Future changes in temperature extremes in climate variability over Iran

Mohammad Darand\textsuperscript{1,2} \textsuperscript{\textcopyright}

\textsuperscript{1}Department of Climatology, Faculty of Natural Resources, University of Kurdistan, Sanandaj, Iran
\textsuperscript{2}Department of Zrebar Lake Environmental Research, Kurdistan Studies Institute, University of Kurdistan, Sanandaj, Iran

Correspondence
Mohammad Darand, Department of Climatology, Faculty of Natural Resources, University of Kurdistan, Sanandaj, Iran.
Email: m.darand@uok.ac.ir

Abstract
The objective of the current study was to project changes in extreme temperature indices over Iran by the end of the 21st Century based on the Coupled Model Intercomparison Project phase 5 (CMIP5) simulations. We used six extreme temperature indices recommended and defined by the Expert Team on Climate Change Detection and Indices from a set of 18 CMIP5 model simulations from different modelling centres. The extreme temperature indices simulation results of the models were compared with the gridded extreme temperature indices observations of the Asfazari National Database with a spatial resolution of 15 × 15 km during the period 1962–2005. For comparison purposes, the CMIP5 model data and the Asfazari data were regridded to a uniform horizontal resolution 0.5° × 0.5° grid using a bilinear interpolation scheme before further processing. After first validating the model performance by computing bias, future changes in the period 2006–2100 were projected. The modified Mann Kendall trend test and the Sen slope estimator test were used for evaluating the trend of indices and estimating the change rate, respectively, at a 95% confidence level. The results show that the minimum of the daily minimum temperature (TN\textsubscript{n}) and the minimum of the daily maximum temperature (TX\textsubscript{n}) will increase in the future. Warming of night time temperature indices (TN\textsubscript{n} and TN\textsubscript{90p}) are projected to be stronger than those of daytime temperature indices (TX\textsubscript{n} and TX\textsubscript{90p}). Warming is not uniform across the country, with considerably more warming in the western and southern parts. In terms of the frequency of frost days, a decrease is generally projected in the 21st Century. The largest decrease is projected for the Zagros mountain ranges in the west and the mountainous region in the northeastern part of the country with a magnitude of around 8–10 days-decade\textsuperscript{−1}. The number of heat wave days is expected to increase sharply from about 13 days in the reference period (1963–2005) to 100 days by mid-century to more than 235 days by the end of the century under Representative Concentration Pathway 8.5.

KEYWORDS
climate change, CMIP5, extreme temperature, Iran
1 | INTRODUCTION

Temperature is an important component of a climate system. It is a key indicator of the climate response to human emissions of greenhouse gases. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) the global mean temperature is increasing and will continue to rise in the 21st Century (IPCC, 2013). The impact of global warming is greater on extreme climates than the mean climate (Seneviratne et al., 2012), and the probability of occurrence of extreme climate events will continue to increase in the future (IPCC, 2013). The increase of extreme climate events has adverse impacts on human society, health and welfare, the economy and natural ecosystems (Field et al., 2012). Therefore, evaluation of extreme climate events is needed for accurate impact assessment and is crucial for developing adaptation strategies to reduce climate risks, which was the primary motivation for this study. Climatic models are the essential tools accessible for exploring the reaction of the climate system to different forcings, for creating climate predictions on seasonal to decadal time series scales and for providing a basis to project the future change in climate extremes over the coming century and beyond (Flato et al., 2013). In comparison to the previous generation of Atmosphere–Ocean General Circulation Models (CMIP3) (Meehl et al., 2007), the Coupled Model Intercomparison Project Phase 5 (CMIP5) is based on generally more sophisticated climate models and a new suite of forcing scenarios with improved physical parameterizations. The CMIP5 models are widely used by the scientific community to understand various aspects of global and regional climate (Ying et al., 2015; Guo et al., 2016; Alexander and Arblaster, 2017; Almazroui et al., 2017; Bannister et al., 2017; Agykum et al., 2018; Lovino et al., 2018; Ta et al., 2018; Xu et al., 2018; Kataria-Boroujerdy et al., 2019; Sung et al., 2019).

