Diurnal asymmetry in heat stress intensification across Bangladesh, 1985–2024: Accelerated nighttime warming and emerging urban risk

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Abstract

Bangladesh's rapidly growing cities are becoming hotter, but how heat stress is changing over the day–night cycle has remained unclear. Using 40 years (1985–2024) of hourly Universal Thermal Climate Index (UTCI) data from ERA5-HEAT, we examined long-term changes in physiologically relevant heat stress across Bangladesh and its major cities. Results show a clear day–night imbalance in warming: nighttime heat stress ($UTCI_{min}$) is rising faster than daytime extremes. National trends indicate increases of +0.03 °C per decade for $UTCI_{min}$, +0.02 °C for daily mean UTCI, and +0.01 °C for $UTCI_{max}$, with the strongest warming occurring in the early morning hours. This signals a steady loss of nighttime cooling that people rely on for physical recovery. The most pronounced nighttime warming occurs in western and southern Bangladesh. Major cities — including Dhaka, Rajshahi, Khulna, Chattogram, and Sylhet — show additional intensification linked to urban heat-island effects. The number of Very Strong Heat Stress days (UTCI > 38 °C) has increased by 4–15 days per decade, and cities such as Rajshahi and Dhaka now experience more than 150 such days annually. Together, these findings indicate a transition from occasional heat extremes to persistent, 24-hour heat stress, increasing risks to health, labor productivity, and urban resilience. By identifying when heat stress is rising fastest and where it is concentrated, this study provides evidence to support city-specific heat-action plans, early-warning systems, and climate-responsive urban design in rapidly warming regions.

Keywords: Universal Thermal Climate Index (UTCI); Urban heat stress; ERA5-HEAT reanalysis; Diurnal thermal range; Nighttime warming; Bangladesh cities; Climate adaptation; Urban resilience

Introduction

Thermal comfort represents the subjective perception of how individuals experience temperature, humidity, and airflow, and it is a key dimension of urban liveability and sustainability. However, as global temperatures rise, urban populations increasingly face conditions that exceed not only comfort thresholds but also the limits of physiological tolerance. While thermal discomfort reflects a decline in perceived well-being, heat stress occurs when environmental conditions impair the body's ability to dissipate heat, triggering measurable physiological strain. This distinction is critical: a population may feel uncomfortable at moderate temperatures, but health risks escalate sharply when conditions surpass biophysical thresholds for heat dissipation, particularly in humid, densely built environments[1–4]. Extreme heat is now associated with rising mortality, reduced labour productivity, accelerated environmental degradation, biodiversity loss, and broader economic instability[5–11]. In rapidly urbanizing regions, land-use change and limited heat-resilient infrastructure further intensify exposure, underscoring the importance of monitoring human heat stress—not comfort alone—to assess vulnerability and inform targeted urban adaptation strategies [12].

Although more than sixty indices have been developed to quantify and assess heat stress [13], the widely used indices such as the Wet Bulb Globe Temperature, Effective Temperature, and Discomfort Index often oversimplify the thermal environment settings by neglecting factors that influence thermal comfort experienced by individuals, such as radiant heat and evaporative cooling [14–18]. The indices also fail to account for individual variation in heat perception due to acclimatization, hydration, clothing, or cultural practices. The Universal Thermal Climate Index (UTCI) overcomes these shortcomings by incorporating meteorological inputs (air temperature, humidity, wind speed, and mean radiant temperature) with a dynamic physiological model of thermoregulation [19–21]. By simulating the human heat budget, incorporating conduction, convection, radiation, and latent heat loss, the UTCI expresses physiological strain as an equivalent air temperature under standardized conditions. Its validity across diverse climates has led to its widespread adoption in North America, Europe, Asia, and the Middle East, but its application to the South Asian context remains limited [22–31].

In this regard, the urgency of studying heat stress in South Asia stems from rapid urbanization, high population density, and limited heat-adaptive capacity. Recent evidence shows UTCI warming of 0.25–0.75 °C per decade during the pre-monsoon and monsoon seasons in India and Pakistan, which coincides with peak outdoor labour periods in these countries and exacerbates health risks [32,33]. Another densely populated country in South Asia, Bangladesh, is also highly vulnerable to heat stress due to its rising urban population in major cities like Dhaka, Chittagong, Rajshahi, Sylhet, and Khulna (25% in the 1980s to nearly 40% by 2020), exacerbating urban heat island effects caused by vegetation loss and unplanned urban expansions [34,35]. Recent projections from the International Labour Organization (ILO) suggest a 4.8% reduction in working hours by 2030 due to heat stress, and that 37.5% of the population will be at high risk from heat exposure from outdoor agricultural activities [36]. Other studies report that 21 billion working hours could be lost annually due to a 1 °C temperature rise, disproportionately affecting outdoor labourers such as construction workers and rickshaw pullers [36–38]. Health burdens are likely to grow sharply in the country, as evidenced by the 138% increase in elderly mortality (comparing between 2000-2004 vs 2018-2022), which overlaps with 8–9 heatwave day exposures per year during the 2014-2023 period [39–41].

Despite growing interest in thermal risk in South Asia, Bangladesh still lacks a mechanistic, long-term understanding of human heat stress that reflects both atmospheric conditions and urban morphological change. First, most heat-stress studies in Bangladesh rely on satellite-derived land surface temperatures (LST), which do not capture physiological discomfort [42–45]. Second, most studies focused primarily on Dhaka and used narrow timeframes that were often insufficient to capture long-term spatiotemporal trends and changes in alignment with urban and population growth [45,46]. As a result, secondary cities remain understudied, leaving critical gaps in understanding urban heat exposure and resilience in the country [42,43]. To address these gaps, this study provides the first national-scale, 40-year climatology of UTCI for Bangladesh (1985–2024), quantifying changes in minimum, mean, and maximum thermal conditions and resolving their diurnal structure. By coupling multidecadal UTCI analysis with a regionally adapted heat-stress classification and city-specific decomposition for Dhaka, Chattogram, Rajshahi, Khulna, and Sylhet, the study reveals previously undocumented patterns: accelerated nighttime warming, contraction of the diurnal thermal recovery window, and systematic shifts from "Strong" to "Very

Strong" heat-stress days in major urban centres. These contributions establish the first comprehensive evidence base for understanding the intensification of physiologically relevant heat stress in Bangladesh and provide a foundation for targeted urban resilience and public-health planning.

Materials and methods

Study Area

The study area is Bangladesh, situated between latitudes 20.5°-26.5°N and longitudes 88.0°-92.7°E, characterized by a diverse agroecological and climatic landscape under a tropical monsoon climate. The country has hot, humid summers and mild winters, with temperatures ranging from 5°C in winter to over 40°C in summer [47]. Due to its high population density, rapid urbanization, and low elevation, Bangladesh is highly susceptible to climate-related health risks, notably heat stress [2].

This study analyzes thermal stress in five major cities in Bangladesh: Dhaka, Chittagong, Rajshahi, Khulna, and Sylhet. These cities were selected because they span diverse geographic and climatic zones across Bangladesh, from coastal lowlands to inland plains, and because of their demographic and socioeconomic significance. This diversity enables a comprehensive evaluation of heat-stress dynamics, as each city presents unique risk factors. For instance, Dhaka, the capital city, suffers from a strong UHI effect due to its high population density and dense infrastructure. The coastal megacity of Chittagong faces heightened thermal risks due to high humidity and urban congestion, whereas Rajshahi, located in the arid northwest, is characterized by consistently high daytime temperatures. Finally, Sylhet and Khulna represent varied topographies and urban development patterns in the hilly northeast and the coastal southwest, respectively.

Fig 1. Elevation map of Bangladesh depicting the key city corporations—Dhaka, Chittagong, Sylhet, Rajshahi, and Khulna—highlighted by their administrative limits.

Data

This study employed the UTCI from the ERA5-HEAT dataset, a global gridded reanalysis product developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) and distributed by the Copernicus Climate Change Service (C3S). ERA5-HEAT derives hourly UTCI values by integrating meteorological reanalysis (ERA5) with a polynomial approximation of the Fiala multi-node thermoregulation model [28,48]. ERA5 itself assimilates satellite, ground-based, balloon, and buoy observations using advanced four-dimensional variational (4D-Var) data assimilation techniques, producing a consistent and high-quality global climate record.

ERA5-HEAT provides UTCI estimates at a spatial resolution of 0.25° × 0.25°, covering the globe between 90°N–60°S and 180°W–180°E from 1940 to the present. For this study, hourly data for Bangladesh were extracted from January 1985 to December 2024. A total of 194 grid points within the country's boundaries were retained, allowing high-resolution spatiotemporal analysis of thermal stress across diverse urban morphologies. The dataset was accessed via the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/datasets/derived-utci-historical).

Universal Thermal Climate Index (UTCI)

The UTCI is a physiologically based index designed to capture the dynamic interaction between meteorological conditions and human thermoregulation [19,20]. It integrates air temperature, wind speed, relative humidity, and mean radiant temperature with physiological factors such as metabolic rate and clothing insulation. The UTCI is expressed as an equivalent air temperature that elicits the same physiological response as a standardized reference environment (50% relative humidity, 0.5 m/s wind).

ERA5-HEAT computes UTCI using a sixth-order polynomial regression function approximating the complete Fiala model, with a root mean square error of 1.1 °C [20,28,49]. The UTCI is expressed as an equivalent air temperature that accounts for the combined physiological effects of thermal radiation, wind speed, and humidity, as defined by Equation (1):

$$UTCI = T_a + \Delta T_{Offset} \tag{1}$$

where ΔToffset represents the offset from air temperature computed through a sixth-order polynomial regression of mean radiant temperature (Tmrt), wind speed (va), and relative humidity (RH). The polynomial approximation has a root mean square error of 1.1°C relative to the complete

Fiala multi-node thermoregulation model (Di Napoli et al., 2021). ERA5-HEAT provides UTCI values calculated using this validated polynomial implementation.

Where:

UTCI = Universal Thermal Climate Index (°C) Ta = air temperature (°C) Tmrt = mean radiant temperature (°C) va = wind speed (m/s) RH = relative humidity (%) ΔToffset = thermal offset accounting for radiation, wind, and humidity effects

Globally, UTCI values are categorized into ten thermal stress classes, ranging from extreme cold stress to extreme heat stress [19]. However, Bangladesh's subtropical climate exhibits a UTCI range of approximately 0–46 °C, indicating that cold-stress classes below 0 °C and extreme heat classes above 46 °C do not occur in this region. For this reason, the analysis adopts a regionally appropriate subset of five categories (Table 1), spanning *Slight Cold Stress* to *Very Strong Heat Stress*. This approach aligns with existing practices for tailoring indices to regional climates in which cold stress is negligible [28,50].

Table 1. UTCI assessment scale applied in this study

Category	**UTCI Range (°C)**	**Stress Category**	**Thermal Perception**	**Physiological Sensitivity Notes**
1	0–9	Slight Cold Stress	Cold	Minimal relevance in Bangladesh; occurs on only a few winter mornings.
2	9–26	No Thermal Stress	Comfortable	The upper boundary (26 °C) marks the transition from passive to active heat dissipation (sweating onset).
3	26–32	Moderate Heat Stress	Warm	Sensitivity increases with humidity; exceeding 32 °C indicates reduced evaporative cooling efficiency**.**
4	32–38	Strong Heat Stress	Hot	Values approach cardiovascular strain thresholds; small increases in RH or solar load can push UTCI above 38 °C.

