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Assessing the effects of climate change on temperature for Iraq using SSP scenarios

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Abstract

Iraq is among the five countries most affected by extreme temperatures, low precipitation, drought, and desertification. In Iraq, water and agricultural resources are under stress due to population growth and urbanization. Changes in temperature and precipitation, combined with more frequent and severe droughts and heat waves, could strain resources and increase vulnerability. This study uses ERA5 reanalysis data from 1951 to 2023 to assess the effects of climate change on temperature in Iraq and three cities: Mosul, Baghdad, and Basra. Also, this study uses the statistically downscaled Coupled Model Intercomparison Project Phase 6 (CMIP6) dataset, which includes the Shared Socioeconomic Pathways (SSPs). To estimate temperature changes, four distinct SSPs (SSP1-1.9, SSP2-4.5, SSP3-7.0, and SSP5-8.5) were chosen from global climate models. According to the findings, Iraq's temperature would rise more quickly than the global average. Under SSP5-8.5, the predicted temperature would increase by 7.2°C between 2071 and 2100 relative to the baseline. Rising temperatures will adversely affect human health and water resources, while variability in seasonal and sub-seasonal precipitation will exacerbate these risks. Temporal analysis demonstrates that to adapt to the changing climate, particularly the rapid changes resulting from the SSP5-8.5 scenario, it is imperative to strengthen adaptation and mitigation measures nationwide and build capacity.

INTRODUCTION

Climate change is characterized by notable shifts in several climate variables, including precipitation, wind patterns, temperature, and humidity over extended periods. These changes can occur over a wide range of timescales, from a few decades to several millennia, demonstrating the profound and ongoing impact of climate on Earth's ecosystems and climate systems (Zhang et al., 2021). The world's climate has gotten less stable and more dangerous for both people and the environment. There are significant obstacles associated with this shift that demand everyone's immediate attention and action (Abbass et al. 2022). Temperature is the most significant meteorological factor because its variations are evident across many regions of the world. Human and natural activities have altered the composition of atmospheric gases since the Industrial Revolution, increasing greenhouse gas concentrations and reducing the absorption of solar radiation. These gases have different effects on the atmosphere, with carbon dioxide having a significant greenhouse gas effect (Lopes 2025). Rising temperatures affect the balance of supply and demand for nearly all natural resources, particularly water resources, which are essential for life, humidity, and weather formation. Climate change may pose a threat to the future of ecosystems. It can affect human activities, natural resources, plant and agricultural growth, and living conditions in multiple ways (Dutta et al., 2023). A global problem, climate change affects ecological, environmental, and socioeconomic facets of life. Iraq is particularly vulnerable due to its arid and semi-arid climates, characterized by high temperatures, low precipitation, and declining water resources. Future effects of climate change are contingent upon demographic shifts, technological developments, and economic expansion. Long-term weather variations brought on by climate change pose a threat to human activity, ecosystems, living conditions, crop and plant growth, and nature reserves. To forecast future climates and trends, scientists investigate temperature and pressure. The Shared Socioeconomic

Pathways (SSPs) provide a comprehensive framework for understanding how global societal decisions shape future development trajectories. They ensure thorough analysis by supporting assessments of global climate change and by coordinating local perspectives with global pathways (Kok et al., 2019; Ibrahim, 2025). As inputs for analyses of climate change challenges and responses, the Shared Socioeconomic Pathways (SSPs) outline tenable alternative evolutions of societal conditions (Wood et al. 2024). The SSPs provide a foundation for consistent assumptions about future societal states and comprise five qualitative storylines, ranging from sustainable development to growth driven by fossil fuels (Moallemi et al., 2022). To create tangible, quantitative socioeconomic scenarios, they provide a framework for integrating demographic, economic, technological, social, governance, and environmental factors. As evidenced by applications across different spatial and temporal scales, these scenarios support climate change projections and the assessment of adaptation and mitigation strategies for each pathway in the MiLESIA project (Kriegler et al., 2017). Many studies worldwide have assessed the impact of climate change on people's lives and on various climate patterns. It is important to examine temperature and pressure before assessing precipitation variability, as both influence human life. Scientists also work to determine future climate and the potential changes in temperature and pressure to predict the climate for a specific location. Climate change-induced temperature increases alter soil properties and processes, including decomposition of organic matter, increased leaching losses, decreased soil water, and degradation through decreased soil moisture (Awadh 2023). Iraq can anticipate more frequent heat waves and a 2°C increase in the annual average temperature by 2050. Reduced precipitation and longer droughts are exacerbating already arid conditions and drier soils due to rising temperatures (Demir et al., 2013). The importance of climate for human existence is linked to its positive and negative impacts on social and economic dimensions, as well as to their interactions (Jaafer et al., 2019). Predicting Iraq's Future Climate Future air temperatures were estimated using the (CCSM4) climate model, which is a component of (CMIP5). According to findings for the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios, temperature expansion is shifting from the south toward Iraq's center, west, and north (Mohammed et al., 2018). Using (CMIP5) models under (RCP4.5), temperature projections over Iran for the twenty-first century show that the average temperature will rise until the end of the century. In 2025 and 2100, the annual mean air temperature was lower under the (RCP) than the (SERS) scenarios in Delta and Middle Egypt (Abdrabbo et al., 2015). To assess the effects of climate change on Iraq's temperature, the study proposes an analysis using the latest CMIP6 global climate models and the SSP framework, which may yield projections consistent with the IPCC Sixth Assessment Report. The main goals are to: (1) measure the faster historical warming trend across Iraq, (2) predict how temperatures will change in the future under different SSP scenarios, and (3) find differences in vulnerability between regions to support national adaptation and mitigation strategies with evidence.

