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Climate change scenario in Bangladesh: historical data analysis and future projection based on CMIP6 model

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During the last two decade, Bangladesh has been experienced a critical climatic anomalies which lead to an increment in enormity and repeat of diverse climate relate extraordinary events. Climate analysts substantiate that around the world temperature and precipitation plan is expected to change, which may result in significant influence on cultivation, work, and organic framework. Bangladesh is subsequently likely to confront critical challenges within the coming decades. In orchestrate to sufficient get it this complex, lively wonders, Analyzing chronicled Climate modify scenarios as well as anticipating its future designs may be a exceptional concern for examiner. This consider focuses to analyzes irrefutable climatic data from (1901–2020), and expect future temperature and precipitation plans in Bangladesh utilizing CMIP6 data. The data utilized in this think-around (Observed data is from CRU TS 4.05 and future data is from CMIP6) have been obtained from WorldClim v2.1. Distinctive techniques tallying relationship, relapse, standard deviation, relationship system, percentiles, cell bits of knowledge, and IDW presentation were performed to analyze the designs, changeability and spatial plans of temperature and precipitation. This think around revealed that Over the irrefutable consider period (1901–2020) Bangladesh has been experienced a vital warming drift with an normal increase in temperature 2 °C and with annually decay of the in general precipitation 607.26 mm adjacent to a move towards drier conditions in show disdain toward of frail relationship with more smoking a long time. Projected climate models talks to that Bangladesh slightest temperature is expected to expand from 1 °C to 4.4 °C as well as most extreme temperatures from 1 °C to 4.1 °C by 2100. In expansion, anticipated precipitation is expected to amplify by 480.38 mm, with the most prominent rises amid storm months. Regional assortments in temperature and precipitation are once more expected, with the Southeast (SE) likely experiencing the first vital warming and the Northeast (NE) seeing the preeminent critical increase in precipitation. In this study highlights the significant impacts of climate change on vulnerable communities in Bangladesh's southwestern coastal region, emphasizing the need for targeted adaptation strategies, local knowledge integration, and proactive national and global level policies to address and manage climate-related challenges.

Keywords Bangladesh, Climate change, Global climate models, Coupled model intercomparison project

Abbreviations

IPCC	Intergovernmental panel on climate change
CCKP	Climate change knowledge portal
WCRP	World climate research programme
GCMs	Global climate models
CMIP	Coupled model intercomparison project
ACCESSCM	Australian Community Climate and Earth System Simulator Model
RCPs	Representative concentration pathway
SSPs	Shared socioeconomic pathways
CRU	Climatic research unit

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GIS	Geographic information system
RS	Remote sensing
IDW	Inverse distance weighting
AIDW	Adjusted inverse distance weighted
SQM	Simple quantile mapping
GBM	Ganges–Brahmaputra–Meghna
NE	Northeast
NW	Northwest
SE	Southeast
SW	Southwest
C or M	Center
T_{min}	Minimum temperature
T_{max}	Maximum temperature

Climate change looms large as the paramount environmental challenge of our era, casting a long shadow over global food security through its manifold impacts on rainfall patterns, rising temperatures, and the escalating frequency of extreme weather phenomena[1,2]. The dynamics of extreme weather—its frequency, intensity, and temporal shifts—have undergone conspicuous transformations globally, regionally, and nationally, all attributable to the juggernaut of climate change[3–6]. Quantifying these changes with precision is paramount for devising effective climate mitigation strategies, especially in regions densely populated yet scant in adaptation options, thus rendering them particularly vulnerable[4].

South Asia, with its intricate atmospheric tapestry and predisposition to extreme weather events, exacerbated by mounting concentrations of greenhouse gases, finds itself increasingly exposed to the vagaries of climate change[7]. Bangladesh, flagged as high-risk by the IPCC (2001), contends with a gamut of natural calamities—from scorching heatwaves and deluging floods to ferocious cyclones and parching droughts—intensifying its climate woes[8,9]. The ripple effects of climate-induced fluctuations in temperature, precipitation, humidity, and wind velocity resonate both globally and locally[10]. Bangladesh's seasonal mosaic—embracing winter, pre-monsoon, monsoon, and post-monsoon phases—witnesses stark temperature escalations in its southeastern fringes in recent times[11,12]. May emerges as the apex of heat, with mercury levels oscillating between 27 °C to 31 °C across diverse regions, occasionally surging to 40 °C in the western expanse[13]. Rainfall paints a diverse canvas nationwide, spanning from 1400 to 4400 mm annually, with a gradient of 7 mm/km from the westward to the eastward[14]. Noteworthy are the evapotranspiration rates pegged at 3.72 mm daily and the daily mean relative humidity steadfastly holding at 80%[15]

Global Climate Models (GCMs), the linchpin for deciphering past and future climates, grapple with intrinsic uncertainties that undercut their veracity at local scales[10,16–22]. The Coupled Model Intercomparison Project (CMIP), leveraging cutting-edge GCMs, furnishes insights into climate dynamics, bolstering IPCC Assessment Reports[23]. CMIP6 augments modeling fidelity with representative concentration pathways (RCPs) and shared socioeconomic pathways (SSPs), offering windows into prospective trajectories[23–29].

The Shared Socioeconomic Pathways (SSPs) are a framework for investigating futures with variable climate change mitigation and adaptation issues[30]. They have been used to evaluate hydropower potential and energy demand in various scenarios[31]. However, these evaluations frequently ignore human vulnerability[32], and their economic growth estimates have been questioned for presuming convergence while underestimating climate change costs for fragile nations[33]. To bridge these gaps, researchers propose scenario matching, expert elicitation, and accounting for growth disruptions in SSP predictions[32,33]. These pathways—SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5—equip stakeholders to brace for impending challenges[34]. Encompassing 27 CMIP6 models, the ensemble forecasts an unbroken ascent in South Asia's mean annual temperature across the twenty-first century under three distinct scenarios. By century's end, temperature escalations are anticipated at 1.2 °C (0.7–2.1 °C) under SSP1-2.6, 2.1 °C (1.5–3.3 °C) under SSP2-4.5, and a striking 4.3 °C (3.2–6.6 °C) under SSP5-8.5 compared to present-day norms. Annual mean precipitation shifts exhibit geographic diversity across South Asian nations, with projections suggesting rises of 17.1% (2.2–49.1%) in Bangladesh, 18.9% (-4.9 to 72%) in Bhutan, 27.3% (5.3–160.5%) in India, 19.5% (-5.9 to 95.6%) in Nepal, 26.4% (6.4–159.7%) in Pakistan, and 25.1% (-8.5 to 61.0%) in Sri Lanka under the SSP5-8.5 framework[35].

Climate permutations—embodying shifts in temperature and precipitation—bear direct socio-economic reverberations for Bangladesh[36]. The nation grapples with the fallout of greenhouse gas emissions, propelled by demographic bulge, rising affluence, urban sprawl, and the heightened carbon footprint of fossil fuels[37]. Coal, diesel, and natural gas-fired plants emit approximately 0.90 kg, 0.76 kg, and 0.566 kg of CO_2 per kWh, respectively[38]. In 2018, methane emissions from enteric fermentation, manure management, direct nitrous oxide emissions, and indirect nitrous oxide emissions comprised 44.0%, 3.6%, 51.5%, and 0.9% of Bangladesh's total GHG emissions, respectively[39]. Bangladesh's vulnerability to natural calamities—ranging from inundating floods and devastating cyclones to debilitating droughts—underscores its susceptibility to the onslaughts of climate change[2]. With temperatures up by 0.5 °C over the last century and profound impacts from tropical cyclones, the imperatives of adaptation and mitigation loom large for the sustainable stewardship of climate dynamics[40–42]

This main objectives of this study seeks to (i) examine climate change patterns: to investigate climate change trends in Bangladesh over the twentieth and twenty-first centuries, (ii) analyze historical climate trends: to review and analyze historical climate data from 1901 to 2020, (iii) assess spatial distribution: to evaluate the spatial distribution of climate trends across the country, specifically concentrate on mapping the distribution of temperature and precipitation, (iv) forecast future climatic scenarios: to utilize emission scenarios from SSPs in CMIP6 Global Climate Models (GCMs) to predict future climatic conditions (Fig. 1).

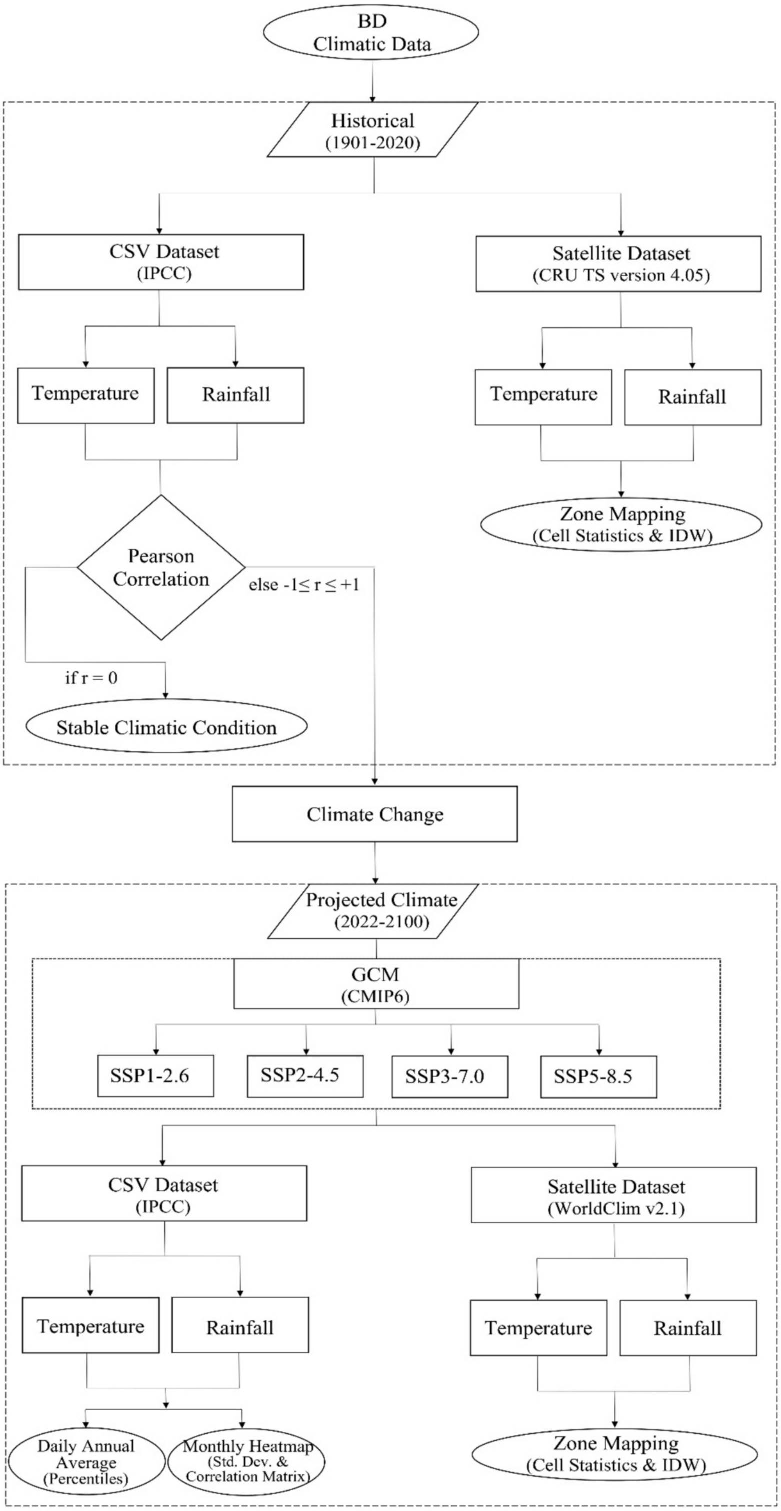

Fig. 1. Framework of the research.

Limitations of the study

i. *Bias correction* The study did not incorporate bias correction techniques for the climate models used as manually. Bias correction is crucial for adjusting systematic errors in model outputs to align more closely with observed data. Without this adjustment, the results may reflect inherent model biases, potentially leading to less accurate or less reliable projections. But CMIP6's downscaled projections, already integrated with improved WorldClim v2.1, offer 10-min resolutions for 20-year periods (2021–2040 to 2081–2100) with bias corrections and refinements.

ii. *Lack of Multi-model ensemble* We did not employ a multi-model ensemble approach using CMIP6 GCMs. Multi-model ensembles, which combine outputs from multiple General Circulation Models (GCMs), provide a more comprehensive view of possible climate scenarios and reduce the uncertainty associated with individual model projections. The absence of this approach may limit the robustness of the findings, as single models might not capture the full range of climate variability and uncertainty

Problem statement

The growing worry about the effects of climate change on societal institutions and resource management necessitates a thorough grasp of possible futures.

i. *Overview of SSPs* The new Shared Socioeconomic Pathways (SSPs) scenarios provide a framework for investigating diverse trajectories of energy use and societal reactions while accounting for varied levels of climate mitigation and adaptation activities.
ii. *Energy use and societal response* SSPs make various assumptions regarding socioeconomic trends, technology breakthroughs, and governmental interventions, reflecting how these elements influence energy consumption patterns and societal resilience.
iii. *Selection rationale* In our analysis, SSPs are chosen to provide a complete view of alternative futures, encompassing a wide range of conceivable outcomes. This selection enables us to evaluate the implications for climate resilience and effectiveness.

