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Variability and trends of annual and seasonal thunderstorm frequency over Bangladesh

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ABSTRACT: The climatology of thunderstorm (TS) activities over Bangladesh has been investigated using monthly, seasonal, and annual time series data of 29 meteorological stations in the country for a maximum period of 35 years (1976–2010). The climatology of the TS and its inter-annual variability and trends have been investigated using country average as well as station-wise data. The results of the trend analysis show that the country average TS frequency exhibits statistically significant trends for annual and seasonal data, except for winter. The monthly TS frequency shows significant increasing trends for the months April–November. The station-wise analysis of annual and seasonal data shows dominant increasing trends over the country, with a few stations having negative trends. The correlation coefficients of the time series of seasonal and annual TS frequency with rainfall and minimum and maximum temperature have been computed. Also, the composite climatology of geopotential height and temperature fields of the troposphere covering Bangladesh and its surrounding areas for the month of May individually for the years with high TS frequency and low TS frequency has been presented and analysed. The low level moisture and meridional component of wind fields have also been considered. Additionally, the correspondence of TS frequency for this month with the low level vertical wind shear (VWS) between 850 and 500 hpa levels for the *u*-component of the wind has also been studied using the data of 1976–2010, which shows that the TS frequency is correlated with VWS.

KEY WORDS thunderstorms; climatology; Bangladesh; variability; trends; atmospheric circulation; vertical wind shear

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1. Introduction

Thunderstorms (TS) are severe localized weather phenomena, which develop mainly due to intense atmospheric convection and are associated with heavy rainfall, lightning and thunder, hail and squall lines. TS are characterized by stormy winds (60–150 km h^{-1}), which sometimes become more severe and turn into tornadoes. TS occur almost everywhere in the world due to atmospheric instability and strong moisture convergence causing severe convections. They are one of the most spectacular atmospheric phenomena that affect the lives of people. More than 1600–2400 TS occur at any moment around the world (Ahrens, 2013). The size of TS varies from a few kilometres to a few hundreds of kilometres, usually with a life span of less than an hour. However, multi-cell TS develop due to organized intense convection may have life spans of several hours and may travel over a few hundreds of kilometres.

TS are very common in Bangladesh and its adjacent areas of India such as Gangetic West Bengal, Assam, Orissa, Jharkhand, and some parts of Bihar. The places of formation of the TS which visit Bangladesh may either be located within Bangladesh or further north over Sub-Himalayan West Bengal, Sikkim, Assam valley, the plateau of Meghalaya, or to the west of West Bengal, and even over the plateau of Jharkhand in India – a good number of those systems then travel to Bangladesh. TS occur predominantly in the pre-monsoon months, especially during March–May; however, they are also found to occur in other seasons. The pre-monsoon (March–May) TS are also designated as Nor'westers in this region, so called because the storms usually approach towards Bangladesh from a northwesterly direction. These are also locally known as 'Kalbaishakhi' in Bengali because of the heavy damage to life and property inflicted by them during the month of Baishakh (from mid-April to mid-May), the first month of the Bengali calendar.

In India and Bangladesh, some studies have been done on the space and time variations of TS and the physical atmospheric conditions favourable for their formation (Chowdhury and Karmakar, 1986; Karmakar, 2000, 2001a, 2001b; Karmakar and Alam, 2005a). The TS mainly originate over the heated land masses with an adequate supply of moisture. In India and Bangladesh, these TS reach severity when the relatively cooler and dryer continental air mass meets warm and moist air from the ocean (DoST, 2005).

The TS mainly originate over the heated land masses that heat up the air mass above it and initiate convection. The advection of cool air in the middle troposphere over the warm and moist air in the lower level enhances the

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probability of TS formation. Ahasan *et al.* (2014) in a modelling exercise with the Weather Research and Forecasting (WRF) model have shown a clear convergence in the lower troposphere and divergence over the upper troposphere at 200 mb. Further to note is that vertical wind shear (VWS) ranging from 12 to 15 $m\,s^{-1}$ between 1000 and 500 mb favours the developments of super-cell TS, which are associated with tornadoes (DoST, 2005 and Ahasan *et al.*, 2014).

The activities of TS occur in the condition of high tropospheric instability. Karmakar and Alam (2005b) have shown that a range of the Showalter Index (SI) within the values between −3 and 3 corresponds to a high frequency of TS activities over the region of eastern India and Bangladesh. A decrease of SI values is closely connected with the sharp increase of probability for convection. It was shown that the modified SI is a suitable predictor for the convective activity of this region. The Total Total Index (TTI) between 40 and 45 and K-Index (KI) ranging from 35 to 40 are favourable for TS formation (Jayakrishnan and Babu, 2014). Karmakar and Quadir (2014) have shown that the TS over Bangladesh and surrounding territories of India are formed if the moisture content is high in the morning time with a mixing ratio >16–22.4 $gm\,kg^{-1}$ (Relative Humidity (RH) > 85%). The above authors have also shown that the high vertical gradient of equivalent potential temperature (EPT) at 0000 UTC in the lower troposphere is an indicator for TS development in the late hours of the corresponding day. It is seen that EPT decreases rapidly with height up to the 500 mb level and then it increases, indicating the possibility of TS activity. It may be noted that the formulation of EPT considers mixing ratio as an element; as a result EPT, as well as its vertical gradient, play an important role in moist convection. Owing to the short temporal and spatial scale of TS, forecasting the precise time and location of occurrences of TS remains a challenge.

The distribution of hourly frequency of Bangladesh TS shows that tornado occurrences are more frequent in the afternoon and early part of the night (Yamane *et al.*, 2010a and Bhattacharya *et al.*, 2013)

In this study, the climatology of monthly, seasonal, and annual TS frequency over Bangladesh and TS temporal trends have been studied using the data from 1976 to 2010. The seasons are winter (December–February), pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–November). The correlation of seasonal rainfall with the respective time series of TS frequency has also been investigated. Further, the climatology of geopotential height and temperature at 925, 500, and 250 hpa levels, and low level moisture and meridional wind, has been investigated for the years of weak and strong TS activities for the month of May. The TS frequency has also been investigated against the VWS between 850 and 500 hpa levels. Though the mechanisms of TS in the pre-monsoon and monsoon seasons are different, the investigation of climatology of the above-mentioned tropospheric parameters has been confined only for the pre-monsoon month of May for this article.

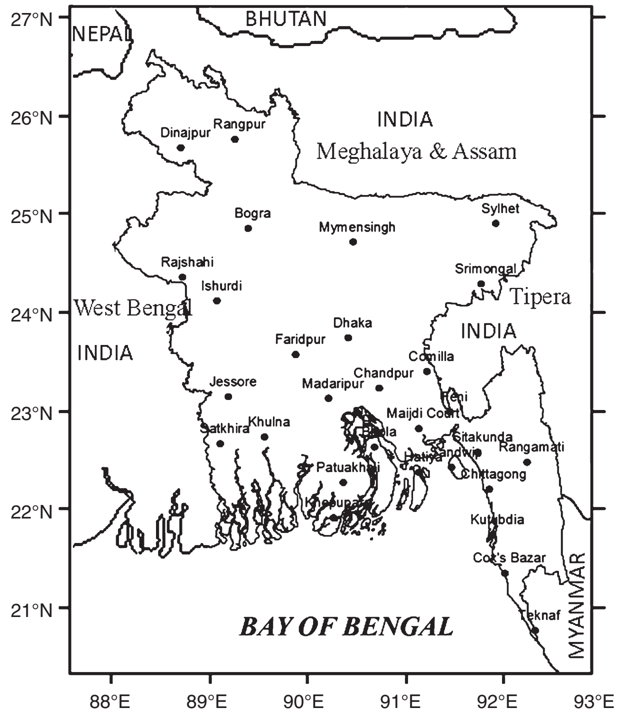

Figure 1. Map showing Bangladesh and surrounding territories with locations of 29 meteorological stations of Bangladesh.

2. Data used

The monthly data of TS frequency, rainfall, and minimum and maximum temperature covering 35 years (1976–2010) or as available for 29 meteorological stations of Bangladesh belonging to the Bangladesh Meteorological Department (BMD) have been used for the study. The locations of the stations are shown in Figure 1. TS events are recorded in each station of BMD eight times a day with an interval of 3 h at the standard World Meteorological Organization (WMO) observation hour. The number of TS recorded in 1 day is considered as the daily TS frequency. The monthly frequency of TS is obtained from the daily data. The seasonal and annual time series of TS frequency have been calculated from the monthly time series data of TS for the individual stations. The country average time series of monthly, seasonal, and annual total frequency of TS have been calculated as the station average of data for 29 stations in Bangladesh. The data have been used for the study of mean monthly, seasonal, and annual climatology of TS frequency. The geographical distribution of TS frequency based on station-wise data has been presented. The time series plots have been shown for the annual and seasonal data overlaid with the 5-year moving average; the latter effectively smooths the time series by filtering the high frequency modes. The trend analysis of the time series of TS frequency has been performed using the least square technique.

The correlation coefficients (CC) have been calculated for the annual and seasonal TS frequency with the corresponding rainfall and minimum and maximum temperatures. The confidence level of slopes of trends and CC are determined by Student's *t*-test.

