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Research Article

Drought Hazard Evaluation in Boro Paddy Cultivated Areas of Western Bangladesh at Current and Future Climate Change Conditions

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Drought hazard is one of the main hindrances for sustaining food security in Bangladesh, and climate change may exacerbate it in the next several decades. This study aims to evaluate drought hazard at current and future climate change conditions in the *Boro* paddy cultivated areas of western Bangladesh using simulated climate data from the outputs of three global climate models (GCMs) based on the SRES A1B scenario for the period between 2041 and 2070. The threshold level of Standardized Precipitation Evapotranspiration Index (SPEI) was employed to identify drought events and its probability distribution function (PDF) was applied to create the drought hazard index. The study demonstrates that enhancement of potential evapotranspiration (PET) will surpass that of precipitation, resulting in intensified drought events in future. In addition, the PDFs of drought events will move the upper tail in future period compared to the baseline. The results showed that the southwestern region was more severe to the drought hazard than the northwestern region during the period of 1984 to 2013. From the results of three GCMs, in the mid-century period, drought hazard will slightly increase in the northwestern region and flatten with a decrease in the southwestern region. The outcomes will help to allocate agricultural adaptation plans under climate change condition in Bangladesh.

1. Introduction

Bangladesh is one of the most natural hazard-prone countries in the world because of its high climatic variability, low flat topography, hydrogeologic setting, and diverse complex geomorphology. Bangladesh has experienced the extreme climate events in almost every year such as droughts, floods, tropical cyclones, and storm surges, causing heavy loss of life and properties [1]. Drought does immense damage to crop production and one of the main limiting factors in the field of agriculture. Being an agriculture based country, Bangladesh is struggling to be able to adapt to the changing climate, along with the challenges of a growing population and sustaining food security. The effects of climate change on the agricultural sector are tremendous. Both positive and negative effects have occurred, but the negative effects are dominated in the agricultural sector of Bangladesh [2, 3]. Besides, climate change is likely to shift the patterns of drought and possibly increase the frequency and intensity of drought events in the foreseeable future [4]. Western region of Bangladesh will be at high risk of drought hazard under climate change conditions [5]. Shahid [6] projected an increased severity of droughts in the near future period in Bangladesh. In recent decades, Bangladesh has shown an increased drought frequency and intensity due to land use pattern changes [7]. Concern among Bangladesh's scientists has increased regarding changes in precipitation, potential evapotranspiration (PET), and drought events. Thus, a better insight into drought frequency and intensity can help decision-making for agriculture allocation and adaptation to climate change, especially during the dry season in the paddy growing regions in Bangladesh.

Drought is apparent over a prolong period of time, generally a season or more in length when precipitation is below the normal levels, but it is difficult to quantify drought characteristics relative to the aspects of intensity, frequency, duration, and spatial extent. To date, more than 50 drought indices have been found for recognizing drought events in the literature; among them, three are the most widely used drought monitoring indices such as the SPI (Standardized Precipitation Index) [8], the PDSI (Palmer Drought Severity Index) [9], and the SPEI (Standardized Precipitation Evapotranspiration Index) [10]. The results of the using SPI are comparable in space and time [11] and its ability to identify various types of droughts. However, the SPI is based only on precipitation data, which does not reflect drought conditions caused by climate variation [12]. The PDSI reveals the drought effects caused by warming [13], considering the temperature data, but it is unable to evaluate multiscale drought characteristics. Recently, several studies in Bangladesh have been carried out to identify drought hazard using drought indices [14–17]. For instance, Shahid and Behrawan [14] applied the SPI based on the monthly rainfall data for the period of 1961–1999 from 12 weather stations to assess the drought risk in the western part of Bangladesh. Similarly, Alamgir et al. [16] used the SPI from the rainfall data during 1961–2010 in Bangladesh to analyze drought events and the results revealed that the spatial characteristics of droughts vary widely according to season. Abdullah [15] assessed the spatial and temporal patterns of drought in Bangladesh using the SPEI. Rahman and Lateh [17] used SPI and monthly rainfall dataset for the period of 1971–2010 to outline the drought years and severity in Bangladesh. However, most of those studies are focused on defining drought and their spatial temporal variations using various methods with present climate condition. Taking into consideration monthly time scale for drought monitoring and assessment under present and future climate change conditions during the winter Boro rice growing season in western Bangladesh, the SPEI is more suitable than other kinds of indices for identifying drought characteristics [10].

Drought hazard has been defined as a combination of probability of drought frequency and intensity [18]. The more frequent drought events with high levels of intensity can produce the severe hazardous effects. The drought hazard assessment has received recently much attention among the scientific community [19–21]. It is necessary for disaster risk assessment, which helps in decision-making for drought adaptation and mitigation plans [14, 22]. Most of the previous studies revealed that drought frequency was considered as a basis of drought hazard; but drought intensity was not taken into account [23, 24]. Several studies have been done by applying drought intensity by dividing drought into different grades on the basis of values of drought index and assigned weights [17, 25, 26]. Conversely, these approaches have limitations because artificial factors influence the grade dividing. In the present study, the frequency distributions of drought intensity within the grades are ignored. The probability density function (PDF) is an approach which takes this advantage over dividing drought intensity into various grades. Mishra et al. [27] applied the PDFs of drought index to demonstrate drought frequency and intensity successfully. A similar approach was used to assess drought hazard for China by Q. Zhang and J. Zhang [21]. The PDFs are much precise technique in comparison with artificial grade dividing of drought index. However, previous studies did not address the projected changes of drought events in terms of frequency and intensity. This study has taken into consideration the changes of future drought events using the PDFs of SPEI values which are defined by the threshold level.