There are a few studies conducted to analyse future temperature projections over Iran based on CMIP5 models. For example, Babaeian et al. (2019) have projected the future temperature change of Iran using CMIP5 climate data models and found that the average temperature of the country increases about 5.2°C up to 2100 in comparison to the base period 1986–2005. Zamani and Berndtsson (2018) have evaluated 20 CMIP5 models for west and southwest Iran and they concluded that the BCC-CSM1.1 and CanESM2 have higher performance than other models. Bucchignani et al. (2018) provided projections for Middle East–North Africa based on the Representative Concentration Pathway 4.5 (RCP4.5) scenario of the CMIP5 model, highlighting a strong warming over high altitude areas of Turkey, northern Iran and Afghanistan. Large increases in temperature are also projected on the boundary between Iran and Iraq. However, the projection of extreme temperature indices has rarely been studied over Iran, even though their impacts have been severe. Most recent studies of extreme events have mostly focused on precipitation (Abbaspour et al., 2009; Molanejad et al., 2014; Raziei et al., 2014; Balling et al., 2016; Najafi and Moazami, 2016; Modarres et al., 2016; 2018). AshraVaghefi et al. (2019) recently projected the future of the extreme climate of Iran based on station analysis. They found that Iran will experience more extended periods of extreme maximum temperatures especially in southern parts, more extended dry periods and a higher frequency of floods. There is lack of a comprehensive study focusing on a climate model CMIP5 evaluation in terms of extreme temperature indices over Iran. In addition, a gridded dataset (Asfazari) on a daily scale based on dense station observations over Iran helps in better evaluating model performance in simulating extremes.

The main aim of the present study was therefore to investigate future changes in temperature extremes over Iran based on the CMIP5 models. The remainder of the paper is ordered as follows. The study area is briefly described in Section 2. Section 3 presents the data and methods used for the study. The results are presented in Section 4 followed by a summary in Section 5.

2 | STUDY AREA

Iran, with a total area of 1.648 million km² is located in southwest Asia, between 25° N to 40° N and 44° E to 64° E. The altitude of Iran ranges between −56 and 5,415 m above sea level. The average annual temperature

![FIGURE 1](image-url)
is about 14°C, with the highest (30°C) in the south and the lowest (6°C) in the northwest (Figure 1).

### 3 | DATA AND METHODS

#### 3.1 | Data

**3.1.1 Observational data**

In the present study, the daily gridded temperature data of the Asfazari National Database with a spatial resolution of 15 × 15 km during the period 1962–2005 were used as reference temperature data. This database was provided by Masoodian (2003) at the University of Isfahan. The most widely used ordinary Kriging method was applied to interpolate daily temperature data on 15 × 15 km grids using a dense network of 1,437 meteorological stations. The database has been widely used to access the variability of temperature and extremes and has high reliability over Iran (Masoodian and Darand, 2011; 2012; 2013; Darand, 2014a; 2014b; Darand et al., 2015; Asakereh and Shadman, 2018).
| Index  | Description                                                        | Unit   |
|--------|-------------------------------------------------------------------|--------|
| FD     | Frost days, number of days when the daily minimum temperature is below 0°C | Days   |
| TNn    | Coldest nights, minimum of daily minimum temperature              | °C     |
| TXn    | Coldest days, minimum of daily maximum temperature                | °C     |
| TN90p  | Warm nights, percentage of days when the daily minimum temperature is above the 90th percentile | %      |
| TX90p  | Warm days, percentage of days when the daily maximum temperature is above the 90th percentile | %      |
| WSDI   | Warm spell duration index, annual count when at least six consecutive days of maximum temperature are above the 90th percentile | Days   |

**FIGURE 2** Spatial distribution of the frost days (FD) index for observations and all models during the base period (1962–2005)
3.1.2 Model data

We used the Expert Team on Climate Change Detection and Indices (ETCCDI) from a set of 18 CMIP5 model simulations from different modelling centres that were available from ftp://ftp.cccma.ec.gc.ca/data/climdex/CMIP5/ and had been calculated for the studies of Sillmann et al. (2013a; 2013b). The models that were used in this study are summarized in Table 1. The model data include historical (1901–2005) and future (2006–2100) periods.

Here we used CMIP5 model results for three RCPs (RCP2.6, RCP4.5 and RCP8.5), adopted by the IPCC for its Fifth Assessment Report (IPCC, 2013). These new RCPs are based on the latest socioeconomic data, new technologies, changes in land cover and changes in land use (Moss et al., 2010).

