Intercomparison of Historical Simulation and Future Projection of Rainfall and Temperature by CMIP5 and CMIP6 GCMs Over Egypt

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Abstract

The performances of the Global Climate Models (GCMs) of recently released Coupled Model Intercomparison Project phase 6 (CMIP6) compared to its predecessor, CMIP5 are evaluated to anticipate the expected changes in climate over Egypt, globally one of the most environmentally fragile countries due to water insecurity and climate change. Thirteen common GCMs and their multi-model ensemble (MME) of both CMIPs were used for this purpose. The future projections were compared for two radiative concentration pathways (RCP 4.5 and 8.5), and two shared socioeconomic pathways (SSP 2-4.5 and 5-8.5) scenarios. The results revealed improvement in most CMIP6 models in replicating historical rainfall, maximum temperature (Tmax) and minimum temperature (Tmin) climatology over Egypt. The MME of the CMIPs revealed that both could reproduce the spatial distribution and seasonal variability of climate in Egypt. However, the bias in CMIP6 is much less than that for CMIP5. The uncertainty in simulating seasonal variability of rainfall and temperature was lower for CMIP6 compared to CMIP5. The future projection of rainfall using CMIP6 MME revealed a higher reduction of precipitation (4 to 10 mm) in the economically crucial northern region compared to that estimated using CMIP5 (10 to >15 mm). CMIP6 also projected a 1.5 to 2.5°C more rise in Tmax and Tmin compared to CMIP5. The study indicates more aggravated scenarios of climate changes in Egypt than anticipated earlier, using the CMIP5 model. Therefore, Egypt needs to streamline the existing adaptation measures formulated based on CMIP5 projections.

1. Introduction

Reliable information of possible changes in future climate is vital for planning sustainable development. Generally, Global Climate Models (GCMs) are used for providing future climate information. The GCMs project future climate based on different assumptions of future changes of greenhouse gas (GHG) emissions, land use and socio-economy (Taylor et al. 2011; van Vuuren et al. 2011; Chen et al. 2014). The global GHG emissions and socioeconomic changes depend on political strategies at national, regional and global levels. Climate modelers update climate projections by apprising restructured socioeconomic and land use change scenarios and enhancing modeling techniques. Climate change adaptation and mitigation policies need to streamline based on the updated projections to improve their effectiveness. This is particularly crucial for environmentally fragile regions where minor climate changes can have severe implications for different service sectors.

Egypt is located in North Africa, one of the environmentally most fragile regions of the world (AFED 2017; Collins et al. 2017). The climate in most of the region is hyper-arid (86%) or arid (14%) which has made the country water-deficient and environmentally fragile. High aridity has made about 96% of Egypt a desert. The rest of the land is mainly used for human settlement and agricultural activities. The agriculture sector employs 24 million or nearly 24% of the population and contributes 11% of gross domestic product (GDP) in the country, much higher than the global average (FAO 2020). Agriculture in the country completely depends on the water supply of the Nile River, as Egypt is one of the driest countries in the world. The per capita renewable water in Egypt has declined from 853.5 m³ in 2002 to

722.2 m³ in 2012 (Osman et al. 2016). The rapid declination of renewable water resources has caused a significant impact on water resources, agriculture and livelihood of the vast populace of the country (Nashwan and Shahid 2019).

Egypt experienced a rapid change in climate in recent years. The maximum temperature in the country has increased by 0.07 to 0.24°C/decade and the minimum temperature by 0.08–0.29°C/decade in the last five decades (Nashwan et al. 2019a). The rainfall decreases up to -5.0 mm/decade in the Nile delta (Nashwan et al., 2019), which shares 99.94% of the country's irrigated agriculture and 95% of the total population. This has made the country a hot spot for climatic extremes and aridity. A large increase in extreme temperature days, consecutive hot days, and 1-day maximum precipitation has been reported over 1948–2010. The reduction in mean rainfall but an increase in 1-day maximum rainfall caused an increase in droughts and floods. Rising temperature also increased heatwaves, aridity and desertification. Abahussain et al. (2002) reported that 81.75% of non-desert land in Egypt is under the threat of desertification. Understanding possible climate changes are crucial for the country to anticipate future water stress and aridity and their implications in agriculture and the economy.

Several studies have been conducted to evaluate the changes in climate in Egypt (Baldi et al. 2020; Elbeltagi et al. 2020; Nashwan and Shahid 2020; Nashwan et al. 2020a; Shalby et al. 2020) and nearby regions (Wasimi 2010; Schilling et al. 2012; Terink et al. 2013; Almazroui et al. 2016; Ozturk et al. 2018; Zittis et al. 2021). However, all the projections were based on Climate Model Intercomparison Project phase 5 (CMIP5) GCMs and representative concentration pathway (RCP) scenarios. Recently, a new set of GCM projections have been released under CMIP6. Unlike the previous phase, CMIP6 includes and applied more comprehensive models and experiments to answer a wider variety of scientific queries (Eyring et al. 2016, 2019; Stouffer et al. 2017; Goldenson et al. 2018; Bock et al. 2020). CMIP6 also differs from earlier phases in terms of new future forcing scenarios. Compared to the earlier socioeconomic forcing-based RCPs, CMIP6 employs a framework of Shared Socioeconomic Pathways (SSPs). The new pathways include a bundle of future mitigation, adaptation actions on climate change based on future economic and social projected changes like population and social aspects, resources and economic development, ecosystems, and institutions (O'Neill *et al.*, 2016). The projections for new scenarios can better assess climate change policy impacts through an improved socioeconomic coupling. It would also fill critical gaps in understanding the effects of different forcings, such as land use, temperature overshoots, etc. Besides, CMIP6 is an effort to reduce or eliminate these biases over the different phases of CMIP. CMIP6 emphasizes coordinated experiments to better understand the mechanisms that produce climate variability. Therefore, CMIP6 GCMs are supposed to reduce the model biases more than the earlier version (Iqbal et al. 2021; Song et al. 2021b). Therefore, it is important to conduct a study to assess the relative changes in climate projection between CMIP5 and CMIP6.

The objective of the present study is to assess the relative historical performance and future projections of the GCMs of CMIP5 and CMIP6 in Egypt. Thirteen GCMs common to both CMIP5 and CMIP6 are used for this purpose. The capability of the models was assessed in simulating the spatial and temporal variability of climate for both annual and seasonal scales. Besides, the CMIP5 and CMIP6 GCMs'

projections with associated uncertainty were compared to provide important information on relative changes in climate projection by the CMIPs. The comparison of precipitation and temperature projections of CMIP5 and CMIP6 would help in streamlining the existing adaptation measures formulated based on CMIP5 projections or deriving new measures based on new scenarios of CMIP6.

