Long-Term Trend of the All-Bangladesh Summer Monsoon Rainfall, and its Association with the ENSO Index

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Abstract
Rainfall data for the summer monsoon season (May through October) at 15 weather stations in Bangladesh, for the 60 year period from 1951 to 2010, and ENSO Index data coinciding with the summer monsoon season for the corresponding years were analyzed in order to determine the long-term trends of summer monsoon rainfall and ENSO Index, and association between them. In this study, summer monsoon rainfall in Bangladesh has been expressed as "All-Bangladesh" summer monsoon rainfall, which is an aggregate of the average rainfall at 15 weather stations for the months of June through October, in each year of the 1951-2010 period. Results indicate (a) a very slow increasing trend of All-Bangladesh summer monsoon rainfall, at a rate of 0.2073 mm per year over the 60-year period from 1951 to 2010, (b) a very slow decreasing rate of ENSO Index at a rate of –0.027 per year over the same period, and (c) there is no relationship between All-Bangladesh summer monsoon rainfall and ENSO Index during the same period.
Keywords: All-Bangladesh summer monsoon rainfall; summer monsoon rainfall trend; ENSO Index trend; association between All-Bangladesh summer monsoon rainfall and ENSO Index).

1. INTRODUCTION

The rainy season in Bangladesh coincides with the summer monsoon season (June through October). This season affects the agricultural activities, river drainage system and hydrological parameters in the country (Johnson 1982, Ahmed and Karmakar 1993, Ahmed and Kim, 2004, Shamsuddin and Alam 2015). Summer monsoon season (June through October) accounts for 75-80 per cent of the annual rainfall of the country. Moreover, several floods occur every year in this season (Johnson 1982, Ahmed 1989, Ahmed and Karmakar 1993, Ahmed and Kim 2004), resulting in extensive damage to crops, livestock, life and property. Some of the flood events reach catastrophic situations, such as those of 1987 and 1988 (Brammer 1990), 1998 (GoB Report 2002), and 2007 (BBC 2007) requiring large scale international relief efforts.

There is a large body of literature on the summer monsoon in South Asia, some of which are in the form of scholarly books (e.g. Ramage 1971, Das 1986, Chang and Krishnamurti, 1987, Fein and Stephens, 1987). However, most of these studies were centered on the India Sea and Arabian Sea.

Studies on summer monsoon in Bangladesh are relatively few. Physiographic landscape that led to the extensive floods that occurred in the country in 1987 and 1988 were presented by Brammer (1990). Various dimensions of the 1998 severe floods in Bangladesh were discussed in a Government Report (GoB Report 2002). It was found in a study that large-scale meteorological phenomena such as pressure tendency at Darwin, Australia, sub-tropical ridge and northern hemisphere surface temperatures do not have any effect on the inter-annual rainfall variability over Bangladesh (Kripalini *et al* 1996). A Regional Model-Based study showed that the Model underestimate summer monsoon rainfall in Bangladesh compared to observed data (Rahman *et al* 2007). Another study showed no trend in the summer monsoon rainfall in Bangladesh (Rahman, *et al* 1997). However, contradictory trends in the summer monsoon rainfall in Bangladesh were found by two different studies. A study based on 1961-2010 data showed a decreasing trend at a rate of –0.53 mm/year (Ahasan, *et al* 2010), while an increasing trend was observed by another study based on 1976 – 2008 rainfall data (Basak, *et al* 2013).

There are a few publications on the possible relationship between summer monsoon rainfall in Bangladesh and El-Niño Southern Oscillation (ENSO). A previous study indicates no relationship between summer monsoon rainfall in Bangladesh and ENSO (Singh, *et al* 1992). A similar observation was also made by Ahmed and Kim (2004). A more recent study showed weak connection between summer monsoon rainfall in Bangladesh and ENSO (Wahiduzzaman 2012).

The present study is a first of its kind in the context of Bangladesh because, in this study, summer monsoon rainfall in Bangladesh has been expressed as "All-Bangladesh" summer monsoon rainfall, which is an aggregate average rainfall at 15 weather stations, for each of the 60 year period from 1951 to 2010. Objectives of this study are two-fold. First, it aims at addressing the contradictory claims of the long-term trend in the summer monsoon rainfall in Bangladesh and, second to investigate any association between the All-Bangladesh summer monsoon rainfall and ENSO Index. This study is based on the analysis of monthly rainfall at 15 weather stations during summer season (June through October), over a 60 year period (1951 – 2010). It is firmly believed that the results of this study will enhance the scientific understanding of the summer monsoon rainfall in the country, its long-term trend and association with the El Niño-Southern Oscillation Index (ENSO Index).

