Spatio-temporal patterns of rainfall variability in Bangladesh

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Abstract: Bangladesh is experiencing a more rapid warming trend compared to the global average, facing significant climate-related risks. This study gave a comprehensive assessment of rainfall variability across the whole Bangladesh during 1989–2022. Annual rainfall in Bangladesh exhibited significant decreasing trends and high oscillation patterns. The multi-scale SPI and SPEI analysis revealed that Bangladesh experienced severe droughts in 1995, 1999, 2018, 2021 and 2022. The DFA revealed that rainfall evolution exhibited

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significant long-term positive correlation in almost Bangladesh. These results will support policymakers in Bangladesh to develop suitable strategies in mitigating climate change impacts.

Keywords: rainfall variability; pattern analysis; inter-annual oscillations; drought evolution; long-range correlation; Bangladesh.

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1 Introduction

Climate change has been the most significant global challenge for the world since the 19th century, posing a threat to people's basic needs and well-being. Compared with pre-industrial level, global mean temperature was projected to have an increase of 1.4–5.8ºC by 2100, with likely 1.5ºC and possible 2.0ºC rises (IPCC, 2022). Changes in global climate patterns pose potential risks to long-term rainfall patterns, water availability, and an increased likelihood of both droughts and floods, especially for poor countries with heavy reliance on rain-fed agriculture rainfall patterns. Therefore, examining spatiotemporal dynamics of climate system in rain-fed agriculture regions is crucial for assessing climate-induced changes and proposing suitable strategies for local residents in poor countries. Bangladesh is experiencing a more rapid warming trend compared to the global average (Rahman and Lateh, 2017), facing significant climate-related risks, including floods, cyclones, drought, saline water intrusion, sea-level rise, and heavy monsoon downpours. These risks lead to severe issues including the destruction of agricultural land, crop losses, livelihood disruptions, economic damages, biodiversity depletion, environmental degradation, and psychiatric instability (Hossain et al., 2019).

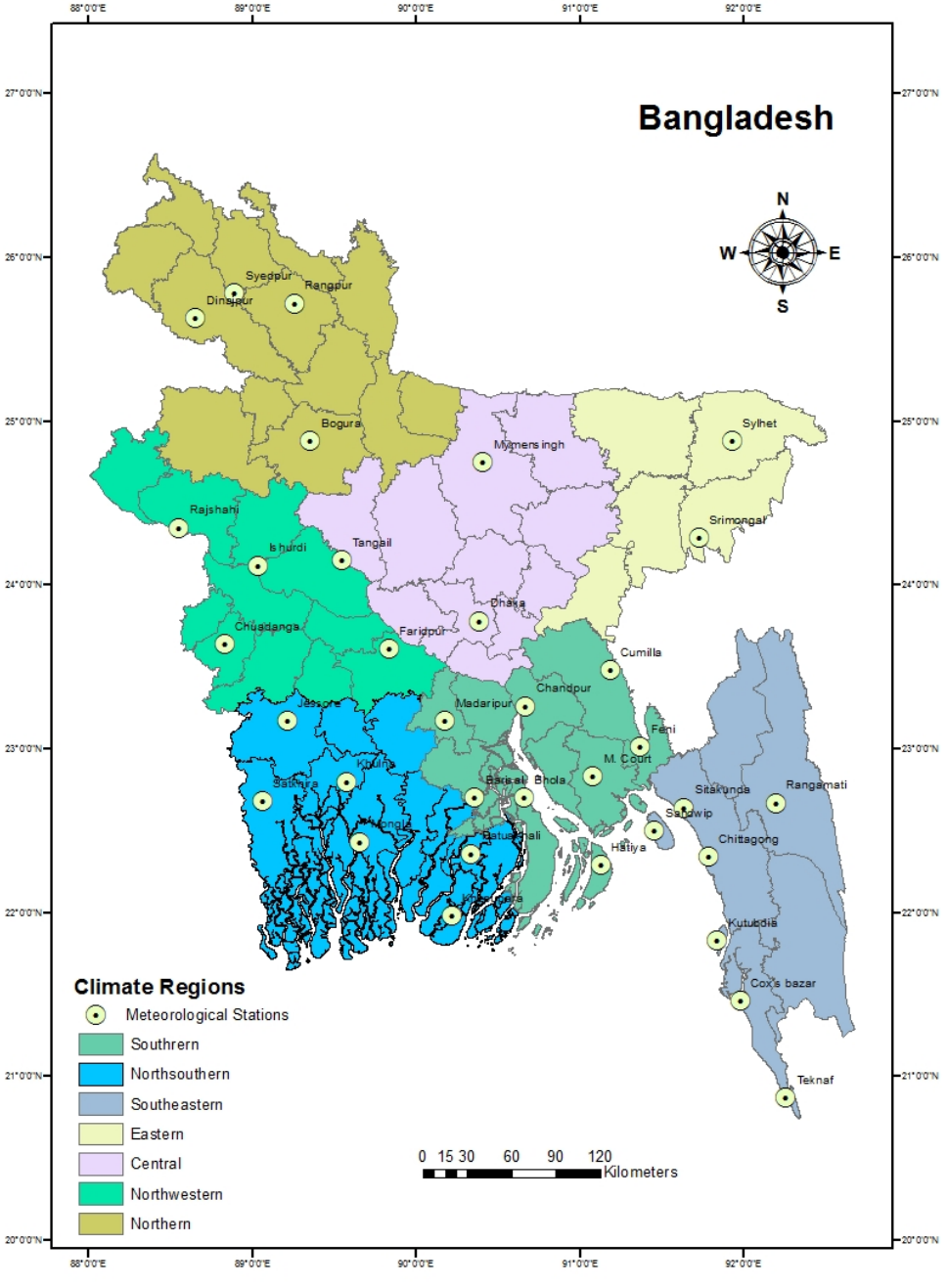
Climatic warming intensifies thermodynamic conditions, leading to increase monsoonal rainfall. This benefits main crops like rice but also causes flash floods during the monsoon season (Kamruzzaman et al., 2023). As Bangladesh is located on the delta plain at the lower reaches of the Ganges, Jamuna and Megna rivers in the northeast of the South Asian subcontinent, its terrain is flat and its river network is dense, leading to low ability to cope with climate disasters. Bangladesh has been rated as the most vulnerable country in the world by the IPCC. The increasing severity and frequency of extreme rainfall events have caused serious losses for socio-economic development of Bangladesh (Hoque et al., 2020; Rahman et al., 2017), especially, the agriculture is the backbone of Bangladesh's economy, leading to that changes of monsoonal rainfall directly affect the agriculture production and life of the people of Bangladesh (Banerjee et al., 2015; Agrawala et al., 2003).