The geographic distribution of composite meteorological fields, namely geopotential height and temperature at 925, 500, and 250 hpa levels and mixing ratio and meridional component of wind at 925 hpa level for the month of May and the respective anomalies covering the area defined by 81°–95°E and 18°–28°N, have been prepared individually for the years of high frequency of TS and low frequency of TS using the reanalysis page of US NOAA/NCAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. Further, the VWS of zonal winds between 850 and 500 hpa levels for the period 1976–2010 has been calculated using the reanalysis data from the above source and averaged over two regions 80°–100°E and 18°–28°N, and 80°–110°E and 5°–20°N, and analysed against TS frequency for the month of May using correlation analysis and time series plots.

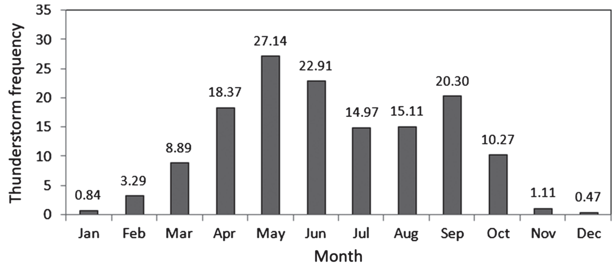

Figure 2. Monthly mean country average thunderstorm (TS) frequency in Bangladesh. The monthly values on top of the bars indicate the mean monthly TS frequency of the corresponding month.

Table 1. Seasonal and annual climatology of country average TS frequency in Bangladesh.

Season	Average TS frequency
Winter	4.6
Pre-monsoon	54.4
Monsoon	73.3
Post-monsoon	11.4
Annual	143.7

3. Results and discussion

3.1. TS climatology in Bangladesh

The country average monthly TS frequency of Bangladesh based on the data of 1976–2010 is shown in Figure 2. It is seen that the frequency of TS is high in the months of April–September, with the highest frequency in the month of May (27.14) followed by June (22.91), September (20.3), and April (18.37). The core monsoon months July and August have relatively low TS frequency, of around 16 for each of these months. Very low frequency is observed during November–February, while the lowest is in December. Table 1 presents the country average seasonal and annual distribution of TS frequency in Bangladesh. It shows that the total frequency in the pre-monsoon and monsoon seasons is 54.4 and 73.3, with monthly averages of 18.13 and 18.33, respectively. The lowest TS frequency is observed in the winter season (4.6). The country averaged annual TS frequency is 143.7.

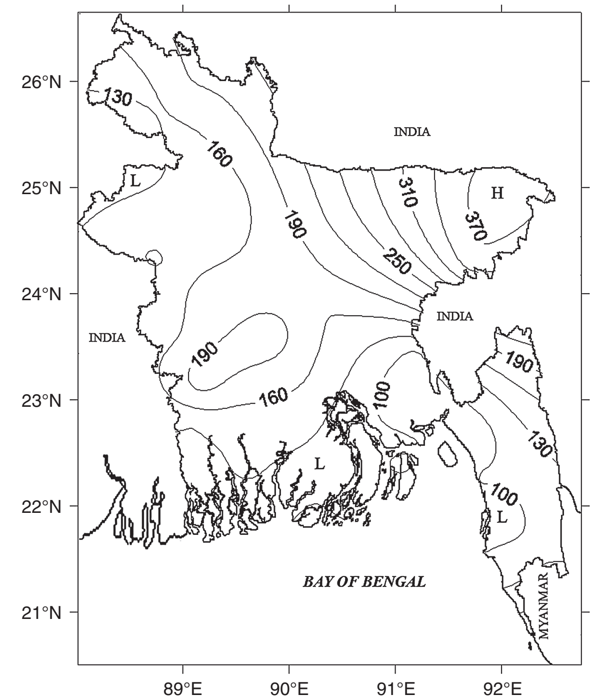

Figure 3. The geographic distribution of annual average thunderstorm frequency in Bangladesh using the data of 29 stations from 1976 to 2010.

3.1.1. *Geographical distribution of TS*

3.1.1.1. Annual: Annual TS frequency distribution in Bangladesh varies from 40 to 360 (Figure 3). The high frequency of TS from 200 to 360 is observed in the northeastern part of the country, and the TS frequency of 160–200 is seen in the central and north-central part of Bangladesh. The western and southern parts of the country experiences low frequency which varies from 40 to 120. The axis of high frequency TS distribution passes from northeast to southwest.

3.1.1.2. Seasonal: The winter season records the lowest number of TS frequency. It is primarily due to stable and dry atmospheric condition prevailing in the country. It appears from Figure 4(a) that the highest frequency is concentrated in the upper southwestern part and northeastern part of the country. On average, the winter experiences 4.6 TS.

The pre-monsoon season is characterized by an increase in TS activity over all parts of Bangladesh, with a remarkable increase in the northeastern part where the highest frequency of more than 150 is observed. Topography, insolation, and advection of moisture under a favourable wind regime contribute to the highest frequency of TS in this

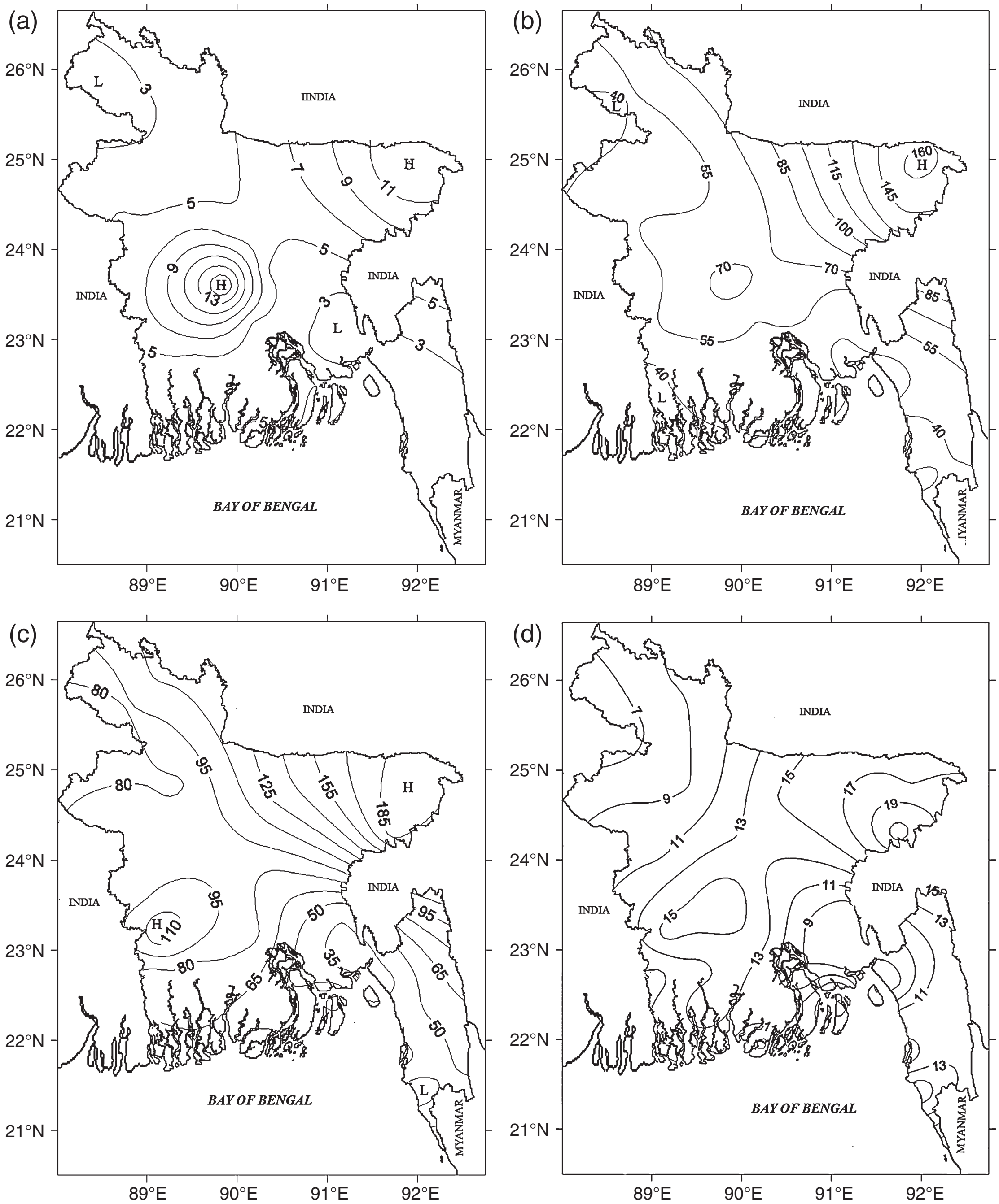

Figure 4. Same as Figure 3 but for winter (a), Pre-monsoon (b), monsoon (c), and post-monsoon (d) seasons.

area. The lowest frequency of 40–55 is observed in the southern, western, and northwestern part of the country (Figure 4(b)).

The monsoon season records the highest TS activity over the northeastern part of Bangladesh and ranges from 120 to 180 (Figure 4(c)). Low TS frequency is observed in the southern part of the country which varies from 20 to 60.

The post-monsoon season shows a marked decrease of TS activity as the monsoon withdraws in this month. The country average TS frequency accounts for 11.5. The maximum TS frequency is concentrated in the north-eastern part and in the mid-western area of the country and the frequency ranges from 13 to 21. The north western and central-eastern part of the country experiences the minimum number of TS (TS = 7–9) in this season (Figure 4(d)).

