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Monitoring and predicting changes in reference evapotranspiration in the Moghan Plain according to CMIP6 of IPCC

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ABSTRACT

Estimating the optimal water requirement requires determining the relationship between climatic conditions and evapotranspiration. As a result, water resource management relies on accurate estimation of evapotranspiration. This study aimed to monitor and predict the reference evapotranspiration, ET_0, in the Moghan Plain, considering the impact of climate change. ET_0 was calculated by the PMF56 method using CROPWAT software. The 30-year data (1993-2022) of the Parsabad synoptic station and the output of CMIP6, including the HadGEM3-GC31-LL model and the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios were used. The results showed that the precipitation, minimum temperature and maximum temperature in the Moghan Plain from 261 mm, 9.95 °C and 21.21 °C in the base period, respectively, will reach 361 mm, 16.04 °C and 27.68 °C at the end of the century. Under the effects of climate change, ET_0 will increase in the future. The severity of the climate change impact on ET_0 in the Moghan Plain is greater in the warm months, and the greatest increase will be under the SSP5-8.5 scenario. The ET_0 in Moghan Plain reached 1114 mm/yr in the base period, with an increase of 20% to 1334 mm/yr at the end of the century. Considering the greater share of Iran's water consumption in the agricultural sector, especially in areas such as the Moghan Plain, ET_0 changes should be considered in engineering and water resource management programs.

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1. Introduction

Climate change is one of the most complex atmospheric phenomena worldwide. It refers to changes in the conditions and averages of climate variables that occur temporally over a long period and spatially on a global scale (Behzadi Karimi et al., 2022). Climate change and increased greenhouse gas emissions have affected various aspects of human life. This phenomenon can lead to a lack of access to sufficient water in some areas and destructive flooding in others. In addition, climate change has direct and indirect effects on agriculture and the environment (Dey and Mishra, 2017; Allahverdipour and Sattari, 2024). Climate change has increased evaporation from various water and agricultural surfaces and the water demand of the agricultural sector. The escalating water demand has rendered management planning for controlling water consumption of paramount importance in the future (Mohammadi and Allahverdipour, 2024). The results of various studies indicate that the challenges caused by climate change on different parts of the available water resources will continue in the future. Therefore, it is essential to forecast climate conditions in future periods, especially in agricultural areas (Tao et al., 2015; Lin et al., 2018).

Reference evapotranspiration (ET_0) is a key variable in hydrology and water resources. ET_0 is defined as the rate of evapotranspiration from a hypothetical reference surface with specific characteristics, such as grass with a uniform height of 8 to 12 cm (Fakhar and Kaviani, 2021). Estimating the optimal water demand requires estimating the relationship between climatic conditions and evapotranspiration in different regions. As a result, water resource management relies on accurate evapotranspiration estimates. (Talebi et al., 2023). The effects of climate change on different parts of water resources, including evapotranspiration, in different regions and basins can have different natures and intensities, and affect water and soil resources in different ways (Azlak and Şaylan, 2024).

The Intergovernmental Panel on Climate Change (IPCC) publishes a report every few years based on different scenarios of greenhouse gas emissions from the Earth's atmosphere. The latest report of this panel is the Coupled Model Intercomparison Project Phase 6 (CMIP6). This report incorporates novel models and scenarios that forecast diverse climatic conditions across various regions. In recent decades, researchers have studied the effects of future climate change on different sectors based on climate reports. Lin et al. (2018) in the Qilian region of China examined the impact of climate change on ET_0 under the models and scenarios of the Coupled Model Intercomparison Project Phase 5 (CMIP5) and the CanESM2 model, which is a comprehensive model developed by the Centre for Climate Modelling and Analysis in Canada (Allahverdipour et al., 2024). The results of this study indicate that the average ET_0 of this region was 1001.5 mm/yr and in the future, an increase of 7.20-31.6, 11.10-41.6, and 58.6-17.66% compared to the base period was predicted under the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively. Gurara et al. (2021) used climate data from 1985 to 2018 and the output of General Circulation Models (GCM) and the Hargreaves (HG) method to investigate the impact of climate change on ET_0 in the upper Wabe Shible River Basin in Ethiopia. The results indicate an increase in the average annual ET_0. Therefore, in 2100 and under the RCP8.5 scenario, very severe ET_0 was predicted at all stations. The average annual ET_0 changes in this region were predicted to decrease by 15.30-4.1% under the RCP4.5 scenario and to increase by 37.6-2.49% under the RCP8.5 scenario. Latrech et al. (2024) examined the effects of climate change on climate variables and ET_0 in the semi-arid region of Cap Bon in Tunisia, using climate data from the 1982-2006 base period and two emission scenarios of RCP4.5 and RCP8.5. The highest ET_0 increase of 11.85% compared to the base period was predicted for the period 2098-2075 and under the RCP8.5 scenario. Azlak and Şaylan (2024) analyzed the impact of climate change on ET_0 in the Central Anatolia region of Turkey using data from 1980 to 2000 and GCM models. The average ET_0 in the base period was calculated to be 1089 mm/yr. The increase in ET_0 by the end of the century was projected to be 11% under RCP4.5 scenario and 19% under RCP8.5 scenario.

