Summer maximum temperature over the gulf cooperation council states in the twenty-first century: multimodel simulations overview

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Abstract

The present study analyzes the Survivability for a Fit Human Threshold (SFHT) maximum temperature during the summer (June–August) over the six Middle Eastern countries known as the Gulf Cooperation Council (GCC) in the twenty-first century. An ensemble of three dynamically downscaled global climate models available from the Coupled Model Intercomparison Project Phase 5 (CMIP5) under the Representative Concentration Pathways (RCPs) RCP4.5 and RCP8.5 emission scenarios is used to analyze the future climate (2006–2099) over the region. The ground-truth air temperature for ten major cities across the GCC countries is utilized for model evaluation and to estimate the model-simulated temperature biases. Both positive and negative biases found during the present climate (1976–2005) are used to adjust the future temperature changes. These adjustments show that the summer maximum temperature is likely to increase continuously for most cities in the GCC countries at the rate of about 0.2 °C (0.6 °C) per decade under RCP4.5 (RCP8.5) for the future period (2020–2099), which is significant at the 99% confidence level. For RCP8.5, the adjusted summer maximum temperature may exceed the SFHT limit of 42 °C in five capital cities of the GCC states and four major cities of Saudi Arabia. The projections based on adjusted values indicate that the average summer maximum temperature should not exceed 52 °C in any city investigated by the end of the twenty-first century. The daily maximum temperature is projected to exceed 55 °C in some cities in the GCC region by the end of the twenty-first century under a business-as-usual scenario that seems to be unrealistic if the biases are not taken into account. It is highly recommended that the GCC states should coordinate their efforts to respond appropriately to these projections using large ensembles of multimodel simulations while allowing for the associated uncertainty.

Keywords Summer temperature · CMIP5 · RCPs · RegCM4 · Gulf Cooperation Council

Introduction

There is a well-recognized link between increased ambient summer temperatures and adverse health outcomes. People in the Gulf Cooperation Council (GCC) countries—consisting of the Kingdom of Saudi Arabia, United Arab Emirates, Kingdom of Bahrain, State of Kuwait, Sultanate of Oman, and Qatar—are worried about the “survivability for a fit human threshold (SFHT)” temperature in the coming decades, particularly at the end of the twenty-first century. The

SFHT is the highest temperature that is tolerable for a healthy human under well-ventilated outdoor conditions (Im et al. 2017). People who live in the GCC states have a sound scientific reason to worry, because the Intergovernmental Panel on Climate Change (IPCC), in its Fifth Assessment Report (AR5), provided a clear indication of increasing global temperature (IPCC 2013) that also projects a steady increase in local temperature over this region. The temperature threshold varies from place to place and from season to season, because of the variability of relative humidity as well as prevailing wind speed and direction. In the current climate (1976–2015), the wet-bulb temperature (which accounts for the effect of both environmental heat and moisture) rarely exceeds 31 °C for a relative humidity of 63% over the Arabian Peninsula (Im et al. 2017; Dee et al. 2011). In the future, there are likely to be many locations over the Arabian Peninsula where the temperature may exceed the SFHT limit (Lelieveld et al. 2016). Therefore, it makes sense to investigate the SFHT at

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Fig. 1 Arabian Peninsula domain with surface elevation and station locations in ten GCC cities. The green dots indicate the location of six capital cities in the Arabian Gulf states and four societal important cities in Saudi Arabia including Makkah and Madinah

major cities in the GCC states to improve the practical utility of CMIP5 scenarios.

The highest extreme temperature ever reported on the earth is about 60 °C, which is substantially higher than the tolerance level (40 °C) above which the human body tends to fall victim to heat stroke (El-Fadli et al. 2013; Parsons 2006; Glazer 2005). If temperatures were to reach such an extreme level (60 °C), it would not only put the human body in danger but also risk the malfunction of machinery that has been designed for the current climate, such as airplane engines, landing gear, and evaporative cooling systems. The maximum temperature in some interior areas and coastal regions of the Arabian Peninsula has already exceeded 50 °C; a typical example is the recorded 52 °C temperature in Jeddah on 22 June 2010 (Almazroui et al. 2014). Recently, Kuwait Meteorological Department recorded a peak temperature of 54 °C at Mitribah on 21 July 2016. This provides supporting evidence for recent studies that highlighted the possibility of large-scale warming over different parts of the Arabian Peninsula in the absence of strong mitigation measures, i.e., the possibility of over 60 °C in Kuwait, eastern Saudi Arabia, and the United Arab Emirates (Lelieveld et al. 2016; Pal and Eltahir 2016). For such extreme situations, the following question arises: how plausible is it that the maximum temperature over the GCC states will reach 60 °C by the end of the twenty-first century? If this is genuinely likely, major adaptation and mitigation measures are required to adapt to such high temperature. Another important question is “how reliable are the

