



Future projection of precipitation and temperature changes in the Middle East and North Africa (MENA) region based on CMIP6

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Abstract

Temperature and precipitation are among the most important climatic elements in the study of climate change due to significant temporal and spatial changes, and the projection of their changes is very important in environmental hazards and planning. Therefore, in this study, the future of temperature and precipitation changes in the Middle East and North Africa (MENA) region was projected. For this purpose, the data of 23 global circulation models (GCMs) from Coupled Model Inter-comparison Project phase 6 (CMIP6) were used as networks under the influence of two scenarios SSP3–7.0 and SSP5–8.5 for temperature and precipitation changes in the two future periods (2020–2049 and 2050–2079) were investigated comparing to the base period (1985–2014). The results showed that the temperature will increase in both periods, which will be between 0.8 and 3.3 °C in the period 2020–2079 compared to the base period. The highest and lowest temperature changes are related to the eastern and northern regions of the study area, respectively. Projection of precipitation changes also showed that the precipitation in most of the study area will decrease in the next two periods compared to the base period, which will be between 5 and 133 mm on average. Most of its changes are related to the northern regions and in the form of a strip from Morocco to the northwest of Iran. In both studied periods, the SSP5–8.5 scenario shows the highest temperature and precipitation changes in the study area.

1 Introduction

The twenty-first century is facing many environmental problems, one of the most important of which is climate change. In the future, the negative effects of climate change can be intensified due to the tendency of communities to have the rapid development of industry and their ignorance of the environment. Also, the increase of greenhouse gases in future periods and as a result of the intensification of changes in climate parameters can have many negative effects on various systems such as water resources, environment, industry, health, agriculture, and all systems that

interact with the climate system. The negative consequences of this phenomenon for human beings can be so devastating that among the ten human threatening factors in the twenty-first century, such as poverty, nuclear weapons, and food shortages, the phenomenon of climate change has got the first rank (IPCC 2007). The process of climate change, especially changes in temperature and precipitation, is the most important issue in the field of environmental sciences. This phenomenon is of increasing importance due to its scientific and practical dimensions (environmental and socioeconomic effects), as human systems dependent on climatic elements such as agriculture, industry, and the like are designed and operate on the basis of climate stability (Zahabioun et al. 2010) and the study of temperature and precipitation changes in the coming years can be the solution to problems such as drought, flash floods, high evaporation, and environmental degradation (Shaemi and Habibinokhandan 2009). There are several ways to do this, the most reliable of which is the use of data from global circulation models or GCMs, which are currently the most powerful tool for generating climate scenarios. These models also simulate the global climate response to greenhouse gas concentrations as well as future climate scenarios for the entire planet (IPCC 2013).

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Several GCMs have been developed, and due to the differences in the structure of these models and the differences in the initial conditions under which they are implemented, their results are different even for the same diffusion scenario. Therefore, for applying in regional studies, it is necessary to downscale the output of these models using a suitable method (Kay et al. 2009). In fact, the outputs of these models have low spatial accuracy. Accordingly, if it is directly used as input to climatic and hydrological models, it will increase uncertainty. For this purpose, to increase the spatial accuracy of these data, downscaling methods are used, which are divided into statistical and dynamic methods (Beecham et al. 2014; Bates et al. 2008). According to the literature, statistical methods are mostly used to downscale climatic data (Wilks and Wilby 1999). One of the reasons for using these models is their quick and easy performance compared to other methods (Dibike and Coulibaly 2005; Kilsby et al. 2007).

As the issue of climate change in the world becomes more serious, the study of climate parameters and elements has been widely considered (Rasouli et al. 2014). In this regard, Sarkar et al. (2015) predicted temperature and precipitation changes using GCMs in India. The results showed that in future periods, the amount of precipitation will decrease by an amount of between 9 and 27%. Hyun Cha et al. (2016) predicted changes in summer precipitation in Korea using the HadGEM2 model under RCP scenarios. Their results showed that the amount of precipitation decreases and its intensity increases. Leong Tan et al. (2017) evaluated the effects of climate change on water resources in Malaysia and pointed to an increase in monthly rainfall in the wet season and a decrease in rainfall in the dry season. Ferreira et al. (2018) investigated the effects of climate change on summer rainfall in the southeastern United States. The results indicate a significant increase in rainfall due to rising temperatures and water vapor flux. Akbary et al. (2019) studied spatio-temporal changes of atmospheric rivers in MENA. The results showed that the ARs in the MENA region experience convergence over this region which causes these events to narrow. Nilawar and Waikar (2019) investigated the effects of climate change on the Purna River in India using RCP scenarios. The results showed that temperature and precipitation will increase in the future under both scenarios. Heydari et al. (2020) predicted temperature and precipitation changes using the HadGEM2 model in the Urmia Lake basin in northwestern Iran. The results showed that in the coming periods, the amount of precipitation will decrease and the temperature will increase. Jiang et al. (2020) projected precipitation changes by the end of the twenty-first century in Central Asia based on 15 models from the CMIP6 under 4 SSP scenarios. The results showed that in all scenarios, a sharp increase in the average annual rainfall is observed. Yue et al. (2021) studied temperature and precipitation changes

in the Yangtze River Basin using GCMs in China. The results showed that temperature and precipitation increase under different SSP scenarios in the long run and despite the accuracy of the model under study, there is uncertainty in the predicted precipitation and temperature. Qin et al. (2021) projected temperature and precipitation changes in northwest China using five CMIP6 models. The results showed that CMIP6 models can simulate temperature better than precipitation. Forecasts also showed that the average temperature and precipitation under different scenarios will increase significantly in the twenty-first century. You et al. (2021) by using 20 GCMs from CMIP6 and three SSP scenarios predicted the temperature changes over China. The results show that in all future periods, the temperature will increase.

The IPCC uses the Shared Socioeconomic Pathways (SSPs) and the Representative Concentration Pathways (RCPs) scenarios in compiling its sixth assessment report to be able to facilitate integrated analysis of climate impacts, vulnerabilities, adaptation, and future mitigation. Therefore, considering the importance of climate change, in this study, we aimed to project future temperature and precipitation changes in the Middle East and North Africa (MENA) in the next two 30-year periods (2020–2049 and 2050–2079) compared to the base period (1985–2014) using the output of the GCMs from CMIP6 under two SSP scenarios.