1.1. Location and Physiography

Bangladesh extends from 20°45'N to 26°40'N, and from 88°05'E to 92°45'E. Most of the country has a homogeneous topography with a low plain, with low hills in the southeastern part. However, it is bordered by the Assam Hills to its east, the Meghalaya Plateau to its northeast with the lofty Himalayas lying farther north. The plain land of West Bengal and the Gangetic Plain of India lies to its west, and the Bay of Bengal to its south.

1.2 General Climatic Conditions

Climatologically speaking, Bangladesh belongs to the Tropical Monsoon region. Its climate is dominated by the seasonal reversal of wind circulation between the summer and winter, with two shorter transitional seasons in between the above two dominant seasons (Spate and Learmonth 1984). Thus, there are four climatic seasons in the country: A cool dry winter season, hot pre-monsoon summer season, rainy summer monsoon season, and the mild and pleasant autumn season.

1.2.1. Cool Dry Winter Season

Cool and dry winter season lasts from mid-November to late February. The sub-tropical high pressure prevails over the Gangetic Plain during this season. As a result, cool dry air flows down the Gangetic plain, from northwest to southeast, then toward south into the Bay of Bengal. January is the coldest month with average temperature ranging from 17°C in the north to 20°C in the south. Rainfall in winter accounts for less than 5% of the annual total, which ranges from 10-20 mm in the west to 40-60 mm in the northeast and east. Traditionally, this season is characterized by shallow fog in the early morning, which dissipates by mid-morning. But, since the 1980s, because of widespread rice cultivation in this season, based on large-scale irrigation, this season is now characterized by occurrences of dense, widespread fog which may last for a few days in a row (Ahmed and Alam 2013).

1.2.2. Pre-monsoon Hot Season

March through May is the pre-monsoon hot season. This is the transition season between the dry winter season with land-to-sea wind and the rainy summer monsoon season with sea-to-land wind. In the early part of this season, a narrow zone of air mass discontinuity lies across the country, from southwest corner to northeast corner. This line of air mass discontinuity lies as an invisible wall between the hot and dry air from the dry interior of northern India and the warm moist air from the Bay of Bengal (Ahmed and Karmakar 1993, Ahmed and Kim 2004). With the progression of the season, this line of air mass discontinuity becomes weak, retreats toward northwest and eventually disappears by the end of May or early June, making room for the arrival of the summer monsoon season.

Pre-monsoon season is characterized by high temperatures and convective storms (thunderstorms). April (in the south) and May (in the west-central part) are the hottest months. Average temperature during the hottest months may range from 27-28°C in the south to 32-33°C in the west-central part of the country. Rainfall in this season accounts for 10-20% of the annual total, which is caused by thunderstorms. Seasonal rainfall ranges from 200-250 mm in the west-central part of the country to 750-800 mm in the northeast (Ahmed and Karmakar 1993, Ahmed and Kim 2004).

1.2.3. Summer Monsoon Season

The summer monsoon season prevails from June through mid-October. This is also the rainy season in the country which accounts for 75-80% of the annual rainfall. This season is characterized by widespread cloud cover, southerly or southwesterly winds from the Bay of Bengal, high humidity, and long spells of rainy days (Ahmed and Kim 2004). Rainfall in this season is caused by weak tropical depressions that enter the country from the Bay of Bengal. These are the remnants of the low pressure waves (or tropical easterly waves) that enter from the western Pacific Ocean to the Bay of Bengal. On average 4-5 such waves enter the Bay of Bengal per month. Of these, 2-3 turn into tropical depressions (Barry and Chorley 2010), which enter Bangladesh with a general duration of 1-2 weeks, producing 25-50 mm of rainfall per day (Ramage 1971, Kutzbach 1987, Barry and Chorley 2010). These tropical depressions enter Bangladesh from the Bay of Bengal with a south-to-north trajectory, then they travel toward northwest up the Gangetic valley, being deflected by the Meghalaya Plateau. As these depression travel farther and farther toward northwest, they lose moisture content, resulting in decreasing rainfall toward the northwest.