Mateials and methods

Study area

Bangladesh is located in South Asia, spanning latitudes 20° 34′ N to 26º 38′ N and longitudes 88° 01′ E to 92° 41′ E. The country covers 148,460 km^2 and is mostly made up of flood plains, with the exception of hilly sections in the southeast and east, which are characterized by deltaic landforms with elevations varying from 1 to 60 m above mean sea level[2,43]**.** In Fig. 2, the study area map of Bangladesh, based on data from 41 meteorological weather stations[44]. This study map divided into five geographical divisions for a comprehensive regional climatic analysis: Northeast (N-E), Northwest (N-W), Center (M), Southeast (S-E), and Southwest (S-W).

Data

Reference data

The CCKP platform offers a comprehensive repository of observed historical climate data spanning the period from 1901 to 2020, facilitating geospatial analysis and seasonal cycle insights[34]. Key to this dataset is the CRU TS version 4.05, renowned for its quality-controlled records of temperature and rainfall derived from numerous global weather stations, excluding Antarctica, mapped on a precise 0.5° latitude by 0.5° longitude grid[45]. Climate projection data on CCKP draws from CMIP6 climate model simulations, a cornerstone of the World Climate Research Program's standardized experiments. These simulations encompass past, present, and future climate scenarios under diverse conditions[23]. CMIP6's downscaled future climate projections, integrated with WorldClim v2.1 as a baseline, offer spatial resolutions at 10-min intervals of longitude and latitude across consecutive 20-year periods (2021–2040, 2041–2060, 2061–2080, 2081–2100)[46]. WorldClim has undergone significant improvements, with implementing bias corrections using streamflow observations to address regional underestimations, and contributing further refinements[47,48]. This framework ensures robust data for studying and anticipating climate dynamics at varying scales (Table 1).

Global climate models (GCMs)

The advancements in CMIP6 modeling are noteworthy, integrating Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs). This amalgamation provides a rich tapestry of perspectives on future scenarios, thereby bolstering preparedness for the challenges inherent in pathways such as SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5[23–29,34].

A significant leap forward is the development of the new version of the Australian Community Climate and Earth System Simulator coupled model (ACCESSCM2). This model is designed to serve a wide array of climate modeling research and applications. Notably, ACCESS-CM2 maintains the same horizontal resolution as its predecessor, ACCESS1.3, with a grid resolution of approximately 135 km in mid-latitude regions (1.258 latitude by 1.8758 longitude). However, the vertical resolution has seen a dramatic enhancement. The older GA1 configuration for ACCESS1.3 had 38 vertical levels, topping out at 40 km. In contrast, the GA7.1 implementation for ACCESS-CM2 boasts 85 levels—50 below 18 km and 35 above, reaching up to 85 km. This improvement is particularly pronounced in the stratospheric resolution[49].

According to Kamruzzaman et al. (2021), as it came to accurately simulating Bangladesh's annual and seasonal rainfall and temperature patterns, MIROC5 showed the most competence among CMIP5 models, while ACCESS-CM2 was the most effective among CMIP6 models. The study also showed that, compared to CMIP5, the CMIP6 multi-model ensemble (MME) significantly outperformed CMIP5 in simulating temperature and rainfall, especially in higher elevation areas during the cold season (winter and post-monsoon), with rainfall showing more notable improvements than temperature[2].

Tools

The research conducted using multiple software tools, such as Excel for data entry and manipulation, SPSS for statistical analysis, Python for data processing and visualization, and ArcGIS and QGIS for spatial analysis.

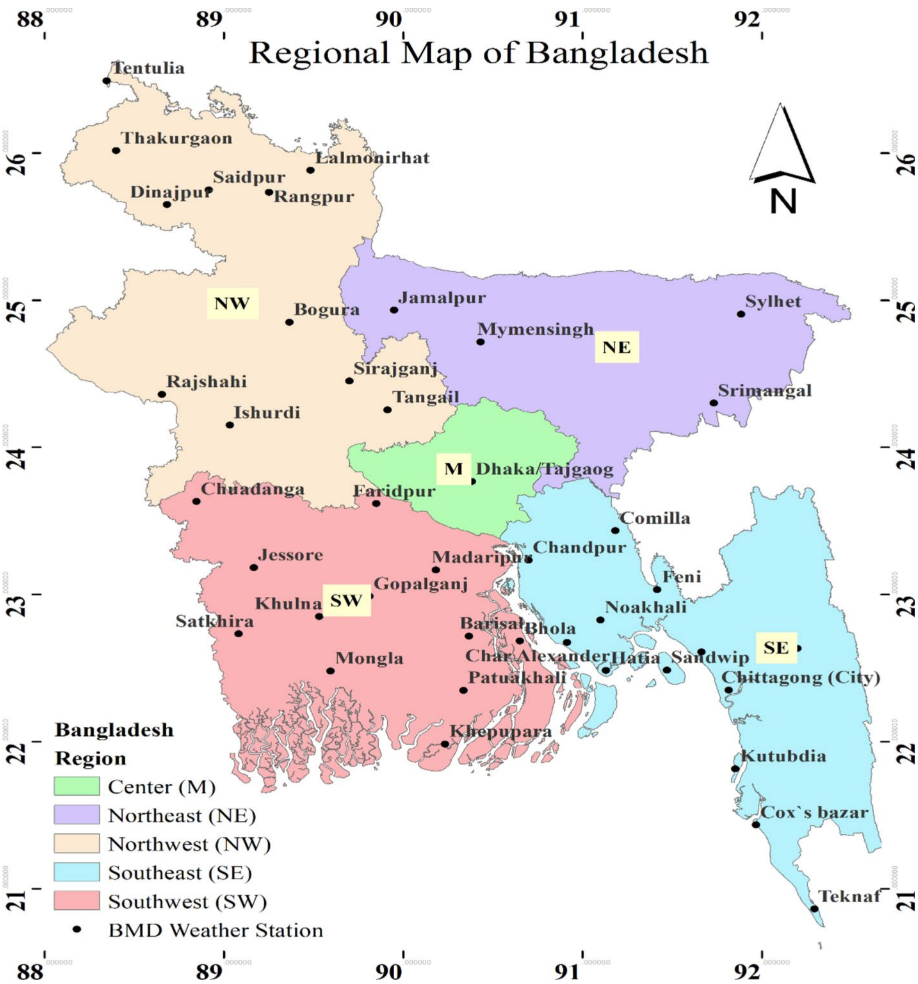

Fig. 2. Regional map with 41 meteorological stations in Bangladesh (complied by author).

Name	Format	Source
Historical Data (1901–2020)	Comma-Separated Values (CSV)	Climate Change Knowledge Portal (CCKP)
Historical Grid Dataset (1901–2020)	Spatial Resolution (0.5° latitude by 0.5° longitude)	CRU TS version 4.05
CMIP6 Dataset	Comma-Separated Values (CSV)	Climate Change Knowledge Portal (CCKP)
CMIP6 Grid Dataset (2021–2100)	Spatial Resolution (10 min longitude by 10 min latitude)	WorldClim v2.1

Table 1. Reference data table.

Methodology

Pearson correlation

The Pearson correlation coefficient, symbolized as 'r' in statistical parlance, serves as a quantifier of the linear correlation between two variables, X and Y. Its value oscillates between -1 and 1. A coefficient of 1 indicates a flawless positive linear correlation, 0 implies the absence of any linear correlation, and -1 signifies a perfect negative linear correlation[50–54]. Correlation coefficient (r) can be calculated by equation (1).

$$r = \frac{\sum_{i=1}^{n}\left(x_{i-}\overline{x}\right)\left(y_i - \overline{y}\right)}{\sqrt{\Sigma_{\mathrm{i}=1}^{n}\left(x_i - \overline{x}\right)^2\Sigma_{\mathrm{i}=1}^{n}\left(y_i - \overline{y}\right)^2}} \tag{1}$$

If we have two variables x and y, and the data take the form of n pairs (i.e. $[x_1, y_1]$, $[x_2, y_2]$, $[x_3, y_3]$, …..$[x_n, y_n$],), where $\overline{x}$ is the mean of the *x* values, and $\overline{y}$ is the mean of the *y* values.

Simple linear regression

Regression analysis, a widely embraced technique in the realm of data analysis, endeavors to extract meaningful insights from experimental data by fitting a function that encapsulates the underlying trend. Often, this involves the application of least squares fitting to align a straight line with the data points—a method known as simple linear regression. This approach facilitates making predictions about the variables under scrutiny[50,51]. To understand this technique, let us start with the equation of a straightline Eq. (2),

$$y = mx + c \tag{2}$$

where *m* is the slope of the line and c is its y-intercept. Since slope and y-intercept determine the orientation and position of the straight line on the *xy* plot, our task is to find their best values.

Standard deviation
Computing the measure of central tendency, such as the mean, offers a distinct advantage: it provides an expectation for future measurements. In essence, it tells us what to anticipate if another measurement is taken. On the other hand, measures of dispersion inform us about the extent of variation or fluctuation around this central value[2,50,55,56]. The most commonly used measure of dispersion is the standard deviation, defined by equation (3),

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n-1}} \tag{3}$$

where σ is the sample standard deviation. x_i is the ith observation in the sample. $\overline{x}$ is the sample mean. n is the sample size. Σ is the summation operator that sums over all observations.

Correlation matrix
In the context of multi-dimensional stochastic volatility models, constructing a correlation matrix involves defining correlations thoughtfully, as noted by Kahl and Günther[57]. This matrix is pivotal for understanding intricate relationships among variables in various domains, including finance and statistics. To effectively visualize and interpret these relationships, correlation plots such as correlation heatmaps are indispensable. These graphical tools provide a concise summary of datasets by depicting variable interdependencies through color gradients and intensity variations. By mapping correlations visually, heatmaps enable analysts to discern patterns, clusters of related variables, and potential outliers[58,59]. The following structure for the correlation matrix[60], defined by equation (4),

$$A = a(i,j)_{1 \le i,j, \le 2n} = \begin{pmatrix} \rho_{(1,1)} & \cdots & \rho_{(1,n)} & \eta_1 & & ? \\ \vdots & & \vdots & & \ddots & \\ \rho_{(n,1)} & \cdots & \rho_{(n,n)} & ? & & \eta_n \\ \eta_1 & & ? & 1 & & ? \\ & \ddots & & & \ddots & \\ ? & & \eta_n & ? & & 1 \end{pmatrix} \tag{4}$$

The structure of such a matrix, defined by Equation (iv), involves placeholders (?), indicating undefined correlations. The completion of such a matrix is a problem directly tied to the graph theory concept of chordal graphs in mathematics. According to Grone et al.[61], Kahl and Günther[57], the completion of symmetric positive definite matrices is feasible if the corresponding graph is chordal and each principal submatrix is positive semidefinite. However, the unique constraints of a correlation matrix—where all entries must satisfy |a(i,j)| < 1—add an additional layer of complexity[57,62].

Percentiles
Percentiles play a crucial role in dividing ordered sample observations into hundred segments, providing a standardized way to gauge distributions. The rank of each percentile, denoted as R_ir (where 1 ≤ i ≤ 99 and 0 ≤ r ≤ 99), follows a specific method known as the Remainder Method, ensuring adherence to the equisegmentation property. This property dictates that each segment contains approximately the same number of observations[63]. Then the following ranks for percentiles satisfy equisegmentation property by the equation (5),

$$R_{ir} = \begin{cases} im + u_{ir}\ if\ \ (r,d) \in A,\ and\ d \le 50 \\ im + u_{ir}\ if\ \ (r,d) \in A,\ and\ d > 50 \\ im + u_{ir}\ if\ \ (r,d) \notin A \end{cases} \tag{5}$$

where i and r are integers with1 ≤ i ≤ 99, 0 ≤ r ≤ 99 , $u_{ir} = i(r+1)/100 = u_{ir} + d/100$ and an admissible set A = {(r,d)} with m = (n − r) /100 ≥ 1 observations in each segment.

