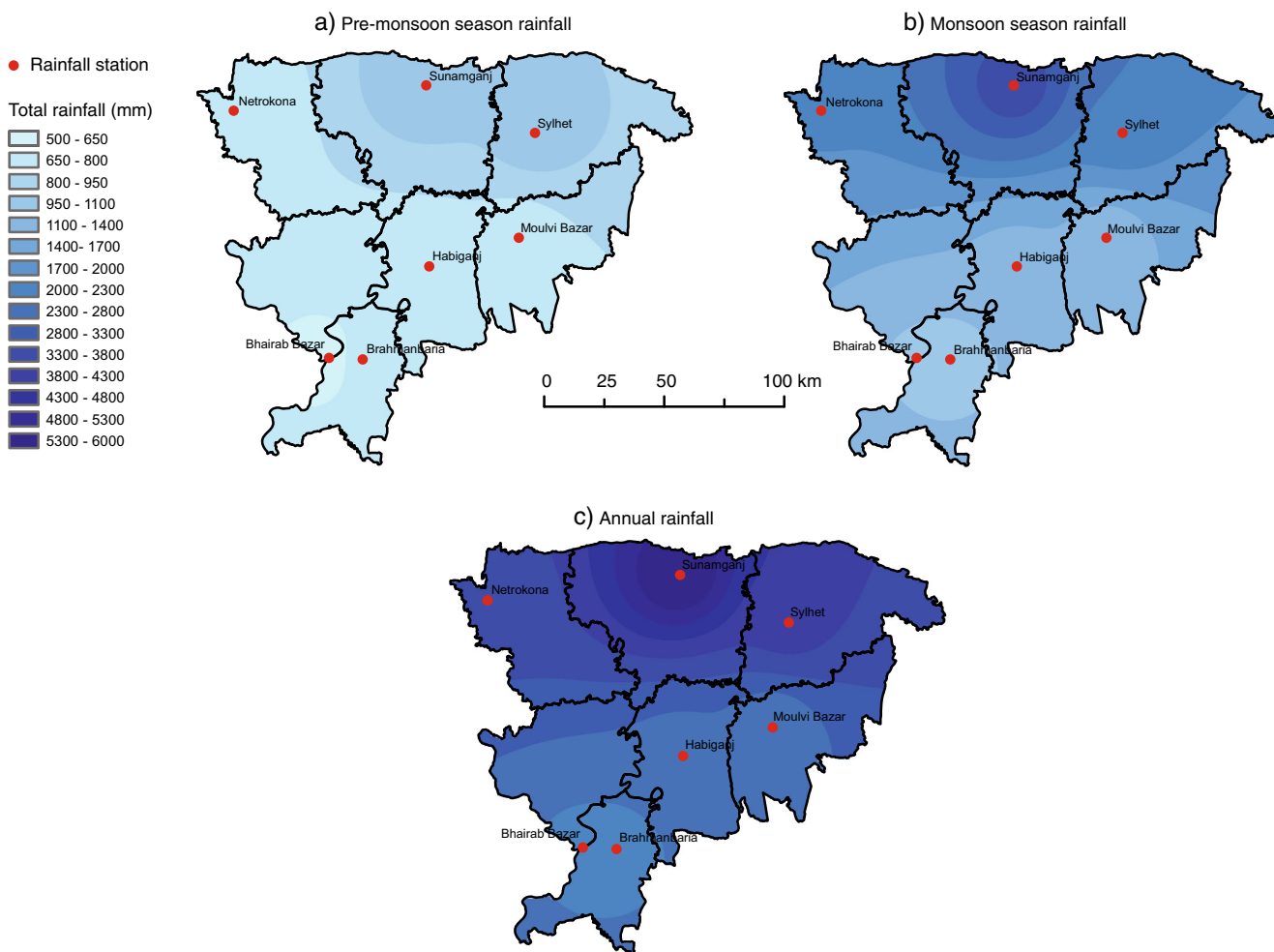


Fig. 3 Spatial distribution of mean rainfall (mm) of the study area for **a** pre-monsoon, **b** monsoon, and **c** annual