3.2. Inter-annual variability and trends of TS

3.2.1. Country average TS variability and trends

The time series plot of country average annual frequency of TS shows that TS are characterized by strong year to year variations, with a time period of around 3–5 years (Figure 5). The thick broken line obtained using the 5-year moving average represents the smoothed time series, where high frequency modes with the time period

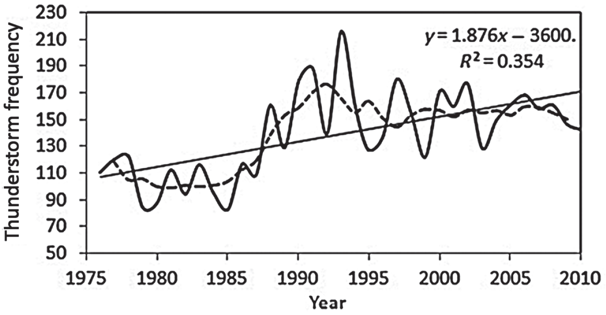

Figure 5. The time series of annual TS frequency from 1976 to 2010. The broken line indicates the 5-year moving average data, while the straight line indicates the trends. In the regression equation, the x-variable is year. R^2 is the coefficient of determination.

Table 2. The trends in annual and seasonal TS frequency (TS per year) of Bangladesh.

Annual/season	Trend (TS per year)	$p<$
Annual	1.88	0.001
Winter	0.04	n.s.
Pre-monsoon	0.37	0.06
Monsoon	0.97	0.001
Post-monsoon	0.22	0.002

Here 'p' indicates the probability determining the significance level as detailed by the note at the bottom of the table. $p < 0.1$ means 90% confidence level; $p < 0.05$ means 95% confidence level; $p < 0.01$ means 99% confidence level, $p < 0.001$ means 99.9% confidence level. Student's t-test has been conducted for evaluating p values.

lower than 5 years have been eliminated by the smoothing. The smoothed time series shows low TS frequency up to 1987, with a minimum in 1985. Thereafter, the frequency increases rapidly up to 1993 and then it decreases up to 1997 by a relatively small value. A decadal variation with an approximate time period of around 20 years is evident from the smoothed line. From 1997, it maintains a more or less steady state of variation up to 2010, when no trend is seen. The trend analysis shows a significant increasing trend of annual TS frequency (1.88 per year). The time series plots of seasonal TS frequency also demonstrate similar variations, but the prominent variations in the decadal scale with a time period of around 15–20 years are evident in the plots of 5-year moving average data (Figure 6(a)–(d)). The purpose of taking the 5-year moving average was to suppress extreme high frequency modes, which allows a better visualization of the long-term variations including the trend. The increasing trends are found to existing all seasons with different levels of significance, except winter when the trend is not significant (Table 2). The trend is high for the monsoon season (0.97 per year). The slopes of trends of monthly TS frequency show that the months March and May–October exhibit significant increasing trends (Table 3) with the highest in June. The months November–February and April do not exhibit much of trends.

For Bangladesh, the warming by about 0.6 °C has been observed using the data from the middle of the 20th century up to 2011 (Scheltinga *et al.*, 2015). But it has not been possible to ascertain if this warming has a connection to the increase of TS frequency in Bangladesh.

3.2.2. *Distribution of station-wise trends of TS frequency*

The station-wise annual and seasonal trends have been estimated and are shown in Table 4. The distribution of

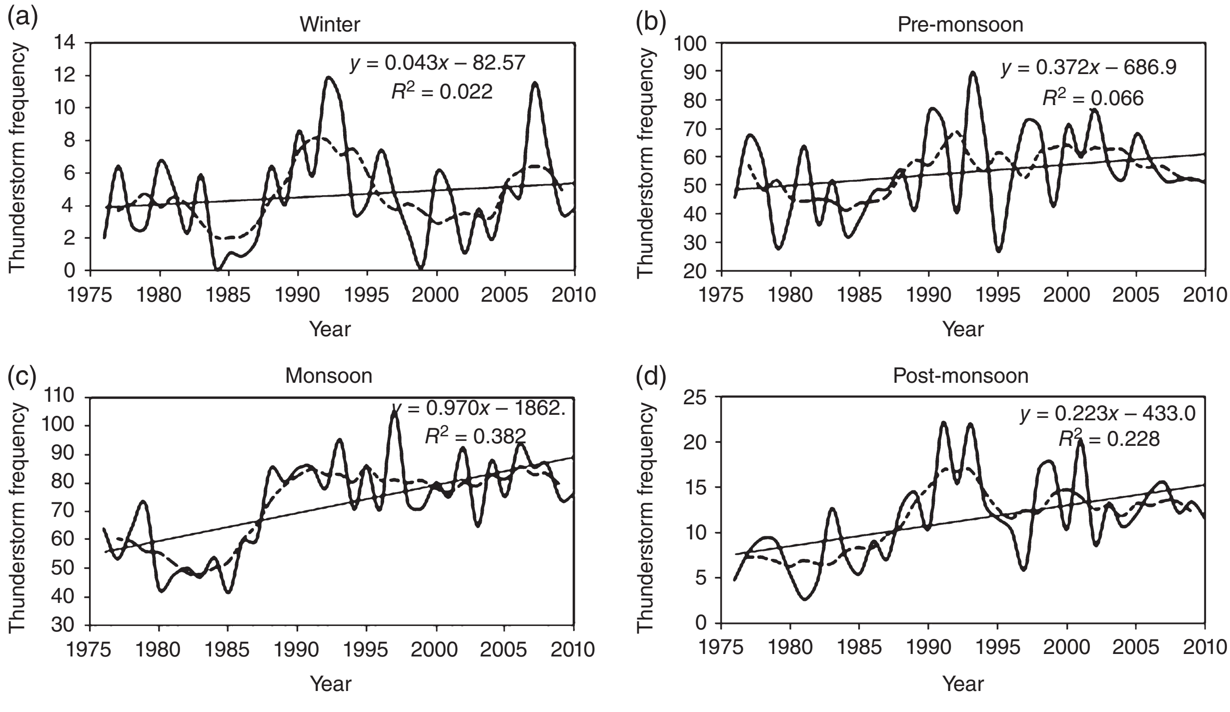

Figure 6. Same as Figure 5 but for TS of winter (a), pre-monsoon (b), monsoon (c), and post-monsoon (d).

Table 3. Table showing the trends of monthly TS frequency (TS per year) of Bangladesh with significance levels based on Student's *t*-test.

Month	Trend (TS per year)	$p<$
January	0.012	n.s.
February	0.021	n.s.
March	0.148	0.10
April	−0.023	n.s.
May	0.313	0.02
June	0.358	0.001
July	0.212	0.004
August	0.287	0.001
September	0.219	0.01
October	0.194	0.005
November	0.033	0.01
December	0.016	0.1

Here 'p' indicates the probability determining the significance level specified in the bottom note of the table. $p < 0.1$ means 90% confidence level; $p < 0.05$ means 95% confidence level; $p < 0.01$ means 99% confidence level, $p < 0.001$ means 99.9% confidence level. Student's *t*-test has been conducted for evaluating p values.

annual trends shows that 16 stations of 29 exhibit significant increasing trends of TS, and 5 stations exhibit significant negative trends. Of the rest, three stations exhibit low positive trends and five stations low negative trends, but these are not statistically significant. The spatial distribution of the annual trends of TS is shown in Figure 7.

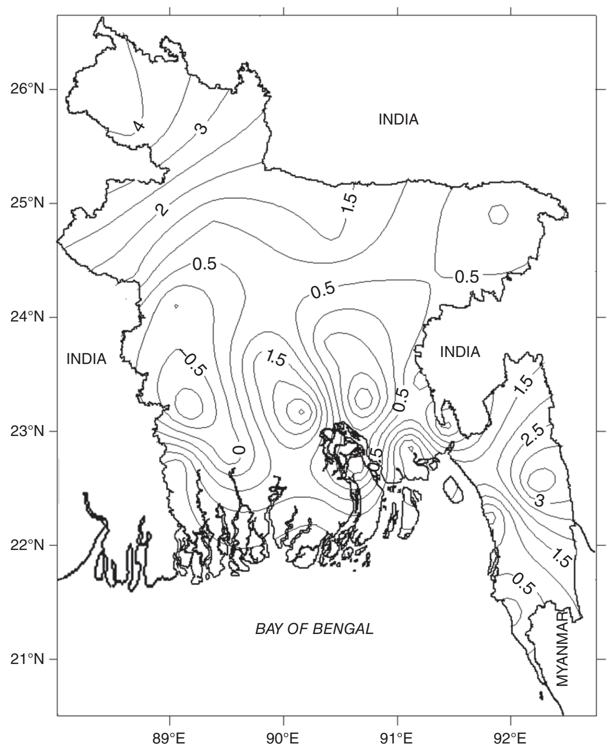

Figure 7. Geographical distribution of annual trend of thunderstorm frequency (TS year^{-1}) in Bangladesh.

Table 4. Seasonal and annual trends of thunderstorm frequency (TS per year) in Bangladesh during the period 1976–2010.