climate projections for this region?”. To address these questions, an analysis of high-resolution and multimodel datasets is required along with present climate observations. Consequently, reasonable estimates of maximum temperatures and related uncertainties are necessary over the GCC states, so that this climate change information can be disseminated to the stakeholders and decision-makers for their long-term planning. In this research, we discuss the past and projected future summer maximum temperatures in the capital city of each GCC state in the Arabian Gulf, along with the two holy cities of Makkah and Madinah as well as Jeddah and Dhahran in the Kingdom of Saudi Arabia, due to their high societal relevance.

Several global climate models (GCMs) and climate system models (CSMs) contributed to the generation of CMIP5 multimodel climate scenarios (Knutson and Ploshay 2016; Meehl et al. 2012; Giorgetta et al. 2013). The horizontal resolutions of GCMs and CSMs are typically quite coarse (Im et al. 2017). The concept and practice of dynamically downscaling GCMs and CSMs using a Regional Climate Model (RCM) are well established for the detailed understanding of climate in a region (Almazroui et al. 2017a, b). In general, downscaled scenarios provide better and more detailed information about the climatic variables (Almazroui et al. 2016a, b). Keeping in mind the importance of climate extremes, the downscaled daily temperatures are also used in the calculation of summer season maximum temperature extremes,

Fig. 2 Observed (a) annual and (b) summer maximum temperature in the capital cities of each GCC country for the period 1978–2019

such as warm/cold days for the GCC states in both present and future climates.

Thus, this study aims to downscale the CMIP5 database using RCM over the GCC states and then use the high-resolution information to analyze the maximum temperature and SFHT limits for the present as well as future climate during boreal summer. We then investigate the possible increase of average summer maximum temperature to 60 °C

over different cities of GCC states, and breaches of SFHT limits, in the future climate under the two Representative Concentration Pathways (RCPs), namely RCP4.5 (a mitigation scenario; Thomson et al. 2011) and RCP8.5 (a business-as-usual scenario; Riahi et al. 2011).

Methodology

In this study, the summer maximum temperature is defined as the average of the monthly maximum temperature for the months from June through August (JJA). Ground-truth values are provided by observational temperatures at stations located throughout the Arabian Gulf states. For simplicity, the temperature at the capital city of each country in the Arabian Gulf states is considered (Fig. 1). In addition, four other important cities, including the holy cities of Makkah and Madinah in the Kingdom of Saudi Arabia, are considered, due to their high societal relevance and because Saudi Arabia covers about

Table 1 Average of annual and summer maximum temperatures trends (°C decade⁻¹) obtained from observed maximum temperature in each GCC capital city for the period 1978–2019. All trends are statistically significant at the 99% confidence level

Capital city	Annual	Summer
Riyadh	0.37	0.33
Abu Dhabi	0.50	0.62
Kuwait	0.49	0.63
Manama	0.52	0.75
Muscat	-0.17	-0.36
Doha	0.21	0.21

Fig. 3 The spatial distribution of model simulated summer maximum temperature over the Arabian Peninsula for (a) BATS ECHAM, (b) BATS GFDL, (c) BATS HadGEM, (d) CLM ECHAM, (e) CLM GFDL, and (f) CLM HadGEM, averaged over the period 1976–2005

80% of the Peninsula area (Almazroui et al., 2012a, b). Quality control of the daily maximum temperature and

management of missing data for the ten surface stations are performed following Almazroui et al. (2013) and corrected