2. Study Area And Data

2.1. Study Area

The study area considered in this paper is Egypt, lying between latitude 22° – 32°N and longitude 25° – 35°E with an area of around 1,000,000 km². Egypt consists of many distinct climatic regions (Ibrahim et al. 1994; HBRC 2006; Noreldin et al. 2016; Ouda and Norledin 2017). Some areas have high annual rainfall (70 to 200 mm), like the Northern Coast lying to the Mediterranean Sea (Nashwan et al. 2020b). Others like the southern region receives almost no rain all year. Also, the southeastern region has the highest minimum and maximum temperature in Egypt. Furthermore, the Sinai Mountains, located in the northeastern peninsula, have the lowest minimum temperature (0.4 to 12.0°C) in Egypt. The local climate of Egypt consists of two main seasons. The weather is rainy and cold in winter between September and February, while it is dry and cool in the summer between March and August (Nashwan et al. 2019a). Elevation in the region ranges from – 130 to 2494 m, with the highest elevation in Saint Catherine Mountains, Sinai.

2.2. Gridded database

This study used a reanalysis gridded dataset, Climatologies at high resolution for the Earth's land surface areas (CHELSA) version 1.2 (from 1979 to 2013), for assessing GCM's performance in simulating rainfall, maximum and minimum temperatures (Tmax, and Tmin, respectively). CHELSA is a monthly dataset of the three climatic variables (e.g., rainfall, Tmax, and Tmin) with a very high spatial resolution of 30 arcsec (Karger et al. 2017). Downscaling daily average temperature data from ERA-Interim six-hourly monthly means produced CHELSA temperature product, and the orographic bias correction of the global precipitation climatology centre (GPCC) data produced CHELSA rainfall. CHELSA was chosen to represent the historical climate of Egypt due to several factors. First, Egypt is a poorly gauged-covered country (Nashwan et al. 2019b), and CHELSA is a very high spatial resolution product that covers the entire country even at un-gauged locations. Second, the quality of CHELSA estimates was verified over Egypt, and it showed a high capacity in reproducing the monthly gauge records even better than GPCC rainfall estimations (Hamed et al. 2021).

Figure 2 shows the geographical distribution of annual mean rainfall, Tmax and Tmin over Egypt. Southeast Egypt experiences the highest Tmax, and the northern coastal region experiences the least, while Tmin is highest in the southeast and lowest in the southwest and elevated northeast region. Rainfall in Egypt is most concentrated in the northern coastal region, while the rest of the country receives a rainfall lower than 16 mm.

2.3. Global Climate Models

Thirteen CMIP5 and CMIP6 GCM's were used in the comparison between the CMIPs phases over Egypt. Table 1 lists the GCMs and their basic description. CMIP5 introduced radiation concentration pathways (RCPs), which explored various potential greenhouse gas emissions scenarios. CMIP6 uses socioeconomic shared pathways (SSPs) for climate projection that considers potential shifts in Earth's environment and global economic and demographic shifts. The radiative forcing in CMIP6 SSP2-4.5 and SSP5-8.5 scenarios are equivalent to CMIP5 RCP 4.5 and 8.5 scenarios. The GCMs were selected following the criteria: (i) availability of the upgraded version of the CMIP5 GCMs from the same institute, (ii) availability of projections of three main climate variables rainfall, Tmax and Tmin, and (iii) availability of future projection for RCP 4.5 and 8.5 (CMIP5) and SSP 2-4.5 and 5-8.5 (CMIP6). The spatial resolution of the selected GCMs ranges from 0.70° to 3.70°. The historical simulation and future projection of GCM's monthly rainfall, Tmax, and Tmin were collected from two different data portals (CMIP5: <https://esgf-node.llnl.gov/search/cmip5/>; CMIP6: <https://esgf-node.llnl.gov/search/cmip6/>).

Table 1
Description of CMIP5 and CMIP6 GCMs used in this study.

Institution / Country	Abbreviation	CMIP 5		CMIP 6	
		Model	Resolution	Model	Resolution
Australian Research Council Centre of Excellence for Climate System Science, Australia	ACCESS	ACCESS1-3	1.90 × 1.20°	ACCESS- CM2	1.87 × 1.25°
Beijing Climate Center, Beijing, China	BCC	BCC- CSM1.1-M	2.80 × 2.80°	BCC- CSM2- MR	1.12 × 1.12°
Euro-Mediterranean Centre on Climate Change coupled climate model, Italy	CMCC	CMCC-CM	0.70 × 0.70°	CMCC- ESM2	0.94 × 1.25°
Canadian Centre for Climate Modelling and Analysis, Victoria, Canada	CANESM	CANESM2	2.80 × 2.80°	CanESM5	2.79 × 2.81°
EC-Earth Consortium, Europe	EC-EARTH	EC-EARTH	1.10 × 1.10°	EC-Earth3	0.35 × 0.35°
Chinese Academy of Sciences Flexible Global Ocean- Atmosphere–Land System model, China	FGOALS	FGOALS- g2	2.80 × 2.08°	FGOALS- g3	2.00 × 2.00°
Geophysical Fluid Dynamics Laboratory, NJ, USA	GFDL-ESM	GFDL- ESM2G	2.50 × 2.00°	GFDL- ESM4	1.00 × 1.25°
Institute for Numerical Mathematics, Russia	INMCM	INMCM4.0	2.00 × 1.50°	INM-CM5- 0	2.00 × 1.50°
Institute Pierre Simon Laplace (IPSL), Paris, France	IPSL-CM-LR	IPSL- CM5A-LR	3.70 × 1.90°	IPSL- CM6A-LR	2.50 × 1.27°
Japan Agency for Marine- Earth Science and Technology (JAMSTEC), Kanagawa, Japan	MIROC	MIROC5	1.40 × 1.40°	MIROC6	1.40 × 1.40°
Max Planck Institute for Meteorology (MPI-M), Germany	MPI-ESM- HR	MPI-ESM- MR	1.90 × 1.90°	MPI- ESM1-2- HR	0.94 × 0.94°
Max Planck Institute for Meteorology (MPI-M), Germany	MPI-ESM-LR	MPI-ESM- LR	1.90 × 1.90°	MPI- ESM1-2- LR	1.87 × 1.86°
Meteorological Research Institute, Ibaraki, Japan	MRI	MRI- CGCM3	1.10 × 1.10°	MRI- ESM2-0	1.12 × 1.12°

3. Methodology

In this study, the CMIP5 and CMIP6 GCMs replicate the historical annual rainfall, Tmax and Tmin over Egypt. CHELSA reanalysis gridded dataset was used as a reference to represent the historical climate of the study area. For an unbiased comparison of GCMs hindcasts and forecasts, all the GCM simulations were gridded to a common resolution of 1.0°×1.0°. CHELSA rainfall and temperature data were also aggregated to the resolution of 1.0°×1.0°. The methods used for the comparison of GCMs are elaborated below.