2 Data and methodology

2.1 Study area

The study area in this research includes the Middle East and North Africa, i.e., the MENA region, which is one of the major regions in the world that is exposed to the negative effects of climate change (Waha et al. 2017). The climate of this region is arid to semi-arid and very unstable and changing. Therefore, it poses new risks to water resources and increases drought and vulnerability (World Bank 2017). This region starts from Morocco in northwestern Africa and extends to Iran, the easternmost country in the Middle East. Figure 1a shows the geographical location of the study area. In 2018, the MENA region emitted 3.2 billion tonnes of carbon dioxide and produced 8.7% of global greenhouse gas emissions (GHG) despite making up only 6% of the global population. These emissions are mostly from the energy sector, an integral component of many Middle Eastern and North African economies due to the extensive oil and natural gas reserves that are found within the region. Gifted with half of the world's known oil and gas reserves, the MENA region is a bedrock of the world's hydrocarbon supply (Tagliapietra 2019). The MENA region is especially vulnerable to such impacts due to its arid and semi-arid environment,

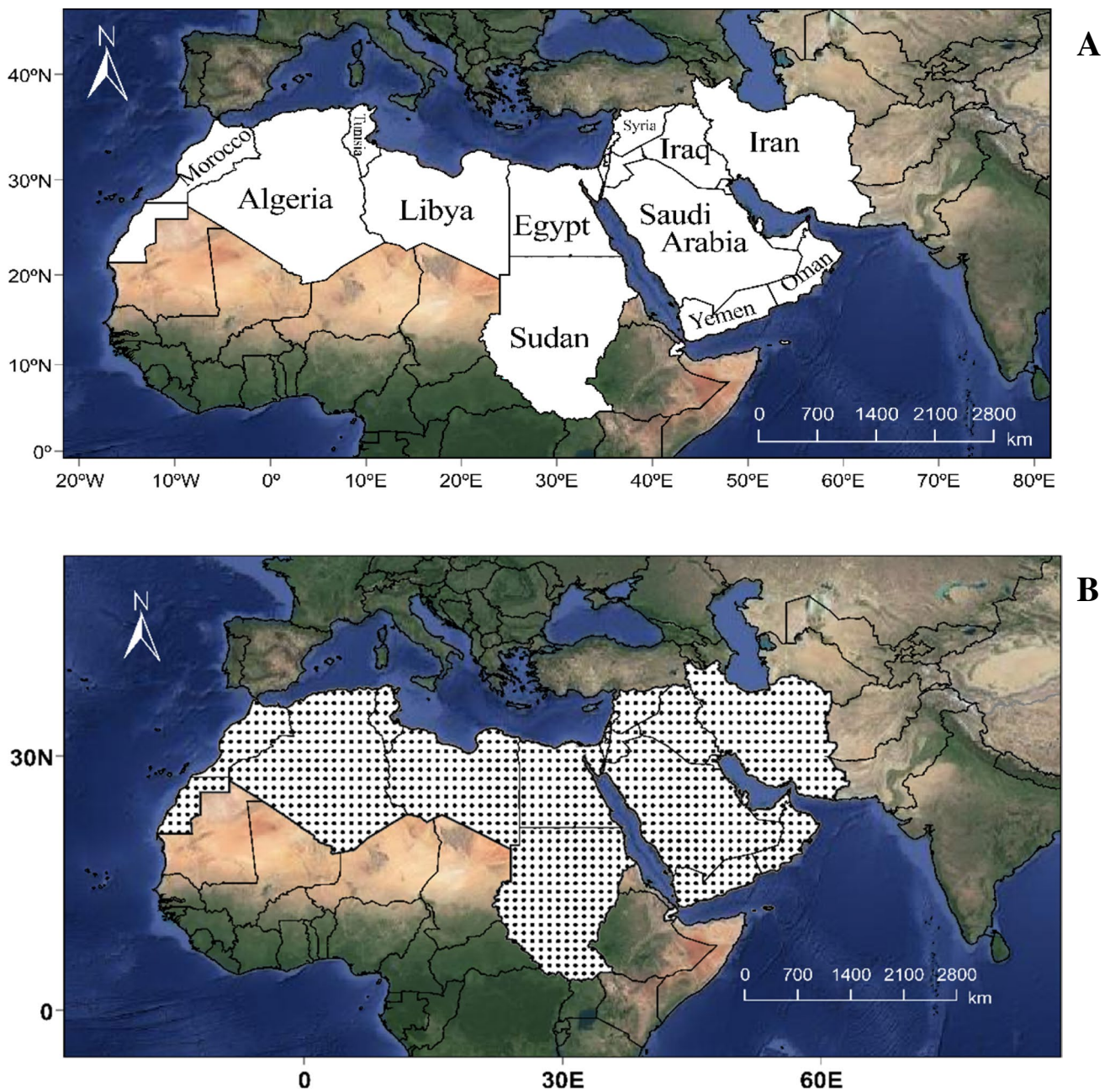


Fig. 1 Geographical location of the study area (a) and the studied grid in the study area (b)

facing climatic challenges such as low rainfall, high temperatures, and dry soil. The climatic conditions that foster such challenges for MENA are projected by the IPCC to worsen throughout the twenty-first century (IPCC 2014). If greenhouse gas emissions are not significantly reduced, part of the MENA region risks becoming uninhabitable before the year 2100 (Pal and Eltahir 2016).

In this study, the monthly averages of 23 GCMs of CMIP6 were used to study climate change, whose specifications are provided in Table 1. Evaluation/ performance

of these models has been done in previous studies such as Al- Almazroui et al. (2021) with 21 models, You et al. (2021) with 20 models, Luo et al. (2020) using 27 models, and Zhu et al. (2020) with 12 models, and concluded that the combination of GCMs gives better results. Therefore, we used the existing data set. The GCM data was downloaded from ESGF (<https://esgf-node.lnl.gov/search/cmip6/>). The changes of precipitation and temperature are calculated at monthly averages of GCM's native resolution as presented in Table 1, followed by a re-gridding to $1^\circ \times 1^\circ$ using bi-linear

Table 1 Information of CMIP6 models used in this study, including model name, institutions, atmospheric resolution, and variant label