MATERIALS AND METHODS

Study area

Iraq is situated between 29° 05 and 37° 23 north and 38° 45 and 48° 45 south in the Northern Hemisphere. It borders Saudi Arabia, Syria, and Jordan to the west; Kuwait and Saudi Arabia to the south; Iran to the east; and Turkey to the north. The total area of Iraq is 438,320 km². To the north, northeast, and east, there are mountains everywhere, some of which are as high as 35.50 meters above sea level. The eastern part of Iraq is a plateau, and the mountains are separated from it by a sedimentary plain (Mutter et al. 2024). The 19 governorates of Iraq are further subdivided into districts, each of which is further subdivided into one or more sub-districts. Iraq is divided into 120 districts. The two oldest governorates are Basra and Baghdad, the most populated. Ninawa, the second most populous province, is located in the northwest upland region. The study area is depicted in Fig. 1. Iraq's climate lies between the continental and the subtropical regions. With daily highs of up to 16°C and nighttime lows of 2°C, winters are usually cool to cold. With daytime temperatures exceeding 43°C in July and August and nighttime lows of 26°C, the summers are hot and dry. Iraq's continental climate, characterized by northwesterly winds, is dominated by hot, dry summers and cool, rainy winters. The majority of rainfall is attributable to wintertime storm systems over the Mediterranean region as they move eastward across northern Iraq. Except in the north and northeast, where the rainy season lasts from November to April, most of Iraq's rainfall occurs during the winter months of December through February, making it a seasonal pattern. The northeastern region of Iraq, which is occupied by the mountains of Iraqi Kurdistan (Zagros and Taurus), experiences 700–1,000 millimeters of precipitation annually, whereas the rest of the country, which is made up of plains or hills, experiences arid weather (Al-Lami et al. 2024; Al-Timimi et al. 2024).

Date Acquisition

Monthly air temperature data derived from the ERA5 reanalysis were analyzed for the period 1951–2023 across the study area. ERA5 data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The data used to develop a robust understanding of current climate conditions to inform future climate scenarios and projected change. ERA5 reanalysis data are produced at a monthly resolution and encompass a wide range of climate indicators.

According to the WMO, the study period can be classified into three phases: long-term trend (1951–2020, 70 years). This time frame provides the broad picture of climate change in Iraq over the past century. It establishes the baseline warming signal for comparison with more recent acceleration. Medium-term trend (1971–2020, 50 years): This 50-year period aligns with the period when human activity had the greatest effect on the climate, and it is the standard time frame for assessing the impact of recent climate change in the IPCC and other major studies. It helps separate the warming signal from the noise associated with rapid industrialization and population growth. Short-term trend (1991–2020, 30 years): is the most recent official "climatological normal." It is the standard timescale for characterizing the current climate and is most strongly influenced by recent forcing and feedback processes. Data are presented at a 0.25 ° × 0.25 ° (25km × 25km) resolution. Data have been analyzed as projected means and presented spatially, and a time series showing seasonal change over long-term

horizons. Data are also analyzed annually by selecting different projected time periods and Shared Socioeconomic Pathways (SSPs). SSPs are designed to provide insights into future climates under defined emissions, mitigation efforts, and development pathways.

Climate projection data are modeled outputs from the global climate model compilations of the Coupled Model Intercomparison Project (CMIP), overseen by the World Climate Research Program. The data presented are CMIP6, derived from the Sixth phase of the CMIPs. The CMIPs form the data foundation of the IPCC Assessment Reports. CMIP6 supports the IPCC's Sixth Assessment Report.

SSPs Scenarios

The Intergovernmental Panel on Climate Change (IPCC) Shared Socioeconomic Pathways (SSPs) provide a robust, modern methodological framework for socioeconomic scenarios. Downscaled perspectives from the entire set of five illustrative SSPs are part of the methodology used to create regional climate change scenarios for arid and semiarid regions. The Shared Socioeconomic Pathways (SSPs) provide a foundation for understanding potential adaptations and mitigation strategies for climate change. The SSP comprises five pathways that address key global mitigation and adaptation challenges and are organized around distinct narratives. See Table 1. SSP1 depicts a comparatively hopeful world in which environmental sustainability is valued, and people adopt more environmentally friendly lifestyles; as a result, mitigation and adaptation challenges are reduced. SSP2 depicts a world in which past trends and rates of development persist without significant deviation, thereby serving as a "middle of the road" scenario that follows contemporary patterns. SSP3 depicts an unbalanced, divided world in which economic and national security are prioritized. This focus raises the bar for climate change adaptation and mitigation. SSP4 explores a world in which adaptation and mitigation challenges are unequally distributed, with some regions facing extremely high challenges and others relatively low. SSP5 examines a development path that places a strong emphasis on fossil fuel-fueled development, which presents substantial mitigation challenges but few adaptation challenges (Kriegler et al. 2017).

Table 1
SSP scenarios, as used in the CMIP6 ensemble and the IPCC Sixth Assessment Report (AR6) (Masson et al. 2021).

SSP	Scenario	Estimated warming (2041–2060)	Estimated warming (2081–2100)	Very likely range in °C (2081–2100)
SSP1-1.9	very low GHG emissions: CO_2 emissions cut to net zero around 2050	1.6°C	1.4°C	1.0–1.8
SSP1-2.6	low GHG emissions: CO_2 emissions cut to net zero around 2075	1.7°C	1.8°C	1.3–2.4
SSP2-4.5	intermediate GHG emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100	2.0°C	2.7°C	2.1–3.5
SSP3-7.0	high GHG emissions: CO_2 emissions double by 2100	2.1°C	3.6°C	2.8–4.6
SSP5-8.5	very high GHG emissions: CO_2 emissions triple by 2075	2.4°C	4.4°C	3.3–5.7

Results and discussion

Figure 2 illustrates the mean air temperature distribution in Iraq from 1951 to 2020. It provides important data for understanding the country's climate patterns and temperature changes. Southern Iraq records the highest temperatures (maximum: 26.6°C). However, Northern Iraq records the lowest temperatures (minimum: 5.8°C). Mosul is located in northern Iraq and experiences relatively moderate temperatures. Baghdad is situated centrally and experiences a moderate thermal gradient. Basra, in the south, records the highest average temperatures. The mean and standard deviation of temperature in Iraq were (19.96 ± 4.7).