Cell statistics
Cell Statistics, a feature available in both ArcGIS Pro and ArcMap, enables the consolidation of values from multiple input rasters into a single output raster. This functionality enhances the analysis of spatial patterns and trends, providing a valuable tool for exploring data patterns[64]. To harmonize spatial resolutions between the different datasets, cell statistics with spatial values are applied for consistency.

Inverse distance weighting (IDW) interpolation
The IDW method estimates unknown values by interpolating known values from nearby points, where the interpolating surface is a weighted average of these points based on their inverse distances distance[65]. However, recognizing the limitations of IDW interpolation, this study introduces an enhanced method called Adjusted Inverse Distance Weighted (AIDW). AIDW incorporates a coefficient (K) into the IDW formula, adjusting distance weights based on the shielded effect of sample point positions. Theoretical analysis and case studies demonstrate that AIDW reduces interpolation errors associated with nonuniform sample point distribution, resulting in more accurate interpolation compared to IDW[66–68]. Additionally, AIDW contour plotting mitigates implausible isolated and concentric circles observed in IDW interpolation, yielding contours more consistent with professional manual identification techniques[69].

The following IDW, defined by Eq. (6),

$$z = \frac{\sum_i^n \frac{z_i}{d_i}}{\sum_i^n \frac{1}{d_i}} \tag{6}$$

where Here, di represents the distance from the interpolation point to each known point, and p is the distance power. When p is low (close to 0), all points contribute relatively equally to the interpolated value regardless of distance. As p increases, points closer to the interpolation location have a greater influence, and distant points contribute less. A higher p value thus emphasizes nearby values more strongly, resulting in a smoother interpolation surface in areas where data points are densely distributed.

Map classification
The statistical analysis of the climatic variables by map provides a clear and concise visualization of the changing temperature and rainfall patterns by 5 class (low-1, moderate-2, high-3, higher-4, highest-5), which highlights the patterns, as well as the spatial and temporal variations in this trend.

Results
Historical climatic data (1901–2022)
Analyzing Bangladesh's historical climate data (1901–2022) suggests a warming trend, with rising temperatures and changes in precipitation patterns[34]. Over the last century, average temperatures have risen, with recent decades seeing the most substantial warming. Rainfall patterns are becoming increasingly irregular, with catastrophic occurrences such as floods and droughts intensifying. These shifts are attributable to global climate change, which is providing enormous difficulties to Bangladesh's agriculture, water resources, and public health.

Observed temperature
Figure 3 shows variations in mean temperature, Tmin, and Tmax as well as historical variations in the yearly daily average air surface temperature from 1901 to 2022. Equation y = 0.005x + 15.49 indicates a rising tendency in the annual daily average mean air surface temperature, which fluctuates between 24.64 °C and 26.60 °C. The yearly daily average air surface temperature has increased from 20.10 °C to 21.73 °C (trend y = 0.005x + 11.45) and from 29.24 °C to 31.57 °C (trend y = 0.005x + 19.64) throughout the course of the century. Interestingly, the statistics show that temperatures have been rising steadily over time.

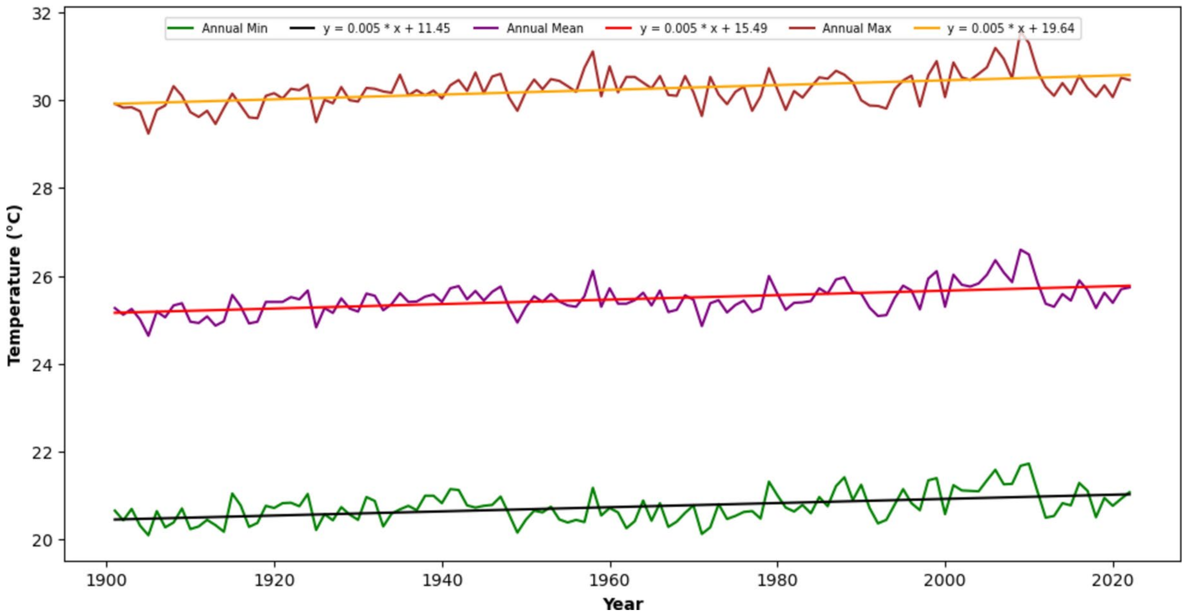

Fig. 3. Observed annual daily average surface air temperature of Bangladesh (1901–2022).

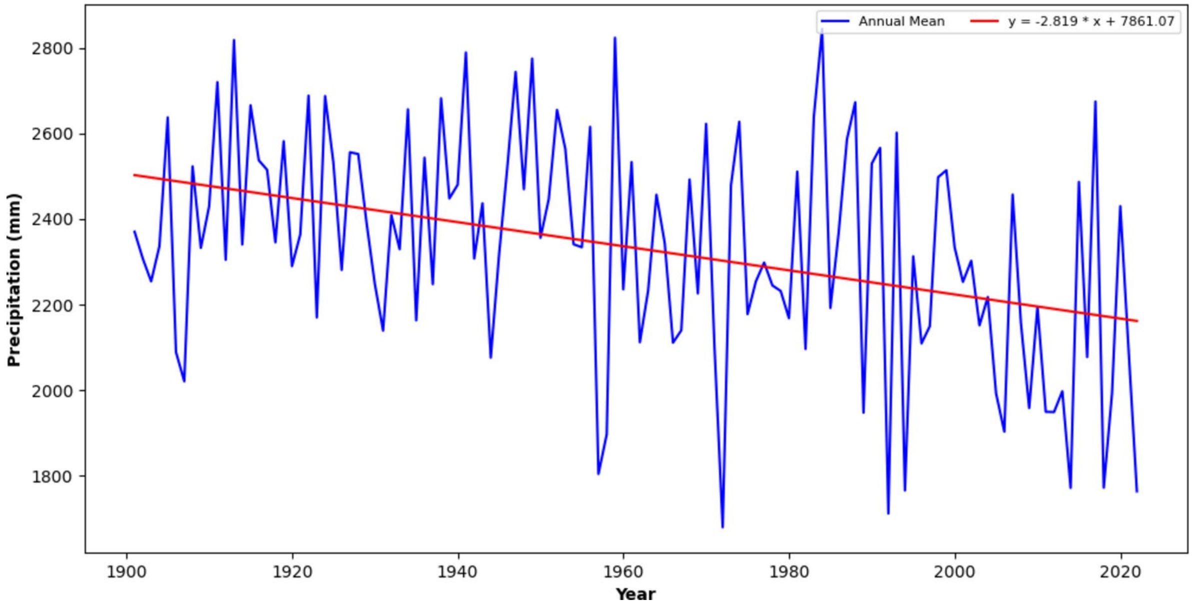

Fig. 4. Observed annual precipitation of Bangladesh (1901–2022).

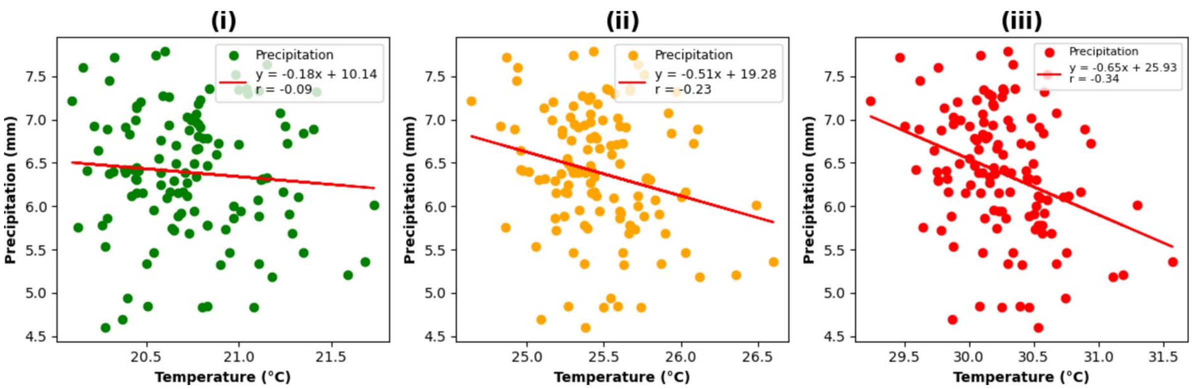

Fig. 5. Observed annual daily average temperature vs precipitation relation in Bangladesh (1901–2022). [(i) Tmin–Pre; (ii) Tmean–Pre; (iii) Tmax- Pre].

Observed precipitation

Figure 4 illustrates historical variations in annual precipitation from 1901 to 2022. The equation $y = -2.819x + 7861.07$ shows the pattern of annual precipitation, which spans from 1678.22 mm to 2843.91 mm. The equation therefore shows how Bangladesh's yearly precipitation is expected to decrease with each subsequent year. This is concerning as it suggests that the nation may be moving toward drier weather.

Observed temperature vs precipitation trend

Figure 5 shows the intricate relationship that develops between temperature and precipitation in Bangladesh (1901–2022),. It's a modest relationship, but hotter years often see somewhat less rain. With rising temperatures, there is a gradual drop in the yearly daily average precipitation. Within the correlation value of $r = -0.09$, the link between (i) Tmin and precipitation is represented by the equation $y = -0.18x + 10.14$. Moreover, for the Tmax $y = -0.65x + 25.93$, $r = -0.34$, and the (ii) mean $y = -0.51x + 19.28$, $r = -0.23$ respectively. Rainfall patterns may also be influenced by other causes, as indicated by the weak relationship revealed by all those correlation coefficients. In-depth research on this complex link is necessary because future water resource management and adaptation plans in Bangladesh depend on a knowledge of the interactions between these important climatic factors.

Historical climatic zone mapping (1901–2020)

The analysis of climate change reveals the changes in climatic variable time series in Bangladesh during the period of 1901–2020.

Historical temperature zone mapping
Figure 6 illustrates decade-wise annual daily average Tmin mapping in Bangladesh, the given region from 1901 to 2020. Between 1901 and 1910, temperatures range from 8.79 to 14.54 degrees Celsius. Subsequent decades show fluctuations- in 1911 to 1920 the temperature varies between 10.9 °C and 15.98 °C, 1921 to 1930 it ranges from 10.7 °C to 15.99 °C, 1931 to 1940 it fluctuates between 10.5 °C and 15.66 °C. The temperature range in 1941–1950 is 9.9 °C to 15.07 °C, 1951–1960 it varies from 8.9 °C to 14.08 °C, 1961–1970 it ranges from 10.1 °C to 15.78 °C, 1971–1980 it fluctuates between 9.8 °C and 15.62 °C, 1981–1990 it spans from 10.32 °C to 15.94 °C, 1991–2000 it ranges from 9.5 °C to 14.8 °C, 2001–2010 it varies from 10.5 °C to 15.61 °C and 2011–2020 the temperature fluctuates between 9.6 °C to 14.89 °C. Also, the individual images of this clearly depict how the temperature zone shifted in different region of the country for each decade of historical time period. In fact, it's range shifting from high to highest in the Southeast (SE) region. Similarly, Northeast (NE) and Northwest (NW) regions experienced low to high temperature. Also, the Central (M) and Southwest (SW) regions experienced high to highest temperatures at various times.

