Linking Future Hydroclimatological Changes With Past Climatic Conditions In Southeastern Iran: Insights From Models And Observations

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Abstract

We compare the predicted results of future hydrological changes based on a thirty-year (1989-2019) weather dataset with paleoclimatic changes inferred based on established proxies from the Jazmurian playa in southeastern Iran. Parallels between expected changes in the future were compared to past climatic conditions to trace the impact this region has undergone in the distant past. The study area is affected by the Indian Ocean Summer Monsoon (IOSM) and the Mid-Latitude Westerlies (MLW). The maximum and minimum temperatures and precipitation were predicted for the future (2061-2080) by statistical downscaling outputs of 5 GCM models (EC-EARTH, GFDL-CM3, HadGEM2-ES, MIROC5, MPI-ESM-MR) under RCP 4.5 and RCP 8.5. The results show that the 20-years average of the mean temperatures ($\frac{T_{\text{max}} + T_{\text{min}}}{2}$) will increase in the range of 3.2 to 4.6 °C under RCP 8.5 compared to the base period. The trends suggest that the region will experience drier conditions than the baseline period in the future under both scenarios. In addition, the GCM predicts a considerable decline in MLW precipitation and little change in future IOSM precipitation under both scenarios compared to the baseline. The decrease in MLW precipitation is consistent with other GCM predictions and real paleoclimatic changes that happened during past warm/wet periods in the region. However, considering the close relationship between the increase in the Earth's radiation budget and enhanced IOSM precipitation in southeast Iran since the late Pleistocene, we postulate that more intensive IOSM activity can be expected in the future.

1. Introduction

Earth's climate has varied due to natural causes such as the change in solar insolation, orbital motion, orogeny, and ocean circulation pattern in the past (Bytnerowicz et al., 2007; Nakicenovic et al., 2000). However, since the industrial revolution began during the 18th-century, a sharp increase in greenhouse gas emissions (i.e., carbon dioxide, methane, nitrous oxide, and ozone) have resulted in global warming and a drastic change in existing climatic conditions (Le Treut et al., 2010; IPCC 2019). In particular, human activities associated with the burning of fossil fuels have increased carbon dioxide levels in the atmosphere from 280 ppm in 1750 to more than 400 ppm in recent years (IPCC 2019, 2021). Since the 1970s, globally averaged surface temperature data have shown a linear warming trend of ca. 0.9°C (Millar et al., 2017). Unlike temperature, which has increased globally, precipitation records indicate a variable response both in frequency and intensity (Archer & Rahmstorf, 2011; Konapala et al., 2020). Hence, there is an ongoing debate about how global warming will affect future precipitation because it has important implications for agriculture practices and food supply (Donat et al., 2016).

The lives of more than two billion people in South and West Asia depend on the summer monsoon precipitation on both short and long timescales (Clift & Plumb, 2008; Cullen et al., 2000). Therefore, understanding how the monsoons will change in the face of the anticipated increase in greenhouse gas emissions and rising global warming is a fundamental challenge. Also, the General Circulation Models (GCMs) face difficulty in simulating the regional distribution of monsoon (Turner & Annamalai, 2012) due to a multitude of physical processes and interactions that influence precipitation (Sperber et al., 2013). To reduce the uncertainty in climate models associated with monsoons and their intensity, we must understand the processes driving monsoons, seasonality, and fluctuations (Turner & Annamalai, 2012; Wang et al., 2017; Zhisheng et al., 2015).

It is suggested that the increase in greenhouse gas concentrations will intensify monsoons mainly due to an increased land-sea difference in temperature and a northward shift of the Inter-Tropical Convergence Zone (ITCZ) (Cao & Zhao, 2020; Li & Ting, 2017; Sachs et al., 2009). One such region of the world is southeastern Iran, which lies on the extreme northern border of the monsoonal domain that may be significantly affected by changes in the monsoon pattern and intensity. Southeastern Iran, straddled between the Indian Ocean Summer Monsoon (IOSM) precipitation zone and the
Mid-Latitude Westerlies (MLW) precipitation zone, makes it highly sensitive to changes in climatic conditions (Hamzeh et al., 2016; Rashki et al., 2021; Vaezi et al., 2019). Furthermore, paleoclimate records indicate that intensity and variation of IOSM and MLW have changed significantly since the late Pleistocene affecting the regional hydrological conditions (Vaezi et al., 2019; Clift & Plumb, 2008; Stevens et al., 2001). Therefore, establishing a better understanding of atmospheric circulation patterns and precipitation in the distant past could help in improving our assessment of future climate change scenarios and variations in regional precipitation patterns (Mehterian et al., 2017).

