Annals of Arid Zone 65(1): 71-84, 2026

Climate Change Projections for Mediterranean Arid Regions: Shared Socio-economic Pathways for Algerian Sahara

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Received: November 20, 2025 Accepted: January 20, 2026

Abstract: Arid regions in northern part of Algerian Sahara are highly vulnerable to climate change, facing rising temperatures and declining precipitation that intensify droughts and strain ecosystems and water resources. These shifts jeopardize agriculture and livelihoods, making future climate predictions vital for developing effective adaptation strategies. This study aims to explore the scenarios of climate change in Biskra region under various Shared Socio-economic Pathways (SSP) scenarios for 2035, 2055 and 2075; and highlights key trends in precipitation and temperature. Main findings show a general decline in average precipitation, dropping from 138.3 mm in 2035 to 122.4 mm in 2075, with variations across scenarios. In the optimistic SSP1-1.9 scenario (low emissions), precipitation remains relatively stable, while high-emission scenarios like SSP3-7 and SSP5-8.5 project sharper declines to 102.5 mm and 110.2 mm by 2075, respectively. Temperature forecasts indicate a steady rise in maximum, minimum and average temperature values. In SSP1-1.9, maximum temperatures slightly decrease from 27.9°C in 2035 to 27.8°C in 2075 and minimum temperatures dip from 16.8°C to 16.7°C. Conversely, in the severe (SSP5-8.5) scenario, maximum temperatures climb from 28.2°C to 31°C and minimum temperatures reach 19.8°C by 2075. Optimistic scenarios (SSP1-1.9, SSP1-2.6) show modest temperature increases and stable precipitation, underscoring the benefits of emission reductions. Pessimistic scenarios (SSP3-7, SSP5-8.5), however, predict significant temperature spikes and precipitation drops, heightening drought and water scarcity risks. These findings emphasizes the urgent need for robust climate strategies in arid regions like Biskra to mitigate worsening impacts of climate change on the existing farming systems, water availability and local communities.

Key words: Climate change, arid regions, precipitation, temperature, SSP scenarios.

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Citation
Zaghouani, A., Chetioui, C. and Hadjeb, A. 2026. Climate change projections for mediterranean arid regions: Shared socio-economic pathways for Algerian Sahara. Annals of Arid Zone 65(1): 71-84

https://doi.org/10.56093/aaz.v65i1.173393

https://epubs.icar.org.in/index.php/AAZ/article/view/173393

The Mediterranean basin, which extends from the southern coasts of Europe to North Africa and the Near East, is widely identified as a region particularly sensitive to climate change, marked by an amplification of global warming and aridification trends (Giorgi, 2006). This vulnerability is exacerbated in arid zones, which dominate the southern part of the region, particularly in Algeria where more than 80% of the territory consists of Saharan deserts and semi-arid steppes. These areas, already subjected to severe water and thermal constraints, are undergoing accelerated transformations due to rising temperatures, reduced precipitation and the intensification of climatic extremes, such as heatwaves and prolonged droughts (Lionello and Scarascia, 2018). In Algeria, the impacts of these changes threaten not only fragile ecosystems but also socio-economic systems dependent on agriculture, livestock and limited water resources, amplifying the risks of desertification and migration (Cramer *et al.*, 2018).

The Mediterranean region is identified as a critical hotspot of climate change, exhibiting warming trends that exceed the global average. This is particularly evident in the western Mediterranean, where long-term trends account for approximately 65% of the observed temperature variation (Campos *et al.*, 2024; Díaz *et al.*, 2024). In the arid regions of Algeria, summer temperatures frequently reach extreme levels, with heatwaves driving temperatures to 45°C and even 50°C. The frequency of heat days, defined as days when temperatures exceed 35°C, is projected to increase significantly under various climate scenarios, with more severe impacts anticipated in higher-emission scenarios (Pongrácz *et al.*, 2024).

At the same time, precipitation, which often falls below 200 mm year^{-1} in these areas, undergoes a significant decrease. The study by Zittis *et al.* (2020), based on CMIP6 models including the Shared Socio-economic Pathways (SSP), projected a reduction of 15 to 40% in rainfall by 2100, depending on emission scenarios (SSP2-4.5 to SSP5-8.5), with more pronounced impacts in the semi-arid regions of northern Algeria, where winter rains are becoming increasingly erratic (Tramblay and Somot, 2018). The reduction in precipitation and the increase in evaporation rates threaten the sustainability of water resources essential to Saharan oases (Sirigu *et al.*, 2024). In terms of water resources, Milly and Dunne (2020) highlighted that Mediterranean arid zone, including Algeria, could see their surface water resources decrease by 30 to 50% by 2050 in intermediate scenarios, increasing dependence on already overexploited aquifers.

The biodiversity of the Biskra region is threatened by climate-induced changes in water availability, which impact habitats and the reproductive cycles of species. This may lead to shifts in species distribution and potential extinctions, particularly for those with specific adaptations to water resource availability (Demir, 2009; Ojija and Nicholaus, 2023). Ecosystem services, such as pollination and carbon sequestration, are also compromised, affecting both natural ecosystems and agricultural productivity (Demir, 2009). The loss of biodiversity and ecosystem services has cascading effects on food security and economic stability, especially for communities reliant on agriculture (Ojija and Nicholaus, 2023).

