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ORIGINAL PAPER

Evaluation of temporal and spatial trends in relative humidity and dew point temperature in Bangladesh

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Abstract Trend analysis of climatic variables on different spatial and temporal scales has been of great concern during the past century because of the attention given to global climate change by the scientific community. In this study, trends of the annual and seasonal relative humidity and dew point temperature time series have been investigated for 15 stations all over Bangladesh during 1961–2010. The magnitude of the climatic trends was derived from the slopes of the Sen's estimator. The statistical significance of the trends was determined by means of the Mann–Kendall test. Pre-whitening was used to eliminate the influence of serial correlation on the Mann–Kendall test. The percentage of stations showing a significant trend is moderate in the case of relative humidity, but is a lot higher in dew point temperature series at the 95 % confidence limit. On average, relative humidity is increasing at 0.53, 0.86, and 1.18 % per decade on annual, winter, and pre-monsoon (summer) scales, respectively, in the western part of the country. Significant negative trends of relative humidity series are apparent in monsoon season. On the other hand, there is no significant decreasing trend in both annual and seasonal dew point temperature time series at any station. Again, a higher magnitude of the significant trends is observed in the western part of the country. The majority of the slopes are above zero, indicating an increasing nature in annual and seasonal dew point temperatures over Bangladesh. This warming of dew point temperature in Bangladesh is analogous to the global trend.

Keywords Relative humidity · Dew point temperature · Mann–Kendall test · Serial correlation · Sen's slope · Bangladesh

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Introduction

Global warming resulting from positive concentrations of atmospheric greenhouse gases is very likely to have an impact upon the global hydrological cycle (IPCC 2007). The impact of climate change is perceptibly greater when it is associated with extreme events, especially where vulnerable populations or high-value properties are at risk (Trenberth et al. 2007). Agricultural productivity in Asia is likely to suffer severe losses because of high temperature, severe drought, flood conditions, and soil degradation (Iqbal and Quamar 2011). In recent decades, many studies have been done on climate trends, especially for precipitation and temperature, compared to the time before the issue of climate change became more prominent during the 1980s. Since then, arguably one of the

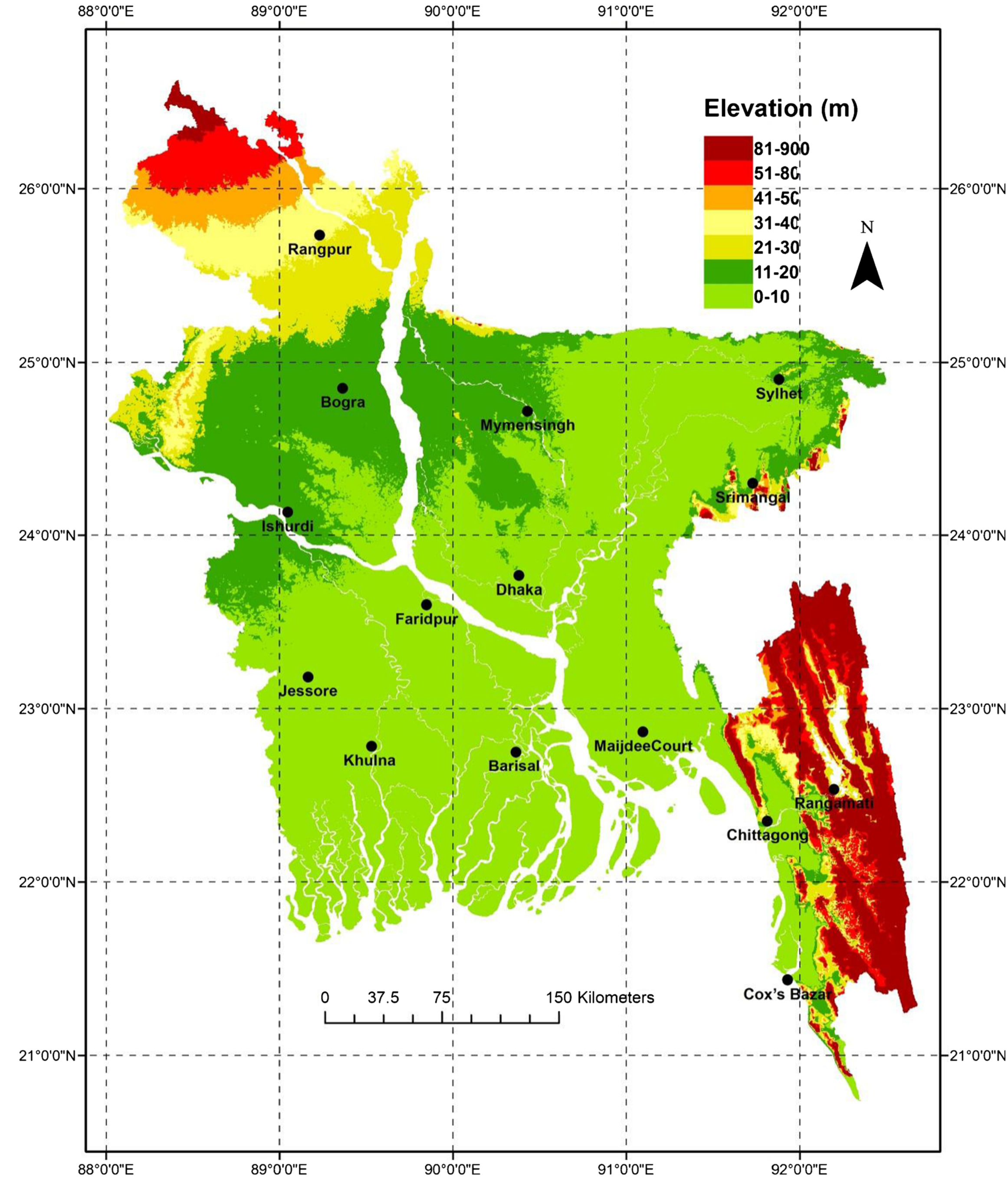


Fig. 1 Elevation profile of the study area and location of the BMD stations

biggest motivations for such studies is to establish if and how global warming might have influenced the climate on a global as well as regional scales. Climate change resulting from global warming could have a critical impact on humidity and, hence, human health.

One important factor is atmospheric water vapor which determines the earth's weather and climate due to its role as a greenhouse gas and on account of the large amount of energy involved as water changes between the gaseous (vapor) phase and liquid and solid phases (Abu-Taleb et al. 2007). At the surface, water vapor (or humidity) is an important meteorological and climate variable that affects human comfort (Changnon et al. 1996). It has practical implications for investigations ranging from evaporation rates (Penman 1955) through plant disease development (Wilks and Shen 1991) to human heat stress (Livezey and Tinker 1996). The importance of high humidity and temperature events for this last impact has been emphasized by Changnon et al. (1996), while concerns about global warming and the possible increase in the frequency of such events (McMichael et al.

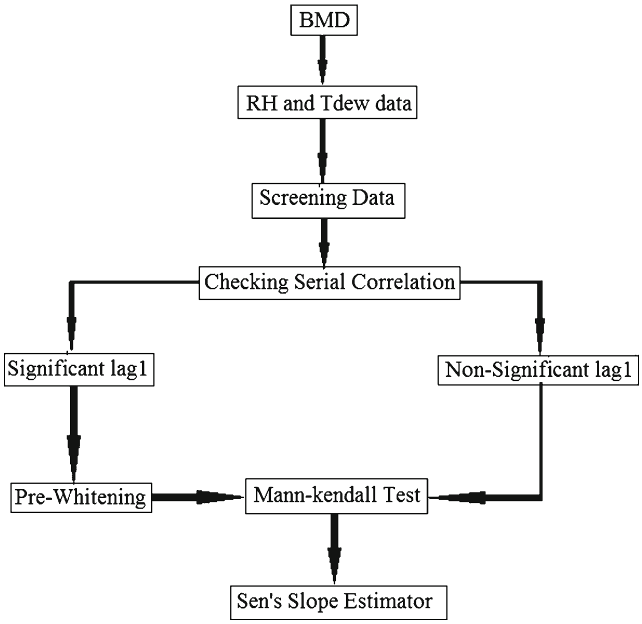


Fig. 2 Methodological flowchart

1996) indicates the need for a close examination of humidity climatology.