GCMs have been widely used to study atmospheric patterns and eventual effects on the global and regional scales. However, output data from GCMs are typically coarse to estimate the hydrological response to climate change on a regional scale. Thus, there is a need to downscale the data from a coarse resolution in GCMs to a ‘local’ sub-grid-scale, weather station scale (Busuioc, 2008; Wilby et al., 2002), which can be achieved either by statistical or dynamical methods. Amongst the statistical downscaling methods, the Long Ashton Research Station Weather Generator (LARS-WG) has been extensively applied and tested in different climatic regions (Luo & Yu, 2012; Qian et al., 2004; Semenov et al., 2002, 2013; Semenov & Barrow, 1997; Street et al., 2009). The simulations in these studies highlight the capability and accuracy of the model in simulating climate change and projections for the future.

In the present study, as a comprehensive climate-driven investigation of the arid Iranian plateau, we developed a general understanding of the qualitative and quantitative impact of changes in precipitation and temperature pattern and their impacts. In this context, daily precipitation and daily maximum ($T_{\text{max}}$) and daily minimum ($T_{\text{min}}$) temperatures in the Jazmurian playa in southeastern Iran were evaluated for the distant future scenario extending from 2061-2080 using statistically downscaled outputs from the 5 GCMs with the LARS-WG model under RCPs 4.5 and 8.5. The predicted results of future hydrological changes based on different global warming scenarios are used to evaluate the performance of the models. To verify if these changes may have also occurred in the past when no direct measurements of precipitation or temperature are available, we refer to the paleoclimate study by Vaezi et al. (2019) on a sediment core from the Jazmurian playa. This study reconstructs the linkages between paleoenvironmental conditions and variability in IOSM and MLW outputs that contributed to various environmental changes in the interiors of West Asia since the late Pleistocene. We compared the variations in future atmospheric circulation and related changes in precipitation to the past cold and warm periods. The predicted simulations and paleoclimate events superimpose a complex mosaic, which can gauge our response and adaptation to climate change scenarios.

2. Study Area

The Jazmurian playa is an inland basin or depression in southeastern Iran located 350 m above mean sea level. At the center of the Jazmurian basin is a seasonal lake that sporadically fills with fresh water. The playa receives ca. 75% of its annual freshwater input from the Halil River in the west. The Bampur River in the east is the other source of fresh water in the playa (Frs, 1975). The playa lies at the northern margin of the ITCZ (Fig. 1A). Scorching and dry summer and relatively mild winter result in high evaporation (ca. 2500 mm/year; Rashki et al., 2017), resulting in arid conditions. The local temperature and precipitation are reported by the Kahnuj and Iranshar stations located to the west and east of the playa, respectively (Fig. 1B). The mean annual temperature at the Iranshahr station is 27.2°C and the mean maximum and minimum temperatures during the warmest and coldest periods of the year are 44.5°C (July) and 8.4°C (January), respectively (Fig. 1B). The mean annual temperature at the Kahnuj station is 27.3°C, and the maximum and minimum temperatures during the warmest and coldest months of the year are 44.4°C (July) and 8.4°C (January), respectively. The annual precipitation around Jazmurian is about 138 mm as reported in Kahnuj (for a 30-years average), whereas Iranshahr reports it as 99 mm. The average monthly precipitation recorded at these two weather stations indicates the highest amount from January to March and dry conditions extending from April to November (Fig. 1B). However, the eastern part of the basin also experiences some precipitation during summer.
3. Materials And Methods

This study uses historical observation weather data (1989–2019) from the two weather stations in the Jazmurian playa (Kahnuj and Iranshahr) to simulate the future scenario. GCM data from the Coupled Model Intercomparison Project Phase 5 (CMIP5) is used namely. EC-EARTH, GFDL-CM3, HadGEM2-ES, MIROC5, and MPI-ESM-MR, to account for intermodal uncertainties. The output from GCMs is statistically downscaled using LARS-WG for the future scenarios RCPs 4.5 and 8.5 for variables precipitation, maximum (Tmax), and minimum (Tmin) temperatures.

3.1. CMIP5 GCMs and RCPs

The specifications and horizontal resolution (latitude/longitude) of CMIP5 global models used in this study are outlined in Table 1. The RCPs represent radiative forcing, where RCP4.5 represents a scenario with medium emissions (650 ppm CO$_2$) and medium radiative forcing (4.5 W/m$^2$) and RC8.5 represents a more significant radiative forcing and increasing radiative forcing projected at 8.5 W/m$^2$ (1370 ppm CO$_2$) by 2100 (IPCC, 2014).

| GCMs          | Research Center                                                                 | Grid Resolution |
|---------------|---------------------------------------------------------------------------------|-----------------|
| EC-EARTH     | EC-EARTH consortium                                                             | 1.1° x 1.1°     |
| GFDL-CM3     | NOAA Geophysical Fluid Dynamics Laboratory                                      | 2.0° x 2.5°     |
| HadGEM2-ES   | United Kingdom Meteorological Office                                            | 1.3° x 1.9°     |
| MIROC5       | Atmosphere and Ocean Research Institute and Japan Agency for Marine-Earth Science and Technology | 1.4° x 1.4°     |
| MPI-ESM-MR   | Max Planck Institute for Meteorology                                           | 1.9° x 1.9°     |

3.2. LARS-WG Stochastic Weather Generator

The LARS-WG software version 6 is a stochastic weather generator used to simulate long-term weather data at the weather station scale under baseline and future conditions (Semenov & Barrow, 1997; Semenov & Stratonovitch, 2010). The model applies different statistical tests (t-test and Chi-square) for comparing the data generated with observed data during the baseline period and tests the model's performance (Semenov et al., 2002). Thus, developing weather data by LARS-WG can be divided into three steps - calibration, validation, and generation of simulated weather data.