We computed linear trends for three periods specified by the World Meteorological Organization (WMO) to examine multi-decadal warming and its acceleration. Figure 3 shows the time series of annual mean temperature for the period 1950 to 2023. Because of natural climate variability (such as El Niño/La Niña cycles and random weather patterns), the annual mean temperature fluctuates substantially and increases from year to year. Also, Fig. 3 shows three separate trends: long-term (1951–2020), medium-term (1971–2020), and short-term (1991–2020), each computed for a different time period (70, 50, and

30 years, respectively). The 1991–2020 trend line (red) is the steepest. This means the rate of temperature increase over the past 30 years has been higher than in previous decades. The Trend 1951–2020 (blue) line, while still rising, has the gentlest slope, indicating a slower average rate of warming over the full period. Regardless of the time period examined (70, 50, or 30 years), the overall trend is an increase in temperature. The slope of the trend lines becomes progressively steeper; this is the most critical finding (see Fig. 3-A).

Figure 3B provides a powerful representation of the increase in temperatures in Mosul. All three trend lines have positive slopes, indicating a consistent rise in average temperatures over the observed periods. Additionally, there is a pronounced acceleration in warming. The trend line for 1991–2020 (red) is the steepest. This indicates that the rate of temperature increase over the most recent 30-year period has been substantially higher than in previous decades. The 1971–2020 trend (yellow) is less steep than the 1991–2020 trend but steeper than the 1951–2020 trend. The trend line for 1951–2020 (blue) continues to rise but has the gentlest slope, indicating a slower average rate of warming when calculated over the entire 70-year period.

Fig. 3-C and 3-D show that the trend line for 1951–2020 will be less steep. The trend line for 1971–2020 (yellow) is the steepest. This indicates that the rate of temperature increase over the most recent 50-year period has been substantially higher than in previous decades in Baghdad and Basrah.

The diverse geography and climatic characteristics of Iraq are fundamentally linked to the disparate temperatures and warming rates observed in Mosul, Baghdad, and Basrah. Mosul, in the northern region, experiences the lowest average temperatures. Its climate is characterized by less pronounced extremes, a consequence of its more northerly latitude, elevated topography (within the Nineveh plains and adjacent to the Iraqi Kurdistan mountains), and greater precipitation. The accelerated increase in temperature since 1991 is particularly alarming. This observation suggests that the influence of greenhouse gases on warming is now surpassing the historical climatic factors that have traditionally governed the northern region. Consequently, the more rapid warming in this area will likely result in accelerated snowmelt in the upstream Tigris headwaters, reduced spring streamflow, and increased evaporation rates. This situation jeopardizes the long-term water security of both the northern regions and the downstream areas that depend on these river systems. Baghdad, in the Central Region, experiences higher temperatures than Mosul due to its lower elevation, more continental climate, and reduced moisture availability. The city is positioned within the Mesopotamian alluvial plains. The most pronounced warming trend occurred between 1971 and 2020. This significant warming in the central region intensifies the urban heat island effect in the capital, thereby increasing evaporation demands. Consequently, this situation directly endangers irrigated agriculture within the central belt. The Tigris and Euphrates rivers are under increased stress due to upstream diversions and reduced water availability. Basrah, located in the southern region, experiences the highest absolute temperatures, a consequence of its proximity to the Persian Gulf, its extensive low-lying terrain, and its encirclement by arid deserts.

The box-and-whisker plot of the air temperature distribution is shown in Fig. 4. For the various regions (Iraq, Mosul, Baghdad, and Basrah), distributions were plotted. Basrah recorded the highest air temperature, at 25.85 ± 0.94°C (mean ± SD). Each region's dataset follows a normal distribution centered on the mean. With average temperatures of 22.35 ± 1.02, 20.43 ± 0.92, and 24.7 ± 1.05°C in Iraq, Mosul, and Baghdad, respectively, the distribution is very narrow.

Changes in climate under different periods from the reference period (1951–1980)

The probability distribution function (PDF) histograms of the average surface air temperature for various time periods in Iraq, Baghdad, Mosul, and Basrah are displayed in Fig. 5. Three histograms are included in each figure, each representing a distinct 30-year period. The blue histogram, which depicts the earliest "baseline" climate, is for the years 1951–1980. An intermediary period is represented by the years 1971–2000 (yellow histogram). The most recent time frame is 1991–2020 (red histogram). The historical baseline period of 1951–1980 has been compared with the periods 1971–2000 and 1991–2020.

The blue histogram depicts the normal (Gaussian or bell-shaped) distribution of air temperature for the base period (1951–1980). The normal distribution of the 1951–1980 base period differs slightly from that for 1971–2000. However, the 1991–2020 histogram indicates that, due to increased temperature variability, this period has warmed more than the 1981–2010 period.

The findings indicate a noticeable shift to the right in the country's overall temperature distribution, indicating that the nation has warmed. The range of temperatures considered "normal" has increased. The findings suggest that the warming trend in the Baghdad area is part of a regional pattern rather than unique to Iraq. A similar shift towards higher temperatures supports a larger change in the climate. Northern Iraq's Mosul: Mosul's temperature range is shifted to the left in comparison to the national average because it is situated in a colder northern region. The three curves will nevertheless continue to exhibit a noticeable rightward shift, suggesting that this area has also warmed considerably. Southern Iraq's Basrah: Situated in the hot, arid south, Basrah has a temperature range that is significantly shifted to the right, indicating that it is naturally much hotter. Its three curves will change markedly, indicating that the already hot area has warmed considerably. Across the 1951–1980 and 1991–2020 curves, all four sites exhibit distinct warming and a steady rightward shift. This indicates that, compared with the middle of the 20th century, the most prevalent, or "normal," temperatures are now much higher. Average years today are warmer than average years in the past, and cold years today are warmer than cold years in the past. The shift to the right may vary in magnitude. The findings for Basrah likely indicate the most pronounced change, suggesting that warming is particularly severe in this arid southern region. Table 2 presents the statistical values for temperature across different periods.

Table 2
The statistical values of the mean and standard deviation of temperature for different periods

Study area	Period	Mean (°C)	S.D(°C)
Iraq	1951–1980	22.35	1.02
	1971–2000	22.66	1.00
	1991–2020	23.20	0.79
Mosul	1951–1980	20.43	1.00
	1971–2000	20.57	1.08
	1991–2020	21.06	1.01
Baghdad	1951–1980	24.69	1.06
	1971–2000	25.03	1.01
	1991–2020	25.61	0.67
Basrah	1951–1980	25.92	0.99
	1971–2000	26.26	0.91
	1991–2020	26.73	0.69

According to the results, the temperature distribution broadens and shifts to the right with global warming in all time periods. This broadening is most likely the result of global warming. In response to approximately 0.5°C of global warming over the previous three decades, the mean air temperature distribution for Iraq, Mosul, Baghdad, and Basrah has changed by 0.85°C, 0.63°C, 0.92°C, and 0.81°C, respectively.