Station name	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Bhola	−0.14**	−0.862***	−0.096	0.076	−1.028**
Bogra	−0.085*	−0.134	1.072***	0.161*	1.00*
Chandpur	−0.176*	−1.544**	−0.423*	−0.008	−2.159**
Chittagong	0.006	−0.099	−0.351*	0.087	−0.367
Comilla	0.031	0.499*	0.752****	0.033	1.303***
Cox's Bazar	−0.040	−0.383*	−0.029	0.152*	−0.292
Dhaka	−0.050	−0.616*	−0.085	0.086	−0.681*
Dinajpur	0.016	1.237****	2.63****	0.225***	4.119****
Faridpur	1.449****	0.777**	0.009	−0.174*	2.042**
Feni	−0.042	−0.592*	−0.162	−0.017	−0.823*
Hatiya	0.562***	−0.986**	2.076****	1.122****	2.757***
Ishurdi	−0.116**	−0.189	−0.299	0.073	−0.538
Jessore	−0.184**	−0.403*	−0.917*	−0.027	−1.551**
Khepupara	0.362****	1.528***	0.504*	−0.082	2.271***
Khulna	−0.046	−0.357	−0.154	0.116	−0.459
Kutubdia	−0.001	0.099	0.609*	−0.028	0.667
Madaripur	−0.076	0.69*	2.308****	0.344***	3.247****
Maijdi Court	0.074*	1.119***	1.746****	0.385***	3.303****
Mymensingh	−0.036	1.021**	0.3	0.109	1.605*
Patuakhali	−0.056	0.502*	1.062***	0.281**	1.779**
Rajshahi	−0.054	0.257	1.177***	0.149*	1.523***
Rangamati	0.006	1.166***	2.134****	0.55****	3.943****
Rangpur	0.002	1.168****	1.715****	0.264****	3.167****
Sandwip	−0.043	0.455**	1.645****	0.439****	2.491****
Satkhira	−0.080	0.782***	1.328***	0.299***	2.316***
Sitakunda	0.043*	0.8**	0.755**	0.132**	1.72***
Srimongal	−0.218	0.873**	0.256	−0.337***	0.571
Sylhet	−0.332	0.336	−0.116	0.018	−0.109
Teknaf	−0.091	0.169	0.328	0.441****	0.851

*p < 0.1 means 90% confidence level; *p < 0.05 means 95% confidence level; ***p < 0.01 means 99% confidence level; ****p < 0.001 means 99.9% confidence level as per *t*-test.

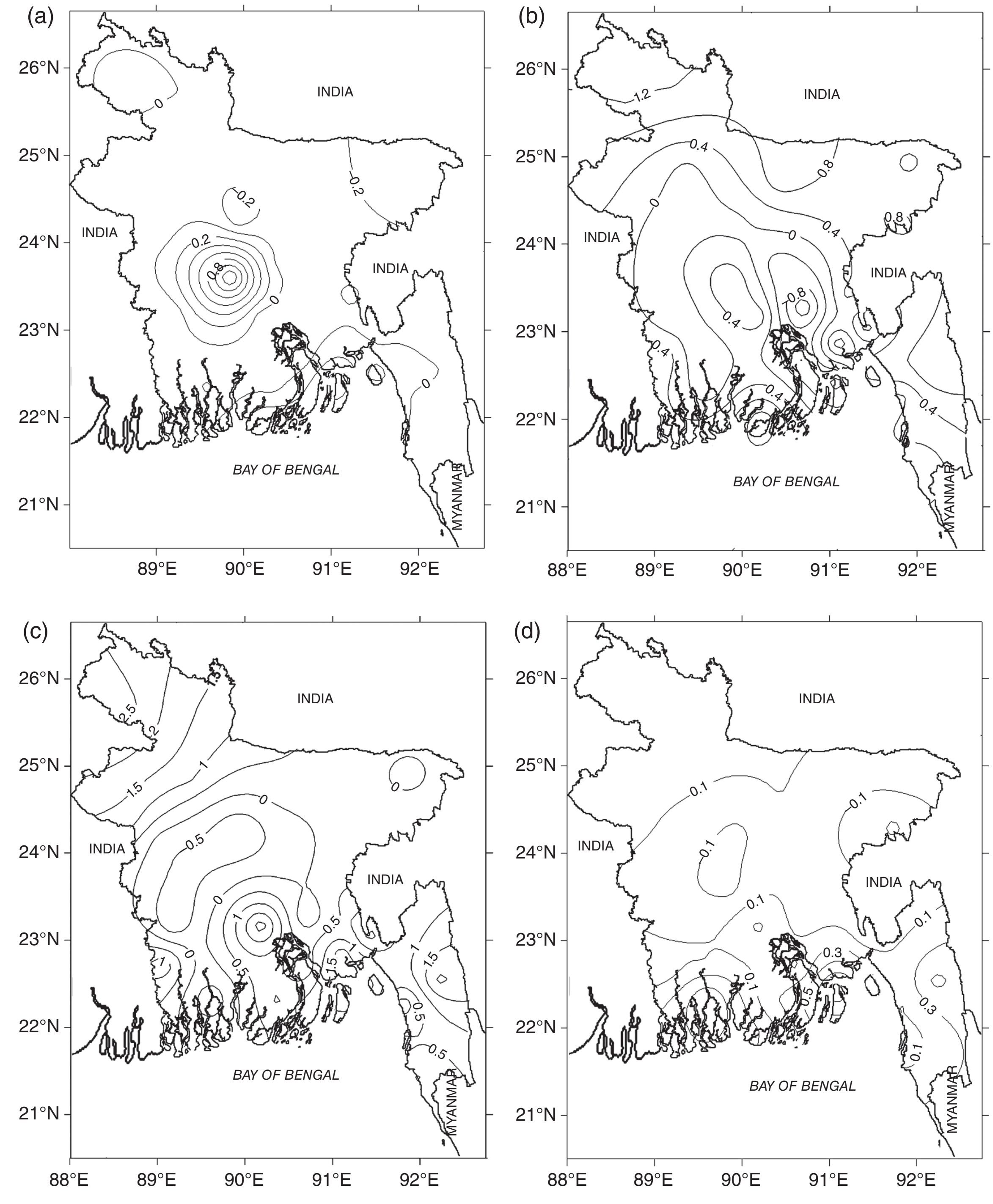

Figure 8. Geographical distribution of trends of thunderstorm frequency (TS year^{-1}) in Bangladesh for (a) winter, (b) pre-monsoon, (c) monsoon, and (d) post-monsoon.

High values of trends in the range 1–4 TS per year cover almost the whole of Bangladesh except for a few pockets where negative trends are observed. The negative trends concentrate in three areas, namely: central region (Dhaka), south-central and eastern coastal zone (Bhola, Chandpur, Feni, Chittagong, Cox's Bazar), and western and south-western region (Ishurdi, Jessore, and Khulna).

The distribution of TS trends for pre-monsoon, monsoon, and post-monsoon seasons exhibits a more or less similar spatial pattern and has close correspondence with annual distribution (Figure 8(a)–(d)). For the pre-monsoon season, 14 stations exhibit significant increasing trends and 7 stations significant decreasing trends. Most of the areas exhibit positive trends except a few small regions showing negative trends (Figure 8(b)). The areas with negative trends are concentrated in the south eastern and upper southwestern coastal zone and over Dhaka, Bogra, and Sylhet (Table 4). For the monsoon season, it is seen that 15 stations have significant positive trends and 3 stations with significant negative trends. The

Table 5. Correlation coefficients (CC) of seasonal and annual thunderstorm frequency with rainfall and minimum and maximum temperature.

Parameters	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Rainfall	0.66****	0.59****	0.05	0.43**	0.20*
T_{min}	−0.06	−0.43**	0.35**	0.30*·	0.17·
T_{max}	−0.31*	−0.58****	0.46***	0.09	0.18

Statistical significance by $p < 0.1$ (90% significance) = *, $p < 0.05$ (95% significance) = **, $p < 0.01$ (99% confidence) = *** and $p < 0.001$ (99.9% confidence) = ***.

high values of positive trends ranging from 0.5 to 2.5 TS per year are seen in the northwestern part of the country. Over the coastal zone and the Hill Track areas, trends ranging from 0.5 to 1.5 TS per year are observed. The areas with negative trends are oriented from northeast to upper southwest. The post-monsoon season exhibits significant positive trends for 16 stations and significant negative trends for 2 stations. The geographic distribution has a more or less similar pattern as that of the monsoon season, both having a narrow negative zone which orients along northeast to upper southwest. The winter season indicates low and insignificant values of trends, but the relatively high trends are concentrated in the upper southwestern part and northeastern part of the country. The results show that the increasing trends of TS frequency are dominant over the country, with some sporadic locations showing weak negative trends. The above discussions reveal that the major areas of positive and negative trends for annual, pre-monsoon, monsoon, and post-monsoon seasons overlap to a large extent, and demonstrate a more or less similar pattern of regional distribution of the trends (excluding the winter season), but the overall positive trends are highly dominant. While the increasing trends may be assumed to be related to global warming, the negative trends are more likely to be related with local factors such as urbanization, deforestations, afforestation, or any other local changes in land-use pattern including agriculture.