Fig. 4 The spatial distribution of observed gridded CRU summer maximum temperature over the Arabian Peninsula for the period 1976–2005

where necessary using Global Telecommunication System (GTS)¹ information. The fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) re-analysis climate and weather data, called ERA5 (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>), is used to fill the observations gap over Kuwait city for the missing observations period from July 1990 to July 1991. The simulated data are from three GCMs (ECHAM, the Max-Planck-Institute Earth System Model called MPI-ESM-MR from Germany; GFDL, the Geophysical Fluid Dynamics Laboratory model called GFDL-ESM2M from USA; and HadGEM, the Met Office Hadley Centre Earth System Model called HadGEM2-ES from UK), downscaled to 25-km resolution by the RCM (RegCM4), using both the Biosphere-Atmosphere Transfer Scheme (BATS) and the Common Land Model (CLM) land surface schemes, for the present climate (1960–2005) and the future climate (2006–2099), under both RCP4.5 and RCP8.5 scenarios. The RegCM4 historical runs are completed for the CORDEX-MENA/Arab domain (7°S–45°N and 26°W–76°E) with ECHAM, GFDL, and HadGEM providing the input for both BATS and CLM surface schemes. In the case of RegCM4 projection runs for the same domain, RCP4.5 and RCP8.5 scenarios are taken into consideration in all three GCMs, along with the BATS and CLM surface schemes. In total there are 18 runs; six historical runs (three with BATS and three with CLM), six projection runs (two for ECHAM, two for GFDL, and two for HadGEM) under RCP4.5 and six projection runs (two for ECHAM, two for GFDL, and two for HadGEM) under RCP8.5. RegCM4 outputs are post-

processed at daily and monthly scales. Details of the downscaling of the GCM database using the RCM for the Arabian Peninsula can be found elsewhere (e.g., Almazroui 2011, 2016). The bias (model minus observation) at each station location is calculated for the present climate. The station-based bias for the current climate is then subtracted from the future scenarios for each model, and the average of this value over all models is referred to as the adjusted temperature. The maximum of maximum temperatures is the highest value of daily maximum temperature (extreme Tmax) at each station. The warming trends are calculated using a simple regression equation. The F-test (Almazroui et al. 2016c) is used to check the statistical significance of the warming trend. A normal quantile plot is used to see the statistical distribution of model simulations and adjusted temperatures. For the calculation of maximum temperature extremes, we used threshold-based and percentile-based extreme indices. The threshold-based hot day metric is calculated using daily maximum temperatures from ≥ 40 to ≥ 50 °C. The percentile-based indices are warm days (TX90p, maximum temperature > 90th percentile), very warm days (TX95p, maximum temperature > 95th percentile), extreme warm days (TX99p, maximum temperature > 99th percentile), and cold days (TX10p, maximum temperature < 10th percentile), following the procedure recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI, <http://iridl.ldeo.columbia.edu/SOURCES/.WCRP/.CLIVAR/.ETCCDI/>). Details of the ETCCDI used for the Arabian Peninsula can be seen in Almazroui et al. (2013), AlSarmi and Washington (2014), Donat et al. (2014), and Islam et al. (2015). This analysis considered only the summer season climate extremes for both present and future climates.

¹ https://www.wmo.int/pages/prog/www/TEM/GTS/index_en.html

Fig. 5 The evolution of model simulated (average from six simulations) summer maximum temperature (red curves and shading (spread)) and associated bias w.r.t. observation (dashed blue curves) in six capital cities in the GCC states and four major cities across Saudi Arabia during the period 1976–2005. The stations are (a) Riyadh, (b) Makkah, (c) Madinah, (d) Jeddah, (e) Dhahran, (f) Abu Dhabi, (g) Kuwait, (h) Manama, (i) Muscat, and (j) Doha. The primary vertical axis represents

Results and discussion

Observed maximum temperature climatology at each GCC capital city

The surface observations averaged over the period 1978–2019 for the six GCC capital cities show that maximum annual mean temperature is within the range of 30.95 °C (Manama) to 34.53 °C (Abu Dhabi), while the range is from 37.97 °C (Muscat) to 45.62 °C (Kuwait) for the summer season only (Fig. 2a, b). For both annual and summer timescales, the maximum temperature shows an increasing trend for all GCC capital cities except for Muscat, which shows a decreasing trend (Table 1). At the annual scale, the maximum temperature increasing trends for five capital cities are within the range of 0.21–0.52 °C decade⁻¹, while Manama shows the highest (0.52 °C decade⁻¹) and Doha shows the lowest (0.21 °C decade⁻¹). For the summer season, the increasing trends are within the range of 0.21–0.75 °C decade⁻¹, while Manama shows the highest at 0.75 °C decade⁻¹ and Doha shows the lowest at 0.21 °C decade⁻¹. The rate of decrease of maximum temperature is –0.17 (–0.36) °C decade⁻¹ at Muscat on the annual (summer) scale. All trends are statistically significant at the 99% confidence level. It is worth mentioning that the proximity of some GCC weather stations near the coast and topography may play an important role in controlling summer maximum temperature.