The approaches can be generalized for arid and semi-arid regions using CMIP6/SSP data and trend analysis to create adaptable frameworks for data-scarce regions. A hotspot identification method employs comparative analysis of regional temperature distributions to prioritize vulnerable areas for adaptation. Additionally, sequential trend calculations reveal nonlinear acceleration in warming, aiding global climate communication. The study links global socio-economic scenarios to local temperature outcomes, offering a model for localizing IPCC projections.

Historical and projected (4 SSPs) air temperature over Iraq from 1950 to 2100

To demonstrate how greenhouse gas emissions will directly affect the magnitude of future warming, four Shared Socioeconomic Pathways (SSPs) were compared. Four scenarios, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.0, were used to forecast the annual mean air temperature over Iraq, Mosul,

Baghdad, and Basrah through the year 2100. Figure 6 illustrates the historical data for the years 1950–2100. A validation point for the models is provided by the historical (black line), which displays the observed temperature change from 1950 to the recent past (up to 2014).

The sustainability scenario is shown in SSP1-2.6 (blue line). With CO_2 emissions drastically reduced and net-zero after 2050, the region moves toward a more sustainable course. This is the only scenario that meets the Paris Agreement's target of keeping the increase in global average temperature below 2°C relative to pre-industrial levels. The "middle of the road" scenario is represented by SSP2-4.5 (orange line). With emissions stabilizing around the middle of the century but not declining substantially, current policies and trends remain in place. This course of action results in further warming, with major climatic effects, likely 2.5–3°C above pre-industrial levels by 2100.SSP3-7.0 (red line): A gloomy situation marked by slow economic growth and regional rivalry. Over the course of the century, emissions have stayed high. By 2100, this results in significant warming of 3–4°C, with severe and pervasive climate impacts. SSP5-8.5 (dark red): A scenario of development driven by fossil fuels. Fossil fuels play a major role in the world's rapid economic growth. The worst-case warming, which will surpass 4°C by 2100, is caused by this extremely high emissions pathway. The effects would be disastrous and possibly irreparable.

According to the SSP5 scenario, the average air temperature is predicted to rise until 2100. By 2100, the mean air temperature is projected to stabilize during the latter half of the 21st century, rising from approximately 22.2°C to 26°C. The findings demonstrate that, relative to the historical baseline, temperature has increased consistently across all scenarios. There is no situation in which the temperature stays constant or drops. Around 2040–2050, the scenarios start to diverge significantly from one another. The order of warming by 2100 is as follows: SSP1-2.6 (coolest) < SSP2-4.5 < SSP3-7.0 < SSP5-8.5 (hottest). This illustrates how emissions from human activity directly affect the climate.

The methodological framework, integrating CMIP6-SSP projections with multi-temporal trend and PDF analysis, offers a transferable model for climate risk assessment in other arid regions. Our findings add to the growing body of evidence that continental interiors and dry areas are hotspots for climate change, warming at rates higher than the global average. This has serious effects on global food and water security. The observed acceleration of warming and the pronounced disparities in outcomes after 2040, contingent on emission trajectories, provide essential insights for regional adaptation strategists and the global climate policy community.

The spatial analysis reveals that climate change is not uniform across Iraq. The physical geography, including latitude, elevation, proximity to water bodies, and degree of continentality, plays a critical role in modulating the impact. While Basrah in the arid south shows the greatest shift in climate distribution, making it a hotspot for extreme heat and salinity intrusion, the accelerated warming in Mosul signals a profound threat to the northern climatic buffers and the country's principal water sources. The central plains around Baghdad are experiencing intensifying heat stress, which challenges water-intensive agriculture and urban sustainability. Consequently, future thermal expansion is projected to radiate from the hyper-arid southern and western regions towards the center, making these zones the most

immediately vulnerable. This geographic disparity necessitates region-specific adaptation strategies; water resource management and agricultural practices must be tailored differently for the water-generating highlands, the water-consuming plains, and the hyper-arid south.

Conclusion

This study presents the first comprehensive evaluation of climate forecasts for Iraq, using the latest CMIP6 climate models and the full set of Shared Socioeconomic Pathways (SSPs). It surpasses previous studies by incorporating nuanced socioeconomic pathways and offering a detailed analysis of historical climate data from 1951 to 2020 through a multi-temporal trend approach, highlighting accelerated warming rates over recent decades. It distinctly evaluates warming signals across different climatic zones, identifying Southern Iraq as the most vulnerable hotspot. The study adeptly links past observed changes to future climate projections, establishing a coherent narrative from historical evidence to projected scenarios.

Over the past 70 years, the study areas have experienced a significant increase in temperature. Accelerating Warming: The rate at which the temperature rises fluctuates. The rate of warming has increased significantly, particularly since the 1990s. Change has accelerated in the last few decades. Analysis of monthly climatological data for three major Iraqi cities indicates significant climate change in the country. This climate change is manifested as clear and consistent warming, with all three trend lines showing a positive slope. The recent short-term trend from 1991 to 2020 shows a faster rate of temperature increase than in previous decades.

