Spatio-Temporal Climatology and Trends of Convective Available Potential Energy (CAPE) over Bangladesh, including three lightning hotspots during 40 years (1982-2021)

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Research Article

Keywords: Climatology, Convective Available Potential Energy (CAPE), Trend analysis, Thunderstorms, Lightning hotspots, Bangladesh

Posted Date: June 7th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3011093/v1

Abstract

This study investigates the climatology of Convective Available Potential Energy (CAPE) over Bangladesh and its eight administrative divisions, along with three lightning hotspots (Sherpur, Shahjadpur, and Bajitpur), using monthly, seasonal, and annual data for 40 years (1982–2021). The monthly CAPE data at 0000 UTC and 1200 UTC has been collected from the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis data (ERA5) at 0.25° resolution. The study reveals that the increasing CAPE trend over Bangladesh may be responsible for the increased frequency of extreme events. Significant CAPE values were observed in Bangladesh's south-west and southern parts from March to May. In April, there was a notable increasing trend in CAPE values, particularly in the north-western region. The average CAPE values for Bangladesh's three lightning hotspot regions (Sherpur, Shahjadpur, and Bajitpur) is higher than 1500 J/kg during the pre-monsoon at 0000 UTC, directly correlating with the lightning and thunderstorm. The Mann-Kendall test has been employed to follow yearly and seasonal trends. Overall, this study provides valuable insights into the spatial distribution of CAPE and its association with thunderstorms in Bangladesh, which can inform the development of effective strategies to manage weather-related hazards in the country.

1 Introduction

Climate change triggers extreme weather events, giving rise to numerous uncertainties about certain weather phenomena. The degree to which climate change impacts an individual extreme weather or climatic event is more challenging to determine and quantify. Reliable detection and attribution of changes in specific climatic events and their impacts are vital for understanding the scientific basis of climate change (Ummenhofer and Meehl 2017; Easterling et al. 2016). Changes in climatic parameters increase the frequency of the variances leading to extreme weather events (Jentsch and Beierkuhnlein 2008). Extreme weather refers to phenomena situated at the extremes of historical distribution and denotes rare occurrences for a given location or time, typically characterized by severe or unseasonal weather conditions. Such events exhibit exceptional values in important meteorological variables, encompassing attributes such as occurrence rate, intensity, temporal duration, and spatial timing scale, where the temporal duration provides a valuable way of classifying extreme weather events (Radović and Iglesias 2019).

Convective phenomena such as thunderstorms can be considered extreme weather events (Stephenson et al. 2008). Thunderstorms develop mainly due to intense atmospheric convection and are associated with heavy rainfall, lightning and thunder, hail, and squall lines. Thunderstorms occur worldwide, followed by mechanisms like air parcel lifting, conditional instability, and strong moisture convergence (Saha and Quadir 2016; Umakanth et al. 2020). Thunderstorm frequency and intensity are changing regionally over recent decades (Price and Asfur 2006; Kunz et al. 2009; Taszarek et al. 2021). The development of thunderstorm convection and lightning occurrence is closely related to the Convective Available Potential Energy (CAPE) that reflects atmospheric instability (Qie et al. 2021).

CAPE could be an essential indicator for predicting thunderstorm-related lightning in Bangladesh (Dewan et al. 2018). It represents the kinetic energy gained by an unmixed air parcel that ascends pseudo-adiabatically in the atmospheric convection process. A positive cloud buoyancy over a significant atmosphere depth is required to maintain the deep convection in the tropics. The buoyancy of the cloud depends on the parameter CAPE for rising air parcels (Tompkins 2001), which is highly sensitive to temperature and moisture variations in the boundary layer (Mapes and Houze 1992; Carlson et al. 1983). Moisture influx through low-level jets enhances CAPE and provides the necessary ingredients for convection in continental regions (Houze 2007; Chou and Neelin 2004). The atmospheric lapse rate also influences CAPE values, albeit as a secondary driving factor (Riemann-Campe et al. 2009). On a seasonal scale, mean CAPE values range from 0 to 7000 J/kg, with higher values typically observed in the northern hemisphere during summer (June-August) and in the southern hemisphere during winter (December–February) (Diffenbaugh et al. 2013). The combination of high CAPE and strong low-level wind shear increases the likelihood of atmospheric conditions contributing to the most severe events (Allen et al. 2014). Significant CAPE increases are seen in the Inter Tropical Convergence Zone (ITCZ), western tropical Pacific, and summer continents, whereas CAPE changes little over winter continents (Christian et al. 2003).

Previous studies have been carried out by Holley et al. (2014), Khan et al. (2022), Meukaleuni et al. (2016), Taszarek et al. (2021), and Sahu et al. (2022) for the climatology of CAPE over the globe. The trend of the CAPE variation is essential to study for predicting future changes in the intensity of severe convective storms. Murugavel et al. (2012) studied how the CAPE trends can influence the atmospheric convective system. Chakraborty et al. (2019) explained how thermodynamic instability or CAPE has been increasing recently and how particular regions, like the coasts and surrounding seas, are prone to be at higher risk of lightning in the future. Earlier, Wahiduzzaman et al. (2020) presented the Thunderstorm frequency trends associated with the CAPE over Bangladesh, but the long-term regional distribution of CAPE is required to study for monitoring the hotspots of lightning in Bangladesh (Wahiduzzaman et al. 2022). Albrecht et al. (2016) identified Earth's lightning hotspots by ranking the climatological flash rate density to highlight their annual and diurnal cycle details of lightning activity. According to that list, three hotspots of Bangladesh are listed as Bajitpur, Sherpur, and Shahzadpur, which is the primary focus of our study (refer to Fig. 1). A similar study was done by Mondal et al. (2022), examining the hotspots region in India with the highest flash rate density that will help provide early warning and arrangements for the safety of the people, livestock, and property.

The topography and wind regimes made Bangladesh and Northeast India bordering Bangladesh highly favourable for the occurrence of thunderstorms (Sahu et al. 2020). Various factors, such as conditional instability and the influx of moist air from the Bay of Bengal, influence Bangladesh's pre-monsoon climate, leading to an increase in thunderstorm activity from March to May, with May experiencing the highest frequency (Srinivasan and Gadgil 1996; Shahid 2011; Karmakar 2001). Therefore, this region experiences a higher frequency of thunderstorm activity than other parts of South Asia. Thunderstorms have affected various Bangladesh regions in the past decades through natural hazards from convective activity. With a population of 163 million, Bangladesh is one of the most vulnerable countries globally to climate risks and natural hazards, regularly facing severe floods, cyclones, droughts, heatwaves, and storm surges (IPCC Report 2022). It is exposed to extreme weather events, which affect most of the population and cause property damage (Ahmed et al. 2019). The number of lightning casualties is higher in pre-monsoon season. Annual averages of 144 fatalities and 88 injuries were found from 1990–2016, although the totals increased sharply in recent years. The urban-rural variation indicated that 93% of lightning fatalities occurred in rural Bangladesh as opposed to 7% in urban areas (Dewan et al. 2017).

It is obvious to study CAPE's recent spatial distribution in exploring this factor's association with the thunderstorm in the changing climate. A long-term study on the related thermodynamic factors for the occurrence of various phenomena needs to be carried out to predict the nature of convective activities. Developing a climatology can bring out the proper distribution of CAPE in Bangladesh, which is the primary concern of the current research. The motivation behind this climatology has come from the unavailability of the current dataset or long-term climatology for Bangladesh in proper resolution. Detailed analysis of the variation in the climate of Bangladesh can help assess the regional climate changes. Understanding the environmental characteristics of lightning occurrence is essential in managing weather-related hazards in Bangladesh.

The study aims to find out the monthly average and trends of CAPE over Bangladesh for 40 years at 0000 UTC and 1200 UTC and to explore the seasonal average and trends of CAPE over Bangladesh for 40 years. Additionally, the study aims to establish the climatology of CAPE on the eight divisions and the lightning hotspots of Bangladesh for 40 years and to investigate the trend analysis of CAPE. Section 2.1 presents the study area in this paper, whereas sections 2.2 and 2.3 describe the data and methodology, respectively. Finally, sections 3 and 4 present the result and discussion.

2 Data and Methodology

2.1 Area of the Study

Much of Southeast Asia holds within the tropical climatic zone with temperatures above 25° C throughout the year. Southeast Asia is highly vulnerable to the effects of climate change in which Bangladesh is situated. Lowlands characterize Bangladesh's topography, and most land seldom rises to 10 m above sea level (Ohsawa et al. 2000). The Assam hills surround it to the east, the Meghalaya plateau to the north, the Bay of Bengal to the south, and the contiguous plain of west Bengal and Gangetic plain of India to the west (Chowdhury and De 1995). Bangladesh belongs to the Asian monsoon regime which is characterized by a seasonal reversal of surface winds and a distinct seasonality of precipitation.

During the boreal summer, winds blow from the Southern Hemisphere from mid-May to September, accumulating moisture and depositing copious amounts of precipitation over the South Asian continent (Shahid 2010). Four distinct seasons can be recognized from the climate perception: (i) the dry winter season from December to February, (ii) the pre-monsoon hot summer season from March to May, (iii) the rainy monsoon season from June to September, and (iv) the post-monsoon autumn season from October to November (Rashid 1991). Southwest and northeast monsoons significantly influence the country's climate, resulting in significant seasonal rainfalls and temperatures (Wahiduzzaman et al. 2022). Bangladesh has eight administrative divisions, which are part of the regional CAPE study connected with the study of 3 lightning hotspots, as shown in Fig. 1 (Albrecht et al. 2016).

2.2 Data

The climatology of CAPE over Bangladesh has been investigated using monthly, seasonal, and annual time series data for 40 years (1982–2021). The monthly CAPE data at 0000 UTC and 1200 UTC has been collected from the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis data (ERA5) at 0.25° x 0.25° horizontal resolution (Hersbach et al. 2020).

2.3 Methodology

Convective Available Potential Energy (CAPE) is calculated as the positive temperature difference between the theoretical parcel and environmental lapse rates, vertically integrated to the natural logarithm of pressure, *P*, between the Level of Free Convection (LFC) and Equilibrium Level (EL).

CAPE= $\int_{LFC}^{EL} R_d(T_{v_p} - T_{v_e})\, d\ln P$

CAPE, measured in J/kg, is directly related to the maximum potential vertical speed within an updraft (wMAX; m/s). The higher range of CAPE values influences the potential for severe convection.

The Grid Analysis and Display System (GrADS) has been used to analyze spatial distribution. The trend analysis of CAPE has been performed using the tools from ArcGIS Pro. It is a full-featured professional desktop GIS application from Esri. The kriging interpolation method of the geostatistical analysis tool in ArcGIS Pro is used in this study. Trend analysis of a time series comprises the status of the trend and its statistical significance. In this study, the Mann-Kendall test has been employed to follow yearly and seasonal trends where the presence of a monotonic increasing or decreasing trend was tested with the non-parametric Mann-Kendall test. For a detailed description of the Mann-Kendall test, refer to Mphale et al. (2014). The Mann-Kendall test can be implemented when a set of time-ordered data follows an increasing or decreasing trend within a significance level.

3 Results and Discussion

3.1 Monthly variation of CAPE

Figure 2 (a) and (b) depict the spatial variations of the monthly average Convective Available Potential Energy (CAPE) at 0000 UTC and 1200 UTC, respectively, over 40 years (1982–2021) in Bangladesh. It shows the peak between April and May; the CAPE values range from 600–3400 J/kg due to strong ground heating (refer to Figure 2 (a) and (b)). Chowdhury and De (1995) reported that the frequency of thunderstorms is highest in May during the pre-monsoon period in Bangladesh. The maximum CAPE values are observed in Bangladesh's southwest and southern regions, extending towards the northwest direction and the Bay of Bengal. These regions are likely responsible for the formation of thunderstorms during this period. CAPE values are prominent every month except from November to February when they are relatively low throughout Bangladesh. CAPE values are slightly consistent across the country from July to October.