A number of studies have focused on drought disaster risk on global and regional scales for present and future climate scenarios [28–30]. It is quite important to predict future drought events on a local scale for drought mitigation and agriculture adaptation purposes. The global climate models (GCMs) and regional climate models (RCMs) have emerged as useful tools for assessing future drought conditions under different scenarios. In this study, three GCMs outputs were used to evaluate future drought hazard using the IPCC SRES (Special Report on Emissions Scenario) A1B scenario for the period of 2041 to 2070. Burke and Brown [31] used the Hadley Center climate model (HadCM3) as well as a multimodel ensemble to evaluate the uncertainties in future drought projection. Chen et al. [32] investigated future drought changes in China using the multimodel ensemble (MME) and a regional climate model (RCMs) under the SRES A1B scenario to project a decrease in drought frequency in most parts of China. On the contrary, Wang et al. [33] assessed future drought in China using a Coupled Model Intercomparison Project Phase 5 (CMIP5) under the scenarios RCP4.5 and RCP.8.5 and showed that extreme drought events will increase in future. Recently, Kim et al. [20] projected future drought hazard in South Korea based on RCP8.5 scenario by the RCMs (HadGEM3-RA) and found that drought frequency and intensity will become severe under future climate change. In Bangladesh, Selvaraju and Baas [34] reported that future drought may increase the probability of a dry year with a certain percentage of below average rainfall by 4.4 time using moderate climate change scenario and concluded that drought-prone areas would expand to include northwest to central regions. Nevertheless, a climate change projected drought hazard study using SPEI technique has not been well documented in existing literature so far especially in the case of western Bangladesh and is the primary justification for this study.

The major *Boro* paddy rice producing areas of Bangladesh are the northwestern and southwestern regions where drought affects 1.2 million hectares of cultivated *Boro* paddy area during the dry season [35]. The Ministry of Agriculture of Bangladesh MoA [36] reported that moderate to very severe drought-prone areas accounted for about 56.9% of the country's total net cultivated area in 2012. The drought in the 1990s in northwestern Bangladesh led to a shortfall of 3.5 million tons of rice [37]. Between 1984 to 2013, drought occurred in these regions in 10 times; severe droughts hit these parts in 1984, 1989, 1991, 1994, 1995, 1998, 2000, 2006, 2009, and 2012 [38]. The average crop production reduced about 25–30% because of the effect of drought in these regions of Bangladesh

[38]. The paddy rice production inevitably incurs significant losses from the drought hazard by threatening the country's food security. Nevertheless, adaptation of drought issues in the study area has been recently brought forward because of the effects of climate change, increasing drought intensity and losses in the crop agricultural production. It is therefore essential to understand that drought hazard during the *Boro* paddy growing season and its future changes can help to formulate an effective drought preparedness and adaptation plans under climate change conditions, particularly in water-scarce agricultural regions in western Bangladesh.

The main objective of this study is to evaluate drought hazard at present and potential climate change conditions, taking into consideration the temporal and spatial changes of future drought events. To achieve the objective, first, we simulated a database of climate data (2041–2070) from the outputs of three GCMs, namely, CGCM3.1, FGOALS-G1.0, and HadGEM1 models, which were downscaled by the LARS-WG (Long Ashton Research Station-Weather Generation) model under the IPCC (Intergovernmental Panel on Climate change) SRES A1B experiment. Second, the SPEI was employed to identify drought conditions by the threshold level (SPEI < −1.0). Third, the probability density function (PDF) of SPEI values was determined to create the drought hazard index during the current and future periods in each subregion of the study area. The results of this study can provide an important support for drought adaptation plans under climate change condition.

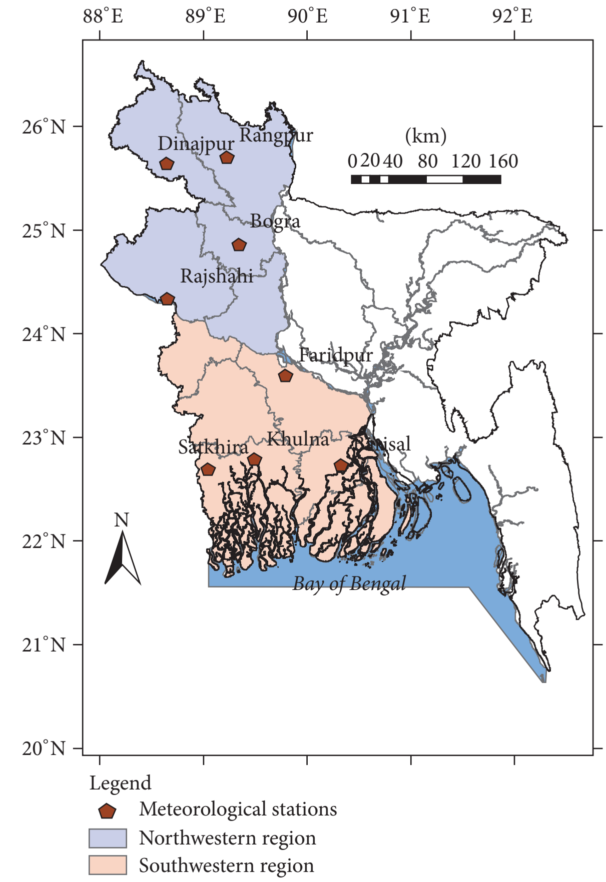


Figure 1: The location map showing meteorological stations and the extent of the northwestern and southwestern regions in western Bangladesh.

2. Data and Methods

2.1. Study Area Description. The study area is western Bangladesh, which is divided into two regions: northwestern region (24°.30′–26°40′N, 88°.01′–89°.90′E) and southwestern region (22°.52′–23°.90′N, 88°.20′–90°.30′E) (Figure 1). These two regions are considered as the main *Boro* paddy rice growing areas of Bangladesh by which country's food security can be ensured to a significant level. Three kinds of rice cropping patterns such as winter (*Boro*), summer (*Aus*), and monsoon (*Aman*) are usually practiced in the study area. Out of these three, high yield variety (HYV) *Boro* rice is the main contributor of total rice production in Bangladesh. This study considers only the *Boro* paddy fields that have been severely threatened by drought events in the last several decades. The *Boro* paddy is grown from January to May in these regions though seed bed preparation started earlier.

Bangladesh enjoys the subtropical monsoon climate with large spatial and temporal variability and has four distinct seasons like winter, spring, summer, and autumn. About 80% of the country's annual rainfall occurs during the summer season, and less than 6% rainfall occurs in the dry season *Boro* rice growing period. The average annual rainfall of Bangladesh is about 2300 mm. But the annual average total rainfall is about 1329 mm in the northwest and about 2023 mm in the southwest region [39]. The average temperature ranges from 17 to 20.6°C in the winter season and 26.9 to 31.1°C in the summer. According to Bangladesh Meteorological Department (BMD), the summer temperature rises up to 45°C and the winter temperature falls at 5°C in the northwest region. These regions experience two extremities that clearly differentiate the climatic behaviors from the rest of the country [40].