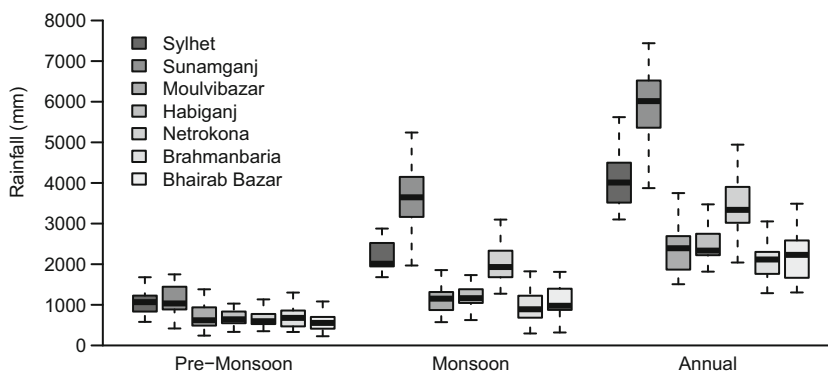
Other stations showed much lower inter-annual variability. These results show how detailed the local meteorology of the northeast region can be varied.

3.2 Quality control of the data

The trend of test statistics for Sunamganj station is not analogous to other stations (Fig. 5). The test statistics for most of the stations decreased from 1992 to 2000 and remained below the

critical line while the Sunamganj test statistic remained above the critical line for the same period. For the data sets to be considered homogeneous, the test needs to give a “test statistic” below a critical value. The critical values are taken from Khaliq and Ouarda (2007) for SNHT and Pettitt (1979) for Pettitt test. The maximum values of test statistics for annual rainfall for all seven stations except Sunamganj stayed below the critical value for the 95% confidence level. Since the null hypothesis for the SNHT as well as Pettitt test were accepted at

Fig. 4 The Box-and-Whisker plot of spatiotemporal variation of rainfall of northeast Bangladesh for the period of 1984 to 2016



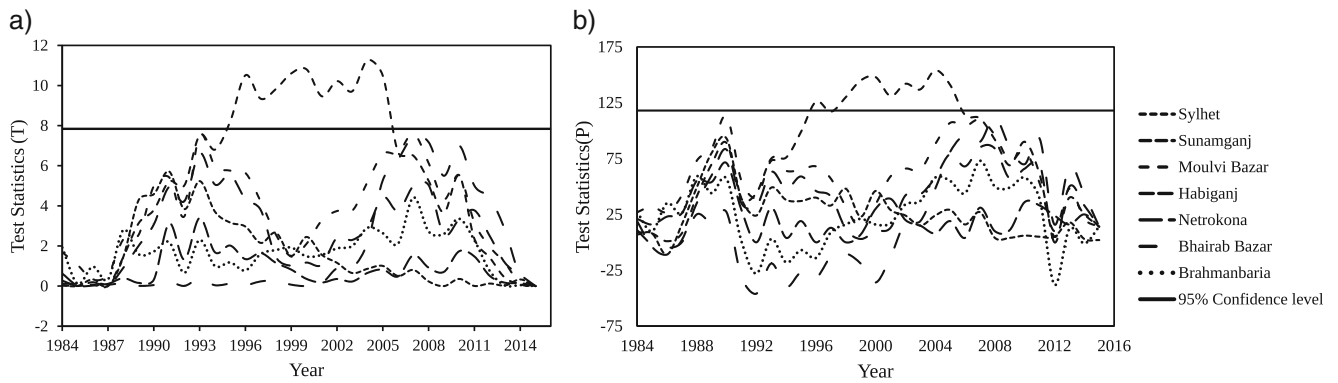


Fig. 5 The test statistics of homogeneity test for annual rainfall for seven stations of northeast of Bangladesh for the period of 1984 to 2016. **a** SNHT test. **b** Pettitt test

95% confidence level, these stations were considered as homogeneous at this confidence level. Whereas, the rainfall of Sunamganj station was said to be inhomogeneous and the null hypothesis was rejected.