3.2 Methods

For brevity, we selected six extreme temperature indices recommended and defined by ETCCDI (Zhang et al., 2011). Three of the six indices, frost days (FD), minimum of daily minimum temperature (TNn) and minimum of daily maximum temperature (TXn) represent cold temperature conditions and the other indices, including warm spell duration index (WSDI), warm days (TX90p) and warm nights (TN90p), reflect hot temperature conditions. Detailed definitions of the selected indices are given in Table 2. The CMIP5 models and the Asfazari data have different spatial resolutions. For comparison purposes, the CMIP5 model data and Asfazari data were regridded to a uniform horizontal resolution 0.5° × 0.5° grid using a bilinear interpolation scheme before further processing. This technique is a resampling

**FIGURE 3** The climatological (1962–2005) area-averaged bias in (a) the annual frost days, (b) TNn, (c) TXn, (d) Tn90p, (e) Tx90p and (f) the warm spell duration index, for each model relative to the observations.
method that uses the distance-weighted average of the four nearest pixel values to estimate a new pixel value (Zhou and Zhao, 2015; Jia et al., 2019) which has little “smoothing” effect on extreme climatic values (Kopparla et al., 2013).

There are uncertainties in climatic model projections (IPCC, 2012); therefore it is essential to evaluate the model performance in simulating extremes in comparison to observations (Ou et al., 2013). To overcome this problem, the bias correction approach was used to eliminate the model biases for RCP scenarios. In this method, the model biases were calculated by taking the difference between the averages over the period 1962–2005 of the model (\( \text{Index}_{\text{CONT}} \)) from the observations (\( \text{Index}_{\text{Obs}} \)). The biases were then adjusted with the future indices time series:

\[
\text{Index}_{\text{deb}} = \text{Index}_{\text{SCEN}} - (\text{Index}_{\text{CONT}} - \text{Index}_{\text{Obs}})
\]

where \( \text{Index}_{\text{deb}} \) is the de-biased (corrected) yearly time series of the index of extreme temperature for future periods. SCEN represents the RCP scenarios for future periods (2006–2100), and Obs and CONT represent the index of extreme temperature based on observations and models, respectively, for the present period (1962–2005). The Taylor diagram was used for summarizing the performance of individual CMIP5 models. We performed the non-parametric modified Mann Kendall trend test and the Sen slope estimator test for evaluating the trend of indices and estimating the change rate, respectively, at the 95% confidence level. More detailed information about the modified Mann Kendall trend test and the Sen slope estimator test can be found in Darand and Sohrabi (2018).

### RESULTS

#### 4.1 Climatology and model bias

We first tested whether the CMIP5 models can reproduce the spatial distribution of extreme temperature over Iran. Figure 2 shows the spatial distribution of frost days...
(FD) from observations and all models over the base period 1962–2005. A higher number of FD mainly occur in western and northwestern parts of Iran, and a lower number occur on the southern coasts of Iran (Figure 2a). It can be seen from Figure 2 that some models capture the spatial pattern of FD well (ACCESS1.0, BCC-CSM1.1 (m), CCSM4, GFDL-CM3, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR and MRI-CGCM3), while others appear not to do so well in capturing spatial patterns (BCC-CSM1.1, CanESM2, CSIRO-Mk3.6.0, FGOALS-s2, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, MIROC-ESM, MIROC5, MIROC-ESM-CHEM, NorESM1-M). CanESM2 tends to overestimate the FD in most of Iran while FGOALS-s2, MIROC5 and MIROC-ESM-CHEM tend to underestimate the FD. The simulated FD are lower than observation by models ACCESS1.0, BCC-CSM1.1 (m), CCSM4, GFDL-CM3, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR and MRI-CGCM3 in regions around the Zagros mountain range and higher than observation by models BCC-CSM1.1, CanESM2, CSIRO-Mk3.6.0, FGOALS-s2, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, MIROC-ESM, MIROC5, MIROC-ESM-CHEM and NorESM1-M. It is important to note, therefore, that although some of the CMIP5 models capture

**FIGURE 5** The projected changes in frost days (FD) over the period 2006–2100 for RCP8.5. All changes are significant at the 95% significant level.
the spatial pattern of FD well, clear biases exist in the magnitude of these patterns. The same results are obtained for the coldest nights (TNn) and coldest days (TXn) indices over Iran (Figures S1 and S2). The large differences between observations and model simulations around the Zagros mountain range may be due to the difficulty for models to describe the influence of the topography correctly (Feng et al., 2011).