3.2.3. Correlation of TS frequency with temperature and rainfall

The CC of annual and seasonal TS frequency individually with the respective rainfall and surface maximum and minimum temperature has been estimated and are shown in Table 5. The seasonal rainfall shows highly significant correlation with TS frequency for the winter and pre-monsoon seasons and moderate correlation for the post-monsoon season, which depicts that the rainfall in these seasons is more or less associated with TS activities. In the winter and pre-monsoon seasons, major rainfall occurs from TS activities which are formed during the passage of mid- and upper-tropospheric troughs over this region. The monsoon rainfall does not show correlation with TS, which depicts that though the TS are frequent in the monsoon season, the bulk of monsoon rainfall occurs due to active monsoonal circulation characterized by the activities of monsoon lows and depressions under the influence of monsoon trough.

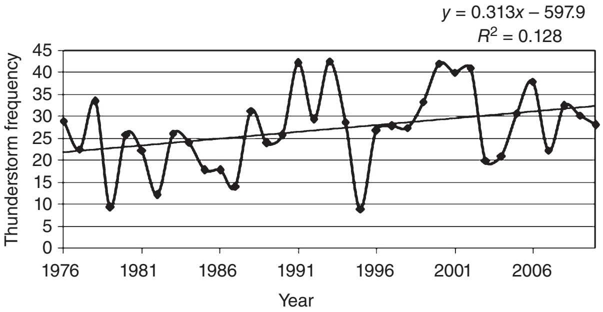

Figure 9. The trends and variability of thunderstorm events for the month of May from 1976 to 2010.

The winter minimum temperature does not show correlation with TS frequency, but the maximum temperature has some weak negative correlation. The pre-monsoon minimum and maximum temperature shows negative correlation (−0.43 and −0.58, respectively). This indicates that the temperature decreases due to cooling caused by rainfall associated with high TS activities, and vice versa. In the monsoon season, both minimum and maximum temperature shows some positive correlation (CC of 0.35 and 0.46, respectively), which depicts that in the monsoon season TS are formed while there are break monsoon episodes when the surface temperature increases due to higher insolation. In the post-monsoon season, only the minimum temperature has some weak positive correlation.

3.3. Circulation pattern characterizing high and low activity in the month of May

Considering the fact that the monthly frequency of TS is highest in the pre-monsoon month of May (Figure 2), it was decided as an initial attempt to investigate the climatology of atmospheric conditions which are favourable to TS formation in this month. The climatology of the composite geopotential height and temperature fields and their anomalies at 925, 500, and 250 hpa levels, and moisture and meridional wind fields and their anomalies at 925 hpa level, have been presented for the area enclosed by approximately 81°–95°E and 18°–28.5°N individually for the years of high TS frequency and low TS frequency. The temporal distribution of TS frequency for the month of May is shown in Figure 9. The figure reveals that the years 1991, 1993, 2000, 2001, 2002, and 2006 belong to relatively high TS frequency; and the years 1979, 1982, 1987, 1995, 2003, and 2004 to low TS frequency. The composite fields of geopotential heights and the respective anomalies for the high TS frequency years are shown in Figure 10(a)–(f).

The composite fields of geopotential heights and the respective anomalies for the high TS activity years are shown in Figure 10(a)–(f). The distribution of geopotential height at the 925 hpa level shows a low level east–west oriented intense trough with the lowest geopotential height of about 730 m at around 25°N and 81°E, and the axis of the trough passes over Bangladesh (Figure 10(e)). A subtropical trough is found to prevail in the composite

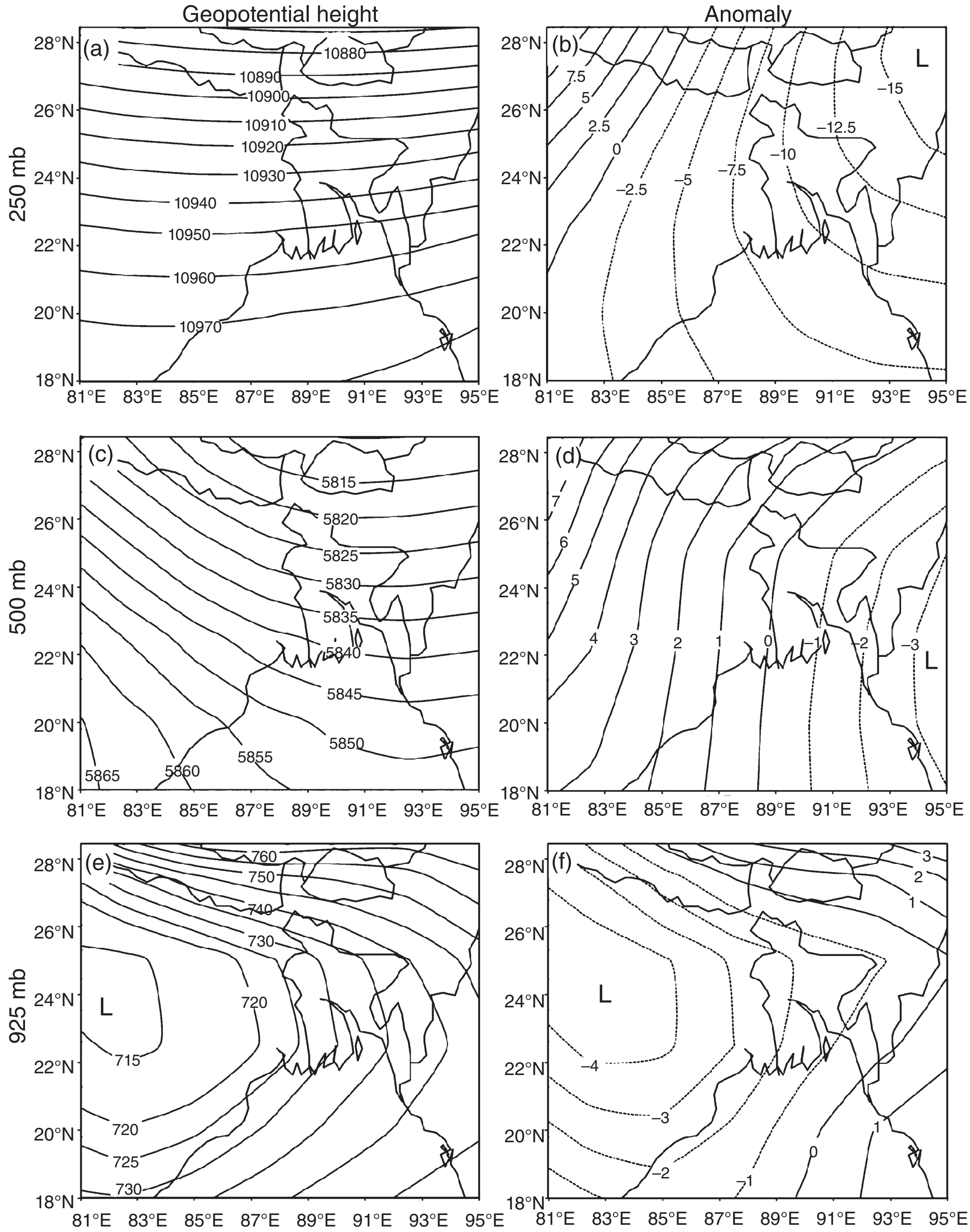

Figure 10. Composite geopotential height at 925, 500, and 250 hpa level (left panel a, c, e) and their respective anomalies (right panel b, d, f) for the month of May of the years 1991, 1993, 2000, 2001, 2002, and 2006 with high TS frequency.

field of the monthly mean geopotential height at 500 hpa level (Figure 10(c)). The negative anomaly is also dominant over most part of Bangladesh in this level. At the 250 hpa level, a weak low pressure trough is found to exist. The geopotential height field exhibits strong negative anomalies with the trough extending over Bangladesh. From the above, it is seen that a pressure drop occurs in the whole atmospheric column in the troposphere for the years with high TS frequency in Bangladesh, which provides a favourable environmental condition for TS formation. It should be mentioned that the subtropical westerly disturbances in the form of troughs seldom pass over this area in the middle and upper troposphere in this month.

The spatial distribution of the geopotential height and the anomalies for the years with low TS activity at 925, 500, and 250 hpa levels are shown in Figure 11(a)–(f). The geopotential height field shows an almost similar but weak low level low pressure trough. The inner most

