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Quantification of rainfall, temperature, and reference evapotranspiration trend and their interrelationship in sub-climatic zones of Bangladesh

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ABSTRACT

Rainfall, temperature, and reference evapotranspiration (ET_0) have a significant influence on irrigation, aridity, flooding, and crop water requirements. The primary aims of this study were to analyze the trends in rainfall, temperature, and ET_0 in seven sub-climatic zones of Bangladesh from 1989 to 2020, as well as examine their interrelationships. The Modified Mann-Kendall method was employed to assess trends, while linear regression was used for trend validation. ET_0 was calculated using the FAO-56 Penman-Monteith method, and Sen's slope was utilized to quantify the magnitude. Spatial analysis was conducted using Inverse Distance Weighting techniques. The findings revealed that annual rainfall increased only in the south-eastern zone, while the other zones experienced a decline. No significant changes were observed in annual maximum temperature, except in the south-eastern, north-eastern, and south-central zones, which showed variations ranging from 0.02 to 0.05 (°C/year). However, the yearly minimum temperature increased in all zones. Additionally, negative changes were observed in the annual magnitude of ET_0 for all zones and seasons, except for the south-eastern and north-eastern zones, with a range of 0.01–0.02 mm/year. It was also noted that rainfall and ET_0 displayed a strong decreasing relationship, except during the pre-monsoon season. Regarding regional variation, the northern regions exhibited a significant decreasing trend in both rainfall and ET_0. The study identified key challenges, including water scarcity and irrigation difficulties due to declining rainfall and evapotranspiration, increased aridity, changing flood patterns, temperature-related impacts on crop growth, regional disparities in climate trends, and the need for effective climate change adaptation measures. Therefore, the study's findings can contribute to knowledge in areas such as irrigation scheduling, promoting climate-smart agricultural practices, encouraging crop diversification to reduce dependence on water-intensive crops cultivation, and planning resilient water resource management to minimize the effects of environmental shifts, regulate human operations, and implement disaster remedial actions in Bangladesh.

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1. Introduction

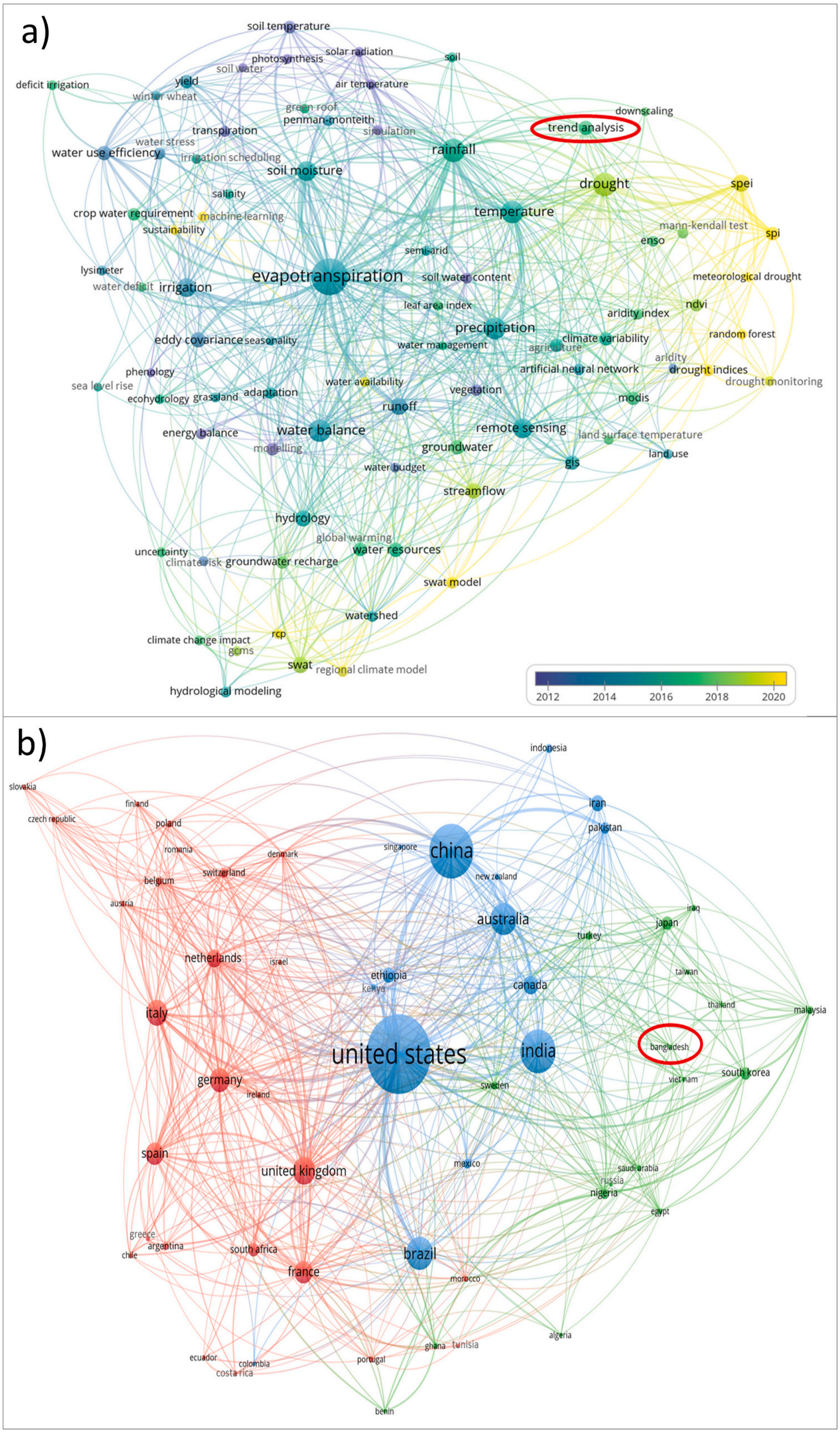
The rapidly changing pattern of climatic variables has led researchers to extensive research. Various investigations and research projects have been inspired by the extraordinary climate variability during the past several decades, particularly after observing significant shifts in regional precipitation and temperature dynamics. The diversified occurrences of rainfall sourcing extreme climatic conditions required an immediate study as it dominates water availability and crop productivity [1]. Diverse patterns and indicators of changing weather patterns derived from preliminary data demonstrate that the mean underlying earth's temperature has been climbing since the mid-nineteenth century, with the largest advancements documented since the mid-1970s [2,3]. Evapotranspiration (ET), in addition to rainfall and temperature, is a significant climatological component [4]. It has become an essential part of the water system and significantly affects agriculture, hydrology, and ecology. Furthermore, the solar radiation of 3 out of 5% in the earth contributes to the energy system and sustains a balanced energy condition [5,6]. Both the process of rainfall and the spatiotemporal trends in temperature may be subject to ET's potential dominance [7]. Additionally, it controls the frequency of heat waves [8]. As a result, ET is particularly tied to temperatures and influences precipitation, so its contribution to defining the pattern of environmental variations, together with precipitation and warmth, is critical.

According to the Intergovernmental Panel on Climate Change (IPCC), global temperatures have risen by 1.50° Celsius (°C) and are anticipated to remain at 2 °C if variations in the spatiotemporal patterns of precipitation and temperature are observed [9]. Various anthropogenic actions and environmental degradation have had a significant impact on the waterways, causing an issue with water management. Any heat flux and precipitation difference substantially affect ecosystem functioning [4,10]. Anthropogenic global warming and the potential effects of humans and domesticated livestock on the environment might worsen the dryness situation in south Asia, particularly in Bangladesh [11]. Zhongming et al. [12] reported that the last seven years had been the hottest ever recorded by a considerable scale except for 2015, 2018 and 2021. The consequences of global warming are visible in various industries, and a certain difference in precipitation could significantly influence Asia-Pacific and Bangladesh's aquaculture, cropping pattern and irrigation system [10,13]. Several regions have observed rising temperatures, as well as an increase in the frequency of calamities such as dryness, overflow, storms, extreme volume precipitation, and so on [14,15]. Li et al. [16] investigated a rise in temperature on the Tibetan Plateau. Numerous regions of North and South America, Central Asia, and eastern northern Europe are experiencing an increase in precipitation, whereas Southern Africa, South Asia, and the Mediterranean are experiencing a decrease [17,18]. Kiran Kumar & Singh [19] observed an increasing rainfall trend in the northern part of India, while Kottayil et al. [20] found the same for the southwestern coast of India. Another country located on Bangladesh's boundary is also experiencing extreme precipitation in its southwest coastal region [21]. However, in Bangladesh increased rainfall trend is found for the coastal and northern zone, while the decrease is documented for the central part [22]. This fluctuating heterogeneous observation could be the effect of increased temperature and reference evapotranspiration. Numerous investigators in distinct geographical areas have analysed precipitation and temperature trends [4,23–25].

The third greatest vital factor regulating the bulk movement and energies among the ambience and extra-terrestrial habitats, after temperature and precipitation, which are both regarded to be crucial factors determining the weather patterns, is ET [26,27]. As it is one of the key elements of the hydraulic processes, accurate assessment is necessary for various monitoring and scheduling tasks in the aquifer services sector. The reference evapotranspiration (ET_0) is an essential ingredient of the water cycle and perhaps the most difficult to understand from all the variables due to the intricate relationships between the terrain, plants, and atmospheric condition [28,29]. According to Koutsoyiannis [30], around sixty per cent of the world's yearly precipitation on the ground is reverted via terrestrial ET. Therefore, quantification and pattern assessment of ET_0 is crucial because it influences water resource management [31], hydrometeorological and ecological investigations [32], identification of farmland production and drought [33], agrarian utilization water and plant output development, moisture and water scarcity conditions, and approaches of ecosystems [34].