Before we took a decision about whether or not to discard the Sunamganj data, we attempted to find out what was wrong with the data set. We started by trying to identify any change points in the time series using Student *t* test at 95% confidence level. It is found that the trend in the Sunamganj data changed at 2005 (Supp. Fig. 1). The field office who is responsible for data collection confirmed us that there were irregularities in the data collection for some years before 2005. The comparison of de-trending annual rainfall of Sunamganj with the nearest and meteorologically similar station of Sylhet also justified the argument of field office (Supp. Fig. 1). We found that the de-trending annual rainfall pattern of these two stations are similar before 1998 and after 2005 which is not the case in between 1998 and 2005.

The interval of autocorrelation coefficient at 95% confidence limit depends on sample size and the order of lag. In our study, the sample size is 33 and hence, for two-sided test, the interval of autocorrelation coefficient at 95% confidence limit is -0.37 to 0.31 . The lag 1 autocorrelation coefficient of indices of rainfall extreme for pre-monsoon and monsoon season were within the range of 95% confidence limit which

means that the indices were not autocorrelated either random event (Table 2).

3.3 Trend of indices of rainfall extremes

The trend analysis was performed on those stations which passed the quality control tests. All the stations passed the autocorrelation test while the Sunamganj station failed to pass homogeneity test. Hence, the Sunamganj station was not considered for trend analysis. The trend of extreme indices for pre-monsoon and monsoon season are discussed separately in the following sections.

3.3.1 Pre-monsoon season

We observed decreasing trends of 1-day maximum rainfall (RX1) for all stations except Sylhet and the 5-day maximum rainfall (RX5) for all stations (Fig. 6a). However, none of the stations showed significant change of these two indices at the 95% confidence level. The largest decreases of RX1 (1.17 mm/year) and RX5 (2.0 mm/year) was at Moulvi Bazar (Table 3). The R25, PRCPTOT, and SDII also decreased in most of the stations but not statistically significantly anywhere (Fig. 6a). The largest decreases of R25, PRCPTOT, and SDII was 0.1 days/year at Habiganj, 7.64 mm/year at

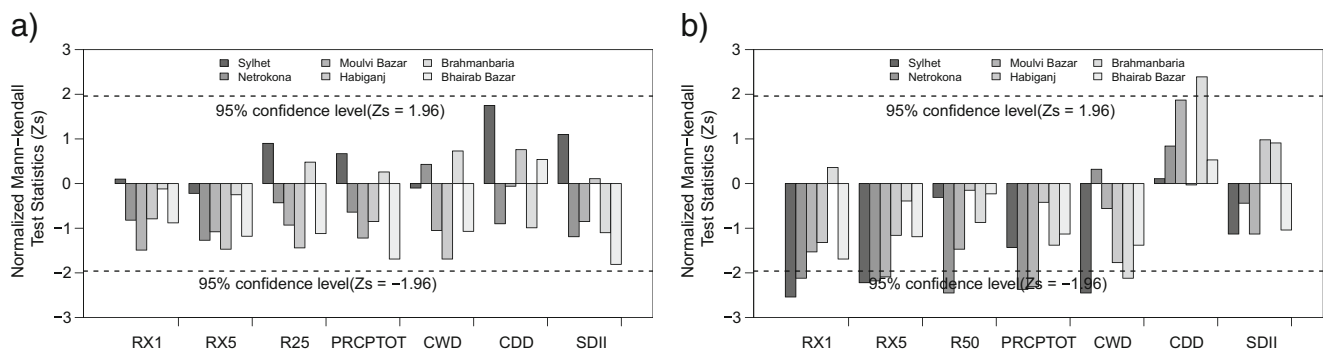


Fig. 6 The normalized test statistic (*Zs*) for the Mann–Kendall test of the indices of rainfall extremes of six stations of northeast Bangladesh for the period of 1984 to 2016: **a** pre-monsoon and **b** monsoon. The absolute *Zs*

value which are greater than critical value ($Z_c = 1.96$) are considered as statistically significant at 95% confidence level