In Iran, some research has been done on how climate change affects evapotranspiration. Fazeli Khiavi et al. (2020) used the CMIP5 models including the HadGEM2 model and RCP scenarios to assess the effects of climate change on ET_0 changes in the Moghan Plain during the two periods, 2011-2030 and 2030-2060. They used the PMF56 and Hargreaves-Samani methods to calculate evapotranspiration. According to the results, the increase in calculated ET_0 was predicted between 4.8-6% in the PMF56 method and between 4.5-7.7% in the HGS method. Babolhekami et al. (2020) used data from four synoptic stations and the PMF56 method in their study to investigate the effect of climate change on ET_0 in Mazandaran Province. The CanESM2 model was used under RCP2.5, RCP4.5, and RCP8.5 scenarios to predict climate variables. The results showed that ET_0 changes in different months of the year ranged from -16.1 to 25.7%, with the lowest and highest changes occurring in March and October, respectively. Mirhosseiny et al. (2021) predicted ET_0 in the Golpayegan Watershed using data from 1992 to 2017 and GCM model outputs under future RCP scenarios. The results indicated an increase in ET_0 under all scenarios in the future. This increase was reported to be 6.31, 7.05, and 7.10% under RCP2.6, RCP4.5, and RCP8.5 scenarios in the near future (2040-2021), 9.69, 9.84, and 11.82% in the mid future (2060-2041), and 8.17, 13.79, and 18.15% in the far future (2061-2080), respectively. Salahi et al. (2023) used the CanESM2 model and RCP scenarios to assess future ET_0 changes in the southern part of the Aras Watershed. They used climate data from six synoptic stations in the basin from 1985 to 2050. According to the results, an increase of approximately 7 mm/year in the ET_0 of this watershed was predicted in the near future (2021-2050) compared with the base period. In terms of stations, an increase of 102 mm was predicted in Parsabad, and 66 mm in Jolfa. Fallah-Ghalhari and Shakeri (2023) assessed the effects of climate change on ET_0 in Iran using data from 52 synoptic stations and the output of CMIP5 models. According to the results, an increase in ET_0 was predicted in all seasons of the year, and the highest increase in the summer season. In addition, the lowest ET_0 was predicted in stations on the northern coasts and northwest of the country, and a relatively high ET_0 was predicted in the southwestern regions of Iran. Ramezani Etedali et al. (2024) estimated ET_0 at 16 Iranian meteorological stations using the Thornthwaite method and based on the two CNRM and ESM models and the SSP scenarios presented in the CMIP6. The maximum ET_0 was estimated at Khorramdareh station (104.29 mm/month) and the minimum at Firuzkoh station (25.60 mm/month) in the 20 years 2025-2044.

Understanding the effects of climate change in the future in different regions is useful for formulating management strategies. The Moghan Plain is considered as an important agricultural region in the country because of its fertile soil and suitable climate. It is necessary to study climate change effects in this region according to the latest climate reports. A review of the research background shows that previous studies used previous IPCC reports, and the application of the CMIP6 report to predict ET_0 in the Moghan Plain has not yet been investigated. This study aims to predict the climate conditions and ET_0 of the Moghan Plain under the influence of climate change in the future. For this purpose, the latest climate statistics and the output CMIP6 and the most recent IPCC report, including three scenarios, SSP1-2.6, SSP2-4.5, and SSP5-8.5, and the HadGEM3-GC31-LL model were used.

2. Materials and Methods

2.1 Study area

The Moghan Plain is located in the north part of the Ardabil Province and near the border of Iran and the Republic of Azerbaijan. This plain covers more than 200,000 ha and is an important area for agricultural production. In this study, climate data from the Parsabad synoptic station located in the Moghan Plain over a 30-year period (1993-2022) were utilized. The data were obtained from the I.R. Iran Meteorological Organization (IRIMO). The Parsabad station is located at approximately 39°60′N latitude, 47°78′E longitude, and 72 m above sea level. According to the De Martonne aridity index, the Moghan Plain has a semi-arid climate with an average annual precipitation of 261 mm and an average annual temperature of 15.5 °C. In addition, the average relative humidity and average wind speed in this region were approximately 71.45% and 2 m/s, respectively. Fig. 1 shows the location of the study area.

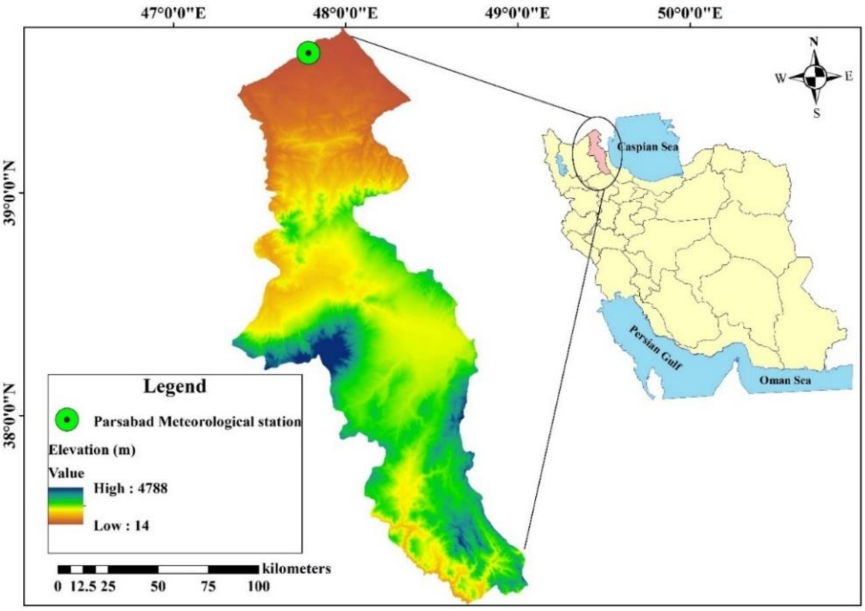

Fig. 1 Location of the study area, Moghan Plain, Iran

In this study, climatic data of precipitation (precipitation), average minimum temperature (T_{min}), average maximum temperature (T_{max}), average mean temperature (T_m), average wind speed (U), sunshine hours (Sunshine), and relative humidity (RHmean) related to the Parsabad synoptic station located in the Moghan Plain were used. Data validation is required for any scientific study that uses meteorological and hydrological data. They cannot be used to extract subsequent results without ensuring the accuracy and quality of the data (Allahverdipour and Sattari, 2023). The data used in this study were first statistically examined and validated, and then steps were taken to complete the missing data and remove outliers.