Biskra region is experiencing increased desertification due to climate change, which results from rising temperatures and reduced precipitation. This process leads to soil degradation, the loss of arable land and a decline in agricultural yields. The degradation of soil quality is a critical consequence, leading to a reduction in soil fertility and an increase in salinity. This impacts the soil's capacity to retain nutrients and water, which is essential for agricultural productivity (Badapalli *et al.*, 2023b; Belghemmaz *et al.*, 2018). As desertification advances, an increasing amount of land becomes unsuitable for agriculture, resulting in a decrease in available arable land. This affects food security and the livelihoods of communities dependent on agriculture (Badapalli *et al.*, 2023a). The combined effects of soil degradation and the loss of arable land contribute to a decline in agricultural yields. This decline poses a significant threat to the region's economy, which heavily relies on agriculture (Badapalli *et al.*, 2023a; Mandal and Roy, 2024). The principal objective of our work is to reveal anticipated changes in temperature and precipitation during three intervals of the twenty-first century in the susceptible Biskra region, providing essential insights for developing effective climate

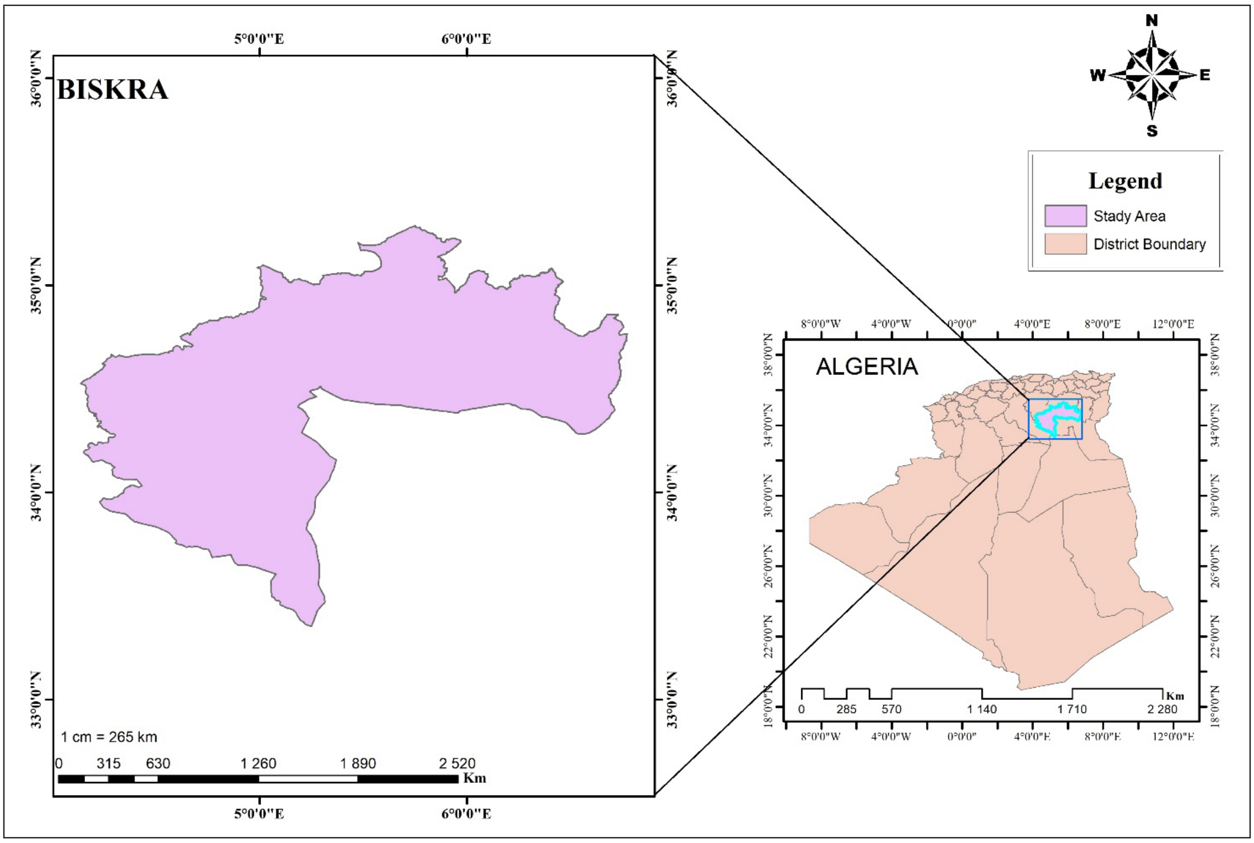

Fig. 1. Map of the Biskra region in Algeria.

change adaptation and resilience methods. This research addresses the scarcity of climate change studies in the northeastern Algerian Sahara, serving as a pivotal advancement that encourages additional investigation through various climate models and scenarios, as well as an analysis of prospective shifts in climate extremes.

Materials and Methods

The province of Biskra is located in the northeastern part of the Algerian Sahara, roughly 420 kilometers southeast of the capital, with an area of 21,509 square kilometers. Biskra is bordered to the North by the Batna province, to the Northeast by the Khenchela, to the Northwest by Msila, to the Southeast by Oued Souf, to the Southwest by Djelfa and to the South by Ourgla province (Fig. 1). As noted by Boudibi (2021), the climate of Biskra is classified as hot desert (Köppen classification), with annual rainfall not exceeding 150 mm, evaporation reaching 2500 mm and temperatures ranging between 11°C in January and 35°C in July. The study area's geography is predominantly flat, characterized by undulating hills and mountain ranges, with a minimum altitude of 43 m in the Oumache region and a maximum of 283 m in the western section of the region. Geologically, the major part of the study area is classified as recent Quaternary, facilitating groundwater recharge and presence (Boudibi, 2021; Sedrati, 2011). The soils in the Saharan zone of Algeria, like those in other arid locations, possess elevated levels of soluble salts, a phenomenon resulting from limited precipitation that hinders the leaching process (Halilet, 1998). Biskra was selected as a model for Mediterranean arid regions due to its pronounced vulnerability to desertification and water scarcity, making it an ideal case study for climate change impacts. These environmental characteristics provide a critical foundation for understanding how climate change affects the region.