Various statistical techniques have been analysed, developed, and applied to detect evolution changes and patterns embedded in observed and simulated climate data. In this study, we will give a comprehensive assessment of rainfall variability across the whole Bangladesh. We employing MMK test and Sen's test to reveal significance and distribution of rainfall trends, empirical orthogonal functions (EOFs) to reveal spatial modes, power spectra analysis to detect Inter-annual oscillations, SPI and SPEI to assess the drought evolution and detrended fluctuation analysis (DFA) to retrieves long-range correlation of rainfall fluctuations. These results will support policymakers in Bangladesh to develop strategies aligned with environmental needs for sustainable economic and environmental outcomes.

2 Study area and data

Bangladesh is a South Asian country with a subtropical climate, great plains with fertile soil, and a long coastline along the Bay of Bengal. Bangladesh is situated between 88.68°E and 92.97°E longitude and 20.87°N to 25.78°N latitude, bordered by the Bay of Bengal to the south, Myanmar to the southeast, and India on other sides (Figure 1). The whole country consists of primarily a flat deltaic plain with low elevation, experiencing a humid subtropical climate and frequent river floods due to tropical cyclones and tidal bores, while Sylhet region gets the highest precipitation due to its proximity to the Himalayan foothills. Bangladesh has three distinct seasons: hot and muggy summer (March–June), monsoon (June–October) with heavy rain, and chilly dry winter (November–February). Bangladesh has experienced average temperatures around 26°C, ranging between 15°C and 34°C annually. Its annual precipitation in Bangladesh ranged from 852 mm to 5,944 mm, with Chuadanga recording the lowest in 2010 and Sylhet the highest. The rainfall during monsoon seasons lasting from June to September contributed around 80% of the total rainfall (Ahmed et al., 2021). This study analysed observed climate data from 34 meteorological stations provided by the Bangladesh Meteorological Department from 1989 to 2022, including daily rainfall, maximum, and minimum temperatures. Figure 1 illustrates the geographical distribution of these weather stations across Bangladesh.

Figure 1 The distribution of 34 meteorological stations over seven regions of Bangladesh (see online version for colours)



3 Methodology

This study analysed climate evolutions in Bangladesh by using non-parametric methods: MMK and Sen's slope test for trend estimation, SPI and SPEI for drought detection, and DFA for long-term correlation assessment.

- *Mann-Kendall (MK) test* is one of the most widely-used non-parametric significance tests to analyse climate data collected over time for consistently increasing or decreasing trends. The MK statistic of any climatic time series is defined as:

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

  Its null hypothesis is that the data are independent and randomly ordered. However, the existence of positive autocorrelation in the data increases the probability of detecting trends by MK tests when actually none exist, so the modified Mann-Kendall (MMK) test introduced by Hamed and Ramachandra Rao (1998), addresses autocorrelation by using the following modified variance V(S):

$$V(S) = \frac{n(n-1)(2n+5)}{18}\left(1 + 2\sum_{k=1}^{n-1}\left(1 - \frac{k}{n}\right)\rho_k\right)$$

  The accuracy of the MMK test in terms of its empirical significance level was proved to be superior to that of the original MK test without any loss of power (Hamed and Ramachandra Rao, 1998).

- *Sen's slope test* is the known non-parametric tests to discover the magnitude of any trend in climatic time series. Since it is fairly resistant to outliers and data errors, Sen's slope test has great advantages over traditional parametric least-squares regression. The core steps in Sen's slope test is to calculate slopes for all pairs of ordered time points and then define the median of all slopes as the trend.