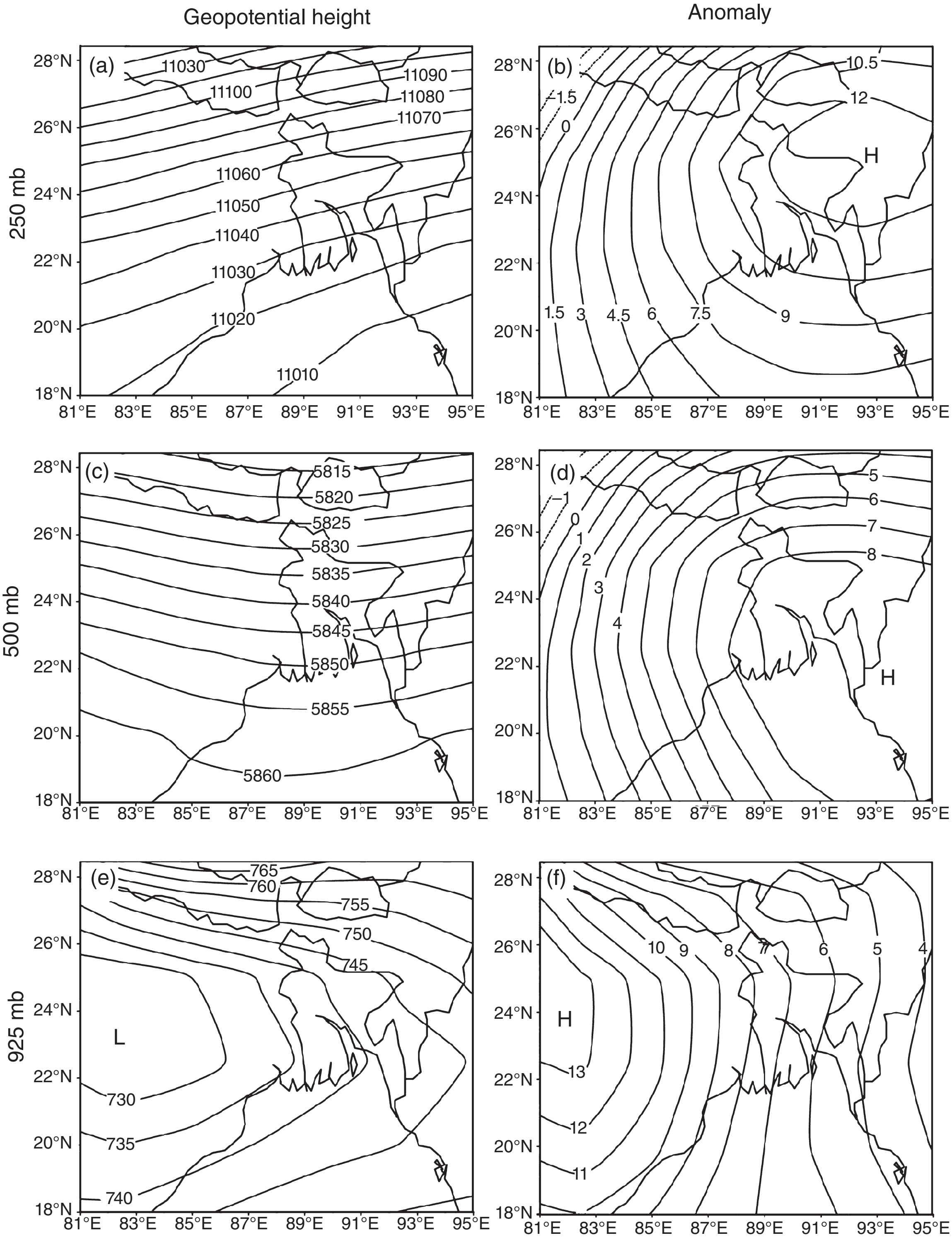

Figure 11. Same as Figure 10 but for the years 1979, 1982, 1987, 1995, 2003, and 2004 belonging to low TS frequency.

contour line is 15 m higher than that of the years of high TS frequency. At the 500 hpa level, the trough is also weak. At 250 hpa, the contours of geopotential height appear almost parallel having the gradient directed towards north, indicating anticyclonic circulation. The strong positive anomaly of geopotential heights exists over the areas in and around Bangladesh throughout the troposphere, which is unfavourable for TS formation. In these years, TS frequency is low because of the fact that the subtropical troughs are weak and the frequency of their passage over Bangladesh and the neighbouring territories are relatively infrequent.

Figure 12(a)–(f) shows the distribution of composite mean temperature for the years of high TS frequency and its anomaly for the month of May for 925, 500, and 250 hpa levels, which shows negative anomaly in

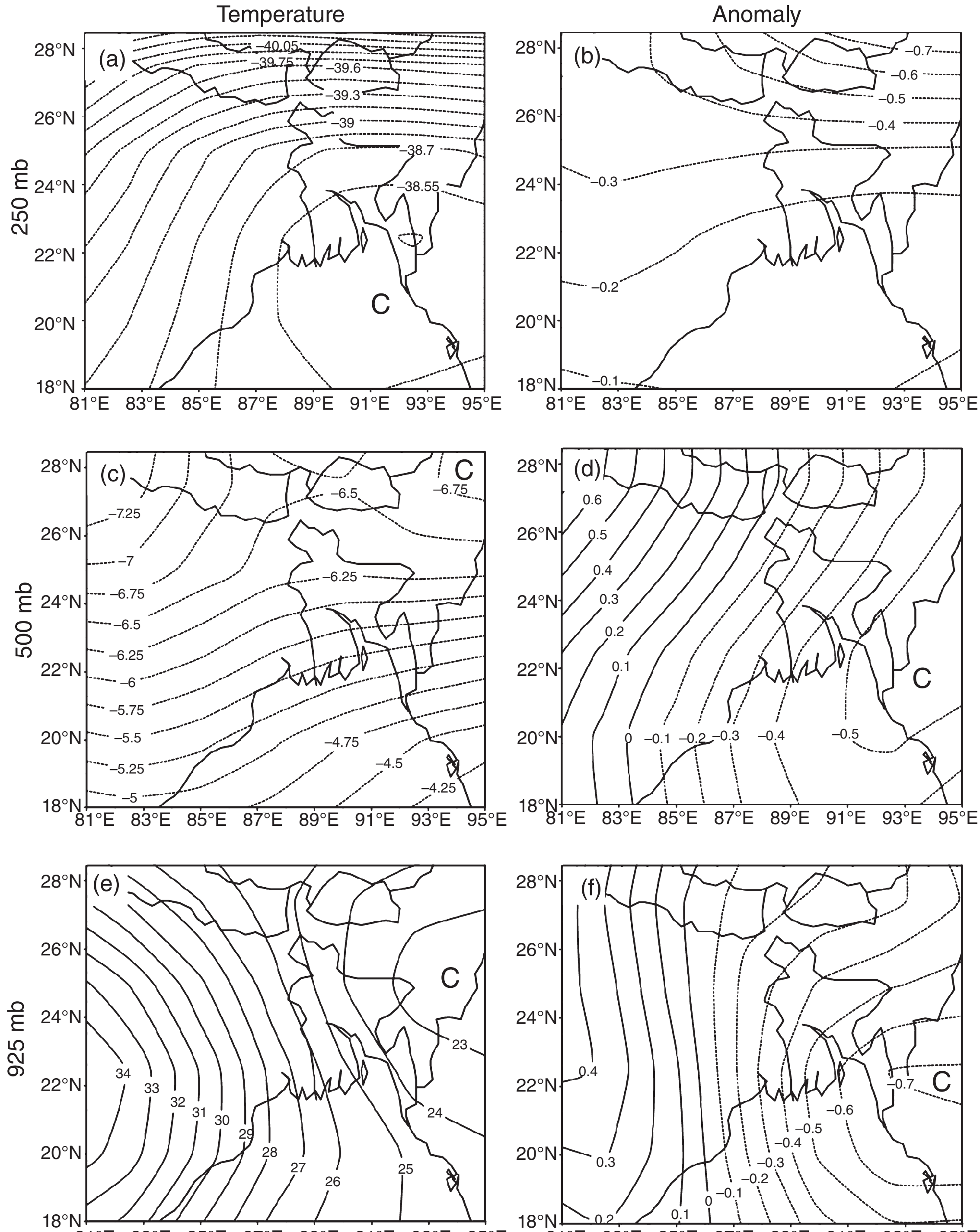

Figure 12. The distribution of composite mean temperature (°C) (left panel a, c, e) and their anomalies (right panel b, d, f) for the month of May of the years 1991, 1993, 2000, 2001, 2002, and 2006 for the high TS frequency.

all these levels. The negative anomaly in the lowest level is because of the reduction of temperature due to high rainfall associated with high TS activity. Over the 500 and 250 hpa levels, the strong negative anomaly is associated with the southward extension of the subtropical westerly disturbances carrying relatively cold air mass which causes higher atmospheric instability compared to the climatological mean condition. For the low TS activity, it is found that the positive anomaly is strong in the 925 and 500 hpa levels, but the 250 hpa level shows a relatively weak negative anomaly over Bangladesh. The strong positive anomaly of temperature in the middle troposphere weakens the vertical temperature gradients and the atmospheric instability which is unfavourable for low TS activity (Figure 13(a)–(f)).

The distribution of a composite specific humidity field for the years with high TS activities shows high moisture content over Bangladesh and adjoining areas to the north