Dewan et al. (2018) found that CAPE increases from March to May and decreases with the onset of the monsoon. Ahmed and Karmakar (1993) mentioned that the pre-monsoon season in Bangladesh marks the transition period between the northerly or north-westerly winter winds and the southerly summer monsoon winds. The persistence in wind direction and speed increases as the season progresses. Moisture-laden winds are divided into two wind branches upon reaching the southernmost part of the Indian Peninsula, with the Bay of Bengal branch being dominant over Bangladesh in summer.

3.2 Monthly spatial trends of CAPE

Monthly spatial Mann Kendall trends of CAPE over Bangladesh at 0000 UTC and 1200 UTC are presented in Fig. 3 (a) and (b), respectively. In this study, we analyzed the Mann-Kendall trends of CAPE over Bangladesh at 0000 UTC and 1200 UTC from 1981 to 2021. Our results indicate that the CAPE trends over Bangladesh vary significantly across different months and regions.

In March, most areas of Bangladesh exhibited a negative trend of CAPE, except for a small portion of the north-western zone (-4.02 ~ -9.65) at 0000 UTC and the south-eastern zone (-6.52 ~ -15.12) at 1200 UTC. In April, a positive trend (0.97 ~ 12.44) is prominent in the northwest and east coastal areas at 0000 UTC and in the north-western region (4.32 ~ 25.10) at 1200 UTC. Negative trends (-2.85 ~ -14.31) at 0000 UTC and (-2.59 ~ -23.36) at 1200 UTC are observed in the south-eastern areas of Bangladesh. In May, positive trends are found in the northern and eastern zones, while negative trends are observed in the southwestern and southern parts of Bangladesh. Except for the eastern part, both times exhibit a negative trend pattern in June and July. In August, a positive trend is observed in the southwestern zone (2.01 ~ 0.08). In September, the north-eastern part of Bangladesh follows a positive trend (5.11 ~ 0.56) at 0000 UTC, while the eastern and north-western zones show a positive increasing trend (15.53 ~ 26.02) at 1200 UTC. In October, a positive trend was observed in the southern part of Bangladesh (12.02 ~ 1.51) at 0000 UTC and in the eastern zone at 1200 UTC. In November, a negative trend covers most of Bangladesh, while from November to February, a similar pattern of positive trend is observed throughout Bangladesh.

The higher positive trend of CAPE value is observed in April, which is more prominent in the north-western part, and in October during post-monsoon. The higher negative trend is depicted in May of pre-monsoon, which is prominent at 1200 UTC over Bangladesh's southern and southwestern portions. Most CAPE increments can be associated with temperature or moisture increases, leading to more condensation and latent heating for the lifted parcel above the LFC and slower cooling as the parcel ascends. The circulation of southerly low-level jet (LLJ) carries moisture content from the Bay of Bengal to the plains of Bangladesh, and the adjoining areas may lead to higher CAPE values.

3.3 Seasonal variation of CAPE

The seasonal variations of CAPE values in Bangladesh were examined at 0000 UTC and 1200 UTC. Pre-monsoon had the highest CAPE values ranging from 600–3000 J/kg and 600–2400 J/kg at 0000 UTC and 1200 UTC, respectively, with the southern part of Bangladesh having the most prominent values due to higher moisture content. The formation of thunderstorms during this season can be attributed to the higher CAPE values, which peak in April. Yamane and Hayashi (2006) showed that CAPE is high during the pre-monsoon season, with a peak in April.

CAPE values decrease from pre-monsoon to post-monsoon, ranging from 3000 J/kg to 800 J/kg in the southern region and 600–1500 J/kg in the northern region during pre-monsoon. Winter had the least CAPE values, ranging from 20–120 J/kg, which is insufficient for thunderstorm formation. The low-level pressures in the Bay of Bengal move towards the central part of the country, causing severe thunderstorms. In monsoon, the northern region of Bangladesh shows the CAPE range from 200–800 J/kg at 0000 UTC, and the western zone of Bangladesh shows a good amount of CAPE values (800 ~ 1200 J/kg) at 1200 UTC. The sea surface temperature gradients control the Bay of Bengal by creating low-level pressure gradients. Wahiduzzaman et al. (2022) observed that the opportunity for thunderstorms to form in Bangladesh is low in winter due to low humidity.

3.4 Seasonal trends of CAPE over eight divisions

This section shows the results of the seasonal trend analysis of the CAPE (J/kg) of eight divisions of Bangladesh. Mann-Kendall test has been employed to follow the seasonal trends using ERA5 data for 40 years (1982–2021) at 0000 UTC and 1200 UTC.

3.4.1 Barisal division

The seasonal Mann-Kendall trends of Barisal at 0000 UTC and 1200 UTC have been illustrated in Supplementary Figure S1 (a) and (b), respectively. The negative trend (-14.12 ~ -19.21) is dominant all over Barisal at 1200 UTC, with higher decreasing trends observed (refer to Supplementary Figure S1 (b)). During the pre-monsoon season, a negative trend is observed throughout Barisal at 0000 UTC, while at 1200 UTC, it covers all areas except the north-western region. In the monsoon season, an increasingly negative trend is found in the northern region of Barisal at 0000 UTC, while at 1200 UTC, it is observed in the north-eastern part, with a negative decreasing trend in the southwestern region. In post-monsoon, a positive trend (-0.09 ~ 0.14) is dominant in most areas of Barisal at 0000 UTC, indicating the possibility of thunderstorm events. At 1200 UTC, the eastern part of Barisal has a decreasing trend, while the north-western part exhibits a positive trend (2.12 ~ 3.88). In winter, an increasing trend (-0.09 ~ 0.14) is observed at 0000 UTC, and a negative trend is dominant throughout the Barisal division at 1200 UTC. The southern portion of Bangladesh displays higher CAPE values due to a significant depression in the region.

3.4.2 Chattogram division

Chattogram, located on the south-eastern coast of Bangladesh, experiences higher CAPE values due to good moisture, creating a conducive environment for thunderstorms. The Mann-Kendall trend analysis indicates varying trends in CAPE values during different seasons and times of the day. The eastern region of Chattogram has a higher decreasing trend at 1200 UTC, while the southern and northern regions have an increasingly negative trend during pre-monsoon. In monsoon, the higher increasing trend is observed at 1200 UTC, and in post-monsoon, the increasing trend is highly prominent except in the southern tip, close to the Bay of Bengal. Winter sees an increasing trend, excluding the southern zone at 0000 UTC, while 1200 UTC has a highly dominant increasing trend all over Chattogram. Supplementary Figure S2 shows the trends in detail. The Mann-Kendall trend values for CAPE at Chattogram vary for different seasons and times of the day. At 0000 UTC, the negative trend ranges from – 6.45 to -2.36 in the eastern Chattogram division during pre-monsoon and – 3.94 to -1.03 in the central Chattogram division during monsoon. In post-monsoon, the increasing trend ranges from – 1.16 to 3.60, and in winter, it is generally increasing, except for the southern zone. At 1200 UTC, the decreasing trend ranges from 0.35 to -2.08 in the southern Chattogram tip during post-monsoon and – 14.08 to -19.22 in the central Chattogram zone during pre-monsoon. In monsoon, the increasing trend ranges from 2.57 to 7.15 over the eastern region of Chattogram, while in post-monsoon, the increasing trend ranges from 7.99 to 14.49 in the eastern part.

3.4.3 Dhaka division

The seasonal Mann-Kendall trends of Dhaka at 0000 UTC and 1200 UTC have been illustrated in Supplementary Figure S3 (a) and (b), respectively. In the pre-monsoon season, the negative trend (-7.14 ~ -4.81) has been observed at the central zone of Dhaka, and the southern and northern parts of Dhaka have followed the decreasing trend (-7.91 ~ -10.20) at 0000 UTC (refer to Supplementary Figure S3 (a)), whereas at 1200 UTC, the decreasing trend (-4.27 ~ -11.70) of CAPE is prominent in most of the areas of Dhaka division except the western part (refer to Supplementary Figure S3 (b)). Afroz et al. (1981) reported that nor'wester occurred most frequently in Dhaka during the pre-monsoon season. In monsoon, the negative trend (-1.45 ~ -0.32) has been projected in most parts of Dhaka except the southern zone at 0000 UTC, whereas at 1200 UTC, the increasing trend (-2.43 ~ -1.53) is dominant over the central part of Dhaka. During post-monsoon season, the positive trend (2.03 ~ 4.12) has been found in central Dhaka at 0000 UTC. At 1200 UTC, CAPE has followed a positive trend (2.74 ~ 1.62) in most regions of Bangladesh during post-monsoon and winter. The eastern zone has an increasing trend (0.10 ~ 0.22) and a decreasing trend in Dhaka's western zone at 0000 UTC in winter.

3.4.4 Mymensingh division

The seasonal Mann-Kendall trends of Mymensingh at 0000 UTC and 1200 UTC have been illustrated in Supplementary Figure S4 (a) and (b), respectively. A decreasing trend has been observed over Mymensingh, the north-eastern part of Bangladesh. Most of Mymensingh's areas have a negative trend (-8.09 ~ -6.26) of CAPE, and the north-western zone has an increasing trend (-8.70 ~ -10.40) at 0000 UTC, whereas at 1200 UTC, the increasing trend (0.76 ~ 6.52) has been found in the northern part of Mymensingh and decreasing trend (-1.15 ~ -6.89) in the eastern part during pre-monsoon. Karmakar and Alam (2007) mentioned that the frequency of nor'westers in Bangladesh usually reaches its maximum in

May, having maximum value over the Mymensingh and Dhaka division. The monsoon shows an increasing CAPE trend (-1.48 ~ -0.78) in the western and eastern parts of Mymensingh at 0000 UTC, whereas, at 1200 UTC, the increasing trend is highly projected over the northern zone. Nor'wester activities in these parts of the region are directly linked with the sun's apparent movement towards the north, causing a steady rise in temperature over southern India and Bangladesh and gradually extending to the north. At 1200 UTC, the positive trend (4.47 ~ 5.68) has maintained a similar trend over the north-western region in the post-monsoon season. At 0000 UTC, the positive trends (1.95 ~ 0.37) are similarly dominant over most post-monsoon areas, like the pre-monsoon period. In winter, the increasing trend has been observed in the north-eastern part of Mymensingh at 0000 UTC (refer to Supplementary

Figure S4 (a)), and the north-western region has a decreasing trend (0.13 ~ 0.00) of CAPE in Mymensingh at 1200 UTC (refer to Supplementary Figure S4 (b)).

3.4.5 Khulna division

Supplementary Figure S5 (a) and (b) show Khulna seasonal Mann-Kendall trends at 0000 UTC and 1200 UTC. Khulna's higher decreasing Mann-Kendall trend was seen at 0000 UTC (Supplementary Figure S5 (a)). Around 0000 UTC in pre-monsoon, the western half of Khulna had a negative CAPE trend (-6.90 ~ -3.71) due to moisture from the Bay of Bengal, while by 1200 UTC, the northern and southern parts had increasing (-1.89 ~ 7.53) and decreasing (-5.04 ~ -14.41) trends, respectively. In monsoon, the negative trend (-6.28 ~ -2.06) dominates Khulna. At 0000 UTC, CAPE values in Khulna are forecast to decrease (-6.29 ~ -9.45), but around 1200 UTC, the trend has increased (-3.35 ~ -0.56) in most parts of the region during monsoon season. During monsoons, CAPE values are more significant in Bangladesh's southwest. Post-monsoon and winter CAPE trends also decrease. At 1200 UTC after the monsoon, Khulna's central zone showed a decreasing trend (1.59 ~ -0.93). This region has grown in winter. During 0000 UTC in winter, Khulna has a more significant Mann-Kendall trend of CAPE values. Karmakar et al. (2015) explained that near Khulna, the southwesterly wind meets the moderate north-northeasterly wind, generating a discontinuous line of moist air from the south and dry air from the northeast.

