Future Changes in Climate over the Arabian Peninsula based on CMIP6 Multimodel Simulations

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Abstract

This paper presents the changes in projected temperature and precipitation over the Arabian Peninsula for the twenty-first century using the Coupled Model Intercomparison Project phase 6 (CMIP6) dataset. The changes are obtained by analyzing the multimodel ensemble from 31 CMIP6 models for the near (2030–2059) and far (2070–2099) future periods, with reference to the base period 1981–2010, under three future Shared Socioeconomic Pathways (SSPs). Observations show that the annual temperature is rising at the rate of $0.63\text{ }^{\circ}\text{C decade}^{-1}$ (significant at the 99% confidence level), while annual precipitation is decreasing at the rate of $6.3\text{ mm decade}^{-1}$ (significant at the 90% confidence level), averaged over Saudi Arabia. For the near (far) future period, the 66% likely ranges of annual-averaged temperature is projected to increase by $1.2\text{--}1.9$ ($1.2\text{--}2.1$) $^{\circ}\text{C}$, $1.4\text{--}2.1$ ($2.3\text{--}3.4$) $^{\circ}\text{C}$, and $1.8\text{--}2.7$ ($4.1\text{--}5.8$) $^{\circ}\text{C}$ under SSP1–2.6, SSP2–4.5, and SSP5–8.5, respectively. Higher warming is projected in the summer than in the winter, while the Northern Arabian Peninsula (NAP) is projected to warm more than Southern Arabian Peninsula (SAP), by the end of the twenty-first century. For precipitation, a dipole-like pattern is found, with a robust increase in annual mean precipitation over the SAP, and a decrease over the NAP. The 66% likely ranges of annual-averaged precipitation over the whole Arabian Peninsula is projected to change by 5 to 28 (–3 to 29) %, 5 to 31 (4 to 49) %, and 1 to 38 (12 to 107) % under SSP1–2.6, SSP2–4.5, and SSP5–8.5, respectively, in the near (far) future. Overall, the full ranges in CMIP6 remain higher than the CMIP5 models, which points towards a higher climate sensitivity of some of the CMIP6 climate models to greenhouse gas (GHG) emissions as compared to the CMIP5. The CMIP6 dataset confirmed previous findings of changes in future climate over the Arabian Peninsula based on CMIP3 and CMIP5 datasets. The results presented in this study will be useful for impact studies, and ultimately in devising future policies for adaptation in the region.

Keywords Projection · Temperature · Precipitation · Arabian peninsula · CMIP6

1 Introduction

The climate of the Arabian Peninsula is semi-arid to arid, with high annual temperatures and low precipitation, making it one of the most climate-vulnerable regions in the Middle East, as well as in Southwest Asia. The northern part of the

Arabian Peninsula is colder than the southern part. In different seasons, observed temperature ranges from 8.57 to $28.32\text{ }^{\circ}\text{C}$ over the northern Peninsula, whereas temperature ranges from 26.68 to $33.97\text{ }^{\circ}\text{C}$ in the southern Peninsula (Almazroui et al. 2013). During summertime, the maximum temperature may exceed $50\text{ }^{\circ}\text{C}$ at some locations over the region (Almazroui et al. 2012; Islam et al. 2015; Pal et al. 2016). The wet season over Arabian Peninsula extends from October to May (Almazroui 2020a), while the dry season lasts from June through September. Over Saudi Arabia (about 80% coverage of the Peninsula area), the annual mean temperature varies from $18.96\text{ }^{\circ}\text{C}$ (in the northwest region) to $31.42\text{ }^{\circ}\text{C}$ (in the western region), and the annual mean precipitation varies from 25 mm (in the northwest region) to 230 mm (in the southwest region) (Almazroui et al. 2012; Almazroui 2012). The wet season precipitation varies from 75 mm (in May) to 200 mm (in April) while the dry season

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precipitation ranges from 20 mm (in June) to 65 mm (in Aug) (Almazroui et al. 2017a).

Surface air temperature is a key component of climate variability and one of the major indicators of climate change on both regional and global scales (Kothawale et al. 2010). The global mean temperature increased by ~ 0.6 °C during the period 1861–2000 (Folland et al. 2001), whereas global warming was ~ 0.85 °C during the period 1880–2012 (IPCC 2013). In the Peninsula, many studies (e.g. Almazroui et al. 2014; Islam et al. 2015) revealed a warming trend in recent decades. For the long-term period 1960–2010, the mean temperature increased significantly by 0.10 °C decade⁻¹ over the Peninsula (Attada et al. 2018a), while for recent decades (1978–2009), the rate of increase over Saudi Arabia (0.60 °C decade⁻¹) has been even larger (Almazroui et al. 2012). Almazroui et al. (2012) found that the rainfall increase during the period 1979–1993 was insignificant, while the decrease over the period 1994–2009 was indeed significant. The rate of decrease was 35.1 mm decade⁻¹ for the wet season and 5.5 mm decade⁻¹ for the dry season. Consistent with these results, AlSarmi and Washington (2013) showed that precipitation decreased over the Peninsula, and showed an insignificant trend for the time period 1986–2008. Hasanean and Almazroui (2015) also reported a downward trend in rainfall over the Arabian Peninsula for the period 1978–2009. Annual precipitation decreased significantly over northern regions of the Peninsula at a rate of 0.66% decade⁻¹, while an increasing trend (1.67% decade⁻¹) occurred over the southern Peninsula. However, precipitation increased at a rate of 0.86% decade⁻¹ over the whole Arabian Peninsula (Almazroui et al. 2017b).

