Research Article

Temperature Changes over the CORDEX-MENA Domain in the 21st Century Using CMIP5 Data Downscaled with RegCM4: A Focus on the Arabian Peninsula

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This paper examined the temperature changes from the COordinated Regional climate Downscaling Experiment (CORDEX) over the Middle East and North Africa (MENA) domain called CORDEX-MENA. The focus is on the Arabian Peninsula in the 21st century, using data from three Coupled Model Intercomparison Project Phase 5 (CMIP5) models downscaled by RegCM4, a regional climate model. The analysis includes surface observations along with RegCM4 simulations and changes in threshold based on extreme temperature at the end of the 21st century relative to the base period (1971–2000). Irrespective of the driving CMIP5 models, the RegCM4 simulations show enhanced future temperature changes for RCP8.5 as compared to RCP4.5. The Arabian Peninsula will warm at a faster rate (0.83°C per decade) as compared to the entire domain (0.79°C per decade) for RCP8.5 during the period 2071–2100. Moreover, the number of hot days ($T_{\max} \geq 50^{\circ}\text{C}$) (cold nights: $T_{\min} \leq 5^{\circ}\text{C}$) will increase (decrease) faster in the Arabian Peninsula as compared to the entire domain. This increase (decrease) of hot days (cold nights) will be more prominent in the far future (2071–2100) as compared to the near future (2021–2050) period. Moreover, the future changes in temperature over the main cities in Saudi Arabia are also projected. The RegCM4-based temperature simulation data from two suitable CMIP5 models are recommended as a useful database for further climate-change-related studies.

1. Introduction

In the present era of climate change, a proper assessment of vulnerable sectors is important in developing strategies for the adaptation and long-term planning by national policy-makers and other stakeholders. In this regard, an accurate climate database is one of the main prerequisites for climate change impacts studies, which remain scarce in the Arab region, particularly in the Arabian Peninsula. The climate of the Arab region is generally governed by the synoptic-scale forcing (e.g., sea surface temperature, moisture, and wind) coming from the Indian and Atlantic oceans, while the Indian Ocean, the Mediterranean Sea, and Sudan low (low pressure zone over East Africa) control the Arabian Peninsula's climate [1]. The regional climate projection for the Arabian Peninsula is a challenging task. For example,

frequent heavy rainfall events occurred in Saudi Arabia over the last decade and temperature often exceeded 50°C, and even reached 52°C in 2010 [2, 3]. Such events need to be predicted because heavy rainfall events cause flash floods and high temperatures can cause heat strokes. Local people, migrant populations, and the Pilgrims from all over the world, are all very vulnerable when exposed to these phenomena. In this connection, reliable climate projections, including increased utilization of climate model data, are essential for the region.

For the years 1956–2005, the Intergovernmental Panel on Climate Change (IPCC) has reported a global warming trend of 0.13°C/decade [4], and in the updated fifth assessment report (AR5), it was updated to 0.12°C/decade for the period 1951–2012 [5]. This global warming and associated climate change undoubtedly has long-term

consequences for many socioeconomic sectors, such as water consumption, power generation, human health, biodiversity, and ecosystems. These may be contributory factors to the formation of certain atmospheric pollutants associated with the rise in air temperature [6–8]. The rise of air temperature is likely to lead to an increase in air pollutants [9]. The IPCC also projected a possible increase in frequency and intensity of extreme temperatures over the Arabian Peninsula [4]. In the coming decades, climate change could have a significant impact on water supplies in many parts of the globe and particularly in the semiarid/arid regions. Therefore, these impacts might be more severe for the Arabian Peninsula, and in particular, for Saudi Arabia, which contains the world's largest continuous sand desert, the Rub Al-Khali [2, 3, 10].

In the temperature climatology of Saudi Arabia, the northern side is colder than the southern side [11]. In the extreme north, the temperature ranges from 8.57°C to 28.32°C through the different seasons, while it ranges from 26.68°C to 33.97°C in the southern regions. The ocean does not contribute to the rapid increase of temperature in the Arabian Peninsula as the ocean temperature increases more slowly than land temperature in the peninsula [12]. Changes in the climate, and particularly changes in temperature, increase the risk of extreme events such as heat and cold waves, in addition to more frequent droughts and probable drought intensification [13]. The trends of annual and seasonal extreme indices over Saudi Arabia over recent decades were studied by [14], who reported a warming trend over the region. Moreover, climate change is likely to be the most dangerous threat to regional biodiversity [15]. Moreover, the Arab region, and particularly the Arabian Peninsula, is one of the most vulnerable areas to the potential threats listed under the dry-land ecosystems [16].