3.1. Comparison of GCM's performance

The relative performance of CMIP5 and CMIP6 GCMs were evaluated using a statistical metric and a graphical method in a common study period (1979 to 2005). The Kling-Gupta efficiency (KGE) (Gupta et al. 2009; Kling et al. 2012) metric was used to evaluate the statistical performance of the GCMs. KGE assesses bias, correlation, and variability together and provides an integrated metric in a range of 1 to -∞, where 1 indicating a perfect match and its equation is shown in equ. (1). It combines Pearson's correlation (r), the ratio of spatial variability and the normalized difference between the gridded dataset (CHELSA) and each GCM model into one metric.

$$KGE = 1 - \sqrt{(r - 1)^2 + \left(\frac{\mu_{GCM}}{\mu_{ref}} - 1\right)^2 + \left(\frac{\sigma_{GCM}/\mu_{ref}}{\sigma_{ref}/\mu_{ref}} - 1\right)^2} \quad (1)$$

where μ_{GCM} and μ_{ref} are the mean, and σ_{GCM} and σ_{ref} are the standard deviation for GCM and CHELSA data, respectively.

The Taylor diagram (Taylor et al. 2011) was used to graphically represent the relative performance of CMIP5 and CMIP6 GCMs. The Taylor diagram provides a concise statistical summary of the degree of correlation (SCC: spatial correlation coefficient (SCC)), centered root-mean-square error (CRMSE), and the ratio of spatial standard deviation (SD) and thus, provides a composite comparison of model performance.

3.2. Future projections of climate

CMIP5 and CMIP6 GCM rainfall and temperature projections for RCP and SSP scenarios, respectively, for two main periods near (2020–2059) and far future (2060–2099) were compared to that of their reference period (1979–2005) to assess the relative changes in Egyptian future climate. The projections of the GCMs for each scenario were used to estimate their ensemble mean and 95% confidence band of projection interval to evaluate the relative changes and associated uncertainty by different CMIP GCMs

for different scenarios. Besides, the maps were prepared to show the difference in the spatial distribution of rainfall and temperature projections by CMIP5 and CMIP6 GCMs.

4. Results

4.1. Performance evaluation of CMIP5 and CMIP6 GCMs

The performances of CMIP5 and CMIP6 GCMs in reproducing the annual rainfall, Tmax and Tmin based on KGE metric are shown in Fig. 3. The figure presents three radar charts, one for each climate variable. Each radar chart presents the KGE values of each model for the two CMIP phases (CMIP5 in light green and CMIP6 in light red). For better representation, KGEs less than zero in rainfall radar were replaced by zero. The figure shows higher KGEs for CMIP6 models for all three variables, indicating better performance than their older versions in CMIP5, except for few models. Furthermore, the CMIP6 models could replicate historical Tmax more accurately than Tmin, which is also better than rainfall. The upgraded models simulated historical Tmax was better than their older versions, except for BCC, IPSL-CM-LR and MIROC. In addition, BCC, CanESM, and EC-Earth CMIP5 were better for Tmin and MRI and MPI-ESM-LR for rainfall. CanESM and MPI-ESM-HR of CMIP6 were the best models in simulating Tmax (KGE = 0.90). Besides, CanESM was the best model in simulating historical rainfall (KGE = 0.75), which showed a zero KGE for its CMIP5 version. ACCESS, MRI and IPSL-CM-LR were the best to simulate historical Tmin (KGEs 0.83, 0.84, and 0.82, respectively) in CMIP6, while CanESM and EC-Earth were the best in CMIP5.

4.2. Taylor diagram of GCMs performance

Figure 4 presents the Taylor diagrams of the annual rainfall, Tmax and Tmin for the CMIP5 and CMIP6 GCMs. The hollow circle in the x-axis indicates CHELSA reanalysis product for rainfall and temperature (reference data). The coloured circles designate the CMIP5 models, while the triangles designate CMIP6 models. The GCM model near the reference circle and lies on its curve indicate better performance in replicating the historical climate of Egypt.

The correlation between CHELSA and GCMs models is better in Tmax, followed by rainfall and Tmin. For Tmax, the correlation between CHELSA and both CMIP models was an average of 0.87, indicating good relationships. For Tmin, the correlation ranged from 0.6 to 0.9, while the rainfall showed an average correlation of 0.85. BCC-CSM1.1-m showed a very high overestimation of annual rainfall, while MRI-CGCM3 showed the highest underestimation. BCC-CSM1.1-m and MPI-ESM1-2-HR showed the highest overestimation of Tmax. The standard deviation of all models was ranged from 0.5 to 1.5 for Tmin.

4.3. Seasonal variability of GCM models with CHELSA

The seasonal variabilities of the historical rainfall and temperature estimates of CMIP5 and CMIP6 GCMs were compared with those of CHELSA. The upper panel of Fig. 5 shows the month-to-month rainfall

variability of median estimates of CMIP5 GCMs as a dashed red line compared to that of CHELSA as a solid black line. Furthermore, each month's 95% confidence interval band estimates are presented to indicate the uncertainty and inter-model variability. The lower panel of the figure shows the same but for CMIP6 models. Both CMIPs' models overestimated the month-to-month rainfall in Egypt for the whole year except CMIP5 in January and February in CMIP6. However, the CMIP6 median was much closer to CHELSA than CMIP5, indicating the improvement of CMIP6 in simulating the seasonal variability of rainfall in Egypt. Furthermore, the uncertainty range in estimation was much higher in CMIP5 compared to CMIP6. The uncertainty range was very wide from February to June and August to October in CMIP5, which dramatically decreased for the later period in CMIP6.

Overall, underestimating Tmax by CMIP5 and CMIP6 GCMs' medians can be observed from Fig. 6 for all months except for June, July and August in CMIP6. However, the Tmax uncertainty band was wider in CMIP6 during summer compared to CMIP5. Furthermore, the figure shows that the inter-model variability (bandwidth) in CMIP5 was nearly consistent all year round. Although of this uncertainty, the overall performance of the CMIP6 ensemble was better than CMIP5 in replicating CHELSA Tmax.

Generally, CMIP5 and CMIP6 models were better in replicating the month-to-month variability of Tmin than Tmax and rainfall, as shown in Fig. 7. Slight underestimation was noticed in CMIP5 in all months except for two periods (February – March and June – July). The median of CMIP6 was nearly identical with CHELSA, except for a slight overestimation during the hottest months (June to September). The inter-model variability was much wider for CMIP5 than CMIP6 in Tmin, which was also wider when compared to Tmax.