5	38–46	Very Strong Heat Stress	Very Hot	Indicates conditions in which cooling capacity may be insufficient, thereby increasing the risk of heat exhaustion and collapse.

Processing of Daily Thermal Metrics

To characterize diurnal heat exposure, hourly UTCI values were aggregated into daily minimum ($UTCI_{min}$), daily mean ($UTCI_{mean}$), and daily maximum ($UTCI_{max}$). $UTCI_{min}$ represents nighttime cooling capacity, $UTCI_{max}$ indicates peak daytime heat stress, and $UTCI_{mean}$ reflects the 24-hour thermal environment. Hourly data were converted from Coordinated Universal Time (UTC) to Bangladesh Standard Time (UTC+6) prior to diurnal analysis.

Climatological Periods

Daily UTCI values were averaged into two 20-year climatological periods: 1985–2004 and 2005–2024. This split reflects observed post-2000 acceleration in regional warming, rapid urban expansion, and intensifying urban heat-island effects across South Asia. Treating these as separate climatological windows enables detection of structural shifts in baseline thermal conditions.

Spatial and Seasonal Characterization

For each climatological period, spatial climatologies of $UTCI_{min}$, $UTCI_{mean}$, and $UTCI_{max}$ were generated at annual and seasonal scales (pre-monsoon, monsoon, post-monsoon, and winter). This approach identifies spatial patterns of heat stress, including thermal hotspots and contrasting conditions across the inland, northern, and coastal regions.

Trend Detection

Long-term monotonic trends in annual UTCI metrics were quantified using Sen's slope estimator, which provides a robust measure of trend magnitude. Statistical significance was assessed using the Modified Mann–Kendall test, which accounts for serial correlation in climatological time series [51]. Trends were mapped at the grid-cell level to capture spatial heterogeneity.

City-Level Analysis

Five major urban centres—Dhaka, Chattogram, Rajshahi, Khulna, and Sylhet—were selected for detailed analysis. Annual and seasonal UTCI metrics were extracted from grid cells corresponding to each city's administrative boundary to evaluate local-scale thermal behaviour and long-term changes.

Results

Spatiotemporal Patterns of Heat Stress in Bangladesh

Climatological Changes Between Early and Recent Periods

Fig 2 compares climatological UTCI conditions between two multi-decadal periods (1985–2004 and 2005–2024) and reveals substantial changes in both nighttime and daytime thermal environments across Bangladesh. The most pronounced increases are observed in daily minimum UTCI ($UTCI_{min}$). Relative to the earlier period, $UTCI_{min}$ increased by approximately 1.0–1.5 °C across most regions, with local increases approaching 2 °C in parts of central and southern Bangladesh.

Daily maximum UTCI ($UTCI_{max}$) also increased between the two periods, accompanied by a clear spatial expansion of high-temperature zones. Areas experiencing $UTCI_{max}$ values above 35 °C, previously concentrated mainly along the southern coastal belt, now extend inland across central, southwestern, and western regions. In these areas, daytime $UTCI_{max}$ increased by approximately 1–2 °C relative to the earlier climatology.

Seasonal comparisons indicate that warming is strongest during the pre-monsoon season (March–May). During this period, $UTCI_{max}$ increased by approximately 1.0–1.5 °C, with May emerging as the month exhibiting the highest climatological UTCI values, exceeding 36–37 °C in several regions. Winter conditions have also shifted, with January–February $UTCI_{min}$ increasing by ~2 °C in many parts of the country. Collectively, these changes indicate a systematic warming of minimum, mean, and maximum UTCI conditions across seasons.

Fig 2. Climatological UTCI patterns in Bangladesh for two separate periods—(A) 1985–2004 and (B) 2005–2024. Panels (a–c) display the spatial distributions of daily minimum ($UTCI_{min}$), mean

(UTCI□$_{ea}$□), and maximum (UTCI□$_{ax}$) UTCI for each period, whereas panel (d) presents the monthly climatological means aggregated across all grid cells, with error bars indicating interannual variability.

Decadal Evolution of Thermal Conditions

Figure 3 illustrates the decadal evolution of UTCI across Bangladesh from 1985 to 2024. During the 1985–1994 decade, nighttime UTCI□$_{i}$□ values generally ranged from 18.5–22 °C, with the lowest values occurring in northern and northwestern districts. By 2015–2024, most regions exhibited increases of 1.0–1.5 °C, and large areas of southern and southwestern Bangladesh consistently recorded nighttime UTCI□$_{i}$□ values above 22.5 °C.

Daytime conditions followed a similar spatial progression. In the earliest decade, UTCI□$_{ax}$ values across most regions ranged between 31–34.5 °C. In contrast, during the most recent decade, extensive areas of central, western, and southern Bangladesh regularly exceeded 35.5 °C, with localized increases of up to 1–2 °C relative to earlier decades.

Daily mean UTCI (UTCI□$_{ea}$□) also increased steadily over time. Whereas earlier decades exhibited mean values between 24.8–27.5 °C, recent decades show increases of 0.8–1.2 °C, with mean UTCI□$_{ea}$□ exceeding 28 °C in southern districts. These decadal changes indicate a progressive shift toward higher baseline thermal conditions across both nighttime and daytime periods.

Fig 3. Decadal spatial distributions of UTCI values across Bangladesh from 1985 to 2024. Each row corresponds to a decade: 1985–1994, 1995–2004, 2005–2014, and 2015–2024. Columns represent (from left to right) daily minimum (UTCI□$_{i}$□), mean (UTCI□$_{ea}$□), and maximum (UTCI□$_{ax}$) UTCI values.

Long-Term Heat Stress Trends and Frequency Shifts

Annual and Seasonal Warming Trends

Fig 4 presents long-term trends in daily minimum (UTCI□$_{i}$□), maximum (UTCI□$_{ax}$), and mean (UTCI□$_{ea}$□) UTCI across Bangladesh for the period 1985–2024. Spatial distributions of Sen's slope estimates (°C decade^{-1}) are shown in Fig 4(a–c), and Figure 4(d) displays the corresponding national mean time series.

Trends in $UTCI_{min}$ show widespread positive values across the country (Figure 4a). Grid-cell Sen's slope estimates range from +0.1 to +0.4 °C decade^{-1}, with higher values concentrated in southern and western regions. More than 80% of grid cells exhibit statistically significant positive trends ($p < 0.05$). The spatially averaged national trend in $UTCI_{min}$ is +0.03 °C decade^{-1}.

Trends in $UTCI_{max}$ exhibit pronounced spatial variability (Figure 4b). Southern and southeastern regions show weak positive trends of approximately +0.1 °C decade^{-1}, whereas northern and northwestern regions display near-neutral to slightly negative trends ranging from −0.1 to 0.0 °C decade^{-1}. Approximately 50% of grid cells show statistically significant trends. The national mean $UTCI_{max}$ trend is +0.01 °C decade^{-1} ($p < 0.05$).

Daily mean UTCI ($UTCI_{mean}$) exhibits positive trends across much of Bangladesh (Figure 4c). Sen's slope estimates range from +0.05 to +0.25 °C decade^{-1}, with higher values observed in central and southern regions. The national mean $UTCI_{mean}$ trend is +0.02 °C decade^{-1} ($p < 0.05$).

Fig 4. Spatial and temporal trends of UTCI indices over Bangladesh during 1985–2024, showing (a) Sen's slope estimates (°C per decade) for daily minimum ($UTCI_{min}$), (b) maximum ($UTCI_{max}$), and (c) mean ($UTCI_{mean}$) UTCI values. Filled black circles indicate statistically significant trends ($p < 0.05$) based on the Modified Mann–Kendall test. Panel (d) presents annual national mean UTCI time series for $UTCI_{min}$ (green), $UTCI_{max}$ (red), and $UTCI_{mean}$ (blue), with linear trends annotated by Sen's slope values.

Seasonal trend patterns are shown in Figure 5. $UTCI_{min}$ displays positive trends in all seasons, with magnitudes ranging from +0.05 to +0.3 °C decade^{-1}. The largest seasonal trends occur during the post-monsoon period, particularly in northwestern and southern regions, where values approach +0.3 °C decade^{-1}. Seasonal $UTCI_{mean}$ trends follow similar spatial patterns but with lower magnitudes. Annual Sen's slope values range from −0.05 to +0.15 °C decade^{-1}, with a national mean of +0.02 °C decade^{-1} ($p < 0.05$).

Fig 5. Seasonal Sen's slope maps showing trends in UTCI values over Bangladesh from 1985 to 2024. Each row represents the annual average for the pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–November) periods. Columns correspond to daily minimum ($UTCI_{min}$), mean ($UTCI_{mean}$), and maximum ($UTCI_{max}$) UTCI trends. Black dots indicate regions with statistically significant trends ($p < 0.05$), and colour gradients represent the rate of change in °C per decade.

Seasonal UTCI$_{max}$ trends are generally weak, with neutral to mildly negative values inland (−0.1 to 0.0 °C decade^{-1}) and small positive trends (≤ +0.05 °C decade^{-1}) in coastal and metropolitan regions. The contrast between stronger UTCI$_{min}$ trends and weaker or mixed UTCI$_{max}$ trends indicates a long-term convergence of nighttime and daytime UTCI trends.

Shifts in the Frequency of Hazardous Heat Days

Fig 6 summarizes long-term changes in the annual frequency of UTCI-based thermal stress categories across Bangladesh for the period 1985–2024. Analysis of daily mean UTCI (UTCI$_{mean}$) indicates a widespread reduction in the number of days classified as No Thermal Stress, with decreases of approximately 5–15 days per decade, most pronounced in northern and western regions. Concurrently, the frequency of days classified as Strong Heat Stress increased by approximately 5–15 days per decade, with the largest increases observed in southern, coastal, and deltaic regions.Changes in the upper range of thermal stress are most evident for daily maximum UTCI (UTCI$_{max}$). The frequency of Very Strong Heat Stress days increased substantially over the study period. In northwestern and central regions, including Rajshahi and Dhaka, increases range from 8 to 15 days per decade. Spatial patterns of these changes are shown in Supplementary Figure S1.Overall, the results indicate a redistribution of UTCI stress categories over time, characterized by declining frequencies of thermally neutral conditions and increasing frequencies of strong and very strong heat stress across large portions of Bangladesh.

Fig 6. Trends in annual frequency of UTCI$_{mean}$ and UTCI$_{max}$ stress categories (1985–2024), in days per decade.

Urban Heat Stress Dynamics and Diurnal Intensification

Intensification of the Diurnal Heat Cycle

Fig 7 compares climatological hourly mean UTCI values across Bangladesh between two periods, 1985–2004 and 2005–2024. Across nearly all hours of the day, UTCI values are higher during the later period. The largest differences occur during early morning hours (05:00–07:00 LT), with national mean UTCI increases of approximately 0.6–0.8 °C. Afternoon UTCI values between

13:00 and 15:00 LT increased by approximately 0.6–0.7 °C. During most hours, mean UTCI values in 2005–2024 exceed those of 1985–2004 by 0.5–1.0 °C.