Model-generated climatic information for both near and more distant future periods is required to assist with long-term planning. In this connection, a global climate model (GCM) is the only tool that can generate future climate [17]. The IPCC AR5 report used the Coupled Model Intercomparison Project Phase 5 (CMIP5) multimodel database developed under the World Climate Research Program. Downscaling is usually used to transform the GCM outputs into a more suitable form [18]. Dynamical downscaling is based on physical models which are in fact the regional climate models (RCMs). Statistical downscaling is another procedure based on empirical nature where downscaled projections remain constant over time [19]. It is used to project the climatic variables used by many researchers (e.g., [18, 20, 21]). There are advantages and disadvantages in both dynamical and statistical downscaling procedures. The statistical downscaling is cheaper and consumes less computing resources [18]. Because our aim is to understand the climate variability, the use of dynamical downscaling is preferred for this analysis where physical parameterization can be selected for optimized results. The CMIP5 GCMs are generally coarse resolution (100–300 km) models and are not suitable for generating detailed climatic conditions over a specific region [22]. GCMs cannot simulate the detailed structure of regional climatic phenomena because they have

no topographic information at finer scales. To overcome this problem, RCMs are considered to be the best tools for downscaling GCM-generated climatic features, to obtain more detailed climate information over a particular region [23, 24]. RCMs are also invaluable over areas where observations are either scarce or absent, as over the Arab region. The RCMs outperform the driving global climate models and provide added value to simulate the climate of a region [25]. Thus, dynamic downscaling of GCM simulations has been a widely used and acceptable strategy [26, 27]. In other words, an RCM can be used to generate future climate simulations as well as to help understand the past climate in a particular region. Thus, the climate variables generated by a suitable RCM can be used in extreme analysis in the Arab region, focusing on the Arabian Peninsula (particularly Saudi Arabia), for the projection period. Therefore, this paper aimed to investigate the changes in temperature over the CORDEX-MENA domain (27°W–76°E and 7°S–45°N) with a focus on the Arabian Peninsula during the 21st century, by using data from three GCMs from CMIP5 project downscaled with an RCM, namely, regional climate model system updated in 2010 (RegCM4).

The CORDEX-MENA domain is defined using sensitivity tests from seven related domains. Details of the domain selection along with the reason for selecting this new domain within the CORDEX framework are provided in [28]. The analysis is mainly focused over Saudi Arabia (about 80% area of the Arabian Peninsula) which is a region with scarce climate change studies. In order to understand the possible changes in temperature, the corrected temperature is projected into the future. This paper also aims to investigate extreme temperatures using thresholds for warm and cold days from regional to local scales and validate with ground stations across Saudi Arabia.

2. Data and Methodology

2.1. Model Description. The regional climate model (RegCM) is a limited-area model developed by the Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, for the purpose of long-term climate simulation. This model is used by a large community of researchers to study regional climate, including over the CORDEX-MENA domain (e.g., [17, 29]). Details about RegCM version 4.3.4 (RegCM4) are available in [30]. RegCM4 uses the dynamical core from [31] and the radiation scheme from [32, 33]. The BATS (biosphere and atmosphere transfer scheme) from [34, 35] and the CLM (community land model) from [36] are also used. The PBL (planetary boundary layer) and ocean fluxes are from [37, 38], respectively.

Multiple cumulus convection schemes are available within RegCM4. Among them, the schemes in [39, 40] and Arakawa–Schubert schemes are assimilated into the more general Grell convection parameterization scheme. The combination of Grell and Emanuel [28], or either of them uniquely, can be used for land and ocean masking. In the present study, the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA-Interim,

hereafter refereed as ERA-Int) $0.75^\circ \times 0.75^\circ$ gridded 6-hourly data (<http://www.ecmwf.int/products/data/archive>) are used to provide initial conditions for three CMIP5 model simulations of both past and future climate. RegCM4 is forced by ERSST, the extended reconstructed sea surface temperature data. The Coordinated Regional climate Downscaling Experiment (CORDEX) recommended use of RegCM4 at 50 km resolution, as used in this study, though it may also be used at higher resolutions [28].

2.2. Experimental Setup. Three CMIP5 models, namely, the HadGEM2 (the UK Met Office Hadley Centre Global Environment Model version 2, $1.2^\circ \times 1.8^\circ$ [41]); CanESM (the Canadian Earth System Model of the Canadian Centre for Climate Modeling and Analysis (CCCma), $2.8^\circ \times 2.8^\circ$ [42]; and ECHAM6 (Atmospheric GCM of Max Planck Institute for Meteorology, Germany, $1.8^\circ \times 1.8^\circ$ [43]), are used for the past climate study. In addition, two representative concentration pathways (RCPs), i.e., RCP4.5 and RCP8.5 are used for the future climate projections. The use of HadGEM2, CanESM, and ECHAM6 is based on [28]. An additional simulation of past climate has also been carried out using ERA-Int reanalysis as the input in RegCM4. As mentioned above, the RCM domain extending from 7°S to 45°N and 27°W to 76°E encompasses the Arab region and is adopted from [28]. This domain is sufficiently large for RCM simulations and is known as the CORDEX-MENA domain (see [28]). This domain was obtained from seven sensitivity experiments, and it fits well with the CORDEX Arab domain. Results of the sensitivity experiments (not shown here) indicate a better performance of the land surface scheme BATS (not CLM) for the analysis domain [28]. This study follows the recommendation in [29] to use the Grell convection scheme over land and the Emanuel scheme over the ocean within the analysis domain.

Prior to starting the long run of the historical and future climates, a number of sensitivity experiments (spanning 2000–2005) were completed with different convective parameterization schemes, domains, and land surface schemes in order to select the best domain, the most suitable convection scheme, and the best land surface scheme (see [17, 28, 29]). Later on, a total of 10 simulations were performed using the optimal settings of RegCM4.6 model, as listed in Table 1. All simulations for this study using RegCM4.6 were performed at 50 km resolution in a single domain without further nesting.