| Row | Model | Atmospheric resolution | Variant label | Institution |
|-----|------------------|------------------------|---------------|--|
| 1 | ACCESS-CM2 | 1.87° × 1.25° | r1i1p1f1 | CSIRO (Commonwealth Scientific and Industrial Research Organization, Australia) and BOM (Bureau of Meteorology, Australia) |
| 2 | ACCESS-ESM1-5 | 1.9° × 1.2° | r1i1p1f1 | |
| 3 | BCC-CSM2-MR | 1.125° × 1.121° | r1i1p1f1 | Beijing Climate Center, China Meteorological Administration |
| 4 | CanESM5 | 2.81° × 2.79° | r1i1p1f1 | Canadian Centre for Climate Modelling and Analysis |
| 5 | CESM2 | 1.25° × 1° | r1i1p1f1 | National Science Foundation, Department of Energy, National Center for Atmospheric Research |
| 6 | CESM2-WACCM | | | |
| 7 | CMCC-ESM2 | 1.3° × 0.9° | r1i1p1f1 | Centro Euro-Mediterraneo per I Cambiamenti Climatici |
| 8 | CNRM-CM6-1 | 1.41° × 1.41° | r1i1p1f2 | Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique |
| 9 | CNRM-ESM2-1 | | | |
| 10 | EC-Earth3 | 0.7° × 0.7° | r1i1p1f1 | EC-EARTH consortium |
| 11 | EC-Earth3-Veg-LR | 1.1° × 1.1° | | |
| 12 | FGOALS-g3 | 2° × 2.3° | r1i1p1f1 | LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences; and CESS, Tsinghua University |
| 13 | GFDL-ESM4 | 1.3° × 1° | r1i1p1f1 | Geophysical Fluid Dynamics Laboratory |
| 14 | GFDL-CM4 | 1.3° × 1° | | |
| 15 | INM-CM4-8 | 2° × 1.5° | r1i1p1f1 | Institute for Numerical Mathematics |
| 16 | IPSL-CM6A-LR | 2.5° × 1.3° | r1i1p1f1 | Institute Pierre-Simon Laplace |
| 17 | MIROC6 | 1.41° × 1.41° | r1i1p1f1 | JAMSTEC, AORI, NIES, and R-CCS |
| 18 | MPI-ESM1-2-HR | 0.93° × 0.93° | r1i1p1f1 | Max Planck Institute for Meteorology (MPI-M) |
| 19 | MPI-ESM1-2-LR | 0.93° × 0.93° | | |
| 20 | MRI-ESM2-0 | 1.1° × 1.1° | r1i1p1f1 | Meteorological Research Institute |
| 21 | NorESM2-LM | 2.5° × 1.9° | r1i1p1f1 | Norwegian Climate Centre |
| 22 | NorESM2-MM | 0.9° × 1.3° | | |
| 23 | UKESM1-0-LL | 1.9° × 1.3° | r1i1p1f2 | Met Office Hadley Centre and Natural Environment Research Council (CMIP6) |

interpolation in order to carry out ensemble-based analyses and statistics (Fig. 1b). After simulating climate variables in the base period (1985–2014) by GCMs, in order to simulate the changes of these variables in future periods, it was required to introduce the status of different scenarios in future periods to these models. The CMIP6 model simulations are made using a combination of a representative concentration pathway (RCP) (Moss et al. 2010; Taylor et al. 2012) and with a Shared Socioeconomic Pathway (SSP) (Meinshausen et al. 2019). Since SSPs often correspond with different radiative forcing values, simulations are named for both the SSP value and the corresponding RCP value (Grose et al. 2020; Meinshausen et al. 2019). There are five SSPs (from SSP1 to SSP5), which represent taking the green road, middle of the road, a rocky road, a road divided, and taking the highway, respectively. The SSP quantifications build upon the collaborative effort between the IAV and IAM community (Grose et al. 2020; O'Neill et al. 2016). Since SSP1 and SSP5 typically lead to 2.6 W/m² and 8.5 W/m² of radiative forcing, they are called SSP1–2.6 and SSP5–8.5, respectively.

In this study, historical outputs of the CMIP6 models are selected during 1985–2014, and simulation outputs under

SSP3–7.0 and SSP5–8.5 are selected during two future periods. Near-term (2020–2049) and mid-term (2050–2079) periods are defined for further investigation. These scenarios represent the medium to high end of the range of future forcing pathways, and high end of the range of future pathways in the IAM literature, respectively (O'Neill et al. 2016). The summary of each is given in Table 2.

To quantify model performance, spatial distribution of bias and ratio of standard deviations are employed to facilitate observation vs. model comparisons; the smaller bias and the more similar standard deviations imply better simulations (You et al. 2021).

3 Results and discussion

In order to evaluate and ensure the capability and accuracy of the GCMs in reproducing temperature and precipitation, the models were first implemented for the base period. Then, the historical data of models, which include temperature and precipitation and the difference between them and observational data (bias) and standard deviations, were examined and validated. Figures 2 and 3 show the

Table 2 Summary of Shared Socioeconomic Pathways (SSP) scenarios used in this study (Riahi et al. 2017)

| Scenarios | Summary |
|-----------|--|
| SSP3 | Regional Rivalry—A Rocky Road (high challenges to mitigation and adaptation): A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions |
| SSP5 | Fossil-fueled Development-Taking the Highway (high challenges to mitigation, low challenges to adaptation): This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy-intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the twenty-first century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary |

observations of temperature and precipitation (Fig. 2a and Fig. 3), the mean temperature and precipitation from the multi-model ensemble mean (MEM) of 23 CMIP6 models (Fig. 2b and Fig. 3b), the spatial distribution of biases between simulations and observation (Fig. 2c and Fig. 3c), and standard deviations (Fig. 3d and Fig. 3d) over MENA during 1985–2014. The results show that the accuracy of the model varies in different regions and for different parameters. Based on the results, the annual bias or difference between the observed temperature and the simulation in the study area is 0.9–1.6 °C. This bias is below 1.3 °C in most areas, but increases to around 1.6 °C over the Iran Plateau,

Saudi Arabia Peninsula, Iraq, Syria, and Algeria (Fig. 2c). The standard deviations range from 0.2 to 1.1, indicating that CMIP6 models show relatively good performances in simulating temperatures over MENA (Fig. 2d). The annual bias of precipitation on average is –20 to 70 mm over MENA. The highest rate of precipitation bias is related to Sudan. However, the rate of precipitation bias in most of the MENA region is less than 40 mm (Fig. 3c). According to the results and comparison of annual bias and standard deviation of observed and simulated temperature and precipitation (Fig. 2d and Fig. 3d), the performance of the model is evaluated as appropriate for the study area. Compared with the observation during 1985–2014, the CMIP6 models generally perform acceptably in simulating the major spatial contrasts in mean temperatures and precipitation over MENA, which is consistent with earlier results of You et al. 2021 and Zhu et al. 2020 studies.

After evaluating the models and ensuring its suitability, the predicted data were examined by the model for the two scenarios of SSP3–7.0 and SSP5–8.5 applying the average of 23 GCMs in two future periods. The results of analyzing temperature changes during the period 2020–2049 compared to the base period (1985–2014) in the study area show that the temperature will increase in the region, which based on SSP3–7.0 is between 0.8 and 1.4 °C, and the most changes of which are related to northwestern Iran and the Middle East, and the least changes are related to countries such as Sudan, Morocco, Yemen, and Oman (Fig. 4a, b). According to SSP5–8.5 scenarios, the temperature will increase by 0.9 to 1.6 °C on average. According to this scenario, changes in the Middle East, including Iran, Saudi Arabia, Iraq, and Syria, are more compared to North Africa (except Algeria). In general, according to both scenarios, the temperature changes in the coastal strip of the study area in the margins of the Red Sea, the Mediterranean Sea, the Atlantic Ocean, and the Indian Ocean are less than other areas (Fig. 4c, d). Accordingly, considering the results of both scenarios, the temperature in the period 2020–2049 in the study area will increase compared to the base period, which will have an average of between 0.8 and 1.6 °C.