In order to assess the ability of each CMIP5 model to reproduce the observed FD, the climatological (1962–2005) area-averaged bias for all temperature indices for the models was also calculated (Figure 3). It can be clearly seen from Figure 3 that, compared to observations, the CanESM2, IPSL-CM5A-MR, CSIRO-Mk3.6.0, IPSL-CM5A-LR, HadGEM2-ES, MRI-CGCM3, BCC-CSM1.1 (m), GFDL-CM3, ACCESS1.0, CCSM4 and GFDL-ESM2G models show a prevailing tendency to overestimate FD, while the others underestimate. The maximum bias for FD simulation comes from the CanESM2 model, with a value of 57 days. The NorESM1-M model performs the best, with a minimum bias of −0.63 day. It can be seen from Figures S3 and S4 that, except for some models (e.g., MIROC-ESM-CHEM, GFDL-ESM2M), the models show higher values for warm nights (TN90p) and warm days (TX90p) compared to observations over Iran. Most of the CMIP5 models (BCC-CSM1.1(m), BCC-CM1.1, FGOALS-s2, GFDL-CM3, GFDL-ESM2M, GFDL-ESM2G, IPSL-CM5A-MR, IPSL-
CM5A-LR, NorESM1-M) show a higher WSDI than observation over the southwestern region (Figure S5) with a value of more than 15 days (Figure S11), while they show a lower WSDI than observation over the Zagros mountain range and the southeastern region with a value lower than −10 days.

The Taylor diagram shows that the multi-model ensemble mean generally outperforms individual models because some of the systematic errors of the individual models are offset in the multi-model ensemble which coincides with the findings reported by Sillmann et al. (2013a), Sheffield et al. (2013) and Siyan et al. (2015). It is also clear from Figure 4 that, among the 18 CMIP5 modes, MIROC-ESM-CHEM appears to give the best performance in simulating TNn, TXn and Tx90p, while for the FD and WSDI BCC-CSM1.1(m) shows the best performance. Our results indicate that models with higher spatial resolution do not always perform better than those with lower spatial resolution. For example, the relatively high resolution MRI-CGCM3 does not necessarily “outperform” lower resolution models such as BCC-CSM1.1 and NorESM1-M compared to observations.

4.2 | Projection of future change

To identify the spatial variation of the extreme temperature indices, the spatial distributions of the trends of the future extreme temperature indices (2006–2100) by the 18 climate models are shown in Figures 5–10. The simulation of all models for the four scenarios predict significant changes in the extreme temperature indices over
the whole country during the future study period. Under all four emission scenarios, decreases in FD are projected whereas increases in TNn, TXn, TN90p, TX90p and WSDI are projected. There are some discrepancies in the changing rate among the models for the RCP scenarios. The projected changes under RCP8.5 are larger than those under the other RCPs. RCP8.5 is the highest radiative forcing and emission scenario, with an increasing radiative forcing to 8.5 W m\(^{-2}\) in 2100. In the present study, the RCP8.5 scenario was analysed to capture the possible extremity of the effect of climate change and global warming on changes in extreme temperature indices.

Figure 5 displays all model changes in FD projected for the period 2006–2100 in the RCP8.5 scenario. There are some spatial differences in the projected change rates in FD and other extreme temperature indices. The annual FD over Iran are generally projected to decrease in the 21st Century. In the base period (1963–2005), the southern part of the country does not experience FD. In the near future, the area with no FD is expected to increase widely. The FD index decreases considerably faster over the Zagros mountain ranges in the west and the mountainous region in the northeastern part of the country, which are regions with a cold climate and minimum temperature (see Figure 1), with a magnitude of around 8–10 days decade\(^{-1}\). A similar spatial pattern of changes in FD is seen for the other RCPs, not shown here.