Several investigations have highlighted the distinction between actual evapotranspiration (ET_a) and reference evapotranspiration (ET_0), widely utilized in scientific studies. The ET_a is the volume of water transmitted from an evaporated ground to the air as liquid water vapor in a real-world scenario. ET_0, on the other hand, reflects the ambient evaporation requirement of a target ground (often a particular vegetation type with defined features), assuming an infinite water system from the field [35]. ET_0 is computed using meteorological observations and is influenced by climatic characteristics. ET_0 expresses the evaporating of the atmospheric scenario at a certain area at a particular epoch, allowing for geographical and historical measurements irrespective of land cover classes and historical variations [36]. Kovoor & Nandagiri [37] employed the Penman-Monteith approach and performed a sensitivity assessment with various evapotranspiration-influencing factors. Song et al. [38] analysed 12, Celestin et al. [39] 32, and Djaman et al. [40] 34 methods and revealed FAO-56 Penman-Monteith method is the potential one for estimation of ET_0. As shown in the preceding articles, there are several studies on statistics with various meteorological parameters, but the integrated research of rainfall, temperatures, and ET_0 at 26 meteorological stations has been scarce from 1989 to 2020 (31 years). The trend analysis provides high or low trends that might result from a normal sequence. In contrast, there were very few investigations upon where there has been an exponential rise or decline in the value of precipitation, temperature, evaporation and transpiration over the past decades, which may also demonstrate environmental change. The link between rainfall and evapotranspiration is presented to determine if water sources may be challenging in regions with low precipitation and high ET_0.

Over the past few decades, numerous studies have examined various aspects related to evapotranspiration, rainfall or precipitation, temperature, water balance, soil moisture and temperature, drought, remote sensing, machine learning, hydrological modelling, and water management and drought monitoring (Fig. 1a). After 2019, the majority of research has focused on assessing drought using machine and deep learning methods, sustainable water management, and regional climate models, indicating a concentration on the



(caption on next page)

Fig. 1. Visualization of research gap identification in meteorological parameter studies using (a) co-occurring keywords and (b) cross-country collaboration. In the figure, the red circle highlights the area requiring future research. The figures were generated using VOSviewer software with data retrieved from the Scopus database in 2023.

impacts of climate change. Few studies, however, have specifically addressed trend analysis, despite previous efforts conducted prior to 2016. It is important to recognize that climate change is a dynamic phenomenon that varies over time and across regions. Trend analysis of climatic parameters plays a vital role in improving our understanding of climate change, guiding decision-making processes, assessing impacts, managing risks, formulating policies, and advancing scientific knowledge. Presently, there is limited evidence regarding trend assessments of climatic parameters, particularly with a focus on the United States, China, India, Australia, Brazil, United Kingdom, Germany, Italy, Spain, France, Canada, and various African countries (Fig. 1b). However, we found only a limited number of studies conducted in Bangladesh.

Most studies have focused on rainfall, specifically the spatiotemporal patterns of monsoon rainfall, variability of annual rainfall, arrival and withdrawal dates of the summer monsoon period, and intra-annual and interannual variations of rainfall across different regions of Bangladesh [41–51]. However, there is limited research conducted on a regional basis. For example, the spatiotemporal variability of precipitation differs along the southwest coast, the Northern region, and various regions of Bangladesh [43,44]. Some studies have examined the relationship between rainfall, temperature, and El Niño-Southern Oscillation (ENSO), with strong connections found by Wahiduzzaman and Luo [52] but weak connections found in other studies [53]. Few studies have focused on temperature, and very few have considered combined spatiotemporal variations in temperature and rainfall at seasonal and annual

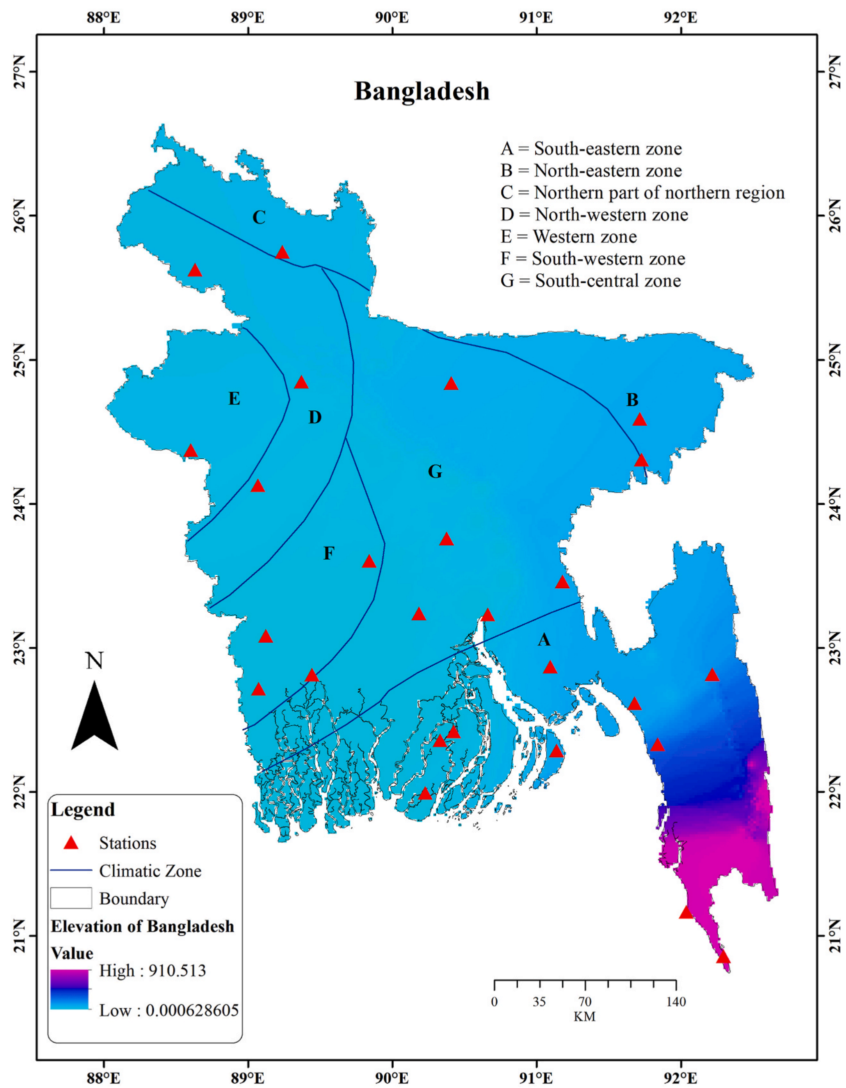


Fig. 2. Study area with climatic stations of Bangladesh (Digital elevation model of Bangladesh).

timescales for different regions and the entire country [45,50,54]. Additionally, limited attention has been given to seasonal timescales, particularly for temperature, and most studies focus on individual stations rather than a regional or national perspective. Insufficient descriptions are provided for the reasons behind spatial variation at seasonal timescales. Therefore, this study employs a range of approaches to explain the spatiotemporal variations between different regions over seasonal and annual timescales. The trends for average climatic variables in each region are tested against trends in other regions using a Modified Mann-Kendall test, which has not been done in previous studies.

This investigation comprised a trend assessment of various meteorological parameters (rainfall, maximum temperature, minimum temperature, and ET_0) to comprehend the current trend and examine the interconnections between these parameters. FAO-56 Penman-Monteith method was utilized to extract ET_0 due to its higher accuracy. Also, the correlation method shows the relationship between the stated variables. Despite the existence of multiple works on climatic tendency, there are limited analyses of the current existence of a reasonable correlation between parameters of rainfall, temperature and reference evapotranspiration. Also, in sub-climatic zones, no study considered ET_0 and rainfall trends. However, Rahman & Azim [4] observed spatiotemporal rainfall trends in sub-climatic zones with limited methodological illustrations of the Mann-Kendall trend test instead of the Modified Mann-Kendall test. Thus, the study's objectives are (i) to investigate the spatiotemporal trends and magnitudes of rainfall, temperature and ET_0; (ii) to determine the existence of relationships between rainfall, temperature, and ET_0; and (iii) to examine the overall net changes in climatic parameters across sub-climatic zones of Bangladesh. Firstly, we calculated the trend and slope coefficient from 1989 to 2020 and then validated our trend value by comparing it with linear regression. In the next step, we demonstrated the interrelationship between rainfall, temperature, and ET_0. We visualized the spatiotemporal variations in trends periodically and annually. Subsequently, we calculated the net change in these climatic parameters to gain an understanding of the overall patterns of climate change. However, to achieve our objectives, the analysis encompassed not only the annual period but also four distinct seasons: pre-monsoon, monsoon, post-monsoon, and winter. The findings of this study are crucial for agricultural irrigation scheduling and related integrated water planning applications.

This article is structured into four sections. The second section provides an explanation of the methodology following the introduction. In the third section, the study findings are presented, including the trends of meteorological parameters, their interrelationship, and an analysis of overall net changes. Furthermore, this section discusses the implications of the research findings for policy and practice. The final section of the article presents the conclusion and limitations.