The southwestern part has experienced more frequent extreme events than the northwestern part and also the rest of the country. The northwestern region has been faced with recurrent mean rainfall 64.94 mm in the last 30-year period (1984–2013) while the southwestern part has experienced mean rainfall 71.94 mm during winter rice growing season (Table 1). It can be seen from Table 1 that northwestern part prevails comparatively higher rainfall variability than southwestern part which is highly significant. The variations in temperature are not so significant in these parts. The northwestern subregions prevail generally warmer and humid climatic conditions than the southwestern subregion. Cropping intensity has increased almost double since last three decades in the northwestern region than southwestern region. Northwestern region belongs to red soil characteristics having low water holding capacity which differentiates it from the southwestern region. Western Bangladesh also varies from altitude; for example, altitude is the lowest (4 m) in Barishal subregion of the southwestern region and altitude is the highest (37 m) in Dinajpur subregion of the northwestern region compared to the rest of the country.

Table 1: The variations in climatic parameters during the winter *Boro* paddy growing season (1984–2013) in western Bangladesh.

Region	Subregion	$T_{\max}$	$T_{\min}$	Precipitation
Northwest	Dinajpur	29.26	17.12	62.21
	Rangpur	28.66	17.26	88.97
	Bogra	30.09	18.29	62.58
	Rajshahi	31.31	17.82	46.16
	Mean	29.83	17.6225	64.98
Southwest	Faridpur	30.71	18.94	80.21
	Khulna	31.42	19.61	66.23
	Satkhira	31.61	19.74	63.49
	Barisal	30.75	19.32	77.71
	Mean	31.1225	19.4025	71.91

However, the severity of drought in southwestern part is moderate compared to northwestern region during the dry winter season [38]. So drought hazard evaluation under climate change condition has been carried out in varying climatic characteristics; western Bangladesh varies latitude and altitude, but longitude is almost similar.

2.2. Datasets Generation and Statistical Downscaling. In this study, we divided the time domain into two periods, current (1984–2013) and near future (2041–2070) for potential drought hazard analysis. According to IPCC [41], the time period of 1984 to 2013 has considered the warmest 30-year period for the last 100 years. For this reason, the daily climate data of 30-year period (1984–2013) was used as an observed period. The historical climate data (e.g., minimum and maximum temperature and precipitation) were obtained from the Bangladesh Meteorological Department (BMD). There are 6 weather stations in the northwestern region and 7 in the southwestern region. Although BMD has 13 meteorological stations in western Bangladesh, few stations, for example, Sayedpur (northwestern region) and Mongla and Chuadanga stations (southwestern region), do not have long-term observed data archives because these are newly established after 1991 and have missing data for significant periods. Thus, data of total 8 meteorological stations in the two regions for a 30-year period (1984–2013) were taken into consideration. The time period of 2041–2070 at centered 2055s is regarded as a planning horizon of crop agricultural productivity. The present study chose to evaluate mid-century future climate (2041–2070) due to the limited ability for developing meaningful crop agricultural management strategies relevant to end of the century climate projections. The IPCC Data Distribution Center provides the three GCMs results based on the SRES A1B scenarios (http://www.ipcc-data.org). The GCMs that provide a result of the A1B scenario applied for the IPCC AR4 were selected: CGCM3.1 (Canada), FGOALS-G1.0 (China), and HadGEM1 (UK). The outputs from three GCMs climate models are employed in this study, as summarized in Table 2. The A1B scenario (balanced across energy sources) represents a medium greenhouse gas emission.

The LARS-WG is a stochastic weather generator, developed by Semenov and Barrow [42], which generates precipitation and maximum and minimum temperature for the time period of 1984 to 2013 and future period of 2041 to 2070. It is a statistical downscaling method, which is used to calibrate the climate model outputs with a statistical relationship between the GCMs result and the observed result. Semenov et al. [43] applied WGEN (weather generator) and LARS-WG method in different climatic zones in Europe and Asia and found that the LARS-WG was more accurate than the WGEN method. The parameters of LARS-WG model were generated from 8 representative weather stations based on the major cultivated *Boro* rice areas in western Bangladesh. The LARS-WG model was downloaded from the department of computational and systems biology, Rothamsted research, UK website (http://www.rothamsted.ac.uk). More detailed description of the LARS-WG modeling procedure can be referred to Semenov and Barrow [42]. It is mentionable that the observed current climate (1984–2013) is significantly different from the climate in the past years, for example, 1961–1990. However, the inverse distance weighting (IDW) interpolation technique was applied to assess drought hazard under climate change in South Korea [19] and in Bangladesh [17] and was also adopted for use in the study. The IDW interpolation technique is simple and in-built within ArcGIS (version 10.2). Additionally, the main advantage of this interpolation technique is fast to compute the interpolated values.

2.3. SPEI and Threshold Level. The Standardized Precipitation Evapotranspiration Index (SPEI) was used to identify the drought characteristics in this study. The SPEI's main advantage lies in its ability to detect the onset and spatial and temporal changes of drought consistently; it is suggested for operational drought monitoring studies worldwide [44, 45]. However, the Standardized Precipitation Index (SPI) does not consider temperature data; it has a limitation, which is unable to reflect the changes in water demand, such as the changes in water budget, like precipitation and PET by the warming. The SPEI rectified this criticism of the SPI considering potential evapotranspiration (PET).

In the present study, the following four steps and specific settings are used to calculate the SPEI [46]. Firstly, the monthly potential evapotranspiration (PET) is computed based on the data of monthly minimum and maximum temperature by using the Thornthwaite equation [47]. Secondly, a simple monthly water balance is expressed as the difference between monthly precipitation (P) and PET. Thirdly, a three-parameter log-logistic distribution is used to fit the data series of monthly water balance. Finally, the original values are normalized to obtain standardized units that are comparable in space and time as the SPEI. The updated version of the R SPEI package (http://cran.r-project.org/web/packages/SPEI) was used to estimate the SPEI in the study. The SPEI was computed at monthly time scale and the smaller negative SPEI means the most serious drought events will be occurring. The negative SPEIs are related to the dry condition; a drought event is defined when the SPEI is continuously negative and reaches a value of "–1.0" or less [10]. So it is

Table 2: Summary of observed and simulated climate data and three GCMs outputs used in this study.

