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RESEARCH

Long-term changes in temperature, specific humidity, and precipitation in Bangladesh revealed by ERA5 data

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Abstract

Bangladesh is known as one of the countries that are most vulnerable to climate change, which promotes continuous scientific attention to the changes in the regional climate of this country. This study examines the long-term changes in the climate of Bangladesh using reanalysis data during the period of 1959–2021, utilizing the linear regression method. Bangladesh has experienced top-heavy tropospheric warming, with the temperature increasing at a rate of 0.21 °C decade^{-1} at 300 hPa and 0.07 °C decade^{-1} at 850 hPa, which has led to a (statistically) significant increase in the tropospheric static stability. The increase in tropospheric stability is most pronounced in the pre-monsoon season, in which the lower tropospheric warming has not occurred. In contrast, the post-monsoon and winter seasons have experienced prominent lower tropospheric warming. In conjunction with the tropospheric warming, the troposphere over Bangladesh has also undergone moistening, indicated by a 6% increase in precipitable water during the study period. The tropospheric moistening is most prominent in the monsoon season. This study reveals that the two rainiest seasons have experienced different long-term changes in precipitation characteristics. In the pre-monsoon season, the precipitation intensity has significantly decreased by 9% during the study period, which is attributable to the stabilization of the upper troposphere and consequent decrease in the potential of deep convection. In the monsoon season, the precipitation amount has significantly decreased by 10% during the study period. This decrease has occurred exclusively in the eastern part of Bangladesh, and it is primarily attributed to the weakening of monsoonal southerly flow and consequent decrease in moisture flux convergence there.

1 Introduction

Climate change is of great concern in the present time. The global mean surface air temperature increased about 0.85 °C during 1880–2012 and is likely to rise ranging from 0.3 to 4.8 °C by the end of this century (Stocker et al. 2013). The adverse impacts of global warming have already affected about 85% of people worldwide (Callaghan et al. 2021) and are expected to increase (Karl and Trenberth 2003). The frequency and intensity of natural hazards are strongly influenced by climate change (Van Aalst 2006; Stott 2016). One of the regions that are most vulnerable to climate change is South Asia (World Bank 2022).

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South Asia, inhabited by about one-fourth of the world population, is the territory with high population density (ACIAR 2021). During the past 20 years, over half of this population has been affected by at least one natural disaster, and this number is expected to increase as global warming continues (World Bank 2022). Studies have shown increases in the severity of various natural hazards in South Asia including floods (Parvin et al. 2016; Saravanan and Abijith 2022; Yaseen et al. 2022), droughts (Sharma et al. 2021; Ullah et al. 2021; Dost and Kasiviswanathan 2023), cyclones (Hoque et al. 2019; Hirano 2021), and heat waves (Khan et al. 2019b; Singh et al. 2021). Among the South Asian countries, Bangladesh is particularly vulnerable to natural hazards caused by climate change due to its unique geography and land features (Al-Amin et al. 2013; Kafle 2017). Bangladesh has the largest delta in the world, and the land surface of the country is mostly low-lying floodplains. Bangladesh frequently experiences floods, droughts, cyclones, storm surges, salinity intrusion, river bank erosion, and tsunamis, among which floods and cyclones have produced significant damage and loss of life in this country (Cash et al. 2013). Many projections indicate that Bangladesh will face increasing risks of natural hazards with continued global warming (Dastagir 2015; Alamgir et al. 2019; Almazroui et al. 2020).

To cope with and mitigate the impacts of global warming, first of all, it is necessary to document and understand the long-term changes in climate variables. Many studies have been conducted to examine the long-term changes in temperature and precipitation in Bangladesh using surface observation data (Shahid and Khairulmaini 2009; Ahasan et al. 2010; Shahid 2010; Hasan and Rahman 2013; Basak et al. 2013; Shahid et al. 2014; Endo et al. 2015; Khatun et al. 2016; Bhuiyan et al. 2017; Bhuyan et al. 2018; Khan et al. 2019a; Ahmed et al. 2020; Das et al. 2022). Using the daily maximum and minimum temperature data at 17 meteorological observatories during 1958–2007, Shahid (2010) showed the increasing trends of 0.091 and 0.097 °C decade^{-1}, respectively. Hasan and Rahman (2013) showed that the temperature rose more rapidly during 1990–2010 than during 1948–2010. The increasing trends of temperature are found across almost all parts of Bangladesh in all seasons (Basak et al. 2013; Bhuiyan et al. 2017; Khan et al. 2019a; Das et al. 2022).

On the other hand, the long-term trend of precipitation in Bangladesh differs depending on region and season. In Bangladesh, the rainy season is divided into three: pre-monsoon (March, April, and May), monsoon (June, July, August, and September), and post-monsoon (October and November) seasons (Das 1968). Using the precipitation data at 24 rain gauges during 1969–2003, Shahid and Khairulmaini (2009) found increasing but statistically not significant trends of annual, pre-monsoon, and monsoon precipitation and a decreasing but statistically not significant trend of winter (December, January, and February) precipitation. Shahid (2010) reported a statistically significant increasing trend of annual precipitation in the western part of Bangladesh during 1958–2007. Ahasan et al. (2010) showed increasing trends of monsoon precipitation in the northwestern, south-central, and southeastern regions. Shahid et al. (2014) reported increasing but statistically not significant trends of annual and monsoon precipitation in the northern region. Karim et al. (2020) showed significant decreasing trends of annual and seasonal precipitation, except for the post-monsoon season. Although increasing or decreasing trends of precipitation are reported in many previous studies, the long-term changes in detailed precipitation characteristics and the factors responsible for them are not well understood. It is noteworthy to mention the study of Azad et al. (2022) which showed that during 1980–2017, light and moderate monsoon precipitation increased while heavy precipitation decreased.