Figure 8 presents analogous diurnal UTCI profiles for five major cities: Dhaka, Rajshahi, Chattogram, Sylhet, and Khulna. All cities exhibit higher UTCI values across the diurnal cycle in the later period. Morning-hour increases range from 0.5–1.0 °C, while afternoon increases range from 0.5–0.8 °C. Rajshahi records the highest midday UTCI values, whereas Dhaka shows comparatively larger increases during evening hours. Supplementary Figure S2 shows consistent long-term increases in daily maximum UTCI across all five cities.

Fig 7. Climatological hourly mean UTCI across Bangladesh for two periods (1985–2004 vs 2005–2024).

Fig 8. Hourly mean Universal Thermal Climate Index (UTCI) for five major cities in Bangladesh (Dhaka, Rajshahi, Chattogram, Sylhet, and Khulna), comparing two climatological periods: 1985–2004 and 2005–2024.

City-Specific Heat Stress Profiles and Trends

Fig 9 shows the distribution of daily maximum UTCI values by thermal stress category for five cities over the period 1985–2024. Median UTCI values within the Very Strong Heat Stress category are highest in Rajshahi (≈40.7 °C) and Sylhet (≈40.4 °C). Extreme values exceeding 45 °C are observed in Rajshahi. Coastal cities, including Chattogram and Khulna, exhibit narrower distributions and lower upper extremes relative to inland cities. Limited overlap among stress-category distributions indicates distinct UTCI ranges associated with each category.

Fig 10 presents annual frequencies of UTCI thermal stress categories for each city. Days classified as Strong or Very Strong Heat Stress dominate the annual distribution across all five cities. Very Strong Heat Stress days frequently exceed 150 days per year in Rajshahi. Days classified as No Thermal Stress occur infrequently, typically fewer than 20 days per year in all cities. Temporal trends in these categories are shown in Figure 11.

Across all cities, the frequency of Very Strong Heat Stress days increased over the study period, accompanied by declines in Strong and Moderate Heat Stress categories. Chattogram exhibits the largest increase (+12.7 days decade^{-1}), offset by reductions in Strong (−10.2 days decade^{-1}) and Moderate (−4.7 days decade^{-1}) categories. Dhaka shows an increase of +8.2 Very Strong Heat Stress days decade^{-1}, alongside a decline of −9.2 Strong Heat Stress days decade^{-1}. Khulna, Rajshahi, and Sylhet exhibit increases of +6.6, +4.5, and +5.0 days decade^{-1}, respectively.

Fig 9. Daily maximum UTCI by stress category for five cities (1985–2024).

Fig 10. Annual frequency of Universal Thermal Climate Index (UTCI) thermal stress categories: No Thermal Stress, Moderate Thermal Stress, Strong Thermal Stress, and Very Strong Thermal Stress for five major cities in Bangladesh (1985 – 2024).

Fig 11. Trends in the number of days per decade for UTCI thermal stress categories: No Thermal Stress, Moderate Thermal Stress, Strong Thermal Stress, and Very Strong Thermal Stress across five major cities in Bangladesh.

Table 2 quantifies pronounced changes in both daytime and nighttime thermal exposure across all five major cities between 1985 and 2024. During daytime hours, the proportion of time classified as Very Strong Heat Stress increased substantially in every city. Rajshahi experienced the highest daytime exposure, rising from 15.7% to 26.4% of daytime hours (+10.7 percentage points), while Dhaka showed an increase from 8.2% to 20.7% (+12.5 percentage points). Comparable increases were observed in Khulna (+11.3 percentage points), Sylhet (+10.0 percentage points), and Chittagong (+11.2 percentage points). These results indicate that extreme daytime heat stress has become markedly more frequent across both inland and coastal urban environments.

Nighttime conditions exhibit an opposing but equally consequential trend. The share of nighttime hours classified as No Thermal Stress declined sharply in all cities, indicating a progressive loss of thermally neutral recovery periods. The largest reductions occurred in Chittagong (−25.5 percentage points) and Dhaka (−21.1 percentage points), followed by Khulna (−18.9 percentage points), Sylhet (−13.6 percentage points), and Rajshahi (−9.7 percentage points). As a result, cities that previously experienced predominantly comfortable nighttime conditions now spend a substantially greater fraction of the night under thermally stressful environments.

Table 2. Intensification of Daytime and Nighttime Heat Stress (UTCI%) in Major Bangladeshi Cities, 1985–2024

City	Very Strong Heat Stress – Day (%) 1985	Very Strong Heat Stress – Day (%) 2024	Δ Day (percentage points)	No Thermal Stress – Night (%) 1985	No Thermal Stress – Night (%) 2024	Δ Night (percentage points)
Dhaka	8.2	20.7	+12.5	57.6	36.5	−21.1
Rajshahi	15.7	26.4	+10.7	49.7	40.0	−9.7
Khulna	8.2	19.5	+11.3	50.9	32.0	−18.9
Sylhet	9.5	19.5	+10.0	55.8	42.2	−13.6
Chittagong	3.2	14.4	+11.2	76.7	51.2	−25.5

Fig 12 presents the diurnal heatmaps of UTCI-derived thermal stress categories across months for five major cities in Bangladesh. Thermally Comfortable conditions dominate the annual cycle in all cities, accounting for 70–77% of total hours. Chittagong exhibits the highest proportion of comfortable conditions (77%), followed by Dhaka and Rangpur (73%), Sylhet (74%), and Rajshahi (70%).

Across all cities, daytime heat stress intensifies seasonally, with Warm, Hot, and Very Hot categories emerging during the pre-monsoon months (March–May). The expansion of heat stress occurs primarily between late morning and late afternoon hours. Rajshahi shows the longest and most persistent daytime exposure to Very Hot conditions during April and May, spanning several consecutive daytime hours. Dhaka and Sylhet also exhibit repeated occurrences of Hot and Very Hot categories during the same period, though with shorter durations. Rangpur displays extended Warm and Hot daytime conditions during the pre-monsoon season, with limited persistence of Very Hot stress.

Chittagong displays a comparatively distinct diurnal pattern, with daytime heat stress present during the pre-monsoon and monsoon seasons but shorter durations of Very Hot conditions relative to inland cities. In all cities, nighttime hours are predominantly classified as Comfortable during winter months, while Warm nighttime conditions become more frequent from April through September, particularly during early morning hours.

Fig 12. Diurnal heatmap of UTCI-derived thermal stress categories across months for five major cities of Bangladesh. Each row represents the hour of the day (0–23), and each column represents months (January to December). Color codes indicate UTCI-based thermal stress levels. The percentage of total time classified as 'Comfortable' is shown for each city.

Discussion

This study examined how heat stress has changed across Bangladesh from 1985 to 2024, using the UTCI. There is a significant gap in research on long-term, city-by-city assessments of how uncomfortable the heat has become in this region. Though, some research has been on South Asian heat stress lately, there is a lack of detailed, long-term studies that link changes in UTCI to seasonal patterns and identify which urban areas are most vulnerable across Bangladesh. By analyzing daily UTCI measurements and categorizing heat-stress intensity, this study shows how the urban heat risk picture has been changing.

The study shows that heat stress has increased significantly between 1985 and 2024, and it is not occurring evenly across the country. The southern regions, which are densely populated and urbanized, have been disproportionately affected. There is warming trends in both nighttime temperatures (UTCI$_{\square i \square}$) and daily averages (UTCI$_{\square ea \square}$), with the national average increasing by approximately 0.03°C per decade and 0.02°C per decade, respectively. In some parts of the country, the warming has been even more dramatic—up to 0.4°C per decade. This fits with what is happening across South Asia more broadly. Kyaw et al. [32] found that UTCI has been rising by 0.25–0.75°C per decade during the pre-monsoon and monsoon seasons, exactly when people are doing the most outdoor labor.

One of the most interesting findings of the study is that nighttime and daytime warming are not happening at the same rate. Nighttime temperatures (UTCI$_{\square i \square}$) are going up pretty much everywhere, but daytime highs (UTCI□ax) show a mixed picture—there is slight warming along the coast but actually some cooling in the north. This means the difference between day and night temperatures is getting smaller, which is significant for public health. Early-morning UTCI has increased by 1.7°C over the past 40 years, indicating that people are losing the crucial cool nighttime hours their bodies need to recover from daytime heat. Without nighttime relief and with the entire 24-hour heat cycle intensifying, people experience cumulative heat strain, increasing their risk of heat-related illnesses. The study, Khan et al. [52] recently identified increasing early-morning heat stress as one of the main drivers of rising thermal risk in South Asia, which supports our findings.

The shift toward a hotter climate really shows up in the numbers of dangerously hot days, especially in cities. The results revealed that the number of days with "Very Strong Heat Stress" (UTCI above 38°C) has increased by up to 15 days per decade in places such as Rajshahi and Dhaka. In Rajshahi, more than a quarter of all daytime hours in 2024 fell into this potentially deadly category—that is up from just 15.7% in 1985. What is particularly concerning is that days that were previously classified as "Strong Heat Stress" are now moving into the "Very Strong" category. This shift is most evident in Chittagong, where it increased about 12.7 "Very Strong" heat-stress days per decade while reduced almost the same number of "Strong" and "Moderate" heat-stress days.

This intensification in urban areas makes sense in terms of the urban heat island (UHI) effect that Dewan et al. [35] explored in detail. Heat from human activities and the concrete and asphalt in cities raise temperatures above those in surrounding rural areas. The elevated UTCI values observed in densely populated cities such as Dhaka and Khulna align with findings from other rapidly growing urban areas worldwide. For instance, Krüger et al. [50] linked increases in UTCI in Brazil to the expansion of paved surfaces. The spatial patterns in the study, with the highest UTCI values concentrated in major cities, show that urban populations are hit with a double whammy—they face both regional climate warming and the localized heating from the urban environment itself.

The increasing frequency and intensity of heat stress have real, serious consequences for public health and economic productivity. UTCI is closely linked to physiological strain—such as changes in core and skin temperatures—which makes it a strong indicator of health risk, as noted by Zare et al. [13]. Cities such as Dhaka and Rajshahi are now experiencing prolonged periods of intense heat, which places enormous strain on people's bodies. This is especially critical for the millions of people working outdoors in informal jobs—construction workers, transportation workers, agricultural laborers—who sustain the urban economy. For these workers, spending long hours exposed to UTCI levels above 32°C during peak working hours (9 AM to 5 PM), as our diurnal heatmaps show during the pre-monsoon season, dramatically increases their risk of heat exhaustion, heat stroke, and physical inability to work effectively.

The trends observed in this study align with regional analyses indicating a sharp rise in high-heat-stress days across South Asian cities and with projections of significant losses in labor productivity. The ILO [36] has projected substantial reductions in working hours in Bangladesh because of heat stress. The Grantham Institute policy brief [53] emphasized that informal workers in Dhaka often lack access to air conditioning, proper insulation, or effective heat-warning systems, leaving them incredibly vulnerable to extreme heat. Our findings, which show UTCI levels consistently rising across major metropolitan areas nationwide, underscore the urgent need for interventions such as shaded rest areas, improved dissemination of early warnings, and adjustments to work hours to protect these at-risk populations.