The temperature and precipitation climatology, along with their trends mentioned above, were analyzed using observed climate data. Future climate projections over the Arabian Peninsula are studied using ensembles of global climate models, and also by downscaling them using regional climate models (e.g. Barfus and Bernhofer 2014; Pal et al. 2016; Almazroui et al. 2013b, 2016, 2017a, b, c; Syed et al. 2019). Using CMIP3 data, Almazroui et al. (2017c) showed that the annual mean temperature could increase by 2.32 ± 2.45 , 3.49 ± 2.49 , and 3.82 ± 1.47 °C, compared to the present climate, under the B1, A1B, and A2 scenarios, respectively, by the end of the twenty-first century. Under the same scenarios, annual precipitation is projected to increase by 5.16 ± 30 , 10.48 ± 34 , and $15.29 \pm 43\%$, relative to the present climate. Using CMIP5 data, Almazroui et al. (2017a) showed that at the end of the twenty-first century, the temperature could increase by 2.51 ± 0.72 , or 4.87 ± 0.86 °C relative to the present-day climate, under the RCP4.5 and RCP8.5 scenarios, respectively. For precipitation, the corresponding projections under these scenarios found an increase in annual precipitation by 8.27 ± 20 and $27.34 \pm 50\%$, respectively. Using both CMIP3 and CMIP5

datasets, they noted that temperature would continue to increase throughout the twenty-first century over the Peninsula, that rainfall will increase over the southern regions of the Peninsula while it will decrease over the northwest region. Similar results were found by Bucchignani et al. (2018) using a regional climate model (COSMO-CLM) simulations. Moreover, climate change increases the risk of extreme events, particularly those related to temperature, which may be responsible for heat/cold waves and frequent drought occurrence over any region (Kotwicki and Al Sulaimani, 2009). Recently, Almazroui (2019) found that over the Peninsula, an increase in the frequency of hot days, and reduction in the occurrence of cold nights, will be more likely in the far future (2071–2100) under RCP8.5 as compared to the near future (2021–2050). Extreme precipitation events will intensify more over the Peninsula, particularly over central and southern regions, in the future climate under RCP8.5 (Almazroui and Saeed 2020).

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) was mainly based on the CMIP5 GCM simulations. Recently, the simulations of some of the climate models for the sixth phase of the Coupled Model Intercomparison Project (CMIP6) have been completed and made available for analysis (Eyring et al. 2016; Haarsma et al. 2016; O'Neill et al. 2016). The CMIP6 dataset is based on a new generation of climate models, a new

Fig. 1 Regional map showing elevation (in meters) over the Arabian Peninsula. The horizontal dashed line divides the analysis domain into northern Arabian Peninsula (NAP) and the southern Arabian Peninsula (SAP) used for area averages in this study

Table 1 List of CMIP6 models used in this study along with horizontal resolution and country of origin

No	CMIP6 model name	Country	Horizontal resolution (lon. by lat. in degree)	Variant label	Key references
1	ACCESS-CM2	Australia	$1.9^{\circ} \times 1.3^{\circ}$	rlilplf1	Bi et al. (2012)
2	ACCESS-ESM1-5	Australia	$1.9^{\circ} \times 1.2^{\circ}$	rlilplf1	Law et al. (2017)
3	AWI-CM-1-1-MR	Germany	$0.9^{\circ} \times 0.9^{\circ}$	rlilplf1	Semmler et al. (2020, in review)
4	BCC-CSM2-MR	China	$1.1^{\circ} \times 1.1^{\circ}$	rlilplf1	Wu et al. (2019)
5	CAMS-CSM1-0	China	$1.1^{\circ} \times 1.1^{\circ}$	rlilplf1	Rong et al. (2019)
6	CanESM5	Canada	$2.8^{\circ} \times 2.8^{\circ}$	rlilplf1	Swart et al. (2019)
7	CESM2	USA	$1.3^{\circ} \times 0.9^{\circ}$	rlilplf1	Lauritzen et al. (2018)
8	CESM2-WACCM	USA	$1.3^{\circ} \times 0.9^{\circ}$	rlilplf1	Liu et al. (2019)
8	CIESM	China	$0.9^{\circ} \times 1.3^{\circ}$	rlilplf1	Lin et al. (2020)
10	CNRM-CM6-1	France	$1.4^{\circ} \times 1.4^{\circ}$	rlilplf2	Voldoire et al. (2019)
11	CNRM-CM6-1-HR	France	$0.5^{\circ} \times 0.5^{\circ}$	rlilplf2	Voldoire et al. (2019)
12	CNRM-ESM2-1	France	$1.4^{\circ} \times 1.4^{\circ}$	rlilplf2	Séférian et al. (2019)
13	EC-Earth3	Europe	$0.7^{\circ} \times 0.7^{\circ}$	rlilplf1	Massonnet et al. (2020)
14	EC-Earth3-Veg	Europe	$0.7^{\circ} \times 0.7^{\circ}$	rlilplf1	Not available
15	FGOALS-f3-L	China	$1.3^{\circ} \times 1^{\circ}$	rlilplf1	He et al. (2019)
16	FGOALS-g3	China	$2^{\circ} \times 2.3^{\circ}$	rlilplf1	Not available
17	FIO-ESM-2-0	China	$1.3^{\circ} \times 0.9^{\circ}$	rlilplf1	Song et al. (2020)
18	GFDL-ESM4	USA	$1.3^{\circ} \times 1^{\circ}$	rlilplf1	Held et al. (2019)
19	INM-CM4-8	Russia	$2^{\circ} \times 1.5^{\circ}$	rlilplf1	Volodin et al. (2018)
20	INM-CM5-0	Russia	$2^{\circ} \times 1.5^{\circ}$	rlilplf1	Volodin et al. (2018)
21	IPSL-CM6A-LR	France	$2.5^{\circ} \times 1.3^{\circ}$	rlilplf1	Not available
22	KACE-1-0-G	South Korea	$1.3^{\circ} \times 0.9^{\circ}$	rlilplf1	Not available
23	MIROC6	Japan	$1.4^{\circ} \times 1.4^{\circ}$	rlilplf1	Tatebe et al. (2019)
24	MIROC-ES2L	Japan	$2.8^{\circ} \times 2.8^{\circ}$	rlilplf2	Hajima et al. (2019)
25	MPI-ESM1-2-HR	Germany	$0.9^{\circ} \times 0.9^{\circ}$	rlilplf1	Gutjahr et al. (2019)
26	MPI-ESM1-2-LR	Germany	$1.9^{\circ} \times 1.9^{\circ}$	rlilplf1	Mauritsen et al. (2019)
27	MRI-ESM2-0	Japan	$1.1^{\circ} \times 1.1^{\circ}$	rlilplf1	Yukimoto et al. (2019)
28	NESM3	China	$1.9^{\circ} \times 1.9^{\circ}$	rlilplf1	Cao et al. (2018)
29	NorESM2-LM	Norway	$2.5^{\circ} \times 1.9^{\circ}$	rlilplf1	Seland et al. (2020, in review)
30	NorESM2-MM	Norway	$0.9^{\circ} \times 1.3^{\circ}$	rlilplf1	Seland et al. (2020, in review)
31	UKESM1-0-LL	UK	$1.9^{\circ} \times 1.3^{\circ}$	rlilplf2	Sellar et al. (2019)