2.3. Analysis Procedures. The interannual variability of simulated air temperature (2 m) for the entire domain and a subdomain over the Arabian Peninsula was compared with observations of the past climate (1971–2000) from the Climatic Research Unit (CRU) dataset [44]. Simulated temperature biases (model minus observation) were also calculated with the CRU data. The CRU gridded dataset has a spatial resolution of 0.5° , the same as the RegCM4 runs. Changes in temperature were generated for two future periods, the near future (2021–2050) and the far future (2071–2100), relative to the base period. The RegCM4-

simulated temperature data were extracted for 11 subdomains within the entire domain (Figure 1), as well as for the 27 meteorological station locations across Saudi Arabia. The ground-truth station data were collected from the General Authority of Meteorology and Environmental Protection (GAMEP). The data extraction near the grid point of each meteorological station was done as in [45, 46]. In this procedure, the station data are interpolated from the nearest points of a grid to where the station is located.

Details of how the 11 subdomains adopted in this study were selected are available in [28, 29], and the characteristics of the 27 meteorological stations may be found in [2, 3]. The extracted data are processed on daily, monthly, and annual time scales and objectively compared with the observed/gridded datasets over the same temporal scale. Regression coefficients are obtained for temperature (mean, maximum, and minimum) of both observed and RegCM4 datasets. The relative temperature is calculated as each time series minus the 1971–2000 average of each source. As in [28], the better land-surface option within RegCM4 is selected for each subdomain and for the entire domain. For this purpose, statistical measures such as mean, bias, correlation (r), root mean square difference (RMSD), and standard deviation (Std) against CRU values are used.

Daily data are used to analyze extreme temperatures such as hot days and cold nights with a certain threshold temperature. In this analysis, hot days and cold nights are defined as those with maximum temperature greater than or equal to 50°C ($T_{\max} \geq 50^\circ\text{C}$) and minimum temperature less than or equal to 5°C ($T_{\min} \leq 5^\circ\text{C}$), respectively. The change in hot days and cold nights was calculated as the number of days/nights in a projected year minus the average number of days/nights over the base period. As given in [12], simple regression methods were employed for trend analysis, while trend significance was assessed using the F -test. The projected temperature was obtained from six simulations (listed in Table 1) for the entire domain and each subdomain, for both near and far future periods, using RCP4.5 and RCP8.5 scenarios. Finally, the future changes in temperature were computed for both the near and far future periods with respect to the past climate. The corrected temperature was obtained by adding the base period (1971–2000) bias to the projected temperature, and the future climate anomaly was obtained by subtracting the average from each time series.

3. Results and Discussion

3.1. Past Climate Temperature. The mean air temperature (at 2 m) averaged over all subdomains (i.e., CORDEX) indicates that model-simulated values correspond well with the observations over the annual cycle (Figure 2(a)). However, there is a little underestimation by RegCM4-HadGEM2 (-1.17 to -2.62°C w.r.t. CRU) and RegCM4-ECHAM6 (-0.91 to -1.91°C w.r.t. CRU) as compared to the CRU and ERA-Int data, while there is very large overestimation by RegCM4-CanESM (6.95°C to 11.63°C w.r.t. CRU). Similar behavior in the mean temperature is also present in the individual subdomains, such as the subdomain over the Arabian Peninsula (Figure 2(b)). In this subdomain, ERA-Int also

TABLE 1: List of simulations performed in this study.

No.	Simulation name	Simulation period	Boundary conditions	RCPs
1	RegCM4-ERA-Int	1979–2015	ERA-Interim	–
2	RegCM4-HadGEM2	1960–2005	HadGEM2	hist
3	RegCM4-CanESM	1960–2005	CanESM	hist
4	RegCM4-ECHAM6	1960–2005	ECHAM6	hist
5	RegCM4-HadGEM2	2006–2100	HadGEM2	RCP4.5
6	RegCM4-CanESM	2006–2100	CanESM	RCP4.5
7	RegCM4-ECHAM6	2006–2100	ECHAM6	RCP4.5
8	RegCM4-HadGEM2	2006–2100	HadGEM2	RCP8.5
9	RegCM4-CanESM	2006–2100	CanESM	RCP8.5
10	RegCM4-ECHAM6	2006–2100	ECHAM6	RCP8.5

FIGURE 1: Analysis domain with 11 subdomains. The subdomain A is over the Arabian Peninsula which is focused in this analysis for detail study. The elevation (in meters) indicates the topography of the domain.

underestimates (-0.51 to -2.54°C) mean temperature compared to the CRU data. Note that CRU is the observed data gridded over the region while ERA-Int is the reanalysis data generated using the assimilation system. In the case of RegCM4-ECHAM6, the underestimation (-0.92 to -1.14°C) occurs mostly during the winter months, while for RegCM4-HadGEM2, the underestimation occurs all year round. For RegCM4-CanESM, the large overestimation is for all months during the year. During the summer months, the overestimation by RegCM4-CanESM can reach above 10°C (11.04°C to 11.90°C). The temperature annual cycle for both the CORDEX domain and the Arabian Peninsula subdomain shows underestimation (e.g., RegCM4-HadGEM2 and RegCM4-ECHAM6) by some models and overestimation (e.g. RegCM4-CanESM) by the other, relative to the temperature climatology. The temporal evolution of the relative temperature (i.e., each time series minus the 1971–2000 average of each source) for the entire domain and Arabian Peninsula subdomain (Figures 2(c) and 2(d)) indicates that there is an increase in temperature over time for all time series. The 10-year moving average indicates a clear trend in the relative temporal evolution. In this analysis, RegCM4-CanESM overestimated the temperature more than 10°C ; an overestimation of about 8°C was also reported by [28]. Because we use the same RegCM4 to downscale the CMIP5 models, the large overestimation in RegCM4-CanESM may be transformed from the global climate model. Therefore, RegCM4-CanESM was not considered further, and only

averages from RegCM4-HadGEM2 and RegCM4-ECHAM6 were used in the rest of the analysis.