4.4. Spatial distribution of bias in GCM MME

The simulations of CMIP5 and CMIP6 models were individually averaged to prepare the corresponding MMEs. The MMEs were compared to CHELSA to assess the spatial distribution of bias in GCMs simulations. The absolute bias of mean annual rainfall, Tmax and Tmin of the MME of both CMIP phases are presented in Fig. 8. The results show an improvement in CMIP6 in replicating the spatial variability for the three climate variables. The CMIP5 MME suffers from underestimating rainfall in the coastal north (-10 to -58 mm/year), where rainfall is heavier than in the south. This bias becomes less in the newer CMIP6 MME, where it ranges between -10 to -40 mm. However, the overestimation of northeastern rainfall became more in CMIP6, reaching 50 mm. The MMEs of both CMIPs overestimated the middle and south Egyptian rainfall, which may be related to the drizzle problem, explained in Dai (2011), which most of the GCMs faces for arid regions. Nonetheless, CMIP6 MME showed better estimates of rainfall than CMIP5 MME in few grids. CMIP5 MME also showed underestimation of historical Tmax and Tmin in most of Egypt except for few locations. In contrast, CMIP6 showed significant improvement. Bias in its simulation reached zero in some locations.

4.5. Projected annual rainfall, Tmax and Tmin

The future projections of rainfall are presented in Fig. 9 for the CMIP phases for median radiation scenarios (RCP4.5 for CMIP5 and SSP2-4.5 for CMIP6) and high radiation scenarios (RCP8.5 and SSP5-8.5). The projections for medium scenarios in both CMIPs are presented using blue and magenta colors, and the high scenarios using green and orange colors. The intermediate dashed lines in the figures represent the median projection, and the band represents the projections with a 95% confidence interval.

As shown in the figure, the median rainfall projections remained the same for the two CMIP phases for the same level of radiations. The projected rainfall of SSP2-4.5 was lower than RCP4.5 by around 5 mm during 2020–2040. In contrast, the projected rainfall in SSP5-8.5 was higher than RCP8.5 during the period 2080 to 2100. Furthermore, the inter-model variability was very wide for RCP4.5 and 8.5 projections, and thinner for the new future scenarios (SSP2-4.5 and 5-8.5). This indicates less uncertainty in the CMIP6 projections of rainfall in Egypt.

Tmax and Tmin showed a gradual increase in future projections for both CMIPs and scenarios, as shown in Fig. 10 and Fig. 11. For Tmax, CMIP5 and CMIP6 95% confidence interval band showed almost similar widths, but CMIP6 band showed an upward shift with an average of 1°C in difference, as shown in Fig. 10. Furthermore, the median of both SSPs showed a sharper rate of increase starting from 2045, which was not projected in both RCPs. Both scenarios of CMIP6 projected a higher increase in Tmax, reaching to 39°C for SSP5-8.5 at 2100. However, their medians were lower than CMIP5 from 2020 to 2040.

On the other hand, CMIP6 models projected higher Tmin than CMIP5, as shown in Fig. 11. The CMIP6 projections 95% confidence interval band was much thinner and shifted upward with an average of 0.5°C compared to CMIP5. The median Tmin was projected as 18.28°C and 19.31°C in 2100 for RCP4.5 and SSP2-4.5. In contrast, those were projected as 20.39°C and 21.13°C in 2100 for RCP8.5 and SSP5-8.5.

4.6. Projected changes in future rainfall, Tmax and Tmin

A multi-model mean ensemble (MME) was formed using the available GCMs for the two CMIP phases. Using the MME, the change in rainfall and temperatures were calculated and presented spatially for two futures (near: 2020–2059 and far: 2060–2099) compared to the base period (1979–2005) for the medium (RCP4.5 and SSP2-4.5) and high (RCP8.5 and SSP5-8.5) emission scenarios.

Figure 12 shows the spatial distribution for the projected changes in annual rainfall (mm). The MME of CMIP5 ensemble projected an increase in rainfall in most of Egypt under RCP4.5 and RCP8.5, with a higher rate under the RCP8.5 in the near future. However, rainfall was projected to decrease in the coastal north by 17.30 mm in the far future. It also projected an increase (8.60 mm) in rainfall in the south for both medium and high radiation scenarios. On the other hand, the CMIP6 MME projected a decreasing rainfall in the Mediterranean coast for the near future, becoming more intense in the far future, reaching –14.44 mm for SSP2-4.5 and –26.74 mm for SSP8-8.5. Also, the CMIP6 MME projected a higher rate of rainfall increase in the southern section of Egypt than that projected by CMIP5. The rainfall in the south was projected to increase 21.54 mm than the base period.

The spatial distribution of the change in Tmax estimated using the MME of the two CMIPs for two future scenarios is shown in Fig. 13. As expected, the Tmax was projected to increase for both futures periods and scenarios. The MME of CMIP6 projected a lower increase in Tmax than CMIP5 MME. For example, the spatial average of projected increase was 1.52°C for SSP2-4.5 and 1.81°C for RCP4.5 in 2020–2059. Besides, the spatial average of the projected increase was 4.27°C for SSP5-8.5 and 4.42°C for RCP8.5 in 2060–2099. Both MMEs projected a gradual change in Tmax where lower changes in the northern coast than the middle and upper (south) Egypt.

Figure 14 shows the spatial pattern in the change in Tmin over Egypt. Both CMIP5 and CMIP6 MMEs also projected an increase in Tmin with a similar spatial pattern like Tmax. Unlike Tmax, CMIP6 MME projected a higher increase in Tmin over Egypt than CMIP5 MME for both futures and projection scenarios. The spatial average of projected increase was 1.61°C for SSP2-4.5 and 1.03°C for RCP4.5 in 2020–2059. Also, the spatial average of the projected increase was 4.61°C for SSP5-8.5 and 3.80°C for RCP8.5 in 2060–2099.

5. Discussion

The present study assessed the performance of GCMs of CMIP5 and CMIP6 in simulating historical annual rainfall, Tmax and Tmin over Egypt for the period 1979–2005, and their projections for the futures. An arid and hyper-arid climate dominates Egypt. Scarce rainfall and high temperature have made the country one of the most water-stressed regions in the world. Moreover, the friable environment has made the country one of the climate change hotspots of the world. Performance of the CMIP5 and CMIP6 GCMs are evaluated in this study to aid climate service in this global climate hotspot.