2. Materials and methods

2.1. Study area

Bangladesh lies between the geographical location of 20°34′ N to 26°38′ N latitude to 88°10′ E to 92°41′ E longitude with an area of 147,610°sq km, which is the largest deltaic country in the world placed in the GBM (Ganges-Brahmaputra-Meghna) river basin [55]. According to *Banglapedia*, this country experiences pre-monsoon (March to May), monsoon (June to August), post-monsoon (September to November), and winter (December to February), which cast over seven climatic zones in Bangladesh (Fig. 2), which are southeastern region (A), northeastern region (B), the northern part of the northern region (C), northwestern region (D), western region (E), southwestern region (F), and south-central region (G) [56]. Bangladesh has a subtropical humid monsoonal climate, with the northwestern area regularly experiencing drought due to insufficient water supplies (annual mean rainfall less than 1200 mm) [57]. Western Bangladesh has always been drier than the rest of the country [58].

2.2. Data acquisition and quality control

Different data were obtained from Bangladesh Meteorological Department (BMD) from 1989 to 2020. Those data sets include rainfall, maximum temperature (T_{max}), minimum temperature (T_{min}), humidity, wind speed, and sunshine hours from 26 meteorological stations for the seven climatic zones of Bangladesh (Fig. 2). It must also be noted that BMD contains 43 stations with newly established stations, and the stations with less than 2% of missing datasets were excluded. The calculated estimates might become wrong if there are more than 2% missing variables, resulting in erroneous findings [10,59]. The homogeneity test was considered to ensure the good quality of datasets called the Standard Normal Homogeneity Test (SNHT). The SNHT and K–S results revealed data uniformity for all variables with a confidence interval of 95%. Therefore, every data set was determined to be suitable for quantitative evaluation.

2.3. FAO-56 Penman-Monteith method evapotranspiration

There are several indirect ways for estimating ET_0, but choosing the optimum approach given the available data and environmental circumstances is tricky. In recent decades, researchers have preferred to estimate reference evapotranspiration (ET_0) by using accessible daily meteorological data [60] and ET_0 prediction equations [57,61–64].

The following Eq. (1) is a representation of ET_0:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{avg}+273} W_s(e_s - e_a)}{\Delta + \gamma(1 + 0.34W_s)} \tag{1}$$

where ET_0 = reference evapotranspiration (mm day^{-1}); R_n = net radiation at the crop surface (MJ m^{-2} day^{-1}); G = soil heat flux density (MJ m^{-2} day^{-1}); T_{avg} = average daily air temperature at 2 m height (°C); W_s = wind speed at 2 m height (ms^{-1}); e_s = saturation vapor pressure (kPa); e_a = actual vapor pressure (kPa); Δ = slope of saturation vapor pressure versus air temperature curve (kPa $°C^{-1}$); γ = psychometric constant (kPa $°C^{-1}$).

2.4. Calculation for trend analysis

In time series data, serial correlation is a typical problem. The Modified Mann-Kendall (MMK) test is used to find trends in hydrological and climatic data using a variance correlation technique, which addresses the issue of serial correlation [65–72]. Therefore, in our study, we employed the MMK test to measure the trend of rainfall, temperature, and ET_0.

The data is adjusted by calculating and subtracting Theil and Sen's median slope. Next, the rankings of the observations are examined, and the autocorrelation among these rankings is assessed. A variance correction factor for positive n is necessary when dealing with positively correlated data. This is because the variance of S is often underestimated in such cases (Eq. (2)).

$$\frac{n}{n_s^*} = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{k=1}^{n-1} (n-k)(n-k-1)(n-k-2)\rho_k \tag{2}$$

where n is the actual length of data, n_s^* is the 'effective' amount of data to account for autocorrelation, and ρ_k is the autocorrelation function of ranks of the data.

The modified variance of statistics, $V^*(S)$ was proposed by Yue and Wang [65] as follows in Eq. (3):

$$V^*(S) = V(S) \times \frac{n}{n_s^*} \tag{3}$$

where V(S) is given in Eq. (4),

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \tag{4}$$

where, $\frac{n}{n^*}$ is a correction factor, and V(S) is calculated by repeating the Mann-Kendall test calculation for a detailed description [65,73,74].

The standardized test statistics Z (N (0,1)) is calculated by Eq. (5),

$$Z_{mk} = \begin{pmatrix} \dfrac{S-1}{\sqrt{V^*(S)}} \; when\ S > 0 \\ 0 \quad when\ S = 0 \\ \dfrac{S+1}{\sqrt{V^*(S)}} \; when\ S < 0 \end{pmatrix} \tag{5}$$

This Z statistic indicates the trend value of each climatic parameter.

2.5. Magnitude analysis

Sen [75] introduced the statistics of the popular slope for quantifying the shift's magnitude over time. The Sen slope estimator was used to detect the change in rainfall trends over time. He & Gautam [76] provide a detailed discussion of Sen's slope estimator calculation.

The Sen's slope is defined as in Eq. (6),

$$Sen's\ slope = Median\left\{\frac{x_j - x_i}{j - i} : i < j\right\} \tag{6}$$

A 1–α confidence interval for Sen's slope can be calculated (Eqs. (7) and (8)) as (*lower, upper*), where

$$N = C(n,2) \quad K = se.z_{crit} \tag{7}$$

$$lower = x_{(N-k)/2}\ upper = x_{\frac{N+k}{2}+1} \tag{8}$$

Here, N = the number of pairs of time series elements (x_i, x_j) where $i < j$ and se = the standard error.

2.6. Simple linear regression analysis

The statistical method of linear regression model indicates the correlation between a dependent variable and one or multiple independent variables (Eq. (9)). It presumes a linear connection between the variables, indicating that variations in the independent variables correspond to proportional changes in the dependent variable. When using linear regression, the objective is to accurately determine the coefficients of the regression equation that best align with the given data. The empirical equation is typically expressed as:

$$Y_t = \beta_0 + \beta_1 X_t + \varepsilon_t \tag{9}$$

where, Y_t is the climatic parameters, i.e., maximum and minimum temperature (°C), rainfall (mm) and ET_0 (mm) at period t; X_t is the climatic trend, i.e., year; β_0 is the intercept term; β_1 is the regression coefficient of each climatic parameters; and ε_t is the error term. A negative β_1 score indicates a downward trend, whereas a positive β_1 value indicates an ascending/upward trend.

2.7. Spatial modelling analysis

In this work, Inverse Distance Weighting (IDW) was utilized as a common and straightforward interpolation approach [77–80]. This strategy is commonly used to figure out unknown hydrological or geographic information. According to this method, each measurement origin has a local effect that diminishes with distance. The impact of an intentional point is weighted based on the distance from an investigated highlight, which is an inexact point.

Following the IDW method formula (Eq. (10)),

$$Z(S_0) = \sum_{i=1}^{N} \lambda_i Z(S_i) \tag{10}$$

Here, $Z(S_0)$ denotes the interpolated value at point S_0, Z (S_i) represents the observed value at a point (S_i), n represents the number of observations, and, λ_i represents the weight. Eq. (11) can be used to calculate the weights λ_i.

$$\lambda_i = \frac{d_{i0}^{-p}}{\sum_{i=1}^{N} d_{i0}^{-p'}}, \sum_{i=1}^{N} \lambda_i = 1 \tag{11}$$

Here, p represents power and d_{i0} is the distance between a target and observations.

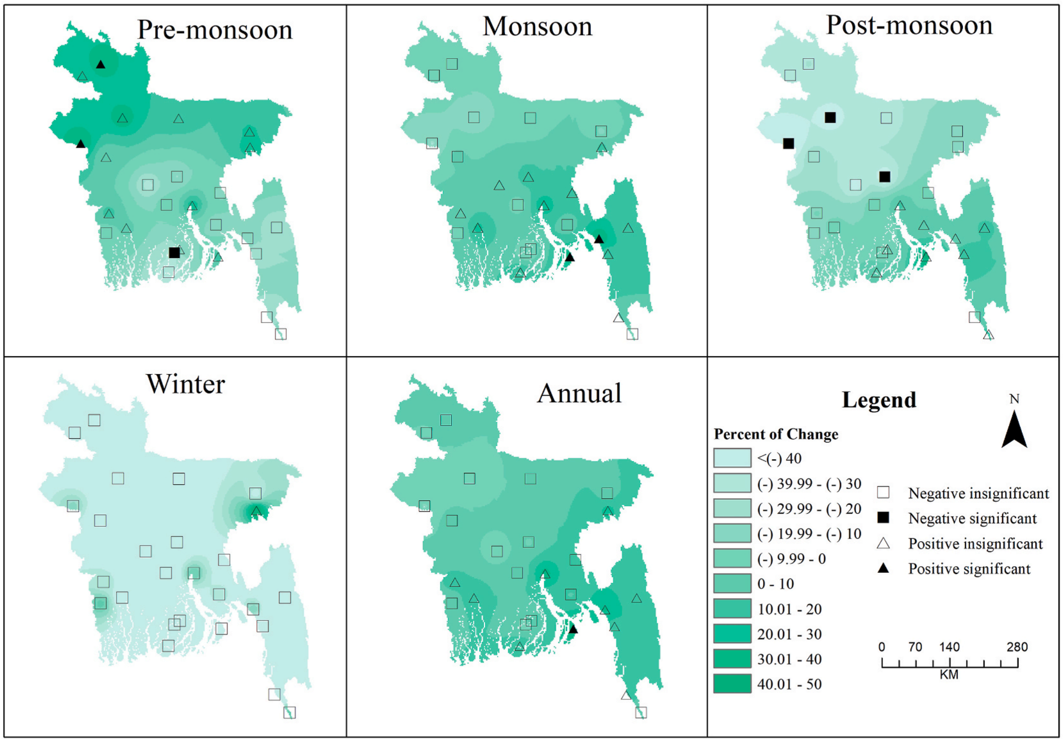


Fig. 3. Spatial distribution of rainfall trend in sub-climatic zones at 95% confidence interval.