Moulvi Bazar, and 0.24 mm/day/year at Bhairab Bazar respectively (Table 3). The CWD of most of the stations showed a decreasing trend, and the CDD of most of the stations showed an increasing trend. However, these indices were not statistically significantly at any of the stations.

3.3.2 Monsoon season

The RX1 at most of the stations exhibited downward trends in which Sylhet and Netrokona decreased statistically significantly at 95% confidence level (Fig. 6b). The RX1 decreased at rate of 2.76 mm/year at Sylhet and 1.90 mm/year at Netrokona (Table 3). The RX5 decreased at all stations in which it decreased significantly at Sylhet, Netrokona, and Moulvi Bazar. The decreasing rates of these three stations are 4.0, 3.43, and 3.33 mm/year respectively. The PRCPTOT also demonstrated falling trends at every station, in which it decreased significantly at Netrokona and Moulvi Bazar stations at the rate of 25.35 and 17.02 mm/year respectively. At all stations, the R50 showed decreasing trend in which one station decreased significantly. The trend of CWD and CDD during monsoon season had almost similar trend like pre-monsoon season where most of the station showed negative trend for CWD and positive trend of CDD. The CWD decreased significantly at Sylhet and Brahmanbaria at the rate of 0.33 and 0.14 days/year respectively. The CDD increased significantly at Brahmanbaria only at the rate of 0.2 days/year. Among six stations, the SDII showed falling trend at four stations while rising trend at two stations. However, none of them were statistically significant.

Several of the stations show decreasing (but not significant) trends in total pre-monsoon rainfall, which agrees with previous studies (e.g., Shahid 2011 and Deka et al. 2013). Overall, the pre-monsoon climate does not seem to be changing very rapidly since we observed no significant trends for any rainfall index during this season. With regards to the monsoon season, previous studies have concluded that long-term monsoon rainfall over the Assam and Meghalaya state of India have decreased, but not significantly (Naidu et al. 2009; Kumar et al. 2010; Kumar and Jain 2011; Deka et al. 2013 and Sinha et al. 2015). Our results show that the monsoon seasonal rainfall has decreased in all stations, most significantly at Netrokona. We also see significantly decreasing trends in RX1 and RX5 at the same station, including Sylhet. These results do not align with the narrative that total rainfall can decrease, but extremes can increase. Overall, the results vary for index to index and station to station. This shows how local the climate can be even in a relatively small region like northeast Bangladesh.

Being located in the downstream part of the Meghna Basin, northeast Bangladesh receives a large portion of water from the adjoining part of India. As we did not have access to observed rainfall data from India, we identified trends using observed data from Bangladesh only. Our trend analysis can therefore not directly indicate any changes in flash flood, riverine flood, or drought occurrence over the entire basin.

4 Conclusion

In this study, we analyzed trends of rainfall extremes of northeast Bangladesh for the period of 1984 to 2016 for the pre-

Table 3 The Sen's slope estimator (Q) for indices of rainfall extremes for six stations of north-east region of Bangladesh for the period of 1984 to 2016 for monsoon. The slope which is significant is in italics