Improvement in CMIP6 models' performance compared to CMIP5 models has been reported across the globe (Gusain et al. 2020; Zhu and Yang 2020; Kamruzzaman et al. 2021; Song et al. 2021c; Su et al. 2021). Zhu and Yang (2020) reported a higher ability of CMIP6 MME to reconstructing historical rainfall in the dry region of the Tibetan Plateau. Su et al., (2021) showed less bias in estimated droughts using CMIP6 GCMs in China. Ga et al., (2021) reported better capacity of CMIP6 GCMs in reproducing southern hemisphere westerlies. However, the lower or similar performance of CMIP6 GCMs compared to CMIP5 GCMs has also been reported in several studies (Srivastava et al. 2020; Zhu and Yang 2020; Song et al. 2021a). Zhu and Yang (2020) showed lower performance of CMIP6 MME in the wet region of the Tibetan Plateau. Song et al., (2021a) showed higher uncertainty in projections for SSP scenarios compared to RCP scenarios. Srivastava et al., (2020) showed similar bias in both CMIPs in reproducing climatology over the United States. The improvement or reduction in performance was also different for different regions. Therefore, it is important to assess the relative performance of the CMIP5 and CMIP6 GCMs at a regional scale. Besides, it is important to update the climate projections based on new scenarios to realigning the adaptation measures with new projections.

The present study evaluated the performance of 13 common CMIP5 and CMIP6 models. The performance was evaluated for both the individual models and their MME mean. In addition, the

performance of individual models in replicating historical climatology was evaluated using KGE, considering its capability to estimate three statistical indices (correlation, bias and variability) together. The results revealed improvement of most CMIP6 GCMs compared to their counterpart in CMIP5 in simulating rainfall and temperature in Egypt.

The MME of CMIP5 and CMIP6 GCMs were compared to evaluate their ability to estimate spatial and seasonal variability of rainfall and temperature. The CMIP6 GCM MME was better capable of replicating the seasonal variability of both rainfall and temperature. The uncertainty in seasonal variability of climate was much less for CMIP6 compared to CMIP5. This was particularly true for rainfall and T_{min}. Both MMEs showed wet bias in dry season rainfall. However, the bias was less for CMIP6 MME. Winter rainfall, which shares the major portion of total annual rainfall in Egypt, was reliably captured by CMIP6 MME, while CMIP5 MME showed a slight underestimation. Both the MME underestimated T_{max}, but the underestimation was less for CMIP6 MME. The seasonal variability T_{min} was also reliably captured by CMIP6 MME. Both the CMIP5 and CMIP6 MMEs could reproduce the spatial pattern of rainfall climatology over Egypt reasonably. However, both the MMEs underestimated rainfall in the northern high rainfall region and overestimated rainfall in the southern low rainfall region. But the biases are less for CMIP6 MME compared to CMIP5 MME.

The results collaborate with the findings in the nearby region. Bağçacı et al. (2021) evaluated the performance of CMIP6 and CMIP5 GCMs in Turkey. They used the MME of only the top four GCMs of both the CMIPs for evaluation. The results showed 11% less bias in rainfall and 6% less bias in temperature in CMIP6 MME compared to CMIP5 MME. Ayugi et al. (2021) compared CMIP6 and CMIP5 models in simulating mean and extreme rainfall over East Africa and reported less bias in CMIP6 MME. Zhu and Yang (2021) evaluated interannual characteristics of CMIP5 and CMIP6 rainfall simulation over North Africa and also showed better performance of CMIP6 models. Studies in other regions also showed better performance of CMIP6 GCMs compared to CMIP5 GCMs.

The present study showed that not all the CMIP6 GCMs have improvements over the CMIP5. Some of the CMIP6 GCMs showed poorer performance in replicating rainfall properties compared to their CMIP5 counterpart. MIROC5 compared to MIROC6 in simulating historical rainfall. CanESM of CMIP5 also showed better performance compared to its counterpart of CMIP6. However, it was noticed that no model was the best performing model for all the three climate variables. For example, CanESM was found the best for simulating T_{max} and rainfall but was the worst for T_{min}. Overall, the performances of CMIP6 GCMs and their MME were better than CMIP5 in Egypt.

Improvement in model resolution from one generation of CMIP to another generation improved the model's performance. For example, the spatial resolution of many CMIP5 models was higher than CMIP3 models. Sun et al., (2015) evaluated the performance of CMIP3 and CMIP5 GCMs. They concluded that improvement in CMIP5 models' skill over CMIP3 models was partially due to spatial resolution improvement. Improved parameterizations and additional process representations improve models' spatial resolution and eventually improve models' skills (Sheffield et al. 2013). The CMIP6 GCMs'

resolutions are not different from CMIP5. Therefore, the performance of CMIP6 GCMs is not much different from CMIP5 GCMs in most of the globe (Rivera and Arnould 2020; Chen et al. 2021; Yazdandoost et al. 2021). The improved performance of some of the CMIP6 GCMs may be due to enhanced parameterization. The present study revealed significant improvement in CMIP6 GCMs and their MME in replicating spatial distribution and seasonal variability of climate in Egypt than CMIP5.

In this study, GCMs were gridded into a resolution of $1^{\circ} \times 1^{\circ}$ for intercomparison. In literature, the performance of GCMs is evaluated for different grid spacings. CMIP5 GCMs have been re-gridded to $2^{\circ} \times 2^{\circ}$ resolution for comparison in a large number of studies as it was nearly equal to the mean grid size of CMIP5 GCMs (Salman et al. 2018; Ahmed et al. 2019, 2020; Iqbal et al. 2020; Khan et al. 2020). It has also been re-gridded to the most common resolution of investigated GCMs (Raju and D. Kumar 2014; Raju et al. 2017). However, CMIP5 and CMIP6 GCMs were mostly re-gridded to the resolution of $1^{\circ} \times 1^{\circ}$. For example, they were re-gridded to finer resolution ($1^{\circ} \times 1^{\circ}$) for comparison of their skill in South America (Rivera and Arnould 2020), East Asia (Chen et al. 2021), Iran (Yazdandoost et al. 2021) and south pacific oscillation (Wang et al. 2021). Varieties of statistical metrics have been used for GCM performance evaluation. The GCM evaluation of performance based on a single metric is always disputed as each metric reflects one aspect of the model performance. Therefore, the present study employed KGE, which can estimate multiple properties, including association, bias and similarity in variability together.

The CMIP6 MME showed a higher rise in temperature compared to CMIP5 MME over Egypt. Both the Tmax and Tmin will rise 0.5°C more compared to that found using CMIP5 model in earlier studies (Nashwan and Shahid 2020). In addition, the decrease in rainfall in the northern high rainfall region, where most of the agriculture activities concentrated, was projected more by CMIP6 MME compared to CMIP5 MME. This indicates a much worse situation in the future in the country compared to that anticipated earlier using CMIP5 models (Nashwan and Shahid 2020). Similar results have been reported by Almazroui et al. (2020) over Africa using CMIP6 models. They showed median warming of CMIP6 ensemble higher than CMIP5.