start year for the future scenarios (2006 in CMIP5; 2015 in CMIP6), and employed a new set of concentrations, emissions, and land-use scenarios (Riahi et al. 2017; O'Neill et al. 2016). This work is the first attempt to examine the projected changes in temperature and precipitation over the Arabian Peninsula using the CMIP6 dataset. The present study further investigates the extent to which the CMIP6 model-simulated climate response to anthropogenic forcing over the Arabian Peninsula differs from those of the CMIP3 and CMIP5 datasets. To the best of our knowledge, no other study has examined future climate change over the Arabian Peninsula using the CMIP6 dataset. Such an analysis of CMIP6 model output over the Arabian Peninsula is important for determining how both CMIP5 and CMIP6 results could be used together in future impact and adaptation

studies. The present study aims to fill this gap by analyzing the dataset from 31 CMIP6 models over the Arabian Peninsula.

2 Data and Methodology

The surface observations for temperature and precipitation for the period 1978–2019 are obtained from 25 station locations across Saudi Arabia collected by the Saudi General Authority of Meteorology and Environmental Protection (GAMEP). The observational temperature and precipitation gridded data used are from the Climatic Research Unit (CRU, Harris and Jones 2015) along with the Global Precipitation Climatology Center (GPCC) version 7 (Schneider et al. 2016) for precipitation, and the University of Delaware

Fig. 2 Observed spatial distribution of temperature (upper panels) and precipitation (lower panels) averaged over the period 1981–2010. The temperature is obtained from gridded CRU (top left) and UoD

(top right) whereas precipitation is obtained from CRU (bottom left) and GPCP (bottom right) data. The units of temperature is $^{\circ}\text{C}$, and precipitation is in mm year^{-1}

(UoD) version 5.01 dataset (Willmott and Matsuura 2001) for temperature. The gridded data are used over the Arabian Peninsula, where the elevation varies from 1 to above 2500 m (Fig. 1). The Peninsula is almost flat to the east of the eastern border of Jordan with Iraq to the eastern border of Yemen with Oman, where all Gulf countries are located, along with the eastern part of Saudi Arabia. The Hijaz Mountains range is in the northwest of Saudi Arabia, whereas the Asir Mountains range from western Saudi Arabia and continue southeastward into Yemen. The Asir Mountains receive the most annual precipitation of anywhere in the Peninsula (Almazroui et al. 2012).

The climate model data is obtained from the CMIP6 database (<https://esgf-node.llnl.gov/search/cmip6>). The 31 CMIP6 models analyzed in this study are listed in Table 1. Since each of the CMIP6 constituent models has different horizontal resolutions, all CMIP6 data sets are regridded from their original spatial resolutions to a

common grid with 1×1 degree resolution. The temperature data are regridded using a standard bilinear interpolation technique, while the precipitation data are regridded using a first-order conservative method. For the analysis of temperature and precipitation data, annual averages are taken over the 30-year time slots for the base period (1981–2010), near future (2030–2059), and far future (2070–2099). Moreover, for seasonal analysis, the summer (JJA) and winter (DJF) seasons are considered for temperature while the wet season (Oct–May) is considered for precipitation. The definition of the wet season over the Arabian Peninsula is adopted from Almazroui (2011, 2020a). In addition to seasonal analysis, regional analysis is performed separately on the northern Arabian Peninsula and the southern Arabian Peninsula due to their differing weather characteristics (Almazroui et al. 2013a, b, 2016, 2017b).

Fig. 3 Observed temperature (a) and precipitation (b) anomalies for the period 1978–2019 with respect to the climatology 1981–2010. Both the temperature and precipitation anomalies are obtained by taking averages from 25 stations observed data (Table 2)

The ensemble from the 31 available CMIP6 models for the present and future climates, along with the range of signals, are considered for temperature and precipitation analyses under the three new future pathways of societal development called Shared Socioeconomic Pathways (SSPs), which are: a low-forcing scenario SSP1–2.6, a medium-forcing scenario SSP2–4.5, and a high-forcing scenario SSP5–8.5. Note that SSPs are based on five narratives that describe alternative socio-economic developments (Riahi et al. 2017): sustainable development (SSP1), middle-of-the-road development (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil-fuels development (SSP5). Detailed descriptions of these SSPs are available in O'Neill et al. (2016). The SSP1–2.6, SSP2–4.5 and SSP5–8.5 forcing scenarios are considered for, respectively, low, medium and high emission scenarios, similar to the RCP2.6, RCP4.5, and RCP8.5 scenarios in CMIP5 models (Riahi et al. 2017). For the assessment of uncertainty associated with the future evaluation of temperature and precipitation under the SSPs, the *likely range* (66% i.e. 17–83 percentile around the median) and the *full range* (results from all models) are used along with median values. Furthermore, the *robustness* of the projected signal is measured based on the agreement of different model projections on the direction of changes (Solomon et al. 2007). According to Haensler et al. (2013), the changes, whether an increase or a decrease, in the projected signal,

will be considered robust if at least 66% of the models agree on the direction of change. In addition, the significance of a change in the projected signal is measured by employing a two-tailed Student *t* test based on equal and unequal variances between future and historical data for each grid box. Equal and unequal variance is determined for each grid box using an *F* test. Analyses are performed over the entire Arabian Peninsula (AP), NAP and SAP. Temperature and precipitation trends are calculated using regression analysis, while the statistical significance of trends is assessed by an *F* test (Almazroui et al. 2013a).