Relative humidity (RH) has direct effect on atmospheric visibility, strongly influencing the formation of clouds, fog, and smog (Elliott and Angell 1997). It plays a vital role in determining the geographical distribution and maximum intensity of precipitation and the potential maximum intensity of tropical cyclones and has crucial effects on the biosphere and surface hydrology (Willett et al. 2007). Relative humidity is a function of the temperature and absolute water vapor concentration. Dew point temperature (T_{dew}) has traditionally been the most commonly used humidity measure. It is an important tool in forecasting both the specific and relative humidity. Hence, a change in dew point temperature results in a corresponding change in relative humidity (van Wijngaarden and Vincent 2003). As water vapor is the strongest contribution to the greenhouse effect, any changes in dew point temperatures would have important implications for climate change.

Examining long-term trends in hydroclimatic parameters and evaluating their statistical significance are elementary tools in the detection of climate change (Huth and Pokorna 2004). The effects of climatic change and variability have been investigated by many researchers throughout the world. However, a few studies have been carried out to examine the trends of RH and T_{dew} compared to air temperature and precipitation. From the trend studies, increasing patterns of RH and T_{dew} have been observed in most parts of the world. Robinson (2000) examined the trends of dew point temperature in different stations of the USA and found an increase in seasonally averaged T_{dew} for the period 1951–1990. In another study in the USA, an increase in specific humidity and T_{dew} was observed over most of the country in winter, spring, and summer (Gaffen and Ross 1999). van Wijngaarden and Vincent (2003) studied the changes in RH in Canada during 1953–2003 and detected a significant decreasing trend in RH throughout the country. Abu-Taleb et al. (2007) found an increase in seasonal and annual RH in Jordan. Seidel et al. (2007) showed a generally decreasing trend in T_{dew} at the Summit of Mount Washington, New Hampshire. Kousari and Zarch (2010) showed a decreasing trend for the mean relative humidity in arid and semi-arid regions, especially during the last few years up to the year 2000. Talaee et al. (2012) reported that annual relative humidity was increased by 1.03 and 0.28 °C per decade at the northern and southern coastal regions of Iran, respectively, while the annual dew point temperature was increased by 0.29 and 0.15 °C per decade at the northern and southern coastal regions of Iran, respectively.

However, with respect to Bangladesh, no suitable climatology of relative humidity and dew point temperature is currently available. Bangladesh has been termed as one of the most vulnerable countries in the world due to climatic change (IPCC 2007). According to the fourth assessment report of the IPCC, there will be an increase of rainfall of 5–6 % by 2030. As the primary impacts of climate change on society result from extreme events (Rodrigo 2002), it might have severe negative consequences for Bangladesh.

The purpose of this study was to detect the trends in relative humidity and dew point temperature on the annual and seasonal scales over the period 1961–2010 at 15 different locations of Bangladesh.

Study area

Bangladesh is a low-lying, riverine country located in South Asia with a largely marshy jungle coastline of 710 km on the northern littoral of the Bay of Bengal. It extends from 20°340 N to 26° 380 N latitude and from 88°010 E to 92°410 E longitude (Fig. 1). The country has a tropical monsoon climate characterized by heavy seasonal rainfall, high temperatures, and high humidity. Maximum summer temperatures range between 38 and 41 °C. April is the hottest month in most parts of the country. January is the coolest month, when the average temperature for most of the country is 16–20 °C during the day and around 10 °C at night. The only exceptions to Bangladesh's low elevations are the Chittagong Hills in the southeast, the Low Hills of Sylhet in the northeast, and the highlands in the north and northwest. The Chittagong Hills constitute the only significant hill system in the country and, in effect, are the western fringe of the north–south mountain ranges of Burma and eastern India (U.S. Department of State 2010; Federal Research Division 1988). The coastal and offshore area of Bangladesh includes tidal, estuaries, and river floodplains in the south along the Bay of Bengal. The coastal area covers about 20 % of the country (Haque 2006). Two major dimensions of climatic changes for Bangladesh are the

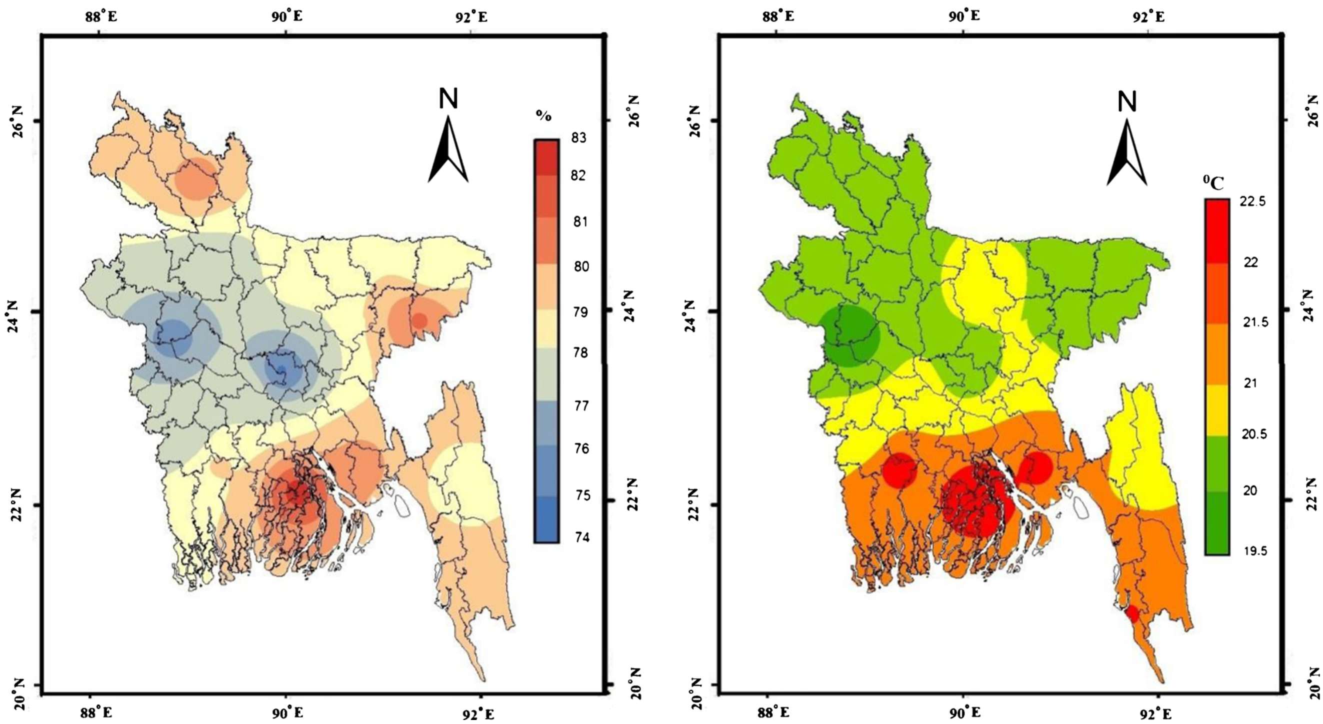


Fig. 3 Spatial distribution of the mean annual (1) relative humidity and (2) dew point temperature over the period 1961–2010

high rate of temperature increase and the large precipitation variability. Apart from these, two other climate change aspects which Bangladesh is exceptionally vulnerable to are the gradual sea level rise with associated increase of salinity in coastal aquifers and the amplified intensity of cyclones falling over the coast. Rajib et al. (2011) identified a high rate of increase in the country's average annual temperature during the recent 20 years since 1990–2009 (about 0.4 °C per decade). However, by segregating the average annual temperature of only the recent 10 years (2000–2009), it was revealed that this rate of temperature increment is even higher and that there has been an almost 1 °C increase since 2000.