The probability distribution functions (PDFs) of air temperature for various time periods were computed for Baghdad, Mosul, and Basrah, Iraq. The study shows a significant shift in Iraq's temperature distribution, indicating a warming trend. The Baghdad area is part of a regional pattern, while Mosul and Basrah show a change to the right, indicating significant warming. From 1951–1980 to 1991–2020, all four sites show a distinct warming and a steady shift to the right, suggesting higher temperatures than in the middle of the 20th century. The mean air temperature distributions for Iraq, Mosul, Baghdad, and Basrah have changed by 0.85°C, 0.63°C, 0.92°C, and 0.81°C, respectively, due to approximately 0.5°C of global warming over the past three decades. The findings suggest that the most pronounced change occurs in Basrah, an arid southern region. The temperature distribution broadens and shifts to the right with global warming, indicating a significant change in the country's climate. To investigate changes in air temperature in Iraq through 2100, the SSP model, based on the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.0 scenarios, was used. The sustainability scenario, represented by SSP1-2.6, aims for net-zero CO_2 emissions by 2050, meeting the Paris Agreement's target of keeping warming below 2°C. The middle-of-the-road scenario, represented by SSP2-4.5, shows emissions stabilizing rather than declining substantially, resulting in further warming and significant climatic effects. SSP3-7.0 represents a gloomy situation with slow economic growth and regional rivalry, leading to significant warming of 3–4°C by 2100. SSP5-8.5 represents a scenario driven by fossil fuels, causing the worst-case warming of 4°C by 2100, potentially irreparable. The southern climatic zone is the most vulnerable in Iraq. The future

direction of thermal expansion is toward the western climatic zone, which is considered less affected by future climate change than the remaining climatic zones in Iraq. The study can help planners and policymakers develop national strategies to address future climate change in Iraq.

This study makes several original contributions to the understanding of the impacts of climate change on Iraq. First, it provides one of the first nationwide evaluations using the new CMIP6-SSP framework. This indicates that Iraq is likely to warm faster than the global average, which could have severe effects in high-emission scenarios. Second, it uses trend analysis across multiple timescales and PDF shifts to show that the country's temperature distribution has changed fundamentally since the middle of the 20th century and that warming is occurring more rapidly. The analysis shows a clear south-to-north gradient of increasing vulnerability, with the Basrah region being the most important hotspot. These findings offer unprecedented, high-resolution data that is crucial for guiding and prioritizing national climate adaptation strategies, infrastructure development, and water resource management in Iraq. The substantial differences among SSP scenarios underscore the importance of taking action to mitigate and adapt to avoid the worst outcomes.

Declarations

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Conflict of interest

The authors declare that they have no conflict of interest.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Figures