Category	Period	Source	Climate model	Spatial resolution (lat × long)
Observed data	1984–2013	BMD (Bangladesh Meteorological Department)	Historical data	—
Simulated data	2041–2070	IPCC Data Distribution Centre (A1B scenario)	CGCM3.1 (Canada)	2.8° × 2.8°
			FGOALS-G1.0 (China)	2.8° × 2.8°
			HadGEM1 (UK)	1.3° × 1.9°

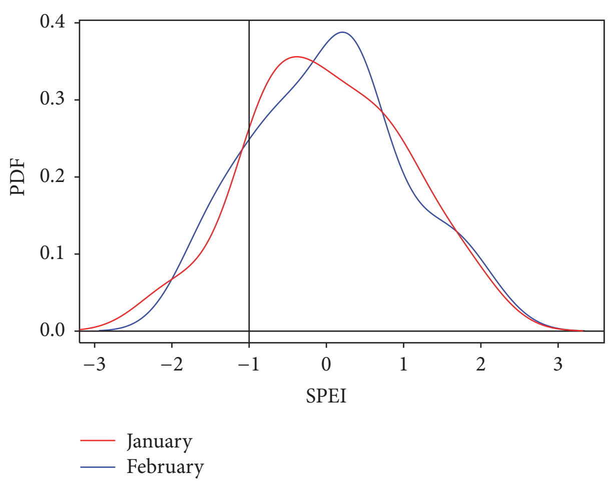


Figure 2: The PDFs of SPEI values in January and February during the observed period of 1984–2013 in Rangpur, northwestern Bangladesh.

assumed that less than "−1.0" is considered as the threshold level and drought events start at this level lower than −1.0 in monthly SPEI values (Figure 2). Two reasons for the choosing of this threshold level are as follos: (1) the SPEI (<−1.0) is a good indication that significant impacts can occur in crop agriculture and possibly other sectors and (2) the threshold level of SPEI (<−1) indicates the start of agricultural drought events in the crop growing season and is also used to identify and explore drought periods. Similarly, Kim et al. [20] used −1.0 as a threshold level when they evaluated future drought hazard of South Korea using SPEI technique.

2.4. Drought Hazard Index. Drought hazard is the product of frequency and intensity of drought events. The SPEI is employed to quantify drought hazard during the current and near future periods. Next, the probability density function (PDF) of SPEI values was determined during these periods in each subregion of the study area. We computed the drought hazard (DH) by using the following equation:

$$\mathrm{DH} = \int_{-1.0}^{-3.5} I\,(\mathrm{SPEI}) \times F\,(\mathrm{SPEI})\,, \qquad (1)$$

where I(SPEI) values denote the intensity of drought and F(SPEI) is the frequency of the SPEI. The justification for this equation's over widely used other drought hazard index lies its ability to take advantage the PDFs of SPEI values in terms of frequency and intensity of drought period to build an index which avoids dividing the drought into various grades. Another advantage is that this equation measures the intensity and frequency of drought events precisely at any location and any time scale.

The PDFs of SPEI values in January and February during the period of 1984–2013 in Rangpur subregion, northwestern Bangladesh, are shown in Figure 2 as an example. It demonstrates that drought frequencies (SPEI < −1.0) are almost same during these two months, but drought intensities vary, when the SPEI values distributed from −1.0 to −2.0 in January and the peak is −1.0 in February. Hence, drought hazard (DH) value in January is higher compared to in February, because drought intensities are greater in January than in February. However, artificial factors often influence drought grade dividing in drought hazard studies. For instance, various weights are assigned to several intensity grades in drought intensity analysis, which sometime mislead the accuracy of the results. For that reason, the frequency distributions of drought intensity within the grades are ignored in the present study.

This study covers only the *Boro* paddy growing season from January to May, where the DH is calculated as the average monthly DHs values. We constructed a database of observed period (1984–2013) and future period (2041–2070) from the three GCMs results which were downscaled by the LARS-WG model under the SRES A1B scenario; a 120-year data sequence of each subregion was used to quantify the SPEI values.

2.5. Validation of Climate Datasets and the LARS-WG Model Performance. The downscaled LARS-WG model was applied to generate simulated climate data for the time period of 2041 to 2070 using the three GCMs results. These climate simulations were verified with observed data (1984–2013). To evaluate the statistically significant differences between the observed and simulated climate data, Q-test was performed, including t-test and F-test using the LARS-WG downscaling technique. Table 3 shows the results of Q-test for precipitation and minimum and maximum temperature at 8 meteorological stations in the study area. The estimated parameters of three climate variables were assessed by Q-test at 5% significance level for almost all stations. During the Boro rice growing period from January to May, the three climate variables at 7-8 stations were verified by Q-test with a 95% confidence level.

Figure 3 uses Rangpur in the northwestern region and Satkhira in the southwestern region as examples to measure the downscaling model performance. Blue lines denote the observation data and red lines indicate simulation data. The LARS-WG model displayed high accuracy projection of

Table 3: The results of Q-test for precipitation and minimum and maximum temperature at 8 meteorological stations in the study area (unit: number of station).

Variables	P value	Jan	Feb	Mar	Apl	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation	<0.05	1	0	0	0	0	2	1	0	1	0	3	1
	≥ 0.05	7	8	8	8	8	6	7	8	7	8	5	7
Minimum temperature	<0.05	0	1	0	0	0	0	0	0	0	0	0	0
	≥ 0.05	8	7	8	8	8	8	8	8	8	8	8	8
Maximum temperature	<0.05	0	0	0	0	0	0	0	0	0	0	0	0
	≥ 0.05	8	8	8	8	8	8	8	8	8	8	8	8