It may be noted that rainfall is enhanced in the coastal southeast and in the northeastern parts of the country due orographic effect in these two regions (Ahmed and Karmakar 1993, Ahmed and Kim 2004). Rainfall in this season accounts for 75-80% of the annual total, ranging from 1200 mm in the west-central part to 3000 mm in the southeast and northeast.

Temperature in the rainy summer monsoon season is slightly lower than what can be expected, being dampened by the widespread cloud cover. Mean temperature in July ranges from 28^{o}C in the east to 29^{o}C in the west. But, on a clear sunny day, temperature may climb to 32-36^{o}C, and sometimes may exceed 40^{o}C mark.

1.2.4. Autumn Season

Autumn is a very short season in Bangladesh, lasting from mid-October to mid-November (Ahmed and Kim 2004). This is a transitional period in wind direction, shifting from the summer's southerly sea-to-land wind to the winter's northwesterly land-to-sea wind. At the beginning of the season, winds are weak and variable in direction. As the season progresses, winds change rapidly to northerly flow (north-to-south direction). This is a pleasant season with mostly clear sky with mild temperatures. Average November temperature ranges from 23^{o}C in the northeast to 25^{o}C in the south. Rainfall in the Autumn season is very low, which accounts for 3-5% of the annual total. Rainfall in this season ranges from 70-75 mm in the southwest to 100-150 mm in the northeast, and 175-200 mm in the southeast.

2. Material and Methods

2.1.Data

(A) Data for Monsoon Rainfall in Bangladesh

Bangladesh has about two dozen weather stations which have archived rainfall data that go back prior to 1950. Out of those two dozen or so stations, this study uses data for 15 stations that have recorded data since 1950, which represents a very good sample size. Location of these sations are shown in Figure-1. These stations represent diverse physio-climatic regions of the country.