6. Conclusion

The statistical and visual investigations have been conducted in this study to evaluate the relative performance of CMIP5 and CMIP6 GCMs individually and their MME in simulating historical climate. Besides, the MMEs were used to project the future climate to understand the difference in projections between the two CMIPs. The studies revealed significant improvement of CMIP6 model performance in Egypt compared to CMIP5. The CMIP6 models collectively can provide a more reliable simulation of spatial distribution and seasonal variability of rainfall and temperature in Egypt. Less uncertainty in climate simulation using CMIP6 would help cost-effective adaptation measures. The study revealed a higher decrease in rainfall and a significantly large rise in temperature for SSP scenarios compared to that projected using RCP scenarios. This indicates a much worse impact of climate change in Egypt than that projected earlier using CMIP5 models. The country needs to streamline its climate change mitigation policy based on the projections for CMIP6 scenarios. In this study, the models were evaluated to simulate

annual rainfall and temperature only. In the future, the models can be evaluated to assess their ability to simulate the spatial distribution of seasonal rainfall and temperature. Besides, more models can be incorporated for comparison when complete datasets for CMIP6 will be released. Societal impacts of climate change mostly arise from climatic extremes. Therefore, the relative changes in the future projection of climatic extremes by CMIP5 and CMIP6 can be evaluated in the future.

Declarations

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Conflicts of interest/Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Code availability

The code was written using R software, R.3.4, to produce the data. The code is available when requested.

Author contributions

All authors contributed to the study conception and design.

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References

1. Abahussain AA, Abdu AS, Al-Zubari WK, et al (2002) Desertification in the Arab Region: analysis of current status and trends. *J Arid Environ* 51:521–545. <https://doi.org/10.1006/jare.2002.0975>
2. AFED (2017) Arab Environment in 10 Years. Annual Report of Arab Forum for Environment and Development. Annual Report of Arab Forum for Environment and Development, Beirut, Lebanon
3. Ahmed K, Iqbal Z, Khan N, et al (2020) Quantitative assessment of precipitation changes under CMIP5 RCP scenarios over the northern sub-Himalayan region of Pakistan. *Environ Dev Sustain* 22:7831–7845. <https://doi.org/10.1007/s10668-019-00548-5>

4. Ahmed K, Sachindra DA, Shahid S, et al (2019) Selection of multi-model ensemble of general circulation models for the simulation of precipitation and maximum and minimum temperature based on spatial assessment metrics. *Hydrol Earth Syst Sci* 23:4803–4824.
<https://doi.org/10.5194/hess-23-4803-2019>
5. Almazroui M, Saeed F, Islam MN, Alkhalaf AK (2016) Assessing the robustness and uncertainties of projected changes in temperature and precipitation in AR4 Global Climate Models over the Arabian Peninsula. *Atmos Res* 182:163–175. <https://doi.org/10.1016/j.atmosres.2016.07.025>
6. Almazroui M, Saeed F, Saeed S, et al (2020) Projected Change in Temperature and Precipitation Over Africa from CMIP6. *Earth Syst Environ* 4:455–475. <https://doi.org/10.1007/s41748-020-00161-x>
7. Ayugi B, Jiang Z, Zhu H, et al (2021) Comparison of CMIP6 and CMIP5 models in simulating mean and extreme precipitation over East Africa. *Int J Climatol* n/a:
<https://doi.org/https://doi.org/10.1002/joc.7207>
8. Bağçacı SÇ, Yucel I, Duzenli E, Yilmaz MT (2021) Intercomparison of the expected change in the temperature and the precipitation retrieved from CMIP6 and CMIP5 climate projections: A Mediterranean hot spot case, Turkey. *Atmos Res* 256:105576.
<https://doi.org/https://doi.org/10.1016/j.atmosres.2021.105576>
9. Baldi M, Amin D, Al Zayed IS, Dalu G (2020) Climatology and Dynamical Evolution of Extreme Rainfall Events in the Sinai Peninsula—Egypt. *Sustainability* 12
10. Bock L, Lauer A, Schlund M, et al (2020) Quantifying Progress Across Different CMIP Phases With the ESMValTool. *J Geophys Res Atmos* 125:e2019JD032321.
<https://doi.org/https://doi.org/10.1029/2019JD032321>
11. Chen C-A, Hsu H-H, Liang H-C (2021) Evaluation and comparison of CMIP6 and CMIP5 model performance in simulating the seasonal extreme precipitation in the Western North Pacific and East Asia. *Weather Clim Extrem* 31:100303. <https://doi.org/https://doi.org/10.1016/j.wace.2021.100303>
12. Chen H, Sun J, Chen X (2014) Projection and uncertainty analysis of global precipitation-related extremes using CMIP5 models. *Int J Climatol* 34:2730–2748.
<https://doi.org/https://doi.org/10.1002/joc.3871>
13. Collins JA, Prange M, Caley T, et al (2017) Rapid termination of the African Humid Period triggered by northern high-latitude cooling. *Nat Commun* 8:1372. <https://doi.org/10.1038/s41467-017-01454-y>
14. Dai A (2011) Drought under global warming: A review. *Wiley Interdiscip Rev Clim Chang* 2:45–65.
<https://doi.org/10.1002/wcc.81>
15. Elbeltagi A, Aslam MR, Malik A, et al (2020) The impact of climate changes on the water footprint of wheat and maize production in the Nile Delta, Egypt. *Sci Total Environ* 743:140770.
<https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.140770>
16. Eyring V, Bony S, Meehl GA, et al (2016) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci Model Dev* 9:1937–1958.
<https://doi.org/10.5194/gmd-9-1937-2016>