TNn and TXn are both projected to increase over the whole country by the end of the 21st Century with stronger warming under RCP8.5 (Figures 6 and 7). The increase in TNn is larger than that of TXn, implying a
larger contribution of warming from increases in the night time temperature. Based on most of the models, TXn is projected to exhibit increases by 0.85 to 1.04°C-decade^{-1} over the southern and southwestern parts of the country. Compared to these areas, most regions in northern parts of the country will experience higher increases in TNn by 1.25 to 1.47°C-decade^{-1} based on the ACCESS 1.0, BCC-CSM1.1 (m), CanESM2 and MRI-CGCM3 models.

The results of trend analysis on the TN90p time series reveal that the increases of future warm nights over Iran vary spatially from 2 to 10.6% decade^{-1} (Figure 8). These changes are statistically significant at the 95% confidence level. Compared to TX90p, the changes are stronger for TN90p over the whole of Iran, indicating that the increase in minimum temperature is projected to become more pronounced than that in maximum temperature for all RCP scenarios. For all RCPs, the projected future TN90p shows larger changes over the southern part of Iran in all models.

Figure 9 shows the spatial distribution of the magnitude of changes in TX90p under the RCP8.5 scenario in the 21st Century. As has been shown, in the future, the TX90p index is projected to have a statistically significant increase ranging from 1.5 to 9% decade^{-1}. As for TN90p, the maximum increase is projected in the southern parts of Iran.

Future changes in the WSDI are shown in Figure 10. As for all previous indices, a widespread increase in the
WSDI covers the whole of Iran during the 21st Century. The maximum increase is projected in the southern and western parts. Despite a significant difference in magnitude, the spatial patterns of change in the WSDI are the same by all four models. The increase of the WSDI is stronger under the RCP8.5 scenario than for the other RCP scenarios. The magnitudes of the changes in the WSDI range from a minimum of 6 to a maximum of 38.6 days/decade under RCP8.5.

Figure 11 shows the area-averaged extreme temperature indices trends of the multi-model ensemble mean for the period 2006–2100. Compared to TXn and TX90p, TNn and TN90p are projected to increase more under all RCPs. According to Figure 11, TNn in the reference period 1963–2005 is below −7.6°C but it is close to zero in the second half of the 21st Century. At the end of the 21st Century, the area-averaged TNn, TN90p, TXn and TX90p values are projected to increase to −2°C, 79%, 10°C and 74%, while FD values are projected to decrease to 7 days under the RCP8.5 scenario. The WSDI is projected to increase steeply from about 13 days in the reference period (1963–2005) to 100 days by mid-century to more than 235 days by the end of the century under RCP8.5. The smallest increment of extreme temperature indices occurs under RCP2.6. The warming under RCP2.6, RCP4.5 and RCP6 is relatively consistent at about 35% for TN90p and TX90p and 78.5 days for the WSDI in 2050. The warming trend slows down or even

**FIGURE 10**  As Figure 5 but for the warm spell duration index
declines after 2050 under RCP2.6. In summary, these results indicate that extreme hot temperature indices will be more frequent and more intense, while extreme cold temperature indices will decrease below the base period under all four RCP scenarios, especially the RCP8.5 scenario, by the end of the 21st Century.

5 | CONCLUSION

The aim of this study was to present projected changes in the extreme temperature indices over Iran considering four RCP scenarios using 18 climate models based on simulations from the fifth phase of the Coupled Model Intercomparison Project (CMIP5). Projected changes in the extreme temperature indices show a significant variability across regions. All 18 climate models produce a warming trend in the 21st Century under the four RCP scenarios. Warming is observed in both TNn and TXn with larger increases in TNn under the RCP8.5 scenario.

The greatest projected warming occurs in the higher elevation regions of western Iran and the southern coastal regions. The number of frost days is expected to decrease with the largest decrease projected in high altitudes in western parts of Iran. As pointed out by Arkian et al. (2014), the number of snow days and both the duration and depth of snow cover in the western part of Iran significantly decreased under global warming. In line
with this statement, the significant decrease in the number of snow days, snow cover and depth led to a reduction of frost days in this region. The warm spell duration index (WSDI) is projected to become longer from about 13 days in the reference period (1963–2005) to 100 days by mid-century to more than 235 days by the end of the century under RCP8.5. Substantial increases of the WSDI are projected in the southern and western parts of Iran, with values increasing from 30 to 38.6 days-decade\(^{-1}\) under RCP8.5, which is consistent with the results presented by AshraVaghefi et al. (2019). Recent studies show that the warm spell durations become more frequent and have higher mean duration and intensity (Darand, 2014; Darand et al., 2015; Abbasnia, 2019). Warm nights (TN90p) and warm days (TX90p) also appear to increase with a greater increase of TN90p under all RCPs. The results indicated the southern parts of Iran to be the most vulnerable parts under projected increases. By the end of the 21st Century, the area-averaged TN90p and TX90p are projected to increase 79% and 74%, respectively. This may be due to an increase of air moisture in the atmosphere in this region by an increase in air temperature, as illustrated by Darand et al. (2019). The projected changes in extreme temperature indices over Iran will be helpful for policymakers due to the vast implications for planning and appropriate strategies to adapt to the projected changes.