During the calibration step, LARS-WG calculates statistical parameters for probability distributions of weather variables and their correlation based on the observed daily weather data. The program employs a semi-empirical distribution of observed weather data to simulate its statistical characteristics. The model also generates site-specific cumulative probability distribution function for climate parameters such as wet and dry days, daily precipitation, minimum and maximum temperature, and solar radiation (Semenov et al., 2002). During validation, the probability distributions of climate variables derived from the calibration processes are used to generate synthetic weather time series of arbitrary length having the same statistical features as the historical weather data (Semenov et al., 2002;
Model validation evaluates and compares the statistical characteristics of the observed and simulated weather data to test the capability of LARS-WG to simulate variable weather. In the last step, statistical parameters derived from the observed weather data during the calibration step are used to simulate future conditions corresponding to a particular climate change scenario simulated by the CMIP5 GCMs (Semenov et al., 2002; Tayebiyán et al., 2014).

4. Results

4.1. Calibration and Validation of LARS-WG
Hence, the observed and generated data have the same frequency distribution. In addition, the t-test results of the three simulate meteorological conditions during the observed period. The Chi-square test results show that p-values support

| Stations | Month | t-test | P-t | χ² | P-χ² | t-test | P-t | χ² | P-χ² | t-test | P-t | χ² | P-χ² |
|----------|-------|--------|-----|-----|-------|--------|-----|-----|-------|--------|-----|-----|-------|
| Iranshahr | Jan   | 0.12   | 0.90 | 0.11 | 1.00 | 0.92   | 0.36 | 0.11 | 1.00 | -0.29  | 0.77 | 0.18 | 0.84   |
|          | Feb   | 1.46   | 0.15 | 0.16 | 0.91 | 1.35   | 0.18 | 0.16 | 0.91 | -0.97  | 0.34 | 0.08 | 1.00   |
|          | Mar   | -0.36  | 0.72 | 0.05 | 1.00 | -1.46  | 0.15 | 0.05 | 1.00 | -0.24  | 0.81 | 0.12 | 0.99   |
|          | Apr   | -0.30  | 0.76 | 0.05 | 1.00 | 0.46   | 0.65 | 0.05 | 1.00 | 0.01   | 0.99 | 0.18 | 0.79   |
|          | May   | -0.64  | 0.52 | 0.11 | 1.00 | 0.16   | 0.88 | 0.05 | 1.00 | -0.48  | 0.63 | 0.44 | 0.02   |
|          | Jun   | 0.97   | 0.34 | 0.11 | 1.00 | 0.64   | 0.52 | 0.11 | 1.00 | -1.33  | 0.19 | 0.26 | 0.39   |
|          | Jul   | 1.07   | 0.29 | 0.11 | 1.00 | -0.61  | 0.54 | 0.11 | 1.00 | -0.51  | 0.61 | 0.19 | 0.78   |
|          | Aug   | 0.09   | 0.93 | 0.05 | 1.00 | -0.09  | 0.93 | 0.05 | 1.00 | -0.82  | 0.41 | 0.22 | 0.57   |
|          | Sep   | -0.12  | 0.91 | 0.05 | 1.00 | -1.94  | 0.06 | 0.05 | 1.00 | -0.04  | 0.97 | 0.17 | 0.84   |
|          | Oct   | 1.99   | 0.06 | 0.11 | 1.00 | 1.20   | 0.24 | 0.11 | 1.00 | -1.08  | 0.28 | 0.13 | 0.98   |
|          | Nov   | -1.08  | 0.29 | 0.05 | 1.00 | -0.79  | 0.43 | 0.05 | 1.00 | -0.74  | 0.46 | 0.35 | 0.09   |
|          | Dec   | -1.05  | 0.30 | 0.05 | 1.00 | -0.88  | 0.38 | 0.05 | 1.00 | -0.94  | 0.35 | 0.14 | 0.97   |
| Kahnuj   | Jan   | 0.14   | 0.89 | 0.11 | 1.00 | 1.36   | 0.18 | 0.11 | 1.00 | 0.60   | 0.55 | 0.13 | 0.99   |
|          | Feb   | 0.96   | 0.34 | 0.16 | 0.91 | 1.15   | 0.25 | 0.16 | 0.91 | -0.33  | 0.75 | 0.08 | 1.00   |
|          | Mar   | -0.86  | 0.39 | 0.05 | 1.00 | -1.16  | 0.25 | 0.05 | 1.00 | -1.47  | 0.15 | 0.13 | 0.98   |
|          | Apr   | 0.72   | 0.48 | 0.11 | 1.00 | 0.34   | 0.74 | 0.05 | 1.00 | -0.29  | 0.77 | 0.19 | 0.78   |
|          | May   | -0.45  | 0.65 | 0.11 | 1.00 | -0.06  | 0.95 | 0.05 | 1.00 | -0.89  | 0.38 | 0.17 | 0.84   |
|          | Jun   | -0.06  | 0.95 | 0.11 | 1.00 | -0.31  | 0.76 | 0.05 | 1.00 | -0.23  | 0.82 | 0.39 | 0.04   |
|          | Jul   | -0.30  | 0.77 | 0.05 | 1.00 | -1.43  | 0.16 | 0.05 | 1.00 | 0.31   | 0.76 | 0.19 | 0.78   |
|          | Aug   | 0.00   | 1.00 | 0.05 | 1.00 | -0.43  | 0.67 | 0.05 | 1.00 | 0.58   | 0.56 | 0.23 | 0.54   |
|          | Sep   | 0.11   | 0.91 | 0.11 | 1.00 | -0.60  | 0.55 | 0.05 | 1.00 | -0.81  | 0.42 | 0.22 | 0.59   |
|          | Oct   | 2.19   | 0.03 | 0.11 | 1.00 | 1.10   | 0.28 | 0.11 | 1.00 | -0.62  | 0.54 | 0.13 | 0.98   |
|          | Nov   | -0.57  | 0.57 | 0.11 | 1.00 | -1.14  | 0.26 | 0.05 | 1.00 | 0.42   | 0.68 | 0.35 | 0.10   |
|          | Dec   | -0.51  | 0.61 | 0.05 | 1.00 | -0.09  | 0.93 | 0.11 | 1.00 | 0.18   | 0.86 | 0.11 | 1.00   |