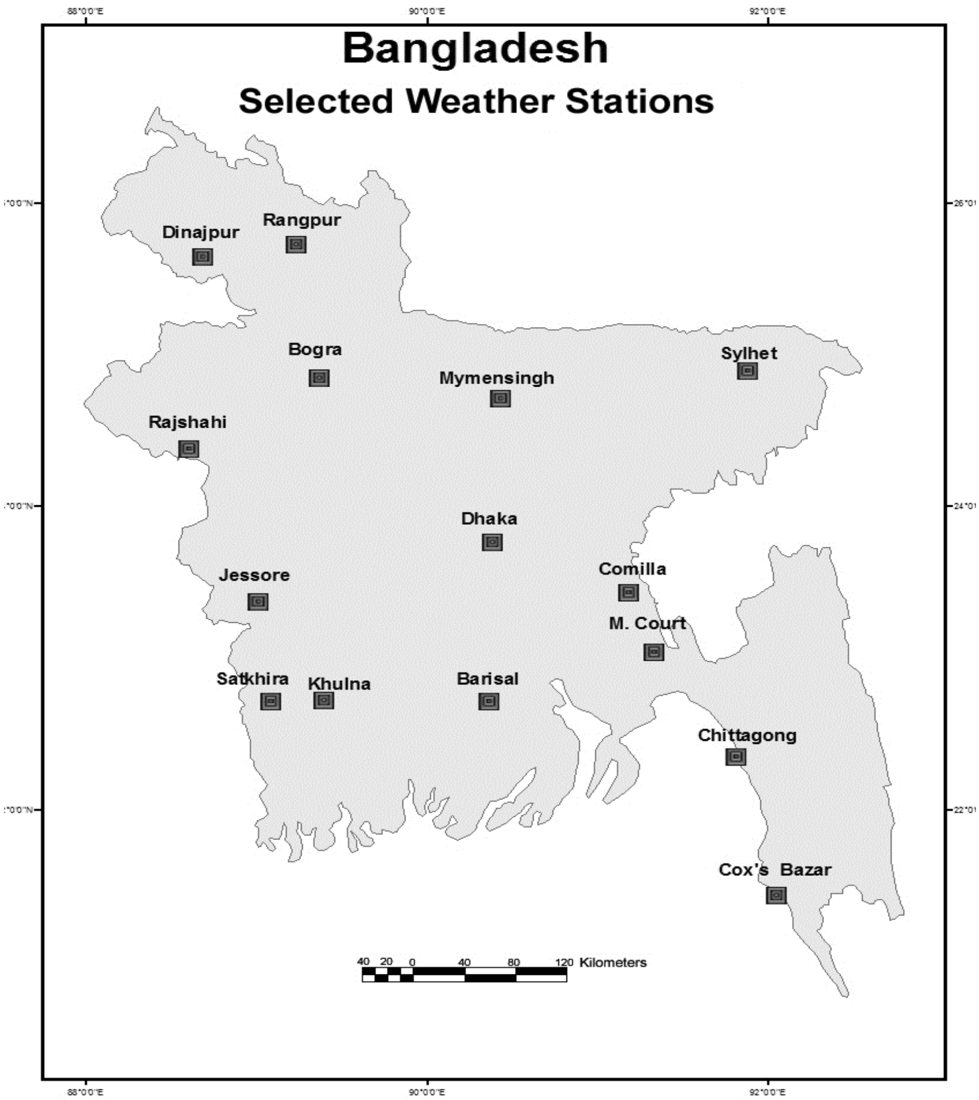

Figure 1. Location of the 15 weather stations used in this study.

The fifteen (15) stations considered in this study are listed blow, with their physio-climatic

characteristis:
(a) Stationa in the eastern part of the country: Sylhet, Comilla, Maijdi Court (M. Court), Chittagong and Cox's Bazar. These five stations are located along the foothills regions, which provide orographic uplifting to the summer monsoon flow, thereby enhancing monsoon rainfall amount. Additionally, Chittagong and Cox's Bazar are located in the costal zone, at the entry point of the summer monsoon flow. So, these stations are in the very high rainfall zone.
(b) Stations in the southern coastal zone: Barisal, Khulna and Satkhira.These three stations are located in the Ganges Delta, as well as along the entry point of the summer monsoon flow. So, these sations are characterized by moderate rainfall amount.
(c) Stations in the north-western part of the country: Dinajpur, Rangpur, and Bogra. These three staions are located in the downwind region of the summer monsoon flow. So, these stations also receive moderate rainfall.
(d) Stations in the west-centarl part of the country: Rajshahi and Jessore. These two stations are located in the reltively low rainfall region of the country.
(e) Stations in the mid-section of the country: Mymensingh and Dhaka. These two stations are located in the central part of the country, halfway between the high rainfall zone along the eastern hilly region and relatively low rainfall region in west-central part of the country.

Monthly rainfall data for the months of June through October for all fifteen stations, for each year for the period from 1951 to 2010, were collected from the Bangladesh Meteorological Department, Dhaka. These monthly data were added to obtain the seasonal total at each station for each year, from 1951 through 2010.

(B) Multivariate El Niño-Southern Oscillation Index (ENSO Index) data
ENSO Index data for the period 1951 – 2010 were collected from the US National Oceanic and Atmospheric Administration (NOAA) website: **http://www.esrl.noaa.gov/.** However, ENSO Index data for the months of June through October, coinciding with the summer monsoon season in Bangladesh, were used in this study.

2.2. Analytical Methods

(A) All-Bangladesh summer monsoon rainfall were calculated as the aggregate average of the 15 stations in a given year. To obtain the aggregate average seasonal rainfall (June – October) in a given year (say in 1951), observed seasonal rainfall of all 15 stations in that year were added, and average were calculated (divided by 15). This method was repeated for the subsequent years (through 2010). It may be noted that, this method was also used in the calculation of the State-wide mean annual rainfall in Wisconsin in different years, from January,1895 to August, 2009 (Hopkins 2009).
(B) Time series of the All-Bangladesh summer monsoon rainfall (1951– 2010) was plotted.
(a) Equation for the long-term trend of the All-Bangladesh summer monsoon rainfall for the period 1951- 2010 was calculated.
(b) The trend line was plotted on the above graph.
(c) Trend line equation and R^2 were written on the graph.
(C) Time series of the El-Niño-Southern Oscillation Index (ENSO Index), 1951-2010 was plotted.
(a) Equation for the long-term trend of the ENSO Index was calculated.
(b) The trend line was plotted on the above graph.
(c) Trend line equation and R^2 were written on the graph.
(D) Association between All-Bangladesh summer monsoon rainfall and ENSO Index (1951-2010). Scatter diagram of All-Bangladesh summer monsoon rainfall and ENSO Index for the period from 1951 to 2010 was plotted to observe any association between the two sets of data.