Simulated summer season maximum temperature climatology

The model-simulated summer maximum temperatures are generally high in the southeast part of the Arabian Peninsula that extends along the Arabian Gulf coast as far as Kuwait (Fig. 3a–f). Conversely, they are relatively low in the southwest hilly areas. RegCM4 with CLM simulates lower temperature over the central Peninsula than it does with BATS, except for the Red Sea coast. There is a large variation in the maximum temperature climatology (1976–2005), ranging from below 35 °C to as high as 55 °C in different parts of the Peninsula. Our concern is how reliable these simulations are, given that there are differences among the models and land surface schemes within RegCM4 and that the climate model simulations are not free from uncertainties. The overall pattern of simulated temperatures is similar to gridded

observations from the climatic research unit (CRU, <http://www.cru.uea.ac.uk>) data (Fig. 4), in particular for GFDL with BATS, although that simulation shows very high temperature in the southeast of the Peninsula. The CRU data shows that summer maximum temperatures are high in the eastern and northeast regions of the Peninsula, while low in the south, southwest, and northwest regions (Fig. 4). The observed maximum temperature ranges from 35 °C to 45 °C. Even though the gridded CRU data are based on a low density station network over the region, the RegCM simulations overestimate temperature for the southeast region, as reported by Almazroui et al. (2016a, b). The reliability of the model simulations in comparison with the meteorological surface observations has not been addressed in earlier studies (e.g., Pal and

Table 2 Observed and simulated model average maximum temperature over three GCC cities for the period 1978–2005. The three selected cities are Jeddah, Kuwait, and Manama showing nominal difference, overestimation, and underestimation, respectively

Year	Jeddah		Kuwait		Manama	
	Observation	Model	Observation	Model	Observation	Model
1978	37.7	39.2	43.0	48.0	36.6	31.2
1979	37.9	37.9	43.4	47.8	37.7	30.8
1980	37.3	38.9	44.9	47.4	38.2	32.0
1981	37.8	38.9	45.3	47.1	38.4	31.2
1982	38.7	38.3	44.7	47.1	37.1	31.3
1983	38.4	38.1	44.9	46.9	36.9	29.9
1984	37.4	38.7	44.2	47.2	36.0	30.6
1985	37.9	39.1	45.1	47.9	37.2	30.9
1986	38.5	39.0	45.1	47.0	38.2	31.3
1987	38.6	38.3	45.4	47.5	38.6	32.1
1988	39.2	38.9	45.0	47.8	38.2	31.5
1989	37.9	38.6	45.9	46.6	38.1	31.6
1990	37.8	39.4	45.1	48.2	38.4	31.4
1991	37.2	38.2	45.0	46.5	36.6	31.8
1992	37.9	38.2	44.1	46.7	38.0	30.9
1993	37.9	39.0	45.5	47.2	38.1	31.2
1994	38.8	38.4	44.9	47.7	37.5	31.2
1995	39.1	38.3	45.3	48.4	38.0	31.4
1996	38.1	38.9	46.1	47.5	39.2	31.3
1997	39.6	38.6	45.2	47.6	38.4	31.7
1998	39.4	38.9	47.1	47.7	40.2	31.8
1999	38.8	39.1	46.3	48.1	40.0	31.7
2000	38.8	39.5	46.7	47.7	40.1	31.7
2001	39.6	38.7	45.8	47.8	39.3	31.8
2002	39.4	39.6	46.1	48.5	39.9	31.8
2003	39.6	39.0	46.0	48.0	39.6	32.0
2004	38.6	39.2	46.0	48.1	39.8	32.4
2005	39.4	39.5	46.3	47.0	39.4	32.7

Fig. 6 The spatial distribution of model simulated summer maximum temperature over the Arabian Peninsula under RCP4.5 for (a) BATS ECHAM, (b) BATS GFDL, (c) BATS HadGEM, (d) CLM ECHAM, (e) CLM GFDL, and (f) CLM HadGEM, averaged over the period 2070–2099

