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Spatiotemporal characterization of relative humidity trends and influence of climatic factors in Bangladesh

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A B S T R A C T

The frequency and intensity of climate change and resulting impacts are more prevalent in South Asian countries, particularly in Bangladesh. Relative humidity (RH) is a crucial aspect of climate, and higher RH variability has far-reaching impacts on human health, agriculture, environment, and infrastructure. While temperature and rainfall have gained much research attention, RH studies have received scant attention in the research literature. This study investigated the trends and variability of RH levels in Bangladesh and the influence of other meteorological factors over the past 40 years. Variabilities in the meteorological factors were identified by calculating descriptive statistics. Innovative trend analysis (ITA) and Mann-Kendall test (MK-test) methods were utilized to assess monthly, seasonal, and annual trends. The magnitude of temperature, rainfall, and windspeed influences on RH variability were identified using Pearson's correlation, Spearman rank correlation, and Kendall correlation model. Variability analysis showed higher spatial variations in RH levels across the country, and RH skewed negatively in all stations. Results reveal that daily, monthly, seasonal, and annual trends of RH exhibited positive trends in all stations, with an increasing rate of 0.083–0.53% per year in summer, 0.43–0.68% per year in winter, and 0.58–0.31% per year in the rainy season. Both ITA and MK-test provided consistent results, indicating no discrepancies in trend results. All three models indicate that temperature, rainfall, and windspeed have weak to moderate positive influences on changing RH levels in Bangladesh. The study will contribute to decision-making to improve crop yields, health outcomes, and infrastructure efficiency.

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1. Introduction

Climate change impacts are getting more intense with time. Due to their geographical location, socio-economic conditions, and high population density, South Asian countries are more susceptible to climate change. Climate change poses a variety of risks to the region, including sea-level rise, flooding, cyclones, droughts, and extreme temperatures [1–3]. Poverty, limited resources, weak infrastructure, and insufficient governance exacerbate these risks. Climate change impacts are now not confined to sea level rise, droughts, floods, and other natural hazards [4]. Climate change has intensified shifts in climatic parameters like temperature and rainfall, further leading to abrupt changes in humidity levels [5]. Changes in relative humidity (RH) levels have significant and far-reaching impacts on human health, agriculture, and infrastructure [6–8]. Due to overpopulation, poor infrastructure, and a highly dependent agriculture-based economy, South Asian countries are more vulnerable to RH changes [9]. This makes understanding the variability and trends of RH in South Asian countries crucial from a regional and global perspective since the region is home to a significant population and contributes to global warming.

In atmospheric science, relative humidity is a concept that describes how much water vapor is in the air relative to how much water vapor the air can hold at a particular temperature. RH is generally expressed as a percentage and is essential to climate and environmental research. Climate science considers RH to be an important measure of the atmosphere's moisture content, which influences cloud formation, precipitation, and other atmospheric phenomena [10]. RH can affect regional and global climate patterns, including the frequency and intensity of extreme weather events like floods and droughts. There are also several important applications for RH in various fields, including agriculture, meteorology, and public health [11]. For instance, RH plays an important role in crop growth, development, and yield in agriculture. RH measurement can provide invaluable information for air traffic control, aviation safety, and other critical purposes in meteorology. In public health RH may influence infectious disease spread and medical treatment efficacy. Higher RH levels affect human health by increasing heat stress while lower RH levels promote fungal growth, respiratory and allergy problems [8–13]. Moreover, high RH levels can cause corrosion and degradation in infrastructure, while low humidity can cause cracking and structural damage [14]. Since RH is an important component of climate science as well as a variety of other fields, the spatiotemporal characterization of RH and its relationship with climatic factors is an important area of research that can help us better understand climate patterns and improve environmental management and planning.

Globally, disaster frequency and severity have increased significantly, and the link between climate change and extreme events is becoming increasingly apparent [15]. Climate change can increase the variability of RH by altering precipitation patterns and temperatures, leading to increased evaporation and changes in atmospheric moisture content. Variability in RH can be extremely harmful to people [13], agriculture [16,17], and the environment [18]. High RH can cause heat stress and increase the risk of heat stroke and other heat-related illnesses. Furthermore, it encourages the growth of certain diseases and pests, negatively impacting crops and livestock [19,20]. In this regard, South Asian countries, particularly Bangladesh, are at serious risk of such losses. Moreover, Bangladesh is a densely populated developing country that is very sensitive to climate change, and the majority of people depend on agriculture. Bangladesh is also exposed to a variety of climatic hazards and natural disasters due to its high degree of environmental volatility [9,21–23]. Floods, riverbank erosion, and cyclones that form in the Bay of Bengal are a few of the many challenges faced by the country every year [24]. These events cause human casualties, livelihood and crop loss, and damage to infrastructure. Therefore, it became urgent to study and understand the impacts of meteorological changes on RH variability to better anticipate and mitigate these negative effects. Though several prior studies investigated the variability and trends of rainfall and temperature change in different countries [25,26], including Bangladesh [27–30], so far, very little attention has been paid on RH. In addition, no research has been found that investigates the influence of meteorological factors on RH dynamics. A few studies have assessed the RH trends [6,31], and all of them are based on China.

The effects of RH on people are substantial and can be very damaging when extremes are experienced over a long period of time [12,32]. Extremes of relative humidity impact human comfort, productivity, and health by deteriorating the thermal environment [33]. Recent studies showed evidence of thermal environmental degradation in the cities of Bangladesh [34–36]. Therefore, the study of RH variability in Bangladesh is crucial to the current debate. In this regard, to fill the existing literature gap, this study provides a comprehensive investigation of the spatiotemporal trends and variability of RH levels in Bangladesh, driven by other meteorological factors. Consequently, the research makes a major contribution to climate change research by demonstrating the trends and variability of RH levels in a South Asian country, and it is one of the first investigations into how meteorological factors influence RH levels. The spatiotemporal characterization will help identify vulnerable communities. Overall, this study will help in sustainable decision-making related to land-use planning, agriculture, water management, infrastructural development, and risk reduction.

2. Methods and data collection

2.1. Study area

With about 170 million people, Bangladesh is the eighth most populated country in the world. It is a developed country located in South Asia. The country shares borders with India on the east, west, and north, as well as Myanmar on the southeast. In addition to being a riverine country with rivers such as the Ganges, Brahmaputra, and Meghna flowing through it, Bangladesh also contains the

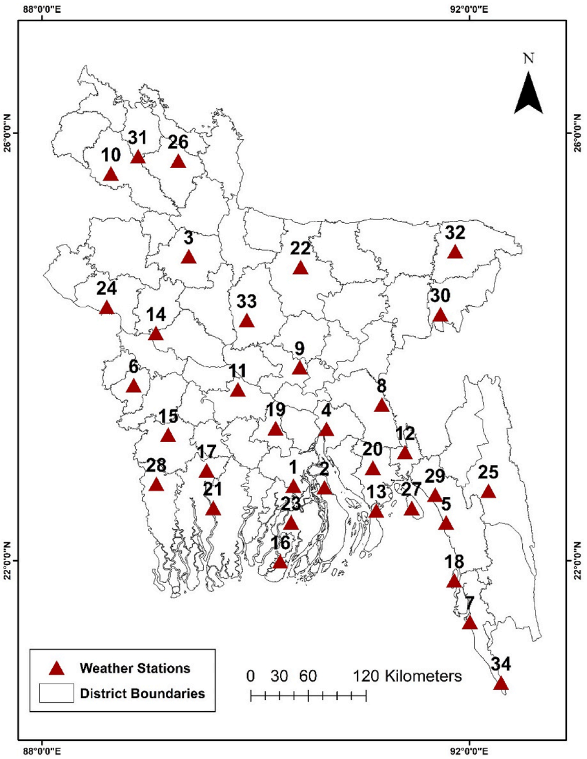


Fig. 1. Meteorological stations in Bangladesh.

coast of the Bay of Bengal [37]. Among the largest deltas in the world, Bangladesh contains 230 large rivers and their tributaries, as well as a dense network of distributaries from the Ganges, Brahmaputra, and Meghna rivers. The total area of the country is 147,570 km^2, most of which consists of low, flat land (about 80% is floodplain). Only in the northwest do elevations exceed 30 m above sea level, making the majority of the country prone to flooding. Flooding occurs on a regular basis in the northern, western, central, southern, and northeastern floodplains. In addition, the country's population density and high population increase its exposure to such risks [9]. The climate of Bangladesh is characterized by high temperatures, heavy rainfall, high humidity, and fairly marked seasonal variations. Since over half of Bangladesh lies north of the Tropics, the climate is tropical most of the year because of the Himalayan Mountain chain, with a warm, relatively uniformly humid climate throughout most of the year. The region has three main seasons: winter (November to February), summer (March to June), and the monsoon season (July to October). The country experiences average temperatures from 24 °C to 30 °C, humidity from 60% to 90%, and an average annual rainfall of 2500 mm [38]. Fig. 1 represents the weather stations in Bangladesh.

Rural areas are home to the majority of the population, and agriculture provides most of the nation's income and employment [23]. However, the country has made significant progress in recent years, with a growing economy and improved living conditions [39–41]. Despite these progresses, poverty remains a major issue in Bangladesh, with a large portion of the population living below the poverty line. Moreover, Bangladesh is vulnerable to several natural disasters, such as cyclones, floods, and droughts, which can negatively impact the country's socioeconomic situation. It disrupts agriculture, damages infrastructure, and causes displacement. In addition, the country is also experiencing industrial pollution [42], impacts of climate change, including the rise of sea levels, the increase in temperature, and changes in precipitation patterns, which exacerbate existing vulnerabilities [9].

2.2. Data collection and descriptive statistics

To fulfill the objective of this study, we collected rainfall, Tmax, Tmin, and humidity data sets during 1981–2020 from the Bangladesh Meteorological Department (BMD). BMD provides historical meteorological data for 34 stations and ensures data quality. Before analyzing the data, homogenization and quality control of the data were checked. The collected dataset's quality control for each hydroclimatic variable was initially checked. Potential outliers, such as negative values or values exceeding the maximum possible values, were manually checked, and corrected. We have also collected daily data from NASA Power Access and compared with BMD data.

The mean, standard deviation, minimum, maximum, and skewness were identified to assess the variability of meteorological factors. The standard deviation indicates how much the dataset for each climatic factor deviates from the mean value of the dataset. The skewness of climatic variables indicates whether the dataset is symmetrical or skewed to one side. Right-skewed distributions, also known as positively skewed distributions, have distribution tails that extend farther to the right of the mean and have more extreme values on the positive side of the distribution when the skewness is positive. In contrast, if the skewness is negative, the distribution is referred to as left-skewed, or negatively skewed, meaning that the tail of the distribution extends more to the left side of the mean and that the negative side of the distribution contains more extreme values.

2.3. Innovative trend analysis

Innovative Trend Analysis (ITA) method is a non-parametric technique introduced by Ref. [43]. It does not involve determining the normal distribution of the data and is unaffected by the serial correlation present in the time series unlike the Mann-Kendall (MK) test. This method allows identification of monotonic and sub-trends in a time series dataset, along with different trend combinations across different time series periods [44]. The time series data is split into two equal sub-series which are organized in ascending order later. The sub series are plotted on the X and Y axes, respectively, following the Cartesian coordinate system [45]. If the plotted data are scattered on the ideal 45° line (1:1), the time series represents a monotonic trend or no trend. Aggregation of data above the ideal line indicates to an increasing trend of the time series whereas the concentration of data below the ideal line represents a decreasing trend of the series [46]. Concentration of the scatter points close to trend line indicates [43]. The trends of time series data can be defined as high, medium, or low in this manner. The ITA slope was derived using Equation (1).

$$B = \frac{1}{n} \sum_{i=1}^{n} \frac{10(x_m - x_k)}{\bar{x}} \tag{1}$$

Where, B represents the ITA slope, n represents the total no. of observations, x_m denotes values from the second sub-series and x_k denotes values from the first sub-series, $\bar{x}$ denotes the mean of the first sub-series values.

The significance of ITA was determined by implementing Probability Distribution Function (PDF) using Equation (2).

$$CL_{(1-\alpha)} = 0 \pm \; S_{ITA^{\sigma_S}} \tag{2}$$

where, CL represents the confidence limit of ITA slope considering confidence interval of standard normal PDF to have mean of 0 and the standard deviation (σ_s) to be at α significance level. S_{ITA} denotes the assessed trend slope of ITA. The null hypothesis of no slope is rejected if S_{ITA} is greater than the significance level. ITA calculation in this study was conducted by adopting python script following a 95% confidence level. The average tendency of change in RH levels (in percentage) was computed using Percent Bias (PBIAS) method [47], as shown in Equation (3).

$$P_{BIAS} = 100 - \sum_{i=1}^{n} \frac{Y_i}{X_i} \times 100 \tag{3}$$

Where, P_{BIAS} denotes precent bias, n denotes the extent of an individual sub-series, Y_i and X_i are the observed values for second and first sub-series accordingly. An increasing trend is indicated by the positive values of P_{BIAS} whereas the negative value in result indicates decreasing trend of RH levels.