The Biskra region in Algeria faces significant challenges due to climate change, primarily driven by desertification, urban transformation and water scarcity. These challenges are compounded by the region's arid climate and socio-economic factors, which collectively threaten ecological balance and regional sustainability. The following sections elaborate on the specific challenges Biskra encounters in the context of climate change.

Biskra is experiencing severe desertification, a process accelerated by both human activities and natural climate shifts. The encroachment of sand from the Sahara Desert into urban areas disrupts daily life and infrastructure (Azzouzi *et al*., 2017). The El-Outaya region in Biskra is particularly affected, with desertification leading to land degradation and a decline in agricultural productivity (Lydia, 2023). The urban transformation of Biskra has resulted in the degradation of its natural heritage, notably the oasis system. This transformation has led to the loss of palm groves and the oasis identity, impacting its ecological balance and tourism potential (Berbache *et al*., 2022). Additionally, urban expansion has contributed to the deterioration of microclimatic quality, affecting pedestrian behavior and urban livability (Boumaraf and Amireche, 2022).

Biskra faces significant water scarcity, exacerbated by reduced precipitation due to climate change and increased evaporation rates (Lange, 2023; Nichane and Khelil, 2015). The region's soils exhibit high salinity levels, particularly gypsum, further complicating agricultural activities and water management (Mostephaoui *et al*., 2017).

The MENA region, including Biskra, is identified as a climate change hotspot, with projections of extreme heatwaves and prolonged heat periods. These conditions heighten the demand for energy-intensive cooling solutions, placing significant strain on local resources (Lange, 2023). The anticipated rise in temperatures and decline in precipitation are likely to intensify existing water and energy challenges, necessitating integrated adaptation strategies (Lange, 2019).

While these challenges are substantial, it is critical to consider the broader context of climate change adaptation in the MENA region. Effective adaptation strategies, such as implementing the water-energy nexus and adopting renewable energy sources, can mitigate some of these impacts. Furthermore, innovative irrigation technologies and sustainable urban planning can help preserve Biskra's natural and cultural heritage while addressing the socio-economic needs of its population. These strategies require coordinated efforts and substantial investment but offer a pathway toward resilience in the face of climate change.

Modelling procedure

The Shared Socio-Economic Pathways (SSPs) constitute a set of scenarios developed to explore alternative futures characterized by diverse challenges related to climate change mitigation and adaptation (O'Neill *et al*., 2014). These pathways provide a framework for understanding how varying socio-economic developments can influence greenhouse gas emissions, land use and other critical factors pertinent to climate change research. The SSPs are designed to be scalable across different regions and sectors, rendering them a versatile tool for integrated assessment models and impact studies (Kriegler *et al*., 2012; O'Neill *et al*., 2017). The SSPs offer the socio-economic context necessary for analyzing the impacts of climate change. They assist researchers in comprehending how different future scenarios may affect vulnerability and adaptive capacities (Reimann *et al*., 2018; Rohat *et al*., 2018). The global storylines that have been employed in the study are summarized in Table 1. The narratives are discussed and described in further detail by Zhang *et al*. (2024).

The Coupled Model Intercomparison Project Phase6 (CMIP6) represents the most ambitious phase of the Coupled Model Intercomparison Project (CMIP), encompassing 21 Model Intercomparison Projects (MIPs) and 190 experiments. These simulations span 40,000 years of climate data, generating approximately 40 petabytes of data (Acosta *et al*., 2024). Over the past four decades, the project has evolved, enhancing the representation of the Earth system while addressing systematic biases and variability. The CMIP6 data infrastructure facilitates the dissemination of climate model outputs, which are critical for international climate assessments and policymaking (Hewitt and Dunne, 2024).The CMIP6 models particularly project significant shifts in global climate zones, with a marked acceleration attributed to higher warming rates compared to previous iterations, such as CMIP5 (Bayar *et al*., 2023). The performance of CMIP6 models has been evaluated in specific regions, such as the IGAD region in East Africa, where they generally capture precipitation regimes but

Table 1. Summary of SSP narratives (O'Neill et al., 2017)

		Focalization	Characteristics	Implications
SSP1	Sustainable development (taking the green path)	emphasizes sustainable development and environmental awareness.	High investments in education and health. Strong global cooperation on environmental issues. Rapid technological advancements in the field of green technologies. Low population growth due to the improvement of education and health services.	This trajectory leads to a reduction in greenhouse gas emissions and a more sustainable future, in accordance with global climate goals.
SSP2	In the middle of the road	Continuation of historical trends without significant deviations	Moderate economic growth and technological development. Mixed progress on environmental and social issues. Population growth is stabilizing at a moderate level.	This scenario presents moderate challenges in terms of climate change adaptation and mitigation, reflecting a balance between sustainability and development.
SSP3	Regional Rivalry (A Bumpy Road)	Nationalism and regional conflicts dominate	Slowdown in economic growth and technological development. Rapid population growth due to limited access to education and healthcare services. Weak international cooperation on environmental matters.	This trajectory leads to high greenhouse gas emissions and significant challenges for climate adaptation, as regional conflicts hinder global efforts.
SSP4	Inequality (a divided road)	Increasing inequalities both within countries and between them. Characteristics:	High economic growth in some regions, while others are lagging behind. Technological development is unevenly distributed. Population growth varies considerably from one region to another.	This scenario yields mixed results regarding climate change, with some regions being able to adapt and effectively mitigate its effects, while others face severe challenges
SSP5	Development based on fossil fuels (taking the highway)	Rapid economic growth driven by fossil fuels.	Significant investments in energy-intensive technologies. Strong economic growth and technological development. Strong population growth due to the improvement in living standards.	This trajectory leads to high greenhouse gas emissions and significant climate challenges, as dependence on fossil fuels continues.

exhibit biases and overestimations (Omay *et al.*, 2023).