Table 2 shows the results of the two statistical tests (t-test and Chi-square) used to evaluate the model's sensitivity to simulate meteorological conditions during the observed period. The Chi-square test results show that p-values support the null hypothesis for each three variables (daily precipitation, minimum, and maximum temperature) for all months. Hence, the observed and generated data have the same frequency distribution. In addition, the t-test results of the three variables indicate that the null hypothesis can be accepted with 95% confidence. Therefore, the mean values of the
observed and simulated data are in similar order. Although the p-value is usually set at 5% in most cases, Semenov and Barrow (1997) suggested a p-value of 0.01 should be used as the acceptable significance level to evaluate the performance of the LARS-WG model (Osman et al., 2014). Based on the values obtained during the simulation, it can be concluded that the model's performance for predicting climate variability, i.e., minimum or maximum temperature, and precipitation is acceptable. A comparison of the simulated versus observed data (Fig. 2) reveals an excellent performance of LARS-WG, especially for predicting temperature. The mean total precipitation simulated indicated a maximum of 8 mm difference for any month.

### 4.2. Future climate scenarios

Statistical parameters derived from the observed data were utilized to generate predictors for variables in future climate scenarios 2061-2080 and RCP 4.5 and 8.5. The histograms (Figs. 3-5) represent the future (2061-2080) scenarios. Each plot has three histograms with different colors corresponding to the future weather for two scenarios and baseline observation data. Generally, it is observed that both minimum and maximum temperatures at both stations increase from baseline and are higher in RCP 8.5 than in RCP 4.5. Although precipitation did not depict a consistent pattern over the stations, variations extending from December to March accounted for most rain.

wherein mean increases in the range of 3.2 to 4.6°C under RCP 8.5 compared to the base periods 1989-2019 (Table 2). The highest increase of average monthly temperature at the stations occurred during May-July under RCP 8.5. The lowest increase in monthly minimum temperature occurred during October (Figs. 3 and 4). Based on both scenarios, GFDL-CM3 and HadGEM2-ES predicted the highest increase in temperature compared to other models. The highest increase in mean temperatures at the Iranshahr station was 2.9 and 4.5°C in the RCP 4.5 and RCP 8.5 scenarios, respectively, GFDL-CM3 projections. The highest increase in mean temperatures at Kahnuj station was 3.0 and 4.6°C in the RCP 4.5 and RCP 8.5 scenarios, respectively, based on the HadGEM2-ES projections.
Table 3
Changes in climatic conditions in the Jazmurian playa based on the scenarios compared to observed data recorded at the weather stations in Iranshahr and Kahnuj. Anomalies of IOSM and MLW precipitation are compared to the baselines as mentioned.