3 Results and Discussion

The distribution of observed temperature and precipitation climatology for the period 1981 to 2010 is shown in Fig. 2. The time period 1981–2010 is selected for the climatology because it is used as the reference (base) period to obtain the changes in simulated climate from the CMIP6 models. The observed data shows that the temperature in the northwest and southwest mountain areas is lower than in the central to eastern regions, as seen in both the CRU and UoD datasets. The annual mean temperature is below 20 °C in the northwestern and southwestern regions, while it exceeds 30 °C in the central to eastern regions. The CRU data shows large precipitation in the southwest Peninsula, which can exceed

Table 2 Surface observational mean annual temperature (in °C) and precipitation (in mm) along with their trends (decade⁻¹) at 25 stations across Saudi Arabia for the period 1978–2019

	Station name	WMO code	Temperature (°C)		Precipitation (mm)	
			Annual Average	Trend	Annual Average	Trend
Northern Arabian Peninsula	Tabuk	40,375	22.37	0.45 ^a	31.4	−2
	Turaif	40,356	19.10	0.38 ^a	84.9	−14 ^a
	Guriat*	40,360	20.27	0.42 ^a	48.7	0
	Rafha	40,362	23.57	0.59 ^a	80.6	−7
	Arar	40,357	22.46	0.68 ^a	59.7	−3
	Al-Jouf	40,361	22.26	0.81 ^a	56.1	5
	Hail	40,394	22.15	0.63 ^a	97.4	−30 ^a
	Gassim	40,405	25.18	0.73 ^a	131.3	−19 ^b
	Riyadh*	40,437	25.71	0.64 ^a	105.5	−14
	Al-Qaisumah	40,373	25.58	0.55 ^a	120.7	−11
	Dammam	40,417	27.36	0.40 ^a	87.4	16
	Al-Ahsa*	40,420	27.51	0.68 ^a	86.5	−3
	Al-Wejh	40,400	25.25	0.49 ^a	31.1	6
	Madinah	40,430	28.37	0.47 ^a	61.0	−5
	Yenbo	40,439	28.04	0.58 ^a	33.0	4
Southern Arabian Peninsula	Jeddah	41,024	28.90	0.41 ^a	51.2	1
	Taif	41,036	23.20	0.41 ^a	162.6	−5
	Makkah*	41,030	31.68	0.76 ^a	98.1	−13
	Al-Baha*	41,055	23.27	0.45 ^a	131.5	−19
	Gizan	41,140	30.79	0.24 ^a	127.8	10
	Khamis Mushait	41,114	20.11	0.67 ^a	184.6	−12
	Abha	41,112	19.22	0.62 ^a	221.2	−25 ^b
	Bisha	41,084	25.35	0.51 ^a	86.4	−8
	Najran	41,128	25.21	0.54 ^a	60.3	9
	Sharorah*	41,136	27.90	0.38 ^a	57.8	−4
	Country		24.64	0.63^a	92.9	−6.3^b

The stations with * indicate data from 1985

The superscript *a* and *b* represent statistical significance level 99% and 90% respectively

400 mm annually. The precipitation is low (below 60 mm) in the northwest part, and over the Rub Al-Khali desert areas. The GPCC data shows a similar distribution of precipitation to the CRU data. There is little variation between the datasets, and overall distributions of temperature and precipitation remain almost the same. The next sections describe the change in temperature over the Arabian Peninsula for the near and far future periods.

The historical trends of temperature and precipitation over Saudi Arabia (which represents 80% of the Peninsula) using the quality controlled and updated data for the period 1978–2019 indicate that the region continues to warm and to dry (Fig. 3). The temperature was slightly below normal (24.39 °C) before 1997 and above normal afterward. The sharp peak in 2010 indicates the warmest year in the historical record. Regression analysis shows that the temperature increased at a rate of 0.63 °C decade⁻¹ for the period 1978–2019, which is significant at the 99% confidence

level. Almazroui (2020a) also found a similar increasing rate in observed annual mean temperatures over the Arabian Peninsula. Annual precipitation is highly variable, however, it tends to be slightly below normal (96.92 mm) after 1998. Precipitation is decreasing at a rate of 6.3 mm decade⁻¹, which is statistically insignificant. Almazroui (2020b) also found a decreasing trend in observed annual precipitation over Saudi Arabia. Details of the temperature

Fig. 4 Spatial distribution of absolute change in annual mean temperature under three scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5) over the Arabian Peninsula for the two time periods (2030–2059 and 2070–2099) as compared to the reference period (1981–2010). The backslash and forward slash represent the grid boxes showing significant and robust change, respectively, while hatching represents the grid boxes having both significant and robust change. Significance is defined based on a two-tailed Student *t* test, while robustness is defined when 66% of all models project a climate change signal in the same direction

Fig. 5 Same as Fig. 4 but for summer season mean temperature

Fig. 6 Same as Fig. 4 but for winter season mean temperature

Fig. 7 Spatial distribution of relative change in annual precipitation for three scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5) over the Arabian Peninsula for the two time periods (2030–2059 and 2070–2099) as compared to the reference period (1981–2010). The backslash and forward slash represent the grid boxes showing significant and robust change, respectively, while hatching represents the grid boxes having both significant and robust change. Significance is defined based on a two-tailed Student *t* test, while robustness is defined when 66% of all models project a climate change signal in the same direction

and precipitation trends at all 25 station locations across Saudi Arabia are provided in Table 2. Overall, a larger rate of increase in temperature is observed in the northern Peninsula relative to the southern Peninsula, which ranges from $0.24\text{ }^{\circ}\text{C decade}^{-1}$ (at Gizan) to $0.81\text{ }^{\circ}\text{C decade}^{-1}$ (et al.–Jouf), and are all significant at the 99% confidence level. Precipitation trends range from $-30\text{ mm decade}^{-1}$ (at Hail) to 16 mm decade^{-1} (at Dammam). Except for four stations, precipitation trends are statistically insignificant. The increasing temperature and decreasing precipitation trends are in line with previous findings obtained for a relatively shorter period (1978–2009) by Almazroui et al. (2012), who reported temperature increase at a rate of $0.60\text{ }^{\circ}\text{C decade}^{-1}$ and precipitation decrease at a rate of $6.20\text{ mm decade}^{-1}$. Note that the non-parametric Mann–Kendall trend analysis for the same data period over Saudi Arabia show almost similar trends for temperature and precipitation, however, to compare results with available literature and IPCC report, linear trends are considered in this analysis (Almazroui 2020b).