	Station	RX1 (mm/year)	RX5 (mm/year)	R25/R50 (days/year)	PRCPTOT (mm/year)	CWD (days/year)	CDD (days/year)	SDII (mm/day/year)
Pre-monsoon	Sylhet	0.06	-0.36	0.09	4.32	-0.02	0.17	0.15
	Netrokona	-0.69	-1.91	-0.02	-2.74	0.04	-0.16	-0.12
	Moulvi Bazar	-1.17	-2	-0.09	-7.64	-0.03	-0.03	-0.17
	Habiganj	-0.64	-1.57	-0.1	-2.98	-0.04	0.13	0.01
	Brahman Baria	-0.17	-0.27	0.05	1.62	-0.09	-0.19	-0.12
	Bhairab Bazar	-0.74	-1.59	-0.07	-6.85	-0.01	0.1	-0.24
Monsoon	Sylhet	-2.76	-4.00	-0.02	-13.61	-0.33	-0.03	-0.11
	Netrokona	-1.90	-3.43	-0.25	-25.35	0.04	0.05	-0.13
	Moulvi Bazar	-1.82	-3.33	-0.11	-17.02	-0.08	0.09	-0.09
	Habiganj	-1.03	-1.95	-0.09	-3.79	-0.11	-0.01	0.10
	Brahman Baria	0.25	-0.76	-0.04	-10.93	-0.14	0.20	0.10
	Bhairab Bazar	-1.19	-2.54	0.02	-12.02	-0.06	0.03	-0.15

monsoon and monsoon seasons. This research was designed and framed through collaboration between scientific and local communities in northeast Bangladesh, as part of a wider effort to co-produced research into climate variability and impacts in that area. From this point of departure, the daily rainfall data of seven stations, representing the seven administrative districts of this region, were used for this study. The trend analysis considered a number of different indices of rainfall extremes, and was performed using the Mann–Kendall trend test and Sen's slope estimator.

Before applying the trend test, the Standard Normal Homogeneity Test (SNHT) and the Pettitt test was applied to check homogeneity of the data. The randomness of the index of rainfall extremes were checked using an autocorrelation test. Among the seven stations, all stations were found to be homogeneous except Sunamganj, which was found to be inhomogeneous, and all the stations passed the correlation test meaning the index of rainfall extremes resulted from random events. Using change point analysis, comparing de-trending annual rainfall with nearby station and information from field office, we identified that there were irregularities in data from the Sunamganj station from 1998 to 2005, which caused inhomogeneity of rainfall data of that station. Hence, the Sunamganj station was not considered for the trend analysis.

In general, all the indices of rainfall extremes showed a decreasing trend in both seasons over the region with most of them were decreased significantly during monsoon. The most important finding is that over this region, the seasonal total rainfall and the consecutive wet day exhibited a decreasing trend, whereas consecutive dry days saw an increasing trend. One the other hand, the decreasing trend of 1-day maximum rainfall, 5-day maximum rainfall, the intensity of the daily rainfall over 25 mm during the pre-monsoon, and 50 mm during monsoon indicate a decrease in the magnitude and intensity of rainfall, with implications for seasonal and flash floods. While these trends were observable over most stations, the trends were not always found to be statistically significant, demanding continued research into rainfall extremes in the future.

The findings of this study are being fed back into the process of co-producing knowledge with communities in northeast Bangladesh, exploring the impacts of reduced rainfall on the lives and livelihoods of vulnerable groups in these communities. In the workshops in March 2016, and again in workshops in May 2017, communities appraise these scientific findings, combine them with their own understandings of the weather and seasons, and look at how this information can support various adaptation strategies. Indeed, these findings corroborate the experience of local people who, in interviews in 2014, voiced a concern about a reduced water supply in the pre-monsoon and monsoon seasons (Bremer et al. 2017). Another important facet to this co-productive scientific research is engaging community actors in the hands-on

measurement and observation of rainfall. We have supplied certain actors in Sunamganj, Jamalganj, Barlekha, and Hakaluki Haor with rain gauges and training in recording rain readings, and schools with weather stations, and we are recording these rainfall readings on an open-access website from 2016 to 2018. In this way, local communities are learning more about rainfall in their region, and perhaps one day their observations can be compared with government measuring stations for insights into rainfall in the region.