- *Standard precipitation index (SPI)* is a drought index to measure the deficiency of precipitation on various monthly and multi-monthly time scales relative to its climatology (Guttman, 1999). On short timescales, the SPI is closely related to soil moisture, while at longer timescales, the SPI is related to groundwater and reservoir storage. The Gamma distribution is used in SPI to calculate the probability distribution of precipitation. Its probability density function with parameters α and β is defined as

$$f(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} \qquad \text{for} \quad x > 0$$

  where $\Gamma(\alpha)$ is the value of known gamma function $\Gamma(x)$ at $x = \alpha$. The raw precipitation data are typically fitted to this Gamma distribution, and then transformed to a normal distribution. The SPI values are defined as the number of standard deviations (SD) by which the observed anomaly deviates from the long-term precipitation mean, so these values can characterise meteorological droughts.

- *Standard precipitation evapotranspiration index (SPEI)* is the extension version of the widely used SPI. The SPEI introduces both precipitation and potential evapotranspiration (PET) in determining drought. The idea behind the SPEI is to compare the highest possible evapotranspiration with the current water availability. Due to lack of enough observation, the Thornthwaite equation, requiring only temperature data, is often used to estimate PET in SPEI. The calculating procedure of SPEI values is similar to that of SPI values, but the SPEI uses the difference between precipitation and evapotranspiration as its input while the SPI only uses precipitation, so the SPEI value can provide a more reliable measure of drought severity than SPI values. The drought classification based on SPI/SPEI indices is outlined in Table 1.

Table 1 Classification criteria for drought indices

Category	*Description*	*Ordinal class*	*SPI and SPEI values*
W3	Extremely wet	7	2+
W2	Very wet	6	1.5 to 1.99
W1	Moderately wet	5	1 to 1.49
W0/D0	Close to normal	4	–0.99 to 0.99
D1	Moderately dry	3	−1 to −1.49
D2	Severely dry	2	−1.5 to −1.99
D3	Extremely dry	1	−2 and less

Source: McKee et al. (1993)

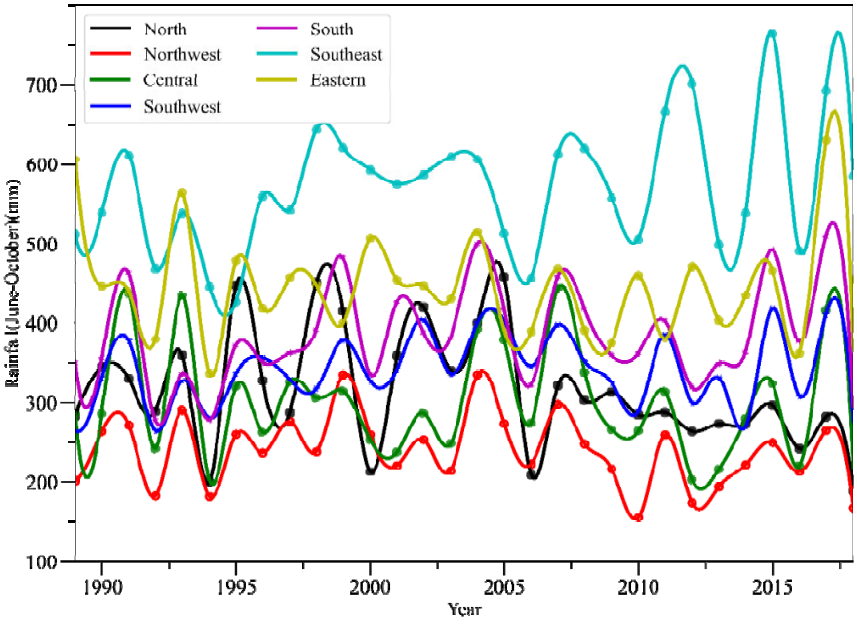
- *DFA* is a fractal technique to retrieves intrinsic self-similarity and detects scaling and long-range correlation characteristics of fluctuations in the presence of possible trends without knowing their origin and shape. The DFA exponent is interpreted as an estimation of the Hurst index in known fractal theory, i.e., the time series is uncorrelated when $\alpha = 0.5$. If $0.5 < \alpha < 1$ then there are positive correlations embedded in climatic time series, leading to that fluctuations are larger under larger time windows than expected by chance. If $\alpha < 0.5$, then there are anti-correlations, leading to that fluctuations are smaller in larger time windows than expected by chance.

4 Results and discussion

Bangladesh has a distinct monsoon season characterised by a significant increase in rainfall in the past 30 years. Generally, mean monsoonal rainfall in the whole Bangladesh showed a slightly increasing trend over the whole Bangladesh. There were six relatively wet years (1991, 1999, 2004, 2007, 2015 and 2017) and five relatively dry years (1992, 1994, 2006, 2013 and 2016). Since rainfall variability is large and rainfall during monsoon seasons contribute around 80% of the total precipitation, Figure 2 further depicts mean monsoonal rainfall over seven regions of Bangladesh. During 1989–2022, the southeastern region received the highest amount of rainfall, especially the unusual high amount (>750mm) was observed in monsoon seasons of 2014 and 2020. The eastern region received the second highest amount of rainfall with peak values >650 mm. Such

abundant rainfall is critical for rain-fed agriculture in these regions. At the same time, the northwestern region experiences the lowest amount of rainfall (<200mm) during monsoon seasons, leading to that it possibly faces water scarcity issues.