2.4. Mann-Kendal test analysis

Mann and Kendall proposed the Mann–Kendall method [48] is a non-parametric rank based statistical method. Mann-Kendall tests measure agreement between the direction of the observed data trend and the expected direction under the null hypothesis that there is no trend through the calculation of a test statistic, known as the Mann-Kendall statistic. The test is designed to be robust to the presence of outliers and can be used with both short and long time series. Since the Mann-Kendall test is non-parametric, it does not make any assumptions about the distribution of the data itself. As a result, it can be a helpful tool for choosing the best parametric model to utilize or when the data is not normally distributed. Trend analysis of climatic data, hydrologic data and meteorological time-series data is mostly determined using this technique [21,49–51]. Equation (4) was applied to measure the Test Statistic (S) [52,53]:

$$S = \sum_{m=1}^{n-1} \sum_{k=m+1}^{n} Sign(y_k - y_m) \tag{4}$$

where, n denotes the total observation number, y_m and y_k represents the rank of mth ($m = 1,2,3 \ldots. n\text{-}1$) and kth ($k = m + 1,2,3 \ldots. n$) observations of time m and k. Significance level calculated using Equation (5).

$$Sign(y_k - y_m) \begin{cases} = +1, if \; (y_k - y_m) > 0 \\ = 0, if \; (y_k - y_m) = 0 \\ = -1, if \; (y_k - y_m) < 0 \end{cases} \tag{5}$$

further, VAR(S) is calculated using Equation (6),

$$VAR(S) = \frac{1}{18}\left\{n(n-1)(2n+5) - \sum_{m=1}^{g} t_m(t_m-1)(2t_m+5)\right\} \quad 6$$

where, VAR(S) represents the variance of test statistic S, g denotes the total tied groups (sample data consisting of similar values), t_m denotes the extent of mth tied number.

Kendall's τ (tau) was applied to determine the data statistic (S) of time series. Used Equations (7) and (8).

$$\tau = \frac{S}{B} \quad 7$$

$$B = \sqrt{\frac{1}{2}n(n-1) - \frac{1}{2}\sum_{m=1}^{g} t_m(t_m-1)}\sqrt{\frac{1}{2}n(n+1)} \quad 8$$

Development of the Z statistic, which is a standardized test measurement is preceded by the determination of S and calculation of VAR(S) while $n > 10$ [54] as shown in Equation (9).

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}, \text{if } S > 0 \\ 0, \text{if } S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}}, \text{if } S < 0 \end{cases} \quad 9$$

The increasing or decreasing time series time series trends are indicated by positive and negative Z values respectively. The presence of no trends and trends is depicted by the null hypothesis (H_0) and the alternative hypothesis (H_A) accordingly at the significance level $\alpha = 0.05$ [55]. The Mann-Kendal test was performed by application of R programming script following a 95% confidence level.

Sen's Slope Estimator was applied to detect the magnitude of RH trend [56]. The determination of slope Q is achieved from a dataset of N pairs using Equation (10).

$$Q_i = \frac{y_k - y_m}{k - m}, i = 1, 2, 3 \ldots\ldots\ldots\ldots N, k > m \quad 10$$

where, Q_i represents the median slope, x_m and x_k represent data values at time m and k respectively.

2.5. Correlation analysis

Correlation analysis is a statistical method that determines the linear relationship between any two quantitative or categorical variables and calculates their association. The application of correlation analysis helps predict future behavior. In this study, the correlation was performed between the four variables RH (RH), Temperature (K), Wind Speed (WS) and Precipitation (PP). Three types of correlations were measured in this study to determine how the variables correlate with each other in different methods which are Pearson correlation, Spearman Correlation and Kendall Rank Correlation [57]. All the analyses were performed using Python programming.

2.5.1. Pearson correlation coefficient

British statistician Karl Pearson introduced the Pearson Correlation (Product – Moment) coefficient in 1895 [57]. The Pearson product-moment coefficient (r_p) measures the strength and direction of a linear relationship among two variables while assuming the variables to be quantitative, normally distributed and calculated on interval scales [58]. The Pearson coefficient was determined using Equation (11).

$$r_p = \frac{\sum(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\left(\sum(X_i - \overline{X})^2\right)\left(\sum(Y_i - \overline{Y})^2\right)}} \quad 11$$

Where, r_p is the Pearson Correlation coefficient with values between $-1 \le r_p \le 1$, X_i and Y_i indicates the values in X and Y variables respectively, $\overline{X}$ and $\overline{Y}$ represents the mean value of X and Y variables respectively.

2.5.2. Spearman rank correlation coefficient

Charles Spearman proposed a distribution-free non-parametric rank correlation coefficient (r_s) in 1904. The arbitrary monotonic association between two ranked variables can be measured in strength and direction by this coefficient [57]. Equation (12) was used to calculate r_s.

$$r_s = 1 - \frac{6\sum d_i^2}{N\left(N^2 - 1\right)} \quad 12$$

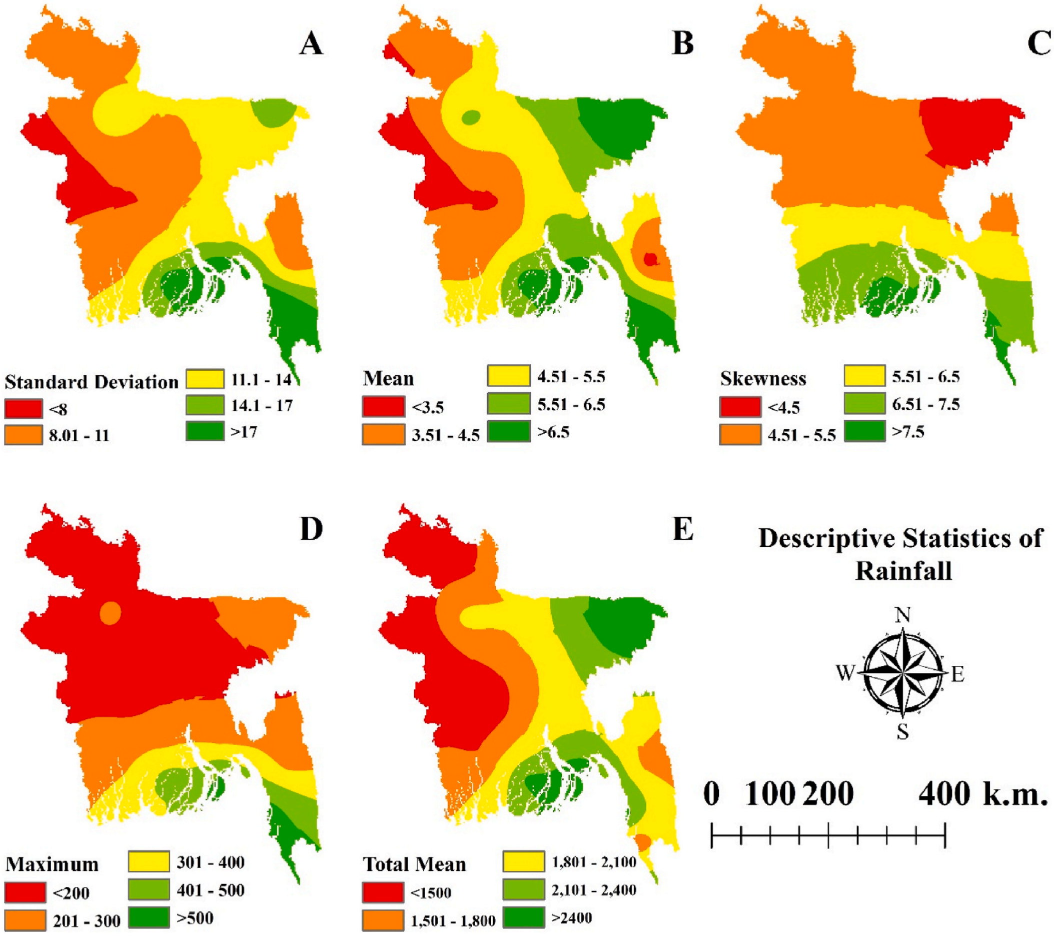


Fig. 2. Descriptive statistics of rainfall in Bangladesh.

where, r_s indicates the Spearman Rank Correlation Coefficient, $d_i = X'_i - Y'_I$ indicates the difference between each of the ranked variable pairs, N denotes the total sample number.

2.5.3. *Kendall Rank Correlation coefficient*

In 1948, Kendall's Tau Rank Correlation was introduced by Maurice Kendall. Kendall Rank Correlation Coefficient (τ) is a non-parametric statistic for statistical dependence measurement between two ordinal or rank-transformed variables [57]. The Tau correlation coefficients were calculated using Equation (13).

$$\tau = \frac{n_c - n_d}{\frac{1}{2}N(N-1)} \tag{13}$$

where, τ represents Kendall's tau coefficient, n_c and n_d represent the number of concordant and discordant pairs respectively, n represent the total observation number.

2.6. *Kriging interpolation*

The spatial distribution of RH was interpolated using Kriging Interpolation method. Kriging Interpolation can fully utilize spatial location information of sample points on a regional variable basis and variogram-centered approach [59]. The benefit of optimal as well as unbiased estimations, this method has been used widely over recent years [60–62]. After completing the extraction of the variable data, the kriging interpolation was performed on the corresponding variable data based on the selected stations using ArcGIS 10.8.1. The data analysis process involved application of Python 3.9 and the "trend change" package of R programming and the maps for data visualization were produced using ArcGIS 10.8.1.

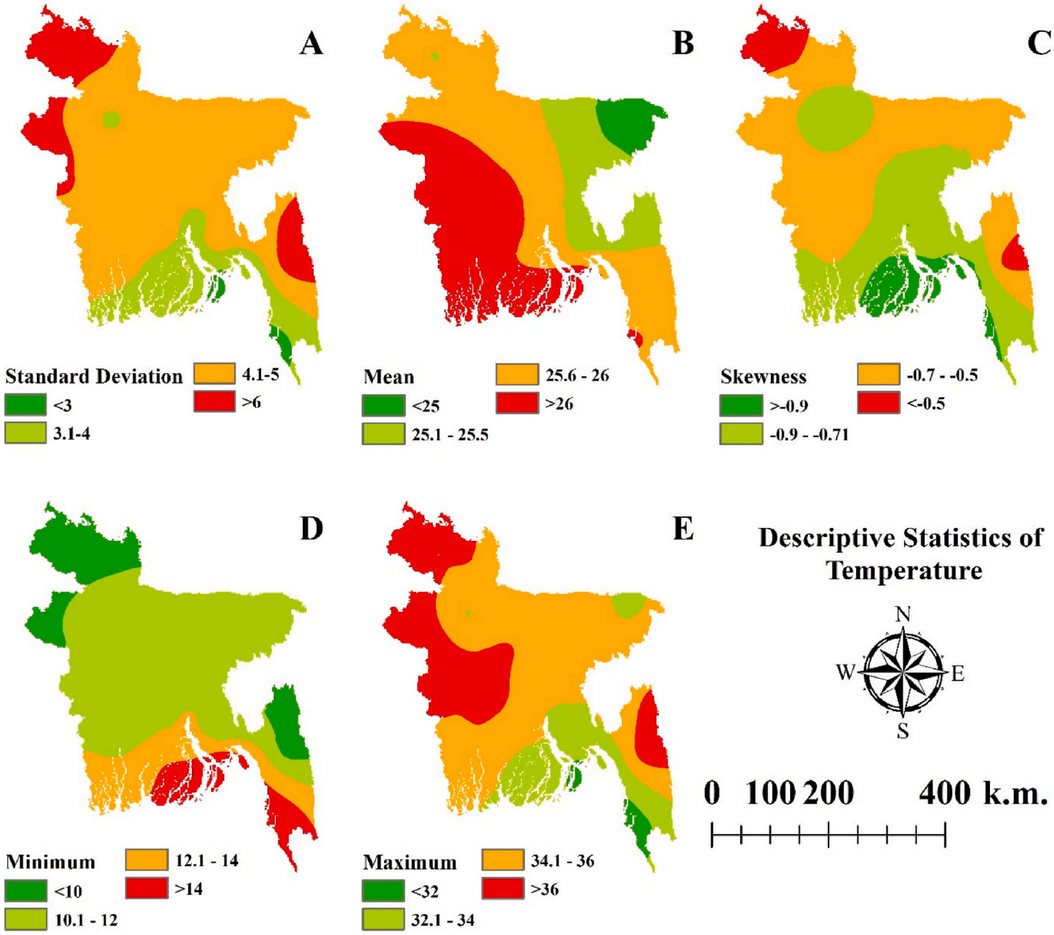


Fig. 3. Descriptive statistics of average temperature in Bangladesh.