3.4.6 Sylhet division

Sylhet seasonal Mann-Kendall trends at 0000 UTC and 1200 UTC are shown in Supplementary Figure S6 (a) and (b). Bangladesh's north-eastern Sylhet has decreased. In pre-monsoon season, Sylhet's western zone has a falling CAPE trend (-7.77 ~ -9.55), while the eastern half has an increasing trend (-7.16 ~ -5.38) at 0000 UTC. By 1200 UTC, most of Sylhet has an increasing CAPE trend (-7.57 ~ -5.14). At 0000 UTC, the negative CAPE trend (-1.12 ~ -1.88) is maintained in central Sylhet except for the eastern part, but at 1200 UTC, it has spread throughout the region. Post-monsoon, a similar pattern of decreasing CAPE trend (1.30 ~ 0.05) has been observed at the central zone of Sylhet, and the increasing trend (1.71 ~ 2.96) has profound values in the western part at 0000 UTC, while the positive decreasing form (4.71 ~ 2.39) of CAPE has been observed all over Sylhet at 1200 UTC. Except for the southwest at 0000 UTC, Sylhet has shown a decreasing trend in winter (Supplementary Figure S6 (a)). CAPE's growing trend (0.19 ~ 0.32) has been projected throughout Sylhet except for the southern section in winter at 1200 UTC.

According to Ohsawa et al. (2000) and Hatsuzuka et al. (2014), southwesterly winds transport warm moisture from the Bay of Bengal to the Meghalaya Plateau. Deep convection and cyclonic activity over the Indian Ocean and the Bay of Bengal move enormous vapour-saturated air masses across Meghalaya, causing Sylhet's maximum rainfall.

3.4.7 Rajshahi division

Rajshahi seasonal Mann-Kendall trends at 0000 UTC and 1200 UTC are shown in Supplementary Figure S7 (a) and (b). Around 1200 UTC in pre-monsoon, Rajshahi had a more significant Mann-Kendall trend (Supplementary Figure S7 (b)). In the pre-monsoon Rajshahi western zone at 0000 UTC, CAPE has increased (-3.35 ~ 0.33) (Supplementary Figure S7 (a)). In pre-monsoon Rajshahi, CAPE is positive (6.39 ~ 11.00) at 1200 UTC (Supplementary Figure S7 (b)). Rabbani et al. (2021) observed that the low-pressure system covered western India and Bangladesh and was connected with thunderstorms. At 0000 UTC, the eastern region has an increasing CAPE trend (-1.58 ~ -0.65), whereas, at 1200 UTC, the south-eastern part of Rajshahi has a negative CAPE trend (-1.45 ~ -2.83). In post-monsoon season, the Rajshahi CAPE trend (2.66 ~ 1.25) decreased everywhere except the western zone at 0000 UTC, and by 1200 UTC, it increased in the north and decreased in the south. The growing trend (0.01 ~ 0.09) has predicted positive values in the northern zone of Rajshahi at 0000 UTC, while the declining CAPE trend (-0.06 ~ -0.13) is present in the southwestern zone at 1200 UTC. The synoptic surface and upper air circulations with troughs stretched eastward up to northwest Bangladesh were favourable for a thunderstorm with moderately heavy to heavy rainfall over Rajshahi, according to Karmaker et al. (2018).

3.4.8 Rangpur division

The seasonal Mann-Kendall trends of Rangpur at 0000 UTC and 1200 UTC are shown in Supplementary Figure S8 (a) and (b). Northern Bangladesh's Rangpur is decreasing. In pre-monsoon at 0000 UTC, the western portion of Rangpur has an increasing CAPE trend (-3.72 ~ -1.35), while the eastern part has a decreasing trend (-4.52 ~ -6.88). The northern portion of the region has a decreasing CAPE trend (3.36 ~ 0.60), while the southern section has an increasing CAPE trend (4.28 ~ 7.04) around 1200 UTC during the pre-monsoon season. At 0000 UTC, the decreasing CAPE trend (-2.63 ~ -3.70) has been well displayed in most regions of Rangpur in monsoon, but at 1200 UTC, the increasing CAPE trend (-1.03 ~ -0.09) has been noticed in some locations. During the post-monsoon season at 0000 UTC, CAPE (2.62 ~ 0.29) has decreased throughout Rangpur. In post-monsoon, the positive CAPE trend (4.57 ~ 6.51) is quite evident all over Rangpur at 1200 UTC, and in winter, the CAPE trend has continued the growing tendency in most parts of Rangpur except the south (refer to Supplementary Figure S8 (b)). In winter, Rangpur's northern foothills have an increasing trend (0.11 ~ 0.15) at 0000 UTC.

3.5 Seasonal temporal changes of CAPE over eight divisions

Figure 5 and 6 show the temporal changes and box plots of CAPE (J/kg) over eight divisions of Bangladesh for 40 years (1982–2021) at 0000 UTC and 1200 UTC, respectively, in (a) Pre-monsoon, (b) Monsoon, (c) Post-monsoon, and (d) Winter season. The variation of the highest CAPE value was found for Barisal among the eight divisions in pre-monsoon at 0000 UTC with a maximum CAPE value in 1997, and the variation of the highest CAPE value was found in Chattogram at 1200 UTC. The range of the CAPE values varies from 578–2224 J/kg for Barisal at 0000 UTC, with a median value of approximately 1174 J/kg. The maximum CAPE value has been found for Chattogram among the eight divisions, with CAPE values varying approximately from 321–1618 J/kg at 1200 UTC with a median value of 830 J/kg. The variation of lowest CAPE values is found for Rangpur among the eight divisions at 0000 UTC and 1200 UTC in pre-monsoon with CAPE values ranging approximately from 4-366 J/kg and 3-265 J/kg at 0000 UTC and 1200 UTC, respectively.

In monsoon, Barisal had the highest CAPE value at 0000 UTC, the maximum in 2009, while Dhaka had the highest at 1200 UTC, the maximum in 1998. Sylhet had the lowest CAPE values variation at 0000 UTC and 1200 UTC monsoon in 40 years. Barisal's CAPE ranges from 574–3070 J/kg in monsoon, with a median value of 1562 J/kg at 0000 UTC. Marioum et al. (2022) suggested that thunderstorms require a CAPE value larger than 1500 J/kg; hence Barisal's CAPE range has the highest probability of thunderstorms. Sylhet and Rangpur had the lowest CAPE values in winter at 0000 UTC, with Sylhet ranging from 177–1071 J/kg and Rangpur from 177–979 J/kg. Dhaka has the highest monsoon CAPE value of 605–2627 J/kg at 1200 UTC, with a median value of 1386 J/kg. The lowest CAPE value was 426–1184 J/kg at Sylhet.

At 0000 UTC, the Barisal division had the highest CAPE value post-monsoon. Rajshahi has the most significant CAPE fluctuation at 1200 UTC. 1988 saw Rajshahi's highest CAPE. The Sylhet division's lowest CAPE value has varied in 40 years at 0000 and 1200 UTC. At 0000 UTC, Barisal has the highest CAPE value, ranging from 449–1511 J/kg, and Sylhet has the lowest, 130–589 J/kg. At 1200 UTC, Rajshahi has the highest, 526–1736 J/kg, and Khulna the lowest, 416–1420 J/kg.

During 0000 UTC and 1200 UTC in the 2012 winter season, the Barisal and Chattogram divisions had the highest CAPE values. Khulna and Sylhet have had the lowest CAPE values at 0000 and 1200 UTC for several years, respectively. At 0000 UTC in winter, Khulna has the highest CAPE value of 0–41 J/kg, while Sylhet has the lowest at 0–23 J/kg. At 1200 UTC in winter, Mymensingh has a maximum CAPE value of 0–40 J/kg, whereas Rangpur has a minimum of 0–22 J/kg.

Barisal's CAPE values are highest pre-, mid-, and post-monsoon. High depressions have plagued the southern coastal region of Bangladesh from March to May, resulting in increased CAPE values in these areas for several days because of this factor. This increased CAPE drives Southcentral Bangladesh's convective occurrences. Barisal and Chattogram in Bangladesh's southeast have the highest CAPE values.

Rangpur and Sylhet CAPE values are the lowest. Sylhet has the lowest post-monsoon and monsoon CAPE values. According to Choudhury et al. (2012), the Shillong/Meghalaya Plateau in northeast Bangladesh blocks Sylhet's southerly or southwesterly monsoon wind. According to Murugavel et al. (2014), high CAPE values alone do not cause thunderstorms. The region's orography and weather conditions are critical since they supply moisture and trigger air convection. Mountaintop radiative cooling at night can cause convective activity in the foothills.

3.6 Seasonal temporal changes of CAPE over three lightning hotspots

Figure 7 presents the temporal changes of seasonal CAPE for three lightning hotspots in Bangladesh, (i) Bajitpur, (ii) Sherpur, and (iii) Shahjadpur. The highest CAPE value was observed for three hotspots at 0000 UTC in 1985 and similarly found for Bajitpur in 1985 at 1200 UTC in pre-monsoon. Sherpur received the highest CAPE value in 2010, and Shahjadpur showed the highest value of CAPE was found in 2003 at 1200 UTC during pre-monsoon. The highest CAPE value was found in 2009 for three hotspots at 0000 UTC and observed for three hotspots in 1998 at 1200 UTC in the monsoon season. The highest CAPE value was found for Sherpur and Shahjadpur in 1988 at 0000 UTC and 1996 at 1200 UTC during post-monsoon season. Bajitpur presented the highest value in 1983 and 2005 at 0000 UTC and 1200 UTC, respectively. In winter, Bajitpur and Sherpur gave the high CAPE value in 2012, whereas Sherpur showed the highest value in 1992 at 0000 UTC. During the winter season at 1200 UTC, the highest CAPE value for Sherpur, Bajitpur, and Shahjadpur was observed in 1993, 2000, and 2012, respectively.

Table 1 shows that the highest CAPE value of 2644 J/kg has been observed in Shahjadpur during the pre-monsoon at 0000 UTC, whereas Sherpur presents the highest CAPE values in monsoon at 0000 UTC and 1200 UTC. Sherpur and Shahjadpur are situated in the north-western region of Bangladesh. The average CAPE values for Bangladesh’s three lightning hotspot regions (Sherpur, Shahjadpur, and Bajitpur) is higher than 1500 J/kg during the pre-monsoon at 0000 UTC, which directly correlates with the lightning and thunderstorm (refer to Table 1). Karmakar et al. (2017) showed that a low-pressure zone prevails over Bihar and adjoining areas extending its trough to the western part of Bangladesh, which is advantageous for the occurrence of severe thunderstorms. Das et al. (2015) showed the presence of a subtropical jet stream with strong vertical wind shear in the low to mid-troposphere over Bangladesh, leading to the development of severe convection through Nor’westers in the north-western region.

Table 1
Convective Available Potential Energy (J/kg) observation for three lightning hotspots in Bangladesh (Bajitpur, Sherpur, and Shahjadpur) at 0000 UTC for 40 years.

Station	Latitude	Longitude	CAPE Pre-Monsoon (J/kg)	CAPE Monsoon (J/kg)	CAPE Post-Monsoon (J/kg)	CAPE Winter (J/kg)	FRD (fl/km^2 yr)
Bajitpur	24.25	90.95	1548.348	453.286	589.552	30.142	62.11
Sherpur	25.25	89.85	1629.667	605.054	408.567	7.582	82.95
Shahjadpur	24.15	89.55	2643.857	526.126	495.272	0.189	54.17

Table 2 shows that the highest CAPE has been found in Bajitpur during pre-monsoon 1200 UTC. Bajitpur is situated in the north-eastern zone. Chaudhuri and Middey (2013) explained that the northern and north-eastern parts of Bangladesh are dominated by moderate terrain, and orographic lifting concerning complex terrain could initiate conditional instability of the atmosphere, favouring the development of thunderstorm-mediated lightning during the pre-monsoon period. Barros et al. (2004) found that the topography of the land surface can significantly change the convective motions in the atmosphere and thus influence thunderstorm formation in that region.