Data sources

As part of the (CMIP6, IPCC updates global climate change models, which are organized by the World Climate Research Program (WCRP) and used in conjunction with IPCC Climate Scenarios (Hausfather, 2019). Since CMIP6 was suggested in the IPCC's 6th Assessment Report, it was chosen for use and serves as the foundation for this investigation.

The World Bank's Climate Change Knowledge Portal provides the climate data (from 1995 to 2014). These data include monthly averages of temperatures, precipitation and evaporation rates, derived from observational records and reanalysis products.

As for the future projections, they were extracted from the CMIP6 archive via the Earth System Grid Federation (ESGF) portal. Eleven General Circulation Models (GCMs) were selected based on their performance in simulating arid climates (Chetioui and Bouregaa, 2024). The bias in the model outputs was corrected and their accuracy was reduced to a 0.5° × 0.5° grid using the quantile mapping technique. https://climateknowledgeportal.worldbank.org/

Execution procedures: The study integrated SSP scenarios with CMIP6 projections to assess the impacts of climate change in Biskra under five pathways (SSP1-SSP5). The simulations were run for three-time horizons: short-term (2025-2050), medium-term (2051-2075) and long-term (2076-2100), using 1995-2014 as the baseline period. The analysis focused on temperatures, precipitation and evaporation. An ensemble approach was used to reduce uncertainty, with averages calculated across the nine models using **OriginPro** 2025.

Results and Discussion

Results of the SSP scenarios

Predictions of annual precipitation: Figure 2 presents projections of annual precipitation

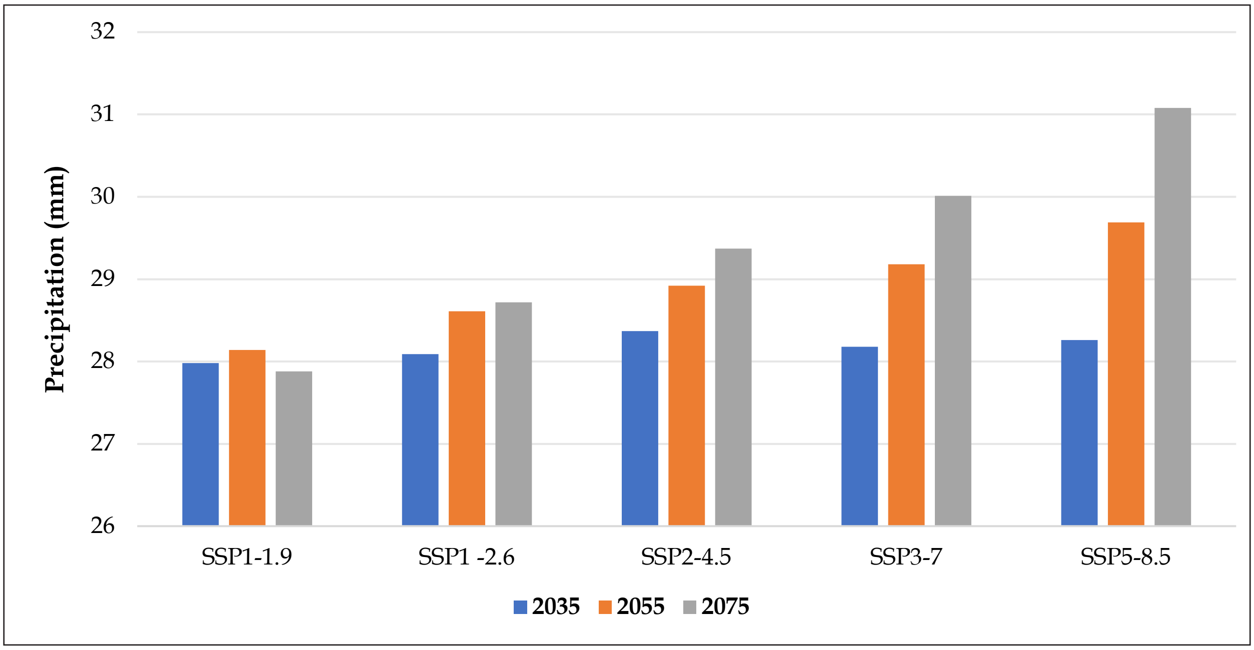

Fig. 2. Predictions of annual precipitation for the arid region of Biskra under SSP scenarios for the years 2035, 2055 and 2075 in comparison to the period 1995-2014.

for the arid region of Biskra under various SSP scenarios, indicating a gradual decline in average precipitation from 138.31 mm in 2035 to 128.11 mm in 2055 and further to 122.41 mm in 2075. The comparison among scenarios reveals divergent trends based on emission trajectories. Under SSP1-1.9, characterized by low emissions and strong commitments to sustainability, precipitation remains relatively stable, suggesting that effective mitigation strategies could help preserve the regional hydrological balance. Similarly, the SSP1-2.6 scenario shows an increase in precipitation in 2055 (144.32 mm), but this is preceded and