3. Results and discussion

3.1. Variability of climatic factors

Spatiotemporal distributions of climatic factors help identify areas that are particularly vulnerable to climate change impacts. This study calculated descriptive statistics (standard deviation, mean, maximum, minimum, average, and skewness) for each meteorological factor. Fig. 2(A–E) represents the outcomes of descriptive statistics of rainfall, Fig. 3(A–E) temperature, Fig. 4(A–E) wind speed, and Fig. 5(A–E) RH in Bangladesh during 1981–2020.

Total annual rainfall for individual stations ranged from the lowest 307.62 mm (Ishurdi in 1992) to the highest 11,194 mm (Kutubdia in 2017) during the study period. Average annual total rainfall ranged between 1080.04 mm and 2890.75 mm. Maximum rainfall was recorded in the northeast region (Sylhet division) and in the eastern coastal districts, while annual total rainfall in the western region ranged from 1080.04 mm to 1500 mm. Mean daily rainfall showed similar spatial variability (Fig. 2B). The annual total rainfall in the central districts of the country recorded 1501–2100 mm (Fig. 2E). The range of STD for daily rainfall calculated 6.42–26.77 and skewness 3.70–10.51. Fig. 2A shows that the daily rainfall pattern varied mostly in the coastal region. The rainfall in the coastal region exhibited higher skewness values. The positive skewness values for daily rainfall indicate that there were more frequent occurrences of lower rainfall than higher rainfall across the country. Windspeed also skewed positively at all stations (Fig. 4C), indicating more frequent occurrences of lower windspeed than higher windspeed during the study period. The average daily wind speed ranged from 0.65 m/s to 4.19 m/s. Higher windspeed was recorded in the coastal region, especially in Chittagong, Cox's Bazar, Barishal, Bhola, and Kutubdia districts, where the average daily windspeed was >10.5 m/s. Windspeed in the western and southern regions was minimal and was less than 2.1 m/s in most of the areas of the country.

Fig. 3 represents the spatial distribution of descriptive statistics for average daily temperature in Bangladesh during 1981–2020. Analysis shows that the yearly average temperature was between 24.61°C-26.51 °C. Both the lowest and highest daily temperatures were observed in the northwest region during winter. The average temperature was maximum (>26 °C) in the western and south-western districts and minimum in the northeast region (Fig. 3B). During winter, the environment was comparatively warmer in the

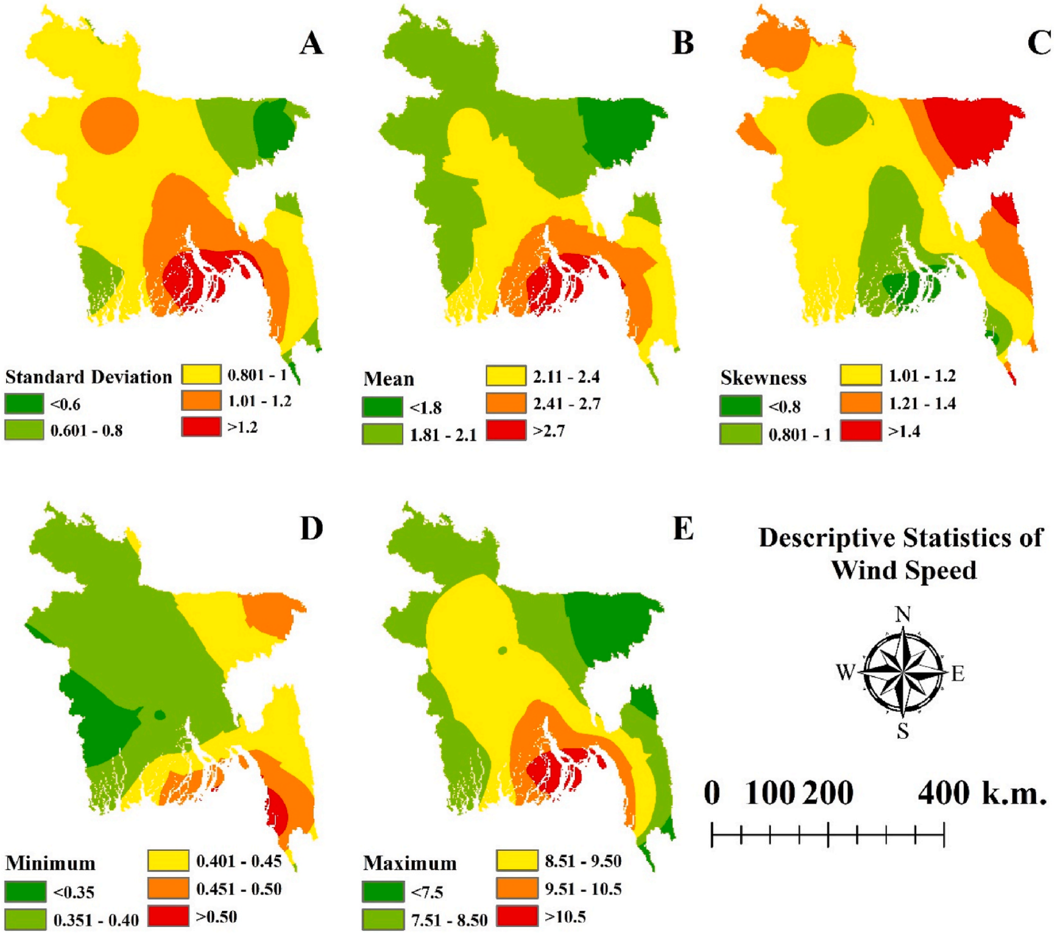


Fig. 4. Descriptive statistics of windspeed in Bangladesh.

southeast coastal region (Fig. 3D) and average Tmin was >14 °C. Fig. 3C shows that the temperature skewed negatively across the country during 1981–2020, implying that the climate was warmer on most days. However, most variations in average temperature were calculated in the northwest region (Fig. 3A). Major portions of the country exhibited similar variations in average temperature.

Fig. 5B shows that the average RH levels ranged from 58.98% to 77.63%. The atmosphere in the southeast coastal region was mostly humid and contained a relatively high amount of moisture. The spatiotemporal distribution of the minimum RH levels also shows a higher RH level in the coastal districts and the lowest in the northwest to central region of the country (Fig. 5D). The spatial distribution of STD shows that RH levels varied mostly in the northwest region. Fig. 5C illustrates that the RH in Bangladesh skewed negatively and was mostly skewed in the northwest region. The spatial distribution of skewness values suggests that the northwest region was comparatively drier with lower RH levels. In contrast, a large portion of the eastern region experienced a more humid atmosphere with higher RH levels during 1981–2020.

3.2. Spatiotemporal distribution of RH

Fig. 6 represents the spatiotemporal distribution of monthly and seasonal RH distributions in Bangladesh over the past four decades. Seasonal distribution suggests a less humid condition in winter with RH levels between 51 and 70%, a humid condition in the rainy season, and a less-dry to humid condition during the summer season. On average, RH was in the range of 31–50% in the northwest region in summer, indicating a less dry condition. While, due to the influence of the Bay of Bengal, the RH level in the coastal belt was >70%, indicating the humid conditions of summer, During the rainy season, the RH level was above 71% across the country. Notably, about 72.71% of areas of Bangladesh were in the less-humid zone (51–70% RH level) during summer, and most of the areas were in the center, northern, and western regions. About 7.36% of areas, particularly the northwestern zone, were in the less humid zone, and the coastal districts of the southeast region were in the humid zone. The whole country experiences a high RH level, or humid condition, during the rainy season. The average RH level of the winter season suggests a less humid condition. Seasonal RH distribution suggests that only a small portion of the country experiences comfortable and healthy living conditions in the summer, and during the other two seasons, people experience high to very high RH levels with an uncomfortable living environment. The monthly RH