Spatial distributions of mean temperature obtained from CRU and RegCM4-ERA-Int show similar patterns of annual, winter, and summer temperatures (Sup 1). At annual scale, the temperature in the latitudinal band from 5° – 25°N is slightly too high and is relatively higher to the south of 15°N during the winter season. The highest temperature is observed in the band from 15° – 35°N in the summer season.

Spatial distributions of simulated temperature bias for the two CMIP5 models downscaled using RegCM4 show that the RegCM4-HadGEM2 and RegCM4-ECHAM6 underestimate temperature relative to CRU observations at both annual and seasonal scales (Figure 3). Quantifying the temperature bias (model minus observation), the underestimation by RegCM4-HadGEM2 and RegCM4-ECHAM6 is about 2°C to 3°C for most of the domain at annual scale (Figures 3(a) and 3(b)). There is a dipole anomaly in the RegCM4-simulated temperature distribution over the Arabian Peninsula: the overestimation (underestimation) or positive (negative) bias over southeast (northwest) Arabian Peninsula for RegCM4-HadGEM2 and RegCM4-ECHAM6. This dipole anomaly in the distribution of temperature in two different areas is most obvious in the summer season (JJA; Figures 3(e) and 3(f)) as compared to the winter season (DJF) (Figures 3(c) and 3(d)).

In the summer months, warm bias exceeds 7°C over Yemen/Oman for the RegCM4 simulations, while studies [17, 29] report that it exceeds 8°C for the dry season months (JJAS). A similar large bias in the ERA-40 and ECHAM5 driving fields, compared to RegCM3 simulations of annual temperature over this region, particularly over the southwestern Arabian Peninsula, has also been reported by [25]. They concluded that RegCM usually simulates lower temperatures than the forcing data; i.e., RegCM3 reduced the warm bias that was seen in the HadGEM2- and ECHAM6-driven runs.

Over the entire domain, RegCM4-CanESM simulates higher temperatures than observed by CRU and ERA-Int, while RegCM4-HadGEM2 and RegCM4-ECHAM6 simulate slight lower temperatures (Figure 4). For the entire domain, RegCM4-HadGEM2 (RegCM4-ECHAM6) underestimates temperature by 1.93°C (1.36°C) (Figure 4(a)). A similar situation is also noticed for the Arabian Peninsula subdomain. In this subdomain, the temperature

FIGURE 2: Annual cycle average temperature for (a) CORDEX-MENA/Arab domain and (b) Arabian Peninsula subdomain for the present climate 1971–2005. Temporal evolution for the relative temperature (each time series minus the 1971–2000 average of each source) for (c) CORDEX-MENA/Arab domain and (d) Arabian Peninsula subdomain.

underestimations are 1.83°C and 4.43°C , by RegCM4-HadGEM2 and RegCM4-ECHAM6, respectively, with reference to the CRU data (Figure 4(b)). The bias may come from the RegCM4 itself for its parameterization or may be from the inherent to the CMIP5 modeling systems.

3.2. Projected Changes in Temperature. Before analyzing the changes in future temperature, the RegCM4-simulated temperatures for the near and far future periods are

compared for two scenarios and three CMIP5 models (Figure 5). The mean temperature for each CMIP5 model and two RCPs for the near and far future averaged over 11 subdomains of the entire domain, and the Arabian Peninsula subdomain, indicates that both RegCM4-HadGEM2 and RegCM4-ECHAM6 simulate nearly similar temperature (Figure 5). For RCP8.5, the average from RegCM4-HadGEM2 and RegCM4-ECHAM6 is 25.03°C (23.66°C) for the near future and 28.69°C (27.27°C) for the far future, over the entire domain (Arabian Peninsula

FIGURE 3: Spatial distribution of air temperature bias (in °C) with respect to CRU data for (a) annual RegCM4-HadGEM2, (b) annual RegCM4-ECHAM6, (c) winter RegCM4-HadGEM2, (d) winter RegCM4-ECHAM6, (e) summer RegCM4-HadGEM2, and (f) summer RegCM4-ECHAM6 averaged over the common period 1971–2000.

subdomain). In this case, the standard deviation is 0.55 (0.58) for the near future and 0.77 (0.90) for the far future over the entire domain (Arabian Peninsula subdomain). For RCP4.5, the projected temperature is 24.67°C (23.30°C) and 26.02°C (24.74°C) for the near and far future, respectively, over the entire domain (Arabian Peninsula subdomain). In this case, the standard deviation is

0.38 (0.38) for the near future and 0.36 (0.46) for the far future over the entire domain (Arabian Peninsula subdomain). This clearly indicates that the RCP8.5 simulates higher temperatures with larger standard deviations as compared to the RCP4.5, particularly in the far future. Note that the past temperature for the entire domain from CRU (ERA-Int) is 24.49°C (24.34°C) and is 22.56°C and

FIGURE 4: Box plots of RegCM4-simulated air temperature (in °C) for each model for the past climate averaged over (a) 11 subdomains for the CORDEX-MENA/Arab domain and (b) subdomain over the Arabian Peninsula. The temperature is averaged over the period 1980–2005.