Table 1 summarizes the statistical characteristics of the data used, and Fig. 2 shows a schematic of the implementation stages of the present study. A relatively large difference was observed between the lowest and highest daily minimum and maximum temperatures in the Moghan Plain. The average minimum and maximum temperatures were 10 and 21.2 °C, respectively. This indicates different atmospheric conditions and large differences between night and day temperatures in the Moghan Plain. The average and standard deviation of daily precipitation are 1 and 3 mm, respectively, which indicates low precipitation (or no precipitation) on most days of the year. The average relative humidity of the Moghan Plain is 71%; therefore, there is noticeable air humidity in the Moghan Plain on most days of the year. The average sunshine hours were 6 hours, which reached 14 hours in the longest case. Considering the average and maximum wind speeds of 2 and 13.5 m/s, respectively, the Moghan Plain was considered a calm area in terms of wind intensity on most days.

Table 1 Statistical characteristics of Parsabad synoptic station data

Statistic	T_{max} (°C)	T_{min} (°C)	T_m (°C)	Precipitation (mm)	RH_{mean} (%)	Sunshine (Hours)	U (m/s)
Minimum	-3.2	-13.2	-8.2	0	31	0	0.0
Maximum	44.0	27.4	32.2	65	100	14	13.5
Mean	21.2	10.0	15.0	1	71	6	2.0
Std	10.1	8.2	9.0	3	12	4	1.6

2.2 The Coupled model intercomparison project phase 6

The output of the GCM models and scenarios published by the IPCC is the main focus of research on climate change worldwide. GCM models are advanced and efficient tools that provide the climate status of different regions of Earth on global and continental scales (Wilby and Harris, 2006). These models were prepared with the aim of examining and assessing how climate variables have changed in the past, present, and future periods and considering scenarios of changes in greenhouse gas concentrations in the future. The IPCC started a project to standardize the use of GCM model outputs in 1990 and presents climate change assessment reports every few years using research from different researchers worldwide. The latest report of this panel, which was compiled in the form of the sixth report, and was used in this study, includes different greenhouse gas emission models and scenarios for the future. For example, in the SSP2.6 scenario, known as the optimistic scenario, global warming is considered to be approximately 2 °C. As a result, the increase in greenhouse gas concentrations should decrease from 2020 onwards and reach approximately zero by 2100. In its latest report, the IPCC, in addition to considering the effect of greenhouse gas concentrations, also considered the effect of other factors, such as economic and social developments. Considering this issue, the scenarios presented in this report are referred to as SSPs.

The general circulation models presented in CMIP6 are improved versions of those in previous reports. Among the advantages of the models and scenarios presented in CMIP6 compared with CMIP5, we can mention the increase in the number of vertical layers to simulate the state of the stratosphere more accurately. More information in this regard is available in Frame et al. (2018) and Riahi et al. (2017).

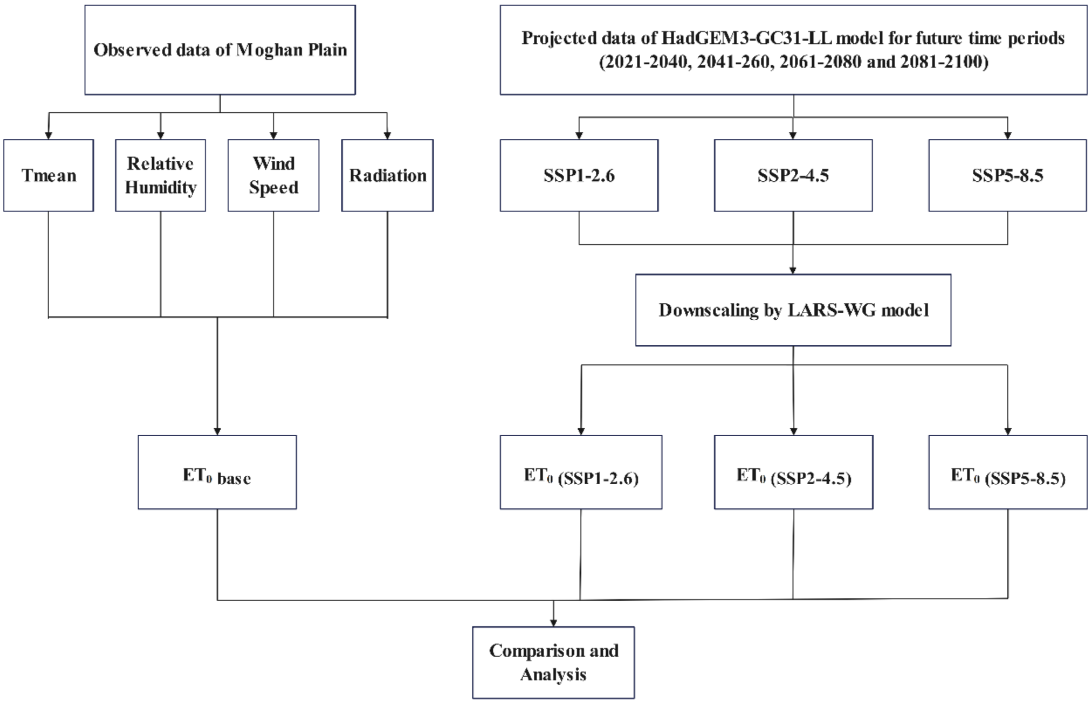

Fig. 2 Flowchart of the implementation stages in present study

In this study, the HadGEM3-GC31-LL model was used to predict climate variables of Moghan Plain under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively optimistic, intermediate, and pessimistic scenarios. This model and scenarios were obtained from the CMIP6.