Fig. 7 The spatial distribution of model simulated summer maximum temperature over the Arabian Peninsula under RCP8.5 for (a) BATS ECHAM, (b) BATS GFDL, (c) BATS HadGEM, (d) CLM ECHAM, (e) CLM GFDL, and (f) CLM HadGEM, averaged over the period 2070–2099

Fig. 8 Normal quantile plot using mean and standard deviation for model simulated (closed triangles and circles, averaged from six simulations) summer maximum temperature with adjusted (open triangles and circles, model minus bias) at six capital cities of GCC states and four major cities over Saudi Arabia under RCP4.5 (green) and RCP8.5 (red) scenarios for the projection period 2006–2099. The stations are (a)

Eltahir 2016). Therefore, for better insight into the temperature over the GCC states, a number of meteorological surface

station locations are selected where both simulated and observed data are compared, as shown in Fig. 5. The model simulation data are extracted at meteorological surface station locations following Islam (2009) and Islam and Uyeda (2007). In this procedure, the nearest grid point value within 25 km from the surface station location is used to provide the simulated data for a particular station. For a detailed understanding of the difference between model simulations and surface observations, summer maximum temperature for three stations

Fig. 9 Frequency (days year⁻¹) and trend (days decade⁻¹) of hot days above a maximum temperature threshold at six GCC capital cities obtained from the surface observations

Fig. 10 Warm days (TX90p), very warm days (TX95p), extreme warm days (TX99p), and cold days (TX10p) obtained from surface observations at GCC capital cities for the present climate 1978–2019

obtained from both model and observations is presented in Table 2. Jeddah is representative of those stations where model simulations have only a nominal difference from observations in most years; both data and observations are very similar. The Kuwait station is representative of those where model overestimated the observed temperatures every year, while the Manama station is one where model underestimated the recorded temperatures every year (Table 2).

As shown in Fig. 5, the model simulations of temperature for Riyadh, Kuwait, Abu Dhabi, Muscat, and Doha show warm bias (overestimation) among the six capital cities of the GCC states, while at Manama the simulations shows cold bias (underestimation). Among the other four important cities of Saudi Arabia, only a nominal bias is found for Makkah, Madinah, and Jeddah, while there is a large positive bias for Dhahran. The temperature bias exceeds 10 °C for Muscat and Dhahran, while it surpasses 7 °C for Kuwait and Doha in some years. This indicates that the model simulations have both warm and cold biases that are location dependent. At some stations, the simulated values are too large while other

locations they are too small. The over- and underestimation of model output still need more investigation. The model-

Table 3 Warm days and cold days trends (days decade⁻¹) obtained from observed and simulated summer maximum temperature in each GCC capital city for the current period 1978–2019. The bold font indicates significant trends at the 90% level, while the asterisk sign (*) indicates significant trends at the 95% level and double asterisk sign indicates significant trends at the 99% level.

	Warm days (TX90p)		Cold days (TX10p)	
	Observation	Model	Observation	Model
Riyadh	2.21	7.99**	−3.22**	−2.64**
Abu Dhabi	3.46**	8.47**	−3.90**	−2.07**
Kuwait	4.37**	8.47**	−4.83**	−2.80**
Manama	4.54**	5.71**	−6.25**	−3.52*
Muscat	−0.94	5.14**	2.22**	−1.67*
Doha	1.58*	7.59**	−1.62**	−2.50**

simulated data for the historical period 1978–2005 indicates that the trend follows the observations for all cities except for Muscat, which shows negative trend. Since the biases (especially the larger ones) appear to be systematic rather than random, we have to consider each location individually. Uncertainty in the simulations is larger for some cities than for others, which can be seen from the range among the models (Fig. 5). Therefore, some temperature adjustment is required based on the location-specific biases. This is a very important and urgent matter for application-oriented projects in the region.

Summer maximum temperature projection

Model projections indicate that the average summer maximum temperatures over the last three decades of the twenty-first century will be much higher than the present climate and in particular will be very high in the eastern areas of the Peninsula (Figs. 6a–f and 7). The average summer maximum temperature could exceed 60 °C in some quarters within the