If these decreasing trends in rainfall continue into the future, the north-east region of the country may suffer from significant water stress. While extreme flooding can be harmful for these communities, they have learned to live with the phases of “normal” flooding. For example, the reduction of pre-monsoon rainfall and increase of consecutive dry days could affect Boro rice production. Likewise, flooding brings a significant amount of coarse sand, stone, and boulders from the surrounding mountains, with the harvesting of this valuable resource employing many people. Similarly, the monsoon floods are necessary for fertilizing the paddy field and replenishing fish stocks in the haor. Hence, the findings from this study together with future climate projection from climate model will be helpful for future planning and management of water resources of the region.

Acknowledgements This study has been funded by TRACKS (*Transforming Climate Knowledge with and for Society: mobilizing knowledge on climate variability with communities in northeast Bangladesh*) project sponsored by the Research Council of Norway.

References

- Ahmed R, Karmakar S (1993) Arrival and withdrawal dates of the summer monsoon in Bangladesh. *Int J Climatol* 13(7):727–740
- Alexandersson H (1986) A homogeneity test applied to precipitation data. *J Climatol* 6:661–675
- Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein TAMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A (2006) Global observed changes in daily climate extremes of temperature and precipitation. *Geophys Res : Atmos* 111(D5)
- Alam MS, Quayum MA, Islam MA (2010) Crop production in the haor areas of Bangladesh: insights from farm level survey. *Agriculturists* 8(2):88–97
- Bartels WL, Furman CA, Diehl DC, Royce FS, Dourte DR, Ortiz BV et al (2013) Warming up to climate change: a participatory approach to engaging with agricultural stakeholders in the Southeast US. *Reg Environ Chang* 13:S45–S55
- Bennett ND, Newham LT, Croke BF, Jakeman AJ (2007) Patching and disaccumulation of rainfall data for hydrological modelling. In *Int. Congress on Modelling and Simulation (MODSIM 2007)*, Modelling and Simulation Society of Australia and New Zealand Inc., pp. 2520–2526
- Birsan M, Molnar P, Burlando P, Pfaundler M (2005) Stream flow trends in Switzerland. *J Hydrol* 314:312–329 2005
- Bremer S, Blanchard A., Mammun N, Stiller-Reeve M, Haque MM and Tvinnereim E (2017) Narrative as a method for eliciting tacit