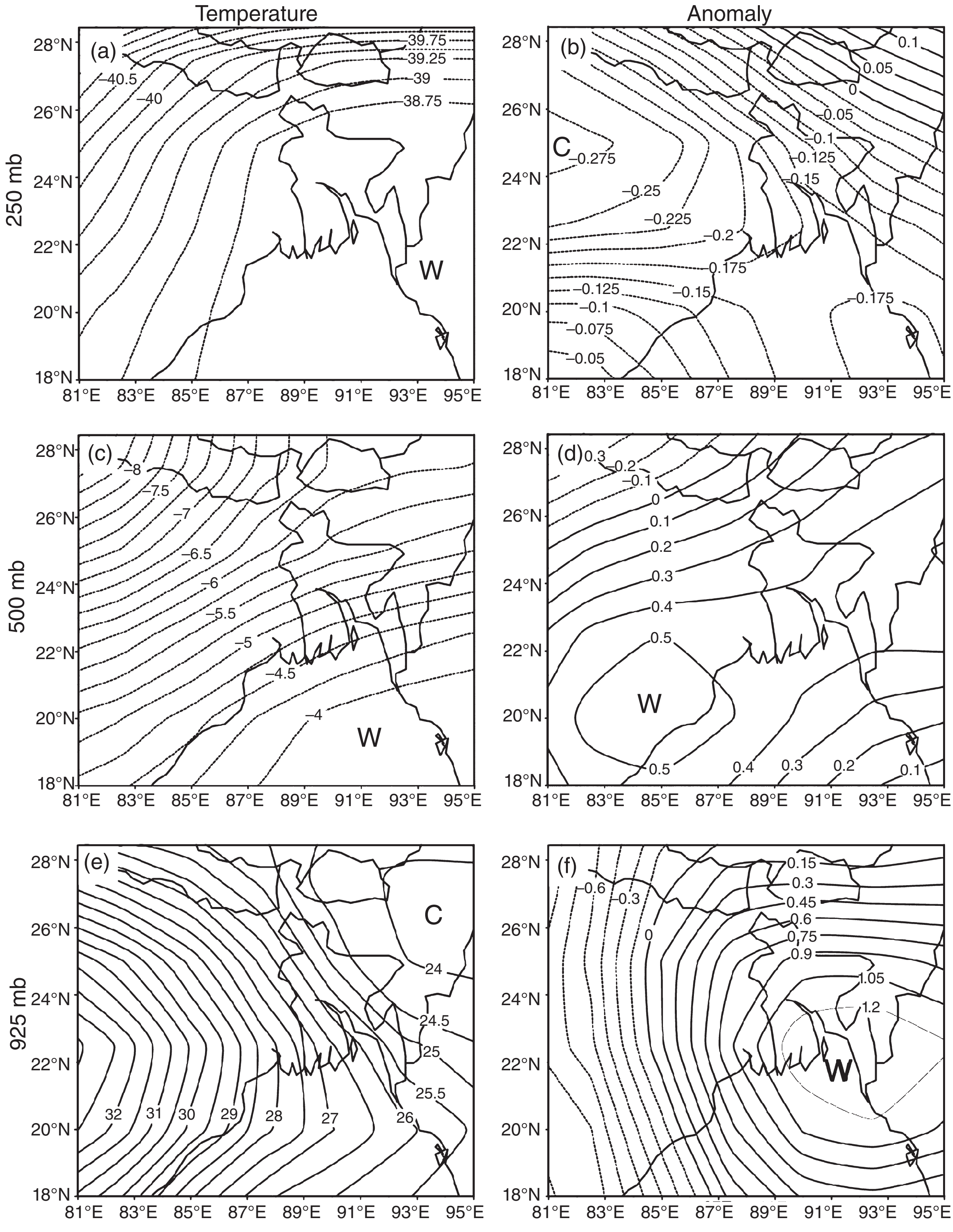

Figure 13. Same as Figure 12 but for the years 1979, 1982, 1987, 1995, 2003, and 2004 belonging to low TS frequency.

and over the Bay of Bengal (Figure 14(a)). The moisture content is high (12–17 $\mathrm{gm\,kg^{-1}}$) over Bangladesh with an extreme high being concentrated over eastern Nepal, western Bhutan, and nearby areas. The dry area is located over central India. Figure 14(b) shows the respective anomaly of moisture distribution, which indicates a positive anomaly over the region of Bangladesh and its surroundings. The distribution of the *v*-component of the winds exhibits the existence of strong low level southerly winds over the northern Bay of Bengal (5.0 $\mathrm{m\,s^{-1}}$) and the territory of Bangladesh (3–4.5 $\mathrm{m\,s^{-1}}$), with an anomaly of around 0.1–0.6 $\mathrm{m\,s^{-1}}$ (Figure 14(c) and (d)). The strong southerly component of the low level wind brings moisture to the land masses of Bangladesh and adjacent

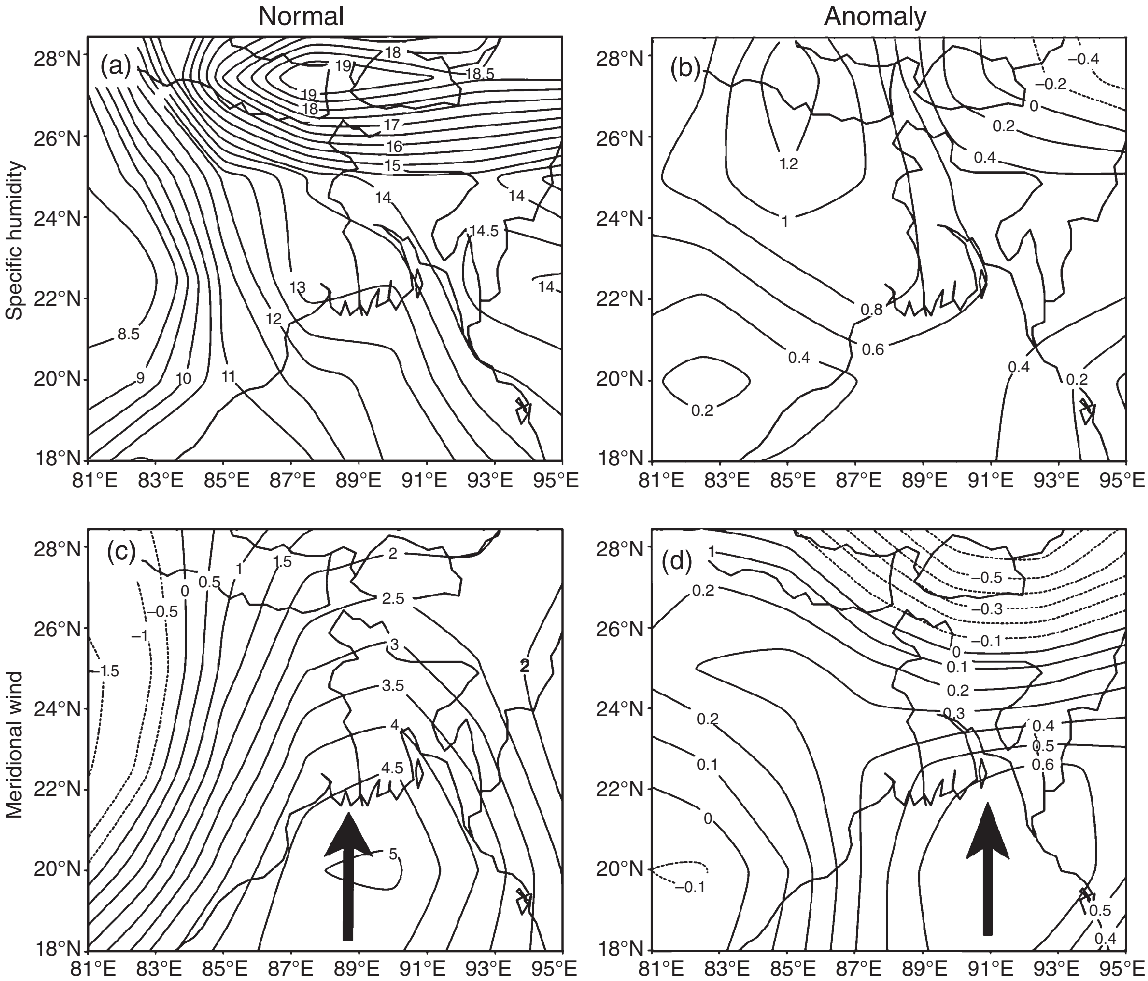

Figure 14. Geographical distribution of composite of specific humidity (gm kg^{-1}) (a) and its anomaly (b), and meridianal wind in m s^{-1} (c) and the respective anomaly (d) for high thunderstorm activity years 1991, 1993, 2000, 2001, 2002, and 2006. The arrows show the direction of meridianal wind as shown in (c) and the direction of the anomaly of the meridianal wind as shown in (d).

areas which, along with favourable circulation and thermal features, provides congenial conditions for atmospheric convection and TS activity.

Figure 15(a) and (c) exhibits a lower moisture level and weak meridional winds at the 925 hpa level in their composites for the years of low TS frequency. Figure 15(b) and (d) exhibits negative anomalies both in moisture content and southerly component of the wind. Thus, the moisture supply to the north from the Bay of Bengal is reduced. This provides a condition unfavourable for convections to occur. A study of TS trends by Kunz *et al.* (2009) for Baden-Württemberg (southwest Germany) has found the correspondence of severe TS with surface temperature and moisture. The authors Kunz *et al.* have further shown that while the annual number of TS days remained almost unchanged, hail damage and hail days significantly increased in the last three decades (1974–2003), and most of the commonly used convective indices that depend on surface temperature and moisture reveal a positive trend regarding the annual extreme values and number of days above/below specific thresholds.

The above discussions reveal that the cooler air mass carried by subtropical westerly disturbances in the middle and upper troposphere is interfaced by low level warm, moist, and light air moving north from the Bay of Bengal, which provides the required instability for the formation and development of the TS cells.

