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Analysis of climate extremes over the Arabian Peninsula using downscaled RCM data

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Abstract. Climate change is likely to severely affect the economies of countries in the Arabian Peninsula and make their populations vulnerable to weather extremes. This study aimed to investigate the changes in future temperature and precipitation extreme indices over the Arabian Peninsula using regional climate model simulations for the future time slices mid-century (2036-2065) and end-century (2071-2100) with respect to the reference period (1976-2005). For this purpose, three Global Climate Models (GCMs) simulations from the WCRP Coupled Model Intercomparison Project phase 5 (CMIP5) are downscaled over the Arabian Peninsula using the International Centre for Theoretical Physics (ICTP) Regional Climate Model (RegCM4). The results show that the warm days/nights (TX90p/TN90p) will increase more than 50% over most parts of the Arabian Peninsula. Warm spell duration index (WSDI) will increase over the Arabian Peninsula while the cold spell duration index (CSDI) will decrease in the mid-century under the high-emission scenario. The number of cold days/nights (TX10p/TN10p) will decrease over most parts of the Arabian Peninsula in the middle of the 21st century. The number of very wet days will increase over the whole Arabian Peninsula under both scenarios (RCP4.5 and RCP8.5). Towards the end-century, it will decrease in the central and southern regions under both scenarios. Heavy rainfall days will increase over the Arabian Peninsula in the mid-century. By the end-century, the number of heavy-precipitation days will mix of decrease and increase depending on region to region and model to model. Overall, the extreme precipitation is projected to increase rather than decrease at the end-century under both scenarios. The number of consecutive dry days (CDD) will increase over a large area of central and western Arabian Peninsula under the moderate scenario in the mid-century while it will decrease under the high-emission scenario. The present findings indicate that a careful interpretation of climate projections is needed for policy purposes as well as for climate change impact and adaptation related studies.

Keywords: Climate Extremes; Arabian Peninsula; RegCM; Climate Projection; Climate Extreme Indices

1. Introduction

The Arabian Peninsula (specifically, Saudi Arabia which covers more than 80% of the Peninsula) is the global hot spot of temperature increase and its warming rate is almost 3 times the global average (Odnoletkova and Patzek, 2021). Recent climate studies indicate a continuous increase of temperature in the future and extreme weather becomes more frequent (Driouech et al., 2020; Almazroui et al., 2017). According to the IPCC Fifth Assessment Report (AR5; Collins et al., 2013), under a high emission scenario RCP8.5, the temperature will increase by about 0.58–0.78

°C in a decade. El-Samra et al. (2017) shows evidence of a significantly drier climate over the northeast Arabian Peninsula from 2016 until the mid-century, and this situation may change to a relatively wetter climate by the end of the century over most parts of the Peninsula under warmer climate (Almazroui et al., 2017). The impacts of climate change will hamper the Arabian Peninsula Countries' economies and make their populations more vulnerable to extreme weather (Kompas et al., 2018). Episodes of heavy rainfall and ensuing flash floods cause loss of life in addition to huge economic losses (Almazroui, 2020 a, b, c). In Jeddah (Saudi Arabia), temperature reached a record maximum of 52°C on 22 June 2010. Jeddah was also seriously affected by two flash floods, 13 months apart, on 25 November 2009 and 26 January 2011 (Almazroui et al., 2012a, b; Atif et al., 2020; Krishna, 2014). With unprecedented growing interest in the effects of climate change in the future, regional projections of climate extremes in the 21st century are playing an essential role in long-term planning and risk assessments. In this direction, the Global Climate Models (GCMs) simulations data such as the Coupled Model Intercomparison Project phase 5 (CMIP5) and phase 6 (CMIP6) multi-model multi-scenario are generally used. The application of these future simulations to regional climate is hindered by the coarse resolution of the models. To utilize these data, they are dynamically downscaled by a Regional Climate Model (RCM) to a finer horizontal resolution. The present study used the RCM named RegCM4 to downscale the coarse resolution CMIP5 dataset to finer scale climate information over the Arabian Peninsula.