Table 1 Descriptive statistics of seasonal RH and T_{dew} series

Station	Pre-monsoon				Monsoon				Post-monsoon				Winter			
	RH		T_{dew}		RH		T_{dew}		RH		T_{dew}		RH		T_{dew}	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Rangpur	73.46	7.68	73.46	7.68	19.4	7.06	85.16	2.18	82.6	4.03	20.71	4.73	79.51	5.8	13.73	10.49
Bogra	68.9	7.56	68.9	7.56	19.33	9.11	85.04	1.75	79.2	2.75	20.48	5.42	72.25	5.09	12.53	12.45
Ishurdi	64.82	8.96	64.82	8.96	18.67	9.32	84.33	2.49	78.78	3.95	20.01	4.65	71.65	6.78	11.86	10.79
Khulna	74.27	5.44	74.27	5.44	22.87	4.55	86.42	3.74	80.09	4.27	21.76	5.19	73.97	6.35	14.59	7.13
Jessore	69.46	6.31	69.46	6.31	21.17	5.48	85.52	1.43	78.86	4.53	20.63	5.09	71.86	6.67	13.06	10.41
Barisal	78.22	3.57	78.22	3.57	22.98	4.53	88.28	1.4	83.83	3.34	22.14	4.38	77.95	4.46	15.01	9.59
Dhaka	69.26	4.45	69.26	4.45	20.48	4.69	83.41	2.59	75.97	3.99	20.32	4.08	68.43	3.64	12.79	7.51
Mymensingh	73.07	7.27	73.07	7.27	20.72	5.98	85.31	2.38	80.11	6.42	21.27	5.12	73.13	7.66	13.77	7.99
Faridpur	71.02	5.36	71.02	5.36	20.99	4.86	85.58	1.64	79.26	2.86	21.18	3.92	73.74	3.57	13.78	6.68
MaijdeeCourt	77.26	4.27	77.26	4.27	22.57	4.3	86.13	1.51	80.3	4.11	21.83	4.35	75.95	5.45	15.09	7.82
Sylhet	73.34	4.66	73.34	4.66	19.65	4.83	86.31	1.69	79.33	2.77	20.44	3.62	70.85	4.46	13.07	9.49
Srimangal	74.38	6.37	74.38	6.37	20.34	6.74	85.32	2.38	84.27	4.06	20.83	4.03	79.51	5.8	13.73	10.49
Chittagong	76.71	3.29	76.71	3.29	22.3	5.07	84.9	2.38	84.27	4.06	20.83	4.03	80.03	5.97	13.31	6.99
Rangamati	72.27	3.81	72.27	3.81	20.94	4.01	84.47	1.59	79.7	2.96	21.89	3.93	72.81	4.27	14.83	5.6
Cox's Bazar	77.16	2.72	77.16	2.72	22.75	2.95	87.23	1.43	81.74	2.53	21.83	3.02	75.11	3.61	14.75	5.49

Table 2 Significant lag-1 serial correlation at the 5 % level

	Relative humidity	Dew point temperature
Winter	15	14
Pre-monsoon	6	6
Monsoon	9	14
Post-monsoon	12	10
Annual mean	14	14

Data quality and homogeneity

Daily relative humidity and dew point temperature data covering the recent period of 1961–2010 have been collected from the Bangladesh Meteorological Department (BMD).

Data quality control is a necessary step because erroneous outliers can seriously impact the index calculation and their trends (Yue et al. 2003). Missing values were screened before the data were used in the subsequent analysis. Stations with too many missing values were dropped. In this regard, some criteria have been applied to the available data; this is in reference to those adopted in the Western Regional Climate Center and other researchers (e.g., Griffiths and Bradley 2007). These criteria include the following:

1. A month is considered as having complete data if there are less than or equal to five missing days.
2. A year is considered complete if all months are complete according to item 1.
3. A station series is considered complete if it has equal to or more than 80 % complete years according to item 2 in different periods.

In this case, a station series is considered complete if it has equal to or more than 40 years complete record in the period from 1961 to 2010. As a result, 15 stations out of 35 have been finally selected for inclusion in the analysis. Figure 1 shows the elevation profile of the study area with the positions of the BMD stations.

The main purpose of this quality control procedure was to identify errors in data processing, such as errors in manual keying. Outliers in daily humidity and dew point temperature were also identified using standard deviation threshold. Outliers that were identified were evaluated by comparing their values to adjacent days, to the same day at nearby stations and, most importantly, to the knowledge of local experts before being edited or removed. As these things are routinely done by the BMD, the errors were minimal.

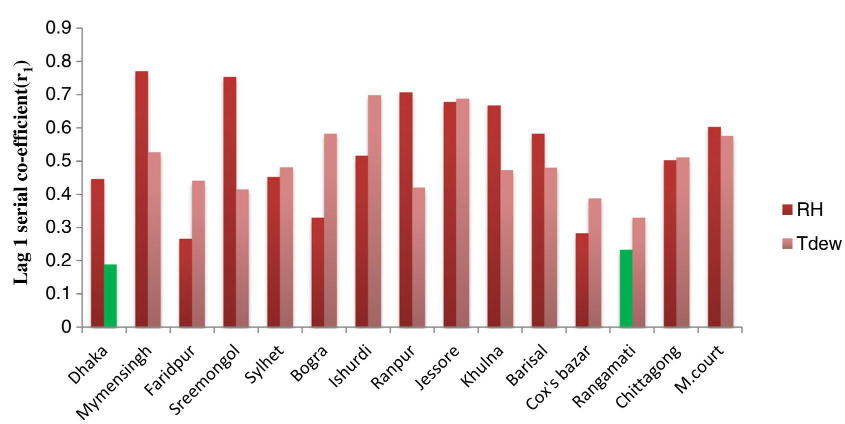
Data quality is a relatively easy problem to address when compared with the problems associated with data inhomogeneity. Erroneous outliers and artificial step changes caused by changes in station location, observing procedures and practice, instrumentation changes, etc. (Aguilar et al. 2003), make trend analysis unreliable, and there is not always a consistent approach to deal with data inhomogeneity (Peterson et al. 1998). However, in this study, the possible non-homogeneities in the data were assessed primarily by visual examination of the plots of the monthly humidity and dew point temperature series at each station. No break points were detected in the time series.

Furthermore, to detect non-homogeneities in the data series, Student's t test was applied to the annual humidity and dew point temperature time series of each station. Student's t test assesses homogeneity by determining whether or not various samples are derived from the same population (Panofsky and Brier 1968). The test was applied on each station. The results reveal that there is no statistically significant variation or break point existing in the time series at the 95 % level of confidence. Moreover, the meteorological stations were at the same place throughout the mentioned time period. The data sets of all the 15 stations are found homogeneous.

Methodology

The methodology of this study consists of (1) testing the serial correlation effect, (2) applying the Mann–Kendall test, and (3) computing Sen's estimator. The methodological procedures are summarized in Fig. 2. As climatologic time series data are

Fig. 4 Lag 1 serial coefficient for annual RH and T_{dew} time series



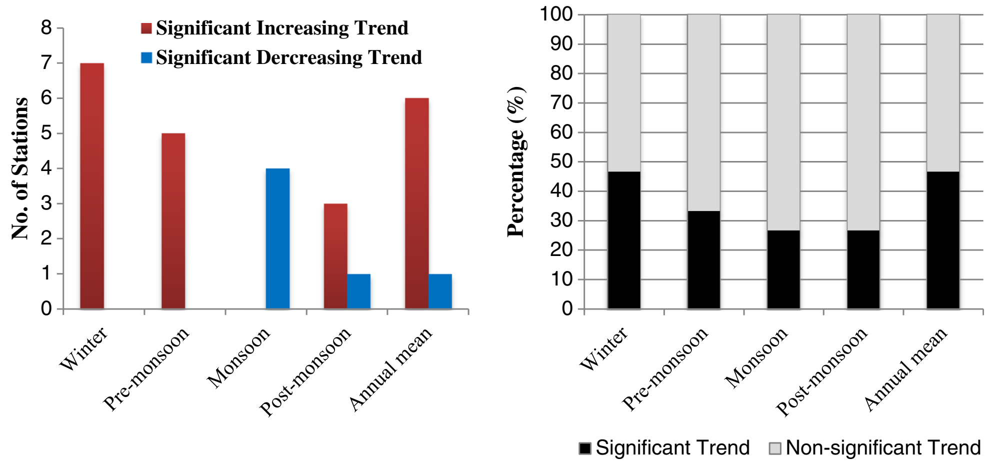


Fig. 5 Mann–Kendall test results for increasing and decreasing trend detection of RH series (α=0.05)