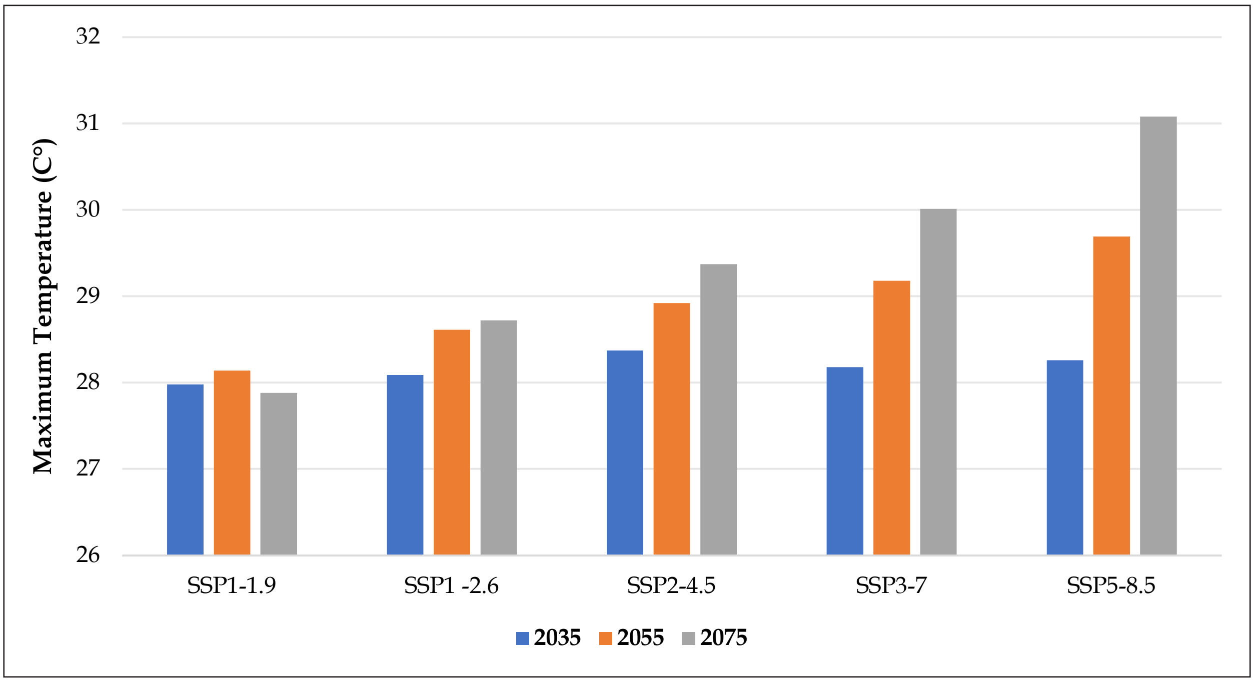

Fig. 3. Prediction of maximum temperature for the arid area of Biskra under SSP scenarios in 2035, 2055 and 2075 compared to the base period of 1995-2014.

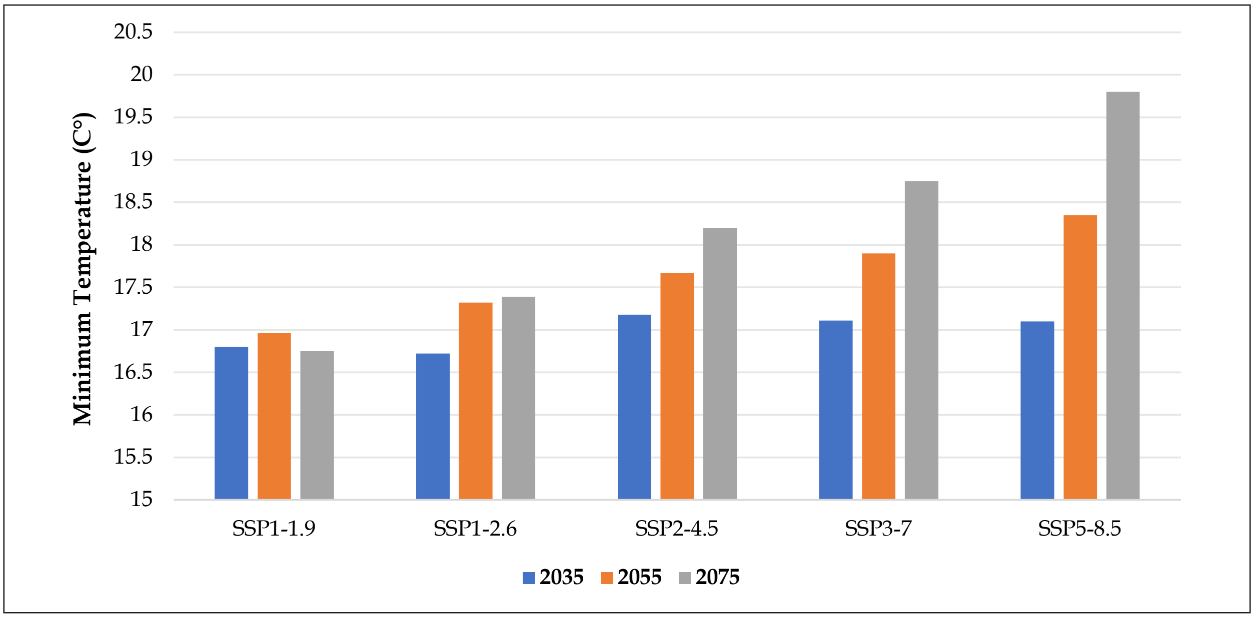

Fig. 4. Prediction of minimum temperature for the arid area of Biskra under SSP scenarios in 2035, 2055 and 2075 compared to the period of 1995-2014.

followed by decreases in 2035 (133.48 mm) and 2075 (131.82 mm), possibly reflecting regional climate variability. In contrast, SSP2-4.5 indicates a significant drop in 2055 (110.88 mm), with higher values in 2035 (140.26 mm) and 2075 (132.29 mm), suggesting a less stable pattern. The high-emission scenarios, SSP3-7.0 and SSP5-8.5, display substantial reductions over time. For SSP3-7.0, precipitation declines from 132.71 mm in 2035 to 123.27 mm in 2055 and 102.57 mm in 2075. SSP5-8.5 shows a similar trajectory, with values decreasing from 146.33 mm (2035) to 128.24 mm (2055) and 110.29 mm (2075). These results underscore the potential impacts of emission-intensive pathways on water availability in arid regions.