Recently, there are some studies that are dedicated to the analysis of the climate extremes (e.g. Almazroui, 2020a, b, c; Almazroui et al., 2014a, b; Atif et al., 2020; Donat et al., 2014; Islam et al., 2014; Krishna, 2014). Most of these works are based on analyzing surface observations while few of them utilized reanalysis and model datasets for the present climate. Almazroui and Islam (2019) used CMIP3 data for the calculation of drought indices Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI) over Saudi Arabia. They analyzed the coarse resolution CMIP3 data for the present climate (1978-2000) without downscaling it. In another study, (Almazroui et al., 2021) the coarse-resolution CMIP6 data were analyzed, and climate extremes examined over different SREX regions. Ntoumos et al. (2020) focused on the study of temperature extremes over the Middle East and North Africa (MENA) region for the period of 1980–2018. They used data from 18 models results from CMIP5, two reanalyses (Era Interim and MERRA-2), and observations (Berkeley Earth). There is almost no study on climate extremes analysis using downscaled climate models datasets for the Arabian Peninsula, which is interesting to discuss.

This present study focuses on the analysis of climate extremes over the Arabian Peninsula in the 21st century using three CMIP5 databases downscaled with the RegCM4 model. The daily maximum temperature, minimum temperature and rainfall are used to compute the absolute indices, relative indices, duration climate indices to study changes in the climate extremes over the Arabian Peninsula. In this direction, the widely used Expert Team on Climate Change Detection, and Indices (ETCCDI) recommended tool RClimDex is employed (Almazroui et al., 2014; Islam et al., 2014; Donat et al., 2014; Zhang and Yang, 2004; Zhang et al., 2011). The next section describes the data and methodology. The results are detailed in section 3 and the conclusions of this work is given in the last section.

2. Data and methods

2.1 Model

The Regional Climate Model (RegCM4) developed by the Abdus Salam International Centre for Theoretical Physics (ICTP) has been used to downscale the CMIP5 data. Model details are available in Giorgi et al. (2012). RegCM4 has been widely used in previous research, e.g. CORDEX for the downscaling of climate datasets (Giorgi and Jones, 2009). The domain area is shown in Fig. 1. The physics schemes chosen for the simulations are listed in Table 1.

2.2 Driving GCMs and evaluation datasets

The hindcast simulation was conducted with European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis datasets. ERA-Interim (Dee et al., 2011) is the successor to ERA-40. It corrects several inaccuracies of the earlier ERA-40 reanalysis and allows for analysis of the meteorological data for the period 1979 - 2018. In the next step, the three GCMs were selected for downscaling. These models are (i) ECHAM-5 (Bonaventura et al., 2003), (ii) GFDL (Dunne et al., 2012) and (iii) HadGEM (Baek et al., 2014). These CMIP5 models were also downscaled using RegCM4 and used in earlier climate studies over the Arabian Peninsula (Almazroui 2015, 2019a, b). The CMIP5 models are used to force the RegCM4 model. The present study used two future forcing scenarios: the mid-range RCP4.5 and the high-emission scenario RCP8.5. For evaluation of RegCM4-simulated historical precipitation, gridded observations from the Climatic Research Unit (CRU), ECMWF ERA5-Land (hereafter ERA5L) and two other datasets were used. The use of CRU rainfall is in line with that of Almazroui (2012a,b) and Almazroui et al. (2013a, b). MSWEP data, which provided historical global precipitation for the period 1976–2016, at 3-h time intervals and 0.1° spatial resolution was also used. For evaluation of hindcast simulations and future climate anomalies, the base period of 1976–2005 was selected. Future changes in extremes were quantified with respect to the mean climate of the base period. The future time slices 2036–2065 and 2071–2100 were used to represent mid-century and end-century time periods, respectively.

The downscaling simulations are performed at a horizontal resolution of 50 km. The topographic elevation of the RCM domain is shown in Fig. 1. The RCM domain covers the Middle East and parts of eastern Africa, while the focus is over the Arabian Peninsula, in particular Saudi Arabia, which covers more than 80% of the Arabian Peninsula. In the southwestern region of Saudi Arabia, several mountain ranges with the highest peak (Jabal Sawda) measuring 3133 m above the sea level is the highest elevation in the country.