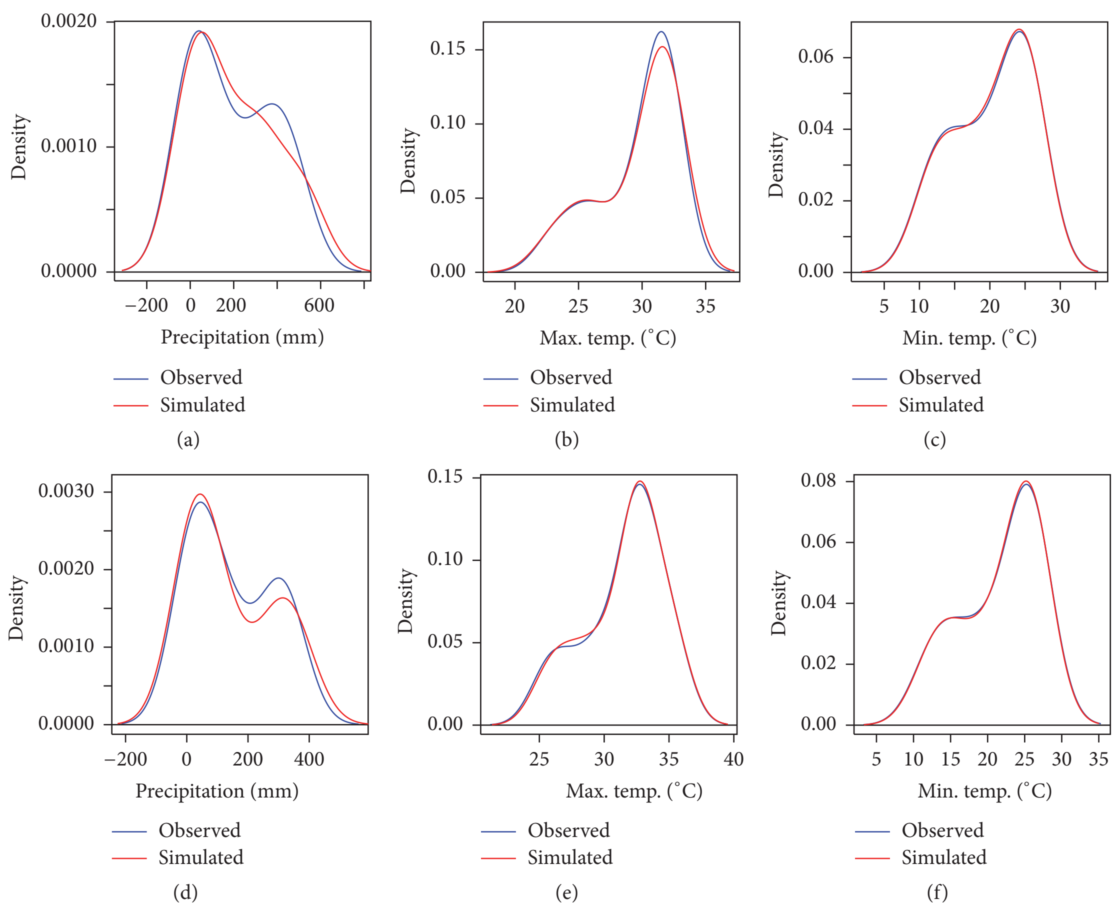
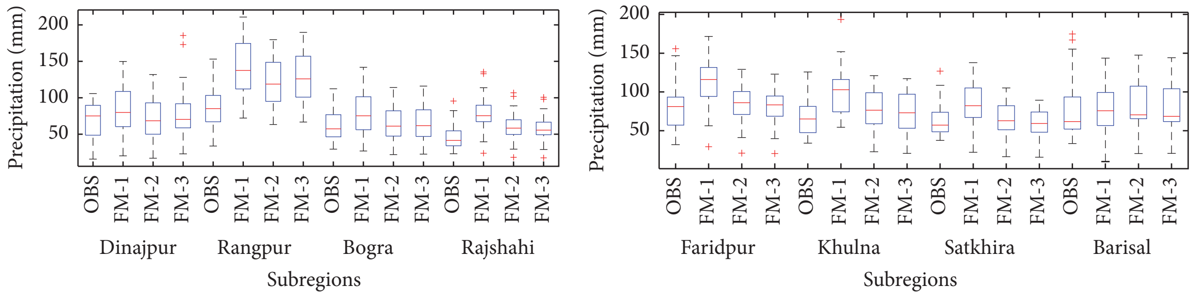


Figure 3: Comparison of observed and simulated climate variables in the paddy growing season. (a–c) show precipitation and maximum and minimum temperature in Rangpur subregion, northwestern Bangladesh; (d–f) represent precipitation and maximum and minimum temperature in Satkhira subregion, southwestern Bangladesh.

monthly maximum and minimum temperature in case stations (Figure 3). The justification is that these two representative stations are used as an example, because these stations exhibit rainfall variability that are statistically significant. The rainfall patterns of two stations are changing increasingly and annual rainfall shows a declining trend [14]. The model showed the better performance in the southwestern than the northwestern region for precipitation. The linear regression analyses confirmed a very high correlation between the observed and simulated precipitation ($r^2 = 0.97$ and 0.98) at 0.05% significance level in both regions. Furthermore, the correlation coefficients (r^2) between the simulated and observed temperature are around 0.99. The comparison between simulated and observed data cannot guarantee their validity of future climate because global warming plays a vital role in the near future climate change conditions, which may not be identical to the current climate.

3. Result and Discussions

The ultimate goal of this study is to evaluate drought hazard in typical *Boro* paddy cultivated areas of western Bangladesh at present and future climate change conditions. First, we will show the temporal variations in precipitation, potential



(a) Northwestern region

(b) Southwestern region

Figure 4: The temporal variations in average precipitation during the paddy growing season under observed and future climate change conditions in western Bangladesh. (a) The changes of precipitation in the northwestern region; (b) the changes of precipitation in the southwestern region. FM-1, FM-2, and FM-3 indicate three GCMs, namely, CGCM3.1, FGOALS-G1.0, and HadGEM1 models, respectively.

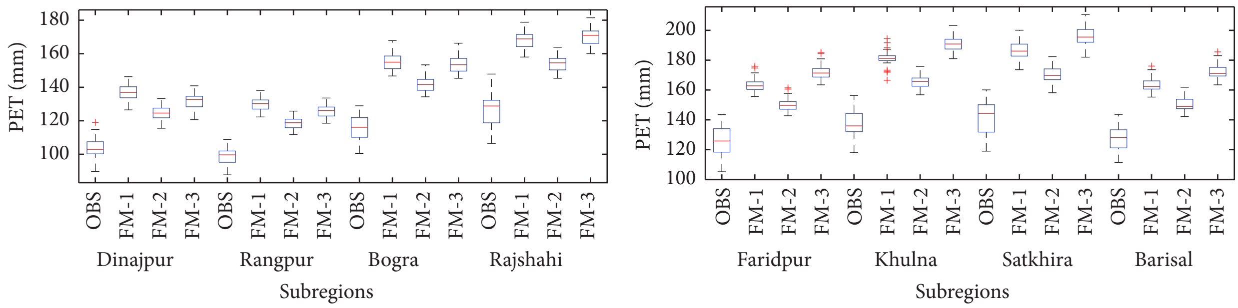
evapotranspiration (PET), and drought events (SPEI < −1) under climate change during the *Boro* rice growing season in the designated areas. This study illustrates the processes that exaggerate drought hazard in the future. Hereafter, we outline changes in precipitation, PET, and SPEI < −1 from the observed (1984–2013) to future periods (2041–2070) in western Bangladesh. The A1B scenario is used under three GCMs outputs which are denoted as future model 1 (CGCM3.1), future model 2 (FGOALS-G1.0), and future model 3 (HadGEM1).