23.13°C for the HadGEM2- and ECHAM6-driven runs, respectively (see Figure 4). Over the Arabian Peninsula subdomain, these values are 25.33°C (23.50°C) for CRU (ERA-Int) and 20.90°C and 22.39°C for HadGEM2- and ECHAM6-driven runs, respectively.

For the RCP4.5 scenario, future changes in the simulated mean temperature (averaged from RegCM4-HadGEM2 and RegCM4-ECHAM6) indicate a rise in the annual mean of around 2°C in the near future over the full domain, which will accelerate to 4°C over the Arabian Peninsula in the far future (Sup 2(a) and 2(b)). In the winter season, the projected change in temperature will reach about 3°C (4°C) for the near (far) future over the peninsula (Sup 2(c) and 2(d)). In the summer season, the rise in temperature will not exceed 2.5° (3.5°C) in the near (far) future over the Arabian Peninsula (Sup 2(e) and 2(f)). Hence, the average data show a larger increase in the winter season temperature compared to the summer season.

For the RCP8.5 scenario, future changes in the simulated mean temperature (averaged from RegCM4-HadGEM2 and RegCM4-ECHAM6) indicate a rise in the annual mean of around 2.5°C in the near future, which will accelerate to 6°C over the Arabian Peninsula in the far future (Sup 3(a) and 3(b)). For the same regions, the future change in temperature will reach about 4°C (7°C) for the near (far) future periods during the winter season (Sup 3(c) and 3(d)). In the summer season, the rise in temperature over the Arabian Peninsula will be within 7°C (Sup 3(e) and 3(f)). Average data show a larger increase in the winter season temperature compared to the summer season. These results support the statement that the environment is warming while cold extremes warm faster than warm extremes by about 30 to 40% globally averaged [47].

Future changes in mean temperature (averaged over all subdomains) indicate that it will be above the 1971–2100

average from the beginning of the 2040s, for both RCP4.5 and RCP8.5 (Figure 6). The temperature anomaly was obtained by adding the base period bias to the projection period (hence called the corrected temperature) and then subtracting the average from each year. Irrespective of the driving model, the RCP8.5 projected higher temperatures than RCP4.5 did. The difference between RCP4.5 and RCP8.5 in the base period is due to the anomaly calculation (yearly value minus the average from 2071–2100) though the data for both scenarios are exactly the same for this period. The spread is for the daily average to obtain an annual value for the different driving GCMs. Averages from RegCM4-HadGEM2 and RegCM4-ECHAM6 over the entire domain indicate that temperature will increase significantly (at 95% level) at the rate of 0.73 (0.27), 0.59 (0.39), and 0.79 (0.20)°C per decade for RCP8.5 (RCP 4.5) during the periods 2021–2100, 2021–2050, and 2071–2100, respectively. A similar increasing trend in temperature is projected for the Arabian Peninsula subdomain. The rate of increase in temperature for this subdomain is projected to be 0.72 (0.29), 0.60 (0.30), and 0.83 (0.25)°C per decade for RCP8.5 (RCP4.5) during the periods 2021–2100, 2021–2050, and 2071–2100, respectively, which are significant at 95% level. Hence, the rising trend in temperature for the RCP8.5 scenario in the far future is higher for the subdomain over the Arabian Peninsula than over the entire domain because the averaging filters out the peak temperatures in the entire domain. These projected changes in temperature are useful in climate change impact studies and vulnerability, adaptation (e.g., [48]) and drought studies (e.g., [49–51]).

3.3. Hot Days and Cold Nights. The projected number of RegCM4-simulated hot days ($T_{\max} \geq 50^\circ\text{C}$) is large in the

FIGURE 5: Box plots of RegCM4-simulated air temperature (in °C) for each model and RCPs for near future and far future averaged over 11 subdomains for CORDEX-MENA/Arab domain (a, b) and subdomain over the Arabian Peninsula (c, d). The Ens2RCP8.5 and EnsRCP4.5 represent the average from HadGEM and ECHAM for the RCP8.5 and RCP4.5, respectively. The red boxes are for RCP8.5 and yellow boxes for RCP4.5.

eastern region of the Arabian Peninsula and may reach about 120 days with RCP4.5 in the near future and above 130 days in the far future (Figures 7(a) and 7(b)). The distribution pattern of hot days for the RCP8.5 case is very similar to the RCP4.5 case for the near future (Figure 7(c)). However, the area covered by more than 130 hot days increased during the far future (Figure 7(d)). Within the analysis domain, the number of hot days will increase for the European regions in the far future and the greater increase will be under the RCP8.5 scenario as compared to RCP4.5. The distribution pattern of cold nights ($T_{\min} \leq 5^{\circ}\text{C}$) is almost opposite to the pattern for hot days (Figures 7(e)–7(h)). In this case, more cold nights are projected in the western region of the Arabian Peninsula and the number of cold nights is larger with RCP4.5 than with RCP8.5. In addition, a higher cold night number is observed in the near future than

in the far future. These results support previous studies (e.g., [29]) which found that warming over the Arabian Peninsula increased in the future and is larger for the RCP8.5 scenarios than for RCP4.5. The European and African regions also show a decrease of cold nights in the far future and a greater decrease for RCP8.5 than for RCP4.5, which in fact indicates the warming.