Peninsula under RCP8.5 (Fig. 7). Similarly, by the end of the twenty-first century, the average summer maximum temperature could exceed 55 °C in the Arabian Gulf coast regions. As mentioned above, the model-simulated temperatures show large biases, both positive and negative, as compared with the observations for the present climate. Therefore, we suspect that these biases also persist in the projected temperature. We understand that the bias in the future climate may not necessarily follow the same pattern as it does in the present climate. However, to understand the likelihood of real temperature rise in the far future period of 2070–2099, the simulated temperature in the six capital cities of the GCC states and four major cities in Saudi Arabia are shown along with the adjusted temperature (model minus base period bias), in Fig. 8. In some cities (e.g., Dhahran, Kuwait, Abu Dhabi, Muscat, Doha), the adjusted projected temperature is much lower than the model simulations, while for Makkah, Madinah, and Jeddah, the adjustments to the simulated temperature are much smaller. The adjusted projected temperature over Manama is much higher than those obtained from model simulations. There is a clear

Fig. 11 Warm days (TX90p) and cold days (TX10p) obtained from RegCM4 simulations under RCP8.5 at GCC capital cities in the present and future climates. The green shade indicates the present climate

Fig. 12 The evolution of the changes in adjusted (model minus bias) average summer maximum temperature (green lines) with uncertainties (blue lines for lower limit and red lines for upper limit) at six capital cities of GCC states and four major cities in Saudi Arabia under RCP4.5 (dashed lines) and RCP8.5 (solid lines) scenarios for the projection period 2006–2099. The stations are (a) Riyadh, (b) Makkah, (c) Madinah, (d) Jeddah, (e) Dhahran, (f) Abu Dhabi, (g) Kuwait, (h) Manama, (i) Muscat, and (j)

indication that the model seems to overestimate temperature by about 8–10 °C for Dhahran, Abu Dhabi, Muscat, and Kuwait. Similarly, underestimation for Manama is about 7–8 °C. Figure 8 also shows that both model and adjusted data do not come perfectly from a standard normal distribution because some of them do not fall neatly along a straight line. For lower values of average summer maximum temperatures, model simulations are in line with adjusted temperature. However, for higher values, i.e., at the end of the twenty-first century, there is a big difference between the simulated and adjusted temperatures.

Considering the dry-bulb temperature SFHT of 42 °C over the region, the adjusted projected temperature will exceed the SFHT limit for all cities except Manama under RCP4.5 (Fig. 8). In the case of the RCP8.5 scenario, the average summer maximum temperature will cross the SFHT limit in all cities. Figure 8 also indicates that the adjusted average summer maximum temperature will not reach 50 °C by the end of the twenty-first century except for Dhahran, Makkah, and Riyadh, which is projected at 51 °C. However, daily extremes may have different characteristics, as discussed in “Changes in summer maximum temperature in the twenty-first century” section.

Table 4 Adjusted average summer maximum temperature increase rate (°C decade⁻¹) in each GCC city for the lower, higher, and ensemble mean under RCP4.5 and RCP8.5 for the future period 2020–2099. The asterisk sign (*) indicates significant trends at the 95% level and double asterisk sign indicates significant trends at the 99% level

City	RCP4.5			RCP8.5		
	Lower	Higher	Ensemble	Lower	Higher	Ensemble
Riyadh	0.17**	0.31**	0.23**	0.52**	0.69**	0.66**
Makkah	0.20**	0.26**	0.27**	0.36**	0.70**	0.63**
Madinah	0.17**	0.22**	0.19**	0.27**	0.61**	0.52**
Jeddah	0.21**	0.30**	0.22**	0.42**	0.61**	0.53**
Dhahran	0.11	0.28**	0.20**	0.37**	0.78**	0.62**
Abu Dhabi	0.17**	0.35**	0.22**	0.48**	0.75**	0.63**
Kuwait	0.09	0.30**	0.20**	0.36**	0.77**	0.60**
Manama	0.17	0.13	0.16	0.45**	0.51**	0.49**
Muscat	0.10*	0.35**	0.19**	0.46**	0.71**	0.58**
Doha	0.13*	0.28**	0.20**	0.30**	0.75**	0.58**

Warm extremes in the present and future period

Threshold-based hot days' frequency is high in Kuwait, Abu Dhabi, and Riyadh while low in Manama and Muscat (Fig. 9). The number of annual hot days with maximum temperature ≥ 40 °C is observed to be 138 days for Kuwait, 128 days for Riyadh, and 107 days for Abu Dhabi, while it is only 53 for Muscat and 33 for Manama. Hence it is clear that cities located in the northern Arabian Peninsula are hotter than the cities in the Southern Peninsula. This result supports the CMIP5 and CMIP6 simulations, which show the Northern Peninsula warming faster than the Southern Peninsula (Almazroui et al. 2017b). The number of hot days with maximum temperature ≥ 45 °C is almost the same for both annual and summer timescales, because the annual count of hot days comes mostly from summer months. The number of hot days shows an increasing trend for all GCC capitals except for Muscat, which has a decreasing trend (negative scale not shown). A large increase in the number of hot days is observed in Kuwait (12-day decade⁻¹ on the annual and 10-day decade⁻¹ on the summer timescales).