Figure 7 illustrates decade-wise annual daily average Tmax mapping in Bangladesh the given region from 1901 to 2020. Between 1901 and 1910, temperatures range from 21.82 to 26.4 degrees Celsius. Subsequent decades show fluctuations- in 1911 to 1920 the temperature varies between 24.3 °C and 27.2 °C, 1921 to 1930 it

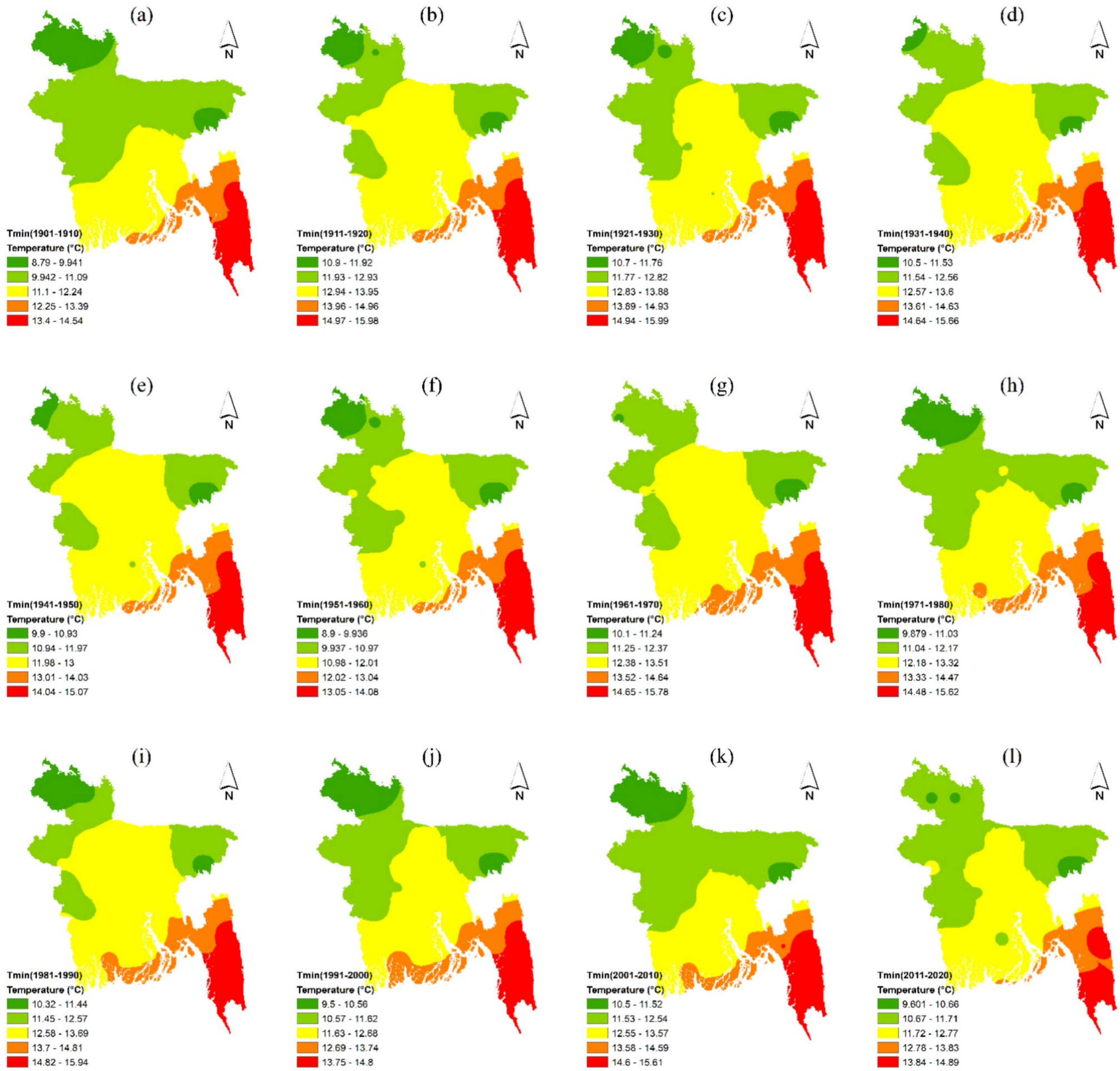

Fig. 6. Historical annual average daily Tmin mapping in Bangladesh (1901–2020). [decadal time period- (**a**) 1901–1910; (**b**) 1911–1920; (**c**) 1921–1930; (**d**)1931–1940; (**e**) 1941–1950, (**f**) 1951–196; (**g**) 1961–1970; (**h**) 1971–1980; (**i**) 1981–1990; (**j**) 1991–2000; (**k**) 2001–2010; (**l**) 2011–2020].

ranges from 24.09 °C to 27.5 °C, 1931 to 1940 it fluctuates between 24.6 °C and 28.1 °C. The temperature range in 1941–1950 is 23.31 °C to 27.3 °C, 1951–1960 it varies from 23.5 °C to 26.8 °C, 1961–1970 it ranges from 24.22 °C to 27.8 °C, 1971–1980 it fluctuates between 23.57 °C and 26.6 °C, 1981–1990 it spans from 21.96 °C to 26.3 °C, 1991–2000 it ranges from 22.37 °C to 26.1 °C, 2001–2010 it varies from 26.1 °C to 28.3 °C and 2011–2020 the temperature fluctuates between 23.88 °C to 27 °C. Also, the individual images of this clearly depict how the temperature zone has been shifted in different region of the country for each decade of historical time period. In fact, it's range shifting from higher to highest in the Southeast (SE) region. Similarly, Northeast (NE) and Northwest (NW) regions experienced moderate to high temperature. Also, the Central (M) and Southwest (SW) regions experienced high to higher temperatures at various times.

Historical precipitation zone mapping

Figure 8 illustrates decade-wise annual daily average precipitation mapping of Bangladesh the given region from 1901 to 2020. Between 1901 and 1910, precipitation range from 9.52 mm to 38.99 mm. Subsequent decades show fluctuations- in 1911 to 1920 the precipitation varies between 1.4 mm and 49 mm, 1921 to 1930 it ranges from 13.03 mm to 45.49 mm, 1931 to 1940 it fluctuates between 0.10 mm and 9.49 mm. The precipitation range in 1941–1950 is 1.4 mm to 27.29 mm, 1951–1960 it varies from 0 mm to 9.69 mm, 1961–1970 it ranges from 2.30 mm to 19.09 mm, 1971–1980 it fluctuates between 6.70 mm and 30.09 mm, 1981–1990 it spans from 18.41 mm to 42.99 mm, 1991–2000 it ranges from 11.02 mm to 32.49 mm, 2001–2010 it varies from 0.11 mm to

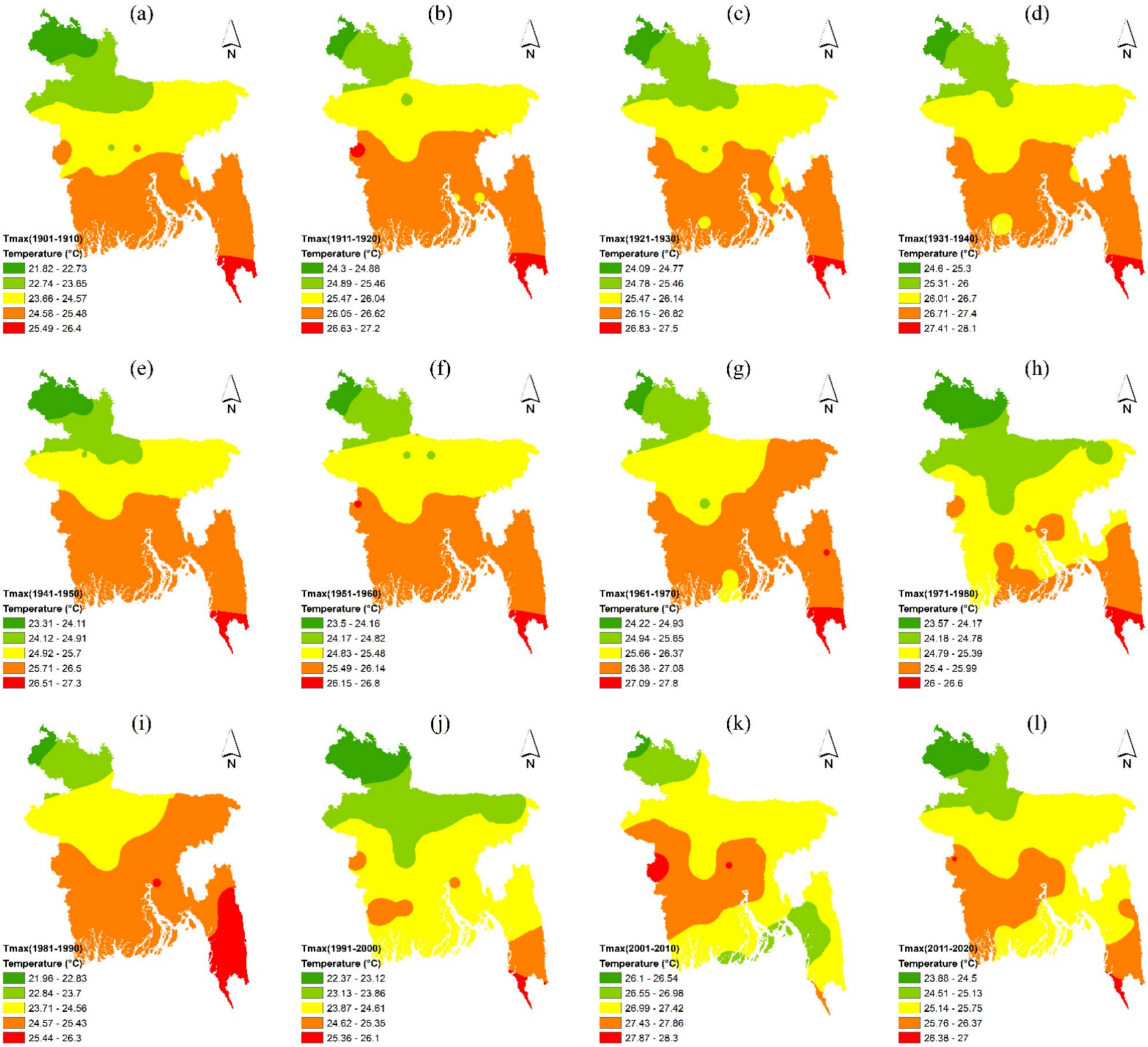

Fig. 7. Historical annual average daily Tmax mapping in Bangladesh (1901–2020). [decadal time period- (**a**) 1901–1910; (**b**) 1911–1920; (**c**) 1921–1930; (**d**) 1931–1940; (**e**) 1941–1950, (**f**) 1951–1960; (**g**) 1961–1970; (**h**) 1971–1980; (**i**) 1981–1990; (**j**) 1991–2000; (**k**) 2001–2010; (**l**) 2011–2020].