ACKNOWLEDGEMENTS

The author sincerely appreciates the three anonymous reviewers for their helpful comments. This work is supported by the Iran National Science Foundation (INSF) with the code 96001347.

ORCID

Mohammad Darand @ https://orcid.org/0000-0001-9254-1370

REFERENCES

Abbasnia, M. (2019) Climatic characteristics of heat waves under climate change: a case study of mid-latitudes, Iran. Environment, Development and Sustainability, 21(2), 637–656. 
Abbaspour, K.C., Faramarzi, M., Ghasemi, S.S. and Yang, H. (2009) Assessing the impact of climate change on water resources in Iran. Water Resources Research, 45, W10434. https://doi.org/10.1029/2008WR007615. 
Agykum, J., Annor, T., Lamptey, B., Quansah, E. and Agyeman, R. Y.K. (2018) Evaluation of CMIP5 global climate models over the Volta Basin: precipitation. Advances in Meteorology, 4853681, 1–24. https://doi.org/10.1155/2018/4853681. 
Alexander, L.V. and Arblaster, J.M. (2017) Historical and projected trends in temperature and precipitation extremes in Australia in observations and CMIP5. Weather and Climate Extremes, 15, 34–56. 
Almazroui, M., Sajjad-Saeed, M.N.I., Alkhalaif, A.K. and Dambul, R. (2017) Assessment of uncertainties in projected temperature and precipitation over the Arabian peninsula using three categories of CMIP5 multimodel ensembles. Earth Systems and Environment, 23, 1–20. 
Arkian, F., Karimkhani, M. and Taheri, H.R. (2014) Variability and trends in the duration and depth of snow cover in Iran in thirty years. Journal of Earth Science and Climatic Change, 5, 239. https://doi.org/10.4172/2157-7617.1000239. 
AshraVaghefi, S., Keykhai, M., Jahanbakshi, F., Sheikholeslami, J., Ahmadi, A., Yang, H. and Abbaspour, K.C. (2019) The future of extreme climate in Iran. Scientific Reports, 9, 1464. https://doi.org/10.1038/s41598-018-38071-8. 
Babaeian, I., Karimian, M., Modirian, R. and Mirzaei, E. (2019) Future climate change projection over Iran using CMIP5 data during 2020–2100. NIVAR. Journal of Meteorological Organization, 43, 61–70. 
Balling, R.C., Keikhosravi Kiany, M.S., Sen Roy, S. and Khoshhal, J. (2016) Trends in extreme precipitation indices in Iran: 1951–2007. Advances in Meteorology, 2016, 1–8. 
Bannister, D., Herzog, M., Graf, H.F., Hosking, J.S. and Short, C.A. (2017) An assessment of recent and future temperature change over the Sichuan Basin, China, using CMIP5 climate models. Journal of Climate, 30, 6761–6722. 
Bucchignani, E., Mercogliano, P., Panitz, H.J. and Montesarchio, M. (2018) Climate change projections for the Middle East North Africa domain with COSMO-CLM at different spatial resolutions. Advances in Climate Change Research, 9, 66–80. 
Darand, M. (2014) Recognition and spatial–temporal analysis of heat waves in Iran. Geography and Development Iranian Journal, 12(35), 167–180. 
Darand, M., Masoodian, A., Nazaripour, H. and Mansouri Daneshvar, M.R. (2015) Spatial and temporal trend analysis of temperature extremes based on Iranian climatic database (1962–2004). Arabian Journal of Geosciences, 8(10), 8469–8480. https://doi.org/10.1007/s12517-015-1840-5. 
Darand, M. and Sohrabi, M.M. (2018) Identifying drought- and flood-prone areas based on significant changes in daily precipitation over Iran. Natural Hazards, 90, 1427–1446. https://doi.org/10.1007/s11069-017-3107-9. 
Darand, M., Pazhooh, F. and Saligheh, M. (2019) Trend analysis of tropospheric specific humidity over Iran during 1979–2016. International Journal of Climatology, 39, 4058–4071. https://doi.org/10.1002/joc.6059. 
Feng, L., Zhou, T.J., Wu, B., Li, T. and Luo, I.J. (2011) Projection of future precipitation change over China with a high resolution global atmospheric model. Advances in Atmospheric Sciences, 28, 464–476. 
Field, C.B., Barros, V., Stocker, T.F. and Dahe, Q. (Eds.). (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge: Cambridge University Press. 
Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S.C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C. and Rummukainen, M. (2013) Evaluation of climate models. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (Eds.) Climate Change 2013. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.
Guo, X., Huang, J., Luo, Y., Zhao, Z. and Xu, Y. (2016) Projection of precipitation extremes for eight global warming targets by 17 CMIP5 models. *Natural Hazards*, 84, 2299–2319.