The number of hot days is relatively low for RCP4.5 and large for RCP8.5, when averaged from RegCM4-HadGEM2 and RegCM4-ECHAM6 for both the CORDEX domain and the Arabian Peninsula subdomain (Figure 8). An increase in hot days is projected after the 2040s and will be large for the Arabian Peninsula subdomain as compared to the CORDEX domain. For the entire domain, the rate of increase rate in hot days is 1.19 and 8.01 days per decade for the RCP4.5 and RCP8.5 scenarios, respectively, during the period 2021–

FIGURE 6: Changes in corrected temperature (base period temperature bias is added with each yearly value) for (a) CORDEX-MENA/Arab and (b) Arabian Peninsula subdomain for the period 1971–2100. Anomaly is obtained from any yearly value minus the average amount. Average is obtained from HadGEM2- and ECHAM6-driven runs for both RCP4.5 and RCP8.5. Shaded area shows the range and gray color indicates the past climate.

2100. For the Arabian Peninsula subdomain, the RCP4.5 (RCP8.5) projected hot days will increase at the rate of 1.57 (11.40) days per decade. All the trends in numbers of hot days are statistically significant at the 95% level. Note that the ERA-Int-driven data available for the period 1979–2015 support the pattern of hot days obtained from RegCM4-HadGEM2 and RegCM4-ECHAM6.

For the entire domain, there is a downward trend in the number of RegCM4-simulated cold nights for both RCP4.5 (–1.52 days per decade) and RCP8.5 (–2.95 days per

decade) scenarios, while the rate of decrease is greater for the Arabian Peninsula subdomain (–3.49 and –6.14 days per decade for RCP4.5 and RCP8.5, respectively) for the period 2021–2100 (Figure 9). All the decreasing trends are statistically significant at 95% level. The decrease of cold nights means the warming which may relate to the climate change in the region. For the cold nights, the average pattern from the HadGEM2- and ECHAM6-driven runs closely follows the pattern from the ERA-Int-driven run during the available period.

FIGURE 7: Spatial distribution of RegCM4-simulated hot days ($T_{\max} > 50^{\circ}\text{C}$) for (a) RCP4.5 near future, (b) RCP4.5 far future, (c) RCP8.5 near future, and (d) RCP8.5 far future along with cold nights ($T_{\min} < 5^{\circ}\text{C}$) for (e) RCP4.5 near future, (f) RCP4.5 far future, (g) RCP8.5 near future, and (h) RCP8.5 far future. Average is taken over HadGEM2- and ECHAM6-driven runs. The near and future is 2021–2050 and 2071–2100, respectively.

FIGURE 8: Number of RegCM-simulated hot days ($T_{\max} \geq 50^{\circ}\text{C}$) for (a) CORDEX domain with RCP4.5, (b) Arabian Peninsula subdomain with RCP4.5, (c) CORDEX domain with RCP8.5, and (d) Arabian Peninsula subdomain with RCP8.5. Average is taken from HadGEM2- and ECHAM6-driven runs. Shaded area shows the range, and gray color indicates the past climate.

3.4. Projected Changes in Hot Days and Cold Nights. Changes in hot days and cold nights using RegCM4-driven by HadGEM2 and ECHAM6, and obtained for future climates relative to the base period, are shown in Figure 10. The number of hot days will rise to about 50 days more in the desert region (Rub Al-Khali) over the Arabian Peninsula in the near future, with respect to the base period. This will reach about 80 days more in the far future for the RCP4.5 scenario (Figures 10(a) and 10(b)). In the case of the RCP8.5 scenario, the number of hot days will reach about 70 days more in the desert region (Rub Al-Khali) over the Arabian Peninsula in the near future, with respect to the base period. This will rise to about 130 days more in the far future (Figures 10(c) and 10(d)). At the end of the 21st century, over most parts of the Arabian Peninsula, the number of hot days will be about 60 days more compared to the base period, although in the southwest hilly region, the projected number is small. The number of cold nights is expected to drop by a large amount in the northwest and by a smaller amount in the southeast areas of the Peninsula. The rate of decrease of cold nights will be large in the far future as compared to the near future for both RCPs (Figures 10(e)–10(h)). Hence, the northwest region of the Peninsula will face great warming, due to the faster rate of decrease of cold nights at the end of the 21st century.

Average values from RegCM4-HadGEM2 and RegCM4-ECHAM6 indicate an increasing (decreasing) number of hot days (cold nights) over both the CORDEX domain and the Arabian Peninsula (Figures 7 and 8). Decadal analysis indicates that the number of hot days is 568 (706) in the decade 2091–2100 as compared to only 15 (184) in the decade 2021–2030 for the entire domain (Arabian Peninsula subdomain) with RCP8.5 (Figure 11(a)). Decadal analysis also displays a decreasing number of cold nights in the last decade (CORDEX/Arabian Peninsula, $-310/-675$) as compared to the earlier decade (CORDEX/Arabian Peninsula, $-118/-278$). Note that the values are negative, so an increased negative value means a decrease in the number of cold nights. The rate of decrease over the Arabian Peninsula is higher than that over the entire domain (Figure 11(b)). These results further indicate a higher warming rate over the Arabian Peninsula as compared to the entire domain during the 21st century.