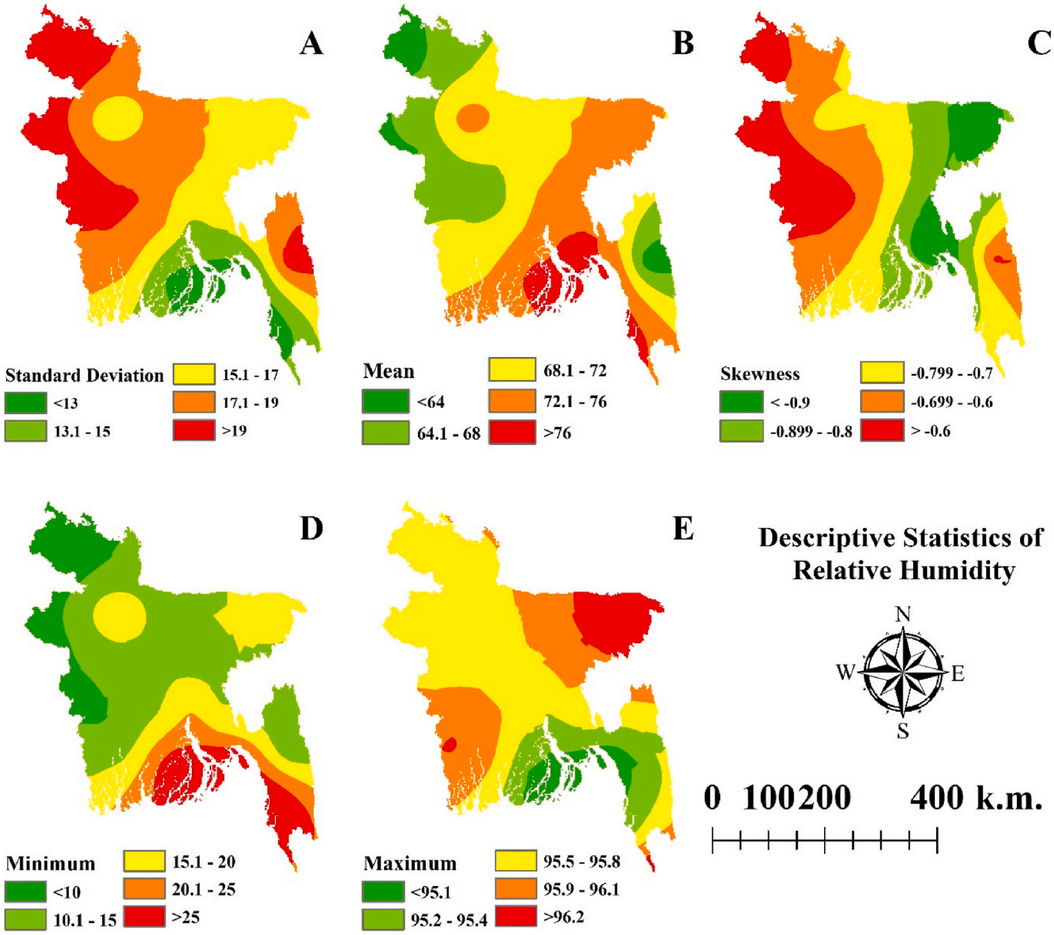


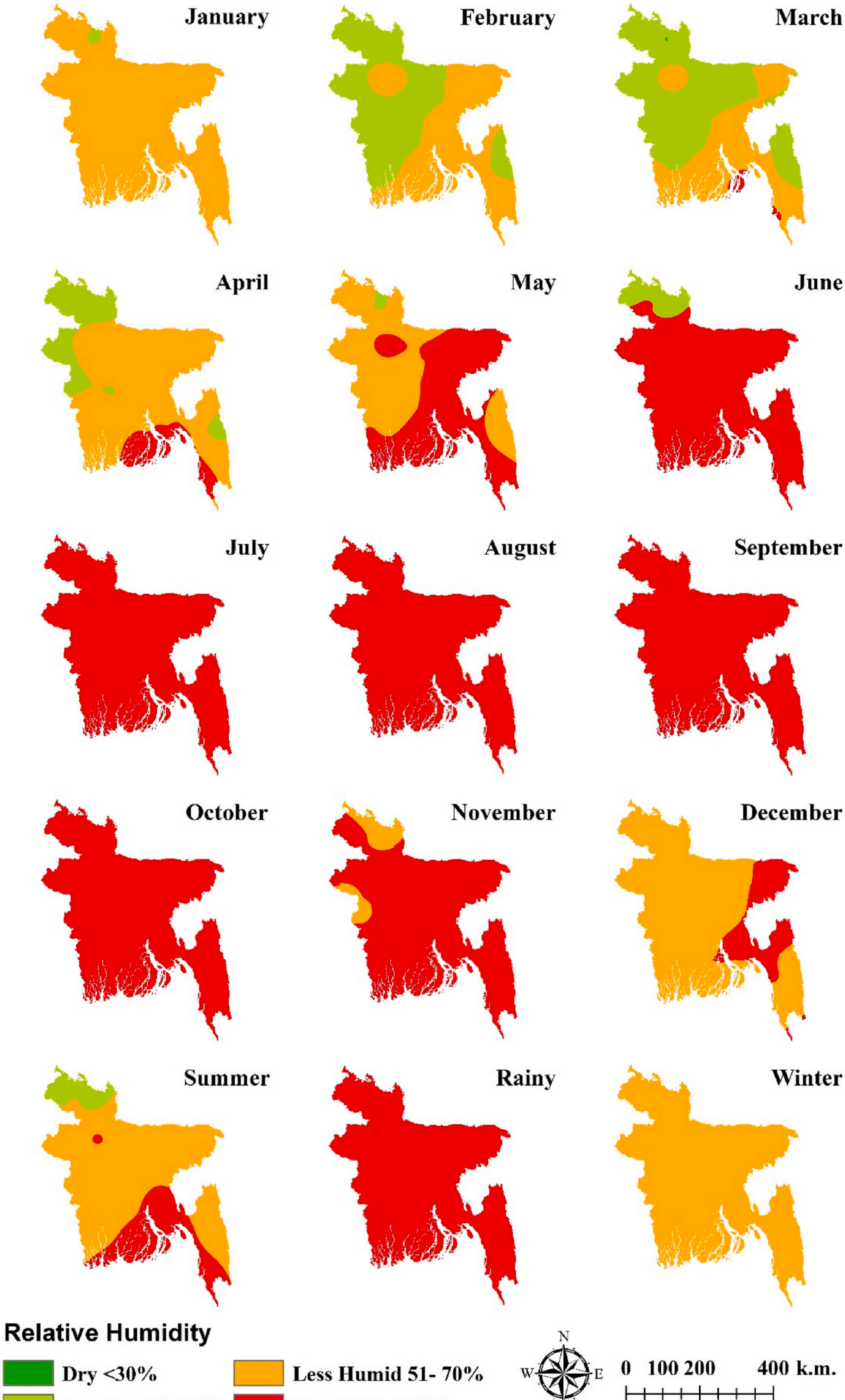
Fig. 5. Descriptive statistics of relative humidity in Bangladesh.

distribution shows a higher RH level from June to October, suggesting a discomforting condition for humans. During February and March, the major portion of the country, from the center to the northwest, experiences a less dry environment. While in December and January, RH levels suggest a less humid condition. However, higher RH in most months may increase discomfort in the living environment. Furthermore, higher RH levels may make it difficult to breathe for people with respiratory conditions.

3.3. RH trends in Bangladesh

3.3.1. Monthly RH trends

This study used the MK-test to assess monthly RH trends in Bangladesh. The calculated Sen's slope of monthly trends is presented in Table 2, and Table 3 represents the Z-statistics. All the stations exhibited positive trends in all months, except Hatia in September, Sandwip, and Hatia in April. The higher most increasing rate was 0.954%/year calculated for Teknaf in December. Sens's slope values suggest the highest increasing rate for January (0.905%/year) in Teknaf, February (0.707%/year) in Tangail, March (0.576%/year) in Sylhet, April (0.616%/year) in Rangamati, May (0.63%/year) in Rangamati, June (0.648%/year) in Dinajpur, July (0.362%/year) in Rajshahi, August (0.30%/year) in Rajshahi, September (0.284%/year) in Rajshahi, October (0.448%/year) in Faridpur, November (0.713%/year) in Rajshahi, and December (0.954%/year) in Teknaf. December exhibited the higher most average RH increasing rate (0.67%/year) while August and September exhibited lowermost increasing rate (0.11%/year) in Bangladesh. The Z-statistics showed higher variability at different stations at different significant levels (Table 2). The scatter plots of the monthly RH trends in Fig. 8 suggest rising trends of monthly RH with a spike in the "medium" zone. The RH data points above the 1:1 line, indicating that Bangladesh experienced a rise in its monthly RH level over the past four decades. The data points above the 5% line and 10% line, indicating that trends were significant at a 95% confidence level and 10% confidence level, respectively.



(caption on next page)

Fig. 6. Monthly and seasonal humidity distribution during the study period.

3.3.2. Seasonal RH trends

The ITA and MK-test were used in this study to assess seasonal RH trends in Bangladesh. The outcomes of these two methods are presented in Fig. 7a-d and Table 1. During the summer season, the ITA slope value ranged from 0.0033 to 0.27 in the coastal region, suggesting a relatively low RH change rate during the study period. This indicates that the RH was relatively stable in the coastal region and had not changed significantly. ITA slopes for the summer season suggest a significant increase in RH levels in 52% of areas of the country at a rate of 0.41% per year to 0.67% per year. The most significant rising trends were observed across the northern districts of the country. The results of Sen's slope were consistent with the ITA.

Seasonal RH trends in the rainy season exhibited large spatial variations. MK test analysis shows significant increasing trends in RH levels in only two stations. Similar to the summer season, RH in the coastal region exhibited lower increasing rates or a relatively stable RH level during the rainy season. According to the ITA slope, 11% of the country experienced the greatest increase in RH level (from 0.40%/year to 0.47%/year). In Bangladesh, the ITA and MK-test revealed a similar spatial distribution of RH increasing rates. The northwestern region experienced the most significant rise in RH levels each year, and the central region experienced a moderate increase.

Fig. 7 depicts a significant increasing trend in RH levels at ten stations during the winter season. Moderate rising trends in RH levels were observed across the central and eastern regions of the country. About 5% of areas exhibited very stable RH conditions in winter; 9% showed stable conditions; 32% showed a moderately rising rate; and 27% showed a strong positive trend rate. The northern region experienced a moderately increasing trend, the western region experienced the highest increasing trend, and the coastal region experienced stable conditions. RH data points above the 1:1 line in all stations indicate positive trends (Fig. 8).

3.3.3. Annual RH trends

Fig. 8 represents the scatter plots of ITA for daily, monthly, seasonal, and annual RH at different weather stations in Bangladesh. The RH data points at the maximum stations are above the 1:1 line, which indicates the rising trends of annual RH at all stations in Bangladesh. RH data points above the 10% line in most of the stations indicate that the trends were significant at the 10% significance level. The scatter plots in Fig. 8 demonstrate that the average annual RH in all the stations is increasing, with the median RH in the second half of the period (2001–2020) being higher than the median RH in the first half of the period (1981–2000).

ITA slopes show that the average RH increasing rate ranged from 0.18% per year to 0.58% per year, while Sen's slopes suggest the range was between 0.21% per year and 0.45% per year. About 8% of areas of the country experienced stable RH conditions (ITAs of 0.18–0.26), 37% experienced a moderate rising trend, and 26% experienced a significant positive rising trend over the past four decades. PBias values ranged between 4.20 and 21 indicating that the country experienced about 4.20%–21% higher RH levels in the second half of the period (2001–2020). Therefore, overall, ITA and MK-Test analysis provide evidence of a statistically significant rising trend in RH levels over the past 40 years.

3.3.4. Daily RH trends

This study used the ITA method to explore daily RH trends, which are graphically presented in Fig. 8. Scatter plots show that the daily RH data points are above the 1:1 line, indicating positive trends at all the stations. The RH data points above the 5% line indicates a significant rising trend in the daily RH level at the 95% confidence level. Fig. 8 shows that all the stations in Bangladesh exhibited a significant increasing trend of RH at a 95% confidence level in the low and medium regions. The data points in the "medium" zone were found above the 10% line, indicating a significant rise in the medium RH level in all stations at the 10% significant level. Data points in the "high" zone found in the 1:1 line indicate that there is no significant trend or change in the daily RH pattern over time.

3.4. Influence of climatic factors

To assess the relationship between RH level and other meteorological factors (temperature, rainfall, and wind speed), three regression models such as Pearson's correlation, Spearman rank, and Kendall regression models were utilized (Fig. 9). Integration of these three models provides a more robust analysis of the relationships and comprehensive insights into the influence of meteorological factors on the variability of RH in Bangladesh.

Fig. 9 suggests that there is a mix of weak to moderate positive correlations between RH levels and other meteorological factors. Pearson's coefficients (*Pr*) suggest that all the stations exhibited a positive relationship between RH and wind speed except Saidpur station. The Spearman and Kendall models showed positive correlations for all stations. The coefficient value for windspeed was found between −0.035 and 0.56, indicating a very weak positive correlation to a moderate positive correlation between RH and windspeed. Analysis suggests that the RH level in Patuakhali and Sandwip has a moderately strong relationship with wind speed. No influence of wind speed on RH was identified in Rangamati. Wind speed at other stations had a weak to moderate positive influence on the RH level. Overall findings suggest that wind speed had a strong influence on RH variability in coastal regions. The possible reason is that the winds blowing from the ocean are usually moist in coastal areas due to the high levels of water vapor in the air. Higher wind speeds transport more water vapor from the ocean surface into the air, resulting in higher RH levels.

Similar to wind speed, temperature and rainfall also showed positive influences on RH in Bangladesh. The P value at different stations ranged between 0.30 and 0.43, which indicates a moderately positive to moderately strong positive influence of rainfall on RH in Bangladesh. No significant variations in Pr values between RH and precipitation were observed at different stations, implying that

Table 1
Details of seasonal and annual humidity trend in Bangladesh.