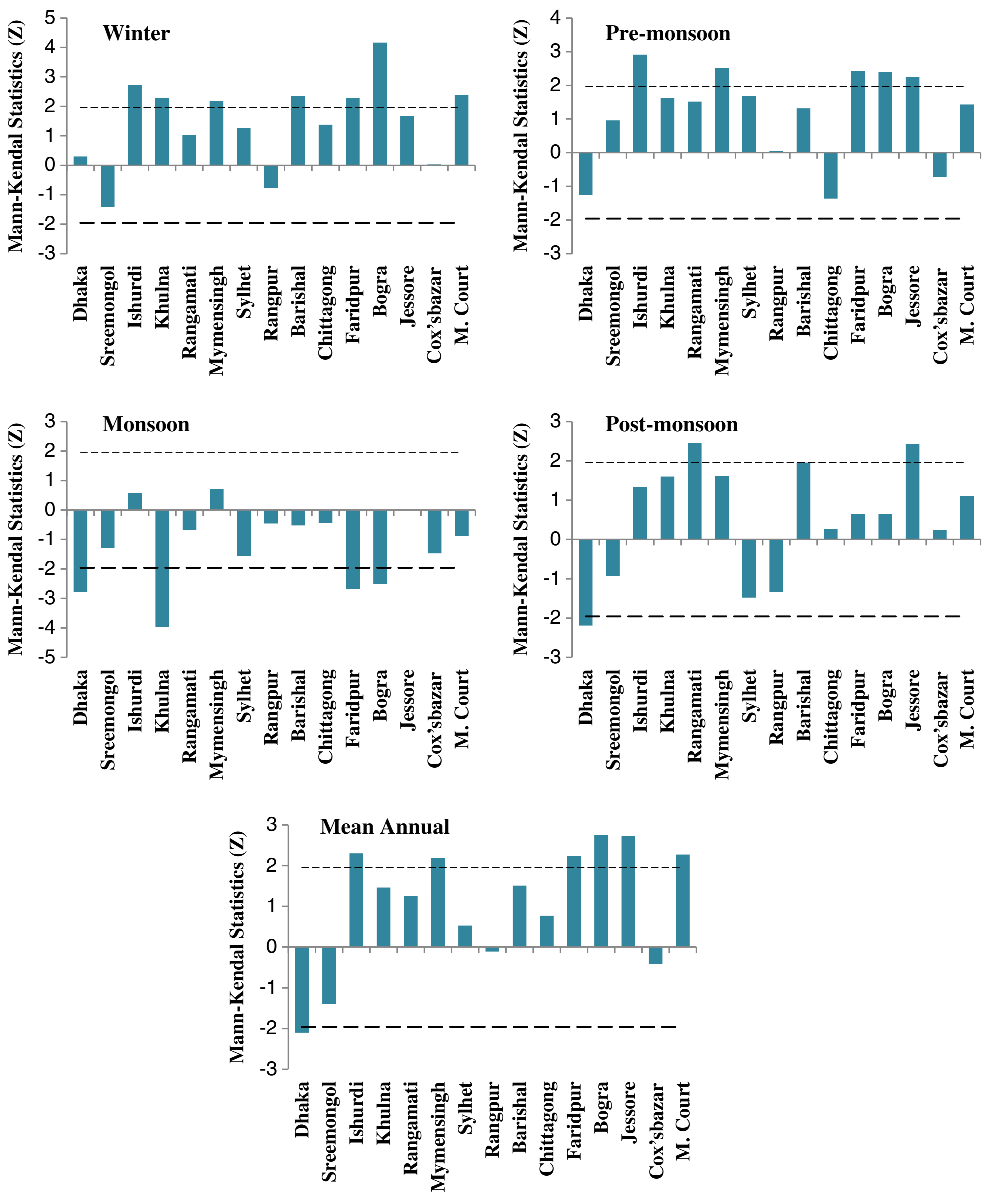


Fig. 6 Values of statistics Z of the Mann–Kendall test for the annual and seasonal T_{dew} series. *Dotted line* indicates the significance level at the 95 % confidence level

not always normally distributed; non-parametric tests were preferred over parametric tests. Non-parametric tests are generally distribution-free; hence, all tests employed in this study are non-parametric. The most commonly used non-parametric tests for trend detection of meteorological data are Mann–Kendall, the seasonal Kendall, and Sen's T. Yu et al. (1993) compared the performance of these methods using the Monte Carlo simulation for each selected sample size, $n=3$; 5, 9, and 15 years. For $n=9$ and 15, there are no significant differences in relative power between these methods. Among these tests, the Mann–Kendall is almost always used and is highly recommended by the World Meteorological Organization to assess the significance of monotonic trends in hydrological series (Mitchell et al. 1966).

Serial correlation effect

The existence of serial correlation in time series can adversely impact the power of the non-parametric test to assess the significance of trends (von Storch 1995; Yue et al. 2002, 2003; Yue and Hashino 2003) and, hence, increases the possibility of making a wrong inference (Khaliq et al. 2009). Specially, if there is a positive serial correlation (persistence) in the time series, then the non-parametric test will suggest a significant trend in a time series that is, in fact, random more often than specified by the significance level (Kulkarni and von Storch 1995). According to von Storch and Navarra (1995), the time series should be "pre-whitened" to eliminate the effect of serial correlation before applying the Mann–Kendall test. Thus, the influence of the lag-1 serial correlation was removed from the relative humidity and dew point temperature time series using the following procedures:

1. Determining the lag-1 serial correlation coefficient (designated as r_1).
2. If the calculated r_1 is not significant at the 5 % level, then the Mann–Kendall test is applied to the original values of the time series.
3. If the calculated r_1 is significant, a "pre-whitened" time series may be obtained as $x_2-r_1x_1, x_3-r_1x_2,\ldots x_n-r_1x_{n-1}$, where x_1, x_2, $x_3,\ldots$, x_n are the time series of relative humidity and dew point temperature. Then, the Mann–Kendall test is applied to the modified series to assess the significance of the trend (Partal and Kahya 2006).

Trend analysis

Trend analysis was conducted using the Mann–Kendall non-parametric test for trend (Mann 1945; Kendall 1975). The Mann–Kendall test is a rank-based method that has been applied in previous studies for identifying trends in meteorological variables (Burn and Hag Elnur 2002; Haktanir et al. 2013).

The Mann–Kendall test is based on the statistic S. Each pair of observed values y_i, y_j $(i>j)$ of the random variable is inspected to find out whether $y_i>y_j$ or $y_i<y_j$. Let the number