2.3 Lars-WG statistical downscaling model

One of the problems associated with the use of GCM models is their cell size. This reduces the accuracy of the spatial predictions and analyses. Therefore, it is necessary to use downscaling models to study climate change at small spatial scales. The most famous and widely used downscaling model is the Lars-WG model, which is used to generate daily precipitation and minimum and maximum temperatures under baseline and future climatic conditions. This model was first presented by Racsko et al. (1991) as part of the Agricultural Risk Assessment Project in Budapest, Hungary, and then revised by Semenov et al. (1998). The Lars-WG model generates climate data in three stages: calibration, evaluation, and meteorological data generation. This model, by receiving a file containing the station's past climate behavior and a climate change model and scenario, produces daily values of minimum and maximum temperatures and precipitation for the station in question in the future (Semenov et al., 1998).

2.4 FAO-Penman-Monteith method for calculating reference evapotranspiration

Various methods for calculating reference evapotranspiration (ET_0) have been proposed (Dinpashoh, 2006). The selection of the appropriate method depends on the data available in the study area as well as the accuracy required in the research. Among the various methods for calculating ET_0, the FAO-Penman-Monteith method (PMF56) is known as a standard method, and many researchers have used this method to estimate ET_0 (Zeraati Neyshabouri et al., 2022). Therefore, in this study, the ET_0 value was calculated according to the PMF56 method using equation (1) (Allen et al., 1998; Dinpashoh et al., 2011).

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

Where, ET_0 is the reference evapotranspiration (mm/day), Δ is the slope of the vapor pressure curve as a function of air temperature (kPa/°C), R_n is the net radiation entering the plant surface (Mj/m^2/day), G is the soil heat flux (Mj/m^2/day), γ is the psychrometric constant (kPa/°C), T is the average air temperature (°C), U_2 is the average wind speed at the height of 2 meters (m/s), e_s is the saturated vapor pressure (kPa), and e_a is the actual vapor pressure (kPa).

To calculate ET_0 during the base period (1993-2022), observational data recorded for various meteorological variables at the Parsabad synoptic station were used. To calculate ET_0 in the future, given that the output of the Lars-WG model does not include the variables of average wind speed, relative humidity, and sunshine hours, the average of these data in the base period was used.

2.5. Evaluation criteria

To examine the performance of the Lars-WG model in simulating the climatic variables of the Moghan Plain in the base period, the statistical criteria of the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE) were used according to equations (2) to (4), respectively (Sanikhani et al., 2012; Sattari et al., 2024).

$$R^2 = \frac{\left[\sum_{i=1}^{N}(O_i - \bar{O}_i)(P_i - \bar{P}_i)\right]^2}{\sum_{i=1}^{N}(O_i - \bar{O}_i)^2 \sum_{i=1}^{N}(P_i - \bar{P}_i)^2} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \quad (3)$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|P_i - O_i| \quad (4)$$

Where, O_i is the observed (actual) value, P_i is the simulated value, $\bar{O}_i$ is the average of the observed values, $\bar{P}_i$ is the average of the simulated values, and N is the number of observations. The higher the R^2 and the lower the RMSE and MAE, the more accurate the model is and the better its performance is considered.

3. Results and Discussion

3.1 Evaluation of the Lars-WG model in simulating climate variables

The performance evaluation statistics for the Lars-WG model simulation of climatic variables in the Moghan Plain during the base period are displayed in Table 2. The data presented in this table indicate that the Lars-WG model simulation demonstrated high accuracy, as evidenced by the values of the statistical criteria for all three variables: precipitation, minimum temperature, and maximum temperature. Consequently, the results of this model demonstrate reliability and can be utilized for the generation of future climatic data.

Table 2 Lars-WG model evaluation results in the simulation of precipitation and temperature of Moghan Plain in the base period (1993-2022)

Variable	R^2	RMSE	MAE
Precipitation (mm)	0.96	1.83	1.65
T_{min} (°C)	0.98	0.19	0.16
T_{max} (°C)	0.98	0.23	0.18

3.2. Predicting climatic variables of the Moghan Plain

Fig. 3a shows the predicted annual precipitation values of the Moghan Plain in the future under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. The annual precipitation of the Moghan Plain under the SSP1-2.6 scenario will continue to increase in the future from 261 mm in the base period (1993-2022). The annual precipitation of the Moghan Plain reaches a maximum of 342 mm. Nevertheless, it will exhibit a decline over the final two decades of the century. Under the SSP2-4.5 scenario, although precipitation changes will increase in different periods, they will fluctuate. Therefore, in the first 20-year period (2040-2021), it will increase to 320 mm, and in the second 20-year period (2060-2041) it will decrease to 279 mm. In the third 20-year period (2080-2061) it will increase again (305 mm) and decrease (313 mm) by the end of the century. Under the SSP5-8.5 scenario, fluctuations in precipitation changes were also observed.