Stations	Annual					Summer					Rainy					Winter				
	Z	SS	IT_D	PB	ITs	Z	SS	IT_D	PB	ITs	Z	SS	IT_D	PB	ITs	Z	SS	IT_D	PB	ITs
Barisal	1.38	0.272	↑	7.96	0.30	2.61	0.191	↑	4.43	0.17	1.16	0.105	↑	2.92	0.13	1.41	0.516	↑	19.39	0.62
Bhola	1.38	0.272	↑	7.96	0.30	2.61	0.191	↑	4.43	0.17	1.16	0.105	↑	2.92	0.13	1.41	0.516	↑	19.39	0.62
Bogura	1.38	0.272	↑	7.96	0.30	2.61	0.191	↑	4.43	0.17	1.16	0.105	↑	2.92	0.13	1.41	0.516	↑	19.39	0.62
Chandpur	1.38	0.272	↑	7.96	0.30	2.61	0.191	↑	4.43	0.17	1.16	0.105	↑	2.92	0.13	1.41	0.516	↑	19.39	0.62
Chattogram	1.28	0.317	↑	9.10	0.33	2.56	0.29	↑	7.14	0.26	1.31	0.113	↑	3.19	0.14	1.94	0.565	↑	19.79	0.63
Chuadanga	2.24	0.400	↑	14.08	0.44	3.22	0.341	↑	11.37	0.32	1.46	0.199	↑	5.71	0.25	2.09	0.68	↑	31.44	0.81
Cox's Bazar	1.13	0.166	↑	4.45	0.17	3.65	0.087	↑	1.89	0.08	0.55	0.056	↑	1.41	0.06	1.61	0.359	↑	11.76	0.40
Comilla	1.26	0.372	↑	10.93	0.40	2.59	0.338	↑	9.00	0.32	1.58	0.11	↑	3.23	0.15	1.36	0.659	↑	24.90	0.76
Dhaka	1.51	0.386	↑	12.57	0.43	2.67	0.328	↑	9.74	0.33	1.41	0.165	↑	5.78	0.25	1.66	0.621	↑	26.53	0.76
Dinajpur	1.96	0.482	↑	20.83	0.61	2.97	0.559	↑	27.21	0.62	1.51	0.261	↑	10.63	0.44	1.99	0.605	↑	31.41	0.83
Faridpur	1.84	0.489	↑	19.13	0.59	2.89	0.469	↑	17.82	0.49	1.28	0.311	↑	10.60	0.44	1.86	0.701	↑	34.40	0.89
Feni	0.8	0.344	↑	10.24	0.38	2.77	0.322	↑	7.81	0.29	1.41	0.1	↑	2.94	0.13	1.48	0.64	↑	23.64	0.76
Hatia	1.06	0.136	↑	3.47	0.14	0.8	0.018	↑	0.06	0.00	0.4	0.031	↑	1.05	0.05	1.86	0.346	↑	11.11	0.37
Ishwardi	1.84	0.489	↑	19.13	0.59	2.89	0.469	↑	17.82	0.49	1.28	0.311	↑	10.60	0.44	1.86	0.701	↑	34.40	0.89
Jashore	2.11	0.385	↑	12.55	0.42	2.77	0.306	↑	8.50	0.26	1.18	0.164	↑	4.89	0.22	2.11	0.682	↑	30.48	0.81
Khepupara	1.76	0.197	↑	4.74	0.18	2.17	0.081	↑	1.32	0.05	1.03	0.075	↑	1.63	0.07	1.86	0.426	↑	13.63	0.43
Khulna	2.11	0.385	↑	12.55	0.42	2.77	0.306	↑	8.50	0.26	1.18	0.164	↑	4.89	0.22	2.11	0.682	↑	30.48	0.81
Kutubdia	1.28	0.293	↑	7.87	0.30	2.49	0.231	↑	5.33	0.21	0.96	0.105	↑	2.99	0.13	1.71	0.532	↑	17.69	0.58
Madaripur	1.86	0.387	↑	12.98	0.44	2.79	0.293	↑	8.59	0.28	1.18	0.169	↑	5.42	0.24	2.16	0.697	↑	30.77	0.84
Maijdee	0.8	0.344	↑	10.24	0.38	2.77	0.322	↑	7.81	0.29	1.41	0.1	↑	2.94	0.13	1.48	0.64	↑	23.64	0.76
Mongla	2.31	0.28	↑	7.76	0.27	2.69	0.181	↑	3.85	0.13	1.58	0.117	↑	2.56	0.12	2.31	0.539	↑	21.19	0.59
Mymensingh	1.58	0.43	↑	15.53	0.52	2.72	0.467	↑	17.61	0.54	1.81	0.198	↑	6.66	0.29	1.89	0.603	↑	27.19	0.77
Patuakhali	1.53	0.183	↑	4.31	0.17	1.96	0.065	↑	0.93	0.04	0.96	0.066	↑	1.52	0.07	1.79	0.406	↑	12.44	0.41
Rajshahi	1.79	0.514	↑	21.48	0.62	3.07	0.509	↑	22.38	0.54	1.41	0.347	↑	11.95	0.48	1.96	0.695	↑	36.27	0.91
Rangamati	1.68	0.438	↑	17.46	0.48	2.59	0.568	↑	22.18	0.44	1.61	0.245	↑	7.26	0.30	2.01	0.519	↑	31.69	0.75
Rangpur	2.31	0.363	↑	18.21	0.56	3.22	0.393	↑	25.38	0.64	1.46	0.198	↑	9.46	0.39	1.96	0.533	↑	24.67	0.71
Sandwip	1.18	0.175	↑	4.68	0.18	2.44	0.077	↑	1.27	0.05	0.88	0.07	↑	1.82	0.08	1.71	0.393	↑	12.77	0.43
Satkhira	2.31	0.28	↑	7.76	0.27	2.69	0.181	↑	3.85	0.13	1.58	0.117	↑	2.56	0.12	2.31	0.539	↑	21.19	0.59
Sitakunda	1.28	0.317	↑	9.10	0.33	2.56	0.291	↑	7.14	0.26	1.31	0.113	↑	3.19	0.14	1.91	0.565	↑	19.79	0.63
Srimangal	1.86	0.372	↑	11.96	0.42	2.39	0.454	↑	15.54	0.51	2.24	0.114	↑	3.22	0.14	1.86	0.5	↑	20.74	0.65
Saidpur	2.11	0.416	↑	17.53	0.53	2.69	0.557	↑	26.41	0.61	1.48	0.206	↑	7.47	0.32	1.96	0.521	↑	25.80	0.71
Sylhet	2.06	0.325	↑	11.48	0.41	2.16	0.465	↑	17.54	0.59	2.49	0.101	↑	2.40	0.11	2.29	0.413	↑	17.91	0.58
Tangail	1.51	0.469	↑	18.57	0.59	2.49	0.496	↑	19.99	0.56	1.08	0.256	↑	9.43	0.39	1.86	0.66	↑	31.24	0.86
Teknaf	1.86	0.467	↑	13.27	0.48	2.11	0.298	↑	8.33	0.30	2.44	0.246	↑	7.34	0.33	2.14	0.833	↑	27.97	0.86

Table 2
Calculated Sen's slope for monthly humidity trends in Bangladesh during 1981–2020.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Barisal	0.624	0.422	0.152	0.168	0.231	0.205	0.122	0.070	0.062	0.157	0.366	0.674
Bhola	0.624	0.422	0.152	0.168	0.231	0.205	0.122	0.070	0.062	0.157	0.366	0.674
Bogura	0.624	0.422	0.152	0.168	0.231	0.205	0.122	0.070	0.062	0.157	0.366	0.674
Chandpur	0.624	0.422	0.152	0.168	0.231	0.205	0.122	0.070	0.062	0.157	0.366	0.674
Chattogram	0.703	0.532	0.276	0.228	0.362	0.301	0.125	0.080	0.076	0.121	0.212	0.581
Chuadanga	0.729	0.601	0.426	0.341	0.340	0.349	0.179	0.154	0.146	0.297	0.627	0.870
Cox's Bazar	0.442	0.291	0.138	0.057	0.106	0.060	0.037	0.016	0.035	0.117	0.193	0.418
Comilla	0.800	0.663	0.315	0.355	0.372	0.236	0.120	0.063	0.061	0.166	0.320	0.639
Dhaka	0.703	0.541	0.313	0.336	0.360	0.314	0.176	0.127	0.108	0.278	0.530	0.693
Dinajpur	0.650	0.635	0.442	0.609	0.565	0.648	0.316	0.228	0.191	0.338	0.552	0.706
Faridpur	0.728	0.631	0.479	0.496	0.488	0.549	0.315	0.257	0.247	0.448	0.687	0.835
Feni	0.800	0.685	0.320	0.301	0.348	0.242	0.120	0.075	0.061	0.131	0.258	0.553
Hatia	0.431	0.260	0.055	−0.059	0.020	0.022	0.027	0.004	−0.011	0.121	0.250	0.410
Ishwardi	0.728	0.631	0.479	0.496	0.488	0.549	0.315	0.257	0.247	0.448	0.687	0.835
Jashore	0.752	0.542	0.265	0.291	0.339	0.364	0.161	0.112	0.114	0.282	0.636	0.927
Khepupara	0.463	0.174	−0.005	0.081	0.115	0.133	0.060	0.040	0.051	0.133	0.366	0.569
Khulna	0.752	0.542	0.265	0.291	0.339	0.364	0.161	0.112	0.114	0.282	0.636	0.927
Kutubdia	0.695	0.471	0.242	0.178	0.275	0.225	0.099	0.062	0.060	0.169	0.313	0.541
Madaripur	0.752	0.578	0.266	0.314	0.345	0.344	0.169	0.119	0.103	0.289	0.618	0.897
Maijdee	0.800	0.685	0.320	0.301	0.348	0.242	0.120	0.075	0.061	0.131	0.258	0.553
Mongla	0.610	0.270	0.064	0.204	0.219	0.228	0.104	0.068	0.078	0.177	0.482	0.826
Mymensingh	0.651	0.558	0.401	0.542	0.528	0.429	0.213	0.144	0.127	0.230	0.494	0.678
Patuakhali	0.437	0.230	0.021	0.056	0.093	0.086	0.049	0.024	0.025	0.135	0.363	0.533
Rajshahi	0.740	0.691	0.492	0.539	0.513	0.591	0.362	0.300	0.284	0.416	0.713	0.825
Rangamati	0.566	0.563	0.470	0.616	0.630	0.623	0.290	0.206	0.185	0.302	0.446	0.551
Rangpur	0.553	0.491	0.342	0.480	0.374	0.369	0.164	0.104	0.125	0.311	0.597	0.703
Sandwip	0.490	0.307	0.094	−0.015	0.101	0.128	0.085	0.032	0.022	0.105	0.228	0.457
Satkhira	0.610	0.270	0.064	0.204	0.219	0.228	0.104	0.068	0.078	0.177	0.482	0.826
Sitakunda	0.703	0.532	0.276	0.228	0.362	0.301	0.126	0.080	0.076	0.122	0.212	0.581
Srimangal	0.604	0.614	0.397	0.503	0.476	0.290	0.128	0.082	0.081	0.107	0.201	0.501
Saidpur	0.519	0.515	0.428	0.611	0.568	0.638	0.219	0.168	0.136	0.261	0.441	0.580
Sylhet	0.432	0.650	0.576	0.588	0.430	0.246	0.115	0.089	0.073	0.123	0.211	0.352
Tangail	0.707	0.707	0.499	0.573	0.555	0.509	0.296	0.296	0.188	0.353	0.589	0.755
Teknaf	0.905	0.465	0.189	0.193	0.454	0.367	0.177	0.143	0.185	0.439	0.640	0.954

all regions across the country experienced similar influences of precipitation on RH. While the correlation value for temperature varied between stations. The temperature exhibited a strong influence on the rise of RH at Cox's Bazar station (Pr = 0.65), followed by Hatia (Pr = 0.61), and Patuakhali (Pr = 0.60). The temperatures at Sandwip (Pr = 0.58), Khepupara (Pr = 0.54), and Kutubdia (Pr = 0.50) stations showed a moderately strong influence on rising RH levels. Very weak or no influence was identified at Rangamati, Rangpur, Rajshahi, Dinajpur, and Faridpur stations. The outcomes of the regression analysis suggest that temperature had the most influence on the variability of the RH level in the coastal district. In contrast, it had the lowest or no influence in the northern region. The possible reasons may be the location of the coastal region in proximity to large water bodies, oceanic advection, and evaporation.

4. Discussion and conclusion

RH is an important meteorological factor that contributes to plant growth and influences human living environments. This study explored the influence of temperature, rainfall, and wind speed on the recent trends and variability of RH in Bangladesh. To assess RH trends, ITA and MK-Test trend analysis methods were utilized. The influence of meteorological factors on RH variability was assessed through the integration of Pearson's correlation, Spearman rank correlation, and Kendall correlation methods.

The variability of rainfall analysis shows that the eastern region, particularly Sylhet and the eastern coastal areas of Bangladesh, receives the maximum daily and annual rainfall. In contrast, the districts in the western and northwestern regions receive the lowest amount of precipitation, less than 1500 mm/year. Similar to this, a prior study found the lowest rainfall in the northwest region of Bangladesh, while the highest was in the Sylhet and Chittagong divisions [27,29]. These results are in accord with the study by Uddin et al. [63]. According to Kamruzzaman et al. [64], the northwestern region of Bangladesh experiences frequent drought events due to lower rainfall rates. In accordance with this study, a prior study found that the southwestern region of Bangladesh has scorching average temperatures with an average value > 26 °C [65]. The spatial distribution of mean temperature illustrates the less warm climatic conditions in the southeast region of Bangladesh. The spatial distribution of windspeed showed significant variations in mean daily windspeed across the country, with the highest values in the eastern coastal region (>2.41 m/s) and the lowest in the Sylhet division. This variability in rainfall, temperature, and wind speed led to higher RH variations across the country. Similar to

Table 3
Z-statistics of MK-test for monthly humidity trends in Bangladesh during 1981–2020.