Table 2
Convective Available Potential Energy (J/kg) observation for three lightning hotspots in Bangladesh (Bajitpur, Sherpur, and Shahjadpur) at 1200 UTC for 40 years.

Station	**Latitude**	**Longitude**	**CAPE Pre-Monsoon (J/kg)**	**CAPE Monsoon (J/kg)**	**CAPE Post-Monsoon (J/kg)**	**CAPE Winter (J/kg)**	**FRD (fl/km^2 yr)**
Bajitpur	24.25	90.95	1606.059	775.853	731.611	12.511	62.11
Sherpur	25.25	89.85	1083.865	1004.834	545.465	2.920	82.95
Shahjadpur	24.15	89.55	1169.545	969.908	491.104	6.250	54.17

3.7 Annual and seasonal variation difference of CAPE over Bangladesh

Seasonal variation of CAPE (J/kg) over Bangladesh for five-year averages of 1982–1986, 2017–2021, and their difference at 0000 UTC and 1200 UTC have been illustrated in Fig. 8 (I) and (II), respectively. The annual variations of CAPE (J/kg) for the five-year average of (i) 1982–1986 are higher than the CAPE values of the later five years (ii) 2017–2021 at 0000 UTC. The (b) difference in CAPE (J/kg) is significant during the pre-monsoon season, indicating that CAPE values were higher during (iii) 1982–1986 than the CAPE values during (iv) 2017–2021 at 0000 UTC. In monsoon, CAPE (J/kg) was moderately higher during (v) 1982–1986 than the CAPE (J/kg) during (vi) 2017–2021 at 0000 UTC. The distinct CAPE values from (viii) 2017–2021 are more prominent all over Bangladesh than the changes from (vii) 1982–1986 in post-monsoon at 0000 UTC. The transitions between the CAPE values of (ix) 1982–1986 and (x) 2017–2021 resemble each other in winter at 0000 UTC.

The annual variations of CAPE (J/kg) for the five-year average of (i) 1982–1986 are neutral to the CAPE values of the later five years (ii) 2017–2021 at 1200 UTC. The (b) difference in CAPE is significant during the pre-monsoon season, indicating that CAPE values were higher during (iii) 1982–1986 than (iv) 2017–2021 at 1200 UTC. In the monsoon season, the (c) difference in CAPE values is positive all over Bangladesh, indicating that CAPE (J/kg) was comparatively higher duration (v) 1982–1986 than (vi) 2017–2021 at 1200 UTC. The distinct CAPE values from (viii) 2017–2021 are more prominent all over

Bangladesh than the changes from (vii) 1982–1986 during post-monsoon at 1200 UTC. The (e) difference in CAPE (J/kg) is presented with no drastic changes between (ix) 1982–1986 and (x) 2017–2021 during winter at 1200 UTC.

The long-time changes in CAPE can affect the rainfall distribution pattern. DeMott et al. (2004) showed that the long-term changes in CAPE are associated with changes in convective activity and rainfall. Zheng et al. (2016) suggested that convection intensifies progressively from the pre-monsoon to the monsoon continued to the post-monsoon periods, which primarily agrees with variations in the CAPE and total precipitable water. The distinct changes in CAPE value are prominent in the post-monsoon at 0000 UTC and 1200 UTC (refer to plots (d) of Fig. 8 (I) and (II)), as negative CAPE values are seen all over Bangladesh, indicating that CAPE (J/kg) was comparatively higher duration (viii) 2017–2021 than (vii) 1982–1986 at both 0000 UTC and 1200 UTC. These long-term changes may contribute to the variation of convective activity, such as rainfall variation with CAPE. The deep convection and related rainfall extremes are triggered by available moisture content and temperature effects on atmospheric stability. The complex interplay of topography, moisture transport, wind shear, and temperature leads to the formation of deep convection that results in extreme rainfall.

3.8 Decadal variation of CAPE over eight divisions of Bangladesh

Figure 9 (i) and (ii) show the decadal variation of CAPE (J/kg) over eight divisions of Bangladesh at 0000 UTC and 1200 UTC for 40 years. 2002–2011 has the highest values of CAPE variation for pre-monsoon and monsoon seasons across all eight divisions, while 2012–2021 has the highest variation in CAPE for the post-monsoon season at 0000 UTC. The most significant changes in CAPE have been observed during the decade 2012–2021 in winter. The Chattogram division has the highest CAPE variation in the pre-monsoon season, while the Rangpur division has the lowest. Similarly, the highest and lowest CAPE values are observed in the monsoon season in the Barisal and Khulna division, respectively. At 1200 UTC during the post-monsoon season, the decade 2012–2021 has the highest CAPE variation. The most significant changes in CAPE have been observed for 2012–2021 in winter.

A significant variation of CAPE (J/kg) was projected in 2002–2011 and 2012–2021 from pre-monsoon to winter. This represents the increasing trend of the CAPE values in the long-term changes with various climate-related factors. The variation of the highest value has been found in Barisal and Chattogram. Barisal is located in the southern part, in which monsoon season in Bangladesh prevails with southerly winds from the Bay of Bengal. Chattogram is situated in the southeast coastal region and on the windward side of the hills, which is considered the entry and exit point of the summer monsoon flux. Dudhia (1989) suggested that the land breeze-related convergence by differential cooling of the ocean and surface cooling produced convection near the coast.

3.9 Monthly climatology of CAPE for 40 years (1982–2021)

The monthly climatology comparison of Convective Available Potential Energy (J/kg) at 0000 UTC and 1200 UTC over the eight divisions of Bangladesh for 40 years (1982–2021) have been illustrated in Fig. 10. The highest annual CAPE values are depicted at 0000 UTC and 1200 UTC for 40 years in May, which is the pre-monsoon season all over Bangladesh, exceeding the range of standard CAPE value (> 1500 J/kg) for the formation of thunderstorms.

The pre-monsoon season in Bangladesh is the transition period between the northerly or north-westerly winds of the winter monsoon and the southerly winds of the summer monsoon, where the supply of moist air from the Bay of Bengal can influence the activity of thunderstorm events during the pre-monsoon season. The highest CAPE values for 40 years have been found in the Barisal division in April at 0000 UTC. The southwest and southern part of Bangladesh represent the highest range of CAPE values in pre-monsoon. This part is surrounded by water bodies, specifically the Bay of Bengal, which circulates sufficient moisture flow. The surface temperature and convective process influence this seasonal transition through the southerly wind through the moisture content and atmospheric buoyancy. Similar observations for higher CAPE values have been projected in May for Dhaka, Chattogram, Barisal, and Khulna at 1200 UTC. The lowest CAPE values are presented for May in the Rangpur division at 0000 UTC and 1200 UTC.

4 Summary and conclusion

This study uses monthly, seasonal, and annual time series data to investigate the climatology of CAPE over Bangladesh and its eight administrative divisions, along with three lightning hotspots (Sherpur, Shahjadpur, and Bajitpur). The monthly CAPE data at 0000 UTC and 1200 UTC for 40 years (1982–2021) has been collected from ERA5 at 0.25° resolution. The study indicates that the escalating CAPE trend in Bangladesh may be accountable for the increased frequency of catastrophic events. This research will help to improve lightning and thunderstorm forecasts in Bangladesh. The study's primary findings are:

- Owing to significant ground heating, CAPE increases from March to May and declines during the monsoon. CAPE is 600–3400 J/kg at 0000 UTC and 600–2600 J/kg at 1200 UTC, as moisture availability is crucial in CAPE development. In the morning, the relative humidity is typically higher due to overnight cooling and the presence of dew or fog. The moisture content contributes to the instability of the atmosphere, enhancing CAPE values. However, as the day progresses and temperatures rise, the relative humidity may decrease, leading to a reduction in CAPE during the evening hours. It's important to note that local topography, land-sea breeze circulation patterns, and other regional atmospheric dynamics may influence the specific diurnal variation of CAPE in Bangladesh. Bangladesh's southwest and southern regions bordering the Bay of Bengal have the highest CAPE, which spreads to the northwest over Bangladesh and may create thunderstorms during this time. Every month except for November through February, CAPE levels are high and affect Bangladesh. From July to October, CAPE levels in Bangladesh are relatively consistent.
- The CAPE falls across most of Bangladesh in March, except for a small portion of the north-western zone at 0000 UTC and the south-eastern zone at 1200 UTC. This is the changeover in Bangladesh's

climate system. In April, the CAPE value climbed between 0000 UTC (0.97 ~ 12.44) and 1200 UTC (4.32 ~ 25.10), particularly in the northwest. After the monsoon, Bangladesh observed a more significant increase in October. Due to insolation and the entrance of moisture, the atmosphere became unstable between midday and midnight, increasing both values. In the pre-monsoon month of May, Bangladesh's southern and southwestern parts have a more significant decreasing trend (-13.6 ~ -24.57) at 1200 UTC. During May, as the region transitions from winter to summer, there is a gradual increase in stability in the atmosphere. This is due to the gradual warming of the lower atmosphere and the associated decrease in the vertical temperature gradient. The stability suppresses the development of convection and limits energy availability for thunderstorm development, resulting in a decreasing tendency of CAPE values.

- In southern Bangladesh, pre-monsoon CAPE values are highest between 0000 and 1200 UTC due to higher moisture content. In southern Bangladesh, pre- and post-monsoon CAPE values range from 3000 to 800 J/kg. In winter, Bangladesh has the lowest CAPE levels (20 ~ 120 J/kg) around 0000 UTC and 1200 UTC, which inhibits the production of thunderstorms.
- Most post-monsoon Barisal has a positive increasing trend (1.54 ~ 3.08) at 0000 UTC, indicating thunderstorms. The southern portion of Bangladesh displays higher CAPE values due to a significant depression in the region. Barisal and eastern Chattogram had the steepest dropping Mann-Kendall trend at 1200 UTC (Supplementary Figures S1 (b) and S2 (b)). CAPE predominates Chattogram except for the southernmost tip near the Bay of Bengal. Post-monsoon, the CAPE has an upward trend (-1.16 ~ 3.60) everywhere in Chattogram besides the southernmost point, near the Bay of Bengal, at 0000 UTC. At 0000 UTC during the winter, the CAPE trend increases everywhere except for the southern zone of Chattogram; but by 1200 UTC, it dominates the entire region. Chattogram contains nearly one-third of Bangladesh's coastline. This region's moisture increases CAPE values, hence encouraging thunderstorms.
- The monsoon indicates a rising CAPE trend (-1.48 ~ -0.78) in Mymensingh's western and eastern parts at 0000 UTC, whereas, at 1200 UTC, the increasing trend is highly projected over the northern zone. The sun's apparent voyage north produces a steady rise in temperature over Southern India and Bangladesh, which gradually extends to the north as the frequency of nor'westers in Bangladesh typically peaks in May over the Mymensingh and Dhaka division. Mymensingh, Sylhet, and Rangpur are towns in north-eastern Bangladesh. Around 0000 UTC in the winter, the northern Himalayan foothills of Rangpur are predicted to rise (0.11 ~ 0.15).
- During the pre-monsoon season, CAPE has increased in the western half of Khulna at 0000 UTC due to moisture from the Bay of Bengal; nevertheless, by 1200 UTC, the northern half has climbed (-1.89 ~ 7.53), whereas the southern half has fallen (-5.04
- ~ -14.41). In the southwest of Bangladesh, monsoon CAPE levels are higher. Post-monsoon and winter CAPE decline as well. After the monsoon, the entire central zone of Khulna showed a downward trend (1.59 ~ -0.93) at 1200 UTC. This winter region is expanding. Winter CAPE levels are higher at 0000 UTC in Khulna. Barisal's CAPE values were highest at 0000 UTC, whereas Chattogram's were highest at 1200 UTC. The local topography of the Barisal and Chattogram can

impact the timing of the highest CAPE values. Barisal is located more inland and may experience less influence from coastal processes, such as sea breezes. The absence of a strong sea breeze circulation can delay the development of convective instability, leading to higher CAPE values at 0000 UTC. Chattogram, located along the coast, is more influenced by maritime air masses and the land-sea breeze circulation. The daytime heating and sea breeze convergence can enhance atmospheric instability and increase CAPE values by around 1200 UTC. Barisal had the highest CAPE value during monsoon at 0000 UTC in 2009, while Dhaka had the highest at 1200 UTC in 1998. Since thunderstorms require a CAPE value of more than 1500 J/kg, Barisal has the highest probability of thunderstorms. Sylhet exhibited the lowest CAPE value variation between 0000 UTC and 1200 UTC during the monsoon and post-monsoon for the past 40 years. At 0000 UTC, winter CAPE is lowest in Sylhet and Rangpur. During the 2012 winter season, the Barisal and Chattogram divisions had the highest CAPE values at 0000 and 1200 UTC. During numerous winters, Khulna has had the lowest CAPE value at 0000 UTC, whereas Sylhet and Rajshahi have had the lowest value at 1200 UTC.