In the period 2050–2079, the temperature increase will continue, which according to SSP3–7.0 scenario would have an increase of between 1.2 and 3 °C (Fig. 5a, b) and according to SSP5–8.5 will increase by 2.1–3.3 °C compared to the base period (Fig. 5c, d). Most of the changes are related to the northwestern regions of Iran and parts of Saudi Arabia and Algeria. In general, the northern and eastern regions of the MENA region will experience more changes, and the coastal areas and the margins of water resources will have the least changes (Fig. 5).

Examining temperature changes, it is expected that the temperature in the MENA region will increase compared to the base period in both periods and in the period 2050–2079

Fig. 2 Spatial distribution of observed (a) and simulated (b) temperature (°C). Biases between simulation and observation (c) and standard deviations (d) in the base period (1985–2014)

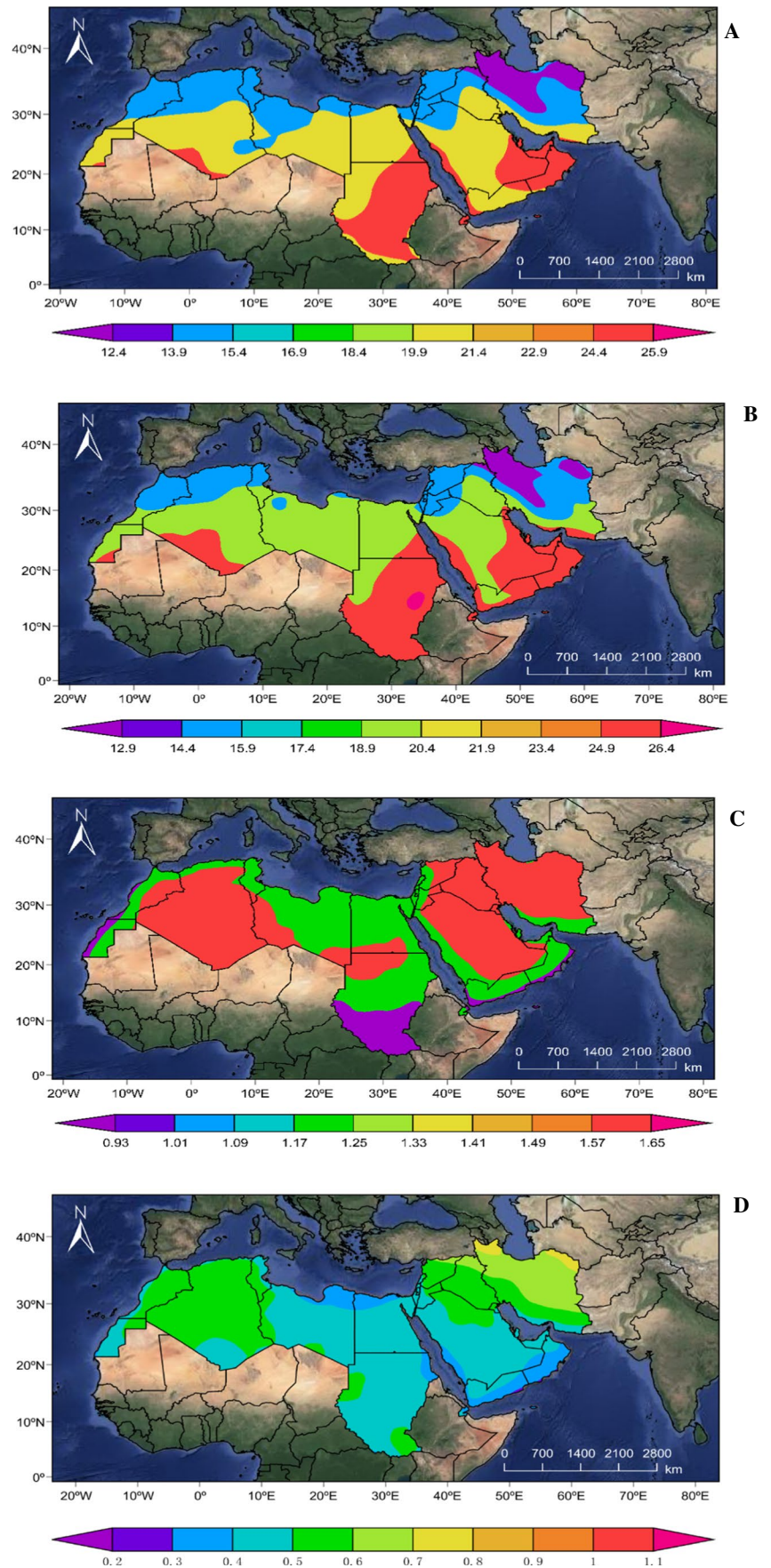


Fig. 3 Spatial distribution of observed (a) and simulated (b) precipitation (mm). Biases between simulation and observation (c) and standard deviations (d) in the base period (1985–2014)