3.4. Dependence of TS activity on VWS for the month of May

The TS frequency has been analysed against the VWS of the *u*-component of winds between 850 and 500 hpa levels. VWS has been calculated from the US National Oceanic and Atmospheric Administration (NOAA)/National Centers for Environmental Prediction (NCEP) gridded data set for the geographic area within 80°–100°E and 18°–28°N which fits the study area does not show representative correlation (CC = 0.012). However, a similar investigation conducted for the area 80°–100°E and 5°–20°N has shown weak positive correlation, based on which a detailed analysis of the relation of VWS with TS frequency has been performed. The monthly distribution of the mean VWS shows that the wind shear is negative from November to April (Figure 16). The high negative values from

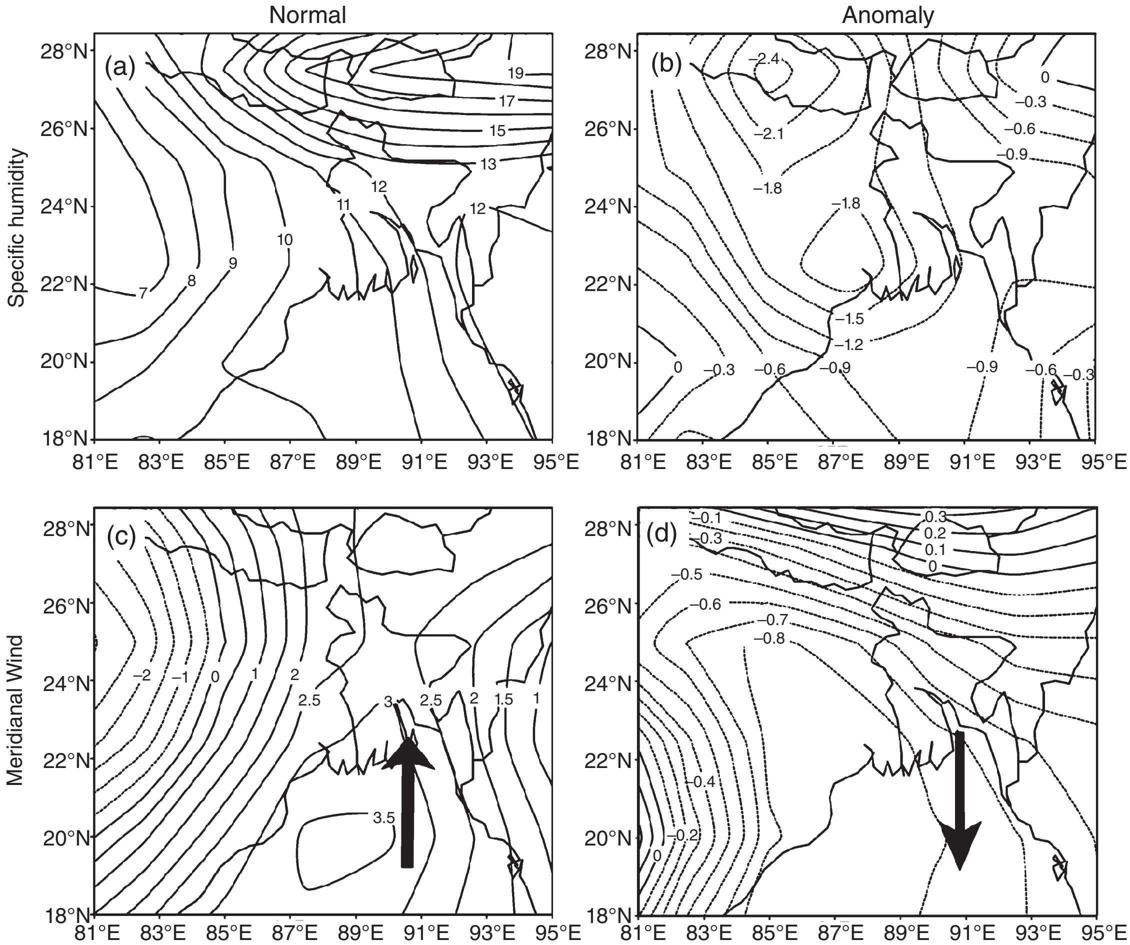

Figure 15. Same as Figure 14 but for the years 1979, 1982, 1987, 1995, 2003, and 2004.

December–February correspond to very low frequency of TS. The month of April has a low negative value which corresponds to relatively high TS frequency. The TS frequency is high for the positive VWS from May to October. The very high VWS is found in July and August but the TS frequency is relatively low in these two core monsoon months compared to that for May, June, and September. The TS frequency is highest in the month of May, when the mean VWS is relatively small, and positive (2.7 m s^{-1}). The analyses using time series plots have been performed using the data of TS frequency and VWS for the month of May (Figure 17).

The time series of TS frequency of May and corresponding VWS shows weak correlation with CC of 0.27 which is statistically significant with $p < 0.05$ as per Student's *t*-test. From the scatter diagram (not shown here), it is found that the TS formation is high if VWS is high, but high scatter of the data points around the regression line in the scatter diagram indicates that the relation is poor, but still supports the view that higher VWS provides favourable environmental condition for TS formation. The above results agree with the findings of DoST (2005) and Ahasan *et al.* (2014), where the high values

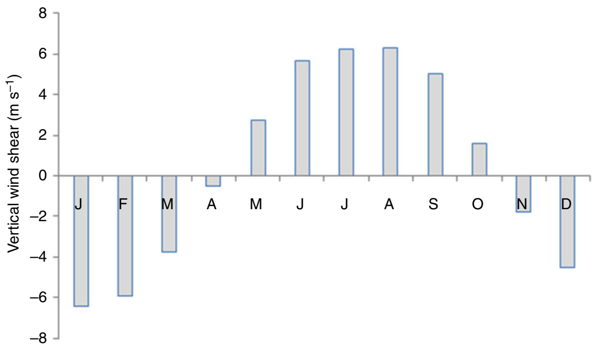

Figure 16. The distribution of monthly mean low level vertical zonal wind shear (u850–u500) m s^{-1} average over the area enclosed 80°–100°E and 5°–20°N and period from 1976 to 2010.

of low level VWS have been described as an important positive factor for severe TS formation and development. The formation and organization of super-cell and multi-cell TS are supported by high low level VWS (Yamane *et al.*, 2010a, 2010b). Diffenbaugh *et al.* (2013) have shown using climate model results that an increase in the occurrence of high convective available potential energy (CAPE) and strong low level wind shear increases the likelihood of atmospheric conditions that contribute to

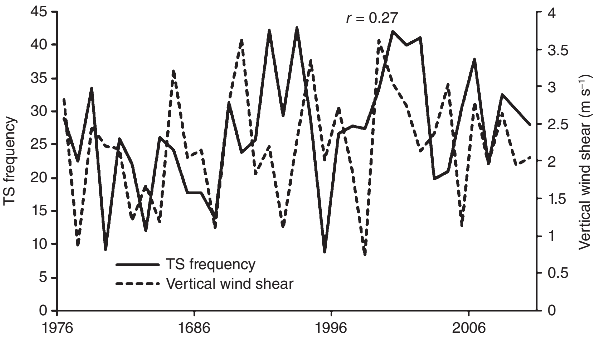

Figure 17. The temporal distribution of TS frequency for the month of May (solid line) and vertical wind shear (VWS) of zonal component between 500 and 850 hpa levels ($u850-u500$).

the most severe events, including tornadoes in the United States.

4. Conclusions

The study of the variability and trends of annual and seasonal TS activities over Bangladesh and the climatology of a few related atmospheric environments over Bangladesh and surrounding areas show the following conclusions:

- The climatology of TS shows that the prominent seasons of TS occurrence are pre-monsoon and monsoon, where the month of May occupies the highest number of TS (27.14). The months of June, September, and April rank second, third, and fourth positions, respectively. The months July and August have relatively lower frequency. The geographic distribution of annual and seasonal TS frequency depicts that northeastern Bangladesh has the highest frequency. The high frequency ridge runs from the northeast to the upper southwest.
- The time series plots of annual and seasonal TS frequency show that the high frequency oscillation of time period around 3–5 years and decadal oscillation of 15–20 years are prominent.
- The trend analysis of annual and seasonal TS frequency shows increasing trends with high statistical significance except for winter when the trend is not statistically significant. The monthly trend analysis shows statistically significant increasing trends for the months May–October. The geographic distribution of the station-wise trend values shows high increasing trends all over the country except a few areas in the southeastern and southwestern coastal zones and intermittently over the Dhaka, Bogra, Ishurdi, and Sylhet areas.
- The correlation analysis of seasonal TS frequency with rainfall of the respective seasons shows positive correlation for the winter, pre-monsoon, and post-monsoon seasons. TS frequency shows negative correlation only for pre-monsoon minimum and maximum temperature, weak negative correlation with the winter maximum temperature, and positive correlation with the monsoon minimum and maximum temperature.
- The investigation of composite fields of geopotential heights at 925, 500, and 250 hpa level for the years with high TS frequency shows that the negative anomaly is dominant in the tropospheric column over Bangladesh, which provides favourable condition for TS formation. The composite fields of geopotential heights for the years with low TS frequency show a positive anomaly over Bangladesh and surrounding areas, which is unfavourable for TS formation.
- The composite fields of temperature show negative anomaly in the whole atmospheric column for the years with high TS frequency. The negative anomaly in the lower atmosphere is due to cooling associated with precipitation caused by TS activity. For the years with low TS frequency, the lower and middle troposphere shows a strong positive anomaly, while the upper troposphere shows a slight negative anomaly.
- The composite fields of moisture show high moisture levels and strong southerly wind at the 925 hpa level over the northern Bay of Bengal for the years with high TS frequency. The anomalies of these fields were found to be positive. The low level southerly wind causes strong advection of moisture over the lands of Bangladesh and surrounding territories, which enhances the probability of TS formation.
- The analysis of the time series of TS frequency with that of low level VWS shows a weak positive correlation and supports the views that intense TS are formed for high VWS in the lower troposphere.

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