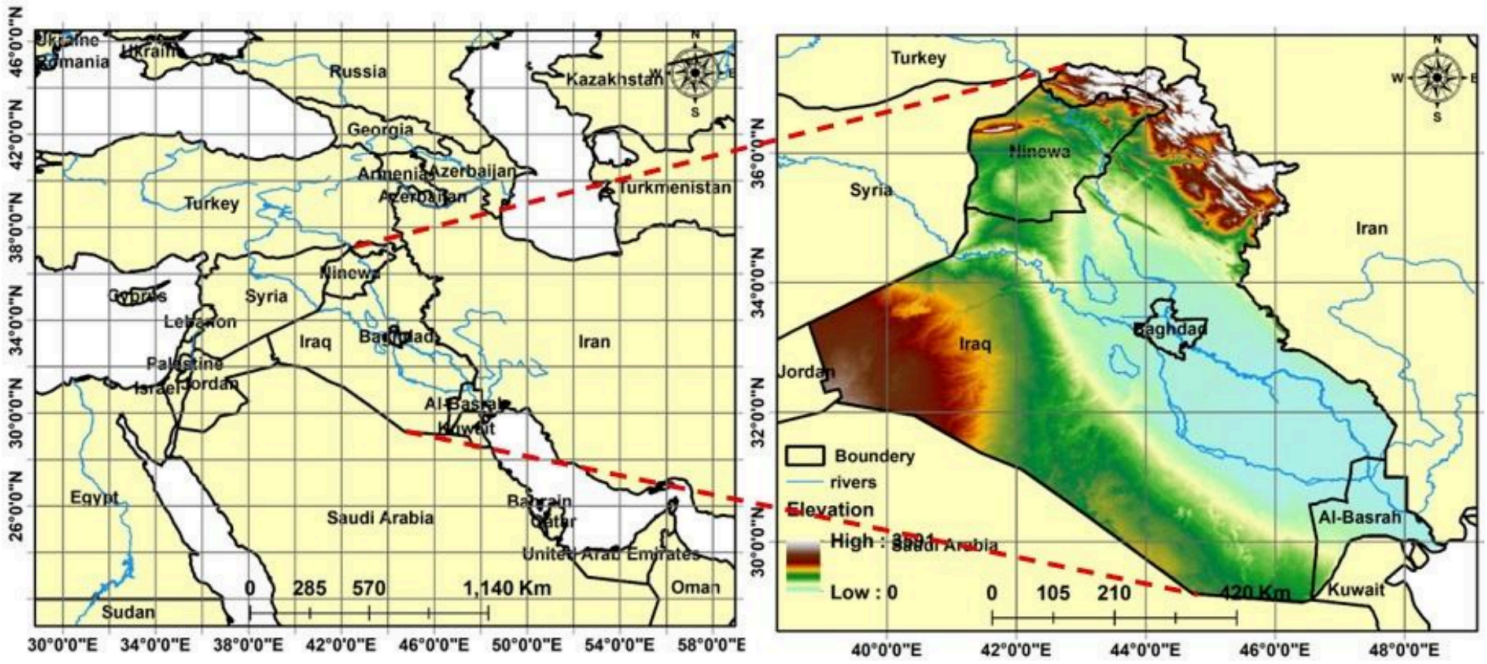


Figure 1

Location of the study area map in the Middle East

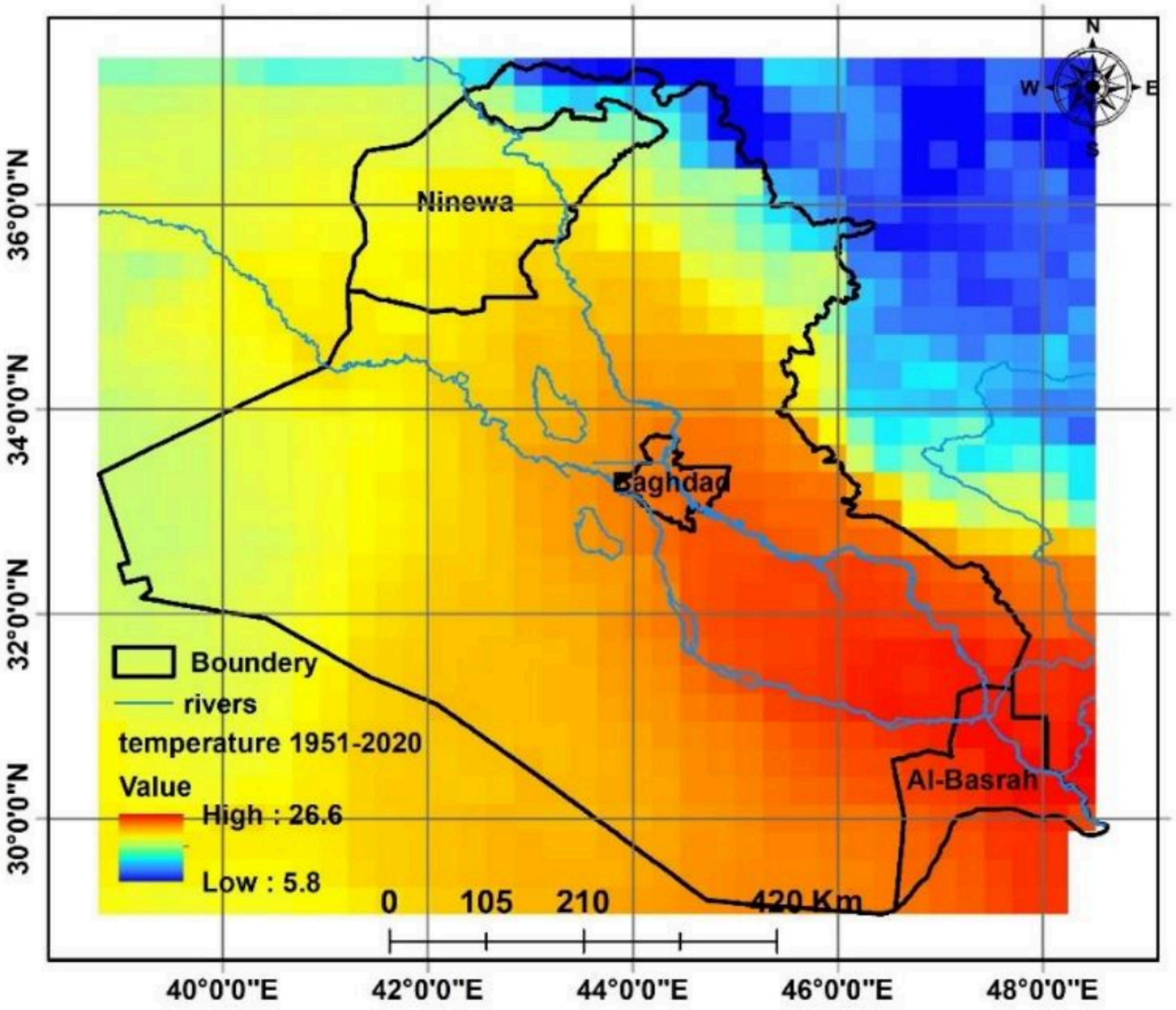


Figure 2

The Spatial distribution of temperature during 1951-2020

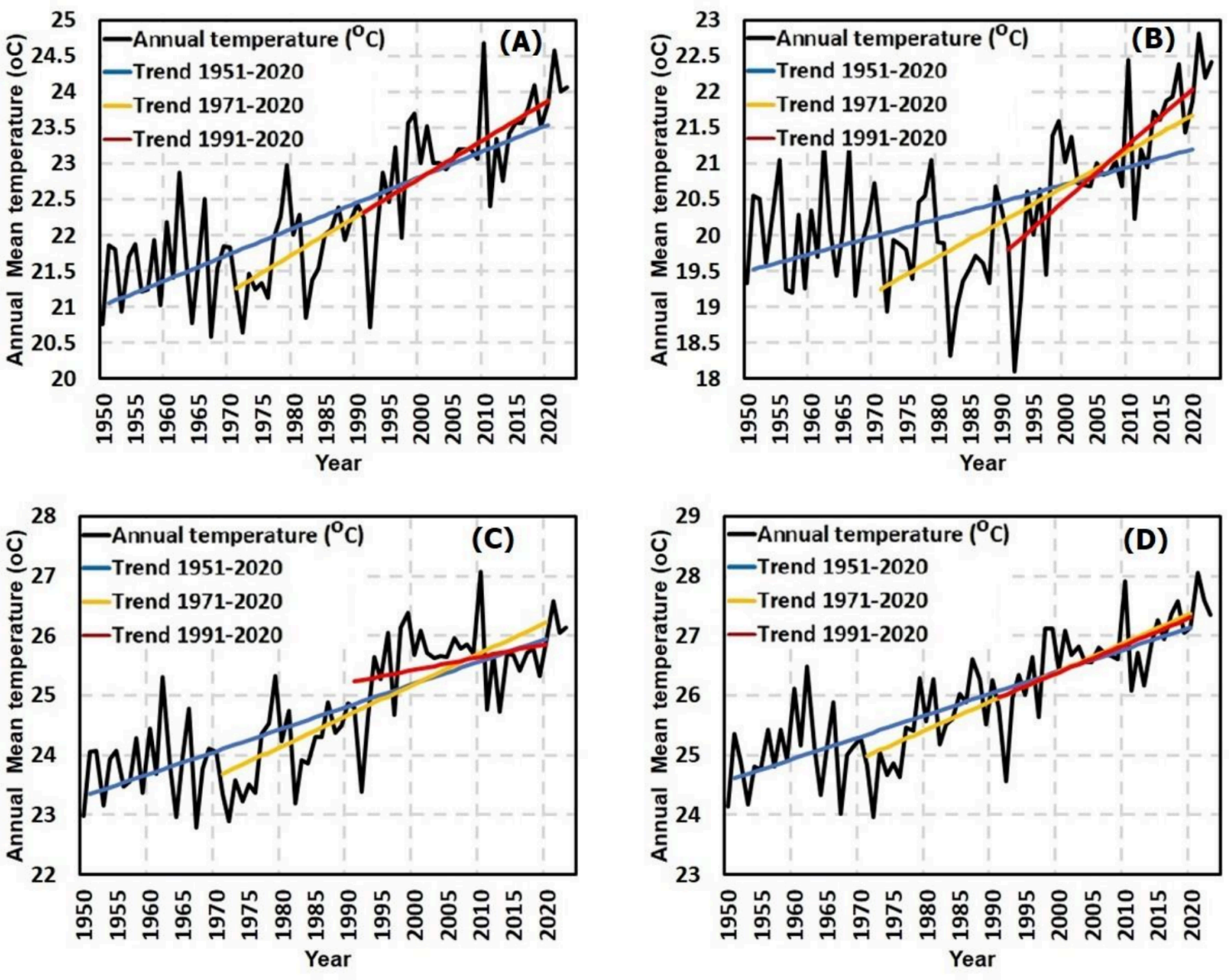


Figure 3

The time series of annual air temperature with trend per decade during 1951-2023, for (A) Iraq, (B) Mosul, (C) Baghdad, (D) Basrah