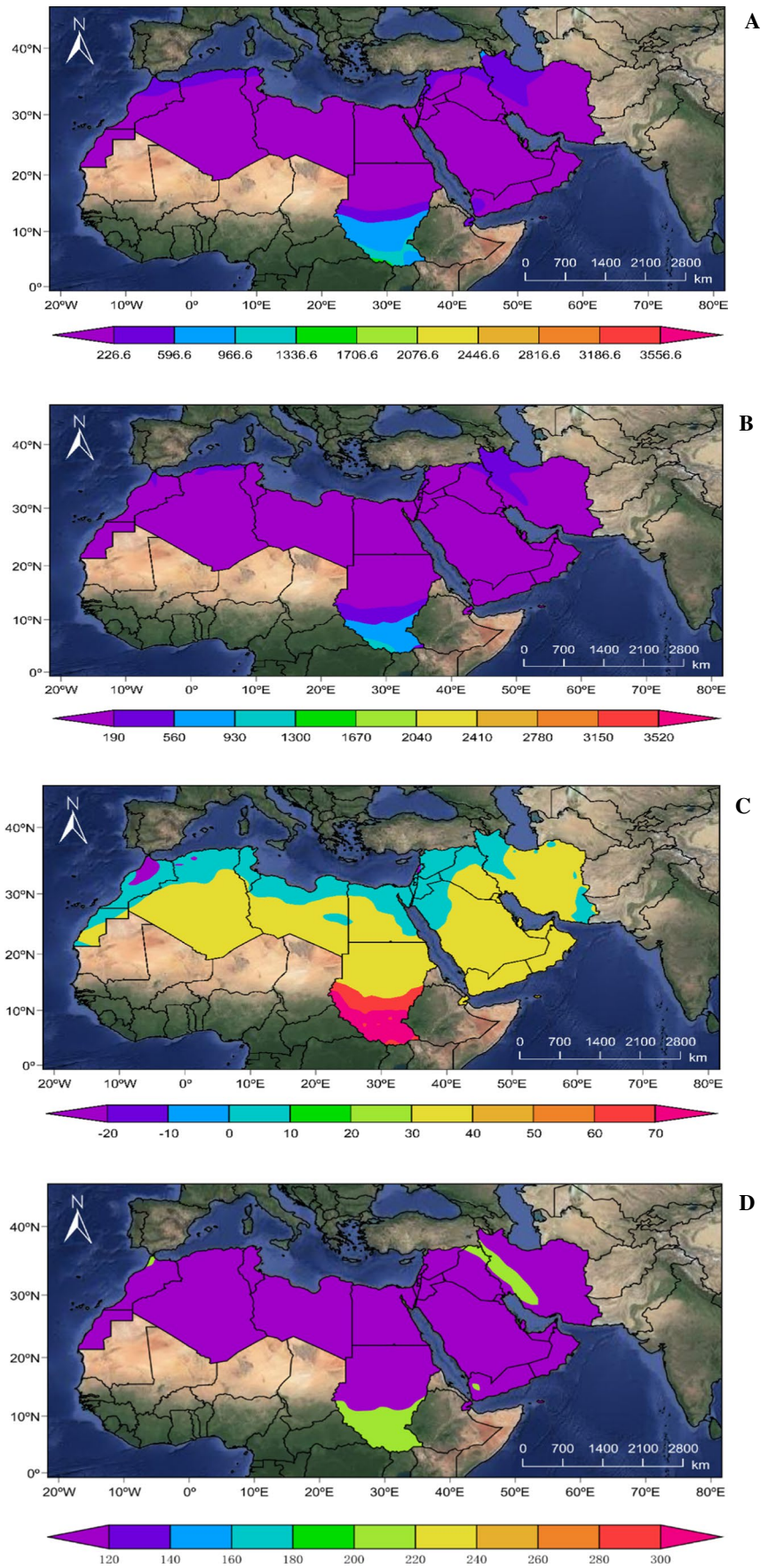


Fig. 4 The spatial distribution of mean temperature from the CMIP6 models over MENA in the period 2020–2049 under SSP3–7.0 (a) and SSP5–8.5 (c) and its changes compared to the base period under SSP3–7.0 (b) and SSP5–8.5 (d). The units are °C

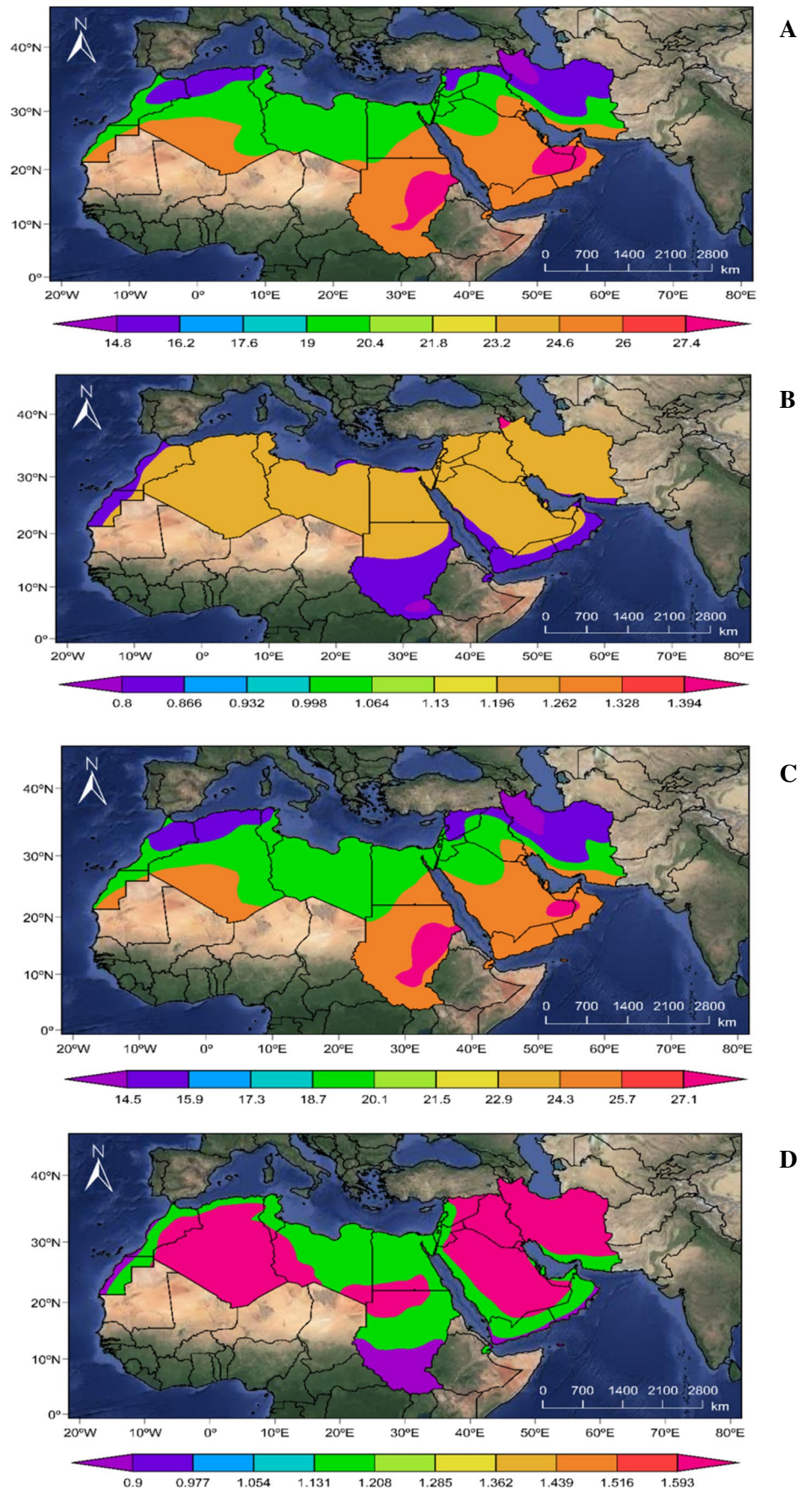


Fig. 5 The spatial distribution of mean temperature from the CMIP6 models over MENA in the period 2050–2079 under SSP3–7.0 (a) and SSP5–8.5 (c) and its changes compared to the base period under SSP3–7.0 (b) and SSP5–8.5 (d). The units are °C