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Barisal	2.09	2.41	1.77	2.03	2.54	2.54	2.19	1.48	2.35	3.19	2.21	1.79
Bhola	2.09	2.41	1.77	2.03	2.54	2.54	2.19	1.48	2.35	3.19	2.21	1.79
Bogura	2.09	2.41	1.77	2.03	2.54	2.54	2.19	1.48	2.35	3.19	2.21	1.79
Chandpur	2.09	2.41	1.77	2.03	2.54	2.54	2.19	1.48	2.35	3.19	2.21	1.79
Chattogram	2.44	2.72	2.52	2.51	2.29	2.64	1.61	1.51	1.28	3.24	1.11	1.58
Chuadanga	2.61	2.97	2.73	2.81	2.26	3.53	4.09	1.76	4.09	2.04	1.79	2.04
Cox's Bazar	2.24	2.16	2.59	1.19	3.70	1.92	1.81	0.55	−0.10	2.64	1.86	1.91
Comilla	2.49	2.74	2.53	2.49	2.56	3.09	1.73	1.46	2.25	3.51	2.24	1.71
Dhaka	2.31	2.51	2.47	2.59	2.59	2.41	1.94	1.46	3.24	2.16	1.94	1.96
Dinajpur	2.19	2.06	3.17	2.74	2.46	3.29	2.26	1.76	1.41	0.75	1.51	1.68
Faridpur	2.06	2.19	3.47	2.39	2.19	2.97	2.61	0.78	2.01	1.43	1.91	1.53
Feni	2.09	2.51	2.61	2.64	2.59	2.82	1.99	1.23	2.64	3.41	2.93	1.56
Hatia	3.02	2.01	0.99	−1.16	0.69	0.05	1.02	−0.23	−0.44	2.72	2.64	1.84
Ishwardi	2.06	2.19	3.47	2.39	2.19	2.97	2.61	0.78	2.01	1.43	1.91	1.53
Jashore	2.49	2.89	1.94	2.71	2.14	2.87	4.04	1.79	3.60	2.19	1.73	2.09
Khepupara	2.74	2.35	−0.15	1.65	1.76	3.06	1.03	1.16	0.78	2.41	2.31	2.01
Khulna	2.49	2.89	1.94	2.71	2.14	2.87	4.04	1.79	3.60	2.19	1.73	2.09
Kutubdia	2.06	2.24	2.44	2.26	2.39	2.61	1.68	1.51	0.70	1.68	1.73	2.01
Madaripur	2.29	2.89	1.84	2.31	2.01	2.77	2.49	1.33	3.39	2.09	1.91	1.91
Maijdee	2.09	2.51	2.61	2.64	2.59	2.82	1.99	1.23	2.64	3.41	2.93	1.56
Mongla	3.02	2.46	0.64	2.20	1.91	3.47	1.89	1.43	2.04	3.25	2.31	2.09
Mymensingh	2.56	2.29	3.39	2.16	2.61	2.59	1.63	1.71	3.41	2.04	1.96	1.76
Patuakhali	2.61	1.89	0.34	0.81	2.60	1.73	0.88	0.70	0.88	2.79	2.54	1.96
Rajshahi	2.39	2.34	3.39	2.64	2.36	3.37	2.36	1.58	1.71	0.98	1.48	1.61
Rangamati	2.19	2.04	3.09	2.41	2.39	3.12	2.24	1.79	2.14	0.96	1.68	1.68
Rangpur	2.39	2.74	2.83	2.94	2.14	2.82	1.71	1.43	1.21	1.16	1.58	1.91
Sandwip	2.14	2.31	0.80	−0.19	2.14	1.89	1.41	0.80	−0.10	2.53	2.14	1.73
Satkhira	3.02	2.46	0.64	2.20	1.91	3.47	1.89	1.43	2.04	3.25	2.31	2.09
Sitakunda	2.44	2.72	2.52	2.51	2.29	2.64	1.63	1.51	1.28	3.24	1.11	1.58
Srimangal	2.24	2.14	3.15	2.41	2.64	3.07	1.66	1.86	3.22	3.33	2.87	2.14
Saidpur	2.54	2.14	2.87	2.72	2.24	3.22	2.31	1.91	1.84	0.88	1.46	1.86
Sylhet	2.87	2.26	3.17	2.24	2.26	2.99	2.24	2.19	2.54	3.06	5.01	3.85
Tangail	2.21	2.19	3.14	2.11	2.41	2.72	2.06	1.41	2.59	1.31	1.31	1.43
Teknaf	2.77	2.64	2.21	1.53	2.14	3.02	3.04	2.94	2.54	2.06	2.21	1.66

temperature, rainfall, and RH level, the southeast coastal region experienced a higher RH level, i.e., humid weather states, while the RH level in the northwest region indicates dry air. Overall, all meteorological factors exhibited higher spatial variations, with notable differences in the eastern, western, and coastal regions. In contrast, the climate in the center region of the country exhibited an average weather state.

The monthly, seasonal, and annual distributions of RH in Bangladesh suggest that a significant portion of the country, particularly the central to western and northwestern regions, experienced less dry air during February and March. In February and March, the country receives less rainfall, and the temperature remains comparatively low, which may lead to a decrease in RH levels and make the environment dry. From April to June, the mean temperature remains high in Bangladesh and remains high until September. Furthermore, Bangladesh receives 80% of its rainfall from June to September. Due to the higher temperature and rainfall in these months, the RH level starts to rise from April and makes the environment hotter, especially from July to October. The findings of this study show that entire Bangladesh experiences a humid climate condition from July to October, which suggests that people feel sticky and sweaty in these months and that the condition is very uncomfortable for some people. These findings suggest that people in Bangladesh feel comparatively comfortable from December to April and uncomfortable from May to November. According to the World Bank, the climate in Bangladesh is humid subtropical characterized by high levels of humidity throughout the year, which support the findings of this study. The Climate Change Knowledge Portal of the World Bank reported that from November to February, Bangladesh experiences its dry season, which is less humid with an average humidity of around 50%. This outcome is consistent with the seasonal RH distribution in this study.

The MK-test and ITA revealed that all 34 weather stations had a rising trend of annual and seasonal RH levels in Bangladesh, with the highest increasing rate (between 0.43% and 0.68% per year) found for the winter season and the lowest rate (between 0.058% and 0.31% per year) for the rainy season. MK-test shows that RH at station 32 exhibited a significant upward trend during summer and 10 in winter. The spatial distribution of ITA and MK-test's slope values suggests that RH change rate varies in different regions in different seasons. The coastal districts experienced relatively stable RH levels in all three seasons, while the northern region experienced relatively higher rising trends. Chowdhury et al. [66] conducted a study on humidity trends at six meteorological stations in Bangladesh between 1976 and 2015, where they found rising trends, which also accord with this study. Moreover, the MK-test and ITA outcomes yielded similar RH level change rates in all the stations. This consistency in the results of two statistical models increases confidence in the outcomes and indicates the good accuracy of the model.

This study, while providing valuable insights, is not without its limitations. While this research has delved explicitly into the

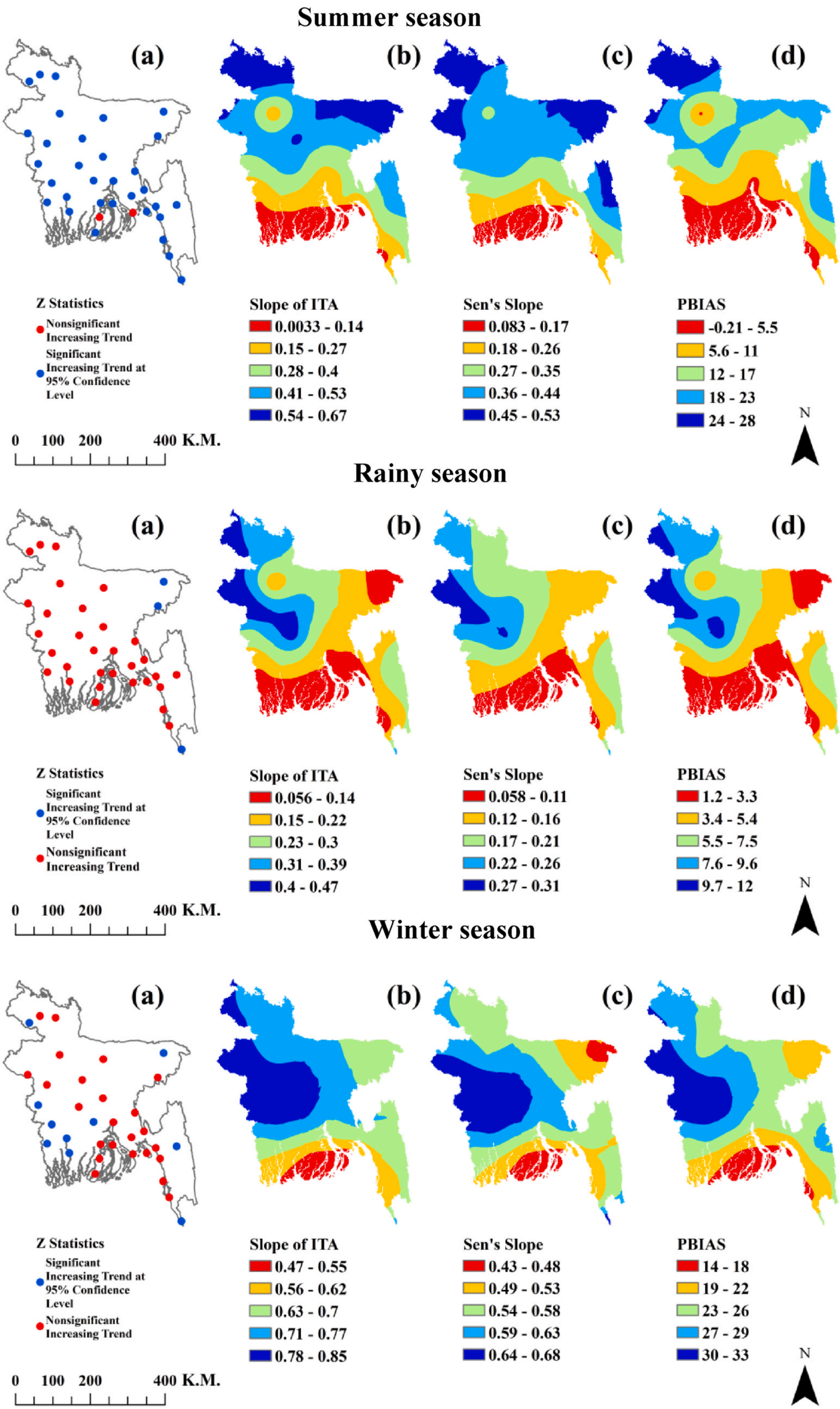


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Fig. 7. Spatial distribution of seasonal ITA slope, Sens's slope and PBIS of humidity trends.

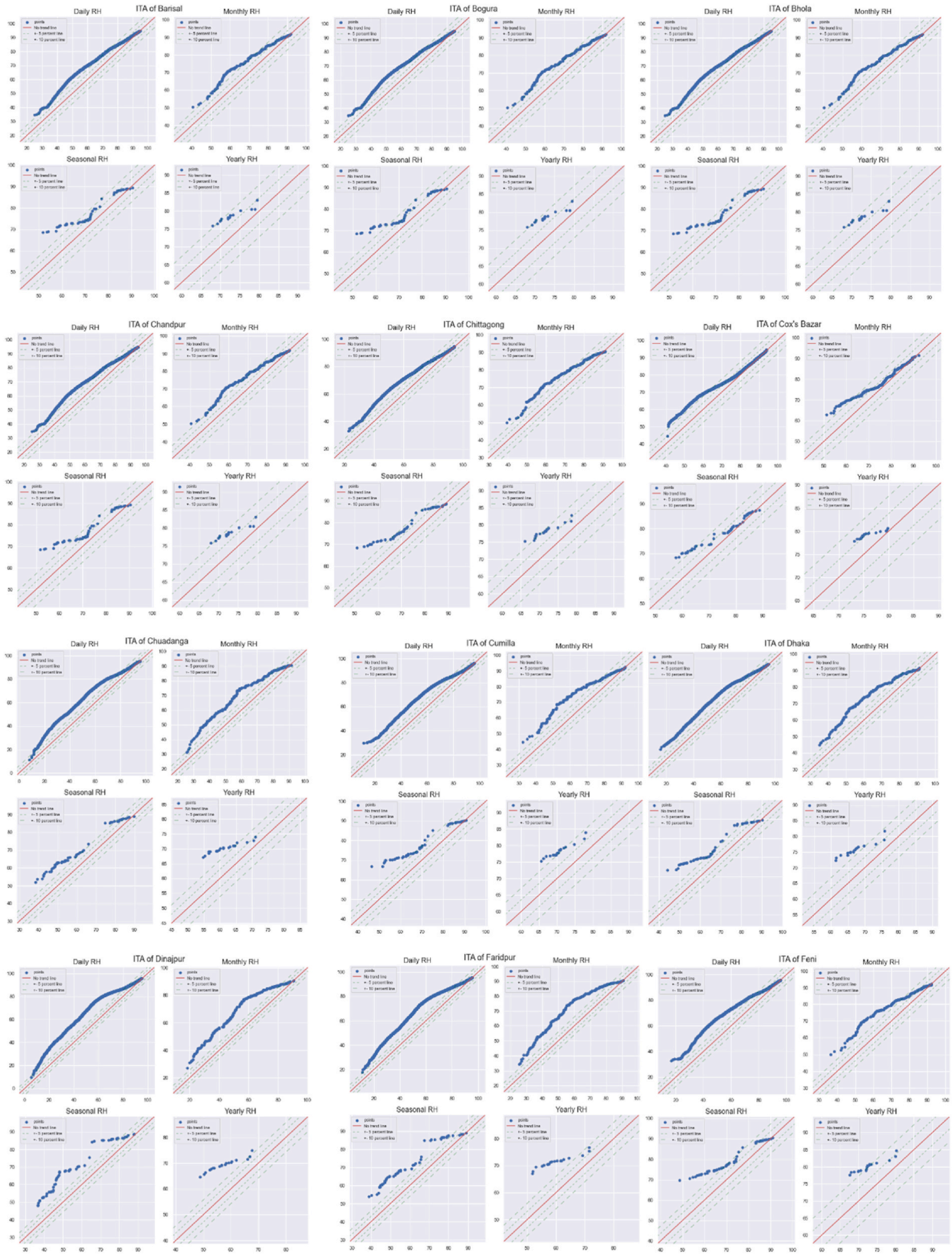

Fig. 8. Graphical representations of daily, monthly, seasonal, and yearly trends of humidity in Bangladesh using ITA.