|                | Pre | Tmax  | Tmin  | Tavg  | IOSM | Pre | Tmax  | Tmin  | Tavg  | MLW  |
|----------------|-----|-------|-------|-------|------|-----|-------|-------|-------|------|
| **Iranshahr**  |     |       |       |       |      |     |       |       |       |      |
| Baseline       | 99  | 34.3  | 20.1  | 27.2  | 0.0  | 138 | 34.3  | 20.2  | 27.3  | 0.0  |
| EC-EARTH      |     |       |       |       |      |     |       |       |       |      |
| RCP45         | 105 | 36.3  | 22.2  | 29.2  | 3.6  | 93  | 36.3  | 22.2  | 29.2  | -41.0|
| RCP85         | 97  | 37.5  | 23.4  | 30.4  | 2.1  | 86  | 37.5  | 23.4  | 30.5  | -44.9|
| GFDL-CM3      |     |       |       |       |      |     |       |       |       |      |
| RCP45         | 109 | 37.2  | 22.9  | 30.1  | 2.0  | 126 | 37.2  | 22.8  | 30.0  | -18.5|
| RCP85         | 104 | 38.7  | 24.6  | 31.7  | 4.5  | 114 | 38.7  | 24.6  | 31.6  | -29.9|
| HadGEM2-ES    |     |       |       |       |      |     |       |       |       |      |
| RCP45         | 94  | 37.2  | 22.8  | 30.0  | 7.0  | 92  | 37.3  | 23.1  | 30.2  | -43.5|
| RCP85         | 114 | 38.6  | 24.6  | 31.6  | 12.2 | 123 | 38.8  | 25.0  | 31.9  | -13.8|
| MIROC5        |     |       |       |       |      |     |       |       |       |      |
| RCP45         | 99  | 36.6  | 22.3  | 29.4  | 1.4  | 93  | 36.8  | 22.3  | 29.5  | -44.5|
| RCP85         | 95  | 37.4  | 23.4  | 30.4  | 9.8  | 100 | 37.6  | 23.6  | 30.6  | -44.8|
| MPI-ESM-MR    |     |       |       |       |      |     |       |       |       |      |
| RCP45         | 76  | 36.2  | 22.0  | 29.1  | -5.2 | 90  | 36.3  | 22.1  | 29.2  | -35.8|
| RCP85         | 90  | 37.8  | 23.6  | 30.7  | -4.9 | 101 | 37.9  | 23.8  | 30.8  | -24.5|

The results indicated that the region would experience more droughts under both scenarios in the future compared to the baseline with increasing temperature and decreasing precipitation. The GCMs predicted a considerable decrease in MLW precipitation in Kahnuj station under both scenarios. MPI-ESM-MR and EC-EARTH have estimated less rainfall in the region in the future compared to the other GCMs (Table 2). Based on the scenarios, Kahnuj will experience a significant drop in precipitation in February, March, and December (Fig. 5).

At Iranshahr EC-EARTH, GFDL-CM3, MIROC5 show little change in future precipitation compared to baseline. However, some decrease in future precipitation was predicted by MPI-ESM-MR. Although HadGEM2-ES and MIROC5 showed an overall reduction in MLW precipitation, they indicated a minor increase in monsoonal precipitation (about 12.2 mm and 9.8 mm under RCP 8.5, respectively) compared to the baseline.

The major decrease in annual precipitation among the GCMs was 51.8 mm (37.6% decrease) under the RCP 8.5 scenario in EC-EARTH at Kahnuj. A slight decrease of 14.8 mm (0.11% decrease) is predicted under RCP 8.5 for HadGEM2-ES. However, the average precipitations under the RCP 8.5 scenario at Iranshahr during 2061-2080 ranges between 113 to 90 mm and shows little change compared to the baseline values (99 mm). As mentioned before, Kahnuj is influenced by MLW precipitation, and Iranshahr is influenced by MLW and IOSM precipitation. Anomalies in IOSM and MLW precipitation compared to the baseline in both stations show that changes in precipitation will mainly be due to the Mediterranean winter precipitation in the region (Table 2). The results show minimal changes in IOSM precipitation.

5. Discussion
The 2015 Paris climate agreement aims to hold the average increase in temperature to well below 2°C, and “pursue efforts” to limit this to 1.5°C. This is the only way to avoid adverse and unpredictable weather effects both on local and regional scales (IPCC, 2021; Millar et al., 2017; Rogelj et al., 2018). The results projected in this study show that
southeastern Iran is firmly set on this path by increasing the current temperature by several degrees by 2080. Consistent with this assessment, temperature changes based on different scenarios simulated in the Jazmurian playa agree with the recent evaluations of future temperature change in southwest Asia (Babar et al., 2016; Evans, 2009; Pal & Eltahir, 2016), which have severe implications on the landscape. However, it is difficult to visualize how the projected changes in temperature and precipitation would impact the landscape from climate simulations based on the instrumental data for the region. For example, have similar climatic conditions occurred in the near past? If so, what was the impact of these changes on the landscape? Combining future simulations with past changes provides a holistic outcome that is easier to visualize.