3.1 Changes in temperature for the near and far futures

The spatial distribution of changes in projected temperature for the near and far futures under all three future scenarios are shown in Figs. 4, 5, and 6. The robust changes in temperature at annual scale over most parts of the Arabian Peninsula are projected to be below $2.0\text{ }^{\circ}\text{C}$ in the near future under the low emission scenario SSP1–2.6 (top panels, Fig. 4). Very similar patterns of changes in annual temperature are obtained for the far future. Robust changes in temperature are also noted for the medium emission scenario SSP2–4.5, where most parts of the Peninsula will be $2.0\text{ }^{\circ}\text{C}$ warmer than the present climate in the near future period, and 3.0 to $4.05\text{ }^{\circ}\text{C}$ warmer in the far future (middle panels, Fig. 4). The high emission scenario SSP5–8.5 indicates a rise in temperature by $3.0\text{ }^{\circ}\text{C}$ compared to the present climate over the entire Peninsula for the near future and more than $4.5\text{ }^{\circ}\text{C}$ over most of the Arabian Peninsula. Under the SSP5–8.5 scenario, some parts of the Peninsula in the north-central region may exceed $6\text{ }^{\circ}\text{C}$ in the far future (lower panels, Fig. 4). This rise of temperature is consistent with CMIP5 data analysis over South Asia under RCP8.5,

which is in the range $3.2\text{--}5.1\text{ }^{\circ}\text{C}$ for the period 2070–2099 (Alamgir et al. 2019). Overall, the change in the future temperature over the northern Peninsula is bigger (exceeding $6.0\text{ }^{\circ}\text{C}$) than over the southern Peninsula, which is in line with the CMIP3 and CMIP5 projections, as shown in Almazroui et al. (2016, 2017b). Summer temperatures over the Arabian Peninsula show a robust increase with a similar pattern to that of annual temperature. However, the magnitude of the temperature increase is more than $4.5\text{ }^{\circ}\text{C}$ in the northern Peninsula under the medium emission scenario (Fig. 5). In this season, the area with a temperature increase above $6.0\text{ }^{\circ}\text{C}$ expands towards the south, east, and west. In the case of winter temperature, the increase is lower than the annual and summer seasons in the northern Peninsula under a low emission scenario for the far future (Fig. 6). The higher increase in temperature over the northern Peninsula compared to the southern Peninsula observed in the summer season is not observed in the winter season. This feature is in line with the results from CMIP3 and CMIP5, as reported in Almazroui et al. (2016, 2017b). Note that the summer temperature of the Peninsula is highly correlated with the quasi-stationary mid-latitude Eurasian Rossby wave train pattern and the Atlantic Ocean sea surface temperature (Attada et al. 2018b; Ehsan et al. 2020; Rashid et al. 2020).

3.2 Changes in Precipitation for the Near and Far Futures

The spatial distribution of changes in projected precipitation for the near and far futures under all three SSPs are shown in Figs. 7 and 8. The projected precipitation shows a robust increase in annual mean precipitation over most of the Peninsula by the end of the twenty-first century under the three future scenarios. A decreasing signal is found over Jordan and adjacent areas of Saudi Arabia which get further intensified under high emission scenario SSP5–8.5. Annual precipitation is projected to decrease in the northwest and increase in the southern region (Fig. 7). The maximum deficit will be about 30%, and the surplus will exceed 50% under SSP5–8.5 in the far future. It is important to mention that because of its hyper-arid climate, the amount of precipitation in the southeastern region is very small. Therefore, a small increase in absolute precipitation may result in a large increase in relative (percentage) terms (Almazroui et al. 2017a; Almazroui and Saeed 2020). Note that the large increase over southwest Saudi Arabia is significant because the annual rainfall is highest in this region. The projected precipitation shows a decrease in the northwest region, which is more pronounced in the far future compared to the near future period, especially for the SSP5–8.5 scenario. This is in agreement with previous findings over the Arabian Peninsula based on CMIP3 and CMIP5 datasets (Almazroui et al. 2017a, b).

Fig. 8 Same as Fig. 7 but for wet season precipitation

Fig. 9 Projected changes in temperature for annual, summer and winter seasons, spatially averaged over three regions i.e. Arabian Peninsula (AP), Northern Arabian Peninsula (NAP) and Southern Arabian Peninsula (SAP). Yellow and red bars represent the results for the near future (2030–2059) and far future (2070–2099), respectively, for

the three scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5). The length of the bars shows Full ranges (results from all the models) and the shaded areas show Likely ranges (66% of all projected changes are within this range)

Over the Arabian Peninsula, the wet season (Oct–May) precipitation contributes the most to the annual total rainfall. The wet season precipitation shows a similar spatial distribution of future precipitation signals as compared to the annual patterns. The southern parts of the Peninsula display an increase, while the northwestern parts show a decrease in the projected precipitation (Fig. 8). The northwestern area of precipitation decrease is smaller in CMIP6 data as compared to CMIP5 data. Interestingly, the projected precipitation change during the wet season displays an identical spatial pattern, with a decrease over northwestern parts and an increase over the southern Arabian Peninsula for different scenarios. For precipitation projections, there is inconsistency among the CMIP6 models over a large part of the Arabian Peninsula. For the wet season, the agreement between CMIP6 model projections improves towards the end of the twenty-first century in both the middle (SSP2–4.5) and high emission scenarios. The signal of projected precipitation in CMIP6 models over the Arabian Peninsula is in agreement with CMIP5 model projections over the same region. The precipitation

variability is reduced in the central Peninsula for the CMIP6 ensemble, as compared to CMIP3 and CMIP5.

3.3 Likelihood of Projected Temperature and Precipitation Signal over the Arabian Peninsula

Projected changes in temperature over the Arabian Peninsula show a large increase in the annual and summer season, which remains a bit higher as compared to the winter (upper panels, Fig. 9). Over the AP, the annual increase of temperature is projected to be 1.56 (1.63) °C with a likely range of 1.16 (1.24)–1.89 (2.1) °C for SSP1–2.6 in the near (far) future (Table 3). The increase will be 1.73 (2.7) °C with a likely range of 1.41 (2.27)–2.08 (3.39) °C under SSP2–4.5, and 2.17 (5.03) °C with a likely range from 1.81 (4.13) to 2.67 (5.81) °C under SSP5–8.5, in the near (far) future. It is worth mentioning that while likely ranges remain similar in the high emission scenario, the full ranges of temperatures are higher in CMIP6 as compared to CMIP5. This points towards the higher sensitivity of CMIP6 climate models to the greenhouse gas (GHG) emissions.