Given the number of people at risk, the growing heat-stress crisis in Bangladesh's urban areas demands urgent, evidence-based policy action. National and local governments should begin incorporating UTCI-based monitoring into their climate adaptation planning. This could help identify high-risk populations and ensure resources for public health interventions are allocated where they are needed most. Ahmedabad's Heat Action Plan demonstrates how early warning systems, microclimate monitoring, and targeted cooling interventions can reduce heat-related mortality. Dhaka South City Corporation's Climate Action Plan 2024 outlines similar priorities—including reflective roofing, urban greening, and social protection for vulnerable groups—but rapid and decisive implementation is now essential. Local governments should also prioritize investing in nature-based solutions, more shade infrastructure, and community cooling initiatives in the most heat-exposed urban areas that have been identified. These strategies directly support Sustainable Development Goals for Health (SDG 3), Sustainable Cities (SDG 11), and Climate Action (SDG 13), and can help us build urban areas that are more climate-friendly, sustainable, and resilient.

While this study provides important evidence on heat stress and exposure across Bangladesh, it has some limitations. The ERA5-HEAT dataset used in this study has a spatial resolution of 0.25°

(approximately 27 km), which means it cannot reliably capture microclimatic differences—such as the cooling effects of green spaces, how building layouts affect temperature, or how urban density matters—at the neighborhood scale. If higher-resolution modeling and data frameworks become available, these gaps can be addressed. For example, coupled traffic-emission-dispersion modeling has shown it is possible to capture fine-scale urban atmospheric dynamics [54], and land-use studies demonstrate that local surface cover can substantially change neighborhood thermal conditions [55]. Future work should aim for sub-kilometer-resolution thermal mapping or urban-scale modeling to better understand exposure gradients within cities. Second, our findings would be more meaningful if it is possible to incorporate socioeconomic vulnerability indicators (e.g., health data or productivity metrics), which are crucial for identifying which subpopulations are most at risk of heat exposure. However, such a detailed socioeconomic vulnerability assessment is beyond the scope of this initial study, which focuses primarily on quantifying and characterizing heat stress in Bangladesh. Future research could integrate socioeconomic vulnerability indicators with UTCI trends to develop composite heat risk indices, thereby generating more contextually relevant and equitable policy recommendations.

Despite these limitations, this study presents strong evidence that heat stress in Bangladesh is increasing, as measured by UTCI. The trends of rising UTCI, longer periods of thermal stress, and the concentration of urban hotspots point to an intensifying public health crisis. By putting these findings in the context of regional and global research, this study provides a critical evidence base to inform targeted urban planning, public health interventions, and climate adaptation strategies. These findings highlight the need for evidence-based adaptation strategies to address escalating urban heat stress.

Conclusion

This study presents four decades of evidence indicating that heat stress in Bangladesh is rising, directly impacting daily living and public health. UTCI trends from 1985 to 2024 indicate a significant alteration in the 24-hour thermal cycle, characterized by nighttime warming surpassing daytime variations. The nighttime UTCI has risen by approximately 1.7°C, diminishing chances for physiological recovery and exacerbating persistent heat stress. Cities like Rajshahi and Dhaka now endure an increase of 8–15 days per decade of "Very Strong Heat Stress," with inland regions—particularly the northwest and southwest—warming at a rate surpassing that of coastal areas. The urban heat island phenomenon exacerbates temperatures in Dhaka and Khulna, endangering outdoor laborers and economically disadvantaged groups the most. These findings emphasize the necessity for prompt, evidence-informed heat adaption. Incorporating UTCI-based monitoring into national climate strategies would facilitate the identification of at-risk populations and enable focused interventions. This analysis is constrained by the spatial resolution of ERA5-HEAT data; yet, the overarching conclusion is unequivocal: heat stress is increasing unevenly yet significantly. The immediate priority is to convert this evidence into prompt policy measures to safeguard health, livelihoods, and urban resilience.

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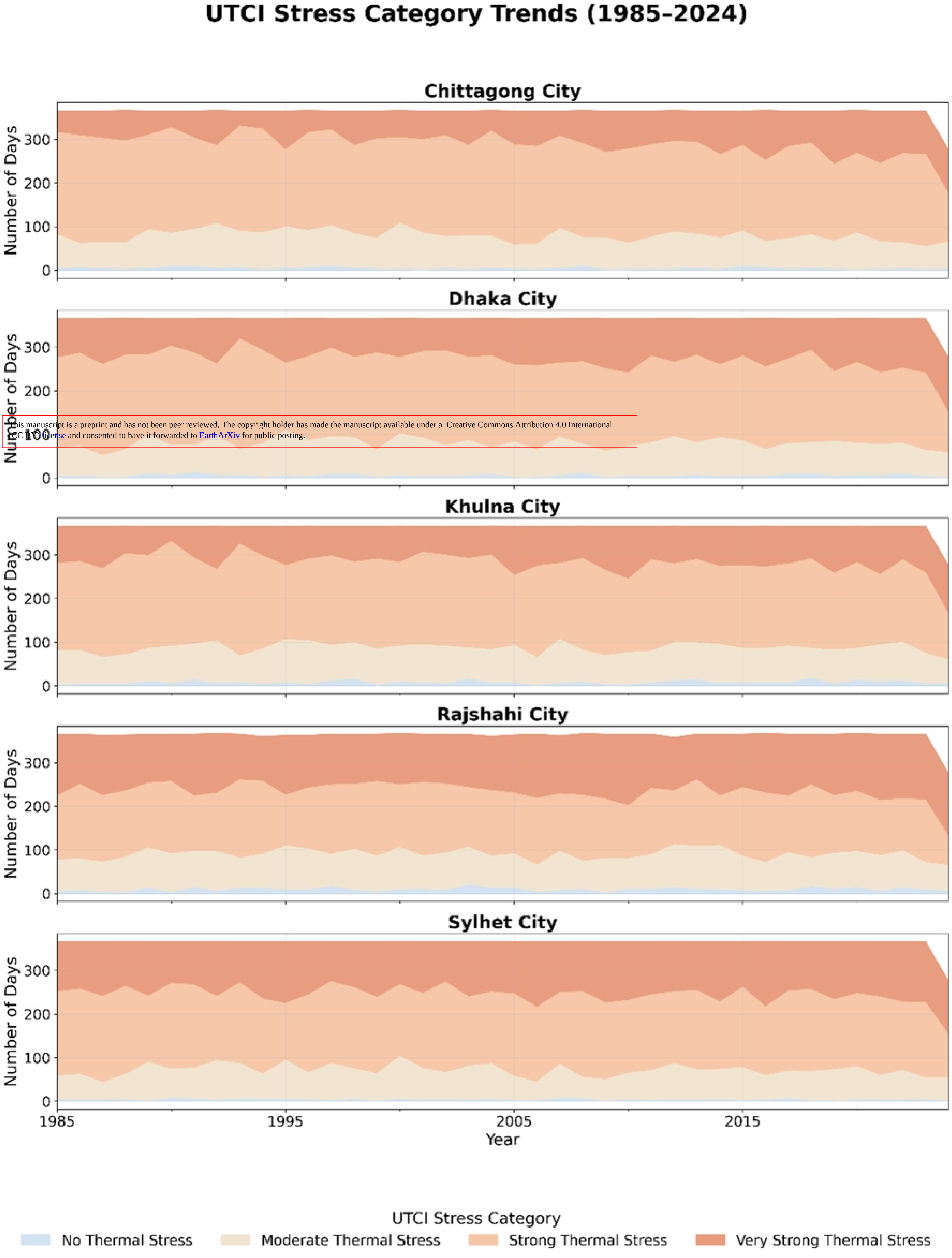
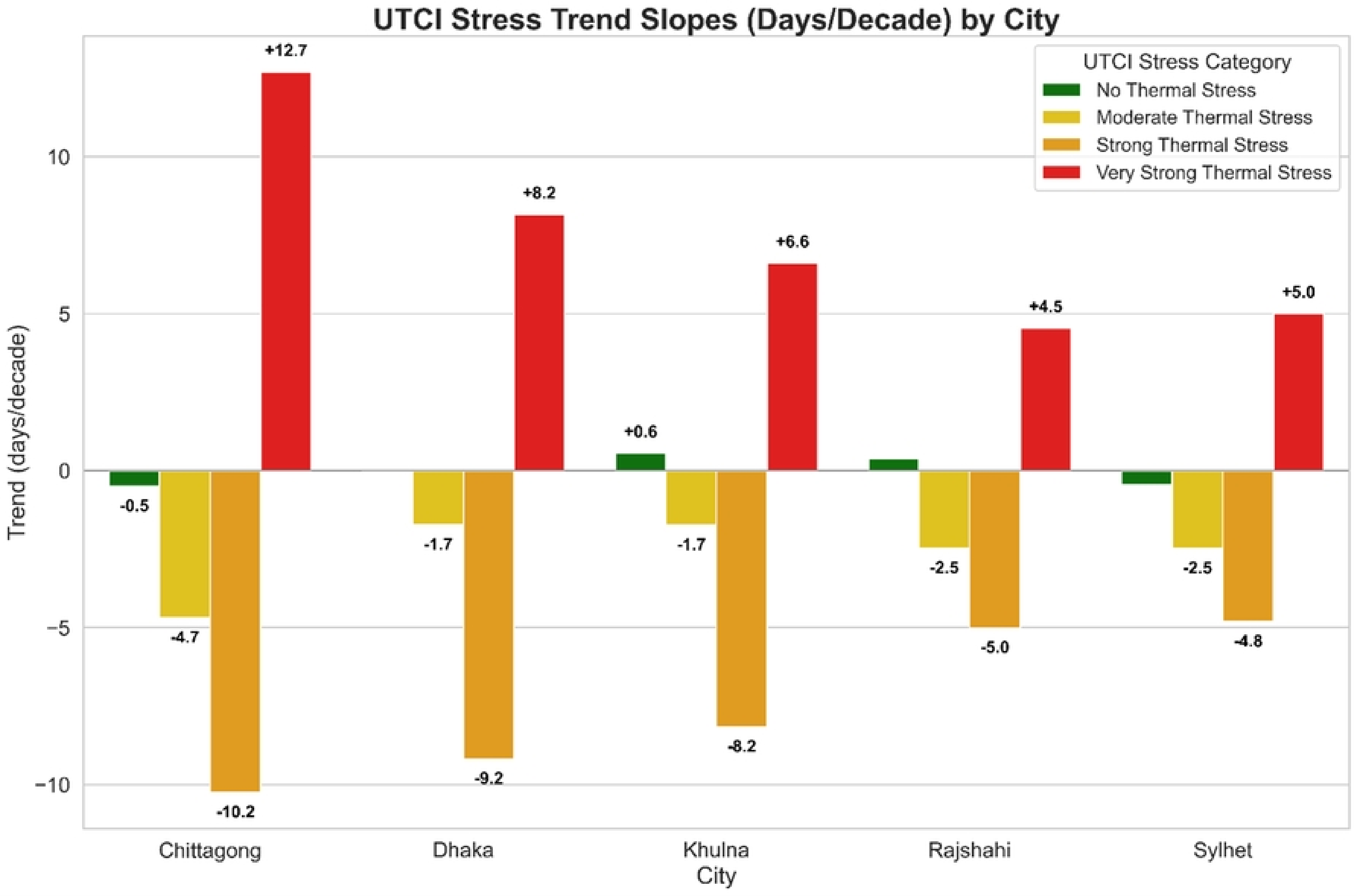
Supporting information