- The pre-monsoon and post-monsoon CAPE values are highest for Barisal. The high depressions are very prominent in the pre-monsoon period (March-May) over the southern coastal part of Bangladesh. The existence of this factor for several days resulted in higher CAPE over these parts of the country. This enhanced CAPE is the reason for the meteorological driving force for the occurrence of convective events over southcentral Bangladesh. Barisal and Chattogram have the highest CAPE values in southern Bangladesh. Sylhet has the lowest CAPE during and after the monsoon season. Thunderstorms cannot be solely attributed to high CAPE values, as the interplay of orographic effects, climatic conditions, and moisture availability in the region serves as crucial catalysts for initiating air convection. Radiative cooling of mountaintops at night can generate convection in foothills.
- The average CAPE values for Bangladesh’s three lightning hotspot regions (Sherpur, Shahjadpur, and Bajitpur) is higher than 1500 J/kg during the pre-monsoon at 0000 UTC, which directly correlates with the lightning and thunderstorm (refer to Table 1). Sherpur and Shahjadpur recorded the highest CAPE values after the monsoon in 1988 at 0000 UTC and 1996 at 1200 UTC. Bajitpur hotspot presented the highest value in 1983 and 2005 at 0000 UTC and 1200 UTC, respectively. In winter, Bajitpur and Sherpur presented the high CAPE value in 2012, whereas Sherpur showed the highest value in 1992 at 0000 UTC. During the winter season at 1200 UTC, the highest CAPE value for Sherpur, Bajitpur, and Shahjadpur was observed in 1993, 2000, and 2012, respectively. As a city in the north-eastern region of Bangladesh with moderate terrain, orographic lifting across complex topography may produce atmospheric instability, hence increasing thunderstorm-mediated lightning during the pre-monsoon season.
- The Post-monsoon CAPE values fluctuate considerably between 0000 UTC and 1200 UTC (refer to plots (d) of Fig. 8 (I) and (II)), as negative CAPE values are observable throughout Bangladesh, indicating that CAPE (J/kg) was the much greater length (viii) 2017–2021 than (vii) 1982–1986 at both 0000 and 1200 UTC. Long-term changes may influence convective activity, such as precipitation reliant on CAPE. Moisture and temperature effects on air stability result in heavy

convection and precipitation. Due to geography, moisture movement, wind shear, and temperature, deep convection creates considerable precipitation.

- During the pre-monsoon and monsoon seasons, 2002–2011 had the highest CAPE variation of eight divisions, whereas 2012–2021 at 0000 UTC had the most in post-monsoon. During the pre-monsoon season, the CAPE variation was highest in Chattogram and lowest in Rangpur. During the monsoon season, Barisal and Khulna's CAPE variance was highest. Several climate-related causes contributed to a rise in the pre-monsoon to winter CAPE values in 2002–2011 and 2012–2021. Barisal is located in the south, where the monsoon season in Bangladesh is dominated by southerly winds from the Bay of Bengal, and Chattogram is situated in the southeast coastal region and on the windward side of the hills, where the summer monsoon flux arrives and departs.
- The highest yearly CAPE values have occurred at 0000 UTC and 1200 UTC in May, the pre-monsoon season in Bangladesh, above the usual CAPE value (> 1500 J/kg) for thunderstorm generation throughout the past four decades (refer to Fig. 10). April at 0000 UTC saw Barisal's most incredible CAPE levels in forty years. Bangladesh's southwest and southern regions have the most significant pre-monsoon CAPE values, where this region receives enough moisture from the Bay of Bengal. This seasonal shift is influenced by moisture and atmospheric buoyancy via the southerly wind, surface temperature, and convection. Dhaka, Chattogram, Barisal, and Khulna predict higher CAPE values in May at 1200 UTC. May has the lowest CAPE values in Rangpur at 0000 and 1200 UTC.

Bangladesh is impacted by climate variables such as temperature, precipitation, humidity, and air pressure to a greater extent than most other nations. Bangladesh could see an increase in thunderstorms. The Numerical Weather Prediction (NWP) study using the Weather Research and Forecasting (WRF) model can track the relationship between Convective Available Potential Energy (CAPE) and other atmospheric variables that influence thunderstorms in the future as a continuation of this work. Analyses of thunderstorm events' physical and kinetic properties are necessary for improved forecasting. The convective system's thermodynamic indices can be analyzed to research extreme weather events.

Declarations

Acknowledgement

The first author (S.S.K.) gratefully acknowledges the Indian National Science Academy (INSA) for support through the Indian Science & Research Fellowship (ISRF) programme (Ref. No. INSA/DST-ISRF/2022). The manuscript is the outcome of her visit to the Department of Atmospheric Science, School of Earth Sciences, Central University of Rajasthan, India, during the period from June 2022 to December 2022. The first author also acknowledges Daffodil International University, Dhaka, Bangladesh, and the Department of Atmospheric Science, Central University of Rajasthan, Rajasthan, India, for all the academic and administrative support to engage in research. Authors gratefully acknowledge ECMWF for ERA-5 reanalysis data for this study. The constructive comments of the reviewers are gratefully acknowledged.

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Data Availability

The datasets generated during and/or analysed during the current study are publicly available at ECMWF https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview.

Conflict of interest: The authors declare that they have no conflicts of interest.

Ethical approval: This article is based on analyses of secondary data and do not contain any experiments conducted on human participants and animals.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Figures

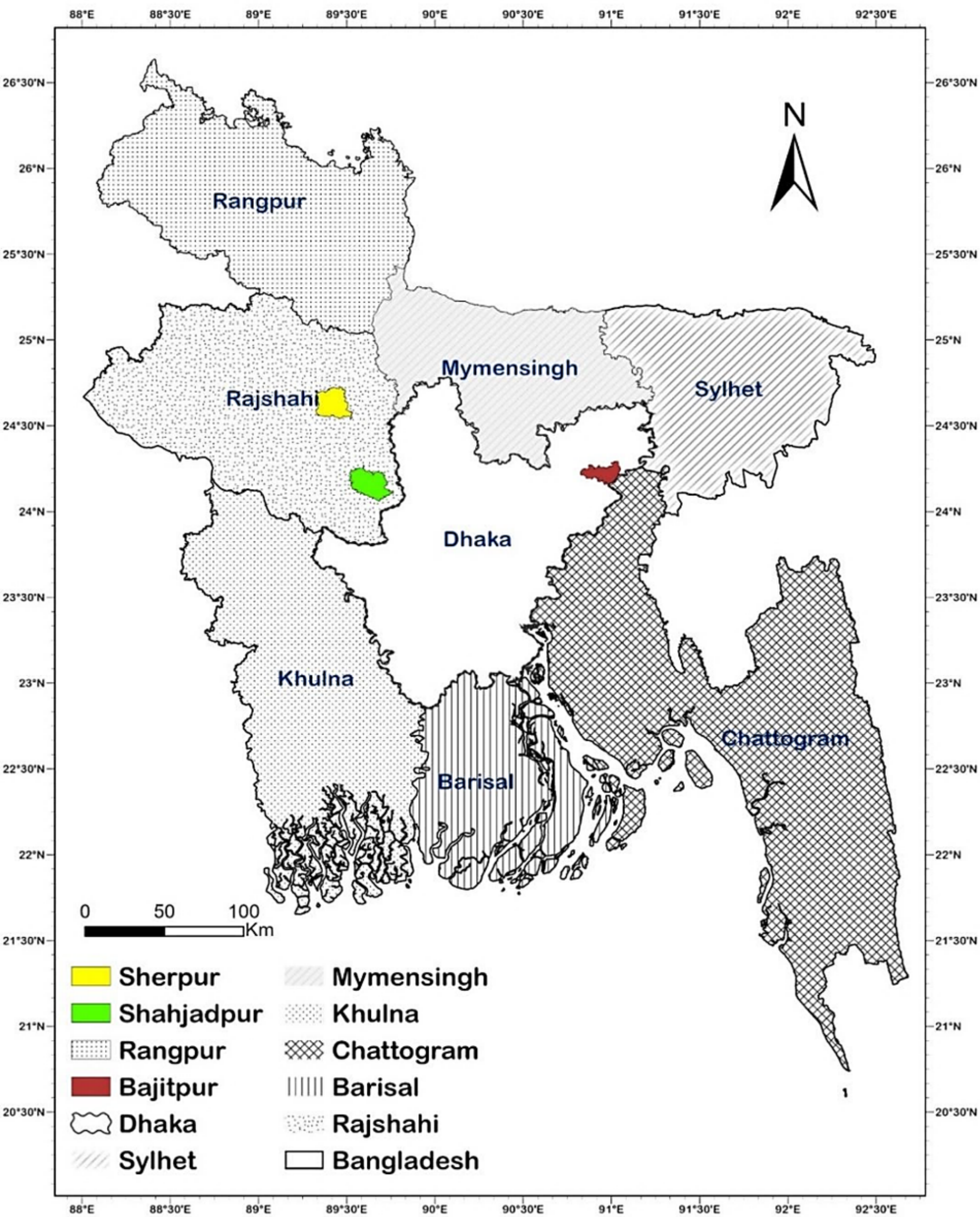

Figure 1

The study domain with eight divisions and three lightning hotspots (Sherpur, Shahjadpur, and Bajitpur) in Bangladesh.