Figure 2 Mean monsoon rainfall over seven regions of Bangladesh (see online version for colours)



4.1 Trend distribution

The MMK test on annual rainfall observed in 34 weather stations in Bangladesh revealed that 10 stations showed an increasing trend, while 24 stations showed a decreasing trend. Since all P-values were greater than 0.05, suggesting that the null hypothesis should be accepted, i.e. no significant trend appeared in annual rainfall. The trend magnitudes of annual rainfall revealed by Sen's slope tests are demonstrated in Figure 3. The increasing trends in annual rainfall only appeared in Bangladesh's coastal regions and southeastern regions. This can be ascribed to the southwest monsoon's effect. On the other hand, the northwestern region showed the highest declining trend in annual rainfall. These findings underscore the importance of considering regional factors and climatic influences when analysing rainfall trends in a country like Bangladesh.

4.2 Spatial patterns

EOFs are a main stream statistical technique to identify dominant spatial patterns of climate variability. Figure 4 demonstrated the first three EOF modes of monsoonal rainfall over Bangladesh. The first EOP (EOF1) explained 42% of the total variance inside monsoonal rainfalls, and its spatial pattern exhibits a dipole structure characterised by strong positive loading in the western coastal and northeastern regions. This suggests

that these regions experienced similar rainfall patterns and received above-average rainfall during monsoon seasons. In contrast, there are strong negative loadings in the remaining regions, indicating below-average rainfall in those regions during the same season. The amplitude of the associated PC1 time series is highest in the year 2004, indicating that rainfall of the year 2004 was dominated by the spatial pattern described in EOF1. Conversely, the lowest amplitude is observed in 1994, suggesting that the rainfall pattern in 1994 had inverse spatial pattern captured by EOF1. The second EOF (EOF2) explained 12% of total variance of monsoonal rainfall and demonstrated increase trends from western to eastern regions. Strong positive loading in EOF2 are observed in the southern and southeastern regions, indicating above-average rainfall in those regions. On the other hand, strong negative loading in EOF2 are found in western coast and northern-southern regions, suggesting below-average rainfall in those regions. The amplitude of the PC2 time series reached the highest in the year 1995, indicating that rainfall in the year 1995 exhibited a prominent expression of the spatial pattern described in EOF2. The PC2 time series has negative values in most of years after 2006, suggesting an inverse pattern captured by EOF2. The third mode (EOF3) explained 8% of the total variance and demonstrated a multi-pole structure, with positive loading in the northern region and negative loading in the central region of Bangladesh. This indicates that the northern region tended to experience above-average rainfall during monsoon seasons, while the central region received below-average rainfall. The amplitude of the PC3 time series reached the highest in the year 2001, indicating that rainfall in 2001 had a prominent expression of the spatial pattern described by EOF3. After 2001, the PC3 time series demonstrated the oscillation mode around zero.

Figure 3 Sen's slope estimates of annual precipitation in Bangladesh (see online version for colours)