5.1. Paleoenvironmental history of the Jazmurian playa and regional hydrology

The paleoenvironmental history of the Jazmurian playa is based on a multi-proxy climate record established by correlating the grain size, magnetic susceptibility, elemental and mineral composition, and stable isotope trends in sediments retrieved from the playa (Safaierad et al., 2020; Vaezi et al., 2019). The observed variations in sedimentology and geochemical trends link the paleoenvironmental conditions and variability in IOSM and MLW output. Furthermore, these changes have been correlated with major climatic events related to possible global teleconnections that may have existed in the past in southeastern Iran (Safaierad et al., 2020; Vaezi et al., 2019).

5.1.1. Dusty dry periods

Variations in dust records from the Jazmurian basin in southeast Iran, located near the world’s largest dust sources, suggest a direct link between frequent occurrences of dust input originating from North Africa and the Arabian Peninsula (Safaierad et al., 2020; Vaezi et al., 2019) with the North Atlantic cold events (e.g., Heinrich event, Younger Dryas, and the 8.2-ka event). Furthermore, model simulations (Kageyama et al., 2013; Marzin et al., 2013; Mohtadi et al., 2014) and multi-proxy paleoclimatic records (McManus et al., 2004; Peterson et al., 2000) suggest that the cold events occurred due to the discharge of icebergs and freshwater from the North American ice sheets (Safaierad et al., 2020). Consequently, this condition reduced the northward heat transport by the Atlantic meridional overturning circulation (Safaierad et al., 2020; Vaezi et al., 2019). Generally, climate conditions over western Asia during the North Atlantic cold events were governed by a southward shift in the MLW and followed by variations in the North American winter ice cover (Safaierad et al., 2020). Significant increase in aeolian sands, high magnetic susceptibility, and the dominance of evaporite minerals during these cold events suggest high salinity coeval to the dusty and arid conditions in the Jazmurian playa (Vaezi et al., 2019). In addition, other paleoclimate records from SE Iran (Safaierad et al., 2020) as well as terrestrial records from West Asia (Sharifi et al., 2018), the Arabian Sea (Deplazes et al., 2013; Pourmand et al., 2004; Sirocko et al., 1996), and northern Oman (Fleitmann et al., 2007), confirm dusty and dry conditions during these intervals. The dusty and dry conditions overlapped with the expansion of the Siberian High (Mayewski et al., 1997) in the interior of West Asia (Sharifi et al., 2015) and changes in Greenland temperature (Svensson et al., 2008). This condition reduced the northward heat transport by the Atlantic meridional overturning (McManus et al., 2004). Moreover, sea surface temperature and salinity in the western subtropical North Atlantic (McManus et al., 2004) indicate a direct link between the decrease in temperature and increases in dust in the region (Safaierad et al., 2020).

Model simulations and paleoclimate reconstructions indicate that the sudden influx of freshwater and icebergs forced the Atlantic meridional overturning during the cold episodes (Denton et al., 2005). The anomalously warm Southern Hemisphere coeval to the anomalously cold Northern Hemisphere caused interhemispheric temperature contrasts (Clark et al., 2012; Singarayer et al., 2017). Consequently, the southward shift of the ITCZ (Kanner et al., 2012; Stríkis et al., 2018) weakened the Afro-Asian northern summer monsoon system (Stager et al., 2011; Wang et al., 2001).
compensate for substantially reduced surface air temperature over the ice-covered ocean (Gray & Wright, 1996; Safaierad et al., 2020), the Hadley circulation and the ITCZ shifted toward the anomalously warm Southern Hemisphere (Safaierad et al., 2020). Moreover, strong pressure and temperature gradients between the ice-covered margins and ocean caused stronger and gustier southward shifts in MLW (McGee et al., 2010).

Adjustment of the atmospheric circulation pattern in the region caused a large-amplitude stationary rise over the Red Sea that reinforced surface convergence over the Arabian Peninsula region (Kageyama et al., 2009; Mohtadi et al., 2014). Whether dry or humid air advected into the surface convergence resulted in widespread aeolian activity (Jish Prakash et al., 2015) or heavy rainfall (Dayan & Abramski, 1983) in West Asia. Similarly, paleoclimatic reconstruction from the Red Sea (Arz et al., 2003) and Arabian Sea (Tierney et al., 2016) showed sea surface cooling during these cold events resulting in the advection of dry air combined with increased aridity and aeolian activity in the Afro-Asian monsoon domains (Kageyama et al., 2009; Marzin et al., 2013).

5.1.2. Warm wet periods

Warm and wet conditions and more intensive IOSM activity dominated southeastern Iran during the Bølling–Allerød and the Early Holocene (Hamzeh et al., 2016; Safaierad et al., 2020; Vaezi et al., 2019; Walker & Fattahi, 2011). An increase in fluvial input, the appearance of illite and paucity of evaporite minerals, and lower salinity from ca. 14 to 13.2 cal kyr BP suggest more significant freshwater input into the Jazmurian playa (Vaezi et al., 2019). An increase in fluvial input into the playa that begins ca. 14 cal kyr BP is consistent with the intensification of IOSM recorded in other paleoclimate records from southeastern Iran (Safaierad et al., 2020) as well as in the Arabian Sea (Overpeck et al., 1996). Furthermore, this wet period in Jazmurian was synchronous with the Bølling–Allerød wet and warm period recognized in northwestern Europe (Sharifi et al., 2015; Weaver et al., 2003).