17. Eyring V, Cox PM, Flato GM, et al (2019) Taking climate model evaluation to the next level. *Nat Clim Chang* 9:102–110. <https://doi.org/10.1038/s41558-018-0355-y>
18. FAO (2020) Egypt at a glance. In: Food Agric. Organ. United Nations. <http://www.fao.org/egypt/our-office/egypt-at-a-glance/en/#:~:text=The agricultural sector is the,the farming and fishing industries>
19. Gao M, Kim S-J, Yang J, et al (2021) Historical fidelity and future change of Amundsen Sea Low under 1.5 °C–4 °C global warming in CMIP6. *Atmos Res* 255:105533. <https://doi.org/https://doi.org/10.1016/j.atmosres.2021.105533>
20. Goldenson N, Mauger G, Leung LR, et al (2018) Effects of Ensemble Configuration on Estimates of Regional Climate Uncertainties. *Geophys Res Lett* 45:926–934. <https://doi.org/https://doi.org/10.1002/2017GL076297>
21. Gupta H V, Kling H, Yilmaz KK, Martinez GF (2009) Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *J Hydrol* 377:80–91. <https://doi.org/10.1016/j.jhydrol.2009.08.003>
22. Gusain A, Ghosh S, Karmakar S (2020) Added value of CMIP6 over CMIP5 models in simulating Indian summer monsoon rainfall. *Atmos Res* 232:104680. <https://doi.org/https://doi.org/10.1016/j.atmosres.2019.104680>
23. Hamed MM, Nashwan MS, Shahid S (2021) Performance Evaluation of Reanalysis Precipitation Products in Egypt using Fuzzy Entropy Time Series Similarity Analysis. *Int J Climatol* n/a: <https://doi.org/10.1002/joc.7286>
24. HBRC (2006) The Egyptian Code for Enhancing Energy Use in Buildings. Housing and Building Research Center (HBRC), Cairo, Egypt
25. Ibrahim YAE, Nasr NE-S, Ghalab ME-S, Abd El-Hakim MS (1994) Geography of Egypt, (In Arabic). General Egyptian Organization for Books, Egypt
26. Iqbal Z, Shahid S, Ahmed K, et al (2021) Evaluation of CMIP6 GCM rainfall in mainland Southeast Asia. *Atmos Res* 254:105525. <https://doi.org/https://doi.org/10.1016/j.atmosres.2021.105525>
27. Iqbal Z, Shahid S, Ahmed K, et al (2020) Evaluation of global climate models for precipitation projection in sub-Himalaya region of Pakistan. *Atmos Res* 245:105061. <https://doi.org/10.1016/j.atmosres.2020.105061>
28. Kamruzzaman M, Shahid S, Islam ARMT, et al (2021) Comparison of CMIP6 and CMIP5 Model Performance in Simulating Historical Precipitation and Temperature in Bangladesh: A Preliminary Study
29. Karger DN, Conrad O, Böhner J, et al (2017) Climatologies at high resolution for the earth ' s land surface areas. *Sci Data* 4:1–20. <https://doi.org/10.1038/sdata.2017.122>
30. Khan N, Shahid S, Ahmed K, et al (2020) Selection of GCMs for the projection of spatial distribution of heat waves in Pakistan. *Atmos Res* 233:104688. <https://doi.org/https://doi.org/10.1016/j.atmosres.2019.104688>
31. Kling H, Fuchs M, Paulin M (2012) Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. *J Hydrol* 424–425:264–277.

<https://doi.org/10.1016/j.jhydrol.2012.01.011>

32. Nashwan MS, Shahid S (2019) Spatial distribution of unidirectional trends in climate and weather extremes in Nile river basin. *Theor Appl Climatol* 137:1181–1199. <https://doi.org/10.1007/s00704-018-2664-5>
33. Nashwan MS, Shahid S (2020) A novel framework for selecting general circulation models based on the spatial patterns of climate. *Int J Climatol* 40:1–22. <https://doi.org/10.1002/joc.6465>
34. Nashwan MS, Shahid S, Abd Rahim N (2019a) Unidirectional trends in annual and seasonal climate and extremes in Egypt. *Theor Appl Climatol* 136:457–473. <https://doi.org/10.1007/s00704-018-2498-1>
35. Nashwan MS, Shahid S, Chung ES (2020a) High-resolution climate projections for a densely populated mediterranean region. *Sustain* 12:. <https://doi.org/10.3390/su12093684>
36. Nashwan MS, Shahid S, Chung ES (2019b) Development of high-resolution daily gridded temperature datasets for the central north region of Egypt. *Sci Data* 6:0–13. <https://doi.org/10.1038/s41597-019-0144-0>
37. Nashwan MS, Shahid S, Dewan A, et al (2020b) Performance of five high resolution satellite-based precipitation products in arid region of Egypt: An evaluation. *Atmos Res* 236:104809. <https://doi.org/10.1016/j.atmosres.2019.104809>
38. Noreldin T, Ouda S, Amer A (2016) Agro-climatic zoning in Egypt to improve irrigation water management. *J Water L Dev* 31:113–117. <https://doi.org/10.1515/jwld-2016-0041>
39. O'Neill BC, Tebaldi C, Van Vuuren DP, et al (2016) The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci Model Dev* 9:3461–3482. <https://doi.org/10.5194/gmd-9-3461-2016>
40. Osman R, Ferrari E, McDonald S (2016) Water Scarcity and Irrigation Efficiency in Egypt. *Water Econ Policy* 02:1650009. <https://doi.org/10.1142/S2382624X16500090>
41. Ouda SAH, Norledin TA (2017) Evapotranspiration data to determine agro-climatic zones in Egypt. *J Water L Dev* 32:79–85. <https://doi.org/10.1515/jwld-2017-0009>
42. Ozturk T, Turp MT, Türkeş M, Kurnaz ML (2018) Future projections of temperature and precipitation climatology for CORDEX-MENA domain using RegCM4.4. *Atmos Res* 206:87–107. <https://doi.org/https://doi.org/10.1016/j.atmosres.2018.02.009>
43. Raju K, D. Kumar (2014) Ranking of global climate models for India using multicriterion analysis. *Clim Res* 60:103–117
44. Raju KS, Sonali P, Nagesh Kumar D (2017) Ranking of CMIP5-based global climate models for India using compromise programming. *Theor Appl Climatol* 128:563–574. <https://doi.org/10.1007/s00704-015-1721-6>
45. Rivera JA, Arnould G (2020) Evaluation of the ability of CMIP6 models to simulate precipitation over Southwestern South America: Climatic features and long-term trends (1901–2014). *Atmos Res* 241:104953. <https://doi.org/10.1016/j.atmosres.2020.104953>