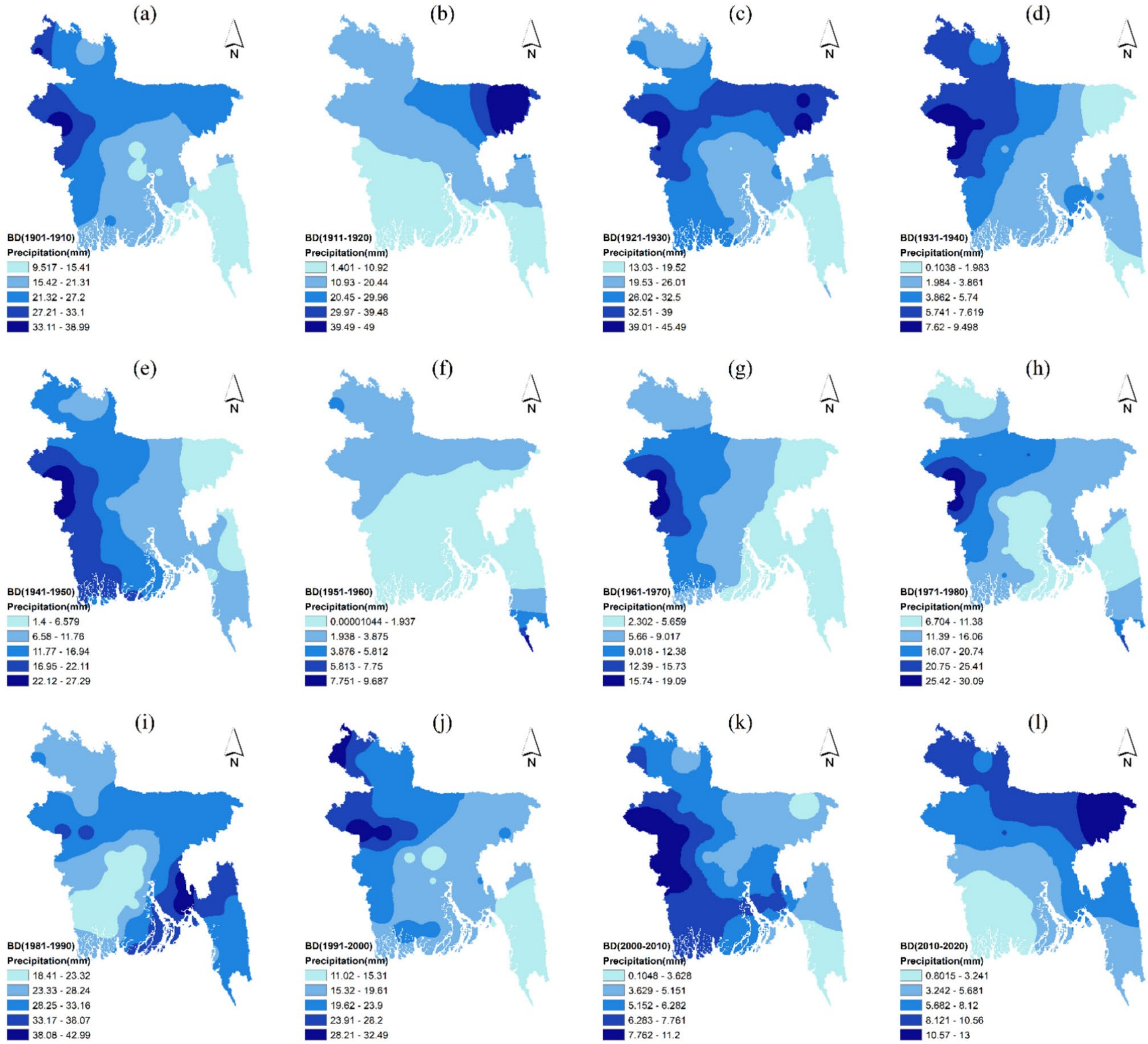

Fig. 8. Historical annual average daily precipitation mapping of Bangladesh (1901–2020). [decadal time period- (**a**) 1901–1910; (**b**) 1911–1920; (**c**) 1921–1930; (**d**) 1931–1940; (**e**) 1941–1950, (**f**) 1951–1960; (**g**) 1961–1970; (**h**) 1971–1980; (**i**) 1981–1990; (**j**) 1991–2000; (**k**) 2001–2010; (**l**) 2011–2020].

11.2 mm and 2011–2020 the temperature fluctuates between 0.80 mm to 13 mm. Also, the individual images of this figure clearly depict how the precipitation has changed in different parts of the country every decade. In fact, it's range low to moderate in the Southeast (S-E) region. Similarly, Northeast (N-E) and Northwest (NW) regions experienced low to very high precipitation. Also, the Central (M) and Southeast (S-E) regions experienced low to high precipitation at various times.

CMIP6 model based projected climate (2022–2100)

In their study using CMIP6, projected shifts in precipitation and temperatures across Bangladesh. They employed Simple Quantile Mapping (SQM) to correct biases in Global Climate Models (GCMs). The Multi-Model Ensemble (MME) mean of these adjusted datasets assessed changes under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios for near, mid, and far future periods compared to historical records[2].

Projected temperature

Figure 9 depicts that the projected annual daily average surface air Tmin in Bangladesh is expected to increase from 1950 to 2100 under all four SSPs. However, the rate of increase will vary depending on the SSP. In the historical reference period (1950–2014), the temperature range 21.21 °C–21.6 °C. But in the projected period (2014–2100), the Tmin reach at 21.6 °C to 22.6 °C for SSP1-2.6, representing an increase of about 1 °C. Similarly, for SSP2-4.5, SSP3-7.0 and SSP5-8.5 it will reach at respectively 21.6 °C to 23.56 °C, 21.6 °C to 24.92 °C and

21.6 °C to 26.04 °C. In this case, it is clearly seen that the future temperature will increase by ~ 2 °C, 3.3 °C and 4.4 °C respectively.

Figure 10 illustrate that the projected increase in annual monthly one-day average surface air Tmin in Bangladesh is expected to vary depending on the different SSP scenario. The highest SSP scenario (SSP5-8.5) projected the highest increase in Tmin, while the lowest SSP scenario (SSP1-2.6) projected the smallest increasement with fluctuation. The SSP2-4.5 and SSP3-7.0 depicts medium level of temperature variation.

Figure 11 shows that under all four SSPs, the predicted yearly daily average surface air Tmax in Bangladesh is forecast to rise from 1950 to 2100. But the pace of growth will differ according on the SSP. The temperature range in the historical reference period (1950–2014) was 30.1 °C to 30.2 °C. However, with SSP1-2.6, the Tmax reach around 30.2 °C to 31.15 °C in the anticipated period (2014–2100), indicating a rise of around 1 °C. In a similar vein, it reached 30.2 °C to 31.86 °C for SSP2-4.5, 30.2 °C to 32.78 °C for SSP3-7.0, and 30.2 °C to 34.32 °C for SSP5-8.5. In this instance, it is evident that there will be future temperature increases of 1.7 °C, 2.6 °C, and 4.1 °C, respectively.

Figure 12 shows how different SSP scenarios will have varied effects on Bangladesh's estimated yearly monthly one-day average surface air temperature increase. The predicted medium level of temperature variation was SSP2-4.5 and SSP3-7.0. The maximum Tmax rise was predicted by the greatest SSP scenario (SSP5-8.5), whereas the minimum increase with variation was predicted by the lowest SSP scenario (SSP1-2.6).

Projected precipitation

Figure 13 all four SSPs predict that Bangladesh's yearly precipitation will rise between 1950 and 2100. Nevertheless, the pace of rise varies according on the SSP. Precipitation ranged from 2195.94 mm to 2382.77 mm over the historical reference period (1950–2014). However, throughout the anticipated period (2014–2100), SSP1-2.6 had precipitation ranging from 2161.12 mm to 2325.37 mm. The same will apply to SSP2-4.5, SSP3-7.0, and SSP5-8.5, reaching 2161.12 mm to 2354.33 mm, 2495.61 mm, and 2676.32 mm, respectively. In this instance, it is evident that a very low amount of future rainfall will grow dramatically.

Figure 14 shows how different SSP scenarios will have varying effects on Bangladesh's anticipated yearly precipitation increases. The lowest SSP scenario (SSP1-2.6) predicted the least amount of increase with little variability, whereas the highest SSP scenario (SSP5-8.5) anticipated the biggest increase in precipitation. The predicted medium level medium variation for SSP2-4.5 and SSP3-7.0 is shown.

Projected climatic zone mapping (2022–2100)

Projections of future climate change are crucial for understanding and preparing for the impacts of a warming planet. This is particularly relevant for Bangladesh, a nation vulnerable to the effects of rising temperatures and changing precipitation patterns. CMIP6 climate models to map projected climate changes for Bangladesh over the 21's century.

Projected temperature zone mapping

Figure 15 depicts between double decadal projections of annual daily average Tmin in Bangladesh from 2021 to 2100. Between 2021 and 2040, the temperature ranges for SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 are respectively projected 20.94 °C–23.08 °C, 21.18 °C–23.18 °C, 21.13 °C–23.17 °C, and 21.14 °C–23.14 °C.

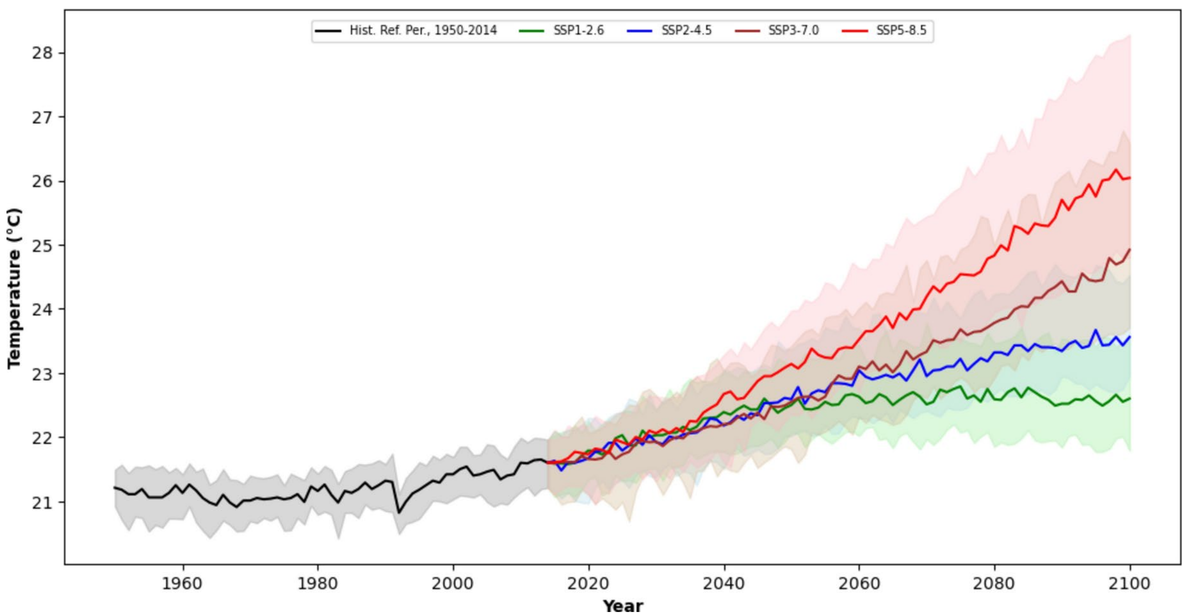

Fig. 9. Projected annual daily average surface air tmin of Bangladesh (ref. period 1995–2014), multi-model ensemble.

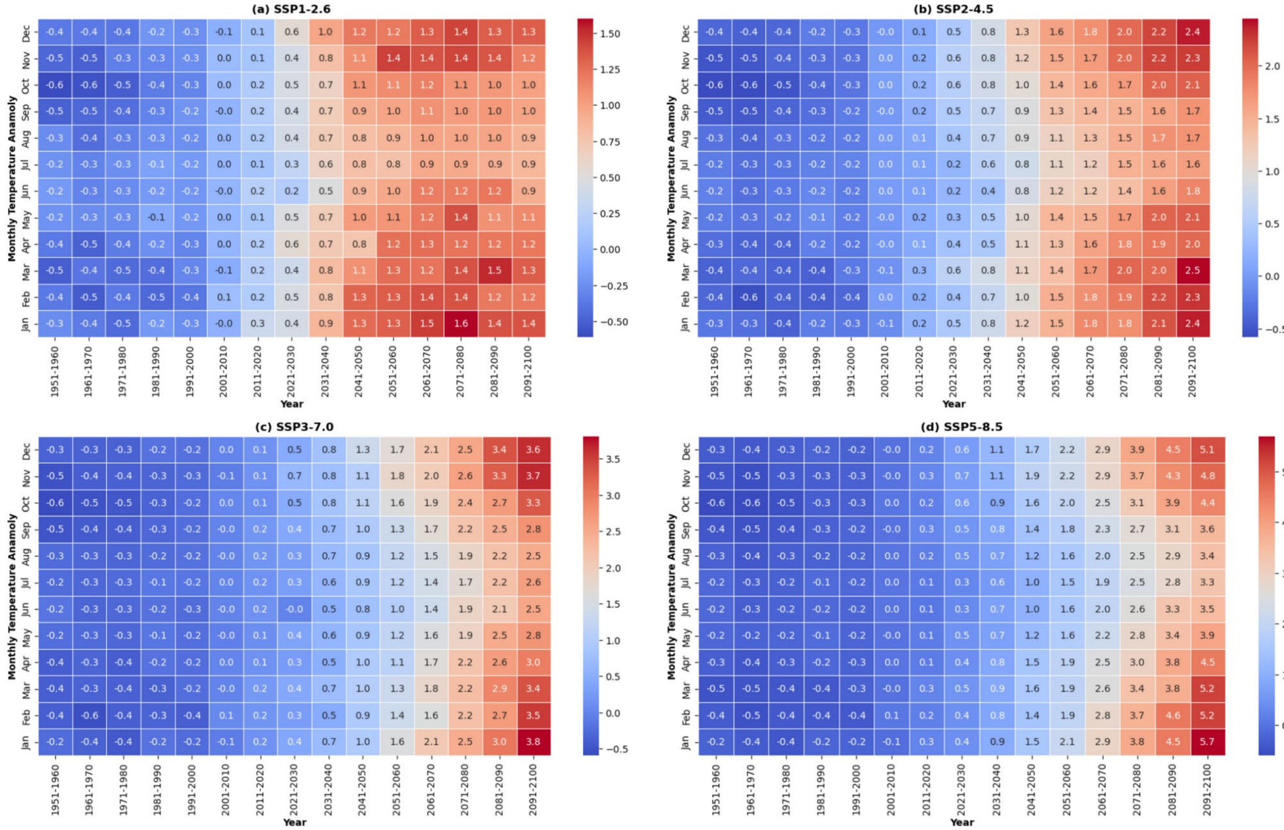

Fig. 10. Projected annual monthly one-day average surface air tmin anomaly of Bangladesh (ref. period 1995–2014), multi-model ensemble. [(**a**) SSP1-2.6, (**b**) SSP1-4.5, (**c**) SSP3-7.0, (**d**) SSP5-8.5].