2.8. Overall net change analysis

The overall net change is calculated (Eq. (12)) using the rate of change method for two periods, as described by Kundu et al. [81].

$$ONC = \frac{\sum_{t=1}^{n}\left(\frac{MP_t - MP_{t-1}}{MP_{t-1}}\right)}{T} \tag{12}$$

where, ONC is the overall net change, MP_t is the meteorological parameter in period t, MP_{t-1} is the meteorological parameter in period t-1, and T is the total number of study period.

3. Results and discussion

3.1. Rainfall trend and magnitude

Fig. 3 illustrates the significance of rainfall trends in sub-climatic zones and the spatial pattern of the percentage of changes in multiple meteorological stations. Both zone-based and station-based representations greatly enhance the spatial resolution of the results, capturing micro and macro spatial variations. Notably, during the pre-monsoon season, substantial rainfall was observed in the northern, north-western, and certain eastern regions of Bangladesh, in contrast to the declining trend observed in other areas of the country. The northern region exhibited the most substantial percentage change in rainfall (Fig. 3). Furthermore, sub-climatic zones E, C, and B exhibited a dominant increasing trend in the Z statistics (trend value) with values of 2.06, 2.08, and 1.35 mm, respectively, while other sub-climatic zones experienced a decline in rainfall (Table 1). Conversely, a different pattern is noticed during the post-monsoon season, with a rising trend observed in the southern and south-eastern parts, particularly where only zone A demonstrates a positive trend of 1.18 mm (Fig. 3 and Table 1). The monsoon season played a significant role in rainfall patterns in Bangladesh, displaying variable onset dates across different stations within sub-climatic zones. However, an upward trend was observed only in zone A, with a Z statistic of 1.05 mm, while most sub-climatic zones experienced a declining trend (Table 1). During the winter season, all zones and stations experienced a notably negative trend, with C, G, D, and A displaying a particularly steep decline of −1.62, −1.27, −1.25, and −1.20 mm, respectively. The monsoon trend was influential in the annual variation across different sub-climatic zones. Similarly, an increasing trend was observed in monsoon rainfall for zone A, with a value of 0.11 mm for the annual season. Consequently, a consistent upward trend was identified for zone A across all seasons, except for the pre-monsoon and winter periods. During the post-monsoon season, the Sen's slope estimator revealed the lowest trend magnitudes for zone C (−2.09 mm/year) and E (−2.34 mm/year). Also, the annual season exhibited a negative trend in both zone C (−0.56 mm/year) and zone E (−0.76 mm/year), along with the addition of zone D (−0.61 mm/year). However, an increased magnitude of change was only observed in different zones during the pre-monsoon season, including zone B (1.89 mm/year), zone C (1.76 mm/year), and zone E (1.14 mm/year). Consequently, only zone A in the monsoon season displayed a positive magnitude of change of 1.57 mm/year, while other zones and seasons primarily experienced a declined negative magnitude in the trend of rainfall. In Bangladesh, the percentage of changes consistently remained higher in zones A, B, and G during most seasons, except for the monsoon season, where the percentage of changes was highest in zone D and across the country. This indicates an opposite spatial pattern during the monsoon season compared to the rest of the seasons. These findings confirmed with the recent study [4]. Therefore, the decrease in rainfall variation in Bangladesh was associated with the cause of orographic rain. Shahid & Khairulmaini [82,83] also documented an elevation in sea surface temperature due to the effects of global warming, indicating a shift in precipitation in zones A, B, and parts of G, respectively. In addition, ENSO has significant dynamic variables that influence atmospheric airflow during the onset and completion of the monsoon season, resulting in variations in rainfall patterns in Bangladesh [84]. Our study suggests that water resource management and irrigation practices should consider the decreasing trend in rainfall, particularly in the northern regions where a significant decreasing trend was identified. Strategies such as water storage, rainwater harvesting, and efficient irrigation methods may be necessary to mitigate the impact of decreasing rainfall on agricultural activities.

The pattern of rainfall in Bangladesh has undergone a significant change, with an evident increase in monsoon season rainfall while rainfall in other seasons has remained relatively stable. This change can be attributed to the moist air brought by the summer monsoon flow from the Bay of Bengal, resulting in widespread rainfall across the country [48]. Ahmed and Kim [48] further illustrated that the northeast and coastal southeast regions experience prolonged episodes of consecutive rainy days due to the additional influence of geographic uplift from the Meghalaya Plateau. However, the shift in rainfall distribution poses a serious threat to rice production, particularly rainfed rice farming, as it increases the risk of drought and reduces the diurnal temperature range [85]. To safeguard rice production and mitigate the adverse impacts of these climate changes, it is crucial to develop drought-tolerant, heat-resistant, and water-efficient rice varieties that require less irrigation water and can thrive in high temperatures [85]. Additionally, the scarcity of rainfall in certain regions has negative impact on domestic activities, industrial production, declining groundwater levels, and ultimately, the irrigation system. To adapt to these changing climatic conditions successfully, it is essential to prioritize research aimed at adjusting crop calendars and optimizing cropping patterns [85]. The establishment of effective early warning systems and improved water reservoir systems can also contribute to coping with this evolving scenario [86]. By implementing these strategies, we can enhance the resilience of crop cultivation and mitigate the potential challenges posed by climate change.

Table 1
Trend and magnitude of rainfall, maximum temperature, minimum temperature and reference evapotranspiration in the Sub-climatic zones of Bangladesh.

Weather parameters	Season	South-eastern region		North-eastern region		Northern region		North-western region		Western region		South-western region		South-central region	
		Z values	Sen's slope	Z values	Sen's slope	Z values	Sen's slope	Z values	Sen's slope	Z values	Sen's slope	Z values	Sen's slope	Z values	Sen's slope
Rainfall	Pre-monsoon	−1.02	−0.93	1.35	1.89	**2.08**	1.76	0.47	0.37	**2.06**	1.14	−0.47	−0.37	−0.11	−0.16
	Monsoon	1.05	1.57	−0.28	−0.41	−0.37	−1.00	−0.63	−0.88	−1.02	−1.33	0.24	0.37	0.57	0.99
	Post-monsoon	1.18	0.82	−0.03	−0.07	−1.22	−2.09	−1.57	−1.63	**−2.79**	−2.34	−0.79	−0.71	−1.02	−1.05
	Winter	−1.20	−0.27	−0.24	−0.06	−1.62	−0.21	−1.25	−0.14	−0.15	−0.02	−0.71	−0.22	−1.27	−0.28
	Annual	0.11	0.10	−0.11	−0.07	−0.89	−0.56	−0.89	−0.61	−1.64	−0.76	−0.63	−0.26	−0.41	−0.37
Max Temp	Pre-monsoon	**3.75**	0.05	**2.16**	0.04	−0.06	0.00	−0.02	0.00	0.00	0.00	0.86	0.01	1.28	0.02
	Monsoon	**5.24**	0.04	**3.65**	0.00	**3.57**	0.04	**4.01**	0.04	**4.52**	0.06	**3.99**	0.04	**4.01**	0.03
	Post-monsoon	**4.46**	0.04	**4.33**	0.00	**4.74**	0.04	**3.97**	0.03	**4.28**	0.04	**3.65**	0.03	**3.91**	0.03
	Winter	**2.74**	0.03	**2.77**	0.05	0.36	0.00	−0.60	−0.01	−0.21	0.00	0.05	0.00	0.47	0.01
	Annual	**4.78**	0.04	**4.14**	0.04	**2.45**	0.02	1.96	0.01	**2.45**	0.02	**3.00**	0.02	**3.26**	0.02
Min Temp	Pre-monsoon	−0.05	0.00	0.26	0.01	**2.64**	0.03	1.64	0.02	**2.11**	0.04	0.83	0.01	0.50	0.01
	Monsoon	**3.13**	0.02	**4.36**	0.02	**2.58**	0.02	**3.86**	0.03	**4.05**	0.03	**3.29**	0.02	**3.62**	0.02
	Post-monsoon	0.57	0.01	0.76	0.01	**2.12**	0.03	1.64	0.02	1.07	0.01	1.22	0.01	1.51	0.01
	Winter	−0.76	−0.01	1.96	0.03	1.90	0.03	1.12	0.02	1.59	0.02	1.31	0.02	1.93	0.03
	Annual	0.99	0.01	**2.61**	0.02	**3.81**	0.03	**2.64**	0.02	**2.35**	0.03	**2.77**	0.02	**3.26**	0.02
ET_0	Pre-monsoon	1.59	0.01	**2.45**	0.02	**−3.84**	−0.02	−1.61	−0.01	−1.90	−0.01	−1.64	−0.01	1.18	0.01
	Monsoon	**2.25**	0.01	**2.30**	0.01	**−4.79**	−0.02	0.00	0.00	0.34	0.00	0.75	0.00	0.76	0.00
	Post-monsoon	**3.39**	0.01	**4.28**	0.01	−0.52	0.00	**2.01**	0.01	1.55	0.00	1.27	0.00	**2.43**	0.01
	Winter	**2.48**	0.01	**3.70**	0.01	0.89	0.00	−0.96	0.00	**−2.38**	−0.01	−1.27	0.00	**2.09**	0.01
	Annual	**3.52**	0.01	**4.14**	0.01	**−3.16**	−0.01	−1.14	0.00	−1.25	0.00	−0.89	0.00	1.48	0.00

Bold values refer to statistical significance at 95% confidence level.