IPCC. (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G-K., Allen, S.K., Tignor, M. and Midgley, P.M. (Eds.) *A special report of working groups I and II of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press, p. 582.

IPCC. (2013) Climate change 2013: the physical science basis. In: Stocker, T.F., Qin, D., Plattner, G-K., Tignor, M.M.B., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., (Eds.) *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, p. 1552.

Jia, K., Ruan, Y., Yang, Y. and Zhang, C. (2019) Assessing the performance of CMIP5 global climate models for simulating future precipitation change in the Tibetan plateau. *Water*, 11, 1771. https://doi.org/10.3390/w11091771.

Katirae-Boroujerdy, P.S., Asanjan, A.A., Chavoshian, A., Hsu, K.L. and Sorooshian, S. (2019) Assessment of seven CMIP5 model precipitation extremes over Iran based on a satellite-based climate data set. *International Journal of Climatology*, 39, 1–18. https://doi.org/10.1002/joc.6035.

Koppalara, P., Fischer, E.M., Hannay, C. and Knutti, R. (2013) Improved simulation of extreme precipitation in a high-resolution atmosphere model. *Geophysical Research Letters*, 40, 5803–5808. https://doi.org/10.1002/2013GL057866.

Lovino, M.A., Muller, O.V., Bernery, E.H. and Muller, G.V. (2018) Evaluation of CMIP5 retrospective simulations of temperature and precipitation in northeastern Argentina. *International Journal of Climatology*, 38(Suppl.1), e1158–e1175.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, T., Gregory, J.M., Kitch, A., Knutti, R., Murphy, J.M., Noda, A. and Raper, S.C. (2007) Global climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averty, K.B., Tignor, M. and Miller, H.L., (Eds.) *Climate Change 2007: The Physical Science Basis*. Cambridge: Cambridge University Press, pp. 747–845.

Modarres, R., Ghadami, M., Naderi, S. and Naderi, M. (2018) Future extreme precipitation change projections in the north of Iran. *Meteorological Applications*, 25, 40–48.

Modarres, R., Sarchadi, A. and Burn, D.H. (2016) Changes of extreme drought and flood events in Iran. *Global Planetary Change*, 144, 67–68.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T. and Meehl, G.A. (2010) The next generation of scenarios for climate change research and assessment. *Nature*, 463, 747–756.

Najafi, M.R. and Moazami, S. (2016) Trends in total precipitation and magnitude–frequency of extreme precipitation in Iran, 1969–2009. *International Journal of Climatology*, 36, 1863–1872.

Ou, T., Chen, D., Linderholm, H.W., et al. (2013) Evaluation of global climate models in simulating extreme precipitation in China. *Tellus A*, 65(5), 1393–1399.

Raziei, T., Daryabari, J., Bordi, I., Molanejad, M., Soltani, M. and Ranjar-SaadatAbadi, A.R. (2014) Changes in precipitation extremes in climate variability over northwest Iran. *The International Journal of Agricultural Policy and Research*, 2(10), 334–345.