2.3 Bias correction of selected climate models

The simulations produced biases for many reasons such as poor resolution of the models that don't represent well many physical processes, topographic features, the land-atmospheric coupling etc. that occurs at local scales. For more realistic climate representation and impact assessments, it is important to remove these biases from climate model simulations. In this study, they used several methods, which include Scale Distribution Mapping (SDM), Quantile Mapping and recently developed improved Quantile Mapping method (EQA) for precipitation. The EQA stands for Empirical Quantile Adjustment, and it has been developed for bias correction of precipitation in very dry regions (Lehner et al., 2021). Actually, EQA is based on EDCDFm for temperature adjustment (Li et al., 2010) and PresRAT for correcting precipitation (Pierce et al., 2015) but in contrast to these it is purely non-parametric (Vlcek and Huth, 2009). For three downscaled GCMs (ECHAM, HadGEM and GFDL), the precipitation fields, daily minimum and daily maximum temperatures are bias corrected using EQA method. The bias correction is done using ERA5 / ERA5L and on the native grid of ERA5 / ERA5L. Before the bias correction, the model output was resampled to the ERA5 / ERA5L grid by using higher order patch resampling (reference for patch sampling).

2.4 Climate extreme indices

Table 2 describes the extreme indices analyzed in this study. The definition of extremes varies from place to place. Many climatic extreme events are increasing in magnitude and/or frequency due to human induced climatic changes and there is increased potential for impacts due to location of urbanization and the expansion of urban centers and infrastructures (McPhillips et al., 2018). Generally, an extreme event is defined as the occurrence of a value of a climate variable above (or below) a threshold value near the upper (or lower) ends ('tails') of the range of historical values (or control period) of the variable. Some climate extremes (e.g., droughts, floods) may be the result of an accumulation of weather or climate events that are, individually, not extreme themselves (though their accumulation is extreme). As well, weather or climate events, even if not extreme in a statistical sense, can still lead to extreme conditions or impacts, either by crossing a critical threshold in a social, ecological, or physical system, or by occurring simultaneously with other events (Seneviratne et al., 2012).

3. Results and discussion

3.1 Bias correction

Before evaluating the future climate-change signals over the Arabian Peninsula, it is important to consider the representativeness of the RCM simulation of the climatology of both the temperatures and the precipitation of the reference period (1975-2006). Fig. 2 and Fig. 3 show the comparison between the annual mean temperature and precipitation in the reanalysis dataset along with downscaled ECHAM model output before and after the application of the bias-correction.

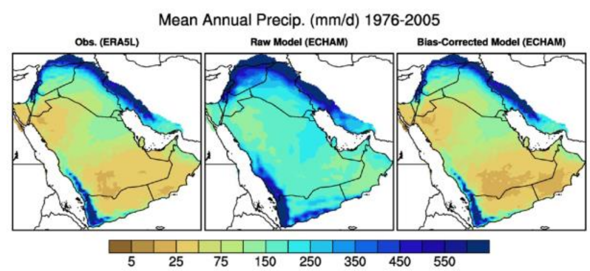


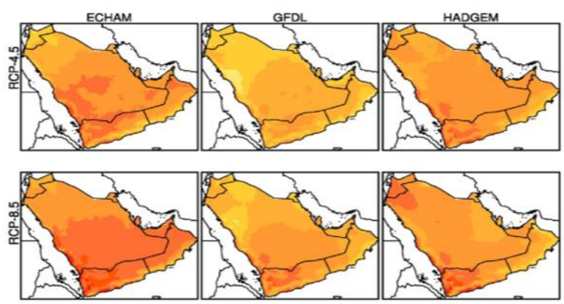
Fig. 3: as in Fig. 2 but for the 30-year annual mean precipitation.