Most previous studies of the long-term changes in the climate of Bangladesh have focused on temperature and precipitation and primarily relied on surface observation data from meteorological observatories. However, the surface observation data have some limitations, one of which is associated with the relatively high concentration of meteorological observatories in the southern region of Bangladesh, which may result in biases in the area mean values over the country. Reanalysis data with high spatial and temporal resolutions can be an alternative to surface observation data. Using reanalysis data, the long-term changes in temperature and specific humidity at different levels in the troposphere and stratosphere as well as surface precipitation can be studied. Revealing the linkages between the long-term changes in thermodynamic conditions and the long-term changes in detailed precipitation characteristics in Bangladesh is a novel aspect of this study. This study will not only contribute to a comprehensive and in-depth understanding of regional climate change in Bangladesh but also enhance insights into the long-term precipitation changes in monsoon-influenced regions.

This study aims to investigate the long-term changes in temperature, specific humidity, and precipitation in Bangladesh and to find causes for the precipitation characteristic changes in the pre-monsoon and monsoon seasons. For this, we use the European Centre for Medium-Range Weather Forecasts Reanalysis version 5 (ERA5) data (Hersbach et al. 2020). Section 2 describes the data and methods used in the study. In Section 3, the analysis results are presented and discussed.

2 Data and methods

To study the long-term changes in temperature, specific humidity, and precipitation in Bangladesh, we utilize the ERA5 data (Hersbach et al. 2020) during the period of 1959–2021. From the ERA5 data with a horizontal resolution of $0.25° \times 0.25°$, the monthly averaged temperature and specific humidity data at four pressure levels in the troposphere (850, 700, 500, and 300 hPa) and one pressure level in the lower stratosphere (100 hPa) are collected. Additionally, the monthly averaged convective available potential energy (CAPE), precipitable water (PW), and precipitation amount are used. These variables are averaged over 183 grid points inside Bangladesh (Fig. 1).

For a more detailed analysis of precipitation characteristics, precipitation frequency and intensity are calculated using the hourly ERA5 precipitation data, for pre-monsoon and monsoon seasons. Here, the precipitation frequency is defined as the relative frequency of the hours that have 1-h precipitation amount larger than 0.5 mm and the precipitation intensity is defined as the mean of hourly precipitation rates larger than 0.5 mm h^{-1}. In this study, we seek the reasons for the changes in precipitation characteristics from two different perspectives: the changes in deep convection development and large-scale flow patterns. To assess deep

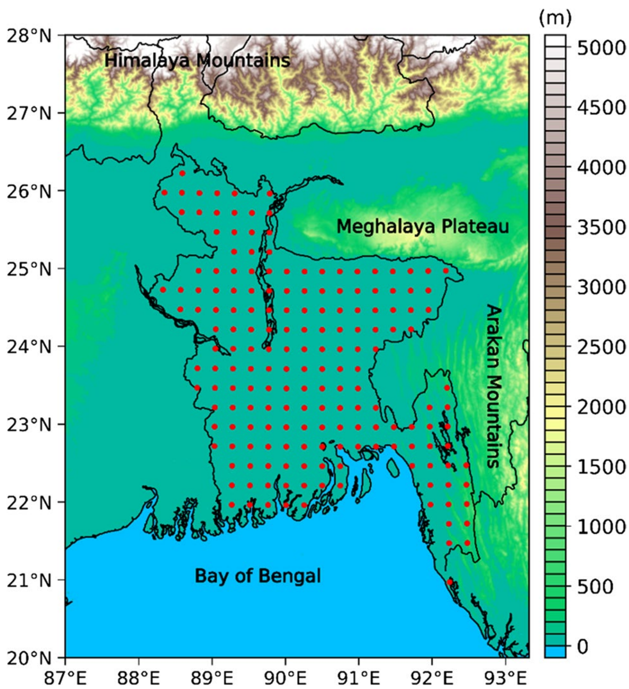

Fig. 1 Topographic map of Bangladesh and surrounding regions. The locations of 183 ERA5 grid points are indicated in red dots

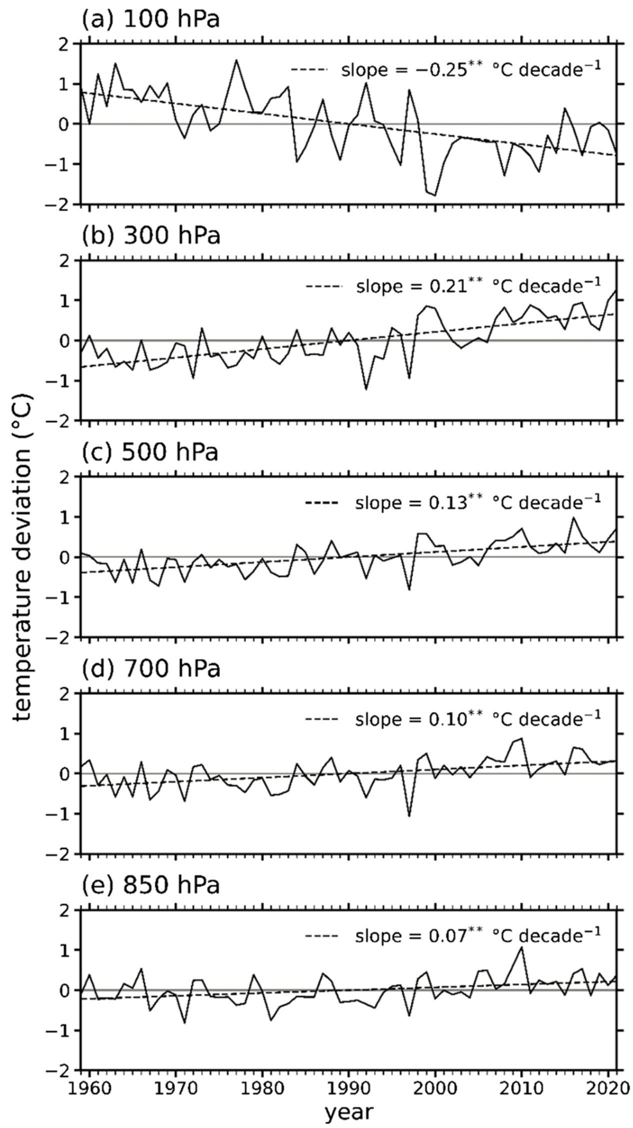

Fig. 2 Yearly variations of temperature deviation from the 63-year mean at the **a** 100-, **b** 300-, **c** 500-, **d** 700-, and **e** 850-hPa levels (solid lines) and their linear trends (dashed lines). The double asterisk (**) indicates statistical significance at the 95% confidence level