3.5. Maximum Temperature at Some Major Cities in Saudi Arabia. From the above discussion, it is evident that the future climate over the Arabian Peninsula during the 21st century will be warming at a higher rate as compared to the entire domain. To understand the real pattern of

FIGURE 9: Number of RegCM-simulated cold nights ($T_{\min} \leq 5^{\circ}\text{C}$) for (a) CORDEX domain with RCP4.5, (b) Arabian Peninsula subdomain with RCP4.5, (c) CORDEX domain with RCP8.5, and (d) Arabian Peninsula subdomain with RCP8.5. Average is taken from HadGEM2- and ECHAM6-driven runs. Shaded area shows the range, and gray color indicates the past climate.

temperature rise over the Arabian Peninsula, the RegCM4-simulated maximum temperature are extracted at 27 meteorological station locations across Saudi Arabia (80% coverage of the Peninsula) and compared with the meteorological station data. This exercise gives us confidence in the performance of RegCM4 for the simulation of temperature over the study region. Note that data available from just one station in each city are taken as representative of the city for the purposes of this study.

The patterns of maximum temperature at some major cities such as Makkah (21.43°N , 39.79°E), Madinah (24.54°N , 39.70°E), and Riyadh (24.92°N , 46.72°E), as well as the average over 27 stations across Saudi Arabia, obtained from RegCM4-simulated averages from HadGEM2 and ECHAM6, along with ERA-Int-driven runs and surface observations, are shown in Figure 12. In general, the simulated maximum temperature follows the pattern of observations closely. For Makkah and Madinah, the ERA-Int is very close to the observations (Figures 12(a) and 12(b)), while for Riyadh (Figure 12(c)), it is overestimated by around 3.5°C (Figure 12(d)). The average temperature of Makkah over the common period of 1985–2014 is 38.26°C (38.55°C) from observations (ERA-Int) while it is 35.86°C from the RegCM4 simulation. For Madinah, the average temperature over the common period of 1985–2014 is 35.21°C (35.66°C) from observations (ERA-Int) while it is

33.81°C from the RegCM4 simulation. In the case of Riyadh, average temperature over the common period of 1985–2014 is 33.29°C (36.75°C) from observations (ERA-Int), while it is 34.90°C from the RegCM4 simulation. Overall, the simulation underestimates the maximum temperature for Makkah and Madinah while overestimating it for Riyadh and for the country as a whole, relative to the surface observations. This indicates regional variations in temperature simulation using RegCM4 which depends on different factors including land use and urbanization. The two holy cities Makkah and Madinah are well developed from the historical period where the model underestimated maximum temperature. This is in line with the general cold bias by the RegCM4 [17]. On the other hand, the capital city Riyadh is expanding with new infrastructures and development programs and rapid growth of urbanization where RegCM4 overestimates maximum temperature. This is similar to the warm bias over Oman/Yemen as reported in [17] and by Wang and Xubin (2013) which might be due to some error or low dense network data coverage in the observations. Therefore, this temperature underestimation by the climate model at some locations and overestimation at other locations are an unresolved issue and need further investigation. Hence, model simulations can provide the overall pattern of the observed maximum temperature at local scale. However, bias varies from location to location and needs to be

FIGURE 10: Spatial distribution of changes in hot days ($T_{\max} > 50^{\circ}\text{C}$) for (a) RCP4.5 near future, (b) RCP4.5 far future, (c) RCP8.5 near future, and (d) RCP8.5 far future along with cold nights ($T_{\min} < 5^{\circ}\text{C}$) for (e) RCP4.5 near future, (f) RCP4.5 far future, (g) RCP8.5 near future, and (h) RCP8.5 far future with respect to the base period (1971–2000). Average is taken over HadGEM2- and ECHAM6-driven runs.

FIGURE 11: Decadal variations of the number of hot days ($T_{\max} \geq 50^{\circ}\text{C}$) and cold nights ($T_{\min} \leq 5^{\circ}\text{C}$) with respect to the reference period (1971–2000) obtained from average of HadGEM2- and ECHAM6-driven runs under RCP8.5 for (a) CORDEX-MENA/Arab domain and (b) Arabian Peninsula subdomain.

considered when using the model data in application-oriented tasks such as heat index calculations. The model-simulated relative humidity for each panel indicates an insignificant rate of decrease. This indicates that because the temperature will increase in the future, warmer air's larger capacity to store water vapor may cause decrease of relative humidity.

For all station averages, the simulations reveal similar patterns for both the RCP8.5 and RCP4.5 scenarios until the mid-2030s. After that, the RCP8.5-based projections deviate to higher values compared to those of RCP4.5. The difference between projected values for the two RCPs is about 3°C at the

end of the 21st century. Based on Figure 12, the maximum temperature simulations based on the RCP8.5 (RCP4.5) scenarios show the following features at some major cities in Saudi Arabia:

- (i) At Makkah, the maximum temperature increase rate is projected to be 0.51 (0.30), 0.60 (0.28), and 0.76 (0.06) $^{\circ}\text{C}$ per decade for the periods 1961–2100, 2021–2050, and 2071–2100, respectively
- (ii) At Madinah, the maximum temperature increase rate is projected to be 0.54 (0.34), 0.57 (0.34), and

FIGURE 12: Simulated maximum temperature extracted nearer grid point of the station locations for (a) Makkah, (b) Madinah, (c) Riyadh, and (d) Saudi Arabia (averaged over 27 stations) for both RCP4.5 and RCP8.5 along with ERA-Int and surface observational data. For RegCM simulations, average taken from HadGEM2- and ECHAM6-driven runs are also shown by solid lines. Shaded area shows the range. The relative humidity (in %) is also shown for each panel (RH85 and RH45 for, respectively, RCP8.5 and RCP4.5).