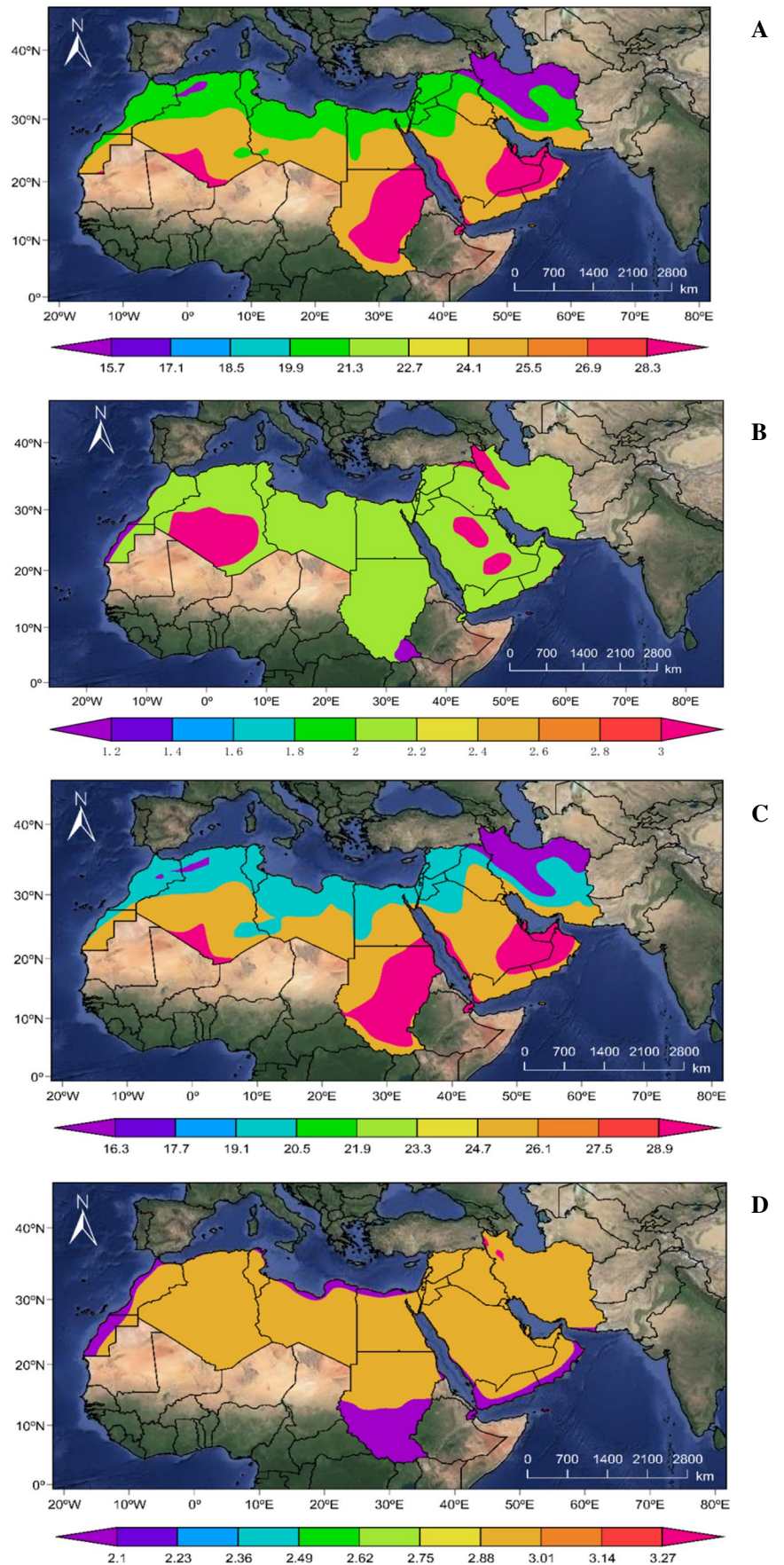


Fig. 6 The spatial distribution of precipitation from the CMIP6 models over MENA in the period 2020–2049 under SSP3–7.0 (a) and SSP5–8.5 (c) and its changes compared to the base period under SSP3–7.0 (b) and SSP5–8.5 (d). The units are mm