Prediction of maximum temperature

The SSP1-1.9 scenario predicts that maximum temperatures will rise slightly, then drop slightly between 2035 (27.98°C) and 2055 (28.14°C) and 2075 (27.88°C) (Fig. 3). The SSP1-2.6 scenario, which is not as optimistic, also predicts that maximum temperatures will rise slowly, reaching 28.72°C in 2075, 28.61°C in 2055 and 28.09°C in 2035. This is still in line with the goal of keeping warming to 2°C. The SSP2-4.5 scenario, which assumes stabilization of emissions in the medium term, indicates a continuous increase in maximum temperatures, rising from 28.37°C in 2035 to 28.92°C in 2055 and 29.37°C in 2075. The SSP3-7.0 scenario, predicts an even more pronounced increase, with a maximum temperature reaching 30.01°C in 2075, compared to 28.18°C in 2035 and 29.18°C in 2055. Finally, the SSP5-8.5 scenario, the most alarming rise in maximum temperatures, reaching 31.08°C in 2075 compared to 28.26°C in 2035 and 29.69°C in 2055.

Prediction of minimum temperature

As shown in Fig. 4, in all scenarios, minimum temperatures show an upward trend over time. But the magnitude of this rise is different in each scenario. The SSP3-7 and SSP5-8.5 pathways, which assume high emissions and little climate change mitigation, have the biggest rises. The analysis of the scenarios reveals contrasting dynamics.

The SSP1-1.9 scenario predicts that temperatures will rise slightly in 2035 (16.80°C) and again in 2055 (16.96°C). After that, they will level off or even go down slightly by 2075 (16.75°C). Similarly, the SSP1-2.6 scenario indicates a progression of temperatures between 16.72°C in 2035, 17.32°C in 2055 and 17.39°C in 2075. The SSP2-4.5 scenario, on the other hand, shows that temperatures will keep going up: 17.18°C in 2035, 17.67°C in 2055 and 18.20°C in 2075. The SSP3-7 and SSP5-8.5 scenarios, characterized by high emissions, show temperatures of 17.11°C, 17.90°C and 18.75°C for SSP3-7 and 17.1°C, 18.35°C and

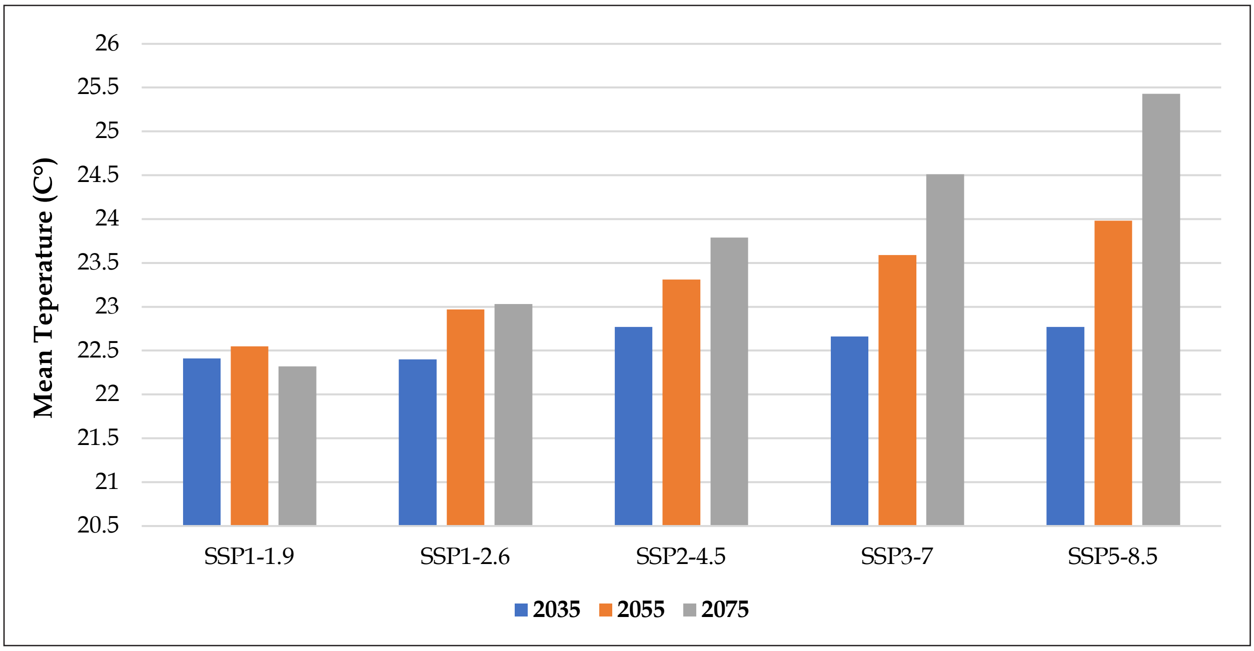

Fig. 5. Prediction of mean temperature for the arid area of Biskra under SSP scenarios in 2035, 2055 and 2075 compared to the period of 1995-2014.

19.80°C for the years 2035, 2055 and 2075, respectively.