3.2. Maximum temperature trend and magnitude

The spatial analysis of the pre-monsoon season's maximum temperature trend revealed a significant upward trend in zone A (3.75 °C), B (2.16 °C), and G (1.28 °C), indicating that the south-eastern, north-eastern, and south-central regions experienced higher maximum temperatures compared to other regions due to reduced cloud cover and increased insulation [50,54]. In contrast, other zones showed insignificant temperature changes, except for zone D with a negative trend of −0.02 °C (Fig. 4 and Table 1). The post-monsoon season exhibited an increasing temperature trend across all sub-climatic zones, ranging from 3.65 to 4.75 °C. Similarly, the monsoon and annual maximum temperature trends were exceptionally high for all the zones, with variations between 3.57 and 5.24 °C for the monsoon season and 1.96–4.78 °C for the annual observations (Fig. 4 and Table 1). During the summer monsoon season, the presence of atmospheric moisture content and cloud cover is most prominent. This phenomenon leads to efficient absorption of outgoing long wave radiation, resulting in heat retention during nighttime [54]. Although zones C, D, E, and F showed no significant changes in temperature magnitude, zones A, B, and G exhibited noticeable increases ranging from 0.02 to 0.05 °C/year. Similar increases in temperature magnitude were observed for the monsoon and post-monsoon seasons, ranging from 0.03 to 0.04 °C/year, except for zone B. Annually, a significant upward magnitude of temperature was found for zone A and B, with a trend of 0.04 °C/year. The remaining zones showed a rise of 0.02 °C/year in temperature trend, except for zone D with a trend of 0.01 °C/year (Table 1). In the zones A, B, and G, the percentage changes of maximum temperature remain consistently higher throughout all seasons, except for the monsoon season. Conversely, the western part (zone D) of Bangladesh experienced a higher percentage change during the monsoon season.

These temperature variations have implications for the frequency and intensity of heatwaves, posing significant risks to human health [87]. Temperature also plays a crucial role in plant development, with the process of pollination being particularly sensitive to temperature extremes, which can significantly impact production across species [88]. Maize, in particular, experiences a substantial reduction in grain yield, reaching up to 80–90% under higher temperature conditions during the reproductive stage [89]. Global studies estimate that a one-degree Celsius increase in the global mean temperature would result in average reductions of 6.0% in wheat yields, 3.2% in rice yields, 7.4% in maize yields, and 3.1% in soybean yields [90]. In Bangladesh, the negative impact of maximum temperature on crop yields has been statistically significant for most crops, except Aus rice [91]. Therefore, it is crucial for relevant authorities to prioritize the development and adoption of drought-tolerant crop varieties, particularly in the Kharif-II season, and understand the interaction between temperature and water in developing effective adaptation strategies to mitigate the impacts of extreme temperature events associated with climate change.

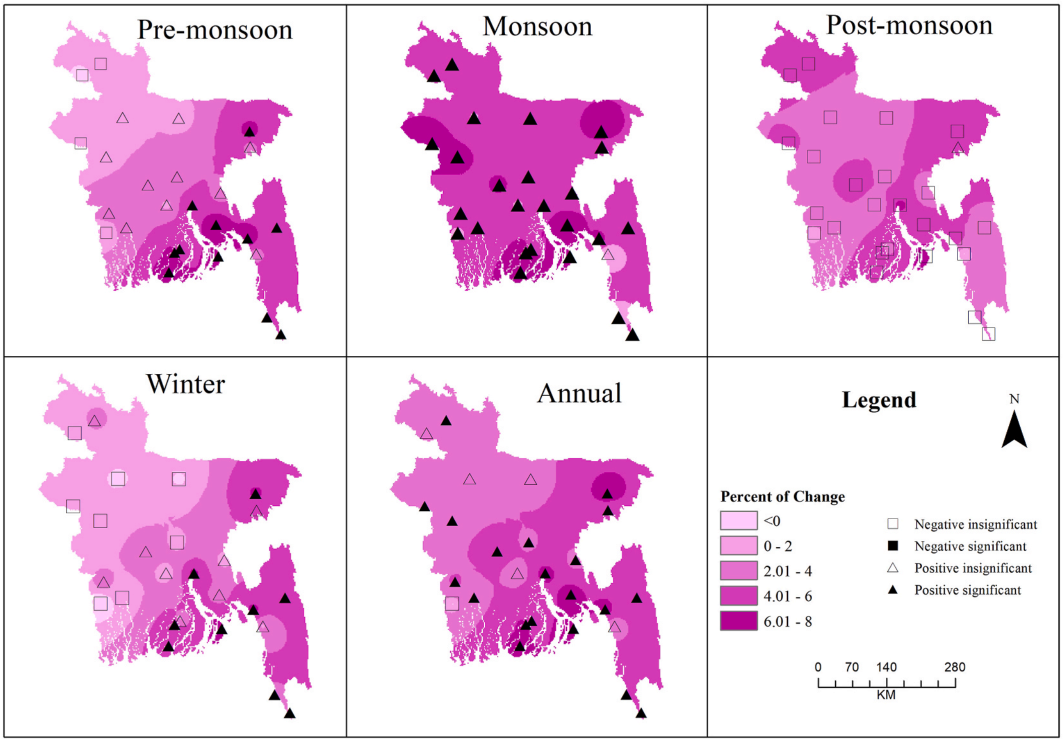


Fig. 4. Spatial distribution of maximum temperature trend in sub-climatic zones at 95% confidence interval.

3.3. Minimum temperature trend and magnitude

The minimum temperature has increased across all climatic zones (Fig. 5 and Table 1). However, zone A exhibited a decreasing trend in minimum temperature during the winter and pre-monsoon seasons (Table 1). This is consistent with the findings of section 3.1, where zone A, characterized by high rainfall and vegetation, experienced lower minimum temperatures. For the pre-monsoon season, zone C (2.64 °C), D (1.64 °C), and E (2.11 °C) showed higher minimum temperature trends compared to other zones. In the monsoon season, all zones experienced a significant increase in minimum temperature ranging from 2.58 to 4.36 °C. The post-monsoon and winter seasons showed slightly lower positive trends in minimum temperature compared to the monsoon season. The yearly minimum temperature also exhibited moderate increases across all zones, with the highest changes observed in zones C (3.81 °C) and G (3.26 °C).

Sen's slope estimator indicated a considerable magnitude of minimum temperature increases for zone C and E of 0.03 and 0.04 °C/year, respectively, during the pre-monsoon season. In the monsoon season, all zones showed a rise in minimum temperature 0.02 °C/year, except for zone D (0.03 °C/year). Zone C (0.30 °C/year) and D (0.02 °C/year) exhibited a larger magnitude of change during the post-monsoon season. Zone A (0.01 °C/year) showed a negative change in minimum temperature during winter, while other zones experienced changes ranging from 0.02 to 0.03 °C/year. The annual change demonstrated a rise in minimum temperatures for all zones, with significant results observed for zones C and E at 0.03 °C/year. During the post-monsoon, winter, and annual seasons, zones A, B, C, and G exhibited a similar trend of higher percentage changes, contrasting the pre-monsoon season. In the monsoon season, most areas in Bangladesh experienced a similar pattern of changes.

Changes in minimum temperature in Bangladesh have significant impacts on various aspects, including infrastructure, human health, agriculture, ecosystems, and daily life [92–94]. Lower minimum temperatures have negative effects such as impaired crop growth, frost damage, disrupted species migration and distribution, increased risk of cold-related illnesses, reduced water availability, infrastructure damage, and transportation disruptions [10,95,96]. Sectors such as agribusiness, horticulture, and tourism are particularly affected [97]. Meehl et al. [98] found that daily minimum temperatures are increasing at a faster rate than daily maximum temperatures, leading to higher daily mean temperatures and an increased likelihood of extreme events that can adversely affect grain yield. To mitigate these effects, adaptation measures such as cold-tolerant crop varieties, improved insulation, and early warning systems are crucial [91]. In Bangladesh, enhancing resilience is essential to minimize the detrimental effects of minimum temperature changes.

In summary, the increase in maximum temperature was more pronounced compared to the rise in minimum temperature in Bangladesh. Similar findings were acknowledged by Mallick et al. [99]. It is important to note that the gradual rise in both maximum and minimum temperatures will continue to exhibit seasonal and spatial variations [100]. These temperature changes have significant implications for Bangladesh, particularly in terms of its drought conditions and cropping systems, given the country's heavy reliance on agriculture as a major component of its economy [101].

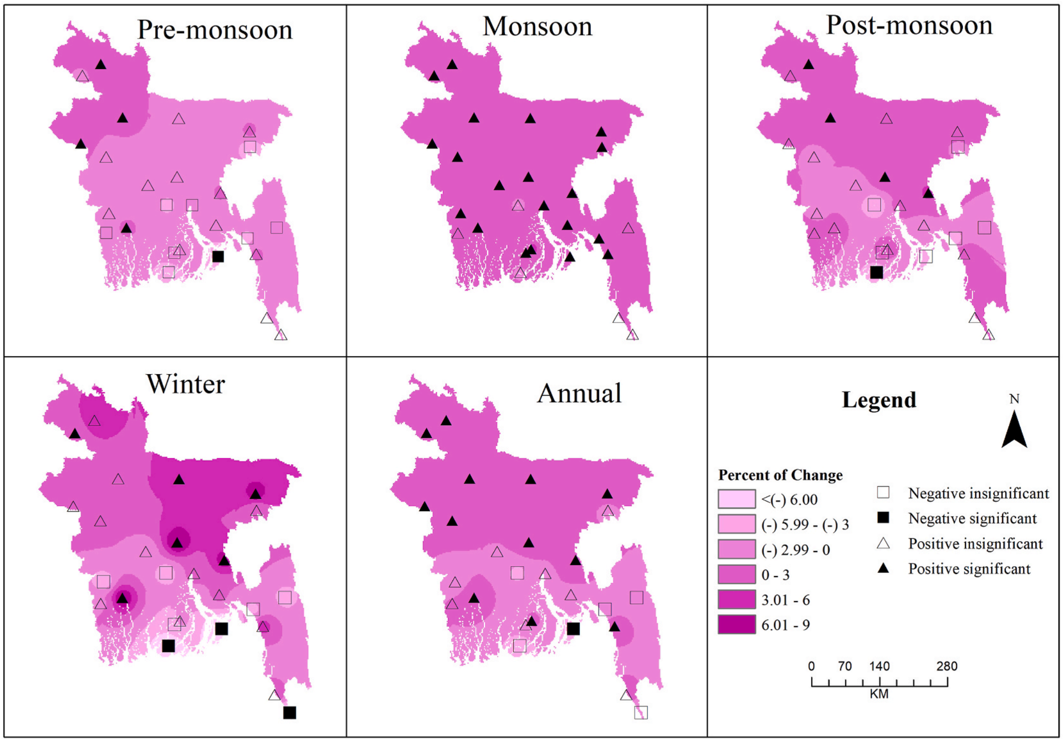


Fig. 5. Spatial distribution of minimum temperature trend in sub-climatic zones at 95% confidence interval.