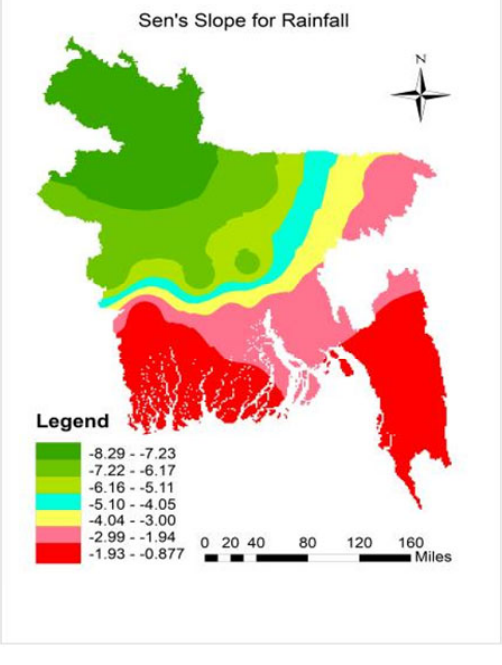
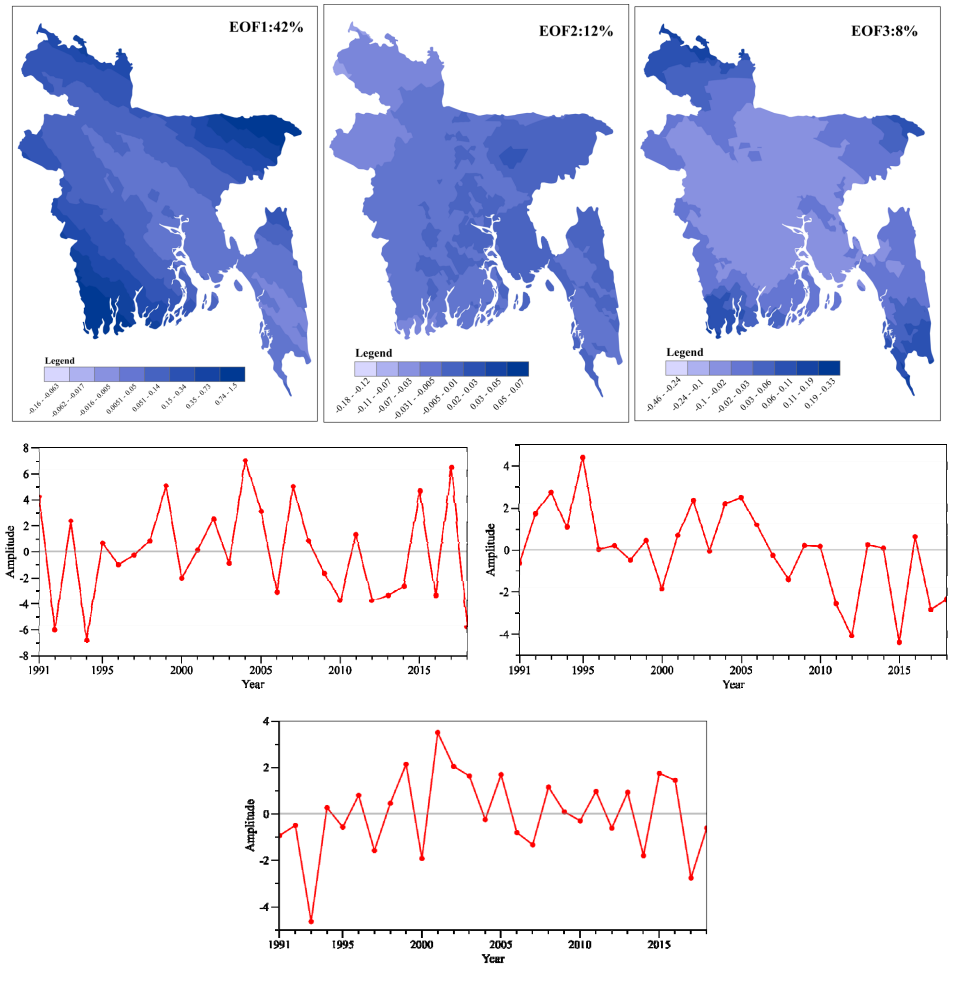


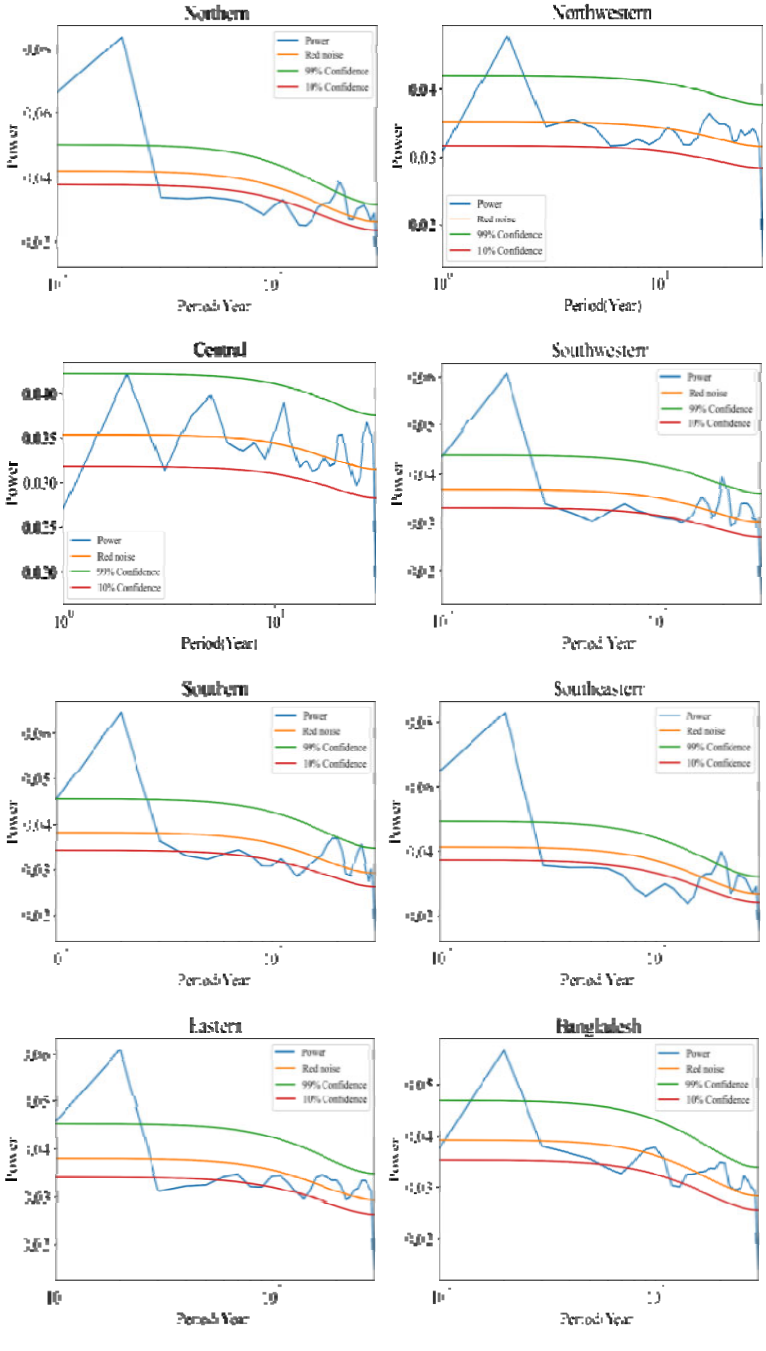
Figure 4 EOF modes and associated PC time series of monsoonal rainfall over Bangladesh (see online version for colours)