Table 3 CMIP6 simulated changes in mean temperature (°C) shown as the median with likely and full ranges for the Arabian Peninsula (AP), Northern Arabian Peninsula (NAP), and Southern Arabian Peninsula (SAP) for the near (2030–2059) and far (2070–2099) futures with reference to the base period (1981–2010) under three different SSP scenarios

Season	Region	Scenario	2030–2059			2070–2099		
			Median	Likely range	Full range	Median	Likely range	Full range
Annual	AP	SSP1–2.6	1.56	1.16–1.89	0.76–2.44	1.63	1.24–2.1	0.67–2.8
		SSP2–4.5	1.73	1.41–2.08	1.14–2.74	2.7	2.27–3.39	1.79–4.3
		SSP5–8.5	2.17	1.81–2.67	1.37–3.48	5.03	4.13–5.81	3.37–7.81
	NAP	SSP1–2.6	1.68	1.26–1.96	0.72–2.53	1.79	1.32–2.19	0.45–2.89
		SSP2–4.5	1.85	1.5–2.26	1.1–2.88	2.9	2.37–3.47	1.78–4.46
		SSP5–8.5	2.3	2–2.79	1.43–3.64	5.32	4.42–6.06	3.45–8.1
	SAP	SSP1–2.6	1.48	1.07–1.77	0.8–2.35	1.46	1.1–1.99	0.82–2.69
		SSP2–4.5	1.58	1.3–1.96	1–2.58	2.59	2.07–3.2	1.79–4.12
		SSP5–8.5	2.02	1.55–2.42	1.22–3.29	4.77	3.91–5.63	3.14–7.46
	AP	SSP1–2.6	1.64	1.17–2.08	0.93–2.46	1.78	1.12–2.31	0.84–2.92
		SSP2–4.5	1.82	1.57–2.26	1.2–2.78	2.92	2.33–3.54	1.95–4.42
		SSP5–8.5	2.37	1.85–2.78	1.48–3.54	5.21	4.14–6.14	3.32–7.85
	NAP	SSP1–2.6	1.87	1.27–2.35	0.99–2.62	1.96	1.4–2.57	0.9–3.09
		SSP2–4.5	2.06	1.69–2.56	1.36–2.97	3.28	2.64–3.85	2.11–4.72
		SSP5–8.5	2.72	2.08–3.1	1.63–3.76	5.87	5.06–6.72	3.63–8.27
	SAP	SSP1–2.6	1.39	0.91–1.88	0.64–2.28	1.51	0.91–2.06	0.7–2.72
		SSP2–4.5	1.59	1.21–1.93	0.93–2.55	2.57	1.83–3.22	1.66–4.08
		SSP5–8.5	1.9	1.41–2.42	1.13–3.28	4.71	3.28–5.61	2.97–7.37
Winter	AP	SSP1–2.6	1.43	1.04–1.82	0.64–2.76	1.35	1.08–1.94	0.24–3.09
		SSP2–4.5	1.57	1.27–2.07	0.9–2.71	2.52	2.02–3.28	1.83–4.47
		SSP5–8.5	1.9	1.51–2.62	1.09–3.38	4.68	3.77–5.73	3.25–7.64
	NAP	SSP1–2.6	1.53	1.14–1.91	0.6–2.74	1.41	1.12–2.04	–0.04–3.13
		SSP2–4.5	1.54	1.26–2.01	0.71–2.81	2.5	2.06–3.09	1.61–4.47
		SSP5–8.5	1.91	1.59–2.49	0.93–3.49	4.74	3.69–5.69	3.23–7.92
	SAP	SSP1–2.6	1.43	1.06–1.79	0.68–2.78	1.32	1.05–1.98	0.55–3.05
		SSP2–4.5	1.51	1.24–2.13	0.88–2.62	2.53	2.06–3.22	1.74–4.46
		SSP5–8.5	1.97	1.53–2.6	1.11–3.33	4.7	3.87–5.63	3.05–7.35

In the summer season, the increase of temperature over the Peninsula will be 1.64 (1.78) °C, 1.82 (2.92) °C, and 2.37 (5.21) °C, under SSP1–2.6, SSP2–4.5, and SSP5–8.5, respectively, for the near (far) future. In the winter season, the increase in the projected temperature is expected to be 1.43 (1.35) °C, 1.57 (2.52) °C, and 1.9 (4.68) °C, under SSP1–2.6, SSP2–4.5, and SSP5–8.5, respectively, for the near (far) future. The projected increase in the summer temperature is larger than the projected increase in the winter temperature. The NAP is also warming faster than the SAP. For example, the increase in NAP summertime temperature is projected to be 5.87 °C, but only 4.71 °C for the SAP at the end of the twenty-first century under SSP–8.5. Similarly, the increase in the annual (winter) projected temperature over NAP is 5.32 (4.74) °C, compared with 4.77 (4.70) °C for SAP under SSP5–8.5. A detailed description of the likely and full ranges associated with projected temperatures

over AP, NAP, and SAP is available in Table 3. Under the SSP5–8.5 scenario, NAP warming is projected to be faster than SAP warming in both summer and winter. Irrespective of the season, region, and scenario, the temperature over the Arabian Peninsula is projected to rise in the twenty-first century. Moreover, the warming over the northern Peninsula will be greater compared to the southern Peninsula in the future. These results are in agreement with the previous studies based on CMIP3 and CMIP5 datasets over Arabian Peninsula (see Almazroui et al. 2016, 2017b).