An important issue is the increase in the total annual precipitation of the Moghan Plain under all future scenarios. Various studies have reported an increase in precipitation in some regions of Iran in the future. Mousavi et al. (2016) predicted an increase in precipitation in Iran, and this increase was predicted to be greater on the shores of the Caspian Sea, Oman, and the Persian Gulf, the western parts of the Zagros Mountains, and the northern parts of the Alborz Mountains than in the central, eastern, and northeastern regions of Iran. In addition, the average precipitation in the periods 2070-2041 and 2071-2100 was predicted to be lower than that in the period 2011-2040. In some studies, a decrease in precipitation during future periods has also been predicted for different regions. For example, the results of the study by Babolhekami et al. (2020) indicated a decrease in precipitation in Mazandaran province between 8-29% in the future. The reason for the difference in the results of the research may be related to the geographical and climatic location of the regions, the models, and the emission scenarios presented in different IPCC reports.

Fig. 3b and 3c show the predicted results of the average minimum and maximum temperatures in the Moghan Plain in future periods until the end of the century, respectively. The minimum and maximum temperatures of the Moghan Plain will increase under all scenarios in the future, until the end of the century. The intensity of the increase under the SSP5-8.5 scenario will be greater than that under the other scenarios. The ranges of the increase in the minimum and maximum temperatures under the SSP1-2.6 scenario are 1.28 and 1.22 °C, under the SSP2-4.5 scenario is 2.46 and 3.16 °C, and under the SSP5-8.5 scenario is 4.85 and 5.14 °C, respectively. The minimum temperature under the most pessimistic scenario (SSP5-8.5) will increase from 9.95 °C in the base period (1993-2022) to 11.19, 27.12, 13.89 and 16.04 °C in the 20-year periods 2040-2021, 2060-2041, 2080-2061 and 2081-2100, respectively. The maximum temperature under the most pessimistic scenario (SSP5-8.5) will increase from 21.12 °C in the base period to 22.54, 23.70, 25.68, and 27.68 °C in the 20-year periods 2040-2021, 2060-2041, 2080-2061 and 2081-2100, respectively. The results of this study are consistent with those of Nateghi et al. (2022), who used RCP emission scenarios in the Halil-rud Watershed in the southeastern Kerman Province. Based on their results, the temperature in this region was predicted to increase over the next 20 years for all scenarios. In addition, the results of the study by Fazeli Khiavi et al. (2020), which was conducted using the scenarios of the CMIP5 in the Moghan Plain, indicated an increase in temperature under all RCP scenarios in future periods. In the study by Behzadi Karimi et al. (2022), an increase in minimum and maximum temperatures was predicted in the Karun watershed under all RCP scenarios in the next 60-year (2080-2021). The increase in minimum and maximum temperatures in the Moghan Plain can affect various areas, including water resources, the time of planting agricultural crops, the growth period of plants, the type of crops that can be cultivated, and the living conditions of humans. Therefore, managers, planners, and decision makers can use the results of this research on various subjects.