convection development, the relative frequency of CAPE exceeding 2000 J kg^{-1} and the ratio of the ice water path to the total water path (hereafter, called the IWP ratio) are calculated. For these calculations, the hourly CAPE data and the monthly averaged ice water path and liquid water path data are used. To examine the changes in large-scale flow associated with precipitation, the linear trends of precipitation amount, 900-hPa zonal and meridional winds, and vertically integrated moisture flux divergence are calculated for each ERA5 grid point, using monthly averaged data.

3 Results and discussion

3.1 Long-term changes in temperature and specific humidity

In this subsection, the long-term changes in temperature and specific humidity together with static stability, CAPE, PW, and precipitation amount in Bangladesh are presented and discussed. Figure 2 shows the yearly variations of temperature deviation from the 63-year mean at 100, 300, 500, 700, and 850 hPa during the period of 1959–2021. Their linear regression lines are also shown. While considerable interannual variations are involved, statistically significant trends of temperature deviation at the 95% confidence level are seen at all pressure levels. The positive trends in the troposphere and the negative trend in the lower stratosphere are clearly observed. This is consistent with the distinctive vertical structure of human-induced warming/cooling signals reported in numerous observational and climate prediction studies (e.g., Tett et al. 1996; Vinnikov et al. 1996; Santer et al. 2013). These studies also demonstrated that near the tropics, the maximum warming occurs in the upper troposphere. The ERA5 data used in this study well capture this feature in Bangladesh, where the steepest positive trend of 0.21 °C decade^{-1} appears at 300 hPa. It is noted that the slope of the linear regression at 300 hPa is larger in recent three decades than in the earlier three decades (0.10 °C decade^{-1} during 1959–1991 and 0.43 °C decade^{-1} during 1992–2021), showing the recent acceleration of upper

Table 1 Slopes of the linear regressions of temperature deviation (°C decade^{-1}) at the 100-, 300-, 500-, 700-, and 850-hPa levels in the pre-monsoon, monsoon, post-monsoon, and winter seasons. The single asterisk (*) and double asterisk (**) indicate statistical significance at the 90% and 95% confidence levels, respectively

	100 hPa	300 hPa	500 hPa	700 hPa	850 hPa
Pre-monsoon	-0.25^{**}	0.26^{**}	0.07^{*}	0.05	-0.07
Monsoon	-0.21^{**}	0.11^{**}	0.09^{**}	0.05^{**}	0.04^{**}
Post-monsoon	-0.37^{**}	0.27^{**}	0.20^{**}	0.17^{**}	0.19^{**}
Winter	-0.24^{**}	0.26^{**}	0.18^{**}	0.18^{**}	0.17^{**}

tropospheric warming in Bangladesh. The slope of the linear regression at 850 hPa is 0.07 °C decade^{-1} which is one third of that at 300 hPa.

To examine the seasonal dependency of the long-term trend of temperature deviation, the slopes of the linear regressions of temperature deviation at the five pressure levels for each season (pre-monsoon, monsoon, post-monsoon, and winter seasons) are presented in Table 1. The linear trend of temperature deviation is statistically significant at the 95% confidence level at all levels in the monsoon, post-monsoon, and winter seasons. In the pre-monsoon season, the linear trend of temperature deviation is statistically significant at the 95% confidence level at 100 hPa and 300 hPa and at the 90% confidence level at 500 hPa. The slopes of the linear regressions at 700 hPa and 850 hPa are considerably larger in the post-monsoon and winter seasons than in the pre-monsoon and monsoon seasons. This indicates much less warming trend in the lower troposphere in the two rainiest seasons. In the pre-monsoon season, the linear trend of temperature deviation at 850 hPa is negative but it is not statistically significant. The slope of the linear regression at 300 hPa in the pre-monsoon season (0.26 °C decade^{-1}) is almost as large as those in the post-monsoon and winter seasons (0.27 °C decade^{-1} and 0.26 °C decade^{-1}, respectively). Accordingly, the tropospheric stability has increased the most in the pre-monsoon season. At 100 hPa, the slope of the linear regression is negatively steepest in the post-monsoon season (-0.37 °C decade^{-1}).

Next, the yearly variations of specific humidity and their linear trends are examined (Fig. 3). The interannual variation of specific humidity is large at all pressure levels. The linear trends of specific humidity at 100, 500, and 700 hPa are statistically significant at the 95% confidence level, and that at 300 hPa is statistically significant at the 90% confidence level. Consistent with the result for temperature deviation, the positive trends in the troposphere and the negative trend in the lower stratosphere are seen for specific humidity. The slope of the linear regression is largest at 700 hPa (0.06 g kg^{-1} decade^{-1}). The level at which the largest slope of the linear regression of specific humidity appears (700 hPa) is lower than that for temperature deviation