- knowledge of local climate variability in Bangladesh. Sustainability Science. Under review
- Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, Guston DH et al (2003) Knowledge systems for sustainable development. *Proc Natl Acad Sci* 100(14):8086–8091
- Cash DW, Borck JC, Patt AG (2006) Countering the loading-dock approach to linking science and decision making: comparative analysis of El Niño/Southern oscillation (ENSO) forecasting systems. *Sci Technol Hum Values* 31(4):465–494
- Deka RL, Mahanta C, Pathak H, Nath KK, Das S (2013) Trends and fluctuations of rainfall regime in the Brahmaputra and Barak basins of Assam, India. *Theor Appl Climatol* 114(1–2):61–71
- Das S, Tomar CS, Saha D, Shaw SO, Singh C (2015) Trends in rainfall pattern over north-east India during 1961–2010. *Int J Earth Atmos Sci* 2:37–48
- Dilling L, Lemos MC (2011) Creating usable science: opportunities and constraints for climate knowledge use and their implications for science policy. *Glob Environ Chang* 21(2):680–689
- Firat M, Dikabas F, Koc AC, Gungor M (2010) Missing data analysis and homogeneity test for Turkish precipitation series. *Indian. Acad Sci* 35(6):707–720
- Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein TAM, Peterson T (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. *Clim Res* 19(3):193–212
- Fu G, Yu J, Yu X, Ouyang R, Zhang Y, Wang P, Liu W, Min L (2013) Temporal variation of extreme rainfall events in China, 1961–2009. *J Hydrol* 487:48–59
- Hasan GMJ, Alam R, Islam QN, Hossain MS (2012) Frequency structure of major rainfall events in the north-east part of Bangladesh. *J Eng Sci Technol* 6(2012):690–700
- Hegger D, Dieperrink C (2014) Toward successful joint knowledge production for climate change adaptation: lessons from six regional projects in the Netherlands. *Ecol Soc* 18(2):34
- Janis MJ, Robeson SM (2004) Determining the spatial representativeness of air-temperature records using variogram-nugget time series. *Phys Geogr* 25(6):513–530
- Jain SK, Kumar V, Saharia M (2013) Analysis of rainfall and temperature trends in northeast India. *Int J Climatol* 33(4):968–978
- Karmakar S, Khatun A (1995) Variability and probabilistic estimates of rainfall extremes in Bangladesh during the southwest monsoon season. *Mausam* 46(1):47–56
- Karmakar S, Alam MM (2006) Instability of the troposphere associated with thunderstorms/nor'westers over Bangladesh during the premonsoon season. *Mausam* 57:629–638
- Kataoka A, Satomura T (2005) Numerical simulation on the diurnal variation of precipitation over northeastern Bangladesh: a case study of an active period 14–21 June 1995. *Sola* 1:205–208
- Kendall MG (1975) Rank Correlation Methods. Griffin, London
- Khaliq MN, Ouarda TBMJ (2007) Short communication on the critical values of the standard normal homogeneity test (SNHT). *Int J Climatol* 27:681–687 (2007)
- Kripalani RH, Inamdar S, Sontakke NA (1996) Rainfall variability over Bangladesh and Nepal: Comparison
- Lang DJ, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P et al (2012) Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustain Sci* 7:25–43
- Kumar V, Jain SK, Singh Y (2010) Analysis of long-term rainfall trends in India. *Hydrol Sci J–J Sci Hydrol* 55(4):484–496
- Kumar V, Jain SK (2011) Trends in rainfall amount and number of rainy days in river basins of India (1951–2004). *Hydrol Res* 42(4):290–306
- Makhuvha T, Pegram G, Sparks R, Zucchini W (1997) Patching rainfall data using regression methods: 1. Best subset selection, EM and pseudo-EM methods. *Theory J Hydrol* 198(1–4):289–307. [https://doi.org/10.1016/s0022-1694\(96\)03285-4](https://doi.org/10.1016/s0022-1694(96)03285-4)
- Mann HB (1945) Nonparametric tests against trend. *Econometrics* 13: 245–259
- Masood M, Takeuchi K (2016) Climate change impacts and its implications on future water resource management in the Meghna Basin. *Futures* 78:1–8
- Meadow AM, Ferguson DB, Guido Z, Horangic A, Owen G (2015) Moving toward the deliberate coproduction of climate science knowledge. *Weather Climate Soc* 7(2):179–191
- Moeletsi ME, Shabalala ZP, De Nysschen G, Walker S (2016) Evaluation of an inverse distance weighting method for patching daily and dekadal rainfall over the Free State Province, South Africa. *Water SA* 42(3):466–474
- Mondal A, Kundu S, Mukhopadhyay A (2012) Rainfall trend analysis by Mann-Kendall test: a case study of north-eastern part of cuttack district, Orissa. *Int J Geol Earth Environ Sci* 2(1)
- Moss RH, Meehl GA, Lemos MC, Smith JB, Arnold JR, Arnott JC et al (2013) Hell and high water: practice-relevant adaptation science. *Science* 8:753
- Mirza MQ, Warrick RA, Ericksen NJ, Kenny GJ (1998) Trends and persistence in precipitation in the Ganges, Brahmaputra and Meghna river basins. *Hydrol Sci J* 43(6):845–858
- Murata F, Terao T, Hayashi T, Asada H, Matsumoto J (2008) Relationship between atmospheric conditions at Dhaka, Bangladesh, and rainfall at Cherrapunjee, India. *Nat Hazards* 44(3):399–410
- Murata F, Terao T, Kiguchi M, Fukushima A, Takahashi K, Hayashi T, Habib A, Bhuyian SH, Choudhury SA (2011) Daytime thermodynamic and airflow structures over northeast Bangladesh during the pre-monsoon season: a case study on 25 April 2010
- Naidu CV, Durgalakshmi K, Muni KK, Ramalingeswara RS., Satyanarayana GC, Lakshminarayana P, Malleswara RL (2009) Is summer monsoon rainfall decreasing over India in the global warming era?. *J Geophys Res : Atmos* 114(D24)
- Onoz B, Bayazit M (2012) The power of statistical tests for trend detection. *Turk J Eng Environ Sci* 27:247–251
- Oza M, Kishitawal CM. (2014) Trends in rainfall and temperature patterns over north east India. *Earth Sci India* 7
- Pettitt AN (1979) A non-parametric approach to the change-point detection. *Appl Stat* 28:126–135
- Prokop P, Walanus A (2015) Variation in the orographic extreme rain events over the Meghalaya Hills in northeast India in the two halves of the twentieth century. *Theor Appl Climatol* 121(1–2): 389–399
- Rafiuiddin M, Uyeda H, Islam MN (2010) Characteristics of monsoon precipitation systems in and around Bangladesh. *Int J Climatol* 30(7):1042–1055
- Rahman MR, Salehin M, Matsumoto J (1997) Trends of monsoon rainfall pattern in Bangladesh. *Bangladesh J Water Resour* 14-18:121–138
- Reeve MA (2015) Monsoon onset in Bangladesh: reconciling scientific and societal perspectives. PhD thesis, University of Bergen, Norway
- Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. *J Am Stat Assoc* 63:1379–1389
- Shahid S (2011) Trends in extreme rainfall events of Bangladesh. *Theor Appl Climatol* 104(3–4):489–499
- Sinha A, Kathayat G, Cheng H, Breitenbach SF, Berkelhammer M, Mudelsee M, Biswas J, Edwards RL (2015) Trends and oscillations in the Indian summer monsoon rainfall over the last two millennia. *Nat Commun* 6
- Stiller-Reeve MA, Syed MA, Spengler T, Spinney JA, Hossain R (2015) Complementing scientific monsoon definitions with social perception in Bangladesh. *Bull Am Meteorol Soc* 2015 Jan 96(1):49–57
- Stiller-Reeve MA, Spengler T, Chu PS (2014) Testing a flexible method to reduce false monsoon onsets. *PloS One* 9(8):e104386
- Terao T, Islam MN, Murata F, Hayashi T (2008) High temporal and spatial resolution observations of meso-scale features of pre-and