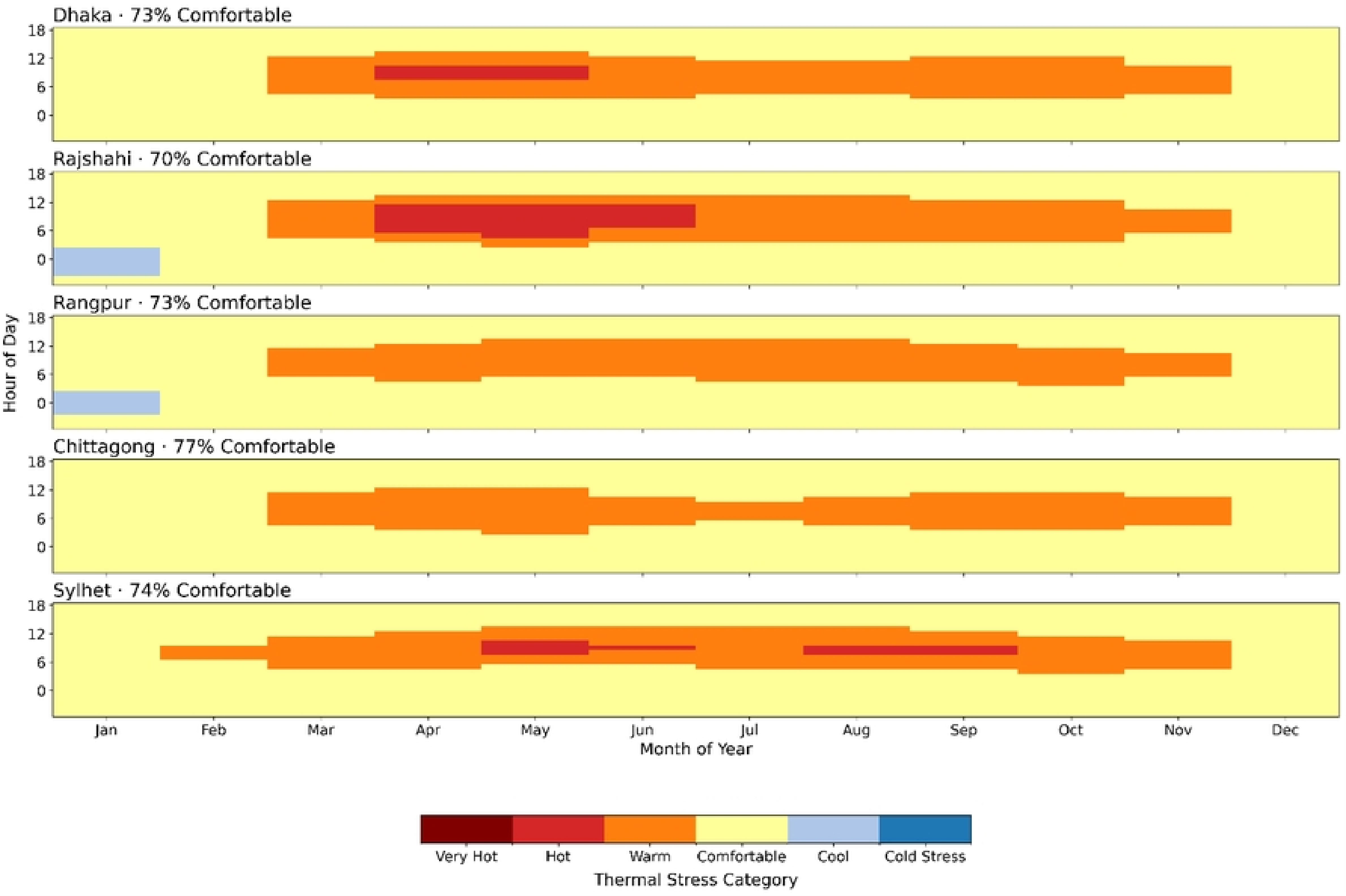
S1 Fig. Spatial visualization framework of decadal UTCI heat stress classification for Bangladesh (1985–2024). The figure systematically arranges UTCI-based categories—*No Thermal Stress, Moderate Heat Stress, Strong Heat Stress,* and *Very Strong Heat Stress*—across minimum (nighttime), mean (average daytime), and maximum (peak daytime) thermal conditions. Each column represents a stress category, while each row corresponds to successive decades.

S2 Fig. Framework for long-term temporal representation of daily maximum Universal Thermal Climate Index (UTCI) across five major Bangladeshi cities (Dhaka, Rajshahi, Chittagong, Sylhet, and Khulna) over the period 1985–2024. The figure applies a 30-day moving average to depict intra-annual variability and multidecadal continuity in daily maximum UTCI values. Distinct color-coded traces represent individual city series, providing a standardized visualization structure for interpreting seasonal cycles and long-term fluctuations in urban thermal environments.

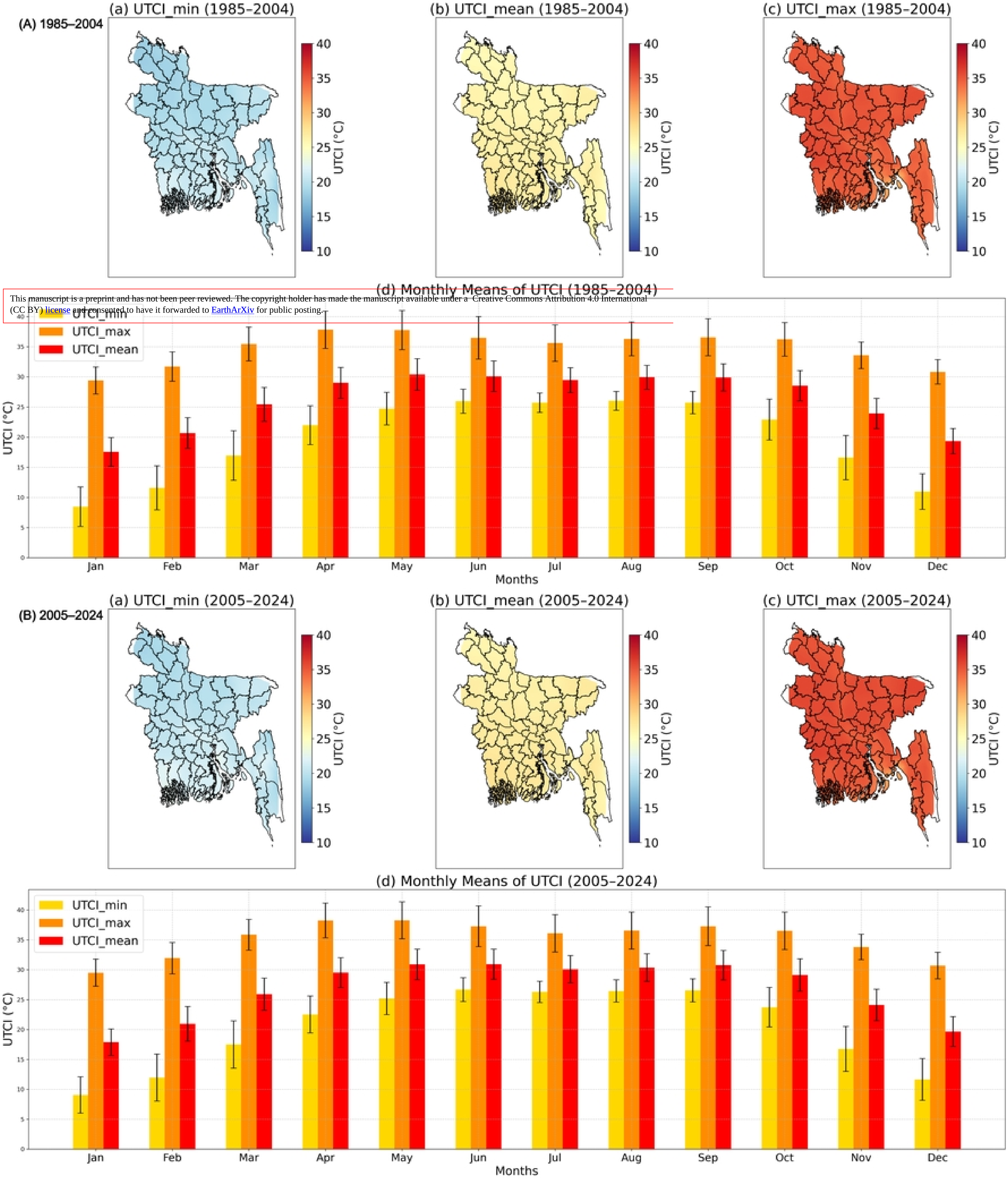

UTCI Stress Category Trends (1985–2024)
Chittagong City
Dhaka City
Khulna City
Rajshahi City
Sylhet City
Number of Days
0
100
200
300
1985
1995
2005
2015
Year
UTCI Stress Category
No Thermal Stress
Moderate Thermal Stress
Strong Thermal Stress
Very Strong Thermal Stress