3. RESULTS AND DISCUSSION

3.1 Summer Monsoon Rainfall and its Co-efficient of Variation.

Distribution of the average summer monsoon rainfall ranges from less than 1200 mm in the west-central region to more than 3000 mm in the northeastern and coastal southeastern parts of the country (Figure 2 (a)). Rainfall is enhanced in the northeast by the orographic uplifting by the Meghalaya Plateau, and by the hills in the coastal southeast.

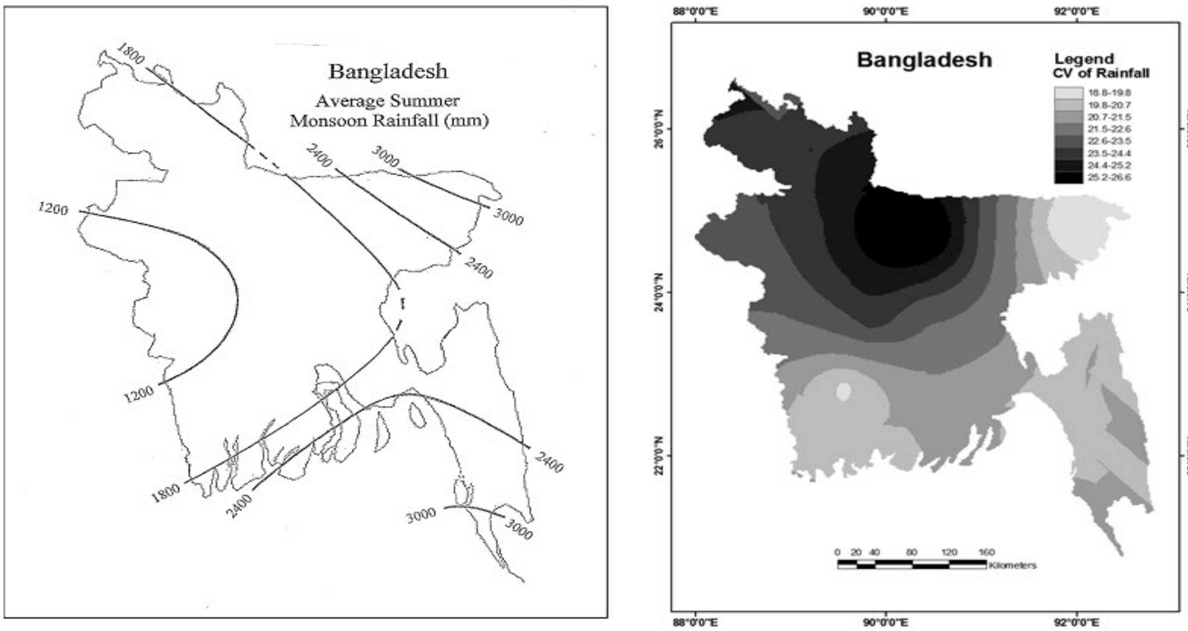

Figure 2 (a) Distribution of average summer monsoon rainfall (mm), and (b) Co-efficient of variation (%) of summer monsoon rainfall in Bangladesh.

Range of the coefficient of variation of summer monsoon rainfall is small, ranging from 18-20% in the south, southeast and northeast to 25-26% in the north-central and northwestern parts of the country (Figure 2(b)).

3.2 All-Bangladesh Summer Monsoon Rainfall (1951 – 2010), and its Trend

All-Bangladesh summer monsoon rainfall during the 1951-2010 period ranged from 1344.2 mm to 2307.1 mm, with a mean value of 1826.3 mm, and a standard deviation of 127.7 mm. Trend of All-Bangladesh summer monsoon rainfall from 1951 to 2010 is shown in Figure 3. The Figure shows year-to-year fluctuations, and that All-Bangladesh summer monsoon rainfall increased at a very slow rate of 0.2073 mm per year over the 60-year period from 1951 to 2010.