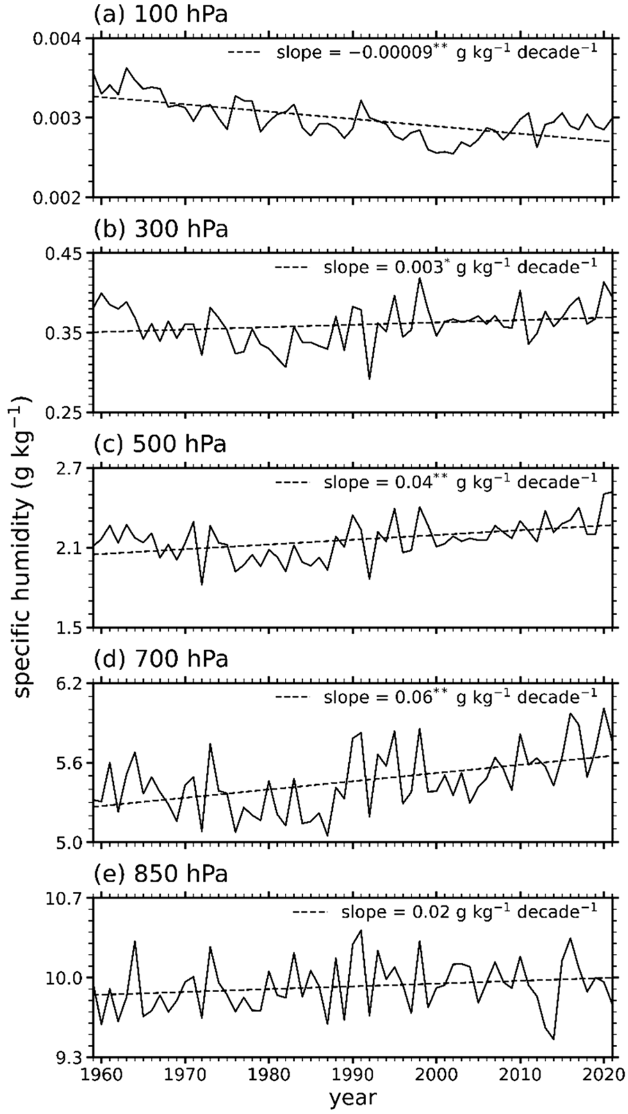

Fig. 3 Yearly variations of specific humidity at the **a** 100-, **b** 300-, **c** 500-, **d** 700-, and **e** 850-hPa levels (solid lines) and their linear trends (dashed lines). The single asterisk (*) and double asterisk (**) indicate statistical significance at the 90% and 95% confidence levels, respectively

(300 hPa). At 850 hPa, the slope of the linear regression is 0.02 g kg^{-1} decade^{-1} but the linear trend is not statistically significant.

Table 2 presents the slopes of the linear regressions of specific humidity at the five pressure levels for each season. The seasonal dependency of the long-term trend of specific humidity is different from that of temperature deviation. Notably, the tropospheric specific humidity increases the most in the monsoon season although the moisture-carrying capacity (temperature) increases more in the post-monsoon and winter seasons than in the monsoon season. In the monsoon season, the slope of the linear regression at 700 hPa is as large as 0.13 g kg^{-1} decade^{-1}, which is twice that in the

Table 2 Slopes of the linear regressions of specific humidity (g kg^{-1} $decade^{-1}$) at the 100-, 300-, 500-, 700-, and 850-hPa levels in the pre-monsoon, monsoon, post-monsoon, and winter seasons. The single asterisk (*) and double asterisk (**) indicate statistical significance at the 90% and 95% confidence levels, respectively

	100 hPa	300 hPa	500 hPa	700 hPa	850 hPa
Pre-monsoon	-0.000083^{**}	0.004^{**}	0.02	0.04^{**}	0.12^{**}
Monsoon	-0.000101^{**}	0.002	0.08^{**}	0.13^{**}	−0.00
Post-monsoon	-0.000116^{**}	0.005^{*}	0.03	0.06	−0.01
Winter	-0.000073^{**}	0.002^{**}	0.01	0.01	−0.01

post-monsoon season. At 500 hPa, the slope of the linear regression is largest in the monsoon season. On the other hand, at 850 hPa, the slope of the linear regression is largest in the pre-monsoon season. The increased static stability in the pre-monsoon season can cause the weakening of convective circulation and thereby reduce the vertical transport of water vapor to upper layers (e.g., Chen et al. 2016).

Figure 4 shows the yearly variations of temperature difference between 850 and 500 hPa (T_{850}–T_{500}), temperature difference between 500 and 300 hPa (T_{500}–T_{300}), CAPE, PW, and precipitation amount and their linear trends. T_{850}–T_{500} and T_{500}–T_{300} exhibit statistically significant decreasing trends (at the 95% confidence level) during the period of 1959–2021, with the slopes of the linear regressions being − 0.06 °C $decade^{-1}$ and − 0.09 °C $decade^{-1}$, respectively. This clearly indicates the increasing trend of static stability and is in line with the top-heavy warming in the troposphere (Fig. 2). CAPE shows a negative trend that is not statistically significant. Consistent with the tropospheric specific humidity increase, PW shows a statistically significant increase during the 63-year period. The slope of the linear regression is 0.36 mm $decade^{-1}$. The precipitation amount shows a negative trend that is not statistically significant. It is noted that while several previous studies reported either positive (Kumar and Jain 2011; Deka et al. 2013) or negative (Mirza et al. 1998; Kumar et al. 2010; Das et al. 2015; Rahman and Abdullah 2022) trends of precipitation amount in Bangladesh, those trends are mostly not statistically significant.