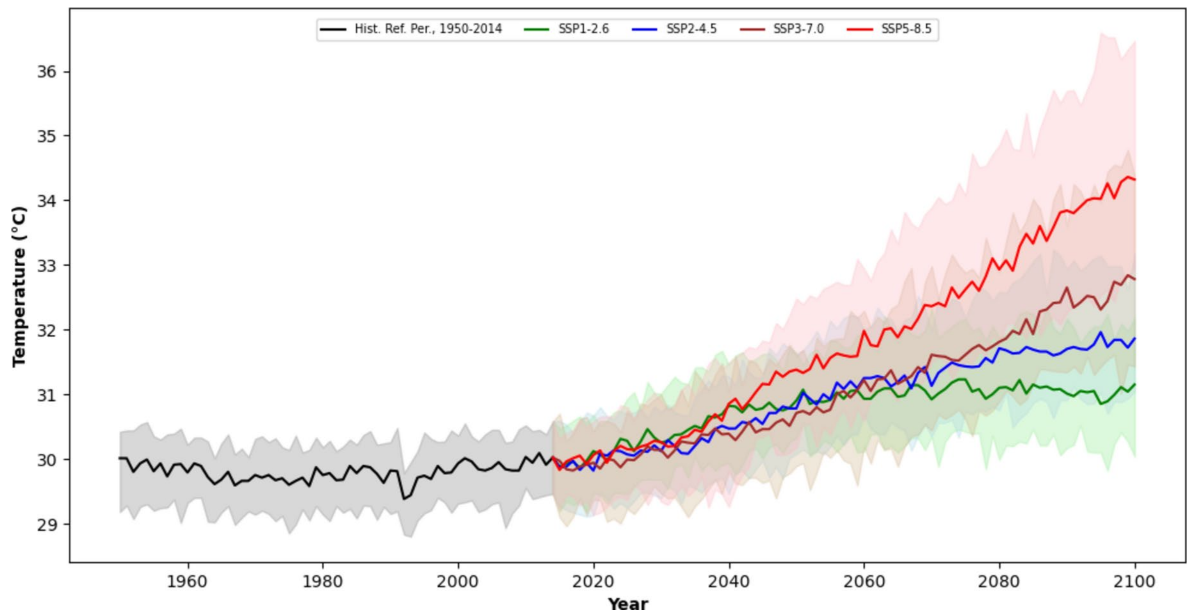

Fig. 11. Projected annual daily average surface air Tmax of Bangladesh (ref. period 1995–2014), multi-model ensemble.

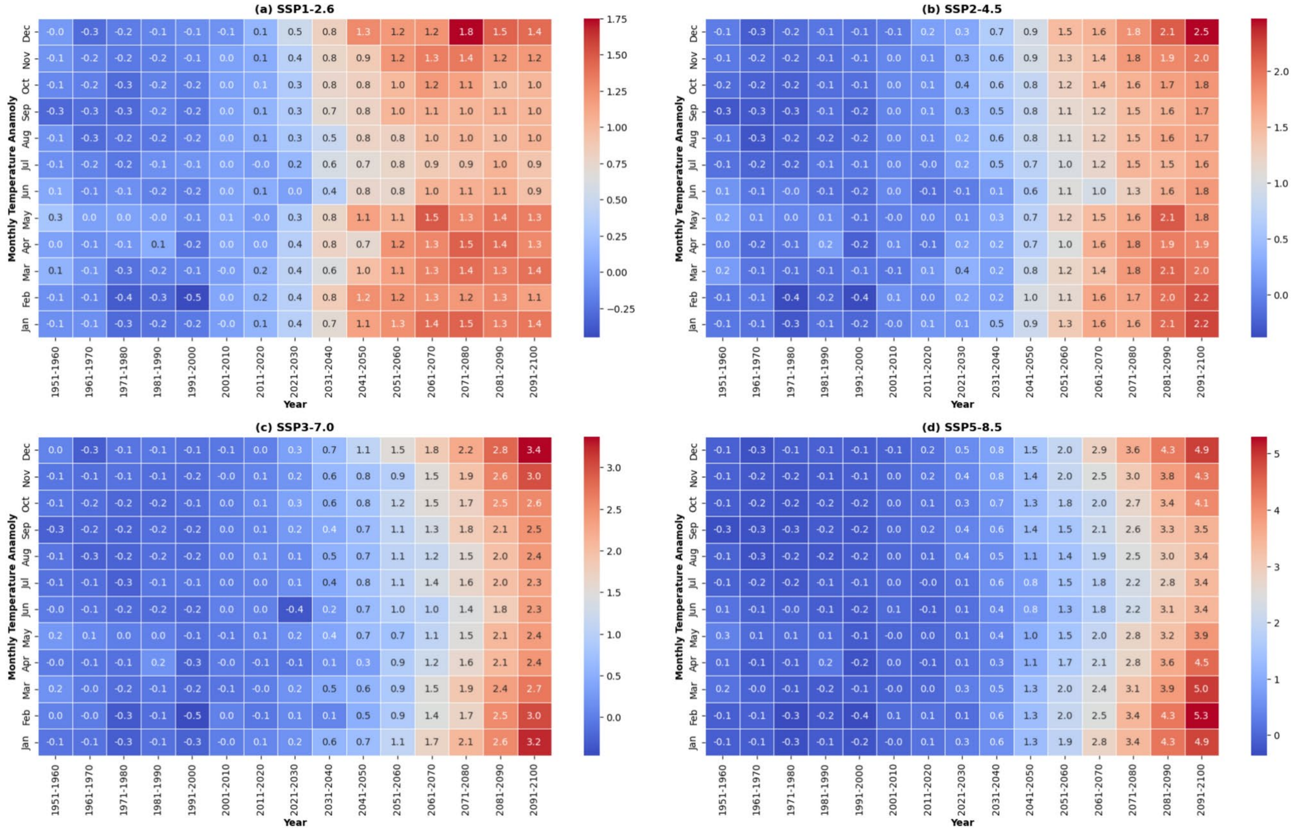

Fig. 12. Projected annual monthly one-day average surface air Tmax Anomaly of Bangladesh (ref. period 1995–2014), multi-model ensemble. [(**a**) SSP1-2.6, (**b**) SSP1-4.5, (**c**) SSP3-7.0, (**d**) SSP5-8.5].

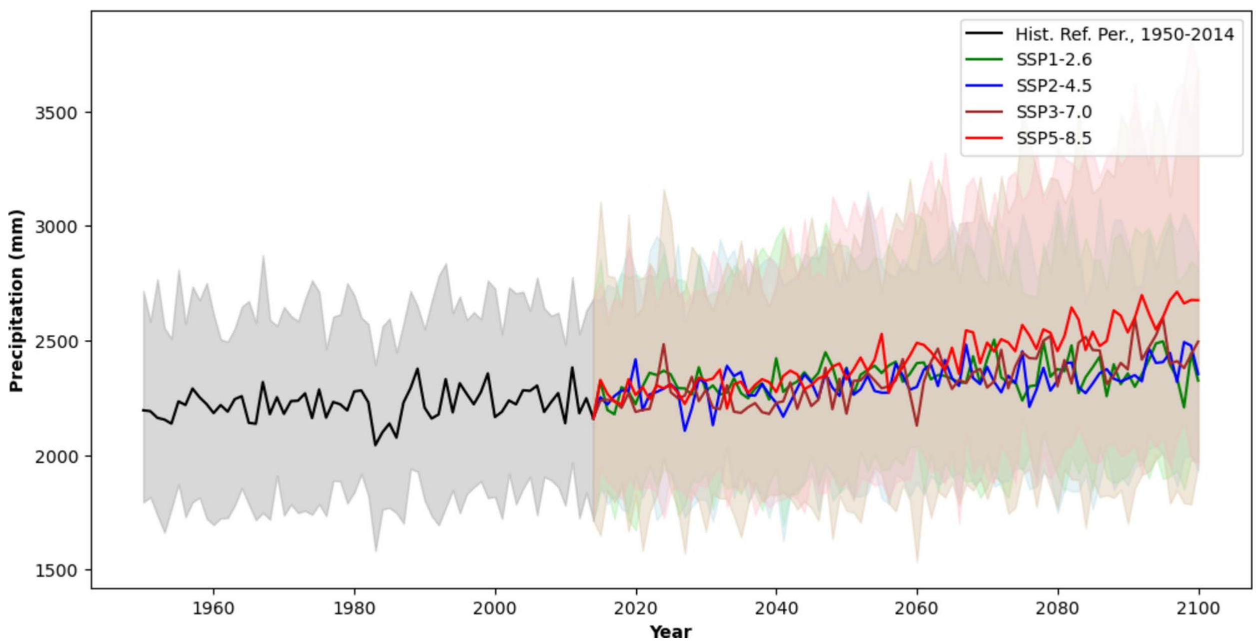

Fig. 13. Projected precipitation of Bangladesh (ref. period 1995–2014), multi-model ensemble.

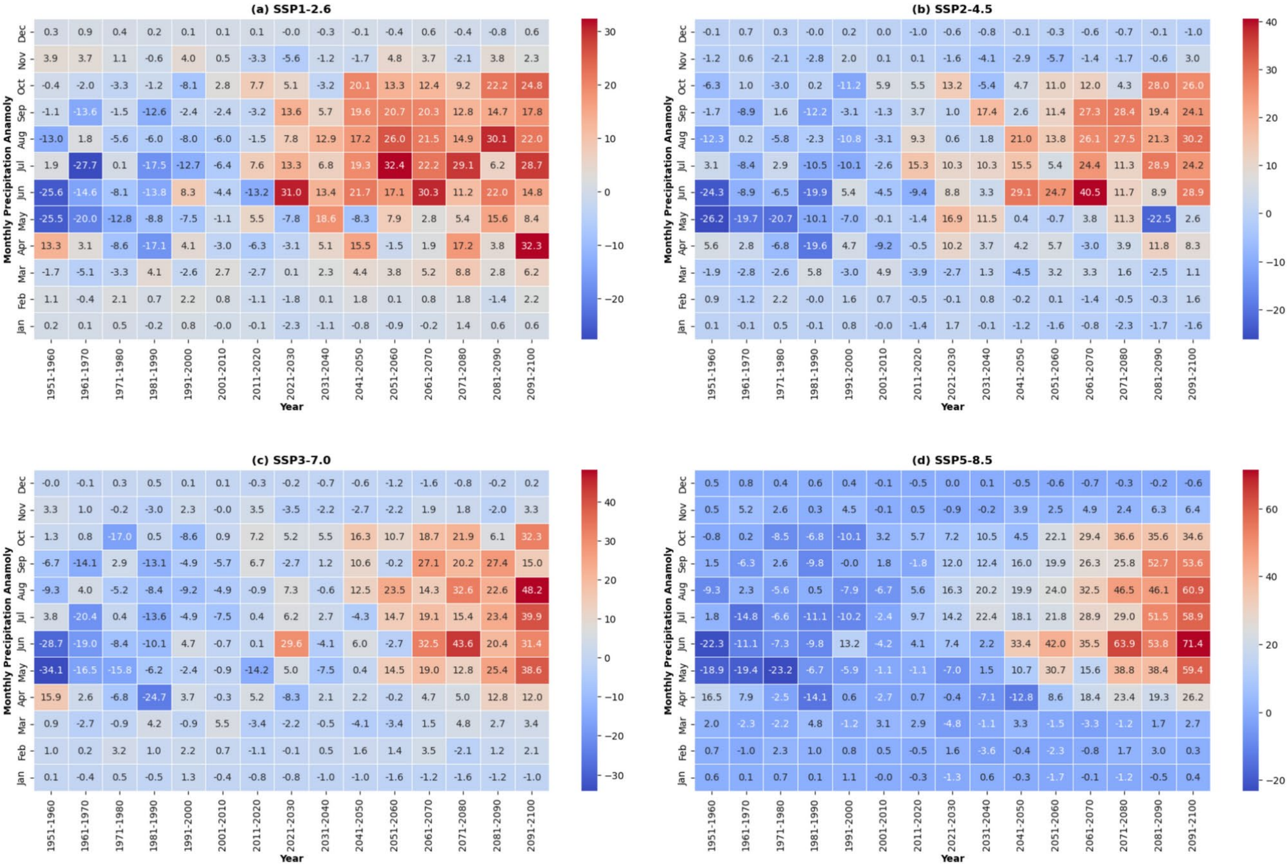

Fig. 14. Projected annual monthly precipitation anomaly of Bangladesh (ref. period 1995–2014), multi-model ensemble. [(**a**) SSP1-2.6, (**b**) SSP1-4.5, (**c**) SSP3-7.0, (**d**) SSP5-8.5].