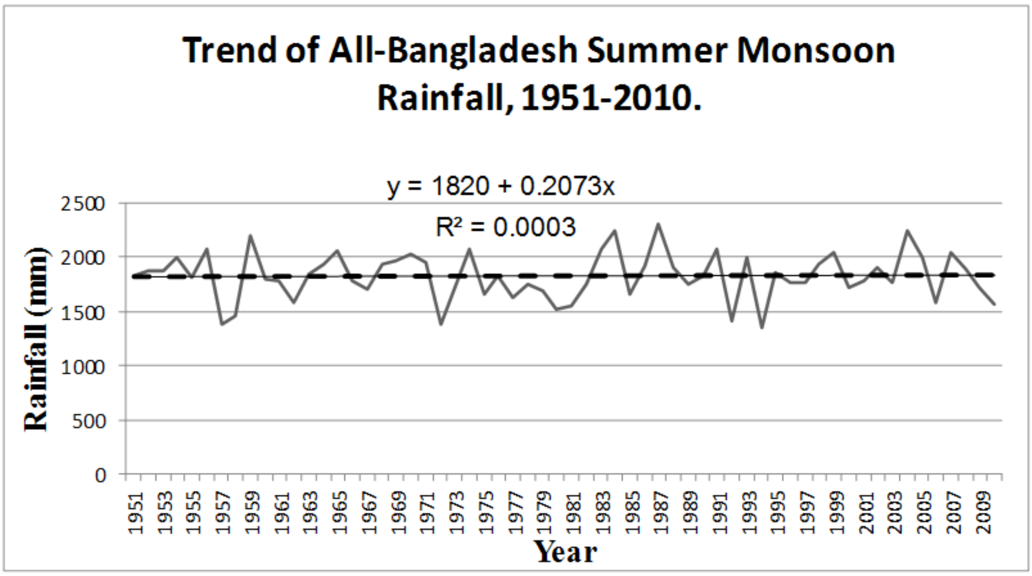

Figure 3. Trend of All-Bangladesh summer monsoon rainfall from 1951 to 2010.

3.3. ENSO Index During the Summer Monsoon Season in Bangladesh (June- October), and its Trend between 1951 and 2010.

The ENSO Index coinciding with the summer monsoon season in Bangladesh (June through October) during the period 1951-2010 ranged between –12.8 and 14.7, with a mean value of 0.9593 and a standard deviation of 5.895. Trend of the ENSO Index during the same period (i.e., 1951-2010) is shown in Figure 4. It shows inter-annual variations, with a slow decreasing trend, at a rate of – 0.027 per year over the 60-year period from 1951 to 2010.

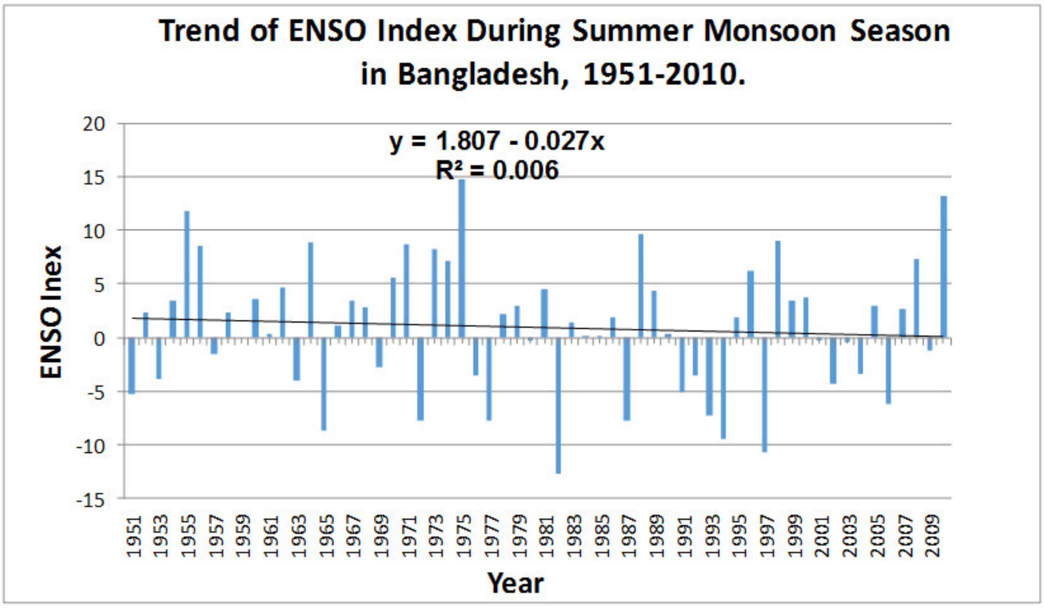

Figure 4. Trend of ENSO Index during summer monsoon season.