4.3 Inter-annual oscillations

The power spectra analysis is a valuable statistical technique to identify periodic variations in climate observations. The analysis of power spectra for monsoonal rainfall in Bangladesh over a 30-year period, showing significant spectral peaks at different inter-annual timescales in seven regions of Bangladesh. Significant spectral peaks appeared, at approximately 1.5 to 2.5 years (Bangladesh), 1 to 2.5 years (southwestern), 2 years (central), 1.5 to 2.5 years (northwestern), and 2.5 years (Northern, Southern, Southwestern) (Figure 5).

Figure 5 Power spectra of monsoonal rainfall over seven regions of Bangladesh (see online version for colours)



Note: The red line indicates mean red noise spectrum and the green/blue dashed line denotes the 10%–90% confidential intervals.

4.4 Drought evolution

Monthly SPI and SPEI values were calculated for 34 weather stations at five time windows (1, 3, 6, 9, and 12 months). These indices provide insights into drought conditions and water availability at various time scales. Figures 6 and 7 illustrates SPI and SPEI values, respectively, demonstrating a fluctuating pattern over time, with negative spikes (indicating dry conditions) and positive spikes (indicating wet conditions).

Figure 6 The evolution of SPI values at five time scale (1, 3, 6, 9, 12 months) (see online version for colours)



The SPI is a drought index to measure the deficiency of precipitation on various monthly and multi-monthly time scales relative to its climatology. On short timescales, the SPI is closely related to soil moisture, while at longer timescales, the SPI is related to groundwater and reservoir storage. At the 1-month time scale (SPI-1), six years experienced extreme wet conditions with SPI > 2, while nine years experienced extreme drought with SPI <-2. At the 3-month time scale (SPI-3), eight years experienced extreme drought conditions, while only three years experienced extremely wet conditions. February 1999 is identified as the peak of the most severe drought detected by SPI-3. The 6-month SPI values reveal eight years of extreme drought, with notable increases in drought frequency in 1991, 1994, 2018, 2022. At the 9-month time scale, there were three years of extreme drought and just one year of extreme wet, with the period from 2003 to

2014 predominantly dominated by drought events. At the 12-month time scale, there were three years of extreme drought and two years of extreme wetness, indicating prolonged period of intense drought from 1992 to 1997 and 2006 to 2014, representing significant precipitation deficits.

Since the SPEI uses the difference between precipitation and evapotranspiration as its input while the SPI only uses precipitation, the SPEI value can provide a more reliable measure of drought severity than SPI values. For SPEI-1, eight years experienced extreme wet conditions and five years indicate extreme drought conditions during the study period. The SPEI-3 values revealed three years of extreme drought and three years of relative moisture. In particular, a large increase in drought severity was recorded in the recent five years. The SPEI-6 values showed four years of extreme drought, with noticeable increases in drought severity observed during 1992 to 1997 and the last decade of the study. SPEI-9 indicates two years of extreme drought and one year of extreme moisture, with the period from 2009 to 2014 showing consistent drought conditions. SPEI-12 exhibits two years of extreme wetness and one year of extreme drought (Figure 7).

Figure 7 The evolution of SPEI values at five time scale (1, 3, 6, 9, 12 months) (see online version for colours)