To examine the seasonal dependencies of the long-term trends of T_{850}–T_{500}, T_{500}–T_{300}, CAPE, PW, and precipitation amount, the slopes of their linear regressions in the pre-monsoon, monsoon, post-monsoon, and winter seasons are given in Table 3. The strongest and significant increasing trend of static stability is seen in the pre-monsoon season. The slopes of the linear regressions of T_{850}–T_{500} and T_{500}–T_{300} in the pre-monsoon season are − 0.14 °C $decade^{-1}$ and − 0.19 °C $decade^{-1}$, respectively, whose magnitudes are much larger than those in other seasons. CAPE decreases in the pre-monsoon and monsoon seasons, but its linear

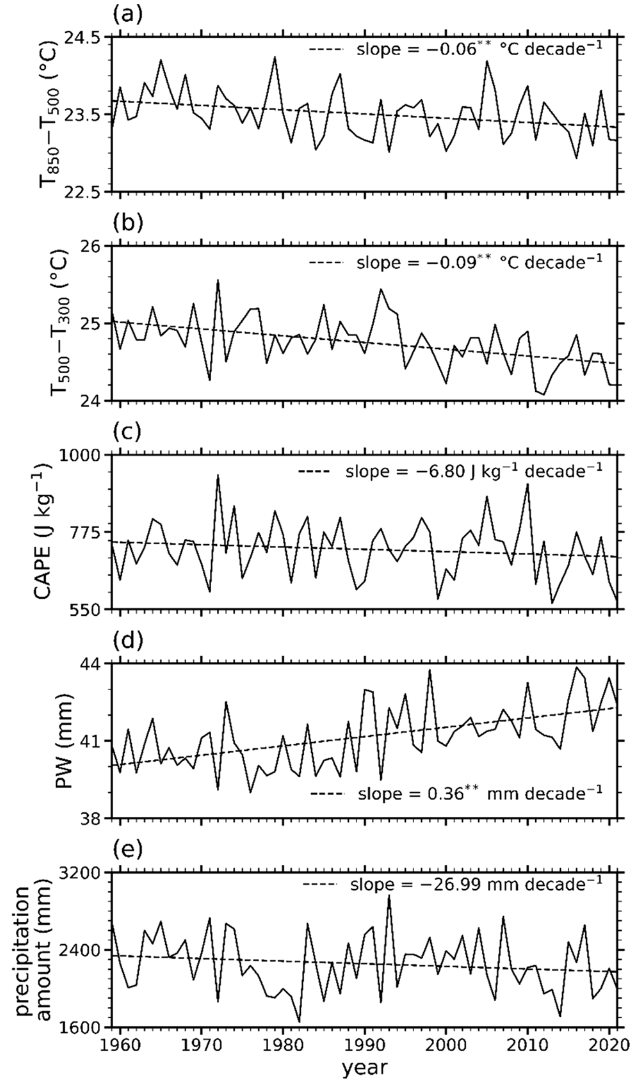

Fig. 4 Yearly variations of **a** temperature difference between the 850-hPa and 500-hPa levels, **b** temperature difference between the 500-hPa and 300-hPa levels, **c** CAPE, **d** PW, and **e** precipitation amount (solid lines) and their linear trends (dashed lines). The double asterisk (**) indicates statistical significance at the 95% confidence level

trends are not statistically significant. PW predominantly increases in the pre-monsoon and monsoon seasons. The precipitation amount in the monsoon season statistically significantly decreases with the slope of the linear regression being − 25.90 mm $decade^{-1}$. Several studies also reported decreases in precipitation amount in the monsoon season in Bangladesh (e.g., Khan et al. 2019a; Rahman and Abdullah 2022). The linear trends of precipitation amount in the pre-monsoon, post-monsoon, and winter seasons are not statistically significant.

For the monsoon season, the correlation between the yearly variation of precipitation amount and the yearly variation of each of T_{850}–T_{500}, T_{500}–T_{300}, CAPE, and PW

Table 3 Slopes of the linear regressions of temperature difference between the 850-hPa and 500-hPa levels (T_{850}–T_{500}), temperature difference between the 500-hPa and 300-hPa levels (T_{500}–T_{300}), CAPE, PW, and precipitation amount in the pre-monsoon, monsoon, post-monsoon, and winter seasons. The single asterisk (*) and double asterisk (**) indicate statistical significance at the 90% and 95% confidence levels, respectively

	T_{850}–T_{500} (°C decade^{-1})	T_{500}–T_{300} (°C decade^{-1})	CAPE (J kg^{-1} decade^{-1})	PW (mm decade^{-1})	Precipitation amount (mm decade^{-1})
Pre-monsoon	-0.14^{**}	-0.19^{**}	-19.96	0.43^{**}	1.12
Monsoon	-0.05^{**}	-0.03^{**}	-13.18	0.45^{**}	-25.90^{*}
Post-monsoon	-0.01	-0.07^{*}	13.59^{*}	0.25	-1.97
Winter	-0.01	-0.08	1.26	0.25^{**}	-1.53

is examined. The correlation coefficient (R) is 0.13 between precipitation amount and T_{850}–T_{500}, -0.11 between precipitation amount and T_{500}–T_{300}, 0.13 between precipitation amount and CAPE, and 0.14 between precipitation amount and PW. The calculated four correlation coefficient values are small and not statistically significant, indicating that the negative trend of precipitation amount in the monsoon season is not well explained by static stability, CAPE, and PW. It appears that the long-term changes in large-scale monsoonal flow need to be considered to understand the long-term change in monsoonal precipitation. In general, the long-term increase in water vapor amount due to global warming has a positive contribution to the long-term increase in precipitation amount. Meanwhile, the dynamic effects on precipitation due to the changes in large-scale flow show a large regional dependency (Emori and Brown 2005; Held and Soden 2006). In the next subsection, we examine the long-term changes in precipitation in association with the long-term changes in convective characteristics and large-scale monsoonal flow.

3.2 Long-term changes in precipitation

In this subsection, the long-term changes in precipitation in Bangladesh are investigated in depth for the pre-monsoon and monsoon seasons. The two seasons are the rainiest seasons in Bangladesh, contributing 23% and 66%, respectively, to the annual precipitation amount. The pre-monsoon season is characterized by frequent occurrences of severe thunderstorms with relatively small sizes attributable to the high thermodynamic instability and strong vertical wind shear in this season (Yamane and Hayashi 2006; Yamane et al. 2010). On the other hand, the monsoon season is characterized by relatively large and slow-moving precipitation systems associated with strong low-level southerly and southwesterly monsoonal flows with a large amount of moisture lifted or deflected by orography in the northeastern and eastern sides of Bangladesh (Rafiuddin et al. 2010; Ahmed et al. 2021). Due to the differences in characteristics between the pre-monsoonal and monsoonal precipitation, their long-term changes in response to climate changes can be different from each other.