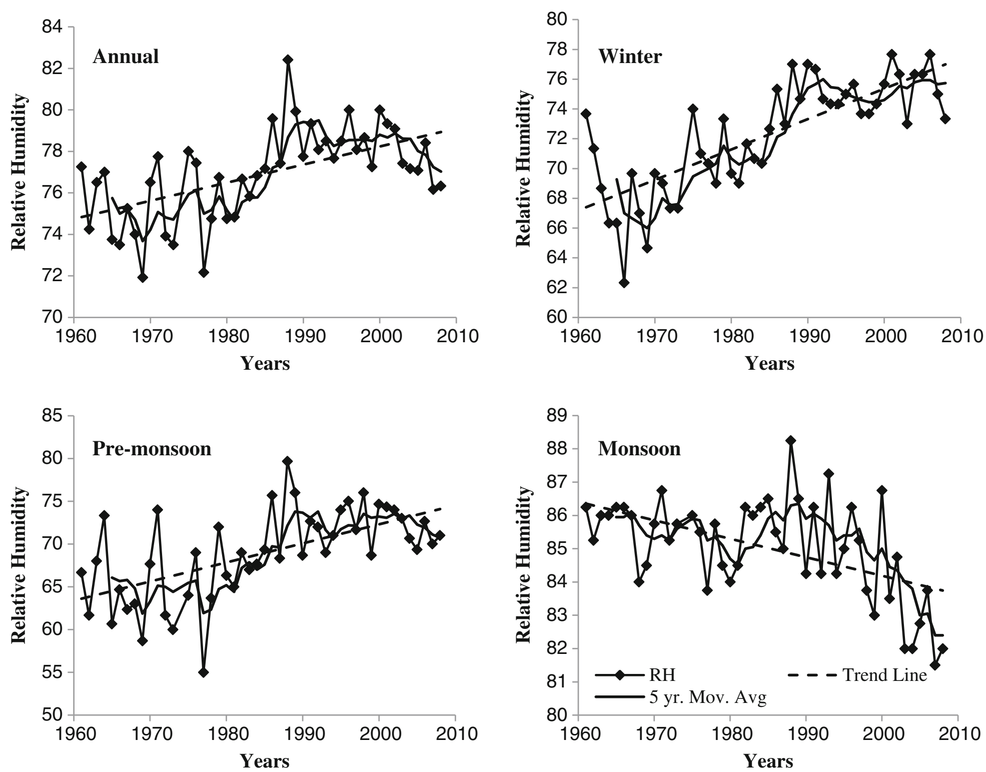


Fig. 7 Time series, 5-year moving average and trend lines of RH with significant trends at Bogra station for the period 1961–2010

of the former type of pairs be P and the number of the latter type of pairs be M. Then, S is defined as

$$S = P - M \tag{1}$$

For $n > 10$, the sampling distribution of S is as follows. Z follows the standard normal distribution, where

$$z = \begin{cases} \dfrac{S-1}{\sigma s} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sigma s} & \text{if } S < 0 \\ \sigma s = \sqrt{n(n-1)(2n+5)/18} \end{cases} \tag{2}$$

There is a correction for ties when $y_i = y_j$ (Salas 1993). The null hypothesis that there is no trend is rejected when the computed Z value is greater than $Z_{\alpha/2}$ in absolute value.

The 95 % confidence level was taken as the threshold to classify the significance of positive and negative trends for all indices. Trends below the 95 % confidence level were not considered. At the 95 % significance level, the null hypothesis of no trend is rejected if $|Z| > 1.96$. A positive value of Z indicates an upward trend; a negative value of Z indicates a downward trend. A comprehensive description and reference list of the Mann–Kendall trend test is provided by Gemmer et al. (2004) and Gao et al. (2010). The Excel template MAKESENS, developed by researchers of the Finnish

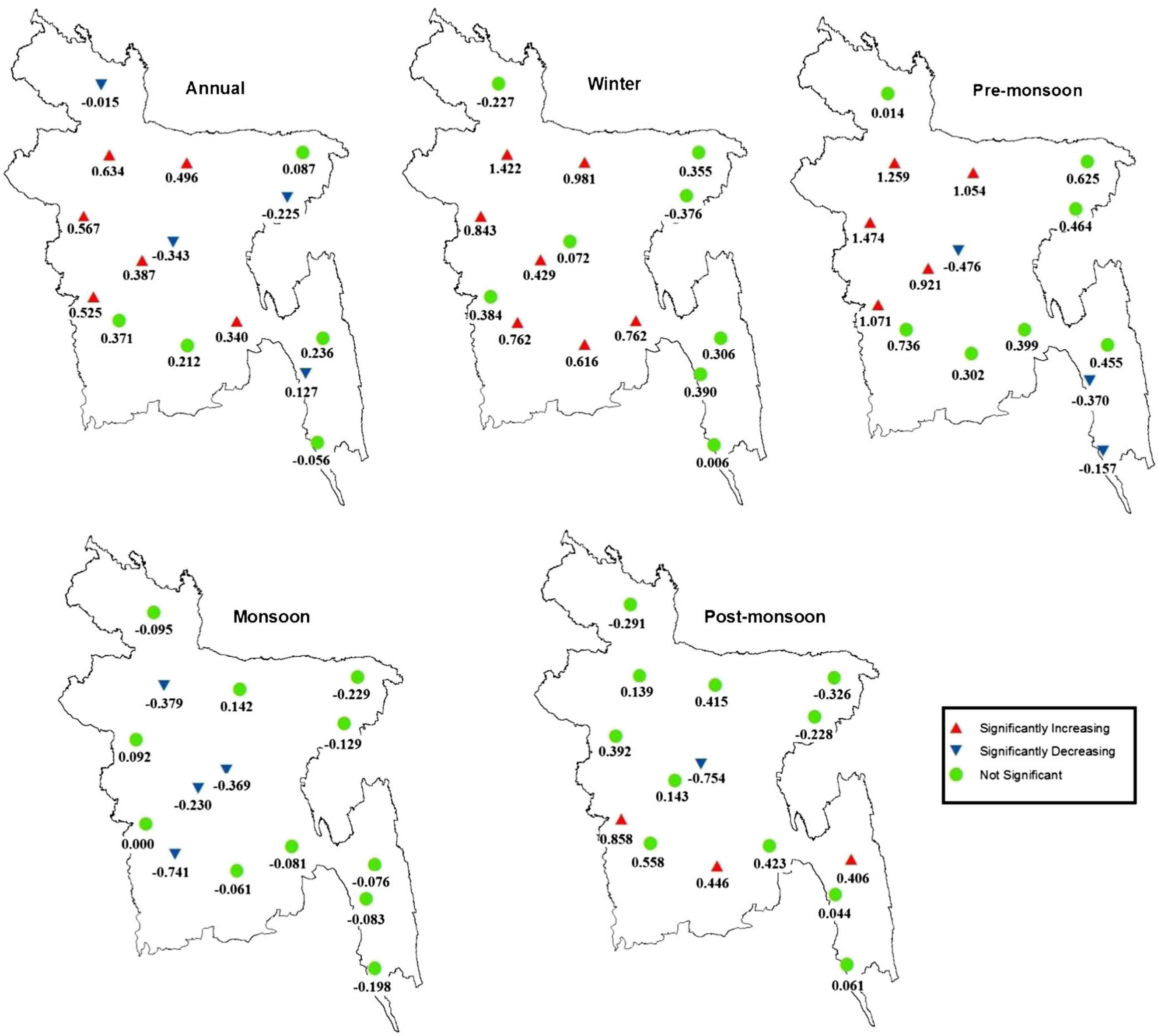


Fig. 8 Spatial distribution of the trends and values of the slope (percent per decade) at different stations of annual and seasonal relative humidity