The projected precipitation also shows robust changes, either increasing or decreasing, over the Arabian Peninsula in the future period for the annual and wet season (Fig. 10). A detailed description of the precipitation changes over AP, NAP, and SAP during the wet season and annual time scale is given in Table 4. By the end of the twenty-first century, the wet season precipitation is projected to

Fig. 10 Same as Fig. 9 expect showing changes in precipitation for the annual and wet season

increase by 5.31/12.23/25.05% under SSP1–2.6, SSP 2–4.5, and SSP5–8.5, respectively, over the Arabian Peninsula (Table 4). For the same period and under the same scenarios, annually, the precipitation averaged over the Arabian Peninsula is likely to increase by 3.76/16.87/31.83%, respectively. Moreover, the annual precipitation is projected to increase more over SAP (10–51%) as compared to NAP (2–19%). Precipitation projections for the wet season are similar (see Table 4). A detailed description of changes in precipitation with associated likely and full ranges under different SSP scenarios for the near and far future with reference to the base period are tabulated in Tables 4. Hence, it is clear that the southern Peninsula is likely to receive more precipitation than the northern Peninsula at the end of the twenty-first century, which is in line with findings obtained from the CMIP3 and CMIP5 datasets (Almazroui et al. 2016, 2017b).

3.4 Trends in Projected Temperature and Precipitation Changes over the Arabian Peninsula

The changes in temperature and precipitation under three SSP scenarios (SSP1–2.6, SSP2–4.5 and SSP5–8.5) for the entire Arabian Peninsula (AP), northern Arabian Peninsula (NAP), and southern Arabian Peninsula (SAP), for the period 2030–2099 with reference to the base period 1981–2010, are shown in Fig. 11. The median values indicate the trends, and the likely ranges (66% around the median) represent the uncertainty ranges. The increase in temperature with reference to the base period will attain maximum value in the 2050s under the SSP1–2.6 scenario, and afterward, the increase is projected to be a bit slower for AP, NAP, and SAP. Over the AP, the rate of temperature

Table 4 CMIP6 simulated changes in mean precipitation (in %) shown as the median with likely and full ranges for the Arabian Peninsula (AP), Northern Arabian Peninsula (NAP), and Southern Ara-

bian Peninsula (SAP) for the near (2030–2059) and far (2070–2099) futures with reference to the base period (1981–2010) under three different SSP scenarios

Season	Region	Scenario	2030–2059			2070–2099		
			Median	Likely range	Full range	Median	Likely range	Full range
Annual	AP	SSP1–2.6	9.56	5–27.92	–15.08–74.45	3.76	–2.56–28.8	–13.29–98.97
		SSP2–4.5	15.54	4.86–31.27	–25.79–57.99	16.87	3.79–48.63	–12.59–85.54
		SSP5–8.5	16.73	0.61–37.97	–10.44–71.03	31.83	11.98–106.52	–8.52–220.78
	NAP	SSP1–2.6	6.17	–2.49–20.86	–11.6–61.55	2.08	–6.41–26.98	–15.07–83.87
		SSP2–4.5	9.13	–2.87–29.27	–15.43–49.9	11.87	0.34–34.45	–14.34–75.88
		SSP5–8.5	14.85	–2.41–22.51	–14.78–46.4	18.89	–0.71–69.54	–14.09–129.6
	SAP	SSP1–2.6	17.1	6.39–38.46	–19.1–89.31	10.32	–6.58–45.64	–19.36–116.35
		SSP2–4.5	20.84	1.58–44.47	–37.72–68.49	26.47	7.03–71.48	–10.58–129.42
		SSP5–8.5	24.17	5.09–63.13	–19.69–121.89	51.25	21–150.89	–7.06–330.71
Wet	AP	SSP1–2.6	9.15	0.68–29.77	–19.50–80.11	5.31	–17.57–114.36	–9.50–28.80
		SSP2–4.5	10.16	–5.88–35.14	–26.42–61.10	12.23	–25.79–86.50	–6.77–45.26
		SSP5–8.5	10.01	–2.28–34.94	–20.53–75.19	25.06	–21.35–178.48	–1.80–96.68
	NAP	SSP1–2.6	5.25	–3.04–21.53	–16.60–61.20	1.73	–21.61–86.55	–10.78–28.23
		SSP2–4.5	8.05	–5.28–28.61	–26.12–52.11	5.30	–20.58–72.03	–4.53–32.12
		SSP5–8.5	2.97	–6.31–20.15	–31.98–46.11	10.28	–28.90–124.14	–14.84–54.99
	SAP	SSP1–2.6	11.91	4.90–36.04	–25.36–101.88	6.21	–25.39–146.38	–9.51–45.30
		SSP2–4.5	13.27	–2.08–35.27	–38.79–71.44	19.93	–31.79–104.32	–6.76–80.33
		SSP5–8.5	17.76	–4.47–58.59	–29.43–125.41	41.50	–28.81–338.246	–0.77–130.80

Fig. 11 The evolution of future changes in temperature (upper panels) and precipitation (lower panels) for the three regions i.e. Arabian Peninsula (AP, left column), Northern Arabian Peninsula (NAP, middle column) and Southern Arabian Peninsula (SAP, right column) during the twenty-first century. The gold, green and red curves represent the result for median values for SSP1-2.6, SSP2-4.5 and SSP5-

8.5 scenarios, respectively, and the shaded areas around each curve represent the likely range (66% of the projected changes). The curves are obtained by taking the difference of each future year with respect to the average from the control period (1981–2010) and then taking the 7-year running average

increase is projected to be $0.05\text{ }^{\circ}\text{C decade}^{-1}$ for the entire period, which includes changes of $0.21\text{ }^{\circ}\text{C decade}^{-1}$ in the

near future, and $-0.05\text{ }^{\circ}\text{C decade}^{-1}$ in the far future. For the NAP (SAP), the rate of increase of temperature is projected