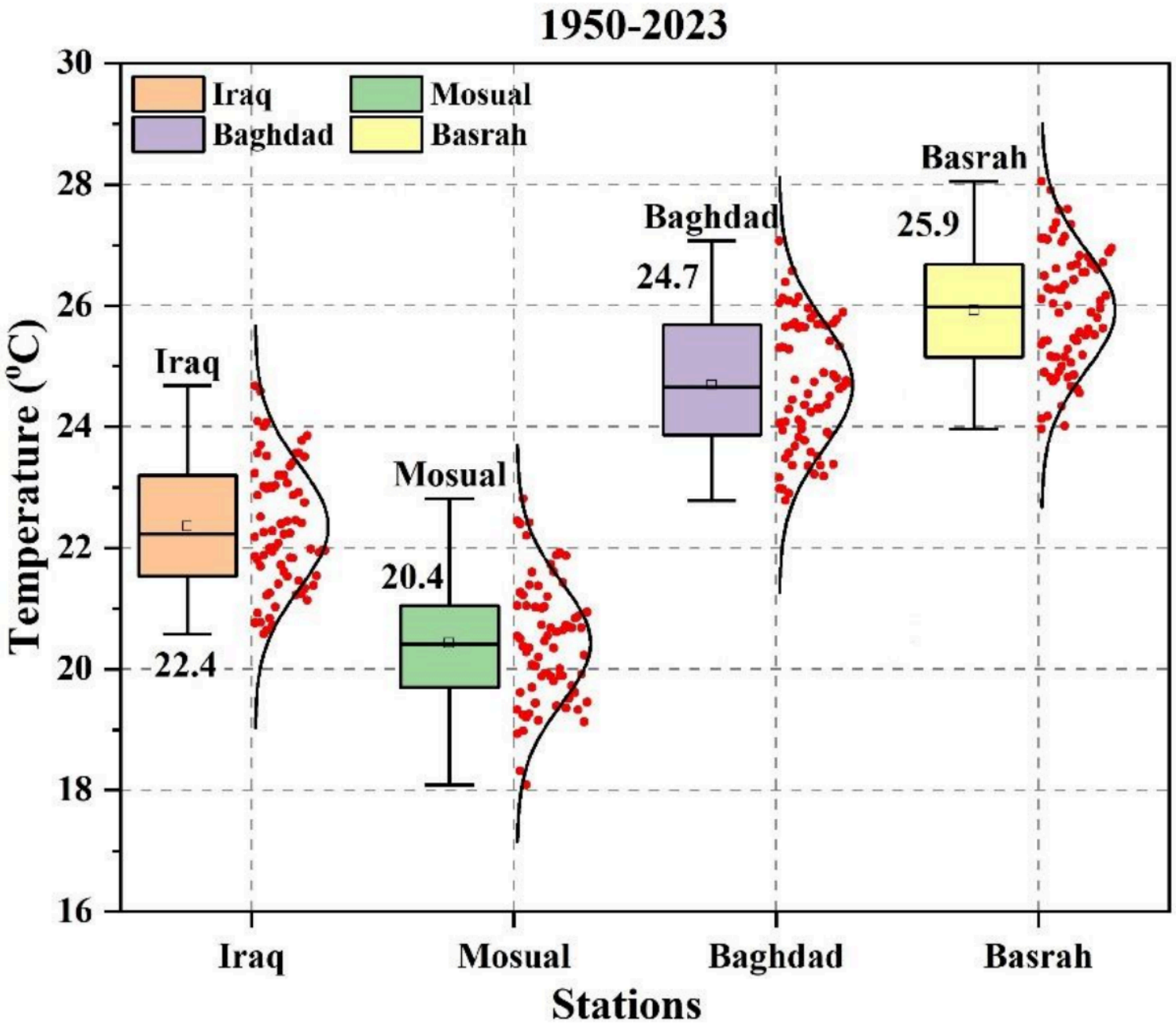


Figure 4

Box-Whiskers and distribution plot for air temperature at different regions

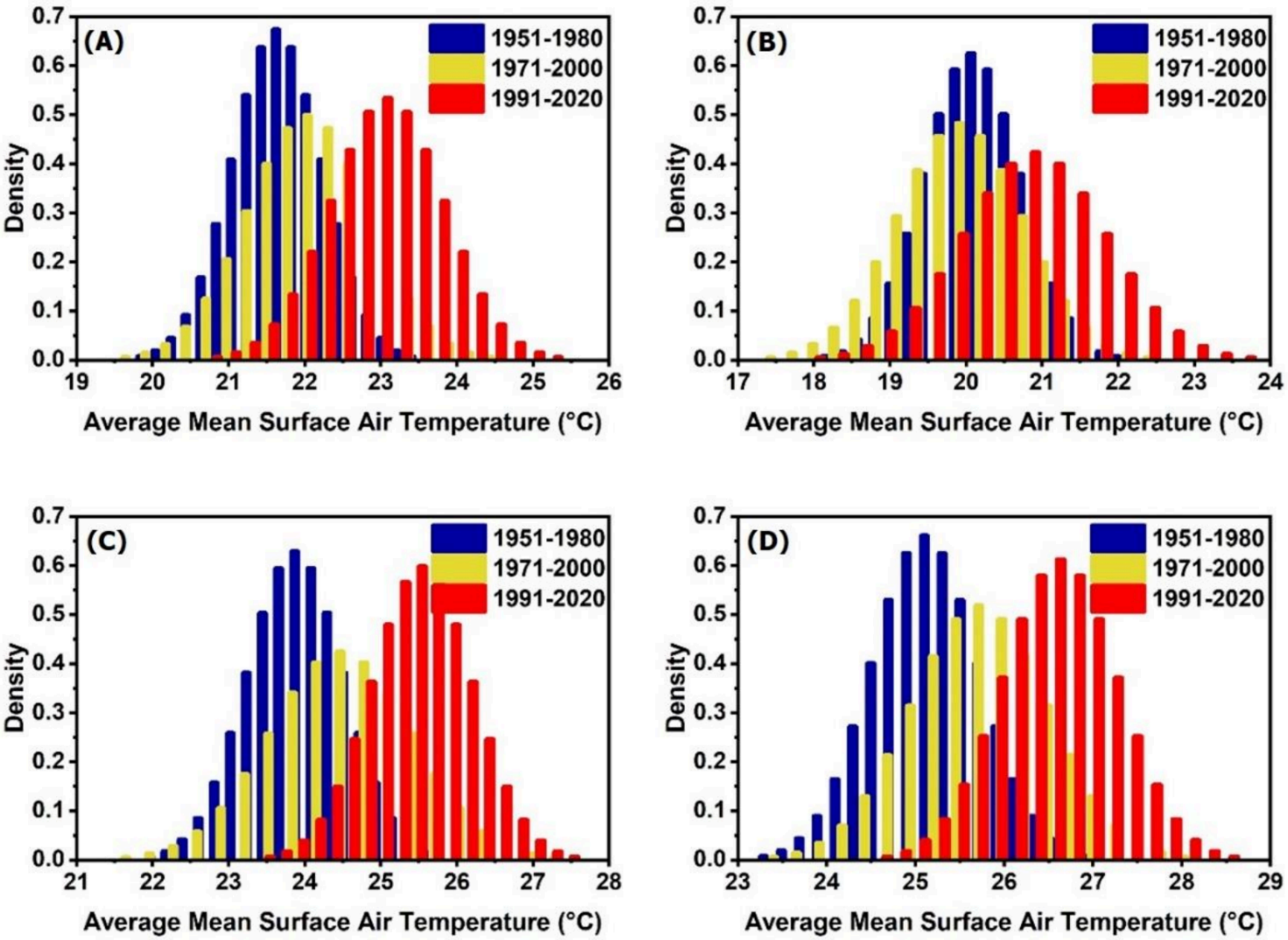


Figure 5

Histograms of probability distribution functions (PDFs) of