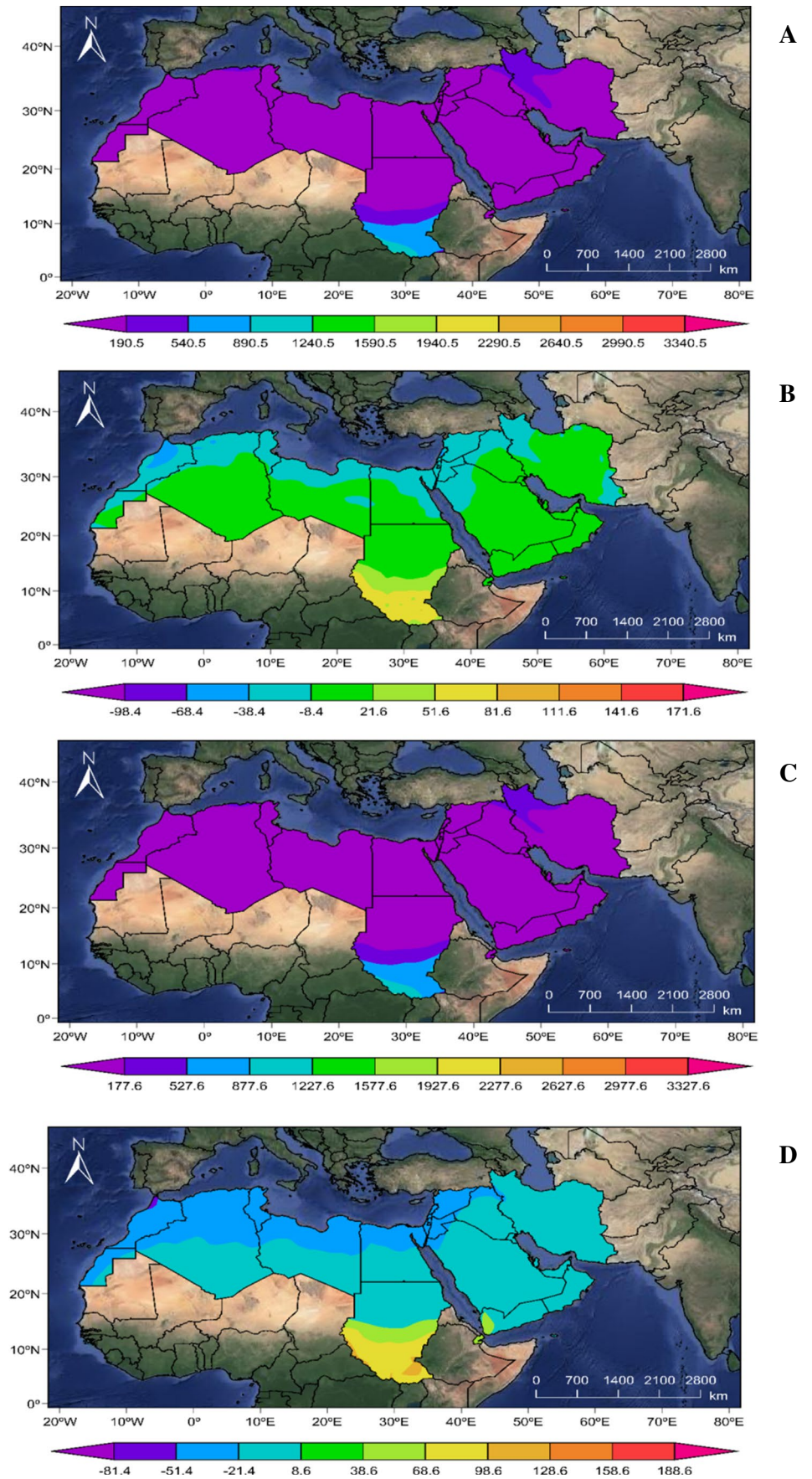
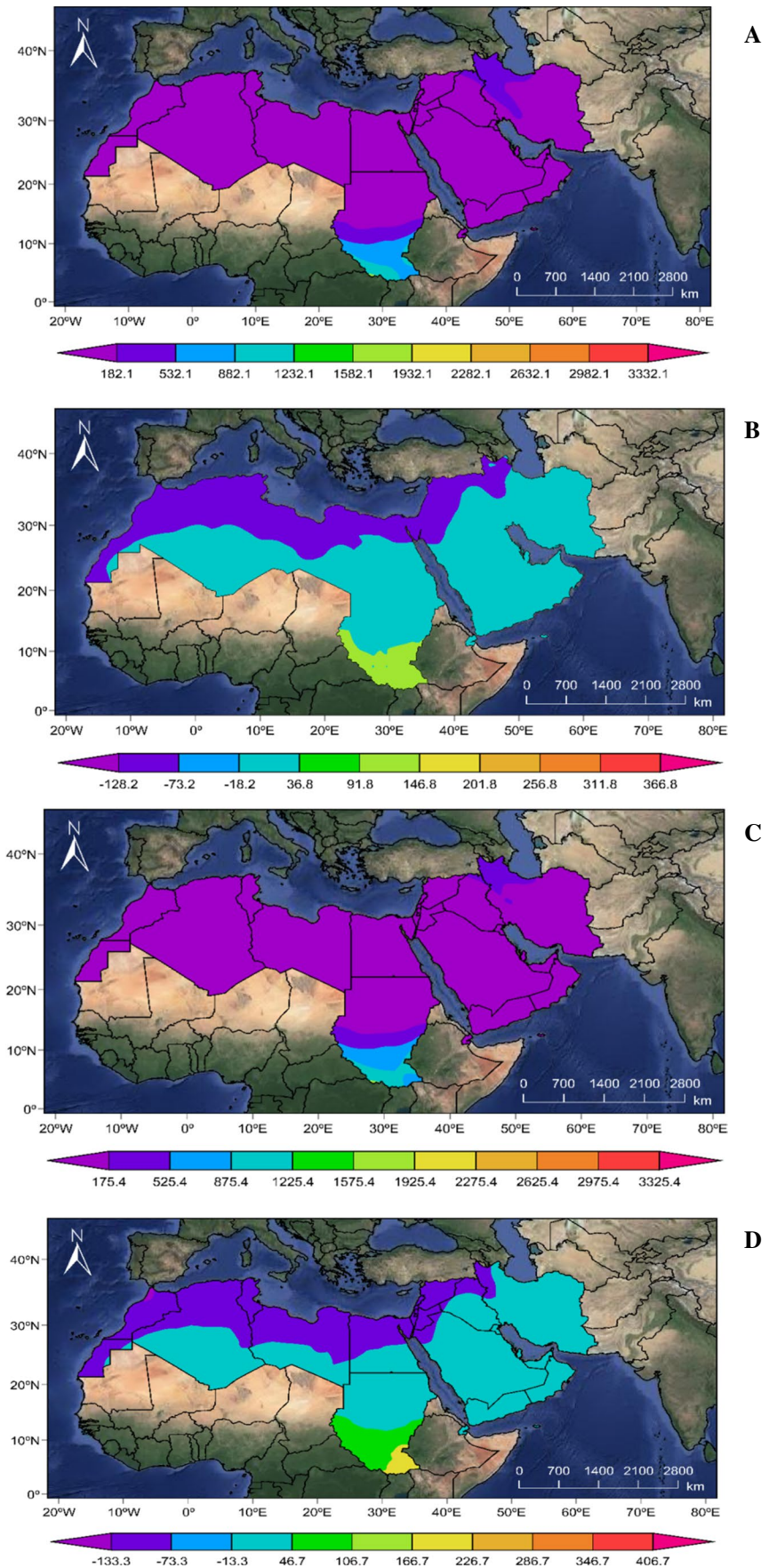


Fig. 7 The spatial distribution of precipitation from the CMIP6 models over MENA in the period 2050–2079 under SSP3–7.0 (a) and SSP5–8.5 (c) and its changes compared to the base period under SSP3–7.0 (b) and SSP5–8.5 (d). The units are mm



compared to the period 2020–2049, the changes will intensify. Also, the SSP5–8.5 scenario shows more changes than the SSP3–7.0 scenario due to the features that each of these scenarios exhibits.

The projection of precipitation changes in the period 2020–2049 compared to the base period (1985–2014) also shows that according to the SSP3–7.0 scenario, the amount of precipitation in the MENA region will change by an amount of between –98 and 172 mm (Fig. 6a, b). The largest increase is related to the southern and eastern regions of the studied area and the largest decrease is related to the northern regions of the region, which has spread as a strip from Morocco to northwestern Iran. According to the SSP5–8.5 scenario, precipitation will decrease in the same area, which will even reach an amount of 81-mm decrease. According to this scenario, there is an increase in precipitation in the region, with a maximum increase of 189 mm. The largest increase is related to the southern parts of the region and the countries which are in the southeast and southwest of the Red Sea (Fig. 6c, d).

The study of precipitation changes in the period 2050–2079 shows that according to the SSP3–7.0 scenario,

the amount of precipitation will change by an amount of between –128 and 366 mm in the MENA region (Fig. 7a, b). According to the SSP5–8.5 scenario, the precipitation change would have an amount of between –133 and 407 mm (Fig. 7c, d). In this period, as in the previous period, the highest amount of precipitation reduction is related to the north of the study area and in the form of a strip from Morocco to the northwest of Iran. Most incremental changes are limited to the southern regions of the study area.