0.66 (0.03)°C per decade for the periods 1961–2100, 2021–2050, and 2071–2100, respectively

- (iii) At Riyadh, the maximum temperature increase rate is projected to be 0.59 (0.38), 0.70 (0.27), and 0.69 (0.15)°C per decade for the periods 1961–2100, 2021–2050, and 2071–2100, respectively
- (iv) Over Saudi Arabia, the maximum temperature increase rate is projected to be 0.59 (0.41), 0.63 (0.29), and 0.67 (0.10)°C per decade for the periods 1961–2100, 2021–2050, and 2071–2100, respectively

The increase rates for the above three stations, and averaged over all stations, are significant at the 95% level. Overall, the simulated maximum temperature follows the pattern of observations. However, caution is recommended before the use of model temperature for application-oriented tasks which vary from location to location. Therefore, the uncertainty at each location must be considered for climate change impact studies using model data. Further study may require using data from the newly developed Saudi-KAU Global Climate Model and focusing on the simulation of climate over the Arabian Peninsula [52–54].

4. Conclusions

In this study, the change in temperature in the 21st century over the CORDEX-MENA domain with a focus on the Arabian Peninsula has been projected from RegCM4 simulations. Data from the three CMIP5 models HadGEM2, ECHAM6, and CanESM were downscaled with RegCM4 (RegCM4-HadGEM2, RegCM4-ECHAM6, and RegCM4-CanESM). The RegCM4-CanESM variant largely overestimated the mean temperature in the past climate and was found to be not useful in climate projection over the analysis domain. The maximum temperatures extracted at few main cities in Saudi Arabia were also projected. The analysis included two RCPs scenarios, namely, RCP4.5 and RCP8.5. In general, the RegCM4 simulations with RCP8.5 were likely to project a warmer climate than those conducted with RCP4.5. The RCP8.5 scenario projected a temperature increase of about 7°C over the Arabian Peninsula by the end of the 21st century. This increase in temperature is more pronounced during the winter season than during the summer. Over the entire domain, the temperature is projected to increase at the rate of 0.73 (0.27), 0.59 (0.39), and 0.79 (0.20)°C per decade under RCP8.5 (RCP4.5) scenarios, for the periods 2021–2100, 2021–2050, and 2071–2100,

respectively. The rate of increase in temperature over the Arabian Peninsula subdomain is projected to be 0.72 (0.29), 0.60 (0.30), and 0.83 (0.25)°C per decade under the RCP8.5 (RCP4.5) scenario, for the periods 2021–2100, 2021–2050, and 2071–2100, respectively. The RCP8.5-projected hot days ($T_{\max} \geq 50^{\circ}\text{C}$) are likely to increase at the rate of 8.01 (11.40) days per decade, while the decrease in cold nights ($T_{\min} \leq 5^{\circ}\text{C}$) is projected to be –2.95 (–6.14) nights per decade for the CORDEX (Arabian Peninsula) domain. All increasing trends in temperature and in hot day numbers and decreasing trends in cold nights are statistically significant at the 95% level. These provide a clear indication of a warming climate in the future over the Arabian Peninsula, even if the warming may vary from region to region. The projected warming rate over the Arabian Peninsula is larger than that over the entire domain. The RegCM4-based temperature follows the pattern of surface observations at the station level across Saudi Arabia. Therefore, HadGEM2- and ECHAM6-driven runs are recommended as input databases for environmental vulnerability assessment studies since the CanESM output was found to be unsuitable. However, more CMIP5 models may be evaluated for their utility in application-oriented tasks in further studies.

Data Availability

The data are run in the supercomputer of the King Abdulaziz University, Jeddah, Saudi Arabia, and it is difficult to share as the data are in gigabyte and there is no way to share the data to the public. We can share the results through the publishing of this paper, and the results can be compared with other studies that have been done over the region. However, some of the data are freely accessible such as (1) GCMs data that are used in the simulations and (2) CRU and CMIP5 data that are available for free and are known to the scientific community GAMEP data for the surface local observations are not for distribution. These data cannot be shared as copyright of the data used is applied for using these data, and if anyone would like to use has to obtain those from the source.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

Sup 1: distribution of air temperature (in °C) obtained from (a) annual CRU, (b) annual ERA-Int, (c) winter CRU, (d) winter ERA-Int, (e) summer CRU, and (f) summer ERA-Int averaged for the common period 1980–2005. The 11 subdomains are drawn following Almazroui (2016) and averaged over these subdomains represent the CORDEX-MENA/Arab domain used for objective analysis later on. Sup 2: spatial distribution of changes in RegCM4-simulated mean temperature under RCP4.5 for (a) annual near future, (b) annual far future (top right), (c) winter season near future, (d) winter season far future, (e) summer season near future, and (f) summer season far future. Data are averaged from HadGEM2- and ECHAM6-driven runs. The change is calculated as average of near (or far far) future minus the base period value. Sup 3: changes in RegCM4 mean temperature (°C) in the future climate under RCP8.5 with respect to the base period (1971–2000) for (a) annual near future, (b) annual far future, (c) winter season near future, (d) winter season far future, (e) summer season near future, and (f) summer season far future. Data are averaged from HadGEM2- and ECHAM6-driven runs. (*Supplementary Materials*)

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