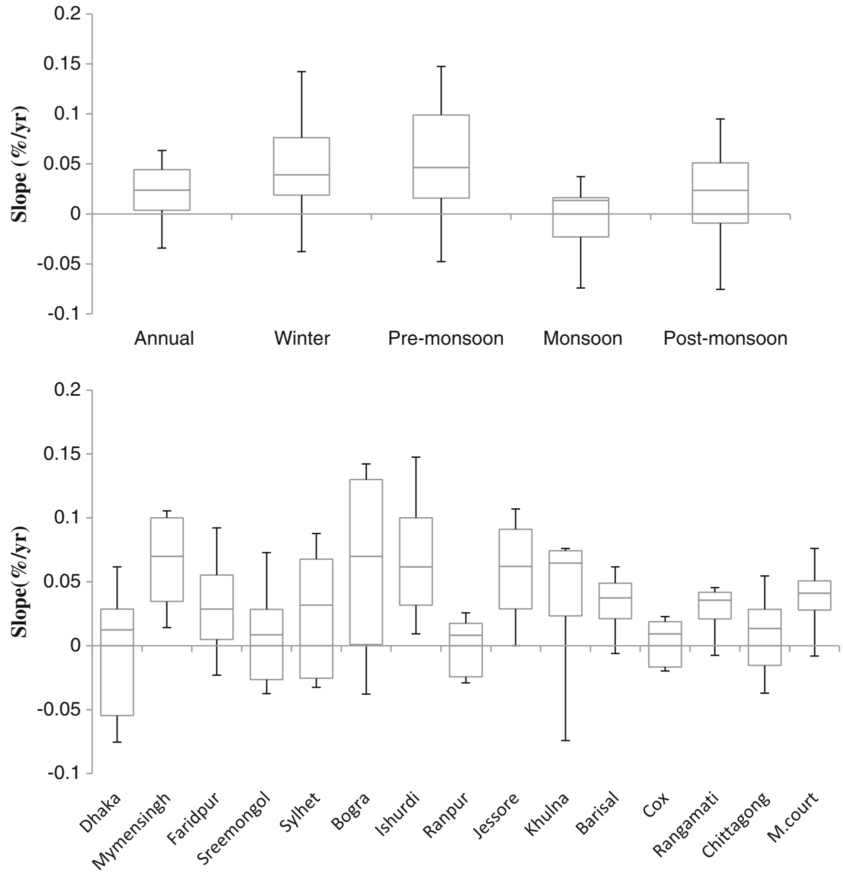


Fig. 9 Box and whisker plots of annual and seasonal trend slope values of all stations (**a**) and seasonal trend slopes at each station (**b**) of T_{dew} for the period 1961–2010

Meteorological Institute (Salmi et al. 2002), was used for the Mann–Kendall test application and the SPSS software for determining the lag-1 serial correlation coefficient.

Trend analyses are conducted on annual and seasonal basis. The standard four seasons are used when computing seasonal time series. They are winter (December–February), pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–November). Pre-monsoon is the summer and monsoon is the rainy season of the country.

Sen's slope estimator

If a linear trend is present in a time series, then the true slope (change per unit time) can be estimated by using a simple non-

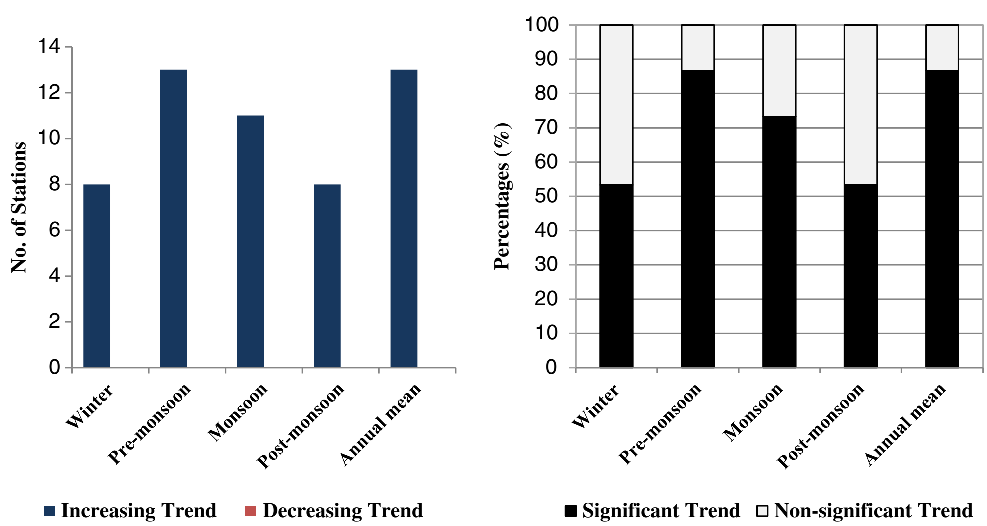


Fig. 10 Mann–Kendall test results for increasing and decreasing trend detection of T_{dew} series (α =0.05)

parametric procedure developed by Sen (1968). Sen's slope method gives a robust estimation of trend (Yue et al. 2002). The slope estimates Q_i of N pairs of data are calculated as

$$Q_i = (X_j - X_k)/(j-k) \text{ for } i = 1, \ldots, N \tag{3}$$

where x_j and x_k are data values at times j and k ($j>k$), respectively. If there are n values x_j in the time series, we get as many as $N=n(n-1)/2$ slope estimates Q_i. Sen's estimator of slope is the median of these N values. The N values of Q_i are ranked from the smallest to the largest, and the Sen's estimator is

$$\begin{aligned} Q &= Q_{(N+1)/2}, \text{ If } N \text{ is odd.} \\ &= \left[Q_{N/2} + Q_{(N+2)/2}\right]/2, \text{ If } N \text{ is even.} \end{aligned} \tag{4}$$

Results

Descriptive analysis and spatial pattern of the mean values

Based on the observed data over 1961–2010, spatial distributions of the annual humidity and dew point temperature are displayed in terms of arithmetic mean in Fig. 3. The annual mean relative humidity is higher in the lower southern and eastern parts of the country than that in the central and western regions. Similar to RH, the mean annual dew point temperature is also higher in the southern part of the country. In most parts of the southern region, the RH value ranges from 78 to 82 %, while the T_{dew} value exceeds 20 °C. It is the coastal region of Bangladesh. The highest coefficient of variation (CV) of the T_{dew} (Table 1) values was observed at Ishurdi, with 9.32 % located northwest of the study area. The CV for

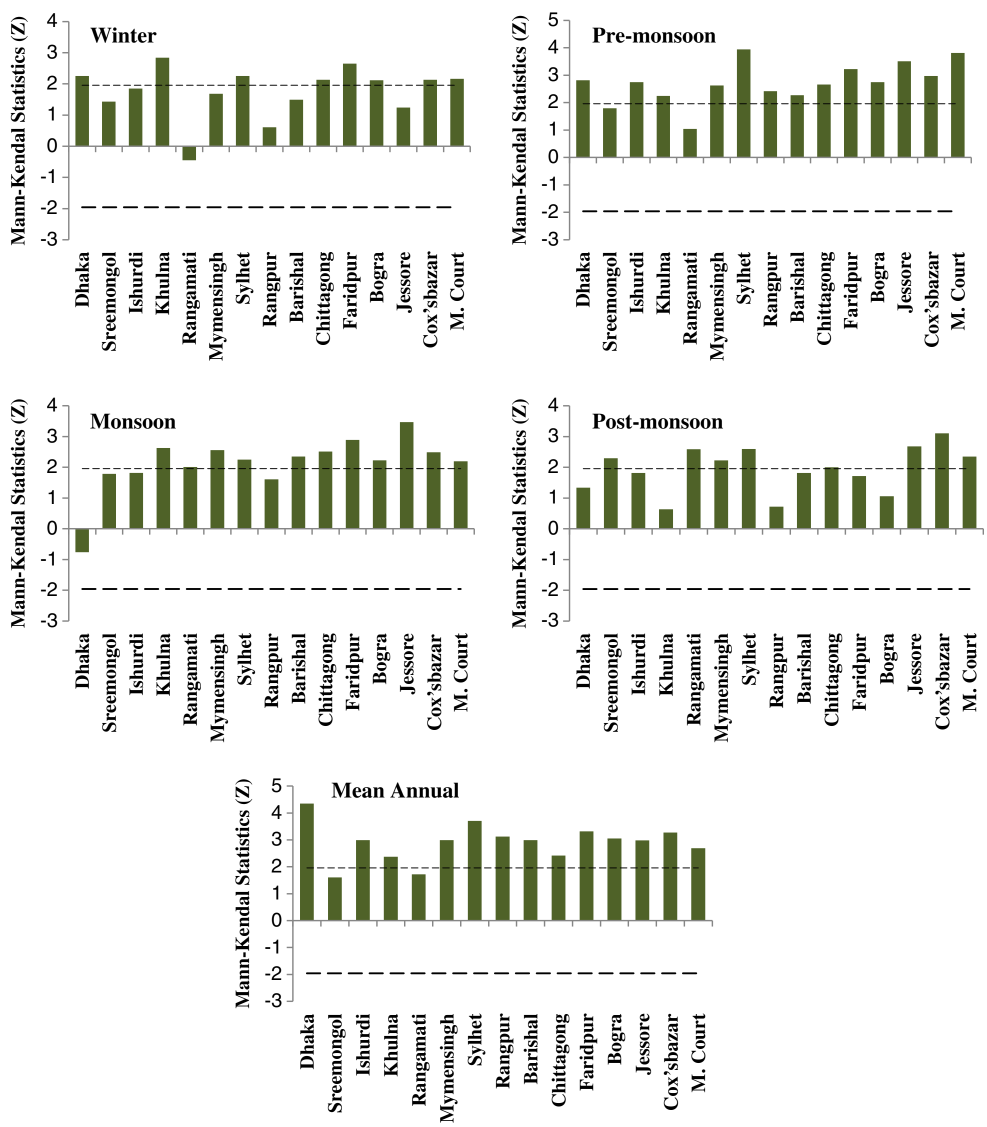


Fig. 11 Values of statistics Z of the Mann–Kendall test for the annual and seasonal T_{dew} series. *Dotted line* indicates the significance level at the 95 % confidence level