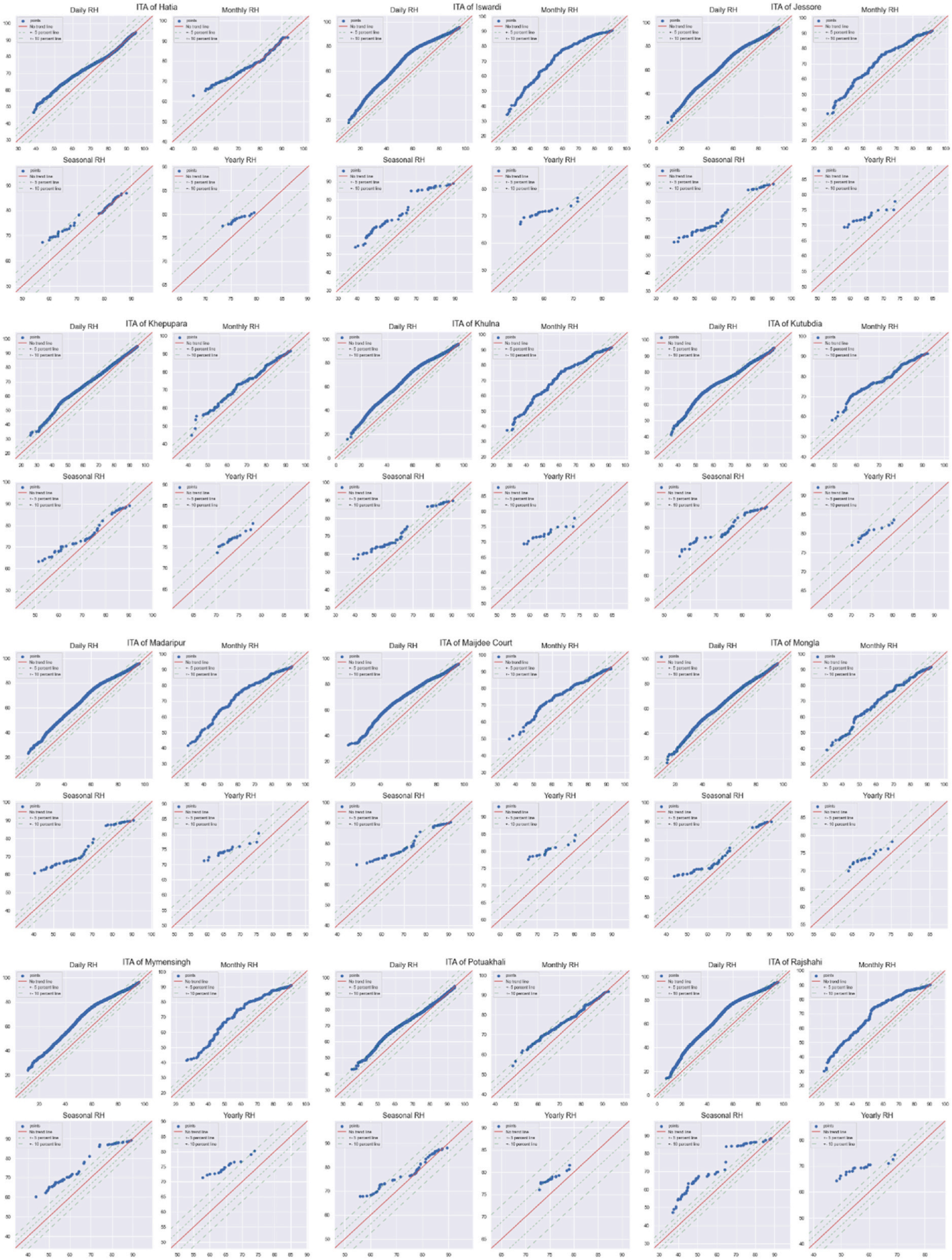

Fig. 8. (*continued*).

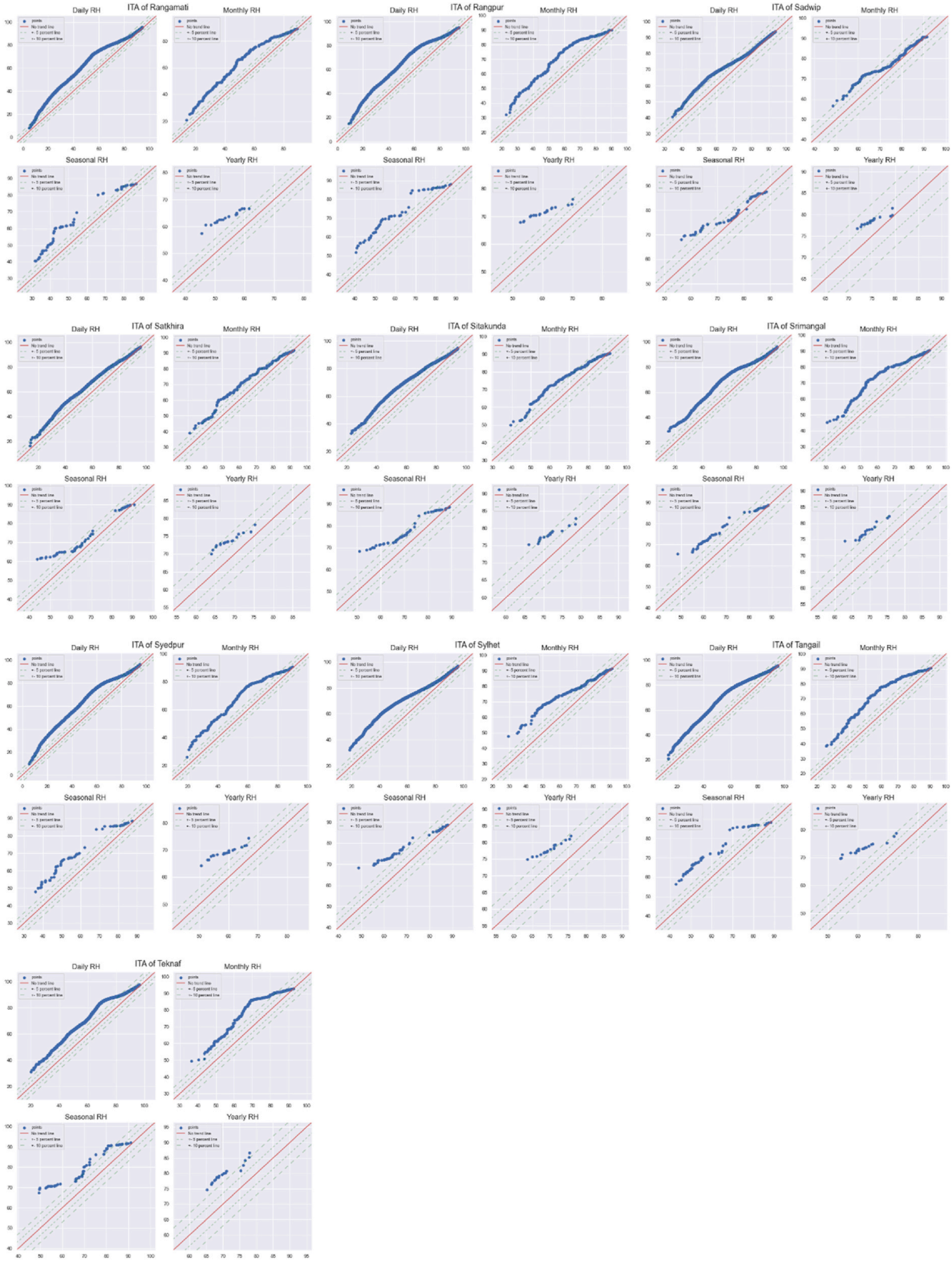

Fig. 8. (*continued*).

Fig. 9. Correlation coefficients at different stations.

Fig. 9. (*continued*).

influence of temperature, rainfall, and windspeed on RH variability, it's important to acknowledge the multifaceted nature of RH determinants. Factors such as cloud cover, thunderstorms, vegetation cover, wind direction, elevation, and proximity to water bodies, as highlighted by Liu et al. [6], also play pivotal roles in shaping RH dynamics. Moreover, this study is focused on a subset of potential variables. Notably, Fattah and Morshed [38] have explored the correlation between vegetation cover change and RH in Bangladesh. However, a more comprehensive understanding necessitates the exploration of the remaining factors' contributions to RH variability. This augmentation could provide a more holistic understanding of RH trends' intricate interplay. Additionally, we used statistical methods to investigate trends and influences. In these methods, linearity, stationarity, and independence of observations are assumed, which might not fully capture the complexities of climate data, and thus, results could be influenced slightly. Notwithstanding these limitations, this study significantly advances the discourse on climate change by bridging existing knowledge gaps. The amalgamation of various trend and correlation models lends a heightened level of credibility to the findings, further reinforcing their significance. This study will help policymakers and environmentalists plan for future climate risks and develop mitigation strategies. Furthermore, on a global scale, the study hold the potential to assist policymakers in the crafting of comprehensive mitigation and adaptation approaches, particularly in regions that are more susceptible to climate vulnerabilities.

Author contribution statement

Md. Abdul Fattah: Conceived and designed the experiments; Analyzed and interpreted the data; wrote the paper.

Sudipta Das Gupta and Md. Zunaid Faroque: Contributed reagents, materials, analysis tools or data; Performed the experiments; Analyzed and interpreted the data.

Bhaskar Ghosh, Syed Riad Morshed, Tanmoy Chakraborty, Abdulla – Al Kafy, and Muhammad Tauhidur Rahman: contributed reagents, materials, analysis tools or 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.