3.4. Reference evapotranspiration trend and magnitude

The seasonal and annual variations of the spatial trend of ET_0 are depicted in Fig. 6. The figure indicates a consistent upward trend, mirroring the temperature trends. Specifically, in the pre-monsoon season, there was a notable increase in ET_0 for zones A, B, and G, with higher proportion changes of 1.59, 2.45, and 1.18 mm, respectively (Table 1). Conversely, zone C exhibited a substantial decrease in ET_0 trend at −3.84 mm/year, with lower percentage changes. During the monsoon period, zone C and D showed extremely negative trends of −4.79 and 0.00 mm, respectively, while other zones exhibited random increases. In contrast, all zones, except zone C (0.52 mm), displayed a significant ascending trend in the post-monsoon season. Additionally, zones A and B had significant increases in ET_0, with values of 3.39 mm and 4.28 mm Z statistics, respectively. The winter season showcased both significantly positive and negative trends, with the highest positive trend observed in zone B at 3.70 mm and the lowest negative trend in zone E at −2.38 mm Z statistics. Furthermore, the annual trend analysis revealed the highest increasing trend in zones A and B at 3.52 and 4.14 mm, respectively, while zones C, D, and E exhibited notable declining trends at 3.16, 1.14, and 1.25 mm, respectively. These findings align with the maximum and minimum temperature trends observed in different seasons. In terms of percentage changes, zones A and B consistently demonstrated higher variations in ET_0 across all seasons, except during the monsoon season when higher changes were observed throughout Bangladesh, except in zone C.

The decrease in the ET_0 trend is supported by the studies of Salam & Islam [57] and Salam et al. [102]. The magnitudes of change in zones A and B remain consistent across all seasons, ranging from 0.01 to 0.02 mm/year. Conversely, zones C and D exhibit similar decreased magnitudes ranging from −0.02 to −0.01 mm/year. Similarly, zones E, F, and G display insignificant negative or lower magnitudes of change in the ET_0 trend across all seasons. This suggests a spatial correlation between temperature and ET_0 trends in Bangladesh, influenced by sub-climatic zone variations [10,15,103].

The agriculture, water resources, and ecosystems in Bangladesh are significantly affected by the seasonal and annual fluctuations in ET_0 [72]. The negative changes in ET_0 suggest a potential decrease in crop water demand for most regions, except in the south-eastern and north-eastern zones. Adapting irrigation practices to match changing ET_0 patterns is crucial for managing crop water demand and optimizing water resources [104]. Changes in ET_0 patterns can also impact river flows, groundwater levels, and overall water availability, which in turn affect water management practices [105–107]. Furthermore, these changes can have adverse effects on aquatic ecosystems, wetland habitats, and biodiversity [108]. To effectively address climate change and ensure sustainable water and agricultural management, it is imperative for Bangladesh to understand and monitor these seasonal and annual fluctuations of ET_0 [109]. Implementing efficient water management strategies, including appropriate irrigation techniques and scheduling, will help align crop water requirements with evolving ET_0 patterns.

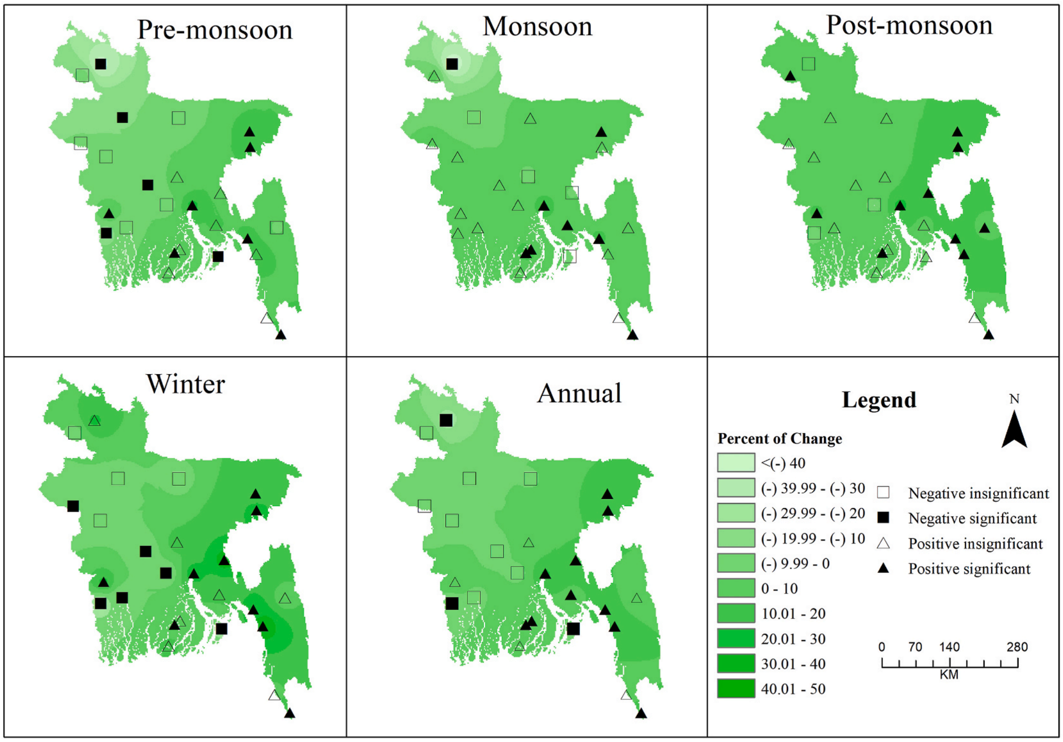


Fig. 6. Spatial distribution of reference evapotranspiration trend in sub-climatic zones at 95% confidence interval.

3.5. Linear regression for validation of MMK test results

The MMK test results for the trend of climatic parameters in the sub-climatic zones of Bangladesh were validated using a linear regression approach. Table 2 provides the details of the slope (trend) and p-values for temperature, rainfall, and reference evapotranspiration in the regression results. Significant increases in the slope of maximum temperature and ET_0 were observed across all seasons in the south-eastern and north-eastern regions (Table 2). The findings of this regression analysis are consistent with the results of the MMK test, except for the ET_0 results during the pre-monsoon season in the south-eastern zone (Table 1). In the north-eastern zone, a significant trend (4.36 °C) in the minimum temperature during the monsoon season was confirmed by a slope of 0.02 °C/year. Moreover, noticeable rises in maximum temperatures were observed in the northern, north-eastern, north-western, western, south-eastern, south-western, and south-central regions during the monsoon and post-monsoon seasons, with an increase slope ranging from 0.04 to 0.08 °C/year. Regression analysis further substantiated these trends, revealing significant upward slopes in all zones. According to regression analysis, a significant upward slope ranging from 0.03 to 0.06 °C/year was observed in the annual maximum temperature across all regions. The highest slope was found in the north-eastern region, while the lowest slope was observed in the north-western region (Table 2). Regarding rainfall, a decreasing slope was observed in all zones except the south-eastern and north-eastern regions, based on annual patterns. In the pre-monsoon season, rainfall trends increased in all zones except the south-eastern and south-western zones. Conversely, in the post-monsoon season, rainfall trends decreased in all zones except the south-eastern zone. During the winter season, rainfall trends decreased in all zones except the north-eastern zone. The trend of rainfall significantly increased, ranging from 1.00 to 1.60 mm/year, and significantly decreased, ranging from 0.22 to 2.28 mm/year, across seasons and regions (Table 2). This indicates that the rate of decrease in rainfall is higher than the rate of increase, posing a serious threat to future water availability for agricultural and domestic purposes. In most cases, the trend parameter was insignificant, indicating erratic and varying rainfall patterns across regions and seasons. These findings align with the results of the MMK test. However, in the northern region, both the pre-monsoon and monsoon seasons of ET_0 exhibited decreasing trends, as confirmed by the regression analysis slopes. Similarly, the post-monsoon ET_0 trend in the north-western region showed an increasing pattern with a positive slope. Conversely, the western zone displayed decreasing trends in ET_0 during the winter and pre-monsoon seasons. These findings were supported by regression analysis, which revealed decreasing slopes of −0.01 mm/year for each respective season. Lastly, the south-central region showed a significant increasing trend in the ET_0 of the post-monsoon and winter seasons (Table 1), as supported by regression analysis, which revealed significant positive slopes (Table 2).