Weak climate action shows the temperature increases were more pronounced and reached concerning levels in 2075, particularly in SSP5-8.5 shows the highest increase, with a projected minimum temperature of around 19.8°C.

Prediction of mean temperature: The Fig. 5 indicates that the future projections of average temperatures in the arid Biskra area under the (SSP1-1.9) scenario are 22.41°C, 22.51°C and 22.32°C in 2035, 2055 and 2075, respectively. The scenario (SSP1-2.6), suggests to a gradual increase in temperatures, reaching 22.4, 22.97 and 23.03°C in 2035, 2055 and 2075, respectively. The scenario (SSP2-4.5) results in a continuous increase in temperatures, reaching 22.77°C, 23.31°C and 23.79°C in 2035, 2055 and 2075. The SSP5-8.5 scenario is particularly alarming, with a significant increase in temperatures reaching 22.77°C, 23.98°C and 25.43°C in 2035, 2055 and 2075, respectively.

Projections of future precipitation and temperature patterns in arid regions require the evaluation of multiple climate scenarios. This study assesses expected trends and variability in precipitation and temperature across different arid regions using an ensemble of CMIP6 climate models under five Shared Socioeconomic Pathways (SSPs) scenarios. These forecasts are crucial for water resource management and understanding the impacts of climate change on these vulnerable areas.

Climate models, like as CMIP6 and CMIP5, indicate a global decline in precipitation areas, particularly between 5° and 50° latitude, impacting regions like the Middle East. This reduction is associated with rising temperatures and a change in precipitation patterns toward the poles (Dobler *et al*., 2023). The Mediterranean region is expected to experience a decrease in average precipitation of 15 to 30% by the end of the century, despite an increase in the frequency of atmospheric rivers (Massoud *et al.*, 2022). The variation in precipitation is expected to be between -77.3 mm and +51.1 mm compared to the reference period (Mesgari *et al.*, 2022). Throughout Algeria, including Biskra, a decrease in average precipitation is expected, particularly under higher emission scenarios such as SSP5-8.5. This corresponds to the general trend of "the dry becoming drier" observed in arid regions (Babaousmail *et al.*, 2022; Mesgari *et al.*, 2022).

These projections suggest significant impacts on ecosystems, agriculture and water resources. These projections are essential for understanding potential challenges and formulating adaptive strategies. Studies indicate a general trend of decreasing precipitation, which could exacerbate water scarcity, affect agricultural productivity and lead to ecosystem degradation. This overview transitions to a detailed examination of the specific impacts on ecosystems, agriculture and water resources.

The reduction in precipitation is likely to accelerate desertification processes, as a decrease in precipitation can lead to the early disappearance of vegetation, an essential component of semi-arid ecosystems (Dixon, 2017). The reduction in water availability can lead to habitat loss and a decrease in biodiversity, as many species in these regions are adapted to specific humidity conditions (Scholes, 2020). The rise in temperatures, combined with the reduction in precipitation, increases evapotranspiration rates, which puts a strain on water-limited ecosystems (Wang *et al.*, 2024).

Agriculture in these arid areas, heavily dependent on precipitation, could face a decline in yields due to water scarcity. The anticipated decrease in precipitation during critical growing seasons could have serious repercussions on crop productivity (Tomaszkiewicz, 2021). With less precipitation, dependence on irrigation will increase, but water resources may not be sufficient to meet agricultural demand, necessitating more efficient irrigation practices (Madani *et al.*, 2024). The reduction in precipitation can lead to soil erosion and degradation, further decreasing the quality and productivity of agricultural lands (Scholes, 2020).

The expected decrease in precipitation will worsen the water shortage, affecting both surface water and groundwater resources. This shortage poses a significant challenge for water resource management in the region (Abdullaeva, 2024). The decrease in precipitation and the increase in temperatures are expected to reduce runoff, which will impact the availability of water for various uses, including domestic, agricultural and industrial (Wang *et al.*, 2024). Existing hydraulic infrastructures may struggle to cope with increased demand and reduced supply, highlighting the need to improve water management strategies (Nichane and Khelil, 2014).

Although projections indicate variable precipitation trends in different arid regions, it is important to take into account the uncertainties inherent in climate modeling. Factors such as model selection, emission scenarios and regional climatic conditions can significantly influence the results. Furthermore, the interaction between increased precipitation and rising temperatures could lead to complex hydrological responses, necessitating a nuanced approach to climate adaptation strategies. The projected maximum temperature for the arid region of Biskra, according to the Shared Socio-economic Pathways (SSP) scenarios, indicates a significant increase in temperature by 2035, 2055 and 2075 compared to the reference period of 1995-2014. The projections are based on various climate scenarios, which suggest a trend of rising temperatures due to climate change. The increase in maximum temperatures is expected to be more pronounced in higher emission scenarios, reflecting the global trend of rising temperatures in arid and semi-arid regions.

According to the SSP2-4.5 scenario, the maximum temperature in Biskra is expected to increase by approximately 1.5°C to 2.0°C compared to the reference period. This increase is consistent with the general warming trend observed in the MENA region, where maximum temperatures are expected to rise significantly in medium emission scenarios (Abed and Selmane, 2023; Almazroui *et al.*, 2021).

The SSP5-8.5 scenario predicts a more significant increase in maximum temperatures, potentially reaching 3.0°C to 4.0°C above the baseline value. This scenario represents a high emissions trajectory, which aligns with the results indicating that the intensity of the hottest days is expected to increase further in extratropical regions, including parts of Algeria (Abed, 2021; Babaousmail *et al.*, 2022). According to the SSP5-8.5 scenario, the maximum temperature could increase by 4.0°C to 5.0°C. This projection is supported by studies indicating that the Sahara region, including Biskra, will experience significant warming, with maximum temperatures potentially reaching extreme levels by the end of the century (ABED and Selmane, 2023; Lelieveld *et al.*, 2016).