3.2.1 Pre-monsoon season

Figure 5 shows the yearly variations of precipitation amount, precipitation frequency, and precipitation intensity and their linear trends in the pre-monsoon season. It is noted that on average, the pre-monsoonal precipitation is more intense but much less frequent (or with smaller spatial coverage) than the monsoonal precipitation (see Fig. 7). The high precipitation intensity in the pre-monsoon season goes through a statistically significant decrease with the slope of -0.04 mm h^{-1} decade^{-1}, which corresponds to a 9% decrease during the period of 1959–2021. This indicates that the highly convective precipitation systems that frequently occur in the pre-monsoon season may have weakened. The precipitation

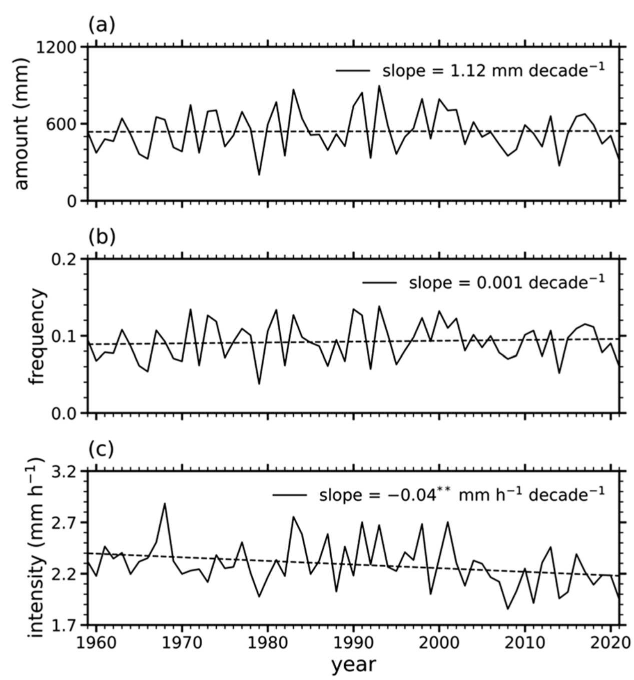

Fig. 5 Yearly variations of **a** precipitation amount, **b** precipitation frequency, and **c** precipitation intensity in the pre-monsoon season (solid lines) and their linear trends (dashed lines). The double asterisk (**) indicates statistical significance at the 95% confidence level

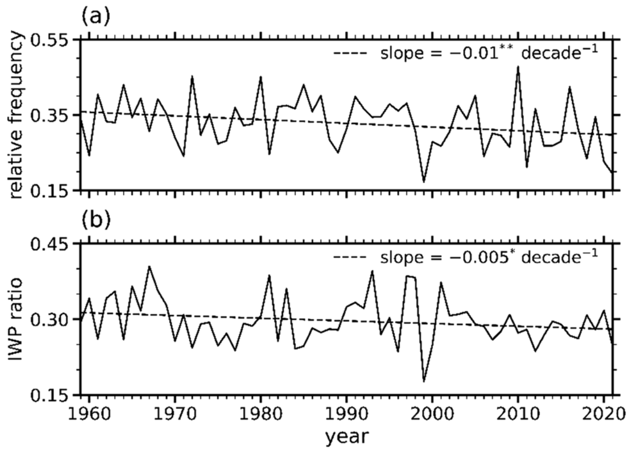

Fig. 6 Yearly variations of **a** relative frequency of CAPE > 2000 J kg^{-1} and **b** IWP ratio in the pre-monsoon season (solid lines) and their linear trends (dashed lines). The single asterisk (*) and double asterisk (**) indicate statistical significance at the 90% and 95% confidence levels, respectively

amount and frequency in the pre-monsoon season do not show statistically significant changes during the period.

The decreasing trend of precipitation intensity in the pre-monsoon season is associated with the decreasing trend of the potential of deep convection. As shown in Table 3, the pre-monsoon season exhibits the most prominent stabilization of the troposphere, which can inhibit the development

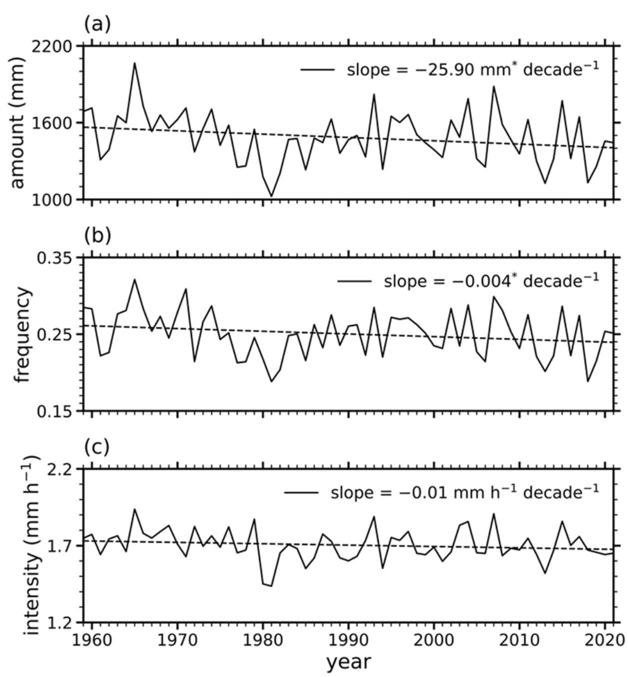

Fig. 7 Yearly variations of **a** precipitation amount, **b** precipitation frequency, and **c** precipitation intensity in the monsoon season (solid lines) and their linear trends (dashed lines). The single asterisk (*) indicates statistical significance at the 90% confidence level