The bias–correction methodology introduced a remarkable improvement in both simulated variables i.e., the annual mean temperature and precipitation. The RegCM4 simulated data without bias correction display marked differences when compared with reanalysis dataset. However, after bias correction the simulated temperature and precipitation spatial distribution closely matched the observed patterns. The bias corrected data reasonably captured the extreme high temperature pattern located over the eastern Arabian Peninsula (Fig. 2). On the other hand, the original RegCM4 downscaled data don't represent well the spatial distribution of precipitation. However, the dry and wet regions over the Arabian Peninsula are well represented in the bias corrected data.

3.2 Future changes in temperature extremes

The spatial distribution of the changes in the climate extreme indices under the future scenarios RCP 4.5 and 8.5 for the mid- and end-of the century in the three models ECHAM, GFDL, and HADGEM with respect to the reference period are shown in Figs. 4-14. Detailed description of projected changes in extreme indices is given below.

Changes in TX90p (days) (2036-2065) from base period (1976-2005)



Changes in TX90p (days) (2071-2100) from base period (1976-2005)

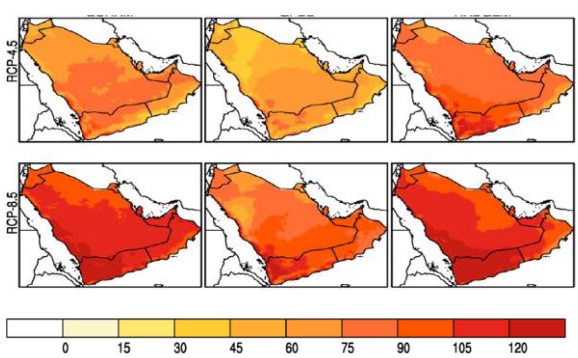


Fig. 4: The projected changes in the number of warm days (%) during the mid-century (upper panels) and end-century (lower panels) with respect to the base period (1976-2005). The name of driving GCMs is listed at the top of each panel. The upper panel shows the changes under RCP4.5 scenario while the lower panel shows change under RCP8.5 scenario.

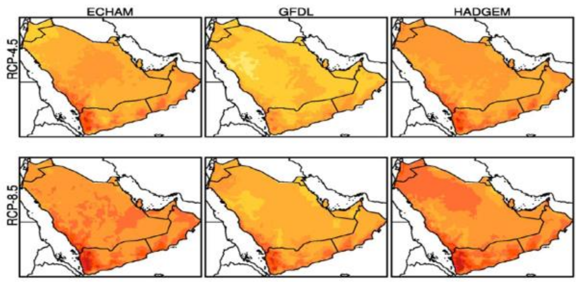
3.2.1 Warm days

The projected changes in the number of warm days (TX90p) in the mid-century and end-century with respect to the reference period are shown in Fig. 4. In the mid-century, all three models show an increase of more than 50% over most parts of the Arabian Peninsula, which increase to more than 70% over the southern part and doubles over Asir Mountains. The increase is largest in the ECHAM model under high emission scenarios. By the end of the century all models under both scenarios tend to have a very large increase in the number of warm days, especially in ECHAM and GFDL derived simulation data display an increase in the warm days that exceeds the double compared to the reference period almost over the whole of the Arabian Peninsula.

3.2.2 Warm nights

Fig. 5 shows the projected changes in warm nights (TN90p) over the Arabian Peninsula. The future changes in the warm nights display a similar pattern as seen in the case of warm days. The southern part of the Arabian Peninsula will witness an increase in the number of warm nights. This is consistent with warms days projected patterns. The projected signals are more evident towards the end of the century especially for high emission scenarios. Interestingly, the projected patterns are mainly consistent among different model simulations; however, slight variation in the projected signal exists among different model simulations.