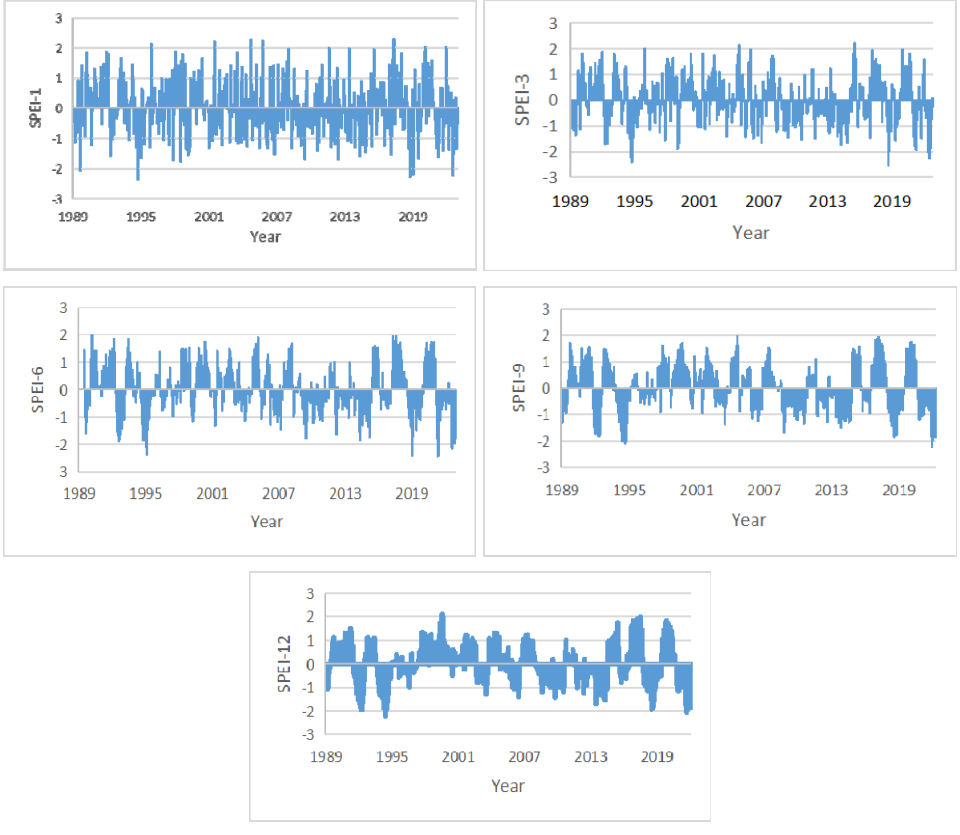


Table 2 Statistics for SPI and SPEI at different time scales during 1989–2022

Time scale	*Index*	*Mean*	*SE*	*Median*	*SD*	*Minimum*	*Year*	*Maximum*	*Year*	*Range*
1-Month	SPI	0.016	0.273	0.034	0.946	–2.991	2022	3.168	2004	6.159
	SPEI	0.017	0.273	0.009	0.946	–2.235	2022	2.298	2017	4.533
3-Month	SPI	–0.006	0.251	0.034	0.869	–3.025	1999	2.599	2004	5.624
	SPEI	0.003	0.239	0.007	0.827	–2.522	2018	2.226	2015	4.748
6-Month	SPI	–0.011	0.223	0.018	0.771	–2.643	1995	2.359	2005	5.002
	SPEI	0.004	0.210	0.007	0.764	–2.444	2021	1.984	1990	4.428
9 Month	SPI	–0.018	0.209	–0.011	0.722	–2.788	1995	2.200	2017	4.988
	SPEI	–0.017	0.21	–0.012	0.728	–2.212	2022	1.943	2005	4.155
12 Month	SPI	–0.026	0.198	–0.003	0.687	–2.848	1995	2.246	2018	5.094
	SPEI	–0.026	0.2003	–0.021	0.694	–2.244	1995	2.120	2000	4.364

Table 2 suggests that SPI and SPEI exhibit similar patterns of drought and wet conditions across different time scales. Minimum and maximum values, mean values, standard errors (SE), and SD are quite comparable for both indices. The SE and SD values for SPI and SPEI show a striking similarity across all time scales. For instance, at the 1-month time scale, both SPI and SPEI have a SE of 0.273 and their SD are 0.946. Tis suggests a consistent deviation of index values from their means for both SPI and SPEI, indicating similar variability and dispersion. The SPI analysis identifies significant drought occurrences, notably emphasising the most severe drought year in 1999 and the peak drought occurrence in February at the 3-month SPI time scale. At the 12-month time scale, the year 1995 is identified as the strongest drought year based on both SPI and SPEI, indicating severe and prolonged dry conditions during that year.

The non-parametric MMK test and Sen's slope test were utilised to analyse drought trends across various time scales in Bangladesh during the study period (Table 3). The decreasing trend was observed across various time scales, especially, the 3-month SPI/SPEI demonstrated the largest downward trends. These trends reflected the worsening drought conditions in Bangladesh in the past 30 years.

Table 3 Trends of SPI and SPEI evolutions in Bangladesh

SPI	*P value in MMK test*	*Sen's slope*	*SPEI*	*P value in MMK test*	*Sen's slope*
SPI-1	0.049	–0.009	SPEI-1	0.062	–0.008
SPI-3	0.192	–0.013	SPEI-3	0.213	–0.015
SPI-6	0.259	–0.014	SPEI-6	0.202	–0.018
SPI-9	0.389	–0.012	SPEI-9	0.441	–0.009
SPI-12	0.573	–0.006	SPEI-12	0.594	–0.004

Figure 8 DFA analysis of annual rainfall over seven regions of Bangladesh (see online version for colours)