3.6. Interrelationship between rainfall, temperature, and ET_0

Temperature and ET_0 trends exhibit a consistent pattern across the country, with the gap between minimum and maximum temperatures strongly correlated to ET_0. The relationship between temperature and ET_0 is such that an increase in temperature corresponds to a rise in ET_0, while a decrease in temperature corresponds to a decrease in ET_0. The detailed description can be found in sections 3.2 and 3.3. Since the temperature and ET_0 display a similar pattern spatially, we have not included a separate figure to illustrate their relationship. Instead, Figs. 4 and 5 provide the same interrelationship information. However, this investigation focuses on exploring the correlation between rainfall and ET_0, which differs significantly as depicted in Fig. 7. Specifically, only the variations in precipitation and ET_0 are presented in the figure due to their close relationship, demonstrating an identical scenario of rising and falling in conjunction with temperature. The annual seasonal analysis reveals a predominance of decreased rainfall and ET_0 in zones C, D, E, G, and F. However, the south-eastern part exhibits increased rainfall and ET_0 in zone A, while the southern part of Bangladesh, covering zones A, F, and G, shows a potential increase in rainfall and decrease in ET_0. Likewise, the annual seasons of monsoon, post-monsoon and winter, rainfall dominated while ET_0 declined in the C, D, E, and F zones, as well as the south-central part of zone G. Similar patterns were observed for rainfall and ET_0 increase in the monsoon, post-monsoon, and annual seasons. Conversely, a decrease in rainfall and ET_0 was observed in the post-monsoon, winter, and annual seasons in the south-eastern, north-eastern, and south-central parts of zones A, B, and G. In the pre-monsoon season, which corresponded to the summer period, there was a dominant increase in rainfall and a decrease in ET_0 in zones C, D, E, and the south-central part of zone G. However, the south-eastern part of zone A deviated from the norm, exhibiting a decrease in rainfall and an increase in ET_0 during the pre-monsoon season. An exception was also observed in zone B, where there was an increase in rainfall and ET_0. These patterns indicated that temperature rise led to an increase in ET_0, which in turn influenced rainfall. However, zones B and G demonstrated contrasting behaviors with decreased rainfall in various parts. Thus, the pre-monsoon season was characterized by a strong relationship between rainfall and ET_0, whether increasing or decreasing. While the monsoon, post-monsoon, winter, and annual seasons were characterized by a dominant decrease in both rainfall and ET_0, posing challenges for water scarcity and food production in the respective zones.

Furthermore, zone A in all seasons except winter, and zone B in the pre-monsoon season, have a moderate impact on water shortages for cropping intensity. Agricultural production in Bangladesh heavily relies on monsoon rainfall, and the southern part of zones F and G, along with the north-western part of zone D, maintain favorable conditions for water availability and the cropping system. These changes in rainfall patterns and increasing temperatures align with previous studies by Rahman & Azim [4] and Wahiduzzaman & Luo [52]. However, Mullick et al. [110] have noted heterogeneous behaviors of rising and falling rainfall and temperature across seasons and recommend a temperature increase throughout Bangladesh. These findings underscore the need for adaptation strategies and sustainable water management practices to mitigate the potential risks and ensure resilient agricultural production in the face of changing climate conditions.

Table 2
Values of slope and P-value from linear regression analysis of maximum temperature, minimum temperature, rainfall, and reference evapotranspiration of sub-climatic zones of Bangladesh.

Weather parameters	Season	South-eastern region		North-eastern region		Northern region		North-western region		Western region		South-western region		South-central region	
		Slope	p-value	Slope	p-value	Slope	p-value	Slope	p-value	Slope	p-value	Slope	p-value	Slope	p-value
Rainfall	Pre-monsoon	−0.92	0.31	2.14	0.22	1.60	0.06	0.65	0.34	1.00	0.08	−0.23	0.68	0.02	0.98
	Monsoon	2.21	0.20	−0.56	0.73	−1.14	0.52	−0.76	0.56	−1.58	0.27	0.74	0.54	0.88	0.52
	Post-monsoon	0.64	0.54	−0.92	0.45	−1.74	0.31	−1.61	0.10	−2.28	0.01	−0.83	0.38	−0.85	0.42
	Winter	−0.33	0.08	0.00	0.99	−0.31	0.02	−0.22	0.08	−0.06	0.76	−0.20	0.43	−0.23	0.24
	Annual	0.40	0.43	0.16	0.84	−0.40	0.57	−0.49	0.35	−0.73	0.11	−0.13	0.75	−0.04	0.94
Max Temp	Pre-monsoon	0.06	0.00	0.05	0.01	0.01	0.60	0.01	0.74	0.01	0.68	0.03	0.14	0.03	0.08
	Monsoon	0.05	0.00	0.06	0.00	0.05	0.00	0.06	0.00	0.08	0.00	0.05	0.00	0.05	0.00
	Post-monsoon	0.05	0.00	0.06	0.00	0.05	0.00	0.05	0.00	0.05	0.00	0.04	0.00	0.04	0.00
	Winter	0.05	0.01	0.05	0.01	0.03	0.23	0.01	0.66	0.01	0.64	0.02	0.37	0.03	0.21
	Annual	0.05	0.00	0.06	0.00	0.04	0.02	0.03	0.04	0.04	0.01	0.04	0.01	0.04	0.01
Min Temp	Pre-monsoon	−0.02	0.48	−0.01	0.52	0.01	0.55	0.00	0.94	0.01	0.57	−0.01	0.72	−0.01	0.64
	Monsoon	0.01	0.42	0.02	0.03	0.01	0.37	0.01	0.28	0.02	0.13	0.01	0.28	0.01	0.42
	Post-monsoon	0.00	0.73	0.01	0.66	0.02	0.25	0.00	0.81	0.00	0.97	0.00	0.87	0.01	0.62
	Winter	−0.02	0.26	0.02	0.27	0.02	0.30	0.01	0.77	0.01	0.69	0.00	0.93	0.01	0.38
	Annual	−0.01	0.53	0.01	0.56	0.01	0.29	0.00	0.74	0.01	0.55	0.00	0.90	0.00	0.74
ET_0	Pre-monsoon	0.01	0.02	0.02	0.01	−0.02	0.00	−0.01	0.03	−0.01	0.02	−0.01	0.10	0.01	0.23
	Monsoon	0.01	0.02	0.01	0.02	−0.02	0.00	0.00	1.00	0.00	0.35	0.00	0.47	0.00	0.18
	Post-monsoon	0.01	0.00	0.01	0.00	0.00	0.99	0.01	0.02	0.00	0.15	0.00	0.27	0.01	0.00
	Winter	0.01	0.00	0.02	0.00	0.01	0.15	0.00	0.55	−0.01	0.02	0.00	0.42	0.01	0.01
	Annual	0.01	0.00	0.01	0.00	−0.01	0.05	0.00	0.42	0.00	0.18	0.00	0.62	0.01	0.01

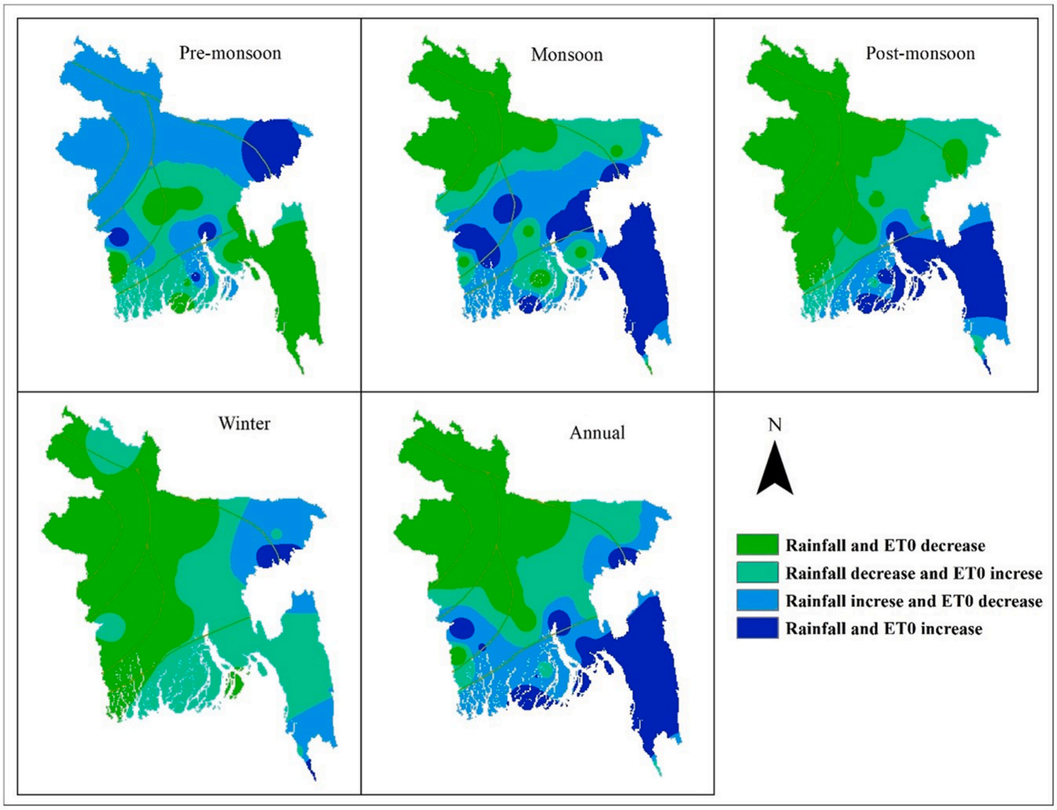


Fig. 7. Interrelationship between rainfall and ET_0.