The time series in Fig. 8 for MENA show relatively small differences in the mean temperature and precipitation anomaly between SSPs for the near-term, but by the long-term period, there are substantial differences. There is particularly rapid change for SSP5–8.5. In general, investigating temperature and precipitation changes in future periods (2020–2079) showed that we can expect an increase in the average of the MENA region. Also, there are uncertainties in projecting precipitation. The uncertainty of precipitation mainly comes from model and scenario uncertainties. Uncertainty increases for the higher SSP scenarios. Overall, in the near-term model, uncertainty is the dominant factor,

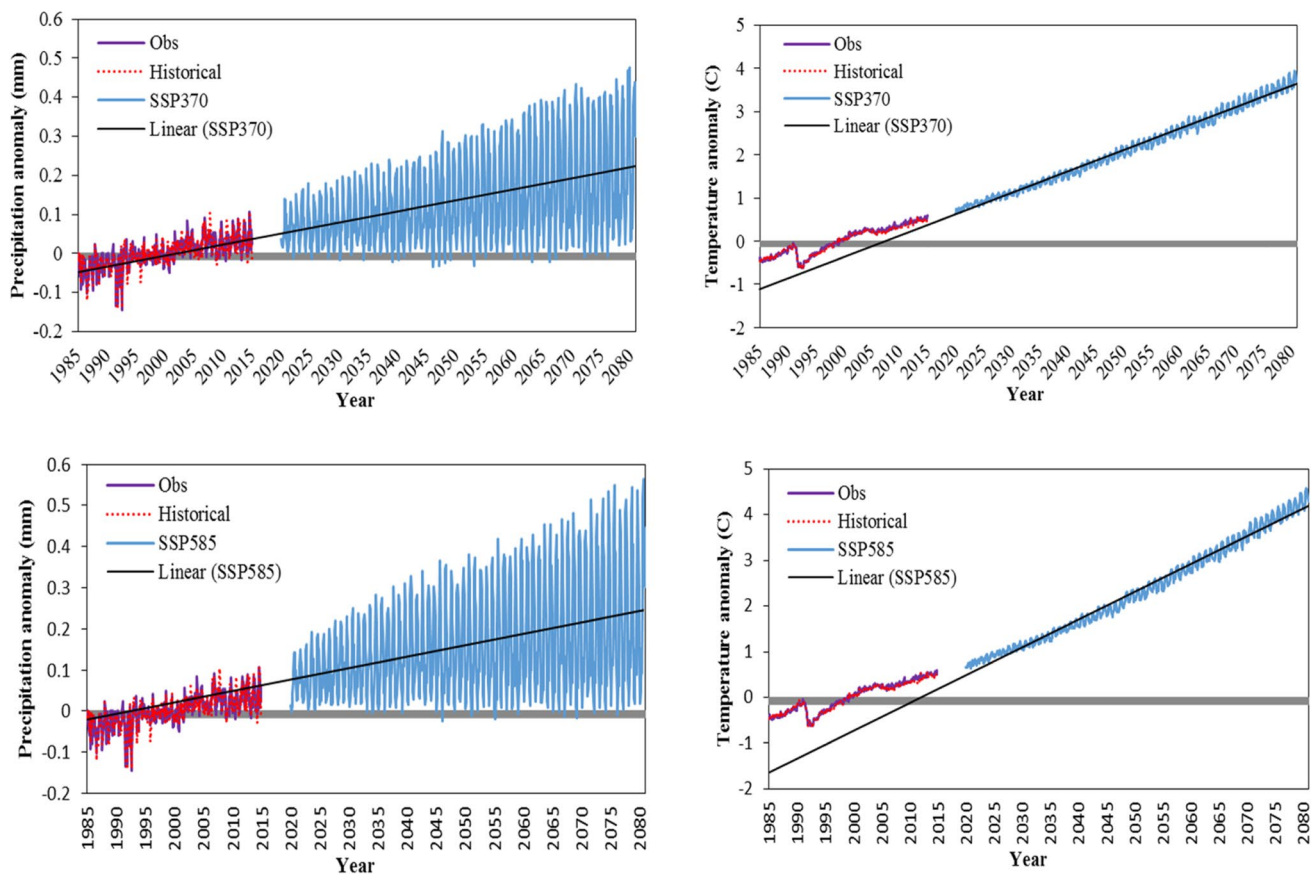


Fig. 8 Time series of monthly anomaly of temperature and precipitation from the CMIP6 models over MENA during 1985–2079 under SSP3–7.0 and SSP5–8.5. The trends are calculated for the observa-

tions and the historical run during 1985–2014, and for the SSP3–7.0 and SSP5–8.5 during 2020–2079

but as time goes on, the scenario uncertainty takes over. The results of this study are consistent with the studies of Nilavar et al. 2019; Heydari et al. 2020; Qin et al. 2021; Yue et al. 2021; and You et al. 2021.

4 Conclusion

This study aimed to project the future of temperature and precipitation changes in the MENA region based on the CMIP6 model under the influence of two SSP scenarios. After evaluating the models for the base period (1985–2014) and determining the accuracy of the models, the future of temperature and precipitation changes in two different time periods (2020–2049 and 2050–2079) was projected compared to the base period. The results of evaluating the performance of the models showed that the average of models has an acceptable ability to simulate temperature and precipitation variables in the base period, but compared to the temperature, the models are less accurate in precipitation simulation, which is due to the complexity of precipitation process as well as the structure of climatic models. Therefore, there are always uncertainties in projecting climate change. The results of future projection of temperature and precipitation changes also showed that in general, in most countries of the MENA region, the amount of precipitation will decrease and the temperature will increase. Most of the decrease in rainfall is related to the northern regions of the study area and in some areas, including the southern regions and coastal areas, an increase in precipitation is also observed. However, the temperature is increasing in the whole MENA region according to the studied models, which varies depending on the topographic characteristics, distance, and proximity to water sources. Based on the results of the output of the studied GCMs in the northern regions of MENA, the amount of precipitation will be reduced compared to the base period, which can reduce the storage and supply of water resources in the region, which would consequently lead to a change in the conditions of the region's agricultural climate. Also, the temperature will increase, which can reduce snowfall, increase evaporation, and increase heavy rainfall, which can consequently lead to an increase in the damage caused by heavy rainfall, water loss, as well as leaching of fertile soils. Therefore, it is necessary for the relevant planners in different sectors and different countries to adopt the necessary strategies to adapt to the new conditions.

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Author contribution Authors 1 and 3: conceived of the presented idea and developed the theory and performed the computations. Authors 2 and 4: verified the analytical methods and supervised the findings of this work. Author 5: encouraged and developed the theoretical formalism. All authors discussed the results and contributed to the final manuscript.

Data availability The data used in this paper have been prepared by referring to Earth System Grid Federation (ESGF) from this link: <https://esgf-node.llnl.gov/search/cmip6/>

Code availability In this paper, custom code in MATLAB software has been used to re-gridding the models.

Declarations

Ethical approval Not applicable, because this article does not contain any studies with human or animal subjects.

Consent to participate The data of this research were not prepared through a questionnaire.

Consent for publication There is no conflict of interest regarding the publication of this article. The authors of the article make sure that everyone agrees to submit the article and is aware of the submission.

Conflict of interest The authors declare no competing interests.

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