Percentile-based warm/cold days obtained from surface observations in six capital cities indicate that the local climate is warming in the GCC region (Fig. 10). All the GCC capital cities show more warm days (TX90p, TX95p, and TX99p) and fewer cold days (TX10p) except for Muscat, which shows insignificantly fewer warm days and significantly more cold days (Table 3). The discrepancy for Muscat may be due to the location of the data collection at the station or for some other reasons that need further investigation. Muscat is located at the coast of the Gulf of Oman, and its maximum temperature has a decreasing trend (see Fig. 2). Because the maximum temperature of Muscat has a decreasing trend, the temperature indices there show the opposite trends compared with other GCC capital cities where maximum temperatures are increasing. RegCM4 simulations show that for the entire analysis period from the present time (1978) to the end of the projection time (2099) under RCP8.5, the number of warm days increases and number of cold days decreases for all the GCC capital cities (Fig. 11). All GCC capital cities show increasing trend for warm days, except Manama shows very strong variability. The warm days trends are statistically significant at the 99% confidence level for Muscat and Doha, 95% for Makkah and Madinah, and 90% for Riyadh and Abu Dhabi. Manama shows inaccurate trend due to station location as Bahrain is an island surrounded by water body, which needs further investigation. The trends in warm and cold days for the current period 1978–2019 indicate that projected trends are reliable (Table 3). Overall, the increase rate of model simulated warm days is higher than the same obtained from the observations. Among the GCC capital cities, observations show that warm days are increasing at a faster rate over Kuwait and Manama which is supported by the faster decreasing of cold

Fig. 13 The evolution of the projected maximum of summer maximum temperature (Extreme Tmax in °C) with uncertainties (shaded) at six capital cities of GCC states and four major cities in Saudi Arabia under RCP4.5 (blue line) and RCP8.5 (red line) scenarios for the projection period 2006–2099 (solid line is the average from all datasets, black represents the running period, and red/blue represents the future period). The stations are (a) Riyadh, (b) Makkah, (c) Madinah, (d) Jeddah, (e) Dhahran, (f) Abu Dhabi, (g) Kuwait, (h) Manama, (i) Muscat, and (j)

days. Riyadh and Abu Dhabi show medium increase (decrease) rate of warm (cold) days, while Doha is the slowest one. Irrespective of magnitude, the sign of trends are the same for all GCC capital cities except for Muscat.

Changes in summer maximum temperature in the twenty-first century

The changes in adjusted average summer maximum temperature in the capital cities of the GCC states and some important cities in Saudi Arabia show an upward surge under RCP8.5 as compared with RCP4.5 (Fig. 12). Over most of the cities, the increase in adjusted average summer maximum temperature is projected to be about 5 °C at the end of the twenty-first century and could exceed 12 °C at the upper end under RCP8.5 but might be as low as 2 °C at the lower end under RCP4.5. The lowest rise is expected for Abu Dhabi (about 9 °C) while the highest rise is projected for Dhahran (possibly ~15 °C). The rate of increase of adjusted ensemble average summer maximum temperature under RCP8.5 for the future period of 2020–2099 is above 0.6 °C decade⁻¹ at Riyadh, Makkah, Dhahran, Abu Dhabi, and Kuwait, while for RCP4.5 it is above 0.2 °C decade⁻¹ at Riyadh, Makkah, Jeddah, Dhahran, Abu Dhabi, Kuwait, and Doha (Table 4). The statistically significant rate of increase of adjusted summer maximum temperature is within the range of 0.49 (Manama) to 0.66 (Riyadh) °C decade⁻¹ under RCP8.5, while it is within the range of 0.16 (Manama) to 0.27 (Makkah) °C decade⁻¹ under RCP4.5. Hence, it is clear that the increase in adjusted temperature over the capital cities of the GCC states varies from place to place, and estimates for one place cannot be applied to other places, especially for application-oriented purposes.