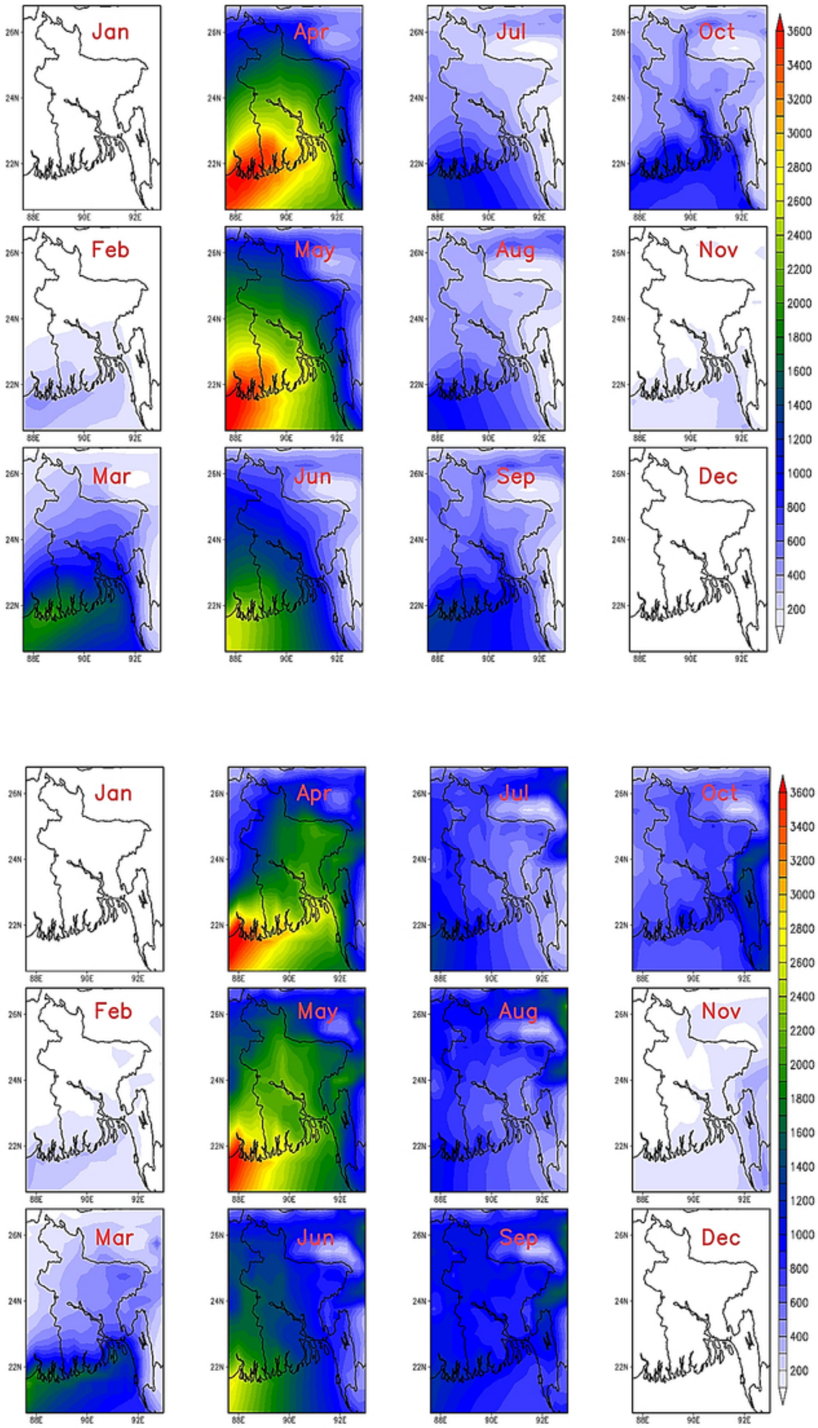

Figure 2

Monthly average of Convective Available Potential Energy (J/kg) over Bangladesh for 40 years (1982-2021) at **(a)** 0000 UTC and **(b)** 1200 UTC.

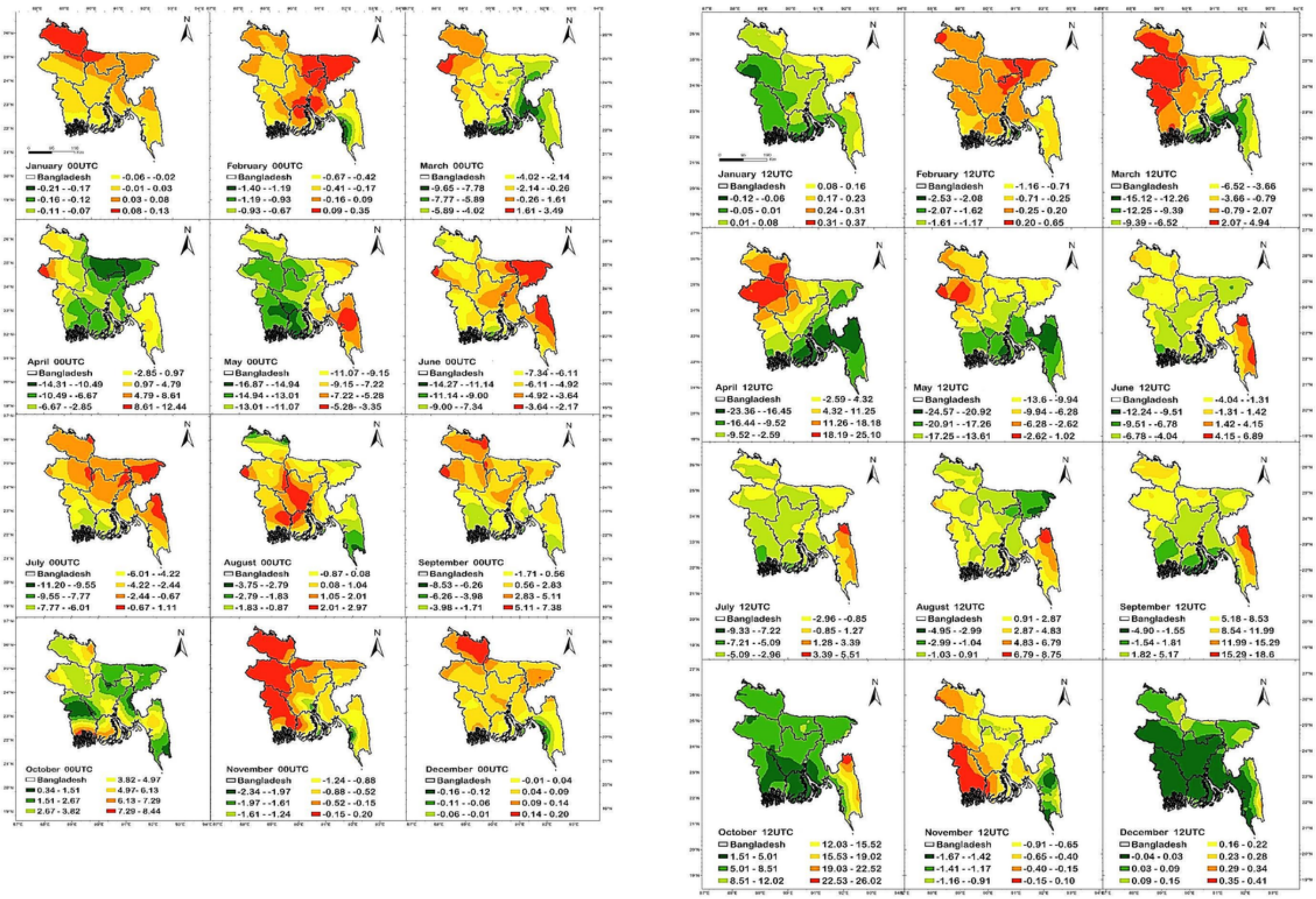

Figure 3

Monthly Mann Kendall trends of Convective Available Potential Energy (J/kg) over Bangladesh for 40 years (1982-2021) at **(a)** 0000 UTC and **(b)** 1200 UTC.

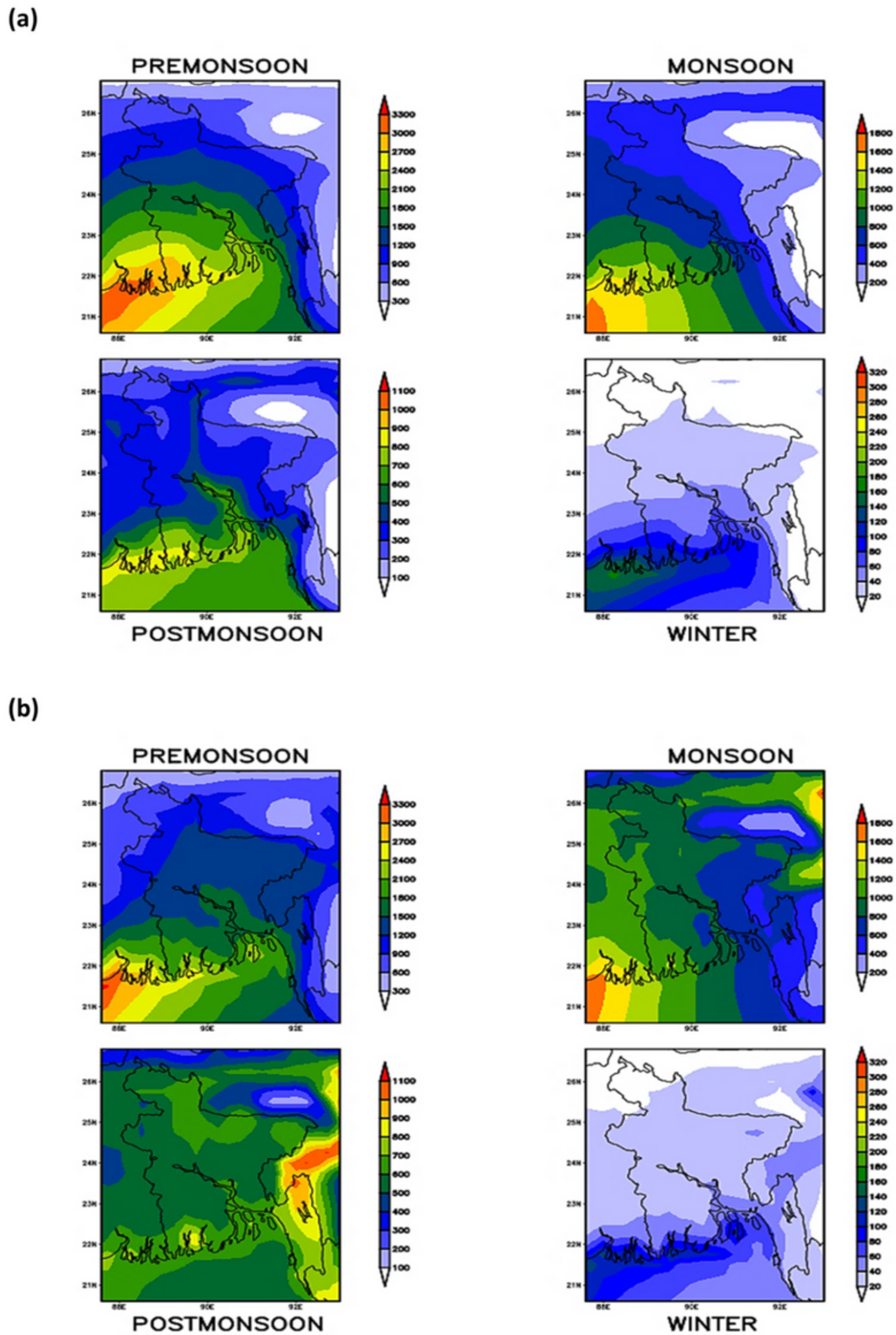

Figure 4

Seasonal average of convective available potential energy (J/kg) over Bangladesh for 40 years (1982-2021) at **(a)** 0000 UTC and **(b)** 1200 UTC.