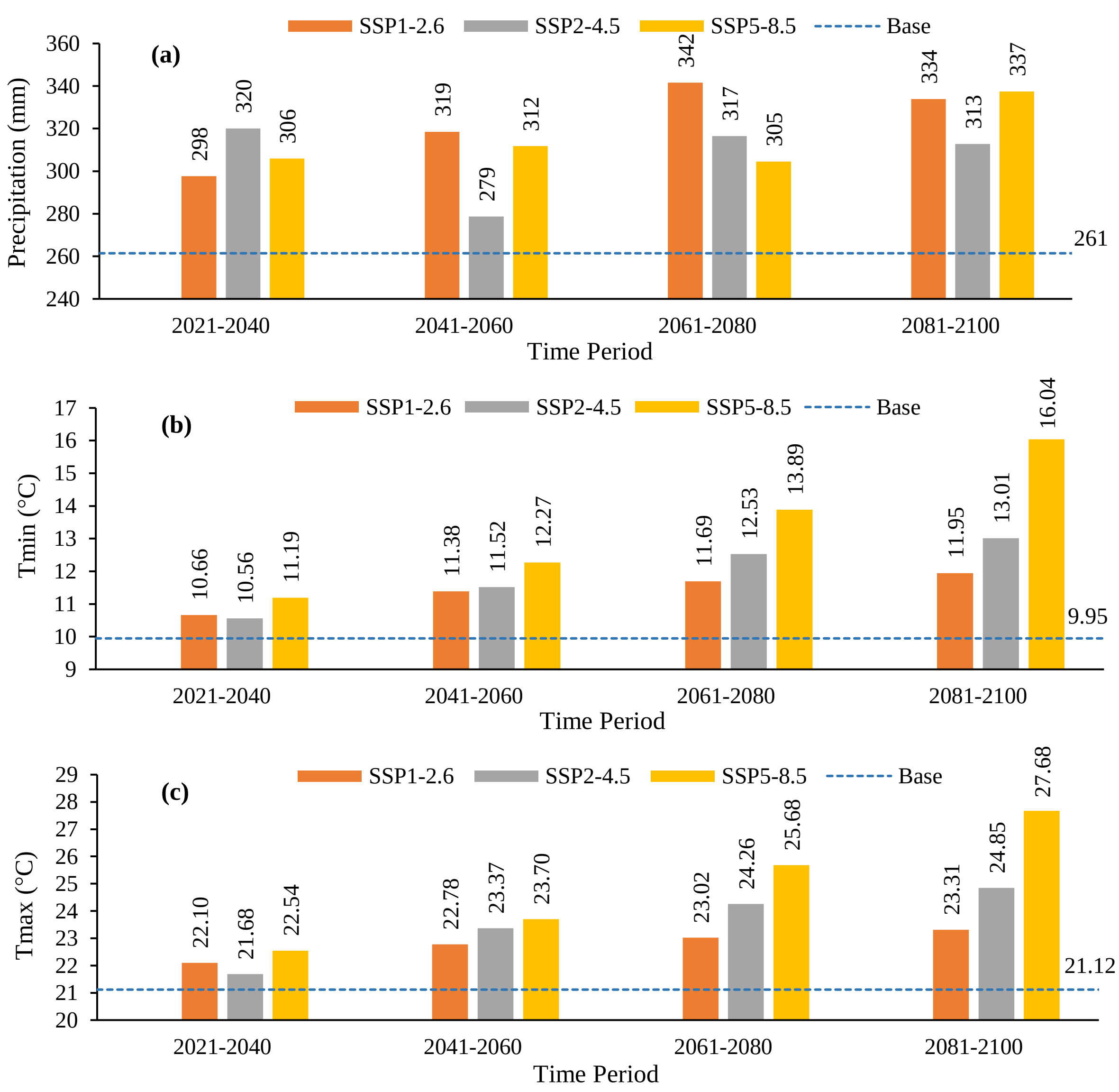

Fig. 3 a) Annual precipitation, b) minimum temperature and c) maximum temperature of Moghan Plain in future periods under different scenarios

3.3. Evapotranspiration predict for the Moghan Plain

Fig. 4 shows the results of the prediction of the ET_0 value of the Moghan Plain for future periods until the end of the century under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios and their percentage of change. The average ET_0 of the Moghan Plain in the base period (1993-2022) was 3.04 mm/day. It was observed that this value will increase in the future and under different scenarios. In the future, and under all three scenarios studied, the percentage of increase in the ET_0 of the Moghan Plain will gradually increase. The highest increase will occur under the SSP5-8.5 scenario. So, the average ET_0 of the Moghan Plain will increase from 3.04 mm/day in the base period by 19.76% to 3.64 mm/day by the end of the century. The lowest increase (3.10 mm/day) was also predicted under the SSP2-4.5 scenario and in the first 20-year period (2021-2040). The results of the study by Paritaghinezhad et al. (2023), which was conducted using the output of the CMIP6 for the Minab Plain, indicated an increase in ET_0 of this region in the future in optimistic and pessimistic cases of 0.31 and 1.23 mm/day, respectively. The results of the study by Fazeli Khiavi et al. (2020), which assessed the effects of climate change on ET_0 of the Moghan Plain, which was conducted using the CMIP5, indicated an increase in ET_0 calculated using the PMF56 method between 4.8-6% in the periods 2011-2030 and 2030-2060. Despite the prediction of an increase in ET_0 in the Moghan Plain for the future, the rate of increase differs from the results of the present study (between 19.76-1.78%). The reasons for this include the different statistical base periods, differences in the report and scenarios used, and differences in the predicted changes in climate variables. In their study, data from 1980 to 2010 were used as the base period; however, in this study, data from 1993 to 2022 were used. They used RCP scenarios (CMIP5), whereas in this study, the latest IPCC scenarios, namely SSP scenarios (CMIP6), were used. According to their results, the maximum annual precipitation in the Moghan Plain in the future was predicted to be between 264.2-297.9 mm, and in the present study, between 279-342 mm. These differences caused differences in the predictions of ET_0 changes in these studies. It is important to note that most studies have predicted an increase in ET_0 in different regions. In the study by Heydari Tasheh Kaboud and Khoshkhoo (2019) which was conducted to predict future ET_0 changes in western Iran, an increase in the average ET_0 was predicted under all scenarios and for all stations (four stations). In general, a review of sources indicates that, despite differences in climatic, hydrological, and other conditions in different regions, the ET_0 value of most regions will increase in the future, and only the intensity of its changes may differ.

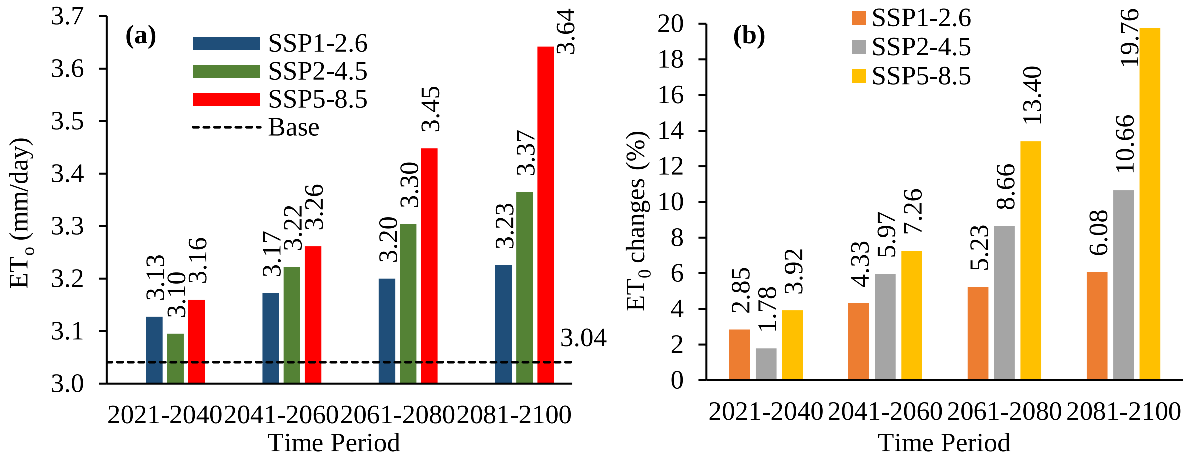

Fig. 4 a) ET_0 value of Moghan Plain and b) changes of ET_0 in future periods, under different scenarios (%)