Maximum of daily maximum temperature in the twenty-first century

The maximum of daily maximum temperature (extreme Tmax) in a year is obtained from the highest temperature in a day over the year. This may exceed the SFHT limit of 42 °C for all the cities, except for Manama, under both RCP4.5 and RCP8.5 scenarios (Fig. 13). The extreme Tmax values exceed 50 °C for all the cities except for Manama and Jeddah for the period 2006–2099. Note that the spread shows the extreme

Tmax from three different driving GCMs and two different surface parameterization schemes. The lowest and the highest values of the extreme Tmax from these three by two matrices delimit the range of uncertainty. The lines represent the average from all six extreme Tmax values in a year. At the end of the twenty-first century, the extreme Tmax could approach and exceed 55 °C in Riyadh, Makkah, Madinah, Kuwait, Muscat, and Doha, while it could reach 60 °C under RCP8.5 in Kuwait, Abu Dhabi, and Muscat. Among all the cities, extreme Tmax is highest for Dhahran, which exhibits values over 60 °C under both scenarios for the entire projected period starting from 2006. Overall, extreme Tmax results are in line with the findings of Pal and Eltahir (2016), who reported that without bias adjustment the extreme Tmax could exceed 60 °C at some places in the Peninsula. However, from Fig. 13, we can argue that extreme Tmax values exceeding 60 °C for the verifiable period (2006 – 2019) in Dhahran and even values exceeding 55 °C at Makkah, Abu Dhabi, Muscat, and Kuwait are not observed, which is different from the conclusion drawn from the abovementioned earlier studies. This disparity warrants further investigation by utilizing data from other driving GCMs and downscaling by using different RCMs, to reduce the uncertainty and enhance the reliability of summer maximum temperature projections over the region. To achieve this, regional coordination among the GCC states is needed to improve the quality of observations, and to develop the tools that make climate change research more useful and reliable for stakeholders and policymakers.

Conclusions

The present study investigates the Survivability for a Fit Human Threshold (SFHT) maximum temperature during the summer (June–August) over the six Middle Eastern countries known as the Gulf Cooperation Council (GCC) in the twenty-first century. An ensemble of three dynamically downscaled global climate models (ECHAM, GFDL, and HadGEM) available from the Coupled Model Intercomparison Project Phase 5 (CMIP5) under the mitigation (RCP4.5) and business-as-usual (RCP8.5) scenarios are used to analyze the future climate (2006–2099) over the region. Future temperature projections are adjusted by removing the bias estimated over the base period for six capital cities in the GCC states and four major cities of Saudi Arabia. The adjusted temperature is required for application-oriented tasks because model simulations of present climate show overestimation for some cities and underestimation for others. Based on these calculations, the adjusted average summer maximum temperature does not exceed 52 °C at the end of the twenty-first century over any capital cities in the GCC states and the four major cities in Saudi Arabia.

However, the maximum of daily maximum temperature could exceed 50 °C for all the cities, except Manama and Jeddah. Moreover, the maximum of daily maximum temperature could reach 60 °C for Abu Dhabi, Kuwait, and Muscat, while it could exceed 60 °C for Dhahran at the end of the twenty-first century. However, as it can be seen in Fig. 13, the maximum of daily maximum temperature at Dhahran is above 60 °C from the beginning of the projection period (2006), which is not observed during the available observational period up to 2019. Moreover, the simulated maximum of daily maximum temperature is almost 55 °C at Makkah, Abu Dhabi, Kuwait, and Muscat for the period 2006–2019, which also are not observed. Therefore, these projections are likely to prove unrealistic because of large biases in the projections for the recent verifiable period of 2006–2019.

For the recent verifiable period of 2006–2019, the model simulations capture the warm/cold day metrics as obtained from observations quite well. The adjusted summer maximum temperature will likely cross the SFHT temperature limit of 42 °C at all capital cities of the GCC states and the four major cities in Saudi Arabia by the end of the twenty-first century. This indicates that climate change has to be considered in the long-term planning of the region, since exceeding the SFHT limit will most likely cause human health-related casualties.

However, further investigations into the daily temperature are required by utilizing projection data from other GCMs and downscale by using RCMs. This can be initiated through regional coordinated research program among the GCC states, which will be complied with carrying out comprehensive and integrated climate change research that not only contributes to our fundamental understanding of climate change but also informs stakeholders and policymakers, to a high degree of confidence, about likely future climate changes in the region.

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