References

[1] M. Ahmed, S. Suphachalasai, Assessing the Costs of Climate Change and Adaptation in South Asia, Asian Development Bank, Mandaluyong City, Philippines, 2014.
[2] IPCC, The IPCC's fifth assessment report: what's in it for South asia? Intergovernmental Panel on Climate Change (2014) 1–38.
[3] J. Roome, SouthAsia4Climate: Solutions to Tackle Climate Change in South Asia. End Poverty in South Asia, 10 2, World Bank Blogs, 2022 [Online]. Available: https://blogs.worldbank.org/endpovertyinsouthasia/southasia4climate-solutions-tackle-climate-change-south-asia. (Accessed 14 March 2023).
[4] United Nations, Climate Change-Induced Sea-Level Rise Direct Threat to Millions Around World 2, Secretary-General Tells Security Council, 2023, p. 14 [Online]. Available: https://press.un.org/en/2023/sc15199.doc.htm#:~:text=The%20world%20will%20witness%20"a,that%20rising%20sea%20levels%20portend.. [Accessed 13 3 2023].
[5] T. Matthews, Humid heat and climate change, Prog. Phys. Geogr. Earth Environ. 42 (3) (2018).
[6] Z. Liu, H. Yang, X. Wei, Spatiotemporal variation in relative humidity in guangdong, China, from 1959 to 2017, Water 12 (12) (2020) 3576.
[7] C. Buonocore, R. De Vecchi, V. Scalco, R. Lamberts, Influence of relative air humidity and movement on human thermal perception in classrooms in a hot and humid climate, Build. Environ. 146 (2018) 98–106.
[8] J. Lepeule, A. Litonjua, A. Gasparrini, P. Koutrakis, D. Sparrow, P. Vokonas, J. Schwartz, Lung function association with outdoor temperature and relative humidity and its interaction with air pollution in the elderly, Environ. Res. 165 (2018) 110–117.
[9] M. Rahman, M. Rahman, J. Biswas, N. Rahman, M. Islam, M. Sarkar, M. Islam, M. Maniruzzaman, Climate change and risk scenario in Bangladesh, Asia-Pacific Journal of Regional Science 7 (2023) 381–404.
[10] S. Vicente-Serrano, N. Raquel, G. Luis, C. Azorin-Molina, A. Drumond, A. El Kenawy, F. Dominguez-Castro, M. Tomas-Burguera, M. Peña-Gallardo, Recent changes of relative humidity: regional connections with land and ocean processes, Earth System Dynamics 9 (2) (2018) 915–937.
[11] S.C. Sherwood, W. Ingram, Y. Tsushima, M. Satoh, M. Roberts, P.L. Vidale, P.A. O'Gorman, Relative humidity changes in a warmer climate, J. Geophys. Res. Atmos. 115 (D9) (2010).
[12] J. Metz, A. Finn, Influenza and humidity – why a bit more damp may be good for you, J. Infect. 71 (2015) 54–58.
[13] Y. Yang, E. You, J. Wu, W. Zhang, J. Jin, M. Zhou, C. Jiang, F. Huang, Effects of relative humidity on childhood hand, foot, and mouth disease reinfection in Hefei, China, Sci. Total Environ. 630 (2018) 820–826.
[14] A. Orcesi, A. O'Connor, E. Bastidas-Arteaga, M.G. Stewart, B. Imam, K. Kreislova, Investigating the effects of climate change on material properties and structural performance, Struct. Eng. Int. 32 (4) (2022) 577–588.
[15] IPCC, Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, Intergovernmental Panel on Climate Change, 2012.
[16] G.-i. Hirai, T. Okumura, S. Takeuchi, O. Tanaka, H. Chujo, Studies on the effect of the relative humidity of the atmosphere on the growth and physiology of rice plants, Plant Prod. Sci. 3 (2) (2000) 129–133.
[17] H. Chowdhury, B. Asiabanpour, A Smart Circular Economy for Integrated Organic Hydroponic-Aquaponic Farming, Texas State University, Austin, Texas, 2023.
[18] Y. Wu, X. Ge, J. Wang, Y. Shen, Z. Ye, S. Ge, Y. Wu, H. Yu, M. Chen, Responses of secondary aerosols to relative humidity and photochemical activities in an industrialized environment during late winter, Atmos. Environ. 193 (2018) 66–78.
[19] S. Chia, M. Lim, A critical review on the influence of humidity for plant growth forecasting, IOP Conf. Ser. Mater. Sci. Eng. 1257 (2022).
[20] M. Chowdhury, S. Kiraga, M. Islam, M. Ali, M. Reza, W.-H. Lee, S. Chung, Effects of temperature, relative humidity, and carbon dioxide concentration on growth and glucosinolate content of kale grown in a plant factory, Foods 10 (7) (2021).
[21] A. Islam, B. Shill, R. Salam, M. Siddik, M. Patwary, Insight into farmers' agricultural adaptive strategy to climate change in northern Bangladesh, Environ. Dev. Sustain. 23 (2021) 2439–2464.
[22] M. Rahman, M. Rony, F. Jannat, Spatiotemporal evaluation of drought trend during 1979–2019 in seven climatic zones of Bangladesh, Heliyon 7 (11) (2021).
[23] Z. Ahmed, G. Guha, A. Shew, G. Alam, Climate change risk perceptions and agricultural adaptation strategies in vulnerable riverine char islands of Bangladesh, Land Use Pol. 103 (2021), 105295.
[24] M. Mutahara, J. Warner, A. Wals, M. Khan, P. Wester, Social learning for adaptive delta management: tidal river management in the Bangladesh delta, Int. J. Water Resour. Dev. 34 (6) (2018) 923–943.
[25] F. Gao, X. Chen, W. Yang, W. Wang, L. Shi, X. Zhang, Y. Liu, Y. Tian, Statistical characteristics, trends, and variability of rainfall in Shanxi province, China, during the period 1957–2019, Theor. Appl. Climatol. 148 (2022) 955–966.
[26] A. Panda, N. Sahu, Trend analysis of seasonal rainfall and temperature pattern in Kalahandi, Bolangir and Koraput districts of Odisha, India, Atmos. Sci. Lett. 20 (10) (2019).
[27] M. Bhuyan, M. Islam, M. Bhuiyan, A trend analysis of temperature and rainfall to predict climate change for northwestern region of Bangladesh, Am. J. Clim. Change 7 (2) (2018) 115–134.
[28] M.H. Imam, M.M. Rahman, S. Roy, F. Hoque, U. Ahsan, S. Abdullah, M. Hossain, M. Rahim, Analysis of diurnal air temperature range variation over Bangladesh, Earth Systems and Environment 6 (2022) 361–373.
[29] H. Imran, J. Kala, S. Uddin, A. Islam, N. Acharya, Spatiotemporal analysis of temperature and precipitation extremes over Bangladesh using a novel gridded observational dataset, Weather Clim. Extrem. 39 (2023), 100544.
[30] M. Rahman, N. Ferdousi, S. Abdullah, S. Kusunoki, A. Islam, Recent climate simulation over SAARC region including Bangladesh using high resolution AGCM, Asia-Pacific Journal of Atmospheric Sciences 55 (2019) 115–134.
[31] Q. Wei, J. Xu, L. Liao, Y. Yu, W. Liu, J. Zhou, Y. Ding, Indicators for evaluating trends of air humidification in arid regions under circumstance of climate change: relative humidity (RH) vs. Actual water vapour pressure (ea), Ecol. Indicat. 121 (2021), 107043.
[32] W. Yang, L. Marr, Dynamics of airborne influenza A viruses indoors and dependence on humidity, PLoS One 6 (6) (2011).
[33] CONDAIR, Humidity, Health and Wellbeing, CONDAIR, 2019.
[34] A.-A.- Faisal, M. Rahman, A.-A. Kafy, S. Roy, A. Khan, M. Rahman, Impact on land surface temperature and urban heat island, due to land use/land cover change in dhaka metropolitan area, using remote sensing and GIS techniques, in: Re-envisioning Advances in Remote Sensing, Taylor & Francis group, 2022, p. 34.
[35] A. Dewan, G. Kiselev, D. Botje, G. Mahmud, M. Bhuian, Q. Hassan, Surface urban heat island intensity in five major cities of Bangladesh: patterns, drivers and trends, Sustain. Cities Soc. 71 (2021), 102926.
[36] M. Saha, A. Kafy, A. Bakshi, A.-A.- Faisal, A.I. Almulhim, Z.A. Rahaman, A.A. Rakib, M. Fattah, K. Akter, M. Rahman, M. Zhang, R. Rathi, Modelling microscale impacts assessment of urban expansion on seasonal surface urban heat island intensity using neural network algorithms, Energy Build. 275 (2022), 112452.
[37] BBS, Population and Housing Census, 2022, Bangladesh Bureau of Statistics, Dhaka, Bangladesh, 2023.
[38] M.A. Fattah, S.R. Morshed, Assessment of the responses of spatiotemporal vegetation changes to climatic variability in Bangladesh, Theor. Appl. Climatol. 148 (2022) 285–301.
[39] D. Argha, A. Hasib, M. Rahman, A comparative study on the variation of air quality index of Dhaka city before and after the nationwide lockdown due to COVID-19, in: International Conference on Engineering Research, Innovation and Education, 2021.
[40] M. Rahman, M. Islam, D. Argha, M. Haque, Present scenario of municipal solid waste management in Satkhira Municipality, in: International Conference on Civil Engineering for Sustainable Development, Khulna, Bangladesh, 2018.

[41] T. Khan, D. Argha, M. Anita, An analysis of existing medical waste management and possible health hazards in Jhenaidah municipality, in: 6th International Conference on Engineering Researach, Innovation and Education, Sylhet, Bangladesh, 2021.
[42] M. Ahmed, P. Roy, M. Shah, R. Riyad, D. Argha, D. Datta, Recycling of cotton dust for organic farming is a pivotal replacement of chemical fertilizers by composting and its quality analysis, Environmental Research and Technology 4 (2) (2021) 108–116.
[43] Z. Şen, Innovative trend analysis methodology, J. Hydrol. Eng. 17 (9) (2012), 1042-1046.
[44] S. Pour, A. Abd Wahab, S. Shahid, Z.B. Ismail, Changes in reference evapotranspiration and its driving factors in peninsular Malaysia, Atmos. Res. 246 (105096) (2020).
[45] A. Girma, T. Qin, H. Wang, D. Yan, M. Gedefaw, A. Abiyu, D. Batsuren, Study on recent trends of climate variability using innovative trend analysis: the case of the upper huai river basin, Pol. J. Environ. Stud. 29 (3) (2020) 2199–2210.
[46] L. Cui, L. Wang, Z. Lai, Q. Tian, W. Liu, J. Li, Innovative trend analysis of annual and seasonal air temperature and rainfall in the Yangtze River Basin, China during 1960–2015, J Atmos Sol Terr 164 (2017) 48–59.
[47] T. Mandal, J. Das, A. Rahman, P. Saha, Rainfall insight in Bangladesh and India: climate change and environmental perspective, in: Habitat, Ecology and Ekistics: Case Studies of Human-Environment Interactions in India, 2020, pp. 53–74.
[48] D. Burn, M. Elnur, Detection of hydrologic trends and variability, J. Hydrol. 255 (1–4) (2002) 107–122.
[49] A. Rahman, C. Jahan, Q. Mazumder, M. Kamruzzaman, T. Hosono, Drought analysis and its implication in sustainable water resource management in Barind area, Bangladesh, J. Geol. Soc. India 89 (1) (2017) 47–56.
[50] J. Das, S. Bhattacharya, Trend analysis of long-term climatic parameters in Dinhata of Koch Bihar district, West Bengal, Spatial Information Research 26 (2018) 271–280.
[51] J. Das, A. Gayen, P. Saha, S. Bhattacharya, Meteorological drought analysis using standardized precipitation index over Luni Basin in Rajasthan, India, SN Appl. Sci. 2 (2020) 1–17.
[52] H. Mann, Non-parametric test against trend, Econometrica 13 (1945) 245–259.
[53] M. Kendall, Rank Correlation Measures, vol. 202, Charles Griffin, London, 1975, p. 15.
[54] R. Gilbert, Statistical Methods for Environmental Pollution Monitoring, John Wiley & Sons, 1987.
[55] E. Pearson, H. Ho. O., Biometrika Tables for Statisticians, third ed., vol. 1, Cambridge University Press, London, 1966.
[56] P. Sen, Estimates of the regression coefficient based on Kendall's tau, J. Am. Stat. Assoc. 63 (324) (1968) 1379–1389.
[57] J. Hauke, T. Kossowski, Comparison of values of Pearson's and Spearman's correlation coefficients on the same sets of data, Quaest. Geogr. 30 (2) (2011) 87–93.
[58] C. Xiao, J. Ye, R. Esteves, C. Rong, Using Spearman's correlation coefficients for exploratory data analysis on big dataset, Concurrency Comput. Pract. Ex. 28 (14) (2016) 3866–3878.
[59] Y. Shao, Z. Ma, J. Wang, J. Bi, Estimating daily ground-level PM2. 5 in China with random-forest-based spatiotemporal kriging, Sci. Total Environ. 740 (2020), 139761.
[60] K. Shukla, P. Kumar, G. Mann, M. Khare, Mapping spatial distribution of particulate matter using Kriging and Inverse Distance Weighting at supersites of megacity Delhi, Sustain. Cities Soc. 54 (2020), 101997.
[61] A. Ayanlade, G. Atai, M. Jegede, Variability in atmospheric aerosols and effects of humidity, wind and InterTropical discontinuity over different ecological zones in Nigeria, Atmos. Environ. 201 (2019) 369–380.
[62] K. Zhang, Q. Wang, L. Chao, J. Ye, Z. Li, Z. Yu, T. Yang, Q. Ju, Ground observation-based analysis of soil moisture spatiotemporal variability across a humid to semi-humid transitional zone in China, J. Hydrol. 574 (2019) 903–914.
[63] M. Uddin, M. Park, S. Hassan, S. Ahmed, M. Mannan, M. Faruq, M. Rahman, A. Hoque, M. Rahman, Variability in rainfall and its extremes in Bangladesh, DEW-DROP 7 (1) (2022).
[64] M. Kamruzzaman, M. Jang, J. Cho, S. Hwang, Future changes in precipitation and drought characteristics over Bangladesh under CMIP5 climatological projections, Water 11 (11) (2019) 2219.
[65] R. Salam, A. Islam, Q. Pham, M. Dehghani, N. Al-Ansari, N. Linj, The optimal alternative for quantifying reference evapotranspiration in climatic sub-regions of Bangladesh, Sci. Rep. 10 (2020).
[66] M. Chowdhury, S. Mondal, J. Islam, Modeling and forecasting humidity in Bangladesh: box-jenkins approach, International Journal of Research 6 (4) (2018) 50–60.