Seneviratne, S., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C. and Zhang, X. (2012) Changes in climate extremes and their impacts on the natural physical environment. In: Field, C., Barros, V., Stocker, T., Qin, D., Dokken, D., Ebi, K., Mastrandrea, M., Mach, K., Plattner, G-K., Allen, S., Tignor, M. and Midgley, P. (Eds.) *Managing the risks of extreme events and disasters to advance climate change adaptation*. Cambridge: Cambridge University Press, pp. 109–230. https://www.ipcc.ch/pdf/special-reports/srex/SREX-Chap3_FINAL.pdf (last accessed September 28, 2017).

Sillmann, J., Kharin, V.V., Zhang, X., Zwiers, F.W. and Bronaugh, D. (2013a) Climate extremes indices in the CMIP5 multi-model ensemble: Part 1. Model evaluation in the present climate. *Journal of Geophysical Research – Atmospheres*, 118, 1716–1733. https://doi.org/10.1002/jgrd.50203.

Sillmann, J., Kharin, V.V., Zhang, X., Zwiers, F.W. and Bronaugh, D. (2013b) Climate extremes indices in the CMIP5 multi-model ensemble: Part 2. Future climate projections. *Journal of Geophysical Research – Atmospheres*, 118, 2473–2493. https://doi.org/10.1002/jgrd.50188.

Siyان, D., Ying, X., Botato, Z. and Ying, S. (2015) Assessment of indices of temperature extremes simulated by multiple CMIP5 models over China. *Advances in Atmospheric Sciences*, 32, 1077–1091.

Sung, J.H., Kwon, M., Jeon, J.J. and Seo, S.B. (2019) A projection of extreme precipitation based on a selection of CMIP5 GCMs over North Korea. *Sustainability*, 11, 1976. https://doi.org/10.3390/su11091796.

Sheffield, J., Barrett, A.P., Colle, B., Fernando, D.N., Fu, R., Geil, K.L., Hu, Q., Kinter, J., Kumar, S., Langenbrunner, B., Lombardo, K., Long, L.N., Maloney, E., Mariotti, A., Meyerson, J.E., Mo, K.C., Neelin, J.D., Nigam, S., Pan, Z., Ren, T., Ruiz-Barradas, A., Serra, Y.L., Seth, A., Thibeault, J. M., Stroeve, J.C., Yang, Z. and Yin, L., (2013) North American climate in CMIP5 experiments. Part I: Evaluation of historical simulations of continental and regional climatology. *Journal of Climate*, 26, 9209–9245. https://doi.org/10.1175/JCLI-D-12-00592.1.

Ta, Z., Yu, Y., Sun, L., Chen, X., Mu, G. and Yu, R. (2018) Assessment of precipitation simulations in Central Asia by CMIP5 climate models. *Water*, 10(1516), 1–14. https://doi.org/10.3390/w10111516.

Xu, Y., Gao, X., Giorgi, F., Zhou, B., Shi, Y., Wu, J. and Zhang, Y. (2018) Projected changes in temperature and precipitation extremes over China as measured by 50-yr return values and periods based on a CMIP5 ensemble. *Advances in Atmospheric Sciences*, 35, 376–388.

Ying, X., Jie, W., Ying, S., Bo-Tao, Z., Rou-Ke, L. and Jia, W. (2015) Change in extreme climate events over China based on CMIP5. *Atmospheric and Oceanic Science Letters*, 8(4), 185–192.
Zamani, R. and Berndtsson, R. (2018) Evaluation of CMIP5 models for west and southwest Iran using TOPSISI-based method. *Theoretical and Applied Climatology*, 137, 533–543.

Zhang, X., Alexander, L., Hegerl, G.C., Jones, P., Tank, A.K., Peterson, T.C., Trewin, B. and Zwiers, F.W. (2011) Indices for monitoring changes in extremes based on daily temperature and precipitation data. *WIREs: Climate Change*, 2(6), 851–870. https://doi.org/10.1002/wcc.147.

Zhou, J. and Zhao, J. (2015) An intercomparison between ERA-interim reanalysis and observed precipitation in Northeast China. *Discrete Dynamics in Nature and Society*, 2015, 1–9. https://doi.org/10.1155/2015/693923.

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Darand M. Future changes in temperature extremes in climate variability over Iran. *Meteorol Appl.* 2020;27:e1968. https://doi.org/10.1002/met.1968