Additionally, considering the period of 2041 to 2060, the temperatures for SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 are projected to range from 21.7 °C to 23.8 °C, 22.01 °C to 23.99 °C, 22.15 °C–24.04 °C, and 22.27 °C–24.29 °C. For the years 2061 to 2080, the projected temperatures are expected to be in the ranges of 21.92 °C–24.07 °C, 22.63 °C–24.66 °C, 23.38 °C–25.2 °C, and 23.8 °C–25.75 °C for SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Finally, from 2081 to 2100, the projected temperatures are anticipated to be within the ranges of 21.83 °C–24.01 °C, 23.03 °C–25.07 °C, 24.44 °C–26.3 °C, and 25.62 °C–27.53 °C for SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Also, the individual images of this clearly depict how the temperature zone shifted in different region of the country for double decadal projected time period from 2022 to 2100. In fact, it's range shifting from higher to highest in the Southeast (SE) region. Similarly, Northeast (NE) and Northwest (NW) regions experienced low to moderate temperature. Also, the Central (M) experienced high to higher and Southwest (SW) regions experienced high to highest temperatures at future.

Figure 16 illustrates between double decadal projections of annual daily average Tmax in Bangladesh from 2021 to 2100. From 2021 to 2040, the temperature ranges for SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 are respectively projected 30.62 °C–31.78 °C, 30.13 °C–31.42 °C, 30.13 °C–31.41 °C, and 30.38 °C–31.32 °C. Considering the period of 2041 to 2060, the temperatures for SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 are projected to range from 31.27 °C–32.67 °C, 31.18 °C to 32.18 °C, 30.96 °C–32.07 °C, and 31.71 °C–32.95 °C. For the years 2061 to 2080, the projected temperatures are expected to be in the ranges of 31.63 °C–33.22 °C, 32.03 °C–33.44 °C, 32.16 °C – 33.35 °C, and 33 °C to 34.45 °C for SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Finally, from 2081 to 2100, the projected temperatures are anticipated to be within the ranges of 31.64 °C–33.27 °C, 32.59 °C–34.33 °C, 33.34 °C–34.63 °C, and 34.88 °C–36.67 °C for SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.

Also, the individual images of this clearly depict how the temperature zone shifted in different region of the country for double decadal projected time period from 2022 to 2100. In fact, it's range shifting from low to moderate in the Southeast (SE) and Northeast (NE) region. Similarly, Northwest (NW) regions experienced low to high temperature. Also, the Central (M) experienced moderate to high and Southwest (SW) regions experienced high to highest temperatures at future.

Projected precipitation zone mapping

Figure 17 illustrates between double decadal projections of annual daily average precipitation in Bangladesh from 2021 to 2100. From 2021 to 2040, the precipitation ranges for SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 are respectively projected 5.13 mm–12.58 mm, 5 mm–13.37 mm, 5.28 mm–13.56 mm and 5.31 mm–13.05 mm.

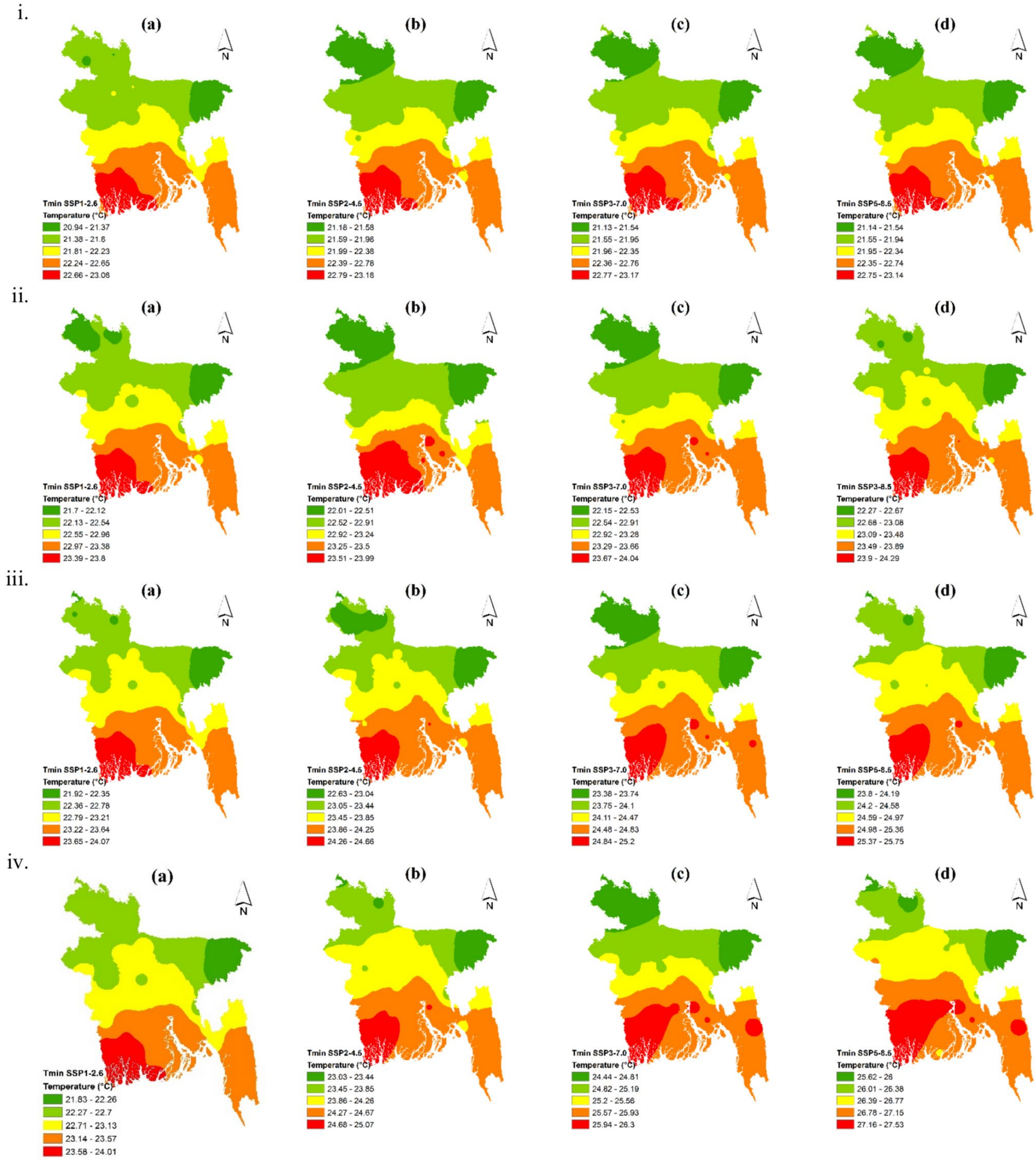

Fig. 15. Projected annual daily average Tmin mapping in Bangladesh (2021–2100). [2 decadal time period- (**i**) 2021–2040-(a) SSP1-2.6, (b) SSP1-4.5, (c)SSP3-7.0, (d)SSP5-8.5; (**ii**) 2041–2060-(a) SSP1-2.6, (b) SSP1-4.5, (c) SSP3-7.0, (d)SSP5-8.5; (**iii**) 2061–2080-(a) SSP1-2.6, (b) SSP1-4.5, (c)SSP3-7.0, (d)SSP5-8.5; (**iv**) 2081–2100-(a) SSP1-2.6, (b) SSP1-4.5, (c)SSP3-7.0, (d)SSP5-8.5;]

In the period of 2041 to 2060, the precipitation for SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 are projected to range from 5.53 mm–13.64 mm, 5.69 mm–14.57 mm, 5.91 mm–15.01 mm and 5.66 mm–14.4 mm. For the years 2061 to 2080, the projected precipitation are expected to be in the ranges of 5.25 mm–13.6 mm, 5.62 mm–14.63 mm, 5.88 mm–16.91 mm and 6.12 mm–17.17 mm for SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Finally, from 2081 to 2100, the projected precipitation are anticipated to be within the ranges of 5.51 mm–13.55 mm, 5.59 mm–14.64 mm, 5.96 mm–18.78 mm and 6.14 mm–20.17 mm for SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Also, the individual images of this clearly depict how the precipitation zone shifted in different region of the

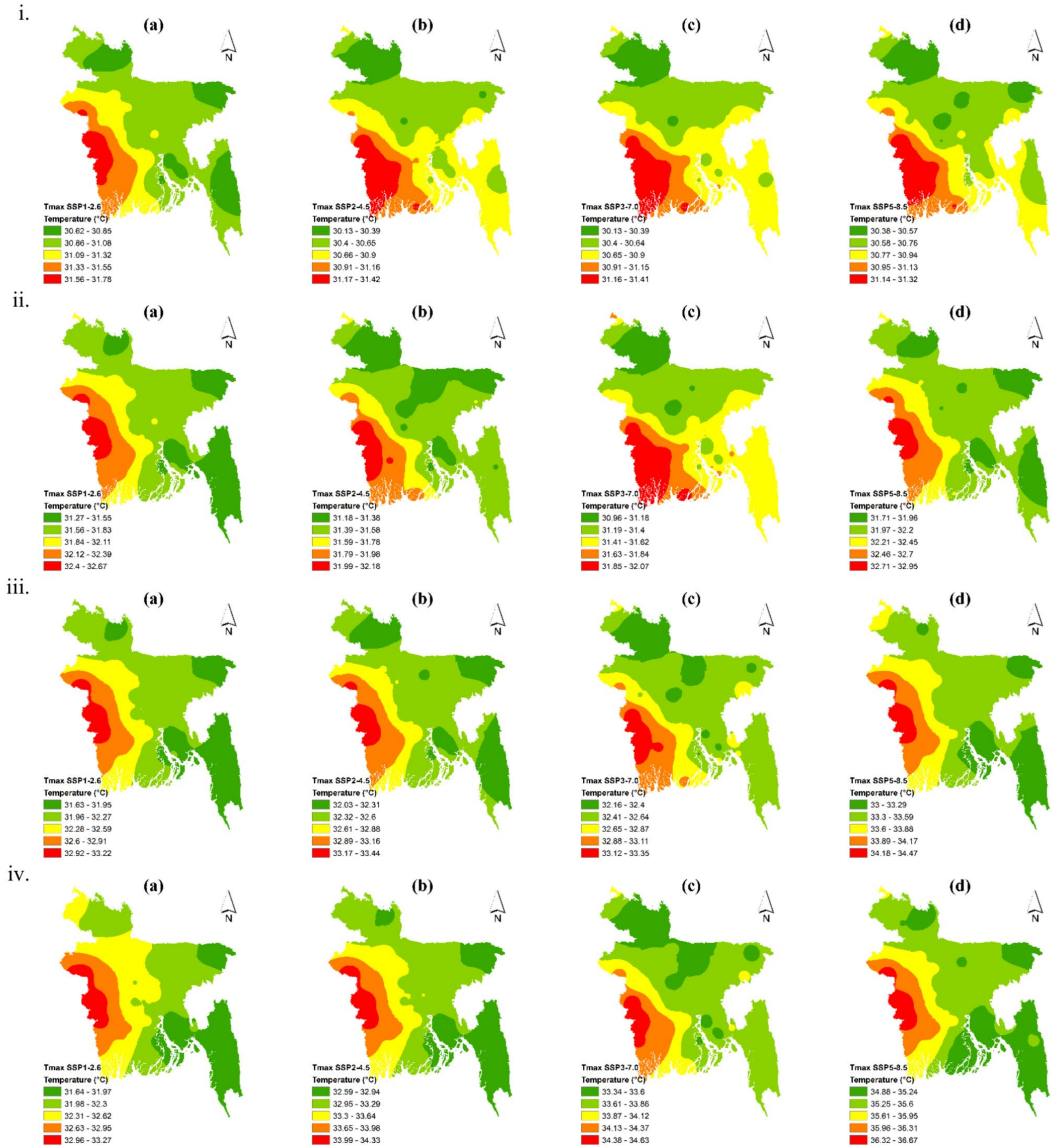

Fig. 16. Projected annual average Tmax mapping in Bangladesh (2021–2100). [2 decadal time period- (**i**) 2021–2040: (a) SSP1-2.6, (b) SSP1-4.5, (c)SSP3-7.0, (d)SSP5-8.5; (**ii**) 2041–2060: (a) SSP1-2.6, (b) SSP1-4.5, (c) SSP3-7.0, (d)SSP5-8.5; (**iii**) 2061–2080: (a) SSP1-2.6, (b) SSP1-4.5, (c)SSP3-7.0, (d)SSP5-8.5; (**iv**) 2081–2100: (a) SSP1-2.6, (b) SSP1-4.5, (c)SSP3-7.0, (d)SSP5-8.5].

country for double decadal projected time period from 2022 to 2100. In fact, it's range shifting from higher to highest in the Northeast (N-E) region. Similarly, Southeast (SE) and Central (M) regions experienced moderate precipitation. Also, Northwest (NW) experienced low to moderate and Southwest (SW) regions experienced low precipitation at future.