the average mean surface air temperature in different periods, for (A) Iraq, (B) Mosul, (C) Baghdad, (D) Basrah

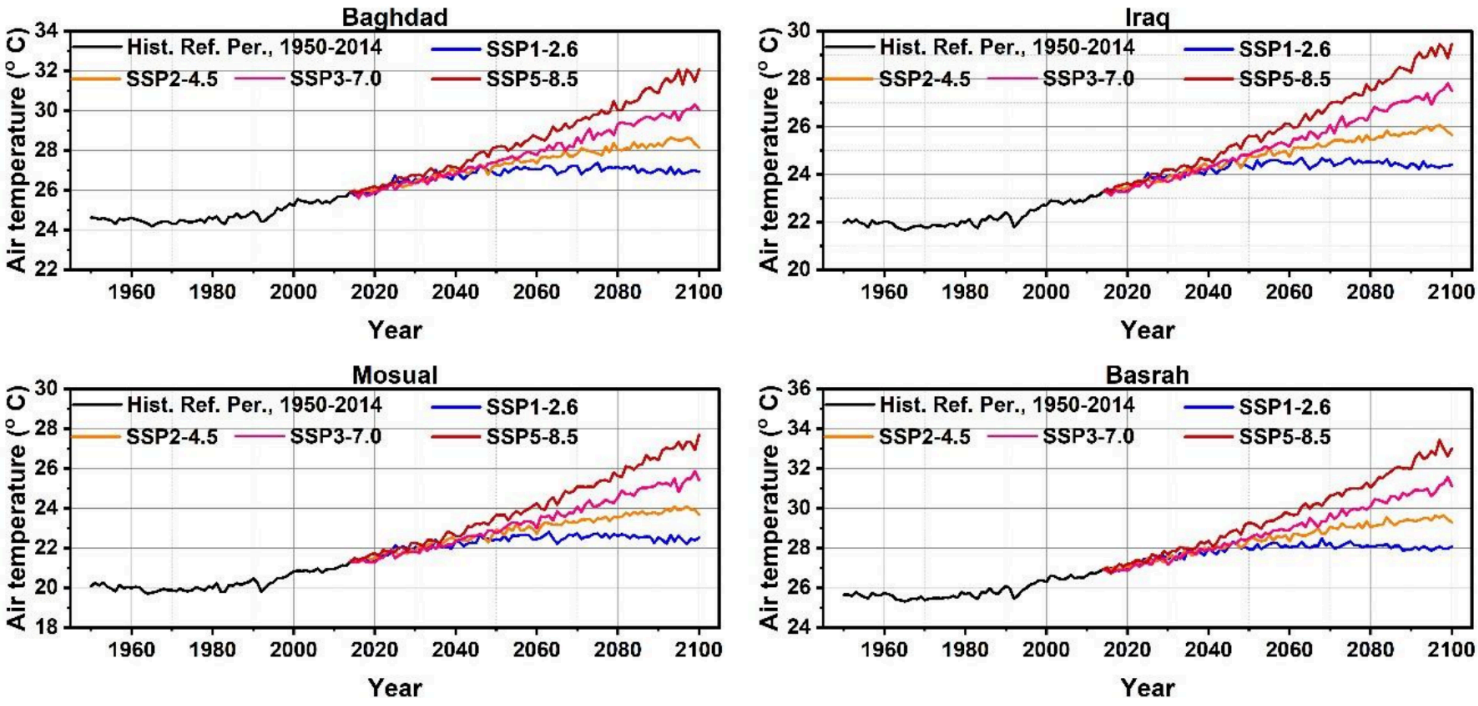


Figure 6

projected mean air temperature (Ref. period: 1995-2014) Multi Model Ensemble