Tables 3 and 4 present the predicted ET_0 values of the Moghan Plain and the percentage of its changes under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios until the end of the century. It can be seen that the annual ET_0 value of the Moghan Plain in the base period (1993-2022) is 1114 mm/yr and does not have the same value in different months of the year. Its lowest value is on December 8.24 mm/month and its highest value is in July 193.44 mm/month. It is predicted that the ET_0 of the Moghan Plain will increase in the future under all scenarios. However, the changes are not the same under different scenarios in different months. In the near future period (2021-2040), the annual ET_0 of the Moghan Plain will reach 1146, 1134, and 1158 mm/yr under the SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively, with an increase of 3, 2, and 4% compared to the base period, respectively. On a monthly scale, the highest increase in ET_0 in this period is in March under all three scenarios, which is predicted to increase by 6, 4, and 8% under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively. In the 2060-2041 period, the annual ET_0 of the Moghan Plain will be 1162, 1180, and 1195 mm/yr under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively, with increases of 4, 6, and 7% compared to the base period, respectively. On a monthly scale, the highest ET_0 increase in this period is in March under the SSP1-2.6 and SSP5-8.5 scenarios, with an increase of 10 and 12%, respectively. Under the SSP2-4.5 scenario, the highest increase was in March and November, with an increase of 11%. In the period 2061-2080, the annual ET_0 of the Moghan Plain will be 5, 9, and 13% higher than the base period under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively, with increases of 1172, 1210, and 1263 mm/yr, respectively. On a monthly scale, the highest ET_0 increase in this period will be in March under all three scenarios, with increases of 11, 1,5, and 20% predicted under SSP1-2.6, SSP2-4.,5, and SSP5-8.5, respectively.

Table 3 ET_0 (mm) of Moghan Plain in the future, under different scenarios

Time period	Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1993-2022	ET_0 (mm)	27.28	33.32	57.97	83.7	128.03	175.2	193.44	173.91	113.1	66.96	36.3	24.8	1114
2021-2040	SSP1-2.6	27.59	33.88	61.38	88.2	132.37	178.5	197.47	177.01	116.4	69.75	37.8	25.42	1146
	SSP2-4.5	27.28	33.60	60.14	86.1	129.89	176.1	196.54	177.32	115.8	68.51	37.2	25.42	1134
	SSP5-8.5	28.21	35.28	62.62	89.1	133.3	180	199.33	178.56	117.3	70.06	38.1	25.73	1158
2041-2060	SSP1-2.6	28.83	35.56	63.55	89.4	133.61	180	198.71	178.56	117.6	70.68	39	26.66	1162
	SSP2-4.5	29.14	36.12	64.48	90	134.23	182.7	202.12	181.35	120	72.85	40.2	27.28	1180
	SSP5-8.5	29.76	36.96	65.1	90.9	135.78	184.5	205.53	185.07	121.8	72.54	39.6	27.28	1195
2061-2080	SSP1-2.6	29.14	36.12	64.17	90	133.92	180.9	200.88	181.04	119.4	71.3	38.7	26.66	1172
	SSP2-4.5	30.69	38.08	66.65	92.7	137.02	184.8	207.08	187.24	123.3	74.09	40.8	27.9	1210
	SSP5-8.5	31.62	39.20	69.44	96.9	143.22	193.8	215.76	194.99	129.3	77.81	42.3	28.83	1263
2081-2100	SSP1-2.7	29.14	36.12	65.41	92.7	136.4	181.2	201.5	181.66	119.4	71.92	39.6	26.66	1182
	SSP2-4.6	31.00	38.36	68.51	95.7	139.81	187.2	210.49	190.65	125.7	75.64	41.4	28.21	1233
	SSP5-8.6	34.10	42.84	74.09	100.2	146.94	201.6	228.78	208.32	138.6	83.39	44.7	30.38	1334

In the far future period (2100-2081), the annual ET_0 in the Moghan Plain will reach 1182, 1233, and 1334 mm/yr under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, with increases of 6, 11%, and 20% compared to the base period, respectively. On a monthly scale, the highest increase in ET_0 in this period will be in March under the SSP1-2.6, and SSP2-4.5 scenarios, with increases of 13 and 18%, respectively. However, under the SSP5-8.5 scenario, an increase of 29% was predicted in February.