3.7. Overall net changes analysis of the climatic variables

The analysis of trends in different climatic zones of Bangladesh reveals both positive and negative trends for variables such as rainfall, temperature, and ET_0. However, relying solely on trend analysis may not provide an accurate representation of the overall climate change throughout the country. It is therefore crucial to calculate the net change in these factors to gain a comprehensive understanding of climate change. Assessing the impact of climate change requires evaluating the net change in the total amount of these factors to determine whether there has been a water loss or gain in the entire region [81].

Fig. 8a provides an overview of the overall net changes in maximum temperature. The figure showed a significant positive increase in maximum temperature across all months and seasons. Among all the months, January exhibited the highest increase with a value of 0.003 °C/year. The post-monsoon season showed the most significant increase in maximum temperature with a value of 0.002 °C/year, followed by winter with a value of 0.001 °C/year. The maximum temperature increases for the other months and seasons ranged from 0.0003 to 0.003 °C/year.

Fig. 8b presents an overview of the net changes in minimum temperature. The majority of the monthly net changes in minimum temperature displayed positive values, ranging from 0.001 to 0.016 °C/year. However, insignificant values were observed in October and December, with values of 0.004 and 0.011 °C/year, respectively. The months of January, March, and December experienced the greatest rise in minimum temperature, while May exhibited the smallest increase. Among all the seasons, winter showed the highest increase in minimum temperature with a value of 0.007 °C/year.

Fig. 8c displays the net changes in rainfall. It was evident that all the net changes in rainfall were positive, indicating an overall increase in rainfall. March and November had the highest increase rates, with 5.32 mm/year and 4.92 mm/year, respectively. However, these values were considered insignificant. The winter season exhibited a significant increase in rainfall with a value of 2.23 mm/year, similar to the pre-monsoon season with a value of 0.20 mm/year. Apart from January and September, which recorded a value of 0.63 mm/year and 0.25 mm/year, respectively, no significant increases/decreases in rainfall were noticed.

Fig. 8d presents the net changes in reference evapotranspiration. The figure revealed that ET_0 experienced nearly identical increases in January, February, March, September, October, and November, with the increases in January, February, and March being significant, while those in September, October, and November were insignificant. Regarding seasonal changes, the pre-monsoon, winter, and annual periods exhibited a significant rise in ET_0, whereas the monsoon and post-monsoon periods showed insignificant increases.

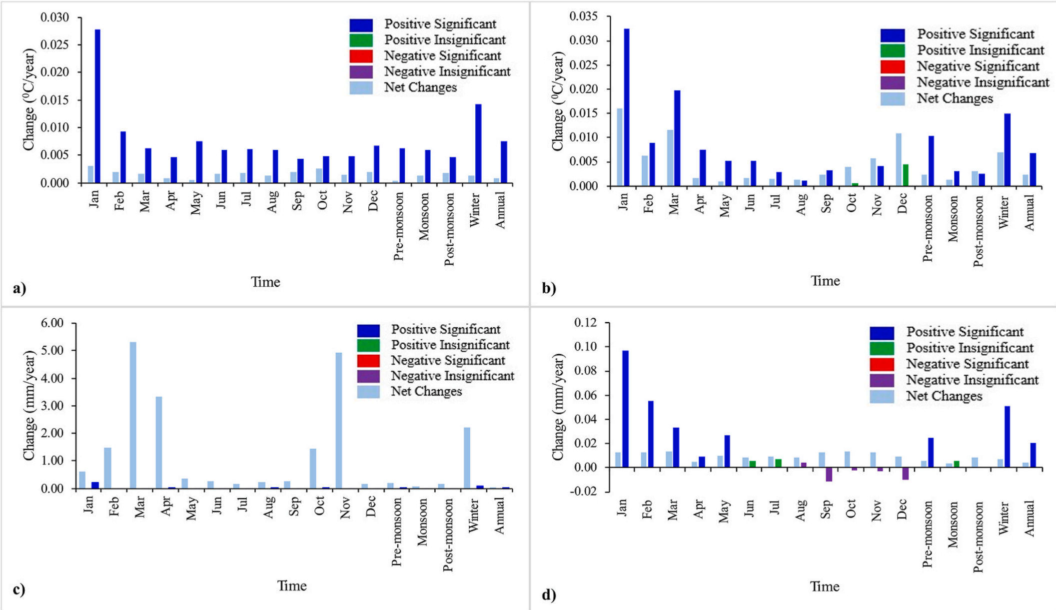


Fig. 8. Overall net changes in the maximum temperature (a), minimum temperature (b), rainfall (c), and reference evapotranspiration (d) in Bangladesh.

The above results demonstrate that climate change has observable effects on various parameters. In fact, all climatic parameters undergo continuous changes at monthly, seasonal, and annual intervals. While opinions on rainfall pattern alterations may differ, the rise in temperature serves as a clear indication of climate change and its leading to global warming. Notably, a reduction in rainfall directly contributes to a decline in water availability, as documented by Gosain et al. [111]. The critical nature of temperature rise becomes apparent through report by Jain et al. [112], who estimate a potential reduction of approximately 5 million tons in wheat production during the growth period due to a 1 °C temperature increase. Additionally, the production of barley, wheat, mustard, and chickpea has either stagnated or even declined as a result of rising temperatures. Changes in evapotranspiration further exacerbate the impact on crop growth and agricultural practices [81]. Thus, a comprehensive understanding the variation of overall net changes in the spatial and temporal distribution of rainfall, temperature, and evapotranspiration, as well as their interrelation, becomes essential for effective planning and equitable distribution of water resources.

4. Conclusions, limitations, and future research scope

The objective of this study was to explore the trends of rainfall, temperature, and ET_0, as well as their interrelationship, in the sub-climatic zones of Bangladesh. In addition, we aimed to understand the overall net changes in climatic parameters to gain insights into the changing climate scenario. To achieve these objectives, meteorological datasets from 26 stations spanning from 1989 to 2020 were utilized. The analysis revealed a declining annual trend in precipitation, as well as rising minimum and maximum temperatures and ET_0. The study findings also indicate that the rate of increase in maximum temperature exceeded the rate of increase in minimum temperature. Moreover, the rate of decrease in rainfall pattern surpassed the rate of increase. The overall analysis of net changes revealed an increase in both maximum and minimum temperatures, accompanied by an increase in ET_0, while rainfall exhibited unpredictable and erratic patterns.

The pre-monsoon season emerged as the most crucial season, receiving the highest share of yearly precipitation for the northern and western regions with trend values of 2.08 mm and 2.06 mm, respectively. However, rainfall decreased during the monsoon season in all zones, except for the south-eastern and north-eastern regions, which exhibited trends of 1.05 mm and 1.57 mm, respectively, contributing to an annual decline in precipitation. Notably, the south-eastern region demonstrated an upward trend of 1.18 mm in rainfall, while all other zones experienced a declining trend. In terms of temperature, the maximum yearly temperature trends were exceptionally high across all zones, with variations observed among seasons. During the pre-monsoon season, the south-eastern zone recorded the highest maximum temperature of 3.75 °C and the lowest minimum temperature of −0.05 °C. In the monsoon season, the south-eastern zone exhibited the highest trend in maximum temperature at 5.24 °C, while the northern zone had the lowest trend in minimum temperature at 2.58 °C. The winter season witnessed the highest maximum temperature in the north-eastern zone (2.77 °C) and the lowest trend in minimum temperature at −0.76 °C. Regarding ET_0, the northern zone (3.16 mm), north-western zone (1.14 mm), and western zone (1.25 mm) experienced a steep decline, while the south-eastern and north-eastern zones showed an increase trend. Strong interrelationships between rainfall and ET_0 were observed annually in the northern, north-western, western, and parts of south-central and south-eastern regions.

The conclusion of this study holds significant practical implications for water resource management and climate-smart technology adaptation strategies in Bangladesh. The findings highlight the declining trend in precipitation, increasing temperatures, and ET_0, which have important implications for agricultural practices, water availability, and overall ecosystem health. These trends necessitate the development and implementation of effective water management strategies to mitigate the potential impacts of declining precipitation and increasing temperatures on crop productivity and water resources. Furthermore, the identified interrelationship between rainfall and ET_0 underscores the need for integrated approaches that consider both variables when developing water resource management plans. This understanding can inform decision-making processes and aid in the equitable distribution of water resources among different sectors.

However, it is important to acknowledge the limitations of this research. One limitation is the reliance on meteorological datasets from a limited number of stations, which may not fully represent the climatic conditions across all sub-climatic zones of Bangladesh. Additionally, the study focused on trends and interrelationships without delving into the underlying mechanisms and drivers of these patterns. Future research should aim to address these limitations by incorporating more comprehensive datasets and conducting in-depth analyses to gain a deeper understanding of the factors influencing the observed trends. Moreover, future research could explore the potential impacts of these climate change trends on various sectors, such as agriculture, water resources, and ecosystems, to guide adaptation strategies and enhance resilience. Also, investigating the effectiveness of different water management practices and adaptation measures in mitigating the adverse effects of climate change would be valuable for guiding policy and decision-making processes. By addressing these limitations and exploring the suggested avenues for future research, we can further advance our understanding of climate change dynamics in Bangladesh and develop more robust strategies to cope with the challenges posed by changing climatic conditions.

Declarations

Author contribution statement

Md. Naimur Rahman: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Syed Anowerul Azim; Md Abdur Rouf Sarkar: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Farhana Akter Jannat; Babor Ahmad: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Md. Rakib Hasan Rony: Analyzed and interpreted the data; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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