It is proposed that at the beginning of the Bølling–Allerød, the rapid increase of temperature over a short time in the moisture origin region of Greenland occurred (Steffensen et al., 2008) due to an abrupt heat migration from Southern Hemisphere to Northern Hemisphere (Gautam et al., 2019; Steffensen et al., 2008). As mentioned earlier, model simulations and paleoclimate reconstruction indicate the link between warm/cold events in North Atlantic and ISM variability with a wet/dry ISM phase (Band et al., 2018; Chiang & Friedman, 2012; Gupta et al., 2013; Mohtadi et al., 2014).

It is proposed that at the onset of the Bølling–Allerød, the temperature increased in the Greenland ice sheet followed by enhanced northward advection of heat and moisture, which resulted in cooling of the Southern Hemisphere due to the northward migration of the southern MLW (Anderson et al., 2009). This thermodynamic exchange between the north and south Atlantic is called the bipolar see-saw (Pedro et al., 2016; Stocker & Johnsen, 2003).

The synchronous δ¹⁸O variation of Greenland ice (Steffensen et al., 2008) with wet drilling during the monsoonal domain in the Southwest Asia like the Arabian Sea monsoon run-off record (Saraswat et al., 2013), clearly indicates a direct linkage between advection of moisture during the intensification of ISM and the contemporaneous northward ITCZ migration (Gautam et al., 2019).

Our record showed a decline in aeolian input coeval to the increase in fluvial sediments and the notable absence of evaporite minerals during the Early Holocene (from 11.4 to 9.4 cal kyr BP) suggest low salinity and high freshwater input from high precipitation. The appearance of illite during the wet period indicates the influence of IOSM in the playa (Vaezi et al., 2019). The strong IOSM activity coincides with a warm and wet early Holocene similar to paleoclimate interpretations based on the high-resolution δ¹⁸O stalagmite record from Oman by Fleitmann et al. (2007). The enhanced summer precipitation noted during the early Holocene is most likely related to high summer insolation and orbital-scale teleconnections (Fleitmann et al., 2007; Gupta et al., 2003; Overpeck et al., 1996).
After the Early Holocene wet period, a decrease in solar insolation occurred, whereby orbital motions led to the
southward migration of the Inter-Tropical Convergence Zone, and consequently, the gradual weakening of monsoons
in the northern hemisphere (Fleitmann et al., 2007; Gupta et al., 2003; Safaierad et al., 2020; Vaezi et al., 2019). Finally,
during the late Holocene, summer insolation decreased, and the IOSM intensity steadily declined to the present-day
condition (Ortega-Ramírez et al., 2004). The mean $\delta^{18}O$ trend in the Jazmurian playa indicates that the precipitation
source from an IOSM dominated regime during the Early Holocene switched to one influenced by the MLW during the
late-Holocene (Stevens et al., 2006; Vaezi et al., 2019).

5.2. Linkages to model output and scenarios

The downscaled GCMs in Jazmurian playa for 2061-2080 show dry conditions compared to the baseline under both
scenarios in southeastern Iran. The results indicate some decrease in the Mediterranean winter precipitation and a
negligible increase in IOSM precipitation. The westerly jet position in the sub-tropical Northern Hemisphere is a
function for changes observed in the temperature gradient between air masses (Kutzbach et al., 2014). When the
temperature gradient is low, the jet stream moves north (towards the pole) with low wind speed (Kutzbach et al., 2014).
Future projections in the Jazmurian playa show the weakening of MLW under RCP 8.5. The GCMs indicate towards
weaker Mediterranean sourced precipitation over the Middle East and southwest Asia (Black et al., 2010; Evans, 2009,
2010; Mehterian et al., 2017) owing to increased global warming. The paleoenvironmental record from Jazmurian
confirms that during high insolation, the MLW is displaced northward. This idea is consistent with other paleoclimate
records in the region (Safaierad et al., 2020). These records indicate that the position of the main axis in the MLW is
displaced to lower latitudes during times of less insolation, such as the late Holocene (Mehterian et al., 2017).

Several studies have addressed the critical issue of monsoon variations due to climatic changes. They conclusively
suggest that an increase in greenhouse gas concentrations will intensify the Asian summer monsoon circulation due
to more substantial warming over the Asian continent (Hu et al., 2000; Turner & Annamalai, 2012). The IOSM
precipitation evaluated by results of CMIP5 simulations shows an increase in mean seasonal precipitation and a
northward shift in monsoon circulation by the end of the 21st century (Menon et al., 2013).