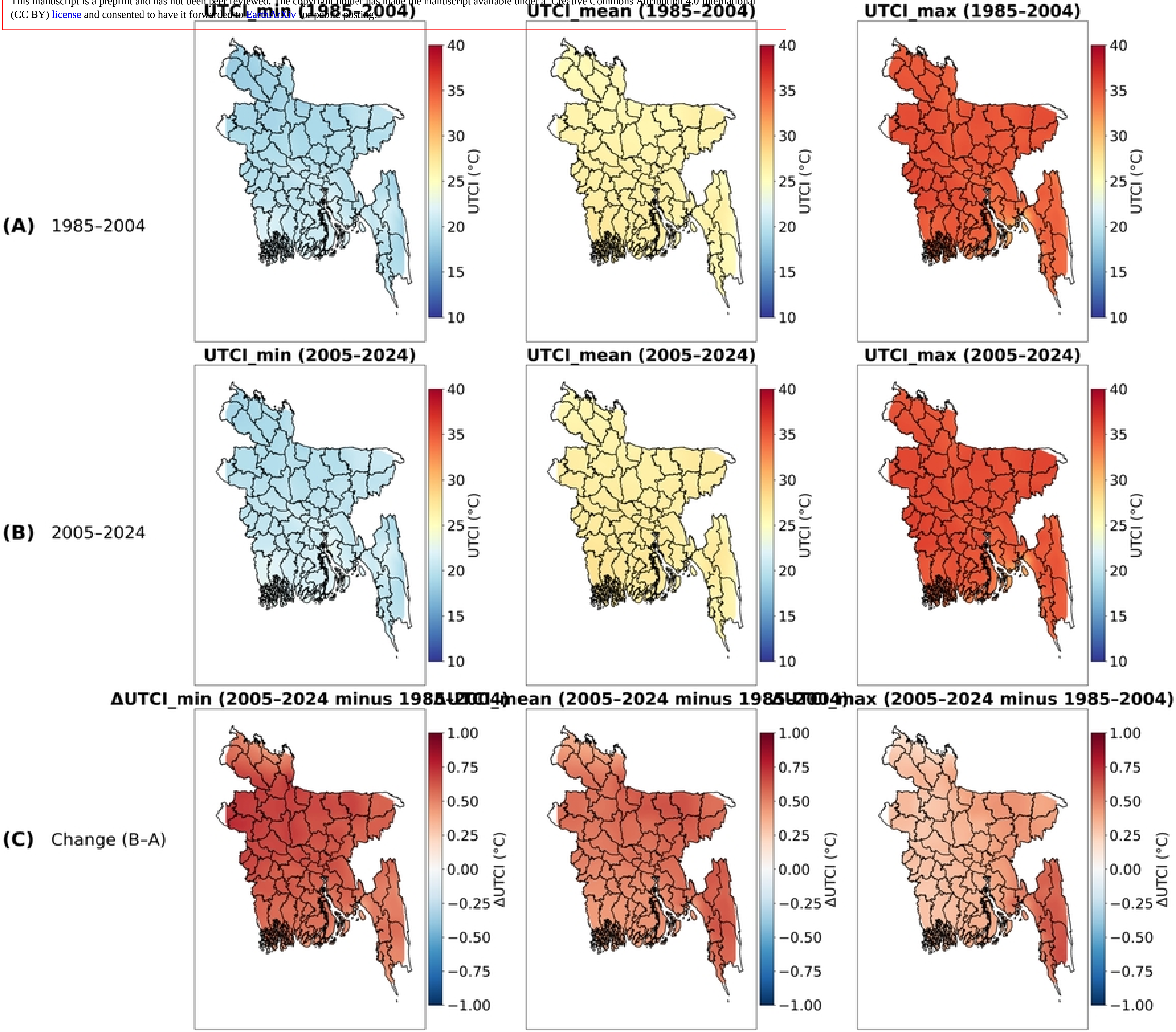


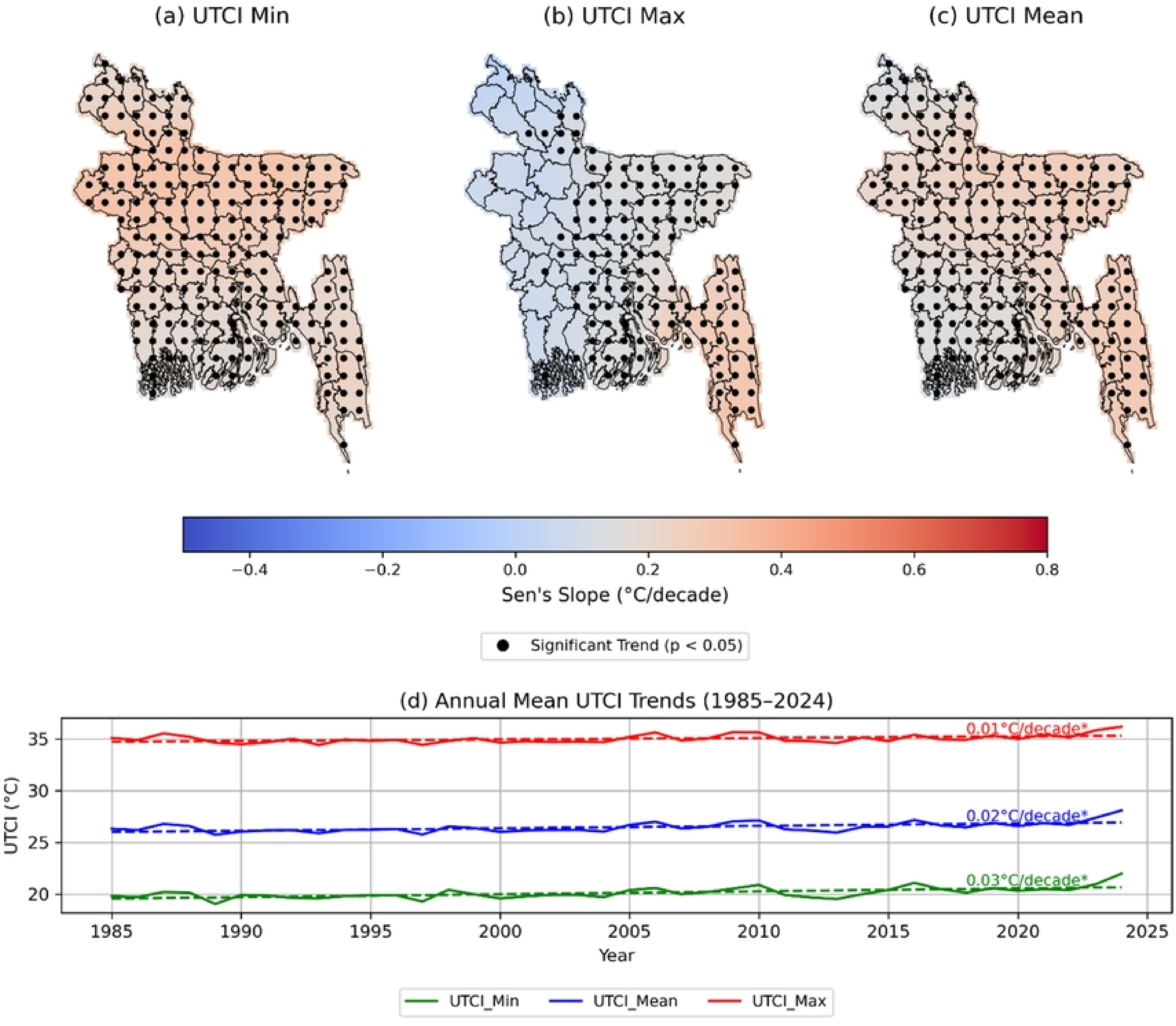
UTCI Stress Trend Slopes (Days/Decade) by City
UTCI Stress Category
No Thermal Stress
Moderate Thermal Stress
Strong Thermal Stress
Very Strong Thermal Stress
Trend (days/decade)
10
5
0
−5
−10
+12.7
-0.5
-4.7
-10.2
+8.2
-1.7
-9.2
+0.6
-1.7
-8.2
+6.6
-2.5
-5.0
+4.5
-2.5
-4.8
+5.0
Chittagong
Dhaka
Khulna
Rajshahi
Sylhet
City

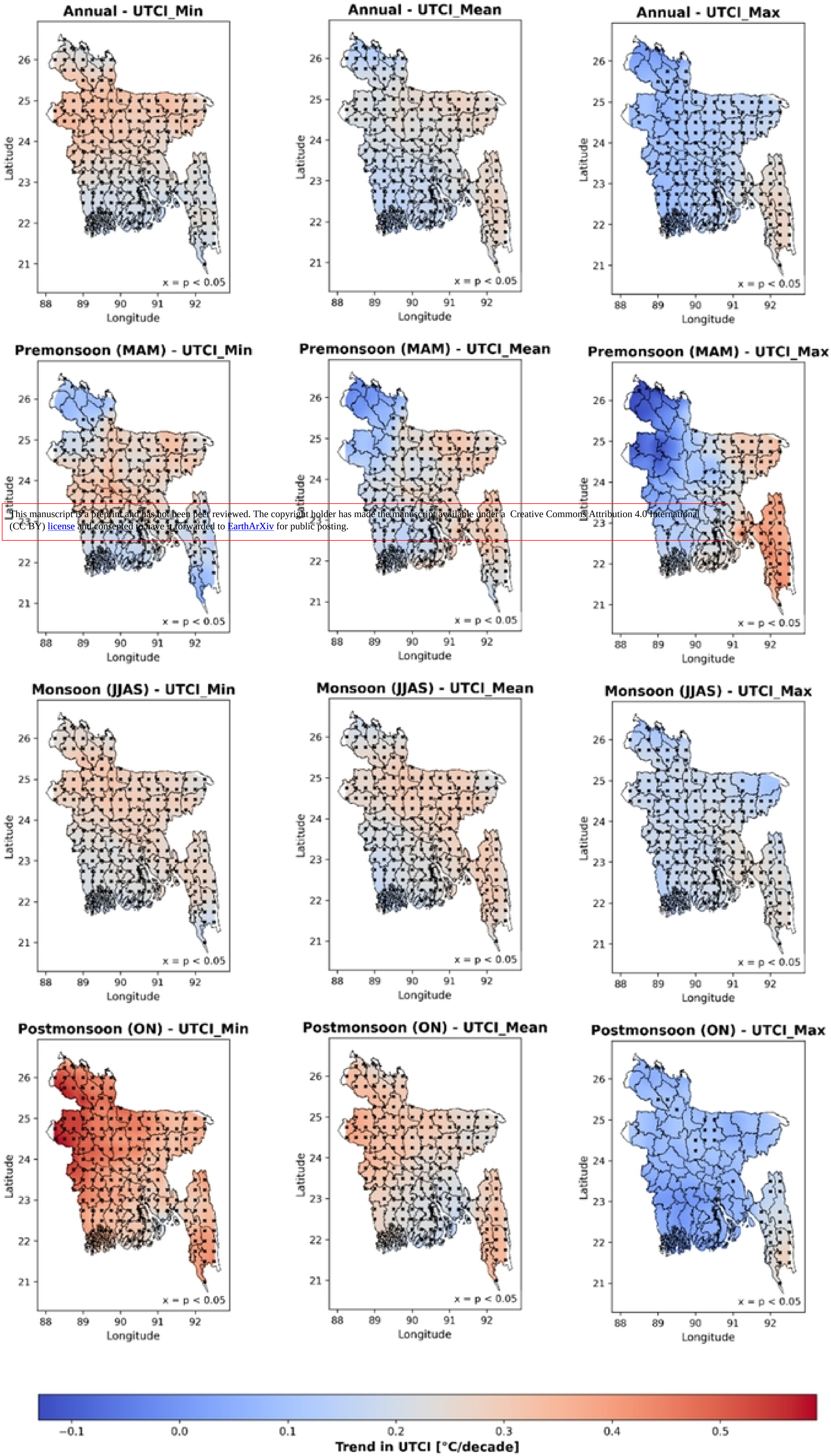


Dhaka · 73% Comfortable
Rajshahi · 70% Comfortable
Rangpur · 73% Comfortable
Chittagong · 77% Comfortable
Sylhet · 74% Comfortable
Hour of Day
18
12
6
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month of Year
Very Hot
Hot
Warm
Comfortable
Cool
Cold Stress
Thermal Stress Category