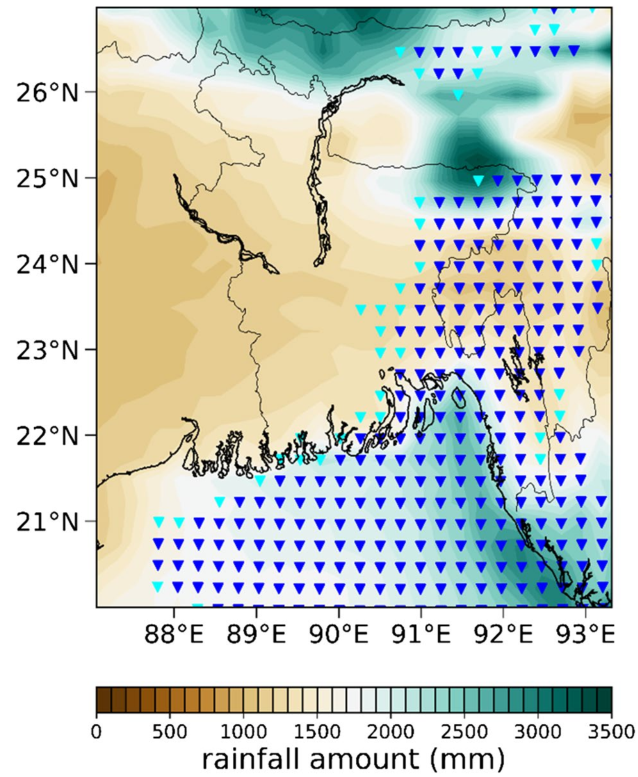

Fig. 8 Fields of precipitation amounts averaged for the period of 1959–2021 (shades) and the linear trends of precipitation amounts (triangles) in the monsoon season. The cyan and blue inverted triangles indicate the decreasing linear trends of precipitation amounts at the 90% and 95% confidence levels, respectively

of deep convection. The relative frequency of CAPE exceeding 2000 J kg^{-1} in the pre-monsoon season has statistically significantly (at the 95% confidence level) decreased with its linear regression decreasing from 0.36 to 0.30 during the 63-year period (Fig. 6a), indicating a decrease in the potential of deep convection. The relative frequency of high CAPE is significantly correlated with both T_{850}–T_{500} (R = 0.48) and T_{500}–T_{300} (R = 0.54), where the correlation with T_{500}–T_{300} is higher. The stabilization of the upper troposphere also leads to the changes in cloud characteristics. The ratio of the ice water path to the total water path (IWP ratio) in the pre-monsoon season has statistically significantly (at the 90% confidence level) decreased with its linear regression decreasing from 0.31 to 0.28 during the 63-year period (Fig. 6b). The relative frequency of high CAPE and the IWP ratio have significant positive correlations with the precipitation intensity (R = 0.37 and 0.42, respectively). These suggest that the stabilization of the upper troposphere due to climate change has weakened the deep convection and cold microphysical processes in the pre-monsoon season, causing a decreasing trend of precipitation intensity. The fact that this impact of climate change is detected in precipitation intensity but not in precipitation amount emphasizes the importance of

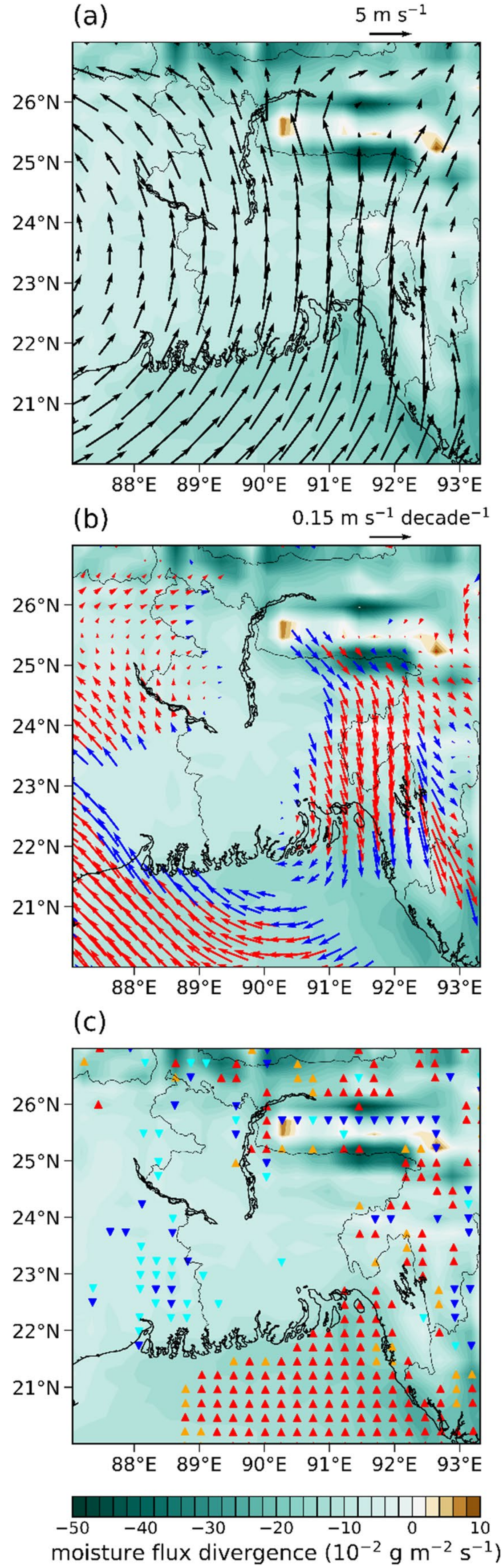

Fig. 9 Fields of **a** 900-hPa horizontal wind vectors averaged for the period of 1959–2021, **b** vectors of linear trends of 900-hPa zonal and meridional winds, and **c** linear trends of vertically integrated moisture flux divergences (triangles) in the monsoon season. Each of the arrows in **b** is colored in blue (red) if at least one of the linear trends of the two wind components is statistically significant at the 90% (95%) confidence level. Each of the triangles in **c** is colored in orange (red) if the linear trend is positive and statistically significant at the 90% (95%) confidence level, and it is colored in cyan (blue) if the linear trend is negative and statistically significant at the 90% (95%) confidence level. The color shades in **a**, **b**, and **c** stand for vertically integrated moisture flux divergence averaged for the period of 1959–2021

examining detailed precipitation characteristics when assessing the impacts of climate change on precipitation.