3.4 Association Between All-Bangladesh Summer Monsoon Rainfall and ENSO Index, 1951 – 2010

Scatter diagram of the ENSO Index versus All-Bangladesh summer monsoon rainfall (1951 – 2010) is shown in Figure 5. Widely scattered distribution of the point values do not represent any relationship between All-Bangladesh summer monsoon rainfall and ENSO Index. This finding is in agreement with two earlier studies (Ahmed and Kim 2004, Singh *et al* 1992).

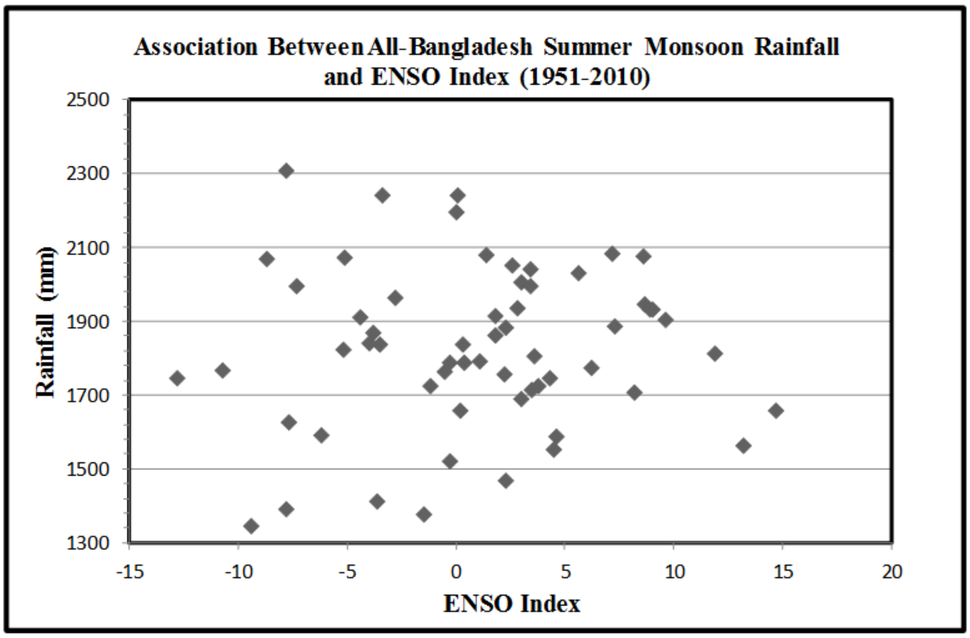

Figure 5. Association between All-Bangladesh summer rainfall and ENSO Index (1951 – 2010).

4. CONCLUSIONS

Based on the discussions in the preceding Sections, the flowing conclusions can be drawn:

(a) All-Bangladesh summer monsoon rainfall during the 1951-2010 period ranged from 1344.2 mm to 2307.1 mm, with a mean value of 1826.3 mm, and a standard deviation of 127.7 mm

(b) All-Bangladesh Summer Monsoon Rainfall increased at a very slow rate of 0.2073 mm per year over the 60-year period from 1951 to 2010.

(c) The ENSO Index coinciding with the summer monsoon season in Bangladesh (June through October) during the period 1951-2010 ranged between –12.8 and 14.7, with a mean value of 0.9593, and a standard deviation of 5.895.

(d) The ENSO Index, coinciding with the summer monsoon season in Bangladesh (June through October) from 1951 to 2010, shows inter-annual variations, with a slow decreasing trend, at a rate of – 0.027 per year over the 60-year period from 1951 to 2010.

(e) Widely scattered distribution of the point values of the ENSO Index versus All-Bangladesh summer monsoon rainfall during the period 1951 – 2010 do not represent any relationship between them.

It is expected that the results of this study will enhance the scientific understanding of the All-Bangladesh summer monsoon rainfall, long-term trends of All-Bangladesh summer monsoon rainfall and ENSO Index, and no relationship between All-Bangladesh summer monsoon rainfall and ENSO Index.

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