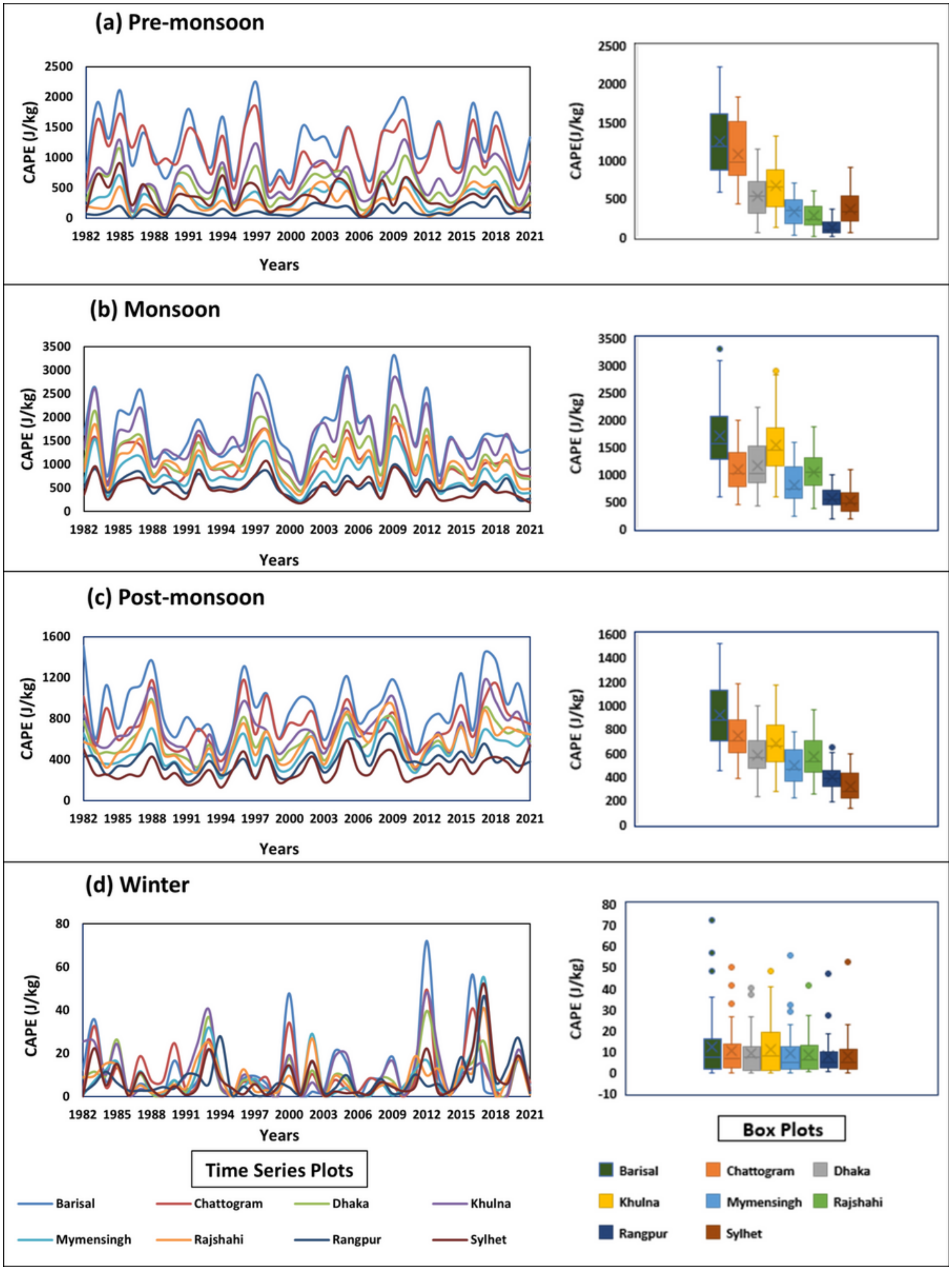

Figure 5

Temporal changes and Box plots of regional Convective Available Potential Energy (J/kg) for the **(a)**Pre-monsoon, **(b)** Monsoon, **(c)** Post-monsoon, and **(d)** Winter season at 0000 UTC over Bangladesh for 40 years (1982-2021).

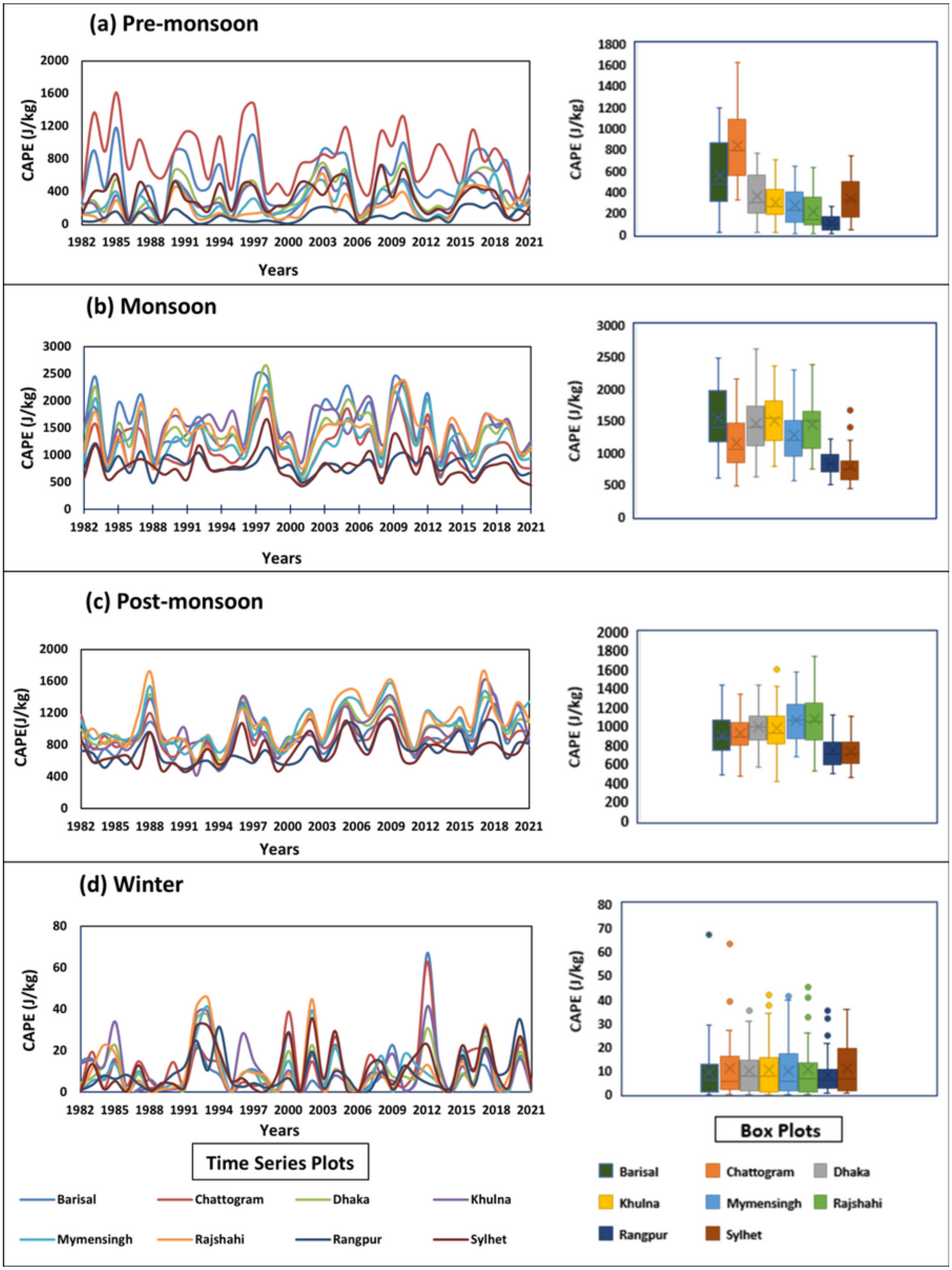

Figure 6

Temporal changes and Box plots of regional Convective Available Potential Energy (J/kg) for the **(a)**Pre-monsoon, **(b)** Monsoon, **(c)** Post-monsoon, and **(d)** Winter season at 1200 UTC over Bangladesh for 40 years (1982-2021).

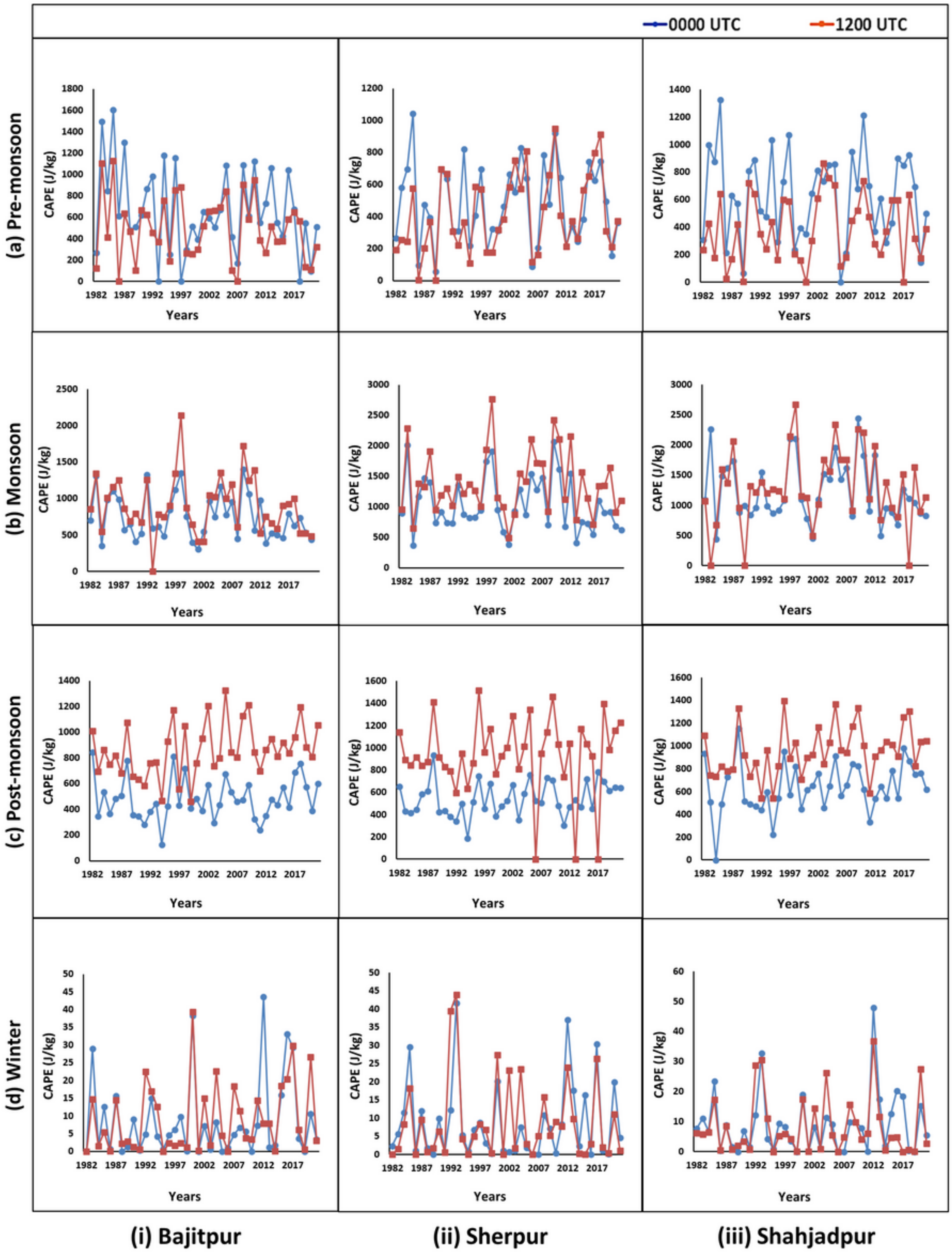

Figure 7

Temporal changes of seasonal Convective Available Potential Energy (J/kg) for three lightning hotspots in Bangladesh, **(i)** Bajitpur, **(ii)** Sherpur, and **(iii)** Shahjadpur for 40 years (1982-2021).