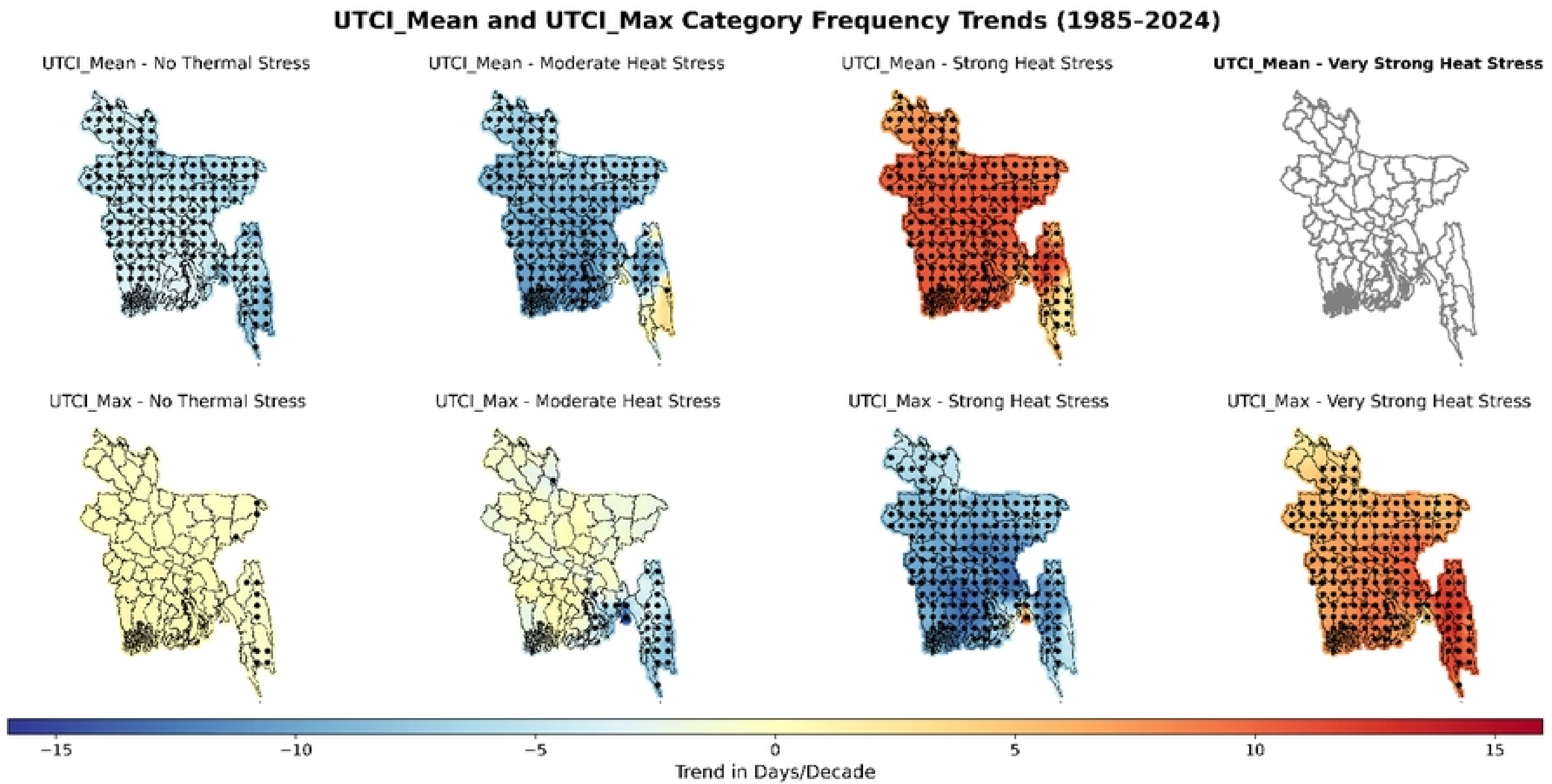

(A) 1985–2004
(a) UTCI_min (1985–2004)
(b) UTCI_mean (1985–2004)
(c) UTCI_max (1985–2004)
UTCI (°C)
10
15
20
25
30
35
40
(d) Monthly Means of UTCI (1985–2004)
UTCI_min
UTCI_max
UTCI_mean
UTCI (°C)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months
(B) 2005–2024
(a) UTCI_min (2005–2024)
(b) UTCI_mean (2005–2024)
(c) UTCI_max (2005–2024)
(d) Monthly Means of UTCI (2005–2024)


UTCI_min (1985–2004)
UTCI_mean (1985–2004)
UTCI_max (1985–2004)
(A) 1985–2004
UTCI_min (2005–2024)
UTCI_mean (2005–2024)
UTCI_max (2005–2024)
(B) 2005–2024
ΔUTCI_min (2005–2024 minus 1985–2004)
ΔUTCI_mean (2005–2024 minus 1985–2004)
ΔUTCI_max (2005–2024 minus 1985–2004)
(C) Change (B–A)
UTCI (°C)
40
35
30
25
20
15
10
ΔUTCI (°C)
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00

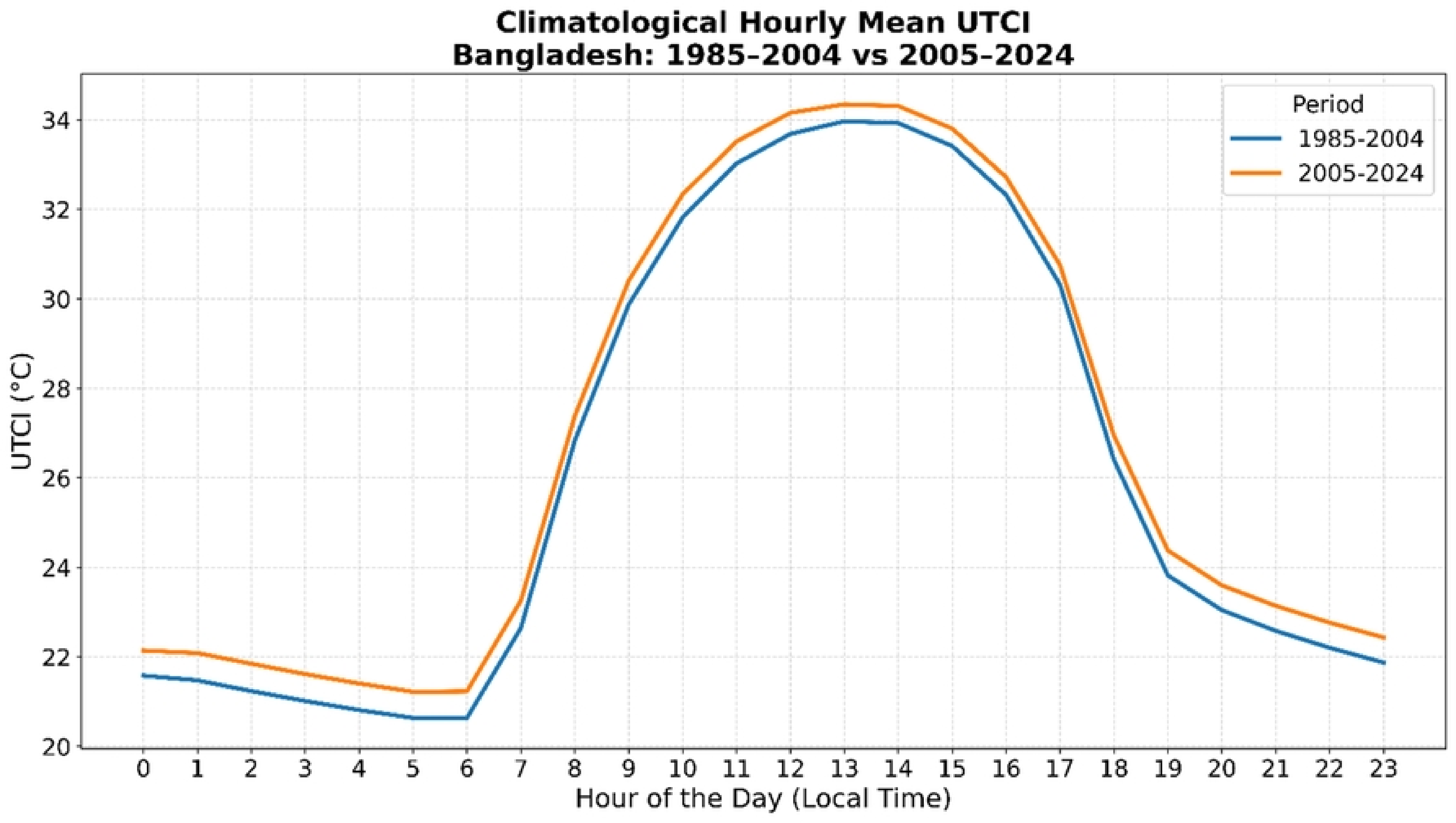

(a) UTCI Min
(b) UTCI Max
(c) UTCI Mean
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
Sen's Slope (°C/decade)
Significant Trend (p < 0.05)
(d) Annual Mean UTCI Trends (1985–2024)
UTCI (°C)
35
30
25
20
0.01°C/decade*
0.02°C/decade*
0.03°C/decade*
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year
UTCI_Min
UTCI_Mean
UTCI_Max



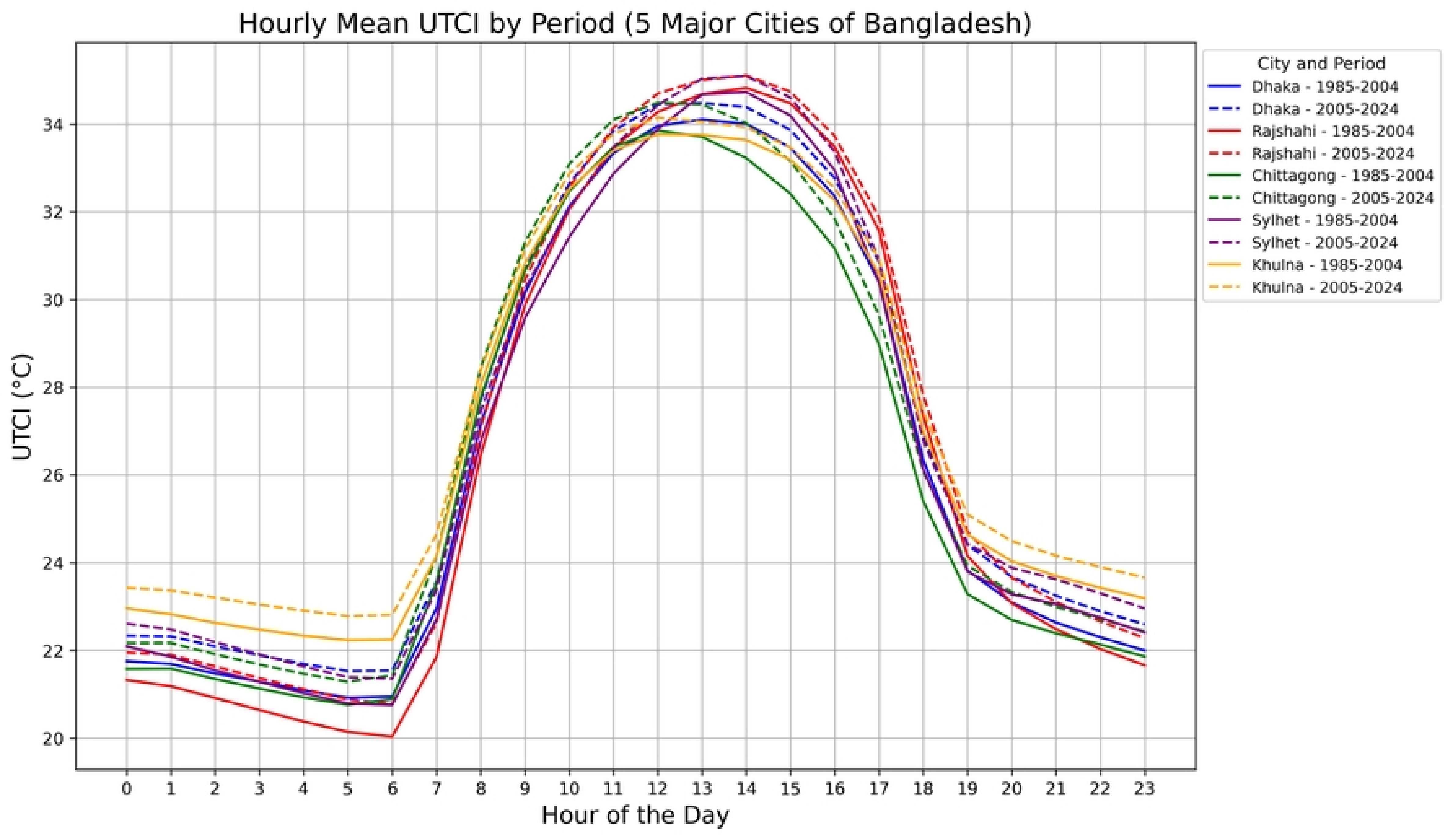
Annual - UTCI_Min
Annual - UTCI_Mean
Annual - UTCI_Max
Premonsoon (MAM) - UTCI_Min
Premonsoon (MAM) - UTCI_Mean
Premonsoon (MAM) - UTCI_Max
Monsoon (JJAS) - UTCI_Min
Monsoon (JJAS) - UTCI_Mean
Monsoon (JJAS) - UTCI_Max
Postmonsoon (ON) - UTCI_Min
Postmonsoon (ON) - UTCI_Mean
Postmonsoon (ON) - UTCI_Max
Latitude
Longitude
x = p < 0.05
−0.1
0.0
0.1
0.2
0.3
0.4
0.5
Trend in UTCI [°C/decade]