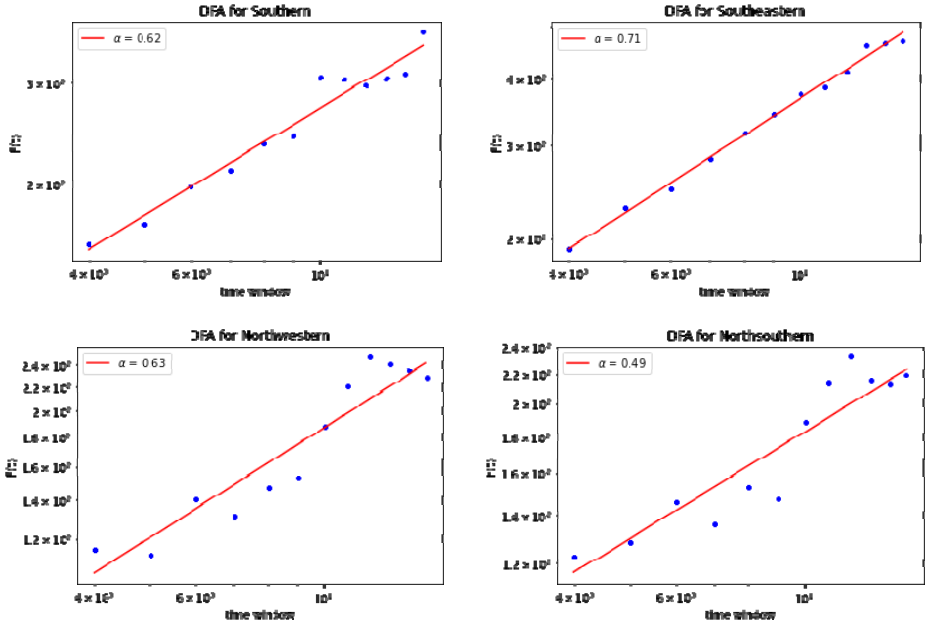
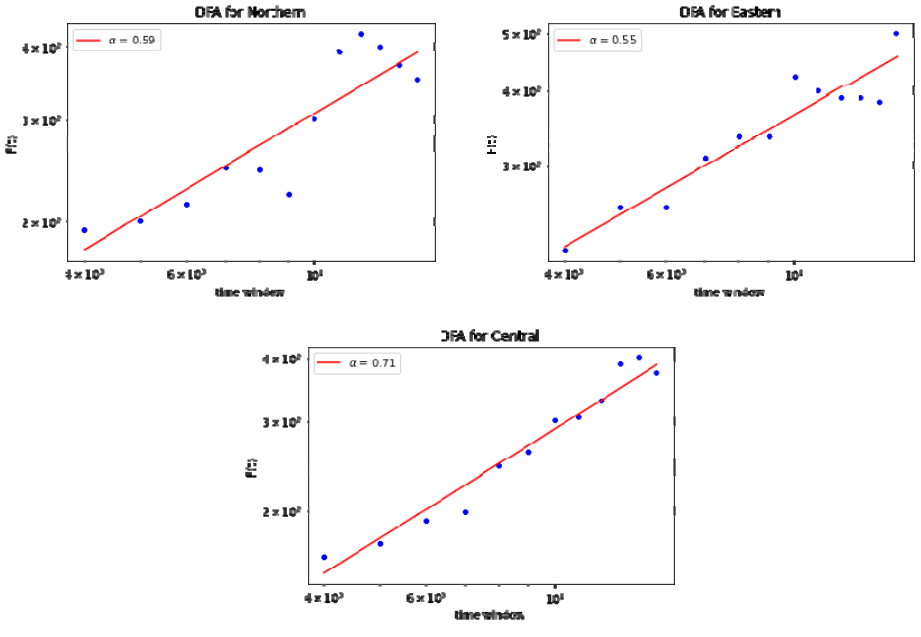


Figure 8 DFA analysis of annual rainfall over seven regions of Bangladesh (continued) (see online version for colours)



4.5 Long term correlation

The DFA results indicate long-term persistence in future rainfall trends in Bangladesh, consistent with historical observations spanning 34 years. It enables estimation of future rainfall trends and drought frequency analysis. We did a DFA to detect the long-term fluctuation of annual rainfall observed at seven regions in Bangladesh. Six regions in Figure 8 exhibited a notable long-term positive correlation with the DFA exponent α ranging from 0.55 to 0.71. The largest long-term positive correlation appeared in the southeastern region. However, the northsouthern region exhibited a slightly negative correlation, where the DFA exponent α = 0.49, a slightly lower than the threshold 0.5.

5 Conclusions

Examining spatiotemporal dynamics of climate system is crucial for assessing climate-induced changes and proposing suitable strategies for local residents in poor countries. Bangladesh is experiencing a more rapid warming trend compared to the global average, facing significant climate-related risks, including floods, cyclones, drought, saline water intrusion, sea-level rise, and heavy monsoonal rainfall. This study gave a comprehensive assessment of rainfall variability across the whole Bangladesh during 1989–2022. We used MMK test and Sen's slope estimator to dectect a substantial decline in rainfall and used spectral analysis to detect significant inter-annual rainfall oscillations at the period 1.5 to 2.5 years. The analysis of SPI and SPEI at various time scales (1, 3, 6, 9, and 12 months) revealed that Bangladesh experienced an increase in

drought severity, especially in the last decade and specific time intervals, especially extreme droughts occurred in 1992, 1994, 1995, and 1999, with SPEI-3 highlighting 1999 as exceptionally severe. The analysis of DFA revealed the largest long-term positive correlation appearing in the southeastern region of Bangladesh, which means the similar drought events will appear again in the near future. These findings are crucial for policymakers and stakeholders, guiding the formulation of effective long-term strategies for water resources, irrigation, and climate control.

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