3.1. Changes of Precipitation, PET, and Drought Events under Climate Change

3.1.1. Changes in the Precipitation. Figure 4 presents the temporal variation in average precipitation during the growing season (January to May) for the current and future periods in the major *Boro* paddy cultivated areas in western Bangladesh. All the subregions showed that the average precipitation during the *Boro* rice growing season in northwestern Bangladesh were 94.95 mm (future model 1), 78.77 mm (future model 2), and 81.63 mm (future model 3) by the period of 2041–2070 compared to 67.20 mm in the current period of 1984–2013. The highest average seasonal precipitation was observed in Rangpur (140.91 mm) using future model 1 while the lowest seasonal precipitation was found in Bogra (56.88 mm) under future model 2. However, Dinajpur demonstrated a decrease in precipitation by the period of 2041–2070 under future model 2 and future model 3 compared to the current period. Conversely, in the case of the southwestern region, all subregions exhibited that average seasonal precipitation was 94.47 mm, 76.53 mm, and 72.26 mm, respectively, in near future period and 72.18 mm in the baseline period. The largest average seasonal precipitation was in Faridpur (112.18 mm) under future model 1 while the smallest average seasonal precipitation was in Satkhira (58.59 mm) using future model 3 (Figure 4). From the results, it is clear that the temporal variations in precipitation are higher in the northwestern region than the southwestern Bangladesh. The increasing tendency of precipitation under potential climate changes may be due to high variations in rainy days, amounts of precipitation, and intensity in the *Boro* rice growing season in Bangladesh. In addition, the huge water vapor transport from the Bay of Bengal and enhanced moisture convergence may be another cause of increasing precipitation in future [33].

3.1.2. Changes in the Potential Evapotranspiration. Figure 5 exhibits future change in average PET in the *Boro* rice growing season for major subregions of western Bangladesh at the current and future periods under A1B scenario. The average seasonal PET during January to May in the northwestern region was 111.41 mm in the observed period and increase in the near future about 147.63 mm (future model 1), 134.87 mm (future model 2), and 145.42 mm (future model 3), respectively, by the period of 2041 to 2070. The highest average seasonal PET was detected in Rajshahi (170.35 mm) under future model 3, whereas the lowest average PET was observed in Rangpur (120.41 mm) using future model 2 (Figure 5).

On the other hand, average PET of four subregions in the southwestern Bangladesh was 133.27 mm for the current period and increase in 173.89, 159.22 mm, and 183.04 mm, respectively, for future period using the three GCMs results. The largest seasonal average PET was noticed in Satkhira (195.11 mm) under future model 3, while the smallest PET was observed in Faridpur (150.43 mm) using future model 2 (Figure 5). The results show that the PET variations in northwestern region are much larger compared to that in southwestern region. Furthermore, the discrepancies between the PET changes using the three GCMs become more noticeable in the mid-century period. This finding is consistent with the previous results of Shahid [6] that showed an increase rate of potential evapotranspiration (PET) in northwestern Bangladesh. The widespread increase in PET is expected to rise in temperature and amounts of solar radiation under climate change conditions that dominate in the western part of Bangladesh. Although the tendency of precipitation and PET are both upward trends, the increasing rate of PET exceeds that of precipitation, indicating that the increasing precipitation is not offsetting effects of higher evaporation. The rise in global temperature and surface warming plays a dominant role in the future PET enhancement. The study implies that enhancement of PET in the study area will aggravate drought frequency and intensity in the near future.



(a) Northwestern region

(b) Southwestern region

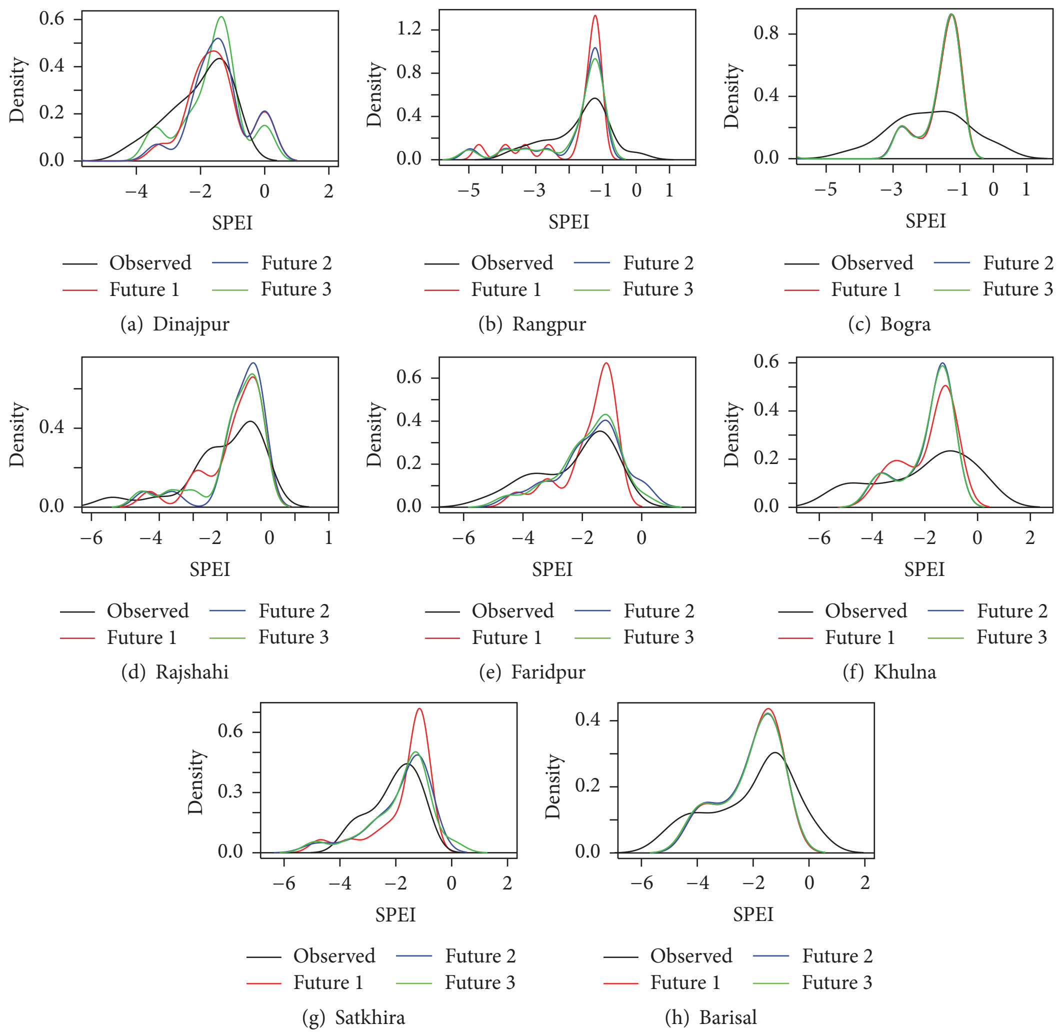
Figure 5: The temporal variations in average PET during the growing season under observed and future climate change conditions in western Bangladesh. (a) The changes of potential evapotranspiration (PET) in northwestern region; (b) the changes of potential evapotranspiration (PET) in southwestern region. FM-1, FM-2, and FM-3 indicate three GCMs, namely, CGCM3.1, FGOALS-G1.0, and HadGEM1 models, respectively.