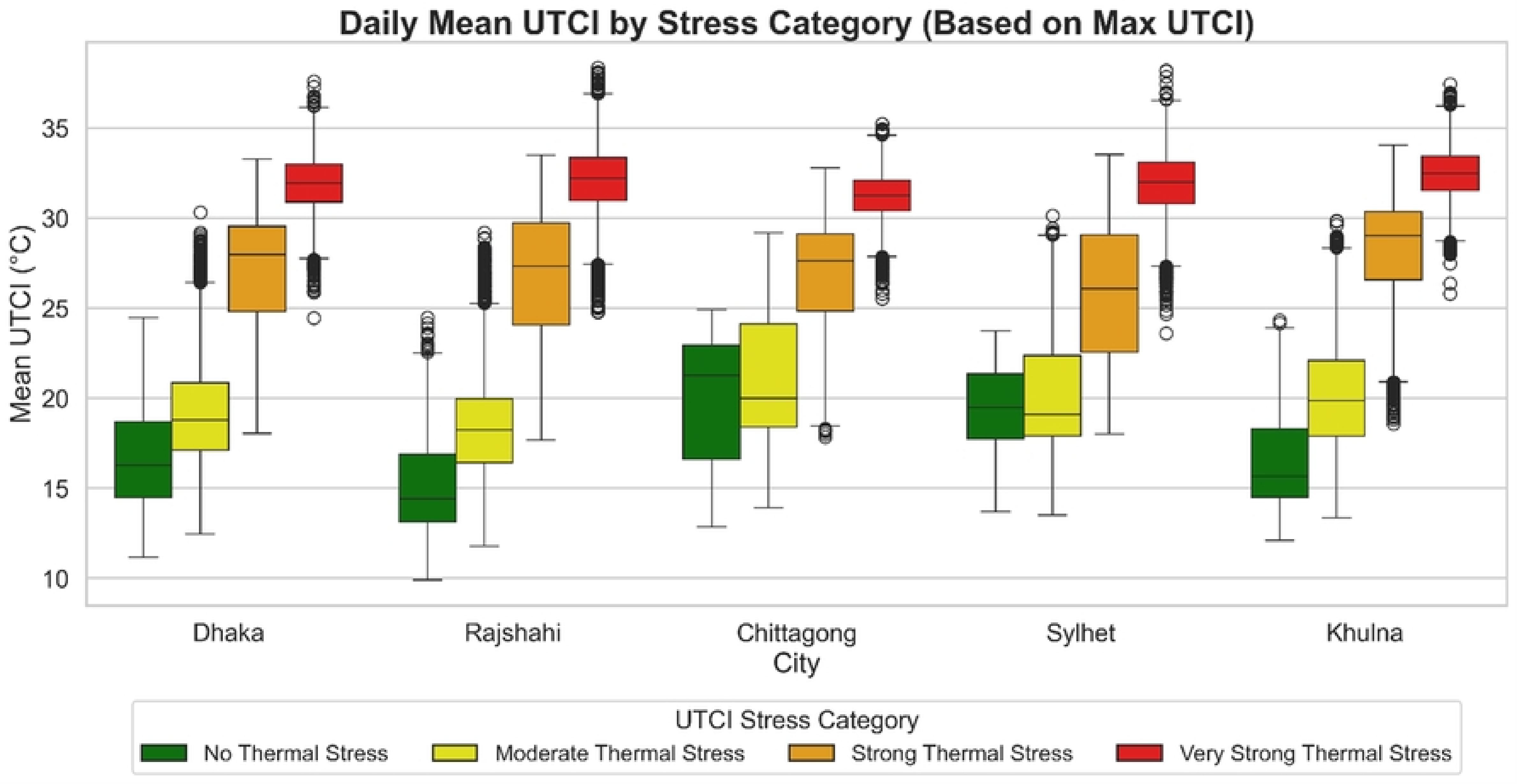
UTCI_Mean and UTCI_Max Category Frequency Trends (1985-2024)
UTCI_Mean - No Thermal Stress
UTCI_Mean - Moderate Heat Stress
UTCI_Mean - Strong Heat Stress
UTCI_Mean - Very Strong Heat Stress
UTCI_Max - No Thermal Stress
UTCI_Max - Moderate Heat Stress
UTCI_Max - Strong Heat Stress
UTCI_Max - Very Strong Heat Stress
−15
−10
−5
0
5
10
15
Trend in Days/Decade



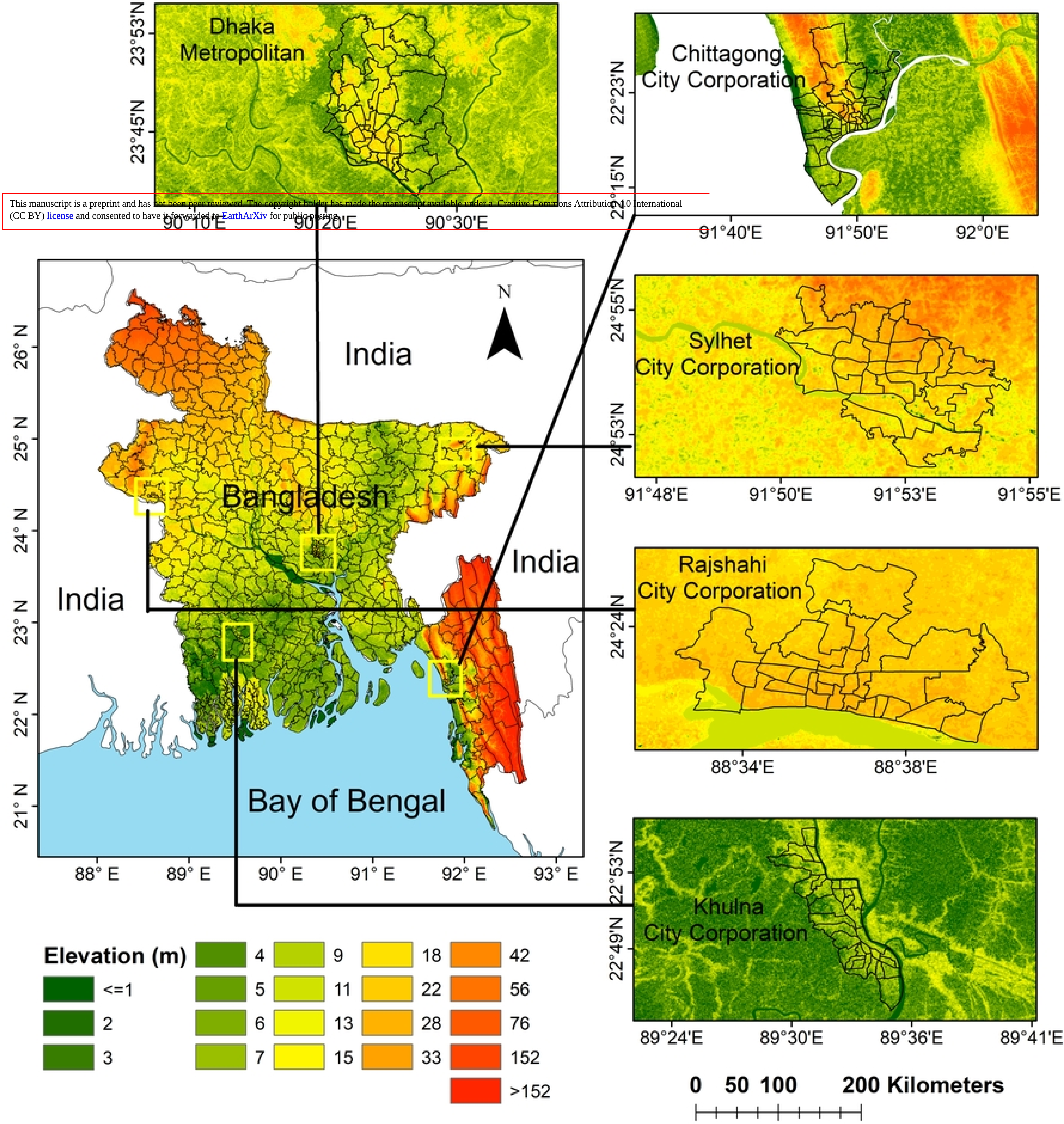
Climatological Hourly Mean UTCI
Bangladesh: 1985–2004 vs 2005–2024
Period
1985-2004
2005-2024
UTCI (°C)
20
22
24
26
28
30
32
34
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour of the Day (Local Time)



Hourly Mean UTCI by Period (5 Major Cities of Bangladesh)
UTCI (°C)
Hour of the Day
City and Period
Dhaka - 1985-2004
Dhaka - 2005-2024
Rajshahi - 1985-2004
Rajshahi - 2005-2024
Chittagong - 1985-2004
Chittagong - 2005-2024
Sylhet - 1985-2004
Sylhet - 2005-2024
Khulna - 1985-2004
Khulna - 2005-2024
20
22
24
26
28
30
32
34
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23



Daily Mean UTCI by Stress Category (Based on Max UTCI)
Mean UTCI (°C)
10
15
20
25
30
35
Dhaka
Rajshahi
Chittagong
Sylhet
Khulna
City
UTCI Stress Category
No Thermal Stress
Moderate Thermal Stress
Strong Thermal Stress
Very Strong Thermal Stress


Dhaka
Metropolitan
23°53'N
23°45'N
90°10'E
90°20'E
90°30'E
Chittagong
City Corporation
22°23'N
22°15'N
91°40'E
91°50'E
92°0'E
Sylhet
City Corporation
24°55'N
24°53'N
91°48'E
91°50'E
91°53'E
91°55'E
Rajshahi
City Corporation
24°24'N
88°34'E
88°38'E
Khulna
City Corporation
22°53'N
22°49'N
89°24'E
89°30'E
89°36'E
89°41'E
N
India
India
India
Bangladesh
Bay of Bengal
26° N
25° N
24° N
23° N
22° N
21° N
88° E
89° E
90° E
91° E
92° E
93° E
Elevation (m)
<=1
2
3
4
5
6
7
9
11
13
15
18
22
28
33
42
56
76
152
>152
0 50 100 200 Kilometers