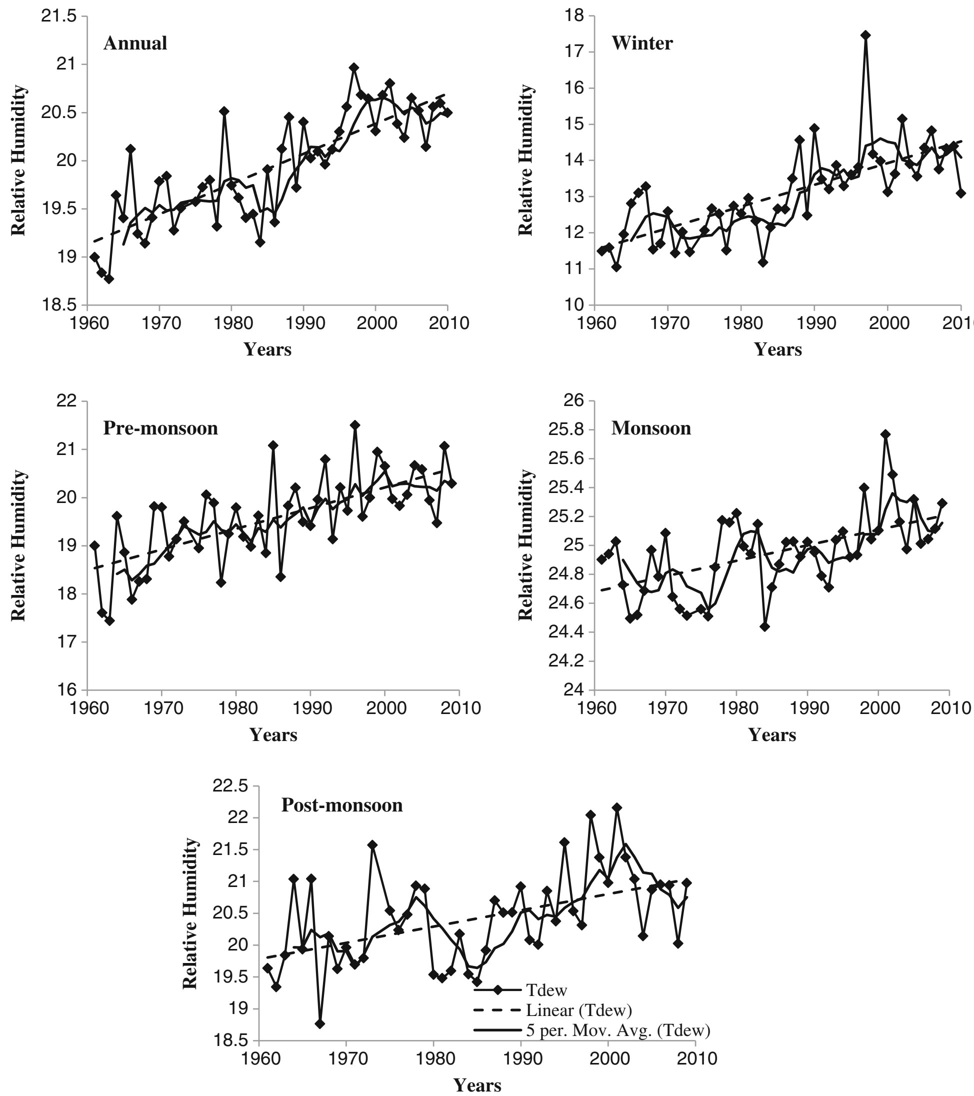


Fig. 12 Time series, 5-year moving average and trend line of T_{dew} with significant trends at Sylhet station for the period 1961–2010

RH series varies from 1.5 to 4.7 % in all the stations. The values of RH and T_{dew} series are highest in monsoon, with mean values of 85.6±1.7 % and 25.4±0.4 °C for the whole Bangladesh. In pre-monsoon, which is the hottest season of the country, the RH value ranges from 65 to 79 % and T_{dew} from 19 to 23 °C throughout the country. Minimum RH and T_{dew} occur in winter at a mean rate of 74 % and 13.8 °C, respectively. The descriptive statistics of the seasonal RH and T_{dew} values at the stations are given in Table 1.

Serial correlation effect

Initially, the autocorrelation test has been performed to all time series in order to check the randomness of the data. The time series which has a significant lag-1 serial correlation coefficient has been "pre-whitened" before the Mann–Kendall test has been applied.

Table 2 and Fig. 4 illustrate the lag-1 serial correlation coefficients for RH and T_{dew} data at the study stations. It is apparent from the table that almost 100 % of the stations showed significant lag-1 serial correlation at the 95 % confidence level in both annual and winter RH and T_{dew} series. It can be determined from Fig. 4 that the RH and T_{dew} data had positive lag-1 serial correlation coefficients at all of the stations in the annual series. The positive correlations were found to be significant at the 95 % confidence level at the whole stations, except Dhaka and Rangamati in the annual RH and T_{dew} series, respectively.

Relative humidity trends

Five time series of RH have been analyzed with the Mann–Kendall test at each station. The results at the 5 % significance level are shown in Figs. 5 and 6. During the period 1961–2010, positive trends are evident both at the annual and seasonal