to be 0.05 (0.04) $^{\circ}\text{C decade}^{-1}$ for the entire period, which results from 0.23 (0.22) $^{\circ}\text{C decade}^{-1}$ in the near future and -0.03 (-0.08) $^{\circ}\text{C decade}^{-1}$ in the far future. For the SSP2–4.5 scenario, the increase in temperature is higher than that in the SSP1–2.6 scenario. Hence the increase will be at the rate of 0.26 $^{\circ}\text{C decade}^{-1}$ for the entire period, or 0.34 $^{\circ}\text{C decade}^{-1}$ for the near future and 0.16 $^{\circ}\text{C decade}^{-1}$ for the far future over the AP. The NAP shows a large increase rate (0.29 , 0.34 , and 0.18 $^{\circ}\text{C decade}^{-1}$ for the entire period, near future and far future, respectively) as compared to the SAP (0.27 , 0.33 , and 0.17 $^{\circ}\text{C decade}^{-1}$ for the entire period, near future and far future, respectively). The SSP5–8.5 scenario shows a gradual increase in temperature, but still higher than in the other two scenarios. The increase rate is projected to be 0.70 , 0.58 , and 0.87 $^{\circ}\text{C decade}^{-1}$ for the entire period, near future, and far future, respectively, over the AP. Over the NAP (SAP), the rise of temperature will be 0.79 (0.68), 0.64 (0.56), and 0.98 (0.75) $^{\circ}\text{C decade}^{-1}$ for the entire period, near future and far future, respectively. All the trends are significant at the 99% confidence level. There is a clear indication that NAP is warming at a higher rate than the SAP for the SSP5–8.5 scenario, and the increase at the end of the century will be higher compared to the previous decades. These results are in line with the CMIP3 and CMIP5 results over the Peninsula (Almazroui et al. 2016, 2017b).

The changes in precipitation for the future climate clearly indicate an increase for the SAP, which is most prominent in SSP5–8.5, while it gradually becomes less pronounced for the other two scenarios. This behavior is also reflected over the full AP. However, NAP does not show a clear trend in any of the scenarios. Over the AP, precipitation will decrease at the rate of 0.83 , 1.27 , and 2.18% decade^{-1} under the SSP1–2.6 scenario for the entire period, near future and far future, respectively. In the case of the SSP2–4.5 (SSP5–8.5) scenario, the projected rate of change is 1.12 (4.27), 2.77 (2.93), and 0.32 (4.17) $\% \text{decade}^{-1}$ for the entire period, near future, and far future, respectively. Over NAP, it is projected at $-0.73/-0.36/2.16$, $-0.73/-0.34/2.16$, and $-1.26/1.02/6.46\%$ decade^{-1} for the SSP1–2.6/SSP2–4.5/SSP5–8.5 scenarios for the entire period, near future, and far future, respectively. Over the SAP, this rate is projected at $-1.26/1.02/6.46$, $0.77/4.25/6.73$, and $-4.90/-3.96/8.56\%$ decade^{-1} for the SSP1–2.6/SSP2–4.5/SSP5–8.5 scenarios for the entire period, near future and far future, respectively. All the trends are significant at the 99% confidence level, except for the SSP2–4.6 scenario over NAP and AP. It is important to note that the likely ranges are very wide for the precipitation, which implies that there is a large variation in the simulation of precipitation from model to model and the uncertainty is very high, at least from the 2050s onwards during the twenty-first century.

4 Conclusions

This study analyzed the multimodel ensemble from 31 CMIP6 models and examined the changes in projected temperature and precipitation over the Arabian Peninsula during the twenty-first century. We first analyzed a more updated and quality controlled observational dataset for the period 1978–2019. The observations reveal a significant increasing trend in temperature (0.51 $^{\circ}\text{C decade}^{-1}$) and a decreasing trend in precipitation (6.3 mm decade^{-1}) over the Arabian Peninsula. In the next step, the changes in projected temperature and precipitation are examined for the near future (2030–2059) and far future (2070–2099) periods, relative to the base period (1981–2010), under three SSP scenarios: SSP1–2.6, SSP2–4.5, and SSP5–8.5. Results indicate robust changes in temperature and precipitation over the Arabian Peninsula during the twenty-first century. The annual mean temperature shows a continuous increase over the Arabian Peninsula in the twenty-first century under three future scenarios. Under SPP2–4.5 (SSP5–8.5) scenarios, the temperature is projected to increase by 1.74 (2.17) $^{\circ}\text{C}$ in the near future and 2.87 (5.28) $^{\circ}\text{C}$ in the far future periods as compared to the base period. Moreover, the rate of increase of annual mean temperature is projected to be 0.34 (0.16) $^{\circ}\text{C decade}^{-1}$ over the Arabian Peninsula in the near (far) future periods under the SSP2–4.5 scenario. Under the SSP2–4.5 scenario, the NAP shows a large rate of increase (0.34 $^{\circ}\text{C}$ and 0.18 $^{\circ}\text{C decade}^{-1}$ for the near future and far future, respectively) as compared to the SAP (0.33 $^{\circ}\text{C}$ and 0.17 $^{\circ}\text{C decade}^{-1}$ for the near future and far future, respectively). The temperature is projected to rise by 0.58 and 0.87 $^{\circ}\text{C decade}^{-1}$ for the near future and far future, respectively, under the SSP5–8.5 scenario over the Arabian Peninsula. Under the SSP5–8.5 scenario, the rate of increase in temperature over the NAP (SAP) is projected to be 0.64 (0.98) $^{\circ}\text{C}$ and 0.56 (0.75) $^{\circ}\text{C decade}^{-1}$ for the near future and far future, respectively. These results indicate that the sensitivity of some of the CMIP6 climate models to GHG emissions is higher than the CMIP5 models.

The projected precipitation shows a robust increase (decrease) in annual mean precipitation over the southern (northern) Arabian Peninsula by the end of the twenty-first century under the three future scenarios. The projected precipitation over central parts of the Arabian Peninsula displays large variability in the future climate. Under three emission scenarios, the annual mean precipitation averaged over the Arabian Peninsula is likely to increase by 3.76 – 31.83% by the end of the twenty-first century. The northwestern parts of the Arabian Peninsula show a significant reduction, while southern parts of the Peninsula display a significant increase in annual mean precipitation by the end of the twenty-first century. The wet season precipitation

is also projected to increase more over the SAP as compared to NAP under all future scenarios. The uncertainty associated with the projected precipitation increases with time; however, the projected precipitation patterns are consistent among the three SSP scenarios.

The results presented in this study are in agreement with previous publications over this region carried out with CMIP3 and CMIP5 datasets (Almazroui et al. 2016, 2017b). Overall, the CMIP6 results further enhanced our confidence in future projections of temperature and precipitation over the Arabian Peninsula for the twenty-first century. The findings of the present study will be useful for further impact studies, and ultimately for the development of adaptation strategies over the region.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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