Discussion

Global Climate Models (GCMs) are valuable for analyzing historical and future climates, yet their precision is constrained by factors such as resolution and initial assumptions. The latest phase, CMIP6, of the Coupled

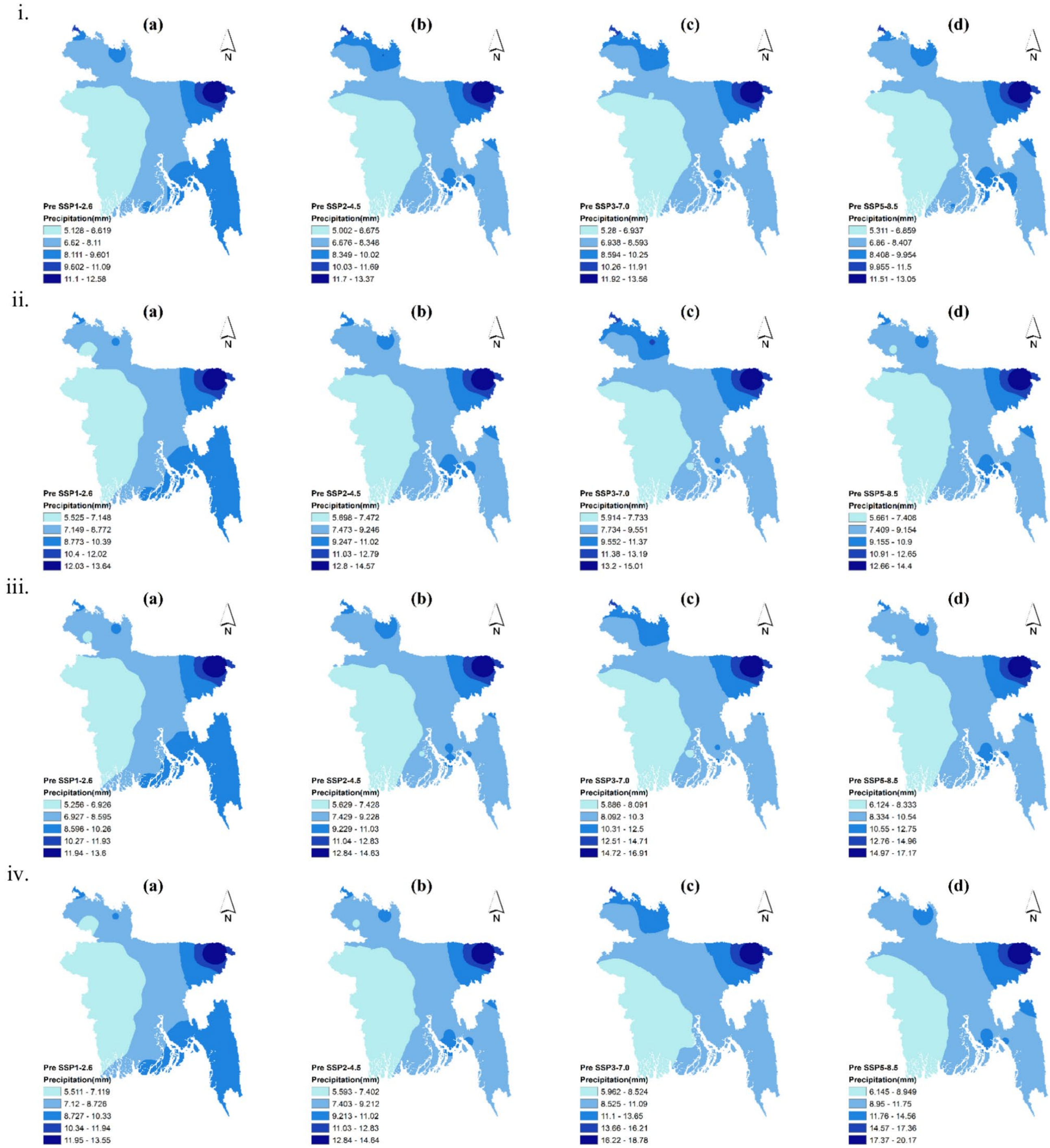

Fig. 17. Projected annual daily average mean precipitation mapping (2021–2100). [2 decadal time period- (**i**) 2021–2040: (a) SSP1-2.6, (b) SSP1-4.5, (c)SSP3-7.0, (d)SSP5-8.5; (**ii**) 2041–2060: (a) SSP1-2.6, (b) SSP1-4.5, (c) SSP3-7.0, (d)SSP5-8.5; (**iii**) 2061–2080: (a) SSP1-2.6, (b) SSP1-4.5, (c)SSP3-7.0, (d)SSP5-8.5; (**iv**) 2081–2100: (a) SSP1-2.6, (b) SSP1-4.5, (c)SSP3-7.0, (d)SSP5-8.5].

Model Intercomparison Project offers diverse scenarios based on various societal development pathways, aiding in comprehending potential future outcomes and preparing for associated challenges[23,70].

Bangladesh, due to its geographical location and dependence on agriculture, is particularly vulnerable to climate change. Its vast floodplains and high population density make it susceptible to flooding and droughts[71]. Understanding future climate projections through tools like CMIP6 is crucial for developing adaptation strategies and mitigating the impacts of climate change on Bangladesh.

Recent studies utilizing CMIP6 models forecast significant climatic changes in Bangladesh by the end of the twenty-first century. Under various SSP scenarios, annual precipitation is projected to increase between

9.48% and 28.17%, with the most substantial rise expected during the post-monsoon season. Temperature forecasts suggest a rise of 1.55 °C to 3.69 °C, with Tmin rising more quickly than Tmax[2]. The northwest and west-central regions are likely to see the highest temperature increases, potentially exceeding 3.8 °C under SSP5-8.5. Additionally, precipitation extremes are expected to worsen, leading to increases in consecutive wet days, heavy rainfall events, and annual maximum precipitation. These changes may result in more frequent and severe flooding, landslides, and adverse effects on agriculture and ecosystems, underscoring the urgent need for localized adaptation strategies[2,72].

Hossain et al. (2012) and Mojid (2020) investigate the substantial effects of climate change on vulnerable people in Bangladesh's southwestern coastal region, focusing on issues such as rising sea levels, increased salinity, and extreme weather events. These conditions endanger agriculture, fisheries, and food security, disproportionately hurting vulnerable communities and worsening poverty. Both research underline the importance of focused adaptation techniques, such as improved flood and water resource management. They advocate for incorporating local knowledge and sustainable practices into development plans to increase resilience. Comprehensive measures are called for to protect livelihoods and promote long-term development in the face of ongoing climate risks[73,74]. Also The climate change's health consequences, focusing on how it exacerbates ailments such as respiratory difficulties, vector-borne infections, and heat-related illnesses. Rising temperatures and extreme weather events exacerbate air pollution and water-related diseases, disproportionately harming disadvantaged communities. Proactive policies and adaptable measures are required to address these rising health hazards, particularly in emerging nations [75].

In contrast, this study briefly describe the historical period from 1901 to 2022 average annual daily mean air surface temperature in Bangladesh has increased from 24.64 °C to 26.60 °C over the past century. This is an increase of 2 °C. Respectively, the Tmin and Tmax have also increased, by 1.63 °C and 2.33 °C but the annual precipitation has declined from 2369.51 mm to 1662.25 mm over the past century, suggesting a shift towards drier conditions. While hotter years tend to see slightly less rain, the correlation is weak ($r = -0.09$ to -0.23), indicating other factors significantly influence rainfall patterns. The Southeast region shifted from "high" to "highest" temperature zone, while Northeast and Northwest regions represent moderate to high increases. Central and Southwest regions exhibited variations between "high" and "highest" categories. While the Southeast region of Bangladesh witnessed the most dramatic warming, shifting from "high" to "highest" temperature zone, other regions displayed diverse patterns. Northeast and Northwest saw moderate to high increases, while Central and Southwest fluctuated between "high" and "highest" categories. Precipitation showed similar regional variability, with no overall trend: Southeast remained mostly "low" to "moderate", Northeast and Northwest fluctuated between "low" and "very high", and Central and Southwest varied between "low" and "high". These intricate spatial and temporal variations in temperature and precipitation highlight the need for nuanced climate change adaptation strategies across Bangladesh.

By the CMIP6 GCM's model across all emissions scenarios (SSP1-2.6 to SSP5-8.5), Bangladesh is projected to experience significant warming, with Tmin temperatures rising by 1 °C to 4.4 °C and Tmax by 1 °C to 4.1 °C by 2100. While all scenarios predict increased precipitation range 2195.94 mm to 2676.32 mm, it will vary, with the biggest rises expected during monsoon months. The Southeast region will experience the most drastic shift, transitioning from "high" to "highest" temperature zone, while Northeast and Northwest see moderate to high increases. Central and Southwest regions will fluctuate between "high" and "highest" categories. Precipitation is also expected to increase, the Northeast region will see the most significant increase, shifting from "higher" to "highest" precipitation zone, while Southeast and Central regions experience moderate precipitation. Northwest sees low to moderate increase and Southwest experiences low precipitation. These projections highlight the need for robust adaptation strategies to address the diverse impacts of climate change.

Bangladesh's approach to addressing climate change encompasses both domestic initiatives and international commitments aimed at mitigating environmental degradation and enhancing resilience. Domestically, country has implemented several key legislative frameworks, beginning with the Bangladesh Environment Conservation Act of 1995, which serves as a foundational law for protecting the environment. The Environment Court Act of 2000 further strengthens the legal system by providing mechanisms to handle environmental disputes. These efforts are supported by the Bangladesh Environment Policy of 1992 and Environment Conservation Rules of 1997, which guide the country's efforts in sustainable environmental management and conservation practices. In disaster preparedness, Bangladesh developed the National Plan for Disaster Management (2021–2025) and Standing Orders on Disaster 2019, which outline comprehensive strategies to respond to and mitigate the impacts of climate-related disasters, such as floods, cyclones, and droughts.

On the international front, Bangladesh has actively participated in numerous global environmental conventions. The country is a signatory to the Vienna Convention (1969) for the protection of the ozone layer and the Ramsar Convention (1971) for wetland conservation. Bangladesh also adheres to the United Nations Convention on the Law of the Sea (UNCLOS, 1982), reflecting its commitment to marine conservation. The Brundtland Commission Report (1987) and international climate agreements like the Montreal Protocol (1987) and Kyoto Protocol (1997), which focus on reducing greenhouse gas emissions, further demonstrate the country's engagement with global environmental governance.

Bangladesh's participation in key climate summits, such as COP21 (2015) in Paris, COP26 (2021) in Glasgow, and COP27 (2022) in Sharm El Sheikh, highlights its continuous involvement in international climate negotiations. These summits, particularly the landmark Paris Agreement from COP21, shape the country's commitment to reducing emissions, enhancing resilience, and accessing climate finance and COP28 (2023), demonstrates its commitment to global climate governance.

Overall, Bangladesh is proactively addressing climate change through domestic legislative frameworks and international commitments, employing strategies such as the CMIP6 models to forecast climate impacts and participating in global conventions and summits to enhance resilience and safeguard vulnerable communities.

Conclusion

Bangladesh faces a stark reality, rising temperatures and changing precipitation patterns. Historical data confirms a 2 °C increase in average annual temperature but precipitation decline from 607.26 mm, with significant regional variations. Projections from advanced climate models paint an even more concerning picture, with Tmin and Tmax respectively rising by 1 °C to 4.4 °C and 1 °C to 4.1 °C by 2100. While precipitation is expected to increase 480.38 mm, the distribution will be uneven, with the Northeast experiencing the most significant rise and the Southwest seeing the least. Rising temperatures and enhanced precipitation extremes are expected to pose serious threats to agriculture, food security, and public health, particularly for vulnerable groups. Urgent, targeted adaptation efforts, combined with proactive health and development initiatives, are required to mitigate these consequences, establish long-term resilience to ongoing climate hazards, and address the diverse spatial and temporal patterns that highlight the importance of incorporating adaptation strategies into policies and practices. Bangladesh is proactively addressing climate change through domestic legislative frameworks and international commitments, using strategies like the CMIP6 models to forecast climate impacts and participating in global conventions and summits to strengthen resilience and protect vulnerable communities.

Data availability

All data generated or analyzed during this study are included in this published article.

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