Although the models provide a general trend of rising temperatures, there is some uncertainty regarding the exact magnitude of the change due to differences between the results and the assumptions of the models. However, the multi-model ensemble mean is considered more reliable for projecting future climate changes (Ntoumos *et al.*, 2022; Zhao *et al.*, 2014).

Unlike the projected increases in maximum temperatures, the potential impacts of these changes on local ecosystems, water resources and human health are the subject of broader discussion. The arid region of Biskra, like other regions of Steppe regions in Algeria, may face challenges related to water scarcity and thermal stress, requiring adaptation and mitigation strategies to cope with the expected climatic extremes. These projections highlight the importance of global efforts to limit greenhouse gas emissions and implement effective climate adaptation measures to mitigate the negative effects of climate change in vulnerable regions like Biskra. The projection of temperature in arid zones constitutes an essential area of study due to the sensitivity of these regions to climate change.

The increase in maximum temperatures is expected to amplify the water limitations of the ecosystem, thereby reducing the cooling capacity through evaporation due to plant transpiration and soil evaporation. This can lead to significant changes in ecosystem functioning and a loss of biodiversity (Denissen *et al.*, 2023, 2024). Arid and semi-arid regions are likely to experience increased soil degradation and loss of biodiversity due to rising temperatures and reduced water availability. These changes threaten the sustainability of local ecosystems and the services they provide (Abdullah *et al.*, 2019; Maestre *et al.*, 2012). The rise in temperatures and changes in precipitation patterns is expected to significantly reduce crop yields. Without adaptation, agricultural production in arid regions could decrease by 50% or more, which would impact food security and agricultural incomes (Phetheet *et al.*, 2021).

The rise in temperatures is expected to reduce water availability by increasing evaporation and decreasing precipitation. This will impact surface water resources, leading to a reduction in flow and water production in arid regions (Abdullaeva, 2024; Al-Hasani *et al.*, 2023). Advanced hydrological models and climate projections are essential for developing effective water management strategies. These models help forecast the evolution of water availability and guide policymakers in implementing adaptive measures (Abdullaeva, 2024).

Although the focus is on adaptive strategies for agriculture, it is important to take into account the broader socio-economic and environmental context. The impacts of climate change are not limited to agriculture but also affect water resources, energy production and social stability. The integration of renewable energy production and the strengthening of social resilience can provide additional support to rural communities facing climate challenges (Herrick and Beh, 2015; Phetheet *et al.*, 2021).

Furthermore, it is essential to understand the interactions between climate change, soil resilience and social stability for effective adaptation planning (Herrick and Beh, 2015). These broader perspectives highlight the need for a holistic approach to climate change adaptation in arid regions like Biskra, Algeria. Technological interventions, such as precision agriculture, integrated nutrient management and resilient cropping systems, are essential for adapting agriculture in arid zones to climate change (Ahmed *et al.*, 2022). In Central Asia, adaptation strategies for crops such as cotton and spring wheat include modifying agroclimatic practices based on changing conditions, as predicted by regional climate models (Shkolnik *et al.*, 2019). The use of advanced climate models and machine learning can provide information on temperature and precipitation patterns, thereby contributing to the development of effective water management strategies (Abdullaeva, 2024). Although projections indicate a challenging future for agriculture in arid regions, there are opportunities for adaptation and mitigation. For example, the potential for expanding agriculture from arid zones into hyper-arid regions, where the availability of green water can increase in future, represents a unique opportunity for sustainable agricultural practices (Shahsavari *et al.*, 2019). Furthermore, the integration of cutting-edge technologies and collaborative efforts among stakeholders can enhance resilience and ensure food security in these vulnerable areas.

Conclusions

The projections indicate a decrease in precipitation and a noticeable increase in temperatures in the Arid Biskra region using a range of CMIP6 models under the five SSP scenarios. Most notably, the SSP1-1.9 scenario indicates a lower rate of temperature rise in the second half. The mean temperature is predicted by SSP8.5 to increase to 22.41°C, 22.51°C and 22.32°C in 2035, 2055 and 2075. In the other half of the year, SSP8.5 predicts that the temperature would rise to 22.77°C, 23.98°C and 25.43°C in 2035, 2055 and 2075, respectively. The SSP1-1.9 scenario forecasts a modest increase in the minimum temperature in 2035 (16.80°C) and another in 2055 (16.96°C). By 2075, they will level out or even significantly decrease (16.75°C). High-emission scenarios, such as SSP5-8.5, display temperatures of 17.1°C, 18.35°C and 19.80°C for the years 2035, 2055 and 2075, respectively. According to the SSP1-1.9 scenario, maximum temperatures will slightly increase in 2035, 2055 and 2075, respectively, before significantly decreasing in 2035 (27.98°C), 2055 (28.14°C) and 2075 (27.88°C). Last but not least, the SSP5-8.5 scenario, which is predicated on robust economic expansion and a greater reliance on fossil fuels, exhibits the most concerning increase in maximum temperatures, rising to 31.08°C in 2075 from 28.26°C in 2035 and 29.69°C in 2055. The average precipitation, however, decreases gradually between 2035, 2055 and 2075, from 138.314 mm in 2035 to 128.11 mm in 2055 and 122.406 mm in 2075, according to the examination of general trends. The lack of climate change research in the northeastern Algerian Sahara is addressed by this study, which is a significant step that motivates more research using other climate models and scenarios and an examination of potential changes in climate extremes.

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Printed in March 2026