3.1.3. Changes in the Drought Events. Figure 6 shows the probability density function (PDF) of the SPEI by the threshold level during the *Boro* paddy cultivating season in northwestern and southwestern regions under current and future climate change conditions at monthly time scale. The total SPEI values <-1 during January to May at current period (1984–2013) are mainly normally distributed according to the mathematical principle of the SPEI procedure. The results reveal that the PDFs become broader with future time and peak probability distribution will increase in the near future for the period between 2041 and 2070 in comparison to the observed period. For instance, Dinajpur subregion shows a severe increased drought events in terms of intensity and frequency under A1B scenario using future model 3 (HadGEM1 GCMs). In addition, Rajsahhi and Bogra subregions exhibit more drought intensity in potential future climate change compared to the current period. The results show that the PDFs will move the upper tail continuously toward the mid-century period and also shift to some extent in left side (Figure 6).

Figure 6 exhibits the trend of a higher increase in the SPEI <-1 in Khulna and Satkhira in future period compared to the others subregions in the southwestern Bangladesh. Comparing to drought events in the southwestern region with the northwestern region, it is obvious that the PDFs of monthly total SPEI values below -1 in the *Boro* paddy cultivated area will change drastically in the near future. The future model 1 (CGCM3.1 GCMs) and future model 2 (FGOALS-G1.0 GCMs) indicate that frequency of extreme drought events (SPEI < -1) is expected to increase dramatically in the western Bangladesh. It is worth mentioning that the risk of extreme drought events tends to increase in future climate conditions. Besides, drought frequency and intensity imply a steady increase from the current to mid-century periods, because the PDFs of SPEI values shift more than one and a half standard deviation, peaking at -1.5 in all the subregions of western Bangladesh during that period. The results of three GCMs show that the upper tail of PDFs will become thicker in future period (Figure 6). The study indicates that the PDFs of drought events will continue to move upward in future period compared to the current period. The results demonstrate that the northwestern region will increase a severe drought frequency and levels of intensity in comparison with the southwestern region in the near future.

3.2. Spatial Variation in Drought Hazard under Climate Change. The spatial variation in drought hazard (DH) for each subregion in western Bangladesh is computed based on the LARS-WG downscaled precipitation and temperature data for the period between 2041 and 2070. Figure 7 displays the spatial distribution in DH during the *Boro* rice growing season using the results of future 1 (CGCM3.1 GCMs), future 2 (FGOALS-G1.0 GCMs), and future 3 (HadGEM1 GCMs) models, respectively.

The DH value in the northwestern region ranges from 1.80 to 2.61 for the current period, with the highest DH value distributed in Rajshahi subregion and the lowest DH value exhibited in Rangpur subregion. Conversely, the DH value in the southwestern region ranges between 2.39 and 3.76 during the baseline period (1984–2013). The highest DH value was found in Satkhira subregion while the lowest DH value was distributed in Faridpur subregion. The obtained results indicated that the amplitude of DH was much larger in the southwestern region than the northwestern region during the period of 1984 to 2013. The findings are consistent with the earlier studies of Abedin et al. [48] and Abdullah [15]; they reported that southwestern coastal region is much drought-prone in comparison to the rest of the country. But the findings of Shahid and Behrawan [14], Alamgir et al. [16], and Islam et al. [49] disagree with the present observation of drought hazard analysis. They found that drought posed a high risk to northern and northwestern part than southern and southwestern parts of Bangladesh in the current period. Shahid and Behrawan [14] used only monthly rainfall data for the period of 1961–1999 with old datasets in the western part of Bangladesh and did not consider temperature data. The present study has taken into consideration both precipitation and temperature data (1984–2070) under current and future climate change conditions in the winter *Boro* paddy growing season of western Bangladesh. This is the reason that the findings are not consistent with those previous studies. In the near future period (2041–2070), especially the northwestern



(a) Dinajpur (b) Rangpur (c) Bogra (d) Rajshahi (e) Faridpur (f) Khulna (g) Satkhira (h) Barisal

Figure 6: The probability density function (PDF) of SPEI values by the threshold level during January to May for the A1B scenario using the three GCMs outputs in the northwestern and southwestern regions. The black, red, blue, and green lines represent the PDFs during the observed period (1984–2013), future 1 (CGCM3.1 GCMs), future 2 (FGOALS-G1.0 GCMs), and future 3 (HadGEM1 GCMs) models, respectively, for the period (2041–2070).

region, the DH increases using the three GCMs results, with ranges between 2.03 and 2.91, 1.92 and 2.78, and 1.99 and 2.73, respectively. Dinajpur subregion reveals the largest DH value except future 3 GCMs model results where Rajshahi exhibits the highest DH values and Rangpur displays the smallest DH value in the northwestern region in the mid-century period. On the other hand, in the southwestern region, the DH decreases almost half under three GCMs using the A1B scenario compared to the current period, with the ranges from 1.17 to 2.20, 1.38 to 2.77, and 1.48 to 2.78 correspondingly. The highest DH value was observed in Khulna subregion and the lowest DH value was detected in Faridpur in future climate condition. The DH value showed a gentle increasing trend in northern and western part of northwestern region than southern part of southwestern region for the period of 2041 to 2070. Such findings are consistent with the previous study of Hossain et al. [50] who revealed that future climate change will increase both frequency and magnitude of severe drought events in the northwestern region. The results of Selvaraju and Baas [34] are also in good agreement with this outcomes at future climate change condition. Under climate change scenario for the 2050, they reported that future drought will be increased in the northwestern to central region of Bangladesh. The study demonstrates that the amplitude of DH variations will increase slightly in the northwestern region and flatten with a decrease in the southwestern region under future climate change conditions. From the analysis results of three GCMs, potential drought hazard areas will shift from the south toward the north and northwest parts of the country in future. It is evident from the study that the high DH occurs in February during the paddy growing season and low DH in April for the current period, but it will shift under future climate change conditions that the high DH will happen in January and low DH in April. It is not surprising that more areas in the northwestern region will be exposed to the severe drought hazard due to the projected