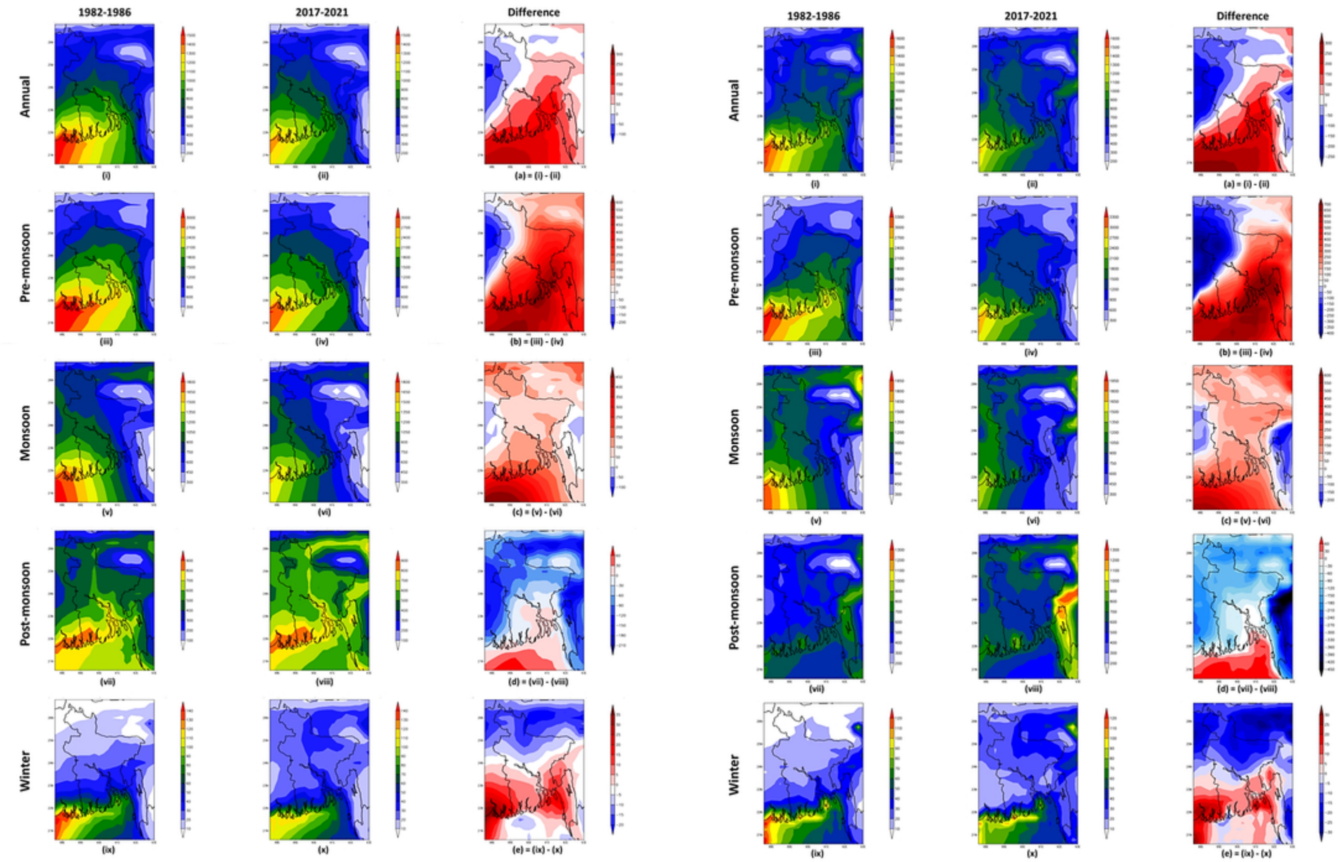

Figure 8

Annual and seasonal variation of Convective Available Potential Energy (J/kg) over Bangladesh for five-year averages of 1982-1986, 2017-2021, and their difference at **(I)** 0000 UTC and **(II)**1200 UTC.

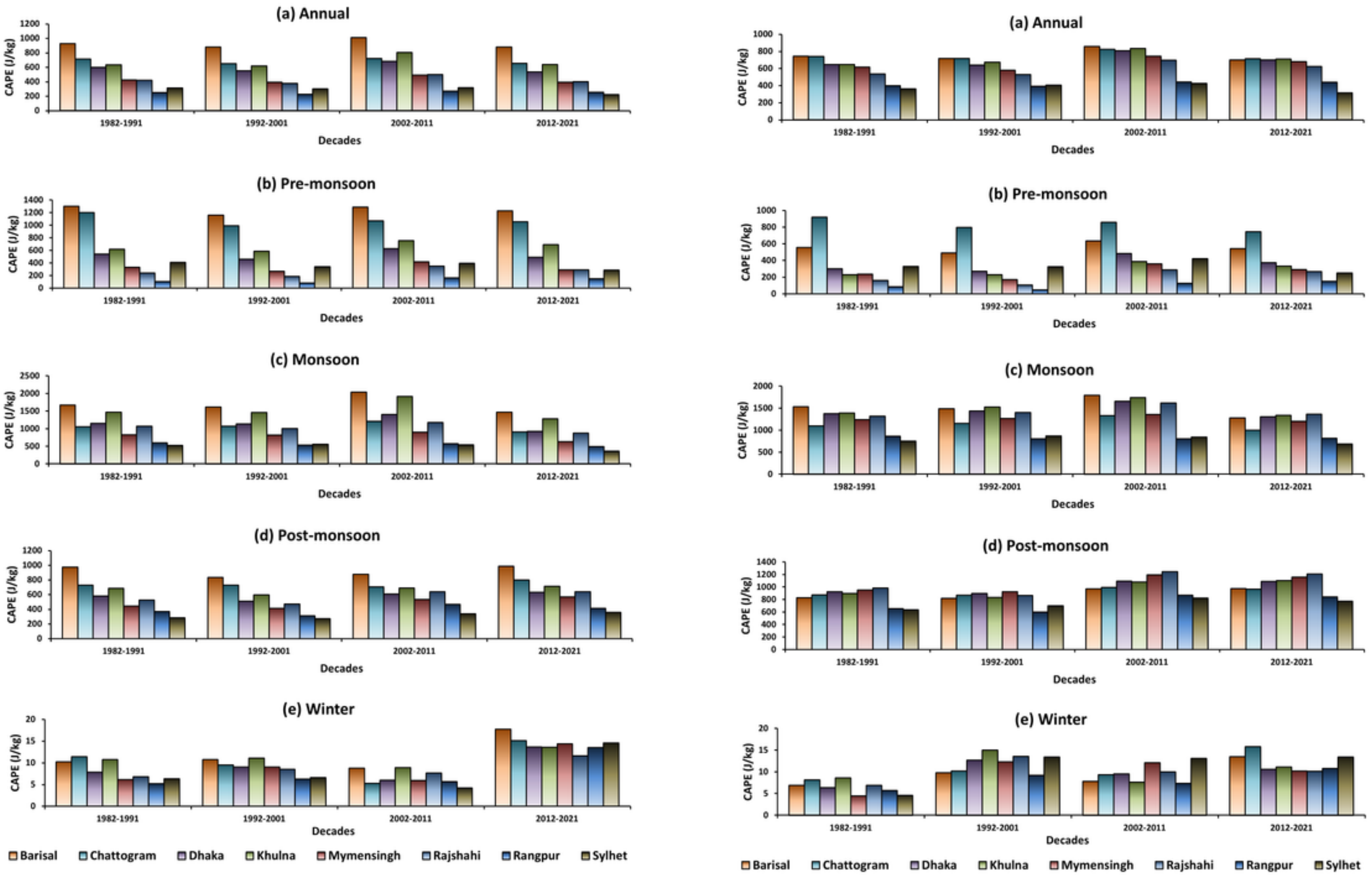

Figure 9

Decadal variation of seasonal Convective Available Potential Energy (J/kg) over the eight divisions of Bangladesh for 40 years (1982-2021) at **(i)**0000 UTC and **(ii)** 1200 UTC.

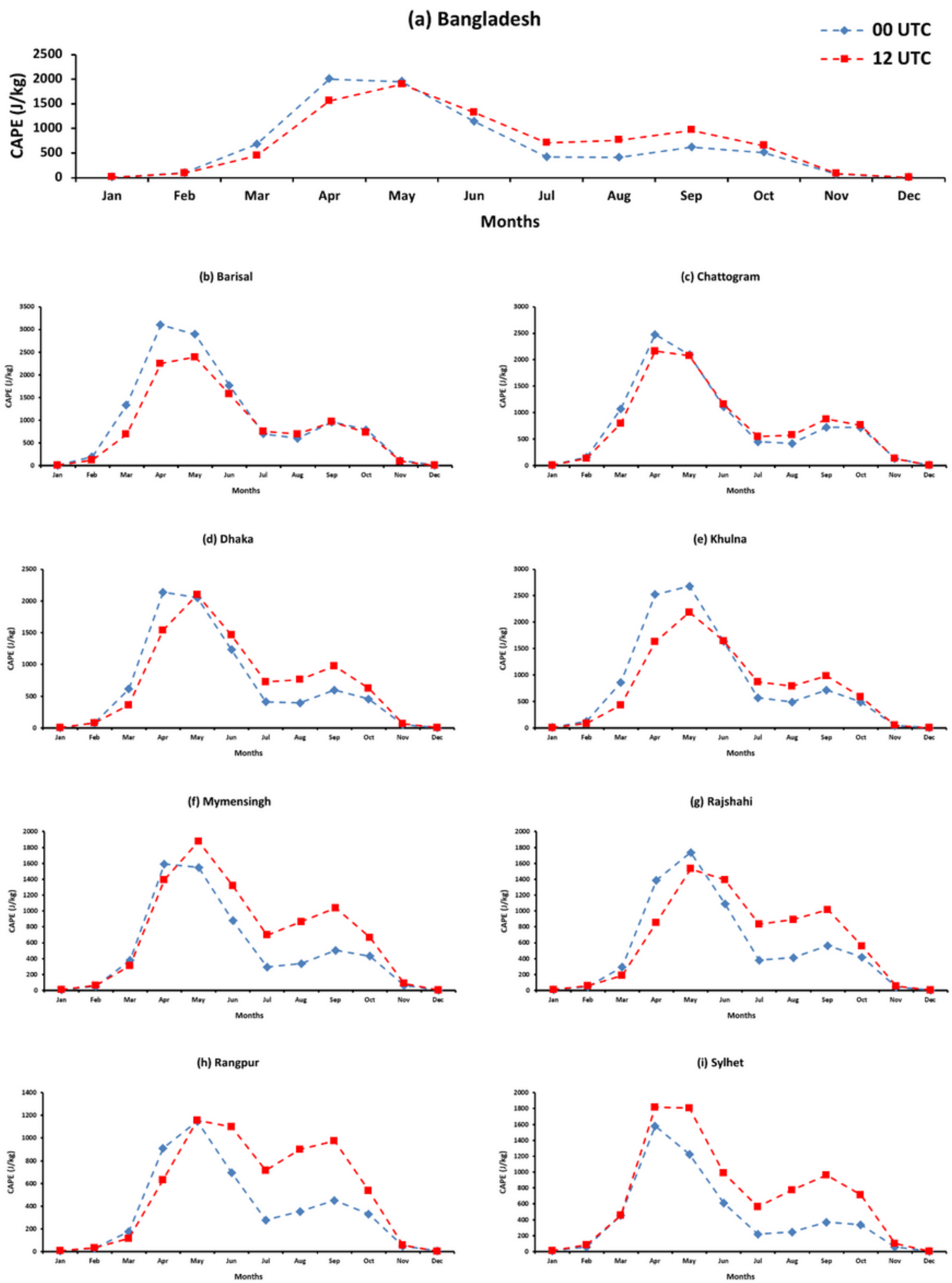

Figure 10

Monthly climatology comparison of Convective Available Potential Energy (J/kg) at 0000 UTC and 1200 UTC over the eight divisions of Bangladesh for 40 years (1982-2021).

Supplementary Files

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- SupplementaryFigures01June2023.docx