3.2.2 Monsoon season

In the monsoon season, the precipitation amount shows a statistically significant (at the 90% significance level) decreasing trend with the slope of – 25.90 mm decade^{-1}, which corresponds to a 10% decrease during the 63-year period (Fig. 7). The decrease in monsoonal precipitation amount is the dominant reason for the decrease in whole-year precipitation amount shown in Fig. 4e. The decrease in precipitation amount is mainly driven by the decrease in precipitation frequency, which is also statistically significant (at the 90% significance level). The precipitation intensity does not show a statistically significant change during the period, which may be associated with the fact that the stabilization of the troposphere in the monsoon season is not as prominent as in the pre-monsoon season (Table 3).

The decreasing trend of monsoonal precipitation amount does not occur throughout whole Bangladesh but only in some parts of the country. Figure 8 shows the signs and statistical significances of the linear trends of monsoonal precipitation amounts in and around Bangladesh along with its climatological mean. Statistically significant decreases occur over the Bay of Bengal, the southeastern region of Bangladesh, and the northeastern region of Bangladesh, which are climatologically wet regions located along the general path of moisture transport by monsoonal flows (Ahmed et al. 2020).

Figure 9 shows the long-term changes in low-level (900 hPa) flow and vertically integrated moisture flux divergence in the monsoon season along with their climatological means. The vector of linear trends of 900-hPa zonal and meridional winds is considered to have a statistically significant trend if at least one of the linear trends of the two wind components is statistically significant. The climatological mean low-level flow is southwesterly over the Bay of Bengal and turns to southerly as it reaches Bangladesh due to the blocking and deflection by the Arakan Mountains (Wu et al. 2014). A large amount of moisture carried by this monsoonal flow causes strong moisture flux convergence along the southeastern coast of Bangladesh and the northeastern border of Bangladesh, which are under orographic influence of the Arakan Mountains and Meghalaya Plateau (see Fig. 1), producing a large amount of precipitation in the southeastern and northeastern regions of Bangladesh. The linear regression of the change in low-level flow shows that the westerly component of the monsoonal southwesterly flow over the Bay of Bengal and the monsoonal southerly flow over the eastern part of Bangladesh have significantly weakened. As a result, the moisture flux convergence over the eastern part of the Bay of Bengal, the southern coast of Bangladesh, and the northeastern border of Bangladesh has been significantly reduced, which leads to the decrease in precipitation amount in the southeastern and northeastern regions of Bangladesh (Fig. 8). It is noted that the interannual variation of moisture flux convergence in Bangladesh shows very strong correlation with that of precipitation amount in the monsoon season ($R = 0.91$). This shows that the decreasing trend of precipitation amount in the monsoon season is caused by the change in the South Asian monsoon. The change in tropospheric stability, on the other hand, is not related to the decrease in monsoonal precipitation amount. T_{850}–T_{500}, T_{500}–T_{300}, and CAPE do not show statistically significant correlations with monsoonal precipitation amount. The findings in this study suggest that climate change can affect precipitation through different pathways for different seasons, which highlights the need for employing multiple approaches in dynamical and thermodynamical perspectives to gain a deeper understanding of how regional precipitation is modulated by climate change.

4 Summary and conclusions

This study investigates the long-term changes in temperature, specific humidity, and precipitation in Bangladesh using the ERA5 data (1959–2021). The temperature trends are characterized by top-heavy tropospheric warming and stratospheric cooling. The tropospheric warming is most pronounced in the post-monsoon and winter seasons. In the pre-monsoon season, the lower tropospheric temperature is not increased (statistically) significantly while the upper tropospheric warming is strong, so the tropospheric static stability is significantly increased. The tropospheric specific humidity is increased, primarily in the pre-monsoon and monsoon seasons. The annual lower and upper tropospheric static stabilities and PW have significantly increased during the 63-year period.

The long-term changes in precipitation characteristics in the pre-monsoon and monsoon seasons are investigated in depth. In the pre-monsoon season, the precipitation intensity significantly decreased by 9% during the 63-year period. This may be attributed to the weakening of deep convective precipitation systems, indicated by the decreases in the relative frequency of high CAPE and the IWP ratio caused by the prominent stabilization of the upper troposphere. In the monsoon season, the precipitation amount significantly decreased by 10% during the 63-year period. The precipitation amount is decreased preferentially in the southeastern and northeastern regions of Bangladesh, where the monsoonal moisture flux convergence is significantly decreased.

While the amount and intensity of precipitation tend to increase globally, the long-term regional changes in precipitation characteristics in Bangladesh have been found to have a complicated seasonal dependency. Many possible mechanisms can be involved, such as positive feedback by low-level moistening, deepening of convection, radiative cooling, and warming by surface flux (Chou et al. 2009). In the near future, a quantitative analysis of the thermodynamic and dynamic contributions to the long-term changes in the frequency and intensity of precipitation can be done with previously devised methods (e.g., Chen et al. 2012).

Author contribution Jong-Jin Baik designed this study. Abeda Tabassum, Kyeongjoo Park, and Han-Gyul Jin performed the data analysis and visualization. All authors discussed the results. Abeda Tabassum, Kyeongjoo Park, Han-Gyul Jin, and Jihoon Shin wrote the original draft. Jong-Jin Baik reviewed and edited the manuscript. All authors read and approved the final version of the manuscript.

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Data availability The ERA5 data were downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store (CDS).

Code availability The codes used for analyses in this study can be obtained from the corresponding author if necessary.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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