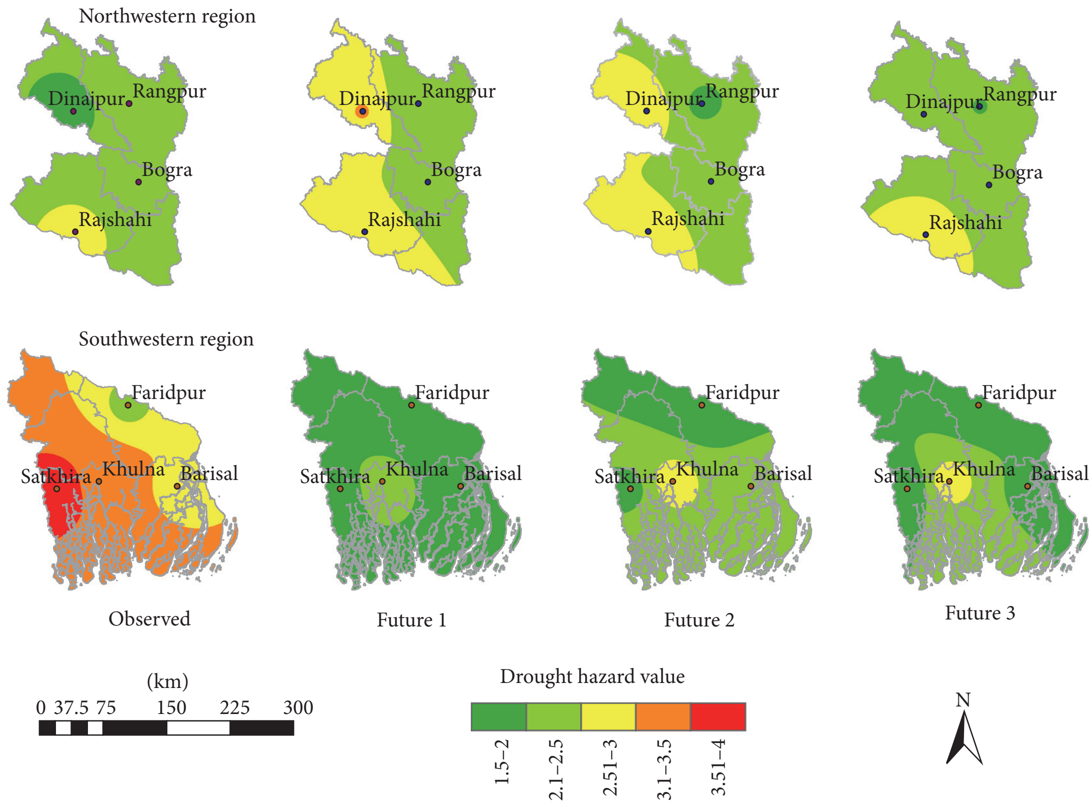


Figure 7: The spatial distribution maps show drought hazard during the Boro paddy growing season of western Bangladesh for future period (2041–2070) relative to the observed period (1984–2013). Three GCMs denote future 1 (CGCM3.1 GCMs), future 2 (FGOALS-G1.0 GCMs), and future 3 (HadGEM1 GCMs) model, respectively.

change in rainfall patterns and PET frequencies with future climate change condition.

4. Conclusions

This study presents the drought hazard index in terms of drought frequency and intensity to evaluate the *Boro* paddy growing season drought hazard in western Bangladesh. We simulated a climate database for future periods (2041–2070) by the downscaled LARS-WG model using the outputs of three GCMs, namely, CGCM3.1 (Canada), FGOALS-G1.0 (China), and HadGEM1 (UK) based on the SRES A1B scenario. The study provides a comprehensive idea about the frequency and intensity of drought events during the *Boro* rice growing season at present and future climate change conditions. The results show that changes in precipitation are fairly varied, with some decrease in the northwestern region and an increase in the southwestern region in future period between 2041 and 2070. The overall increase in PET is closely related to rises in temperature and surface net radiation that dominates in the both regions of Bangladesh. The PET and precipitation exhibit upward trends, implying that the increased rate of precipitation is not outweighed the PET. In this study, the SPEI is used to quantify future drought changes, and the increases in PET with surface warming are anticipated to make more drought events in future. From the results of three GCMs, drought hazard will marginally increase in the northwestern region and a decrease in the southwestern region in the mid-century period. The most important finding is that high drought hazards in the northwestern region are mainly due to the increased rate of PET exceeding that of precipitation in changing climate. In addition, potential drought hazard region will shift from the southwest to northwest parts of the country in the near future, as projected by using the three GCMs.

It is noted that the results of three GCMs using the simulated precipitation and temperature data and uncertainties of the downscaled LARS-WG model to employ a single scenario may have caused some setback in the accuracy of our results. Future studies concentrating on the following will be necessary: comparing different GCMs results in multiple scenarios, improving downscaled method, assessing drought risk from the drought hazard combined with vulnerability, and exposure to the whole *Boro* cultivated area of the country. Since the projected change of rainfall patterns and PET frequencies under climate change condition, particularly in context of global warming having a severe impact on drought, it is essential to formulate the suitable drought adaptation policies and effectively implement these policies with a better provision from the government and nongovernment organizations (NGOs). It can be said that priority should be given in the northwestern region compared to the southwestern region for making future drought management strategies of Bangladesh. As this study evaluated the drought hazard in the *Boro* cultivated areas, it is anticipated that this will be a helpful guide to understanding drought events and aid in formulating a broad adaptation strategy under future climate change condition to overcome the drought problem successfully in the western Bangladesh.

Disclosure

Abu Reza Md. Towfiqul Islam is the first author.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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