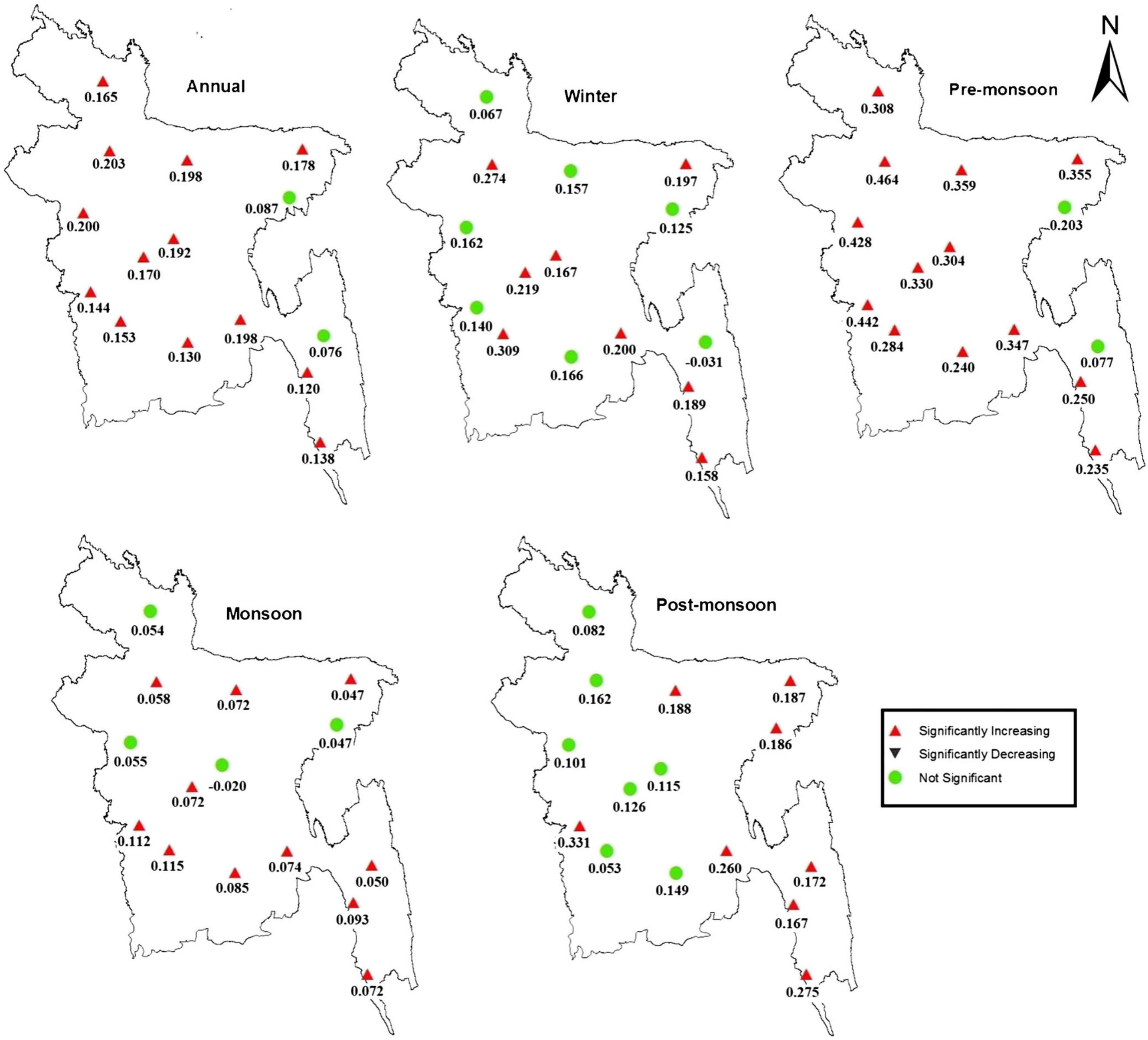


Fig. 13 Spatial distribution of the trends and values of the slope (degree Celsius per decade) at different stations of annual and seasonal dew point temperature

scales, excluding the monsoon season when negative trends can be observed. The percentage of stations showing a significant trend is, however, moderate, reaching a maximum of 47 % at the annual and winter scales and at 27 % during the monsoon and post-monsoon seasons (Fig. 5). The results demonstrated that increasing trends were observed mostly in the winter and pre-monsoon seasons.

The annual RH has been found to be decreased significantly only at Dhaka station, the capital and megacity of Bangladesh, which is due to the downward trend observed in post-monsoon season. Of the stations, 40 % showed a significantly increasing trend in the annual series. The seasonal RH time series showed both increasing and decreasing trends at the study stations. Seven and 5 out of 15 stations showed significant increasing

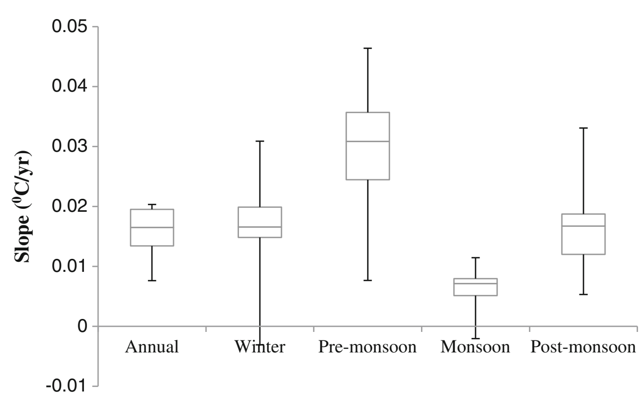


Fig. 14 Box and whisker plots of the annual and seasonal trend slope values of T_{dew} for the period 1961–2010

trends in winter and pre-monsoon, respectively. There is no significant downward trend in these two seasons of RH series. On the other hand, 27 % of the stations exhibited significant trends in monsoon season, and all of them are decreasing. These stations are located at the western part of the country. Figure 7 exhibits the RH time series of the significant trends at Bogra station.

Trend slopes for annual and seasonal RH series were obtained using Sen's slope estimate (Hirsch et al. 1982). Figure 8 exhibits the magnitude (percent per decade) of the trends at each station. The trend slopes are presented as box and whisker plots in Fig. 9. The minimum, 25th, median, 75th percentile, and maximum trend slopes are represented by the lower whisker, the bottom of the box, the line inside the box, the top of the box, and the upper whisker, respectively. The median trend slope values are higher for pre-monsoon and winter. It is apparent that trend slope values are significantly higher in Bogra, Ishurdi, Jessore, Khulna, and Mymensingh stations. The trend results also showed significant increasing trends for these stations in different seasons. Four out of these five stations are located in the western region of the country, which is the hottest part of the country. On average, relative humidity is increasing at 0.53, 0.86, and 1.18 % per decade on the annual, winter, and pre-monsoon (summer) scales, respectively, in the western part of the country. This increase in humidity may result in an increase in apparent temperature (combined effect of humidity and air temperature), which will have impacts on human health and comfort.

Dew point temperature trends

The outcome of the Mann–Kendall test on the annual and seasonal T_{dew} series has been summarized in Figs. 10 and 11. The result showed high percentages of significant trends in T_{dew} series. According to the result, 86.7 % of the stations have shown an increasing trend of annual T_{dew}. There is no decreasing trend in both annual and seasonal time series. Only Sreemongol and Rangamati stations (Fig. 11) did not show any significant trend at the 95 % confidence level, however have got an increasing tendency of annual T_{dew}.

For the different seasons, the greatest number of positive trends is observed in the pre-monsoon. The number of stations showing a significant rising trend ranged between 52 and 87 % in different seasons. From Fig. 11, the dominant pattern of rising trend of T_{dew} is apparent. Only Rangamati in winter and Dhaka in monsoon have negative values of Z. Significant trends of T_{dew} time series at Sylhet station is presented in Fig. 12.

Figures 13 and 14 demonstrate the result of trend slope determined by Sen's estimator. Sen's estimator value ranges from 0.12 °C per decade at Chittagong to 0.203 °C per decade at Bogra for the annual T_{dew} series. A box and whisker plot in Fig. 14 indicates that the trend slopes are maximum in the pre-monsoon season and minimum in monsoon. The magnitude of the trend varies from 0.235 °C per decade at Cox's Bazar to 0.464 °C per decade at Ishurdi in the pre-monsoon season. In fact, this definite increase in T_{dew} during the pre-monsoon season is resulting in an increase of the annual time series. A higher magnitude of the significant trend is observed in the western part of the country. The majority of the slopes are above zero, illustrating an increasing nature in annual and seasonal T_{dew} over Bangladesh. This warming of T_{dew} in Bangladesh is analogous to the global T_{dew} trend. The increasing trend of dew point temperature during the second half of the twentieth century has been reported over the contiguous USA (Gaffen and Ross 1999; Robinson 2000), Canada (van Wijngaarden and Vincent 2003), and Iran (Talaee et al. 2012).

Conclusion

In the present study, the annual and seasonal series of relative humidity and dew point temperature have been analyzed at 15 stations located all over Bangladesh for the period 1961–2010. The trend significance was tested in the 95 % confidence level using non-parametric Mann–Kendall tests. The significant lag-1 serial correlations have been removed from the time series using the trend-free pre-whitening method. The results revealed that 40 % of the stations had significant increasing trends for the annual RH series. Only Dhaka showed a significant decreasing trend. Of the stations, 47 and 33 % exhibited significant trends in winter and the pre-monsoon season, and all of them are increasing. On the contrary, 27 % of the stations have significant decreasing trends in the monsoon season, with no significant increasing trend. Significant positive trends have been found dominating both the annual and seasonal T_{dew} series. No significant downward trend was detected at the 95 % confidence level on both the annual and seasonal scales. A higher magnitude of the significant trends has been observed in the western region compared to the other parts of the country for both RH and T_{dew} series. The trend directions and magnitude identified in this study using non-parametric tests of both relative humidity and dew point temperature may provide helpful information on global warming on a regional scale.

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