The multi-proxy climate record from Jazmurian playa reveals that the regional hydrology of southeastern Iran since ca.
14.7 cal kyr BP is primarily governed by the IOSM strength, which in turn is linked to the position of the ITCZ in
response to orbital-scale changes in summer insolation (Fleitmann et al., 2007; Gupta et al., 2003; Overpeck et al.,
1996). Since 14.7 cal kyr BP (e.g. Bølling-Allerød and early Holocene epochs), Earth's radiation budget has increased
significantly on the Indian Ocean and the adjacent Asian landmass resulting in intensified IOSM in southeastern Iran
(Vaezi et al., 2019). Notably, the position of the ITCZ has also shifted substantially during the past millennium.
Lacustrine records from as far as the Galápagos and Palau Islands show that the ITCZ reached its southernmost
position during the Little Ice Age, which lasted from 1400 to 1850 AD, and since then, it has been creeping northward
over the past 300 years, possibly due to higher solar irradiance (May, 2002; Sachs et al., 2009). Previous studies have
indicated that small changes in the Earth's radiation budget could significantly affect the position of the ITCZ in the
northern hemisphere (Sachs et al., 2009). Hence, more intense IOSM activity could be expected in the Jazmurian playa
with a changing climate towards end of century. Results from the Jazmurian playa also shows a weakening of the
MLW under RCP 8.5, corroborating results from other studies with CMIP5 GCMs (Black et al., 2010; Evans, 2009, 2010;
Mehterian et al., 2017). However, because Jazmurian playa lies on the northernmost border of the monsoon domain,
these results need to be evaluated carefully in that context. Moreover, the results do not match the paleohydrological
changes and intensity of IOSM during past warm periods.

6. Conclusions
In this study on future and paleoclimate changes in an arid region of southeastern Iran situated on the northmost border of IOSM, we presented 1) future simulated precipitation and temperature shifts based on different scenarios in GCMs, and 2) trace real paleoclimatic changes that happened in the Jazmurian playa since the late Pleistocene. The playa's maximum and minimum temperatures and precipitation projections are estimated from the downscaled five CMIP5 GCMs (EC-EARTH, GFDL-CM3, HadGEM2-ES, MIROC5, and MPI-ESM-MR) under RCPs 4.5 and 8.5 using LARS-WG. The paleoenvironmental records are used to examine the relationship between predicted changes in precipitation (variability in IOSM and MLW output) based on two different scenarios.

Future projections of the 20-years average (2061–2080) of the mean temperatures will increase to 3.2 to 4.6°C under RCP 8.5 in southeastern Iran compared to the baseline period. However, the Iranshahr station shows little change in future precipitation compared to its baseline. HadGEM2-ES under RCP 8.5 showed a slight increase (about 12.2 mm) in monsoon precipitation compared to the baseline condition, and it is the highest increase among the GCMs. On the other hand, GCMs predicted a considerable decrease in MLW precipitation in Kahnuj station. Similarly, HadGEM2-ES and GFDL-CM3 indicate a weak decline in precipitation compared to other GCMs at the Kahnuj station for RCP 8.5.

The current study indicates that in the Jazmurian playa, MLW precipitation will decrease, and temperature will increase in future simulations. Infact, Consistent with several GCM studies and real paleoclimatic changes that happened during past warm/wet periods (e.g., the Bølling–Allerød and the Early Holocene) in the region, results emerging from the Jazmurian playa also show a weakening of the MLW under the RCP 8.5. However, in future simulations, we also noted that IOSM projections in Jazmurian playa do not match the actual shift in IOSM intensity or strength, especially during the warm/wet periods. Nevertheless, the results of the multi-proxy data from Jazmurian playa and other high-resolution records represent a similar pattern of intensive IOSM activity and northward movement of the ITCZ in response to the orbital-scale changes in summer insolation.

**Declarations**

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**Data Availability**

The datasets analysed during the current study are available in the www.irimo.ir

**Competing interests:** The authors declare no competing interests.

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Figures
Figure 1

Major climate systems over West Asia (Sharifi et al., 2015; A. Vaezi et al., 2019) and locations of the Jazmurian weather stations (marked as white triangles) and coring site (marked as a black star). A). Dotted lines indicate the approximate current location of the Intertropical Convergence Zone (ITCZ), Mediterranean winter precipitation limits, and the Siberian Anticyclone; IOSM refers to the Indian Ocean Summer Monsoon, B) a 30-years average of the minimum and maximum monthly mean air temperature (°C) and mean monthly precipitation (mm) as recorded in the weather stations of Kahnuj and Iranshahr.
Figure 2

Comparing the monthly mean of maximum and minimum temperatures and precipitation between observed and simulated data.
Figure 3

20-years average of monthly maximum air temperatures (°C) in each GCM model and projected scenario compared to the observed data as recorded at the weather stations in Iranshahr and Kahnuj.
Figure 4

20-years average of monthly minimum air temperatures (°C) in each GCM model and projected scenario compared to the observed data recorded at the weather stations in Iranshahr and Kahnuj.
Figure 5

20-years average of monthly precipitation (mm) in each GCM model and projected scenario compared to the observed data recorded at the weather stations in Iranshahr and Kahnuj.