46. Salman SA, Shahid S, Ismail T, et al (2018) Selection of climate models for projection of spatiotemporal changes in temperature of Iraq with uncertainties. *Atmos Res* 213:509–522. <https://doi.org/10.1016/j.atmosres.2018.07.008>
47. Schilling J, Freier KP, Hertig E, Scheffran J (2012) Climate change, vulnerability and adaptation in North Africa with focus on Morocco. *Agric Ecosyst Environ* 156:12–26. <https://doi.org/https://doi.org/10.1016/j.agee.2012.04.021>
48. Shalby A, Elshemy M, Zeidan BA (2020) Modeling of climate change impacts on Lake Burullus, coastal lagoon (Egypt). *Int J Sediment Res*. <https://doi.org/https://doi.org/10.1016/j.ijsrc.2019.12.006>
49. Sheffield J, Barrett AP, Colle B, et al (2013) North American Climate in CMIP5 Experiments . Part I: Evaluation of Historical Simulations of Continental and Regional Climatology. *J Clim* 26:9209–9245. <https://doi.org/10.1175/JCLI-D-12-00592.1>
50. Song YH, Chung E-S, Shahid S (2021a) Spatiotemporal differences and uncertainties in projections of precipitation and temperature in South Korea from CMIP6 and CMIP5 general circulation models. *Int J Climatol* n/a: <https://doi.org/https://doi.org/10.1002/joc.7159>
51. Song YH, Nashwan MS, Chung ES, Shahid S (2021b) Advances in CMIP6 INM-CM5 over CMIP5 INM-CM4 for precipitation simulation in South Korea. *Atmos Res* 247:105261. <https://doi.org/10.1016/j.atmosres.2020.105261>
52. Song YH, Nashwan MS, Chung ES, Shahid S (2021c) Advances in CMIP6 INM-CM5 over CMIP5 INM-CM4 for precipitation simulation in South Korea. *Atmos Res* 247:105261. <https://doi.org/10.1016/j.atmosres.2020.105261>
53. Srivastava A, Grotjahn R, Ullrich PA (2020) Evaluation of historical CMIP6 model simulations of extreme precipitation over contiguous US regions. *Weather Clim Extrem* 29:100268. <https://doi.org/https://doi.org/10.1016/j.wace.2020.100268>
54. Stouffer RJ, Eyring V, Meehl GA, et al (2017) CMIP5 scientific gaps and recommendations for CMIP6. *Bull Am Meteorol Soc* 98:95–105. <https://doi.org/10.1175/BAMS-D-15-00013.1>
55. Su B, Huang J, Mondal SK, et al (2021) Insight from CMIP6 SSP-RCP scenarios for future drought characteristics in China. *Atmos Res* 250:105375. <https://doi.org/https://doi.org/10.1016/j.atmosres.2020.105375>
56. Sun Q, Miao C, Duan Q (2015) Comparative analysis of CMIP3 and CMIP5 global climate models for simulating the daily mean, maximum, and minimum temperatures and daily precipitation over China. *J Geophys Res Atmos* 120:4806–4824. <https://doi.org/https://doi.org/10.1002/2014JD022994>
57. Taylor KE, Balaji V, Hankin S, et al (2011) CMIP5 data reference syntax (DRS) and controlled vocabularies. San Francisco Bay Area, CA, USA
58. Terink W, Immerzeel WW, Droogers P (2013) Climate change projections of precipitation and reference evapotranspiration for the Middle East and Northern Africa until 2050. *Int J Climatol* 33:3055–3072. <https://doi.org/https://doi.org/10.1002/joc.3650>

59. van Vuuren DP, Edmonds J, Kainuma M, et al (2011) The representative concentration pathways: an overview. *Clim Change* 109:5. <https://doi.org/10.1007/s10584-011-0148-z>
60. Wang Z, Han L, Ding R, Li J (2021) Evaluation of the performance of CMIP5 and CMIP6 models in simulating the South Pacific Quadrupole–ENSO relationship. *Atmos Ocean Sci Lett* 100057. <https://doi.org/https://doi.org/10.1016/j.aosl.2021.100057>
61. Wasimi SA (2010) Climate change in the Middle East and North Africa (MENA) region and implications for water resources project planning and management. *Int J Clim Chang Strateg Manag* 2:297–320. <https://doi.org/10.1108/17568691011063060>
62. Yazdandoost F, Moradian S, Izadi A, Aghakouchak A (2021) Evaluation of CMIP6 precipitation simulations across different climatic zones: Uncertainty and model intercomparison. *Atmos Res* 250:105369. <https://doi.org/10.1016/j.atmosres.2020.105369>
63. Zhu Y-Y, Yang S (2020) Evaluation of CMIP6 for historical temperature and precipitation over the Tibetan Plateau and its comparison with CMIP5. *Adv Clim Chang Res* 11:239–251. <https://doi.org/https://doi.org/10.1016/j.accre.2020.08.001>
64. Zhu Y, Yang S (2021) Interdecadal and interannual evolution characteristics of the global surface precipitation anomaly shown by CMIP5 and CMIP6 models. *Int J Climatol* 41:E1100–E1118. <https://doi.org/https://doi.org/10.1002/joc.6756>
65. Zittis G, Hadjinicolaou P, Almazroui M, et al (2021) Business-as-usual will lead to super and ultra-extreme heatwaves in the Middle East and North Africa. *npj Clim Atmos Sci* 4:20. <https://doi.org/10.1038/s41612-021-00178-7>

Figures

Figure 1

Egypt on the globe and its topography

Figure 2

Geographical variability of mean maximum, minimum temperatures and annual total rainfall over Egypt during the study period 1979–2013 estimated using CHELSA dataset aggregated to the resolution of 1.0°×1.0°.

Figure 3

KGE statistical performance results of CMIP5 and CMIP6 GCMs in replicating historical annual Tmax, Tmin and rainfall during 1979-2005.

Figure 4

Taylor diagrams showing correlations between CHELSA as reference dataset and CMIP5 and CMIP6 GCMs for annual Tmax, Tmin and rainfall.

Figure 5

Seasonal variability in rainfall of CMIP5 and CMIP6 GCMs compared to CHELSA dataset.

Figure 6

Same as Figure 5, but for Tmax.

Figure 7

Same as Figure 5, but for Tmin.

Figure 8

Absolute bias in annual rainfall, Tmax and Tmin (rows) of CMIP5 and CMIP6 MME (columns).

Figure 9

Annual rainfall (mm) projection in CMIP5 and CMIP6 under different projection scenarios.

Figure 10

Maximum temperature (°C) projections in CMIP5 and CMIP6 under different projection scenarios.

Figure 11

Minimum temperature (°C) projections in CMIP5 and CMIP6 under different projection scenarios.

Figure 12

Spatial patterns of change in rainfall (mm) over Egypt estimated using the MME of CMIP5 and CMIP6 for two futures in medium (RCP4.5 and SSP2-4.5) and high (RCP8.5 and SSP5-8.5) projection scenarios.

Figure 13

Spatial patterns of change in Tmax (°C) over Egypt estimated using the MME of CMIP5 and CMIP6 for two futures in medium (RCP4.5 and SSP2-4.5) and high (RCP8.5 and SSP5-8.5) projection scenarios.

Figure 14

Spatial patterns of changes in T_{min} ($^{\circ}\text{C}$) over Egypt estimated using MME of CMIP5 and CMIP6 for two futures in medium (RCP4.5 and SSP2-4.5) and high (RCP8.5 and SSP5-8.5) projection scenarios.