- mature summer monsoon cloud systems over Bangladesh. *Nat Hazards* 44(3):341–351
- Visbeck M (2008) From climate assessment to climate services. *Nat Geosci* 1(2–3):2–3
- Wu X, Wang Z, Zhou X, Lai C, Lin W, Chen X (2015) Observed changes in precipitation extremes across 11 basins in China during 1961–2013. *Int J Climatol*. <https://doi.org/10.1002/joc.4524>
- Xia Y, Fabian P, Winterhalter M, Zhao M (2001) Forest climatology: estimation and use of daily climatological data for Bavaria, Germany. *Agric For Meteorol* 106(2):87–103
- Yamane Y, Hayashi T, Dewan AM, Akter F (2010) Severe local convective storms in Bangladesh: Part II.: Environmental conditions. *Atmos Res* 95(4):407–418
- Yang L, Villarini G, Smith JA, Tian F, Hu H (2012) Changes in seasonal maximum daily precipitation in China over the period 1961–2006. *Int J Climatol* 33:1646–1657. <https://doi.org/10.1002/joc.3539>
- Zarenistanak M, Dhorde AG, Kripalani RH (2014) Trend analysis and change point detection of annual and seasonal precipitation and temperature series over southwest Iran. *Journal of Earth System. Science* 123(2):281–295