Table 4 shows that the highest increase in ET_0 on a monthly scale under all scenarios in all four future periods was related to March. The main variables affecting ET_0 were the minimum and maximum temperature values, which had an inverse relationship with ET_0. Therefore, the greater increase in ET_0 values in March compared to other months could be due to the prediction of the lowest increase in the minimum and maximum temperatures in this month compared to other months. Considering that the SSP scenarios are developed based on different social, economic, and political paths, SSP1-2.6, SSP2-4.5, and SSP5-8.5 are known as optimistic, intermediate, and pessimistic scenarios, respectively. This means that, under the SSP1-2.6 scenario, the lowest temperature increase will occur, and under the SSP5-8.5 scenario, the highest temperature increase will occur by the end of the century. Based on the results of this study, the impact of different scenarios on ET_0 values was evaluated differently. Therefore, the highest increase in ET_0 in the future was predicted under the SSP5-8.5 scenario, which follows IPCC reports. The results of this study can be referred to as the impact of different scenarios on ET_0 changes during different periods. In the near future periods (2040-2021 and 2060-2041), the difference between the percentage changes under different scenarios was smaller. In the third (2080-2061) and fourth (2100-2081) future 20-year periods, the difference between the percentage changes resulting from the different scenarios increased. In the first 20-year period, the percentage changes under different scenarios for all months were between 0-8%. However, in the second future 20-year period (2060-2041) it is between 12-3%, in the third future 20-year period (2080-2061) it is between 20-3% and in the fourth future 20-year period (2100-2081) it is between 29-3%. Another important result of this study was that the range of ET_0 changed under different scenarios. Therefore, the largest range of changes will be in the warm months of the year and the smallest in the cold months of the year under different scenarios. The largest range of changes is in July between 196.54-228.78 mm/month, August between 177.32-208.177 mm/month, and June between 176.6-201.176 mm/month. The smallest range of changes is in December between 25.30-30.38 mm/month, January between 27.34-28.1 mm/month, and November between 37.7-44.2 mm/month.

Table 4 The ET_0 changes (%) in Moghan Plain in the future, under different scenarios

Time period	Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1993-2022	ET_0 (mm)	27.28	33.32	57.97	83.7	128.03	175.2	193.44	173.91	113.1	66.96	36.3	24.8	-
2021-2040	SSP1-2.6	1	2	6	5	3	2	2	2	3	4	4	2	3
	SSP2-4.5	0	1	4	3	1	1	2	2	2	2	2	2	2
	SSP5-8.5	3	6	8	6	4	3	3	3	4	5	5	4	4
2041-2060	SSP1-2.6	6	7	10	7	4	3	3	3	4	6	7	7	4
	SSP2-4.5	7	8	11	8	5	4	4	4	6	9	11	10	6
	SSP5-8.5	9	11	12	9	6	5	6	6	8	8	9	10	7
2061-2080	SSP1-2.6	7	8	11	8	5	3	4	4	6	6	7	7	5
	SSP2-4.5	13	14	15	11	7	5	7	8	9	11	12	13	9
	SSP5-8.5	16	18	20	16	12	11	12	12	14	16	17	16	13
2081-2100	SSP1-2.6	7	8	13	11	7	3	4	4	6	7	9	7	6
	SSP2-4.6	14	15	18	14	9	7	9	10	11	13	14	14	11
	SSP5-8.6	25	29	28	20	15	15	18	20	23	25	23	23	20

In this study, to consider uncertainty in predicting future conditions, three optimistic (SSP1-2.6), intermediate (SSP2-4.5), and pessimistic (SSP5-8.5) scenarios were used. Consequently, instead of a definite and specific value, the range of future changes and their upper and lower limits were determined. The results of this study show that under any scenario, even in the most optimistic case, climate change will lead to an increase in ET_0, and as a result, an increase in the water needs of plants in the Moghan Plain in the future. Therefore, the need for water resources in this region is gradually increasing, which requires the optimal management of water resources. Considering the changes in ET_0 of the Moghan Plain and the agricultural situation of the region, it is necessary to pay attention to land use plans, cropping patterns appropriate to the climatic conditions of the region, water resources engineering and management, and preventive issues in this region.

4. Conclusion

In the present study, the impact of future climate change on the ET_0 of the Moghan Plain was investigated using 30-year base period data (1993-2022) from the Parsabad synoptic station. For this purpose, the output of the CMIP6, including the HadGEM3-GC31-LL model and the SSP1-2.6, SSP2-4.5, and SSP5-8.5, were used. The results showed the following.

1. The total annual precipitation in the Moghan Plain is expected to increase from 261 mm in the base period to 320,

319, 342, and 337 mm in the 20-year periods of 2040-2021, 2060-2041, 2080-2061 and 2081-2100, respectively. This highlights the need to pay attention to climate change and its effects on water resources.

2. Under the most pessimistic scenario (SSP5-8.5) in the 20-year periods 2040-2021, 2060-2041, 2080-2061 and 2081-2100, the minimum temperature in the Moghan Plain will increase from 9.95 °C in the base period to 11.19, 12.27, 89.13 and 04.16 °C, respectively, and the maximum temperature will increase from 12.21 °C in the base period to 22.54, 23.70, 25.68 and 27.68 °C, respectively.

3. The ET_0 value in the Moghan Plain will increase from 1114 mm in the base period to 1158, 1195, 1263, and 1334 mm in the most extreme case under the SSP5-8.5 scenario in the 20-year periods 2040-2021, 2060-2041, 2080-2061 and 2100-2081, respectively.

4. The largest range of ET_0 changes will be in the warm months of the year and the smallest in the cold months. The intensity of the impact of climate change on the ET_0 of the Moghan Plain was greater in the warm months of the year.

One of the limitations of this study is the existence of a synoptic station with long and complete data in the Moghan Plain. More synoptic stations with longer and more complete data could have affected the results. Given that the agricultural sector accounts for the largest share of water consumption in Iran, it is necessary to pay attention to the issue of ET_0 changes affected by climate change in different regions of the country, particularly in regions such as the Moghan Plain, where most agricultural crops are grown.

Statements and Declarations

Data availability

The data used in this research are provided in the text of the article.

Conflicts of interest

The author of this paper declared no conflict of interest regarding the authorship or publication of this paper.

Author contribution

P. Allahverdipour: Data Collection, Methodology, Modeling and Results Analysis, Performing Software and Statistical Analyses, Sources, Writing Draft Article, and Editing Article; Y. Dinpashoh: Research Management, Results Analysis, Editing Article

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