Changes in TN90p (days) (2036-2065) from base period (1976-2005)



Changes in TN90p (days) (2071-2100) from base period (1976-2005)

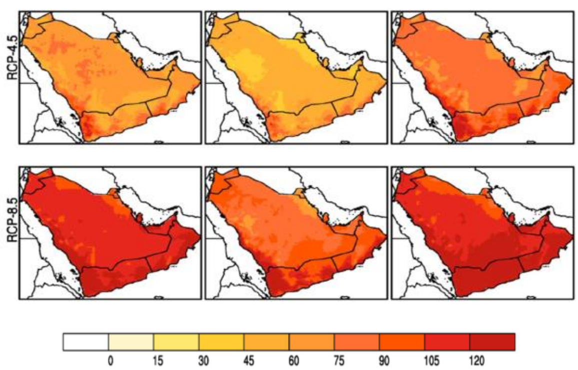
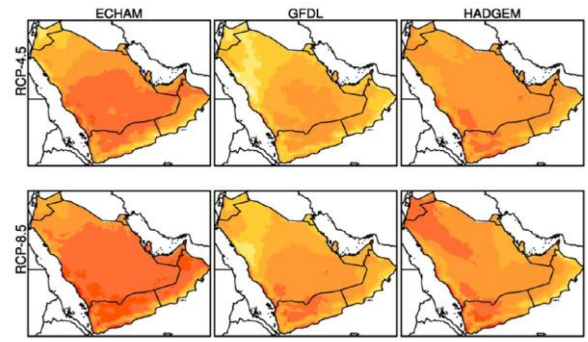


Fig. 5: as in Fig. 4 but for warm nights (%).

3.2.3 Warm spell durations

Fig. 6 illustrate the changes in warm spell duration index (WSDI) for the mid- and end-century periods with respect to the reference period 1976-2005. The WSDI is of great importance because it is a major cause of weather-related mortality. The future projections show an increase in the warm spell duration over the Arabian Peninsula. The increase is more pronounced for high emission scenario compared to the low emission scenario. The duration of warms spells increases more towards the end-century period under high emission scenario (RCP8.5). Models especially GFDL seems to have little change in the spatial pattern in the mid-century in both scenarios. The increase in the warm spells is generally associated with long duration heat waves and drought like conditions. In the case of the Arabian Peninsula, a climate extreme index for very hot and extremely hot days should be introduced to suit the peculiar climatic conditions there.

Changes in WSDI (days) (2036-2065) from base period (1976-2005)



Changes in WSDI (days) (2071-2100) from base period (1976-2005)

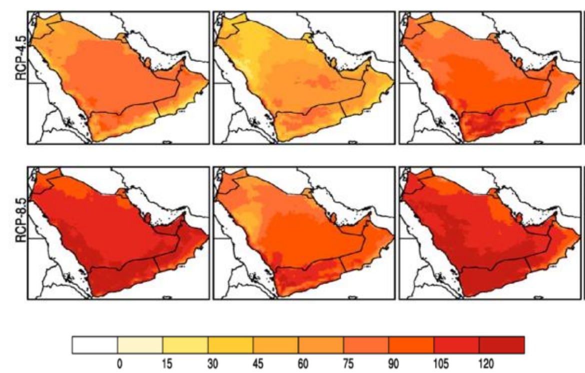
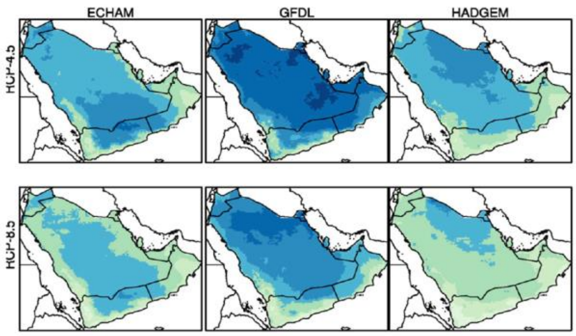


Fig. 6: as in Fig. 4 but for the warm spell duration (days).

3.2.4 Cold days

Fig. 7 shows the projected changes in the cold days (TX10p) for mid- and end-century periods compared to the reference period. The number of cold days decreased over most parts of the Arabian Peninsula in the middle of the 21st century with varying degrees. Both ECHAM and HADGEM show less cold nights in both scenarios than GFDL. The decrease is not actually homogenous over the whole Arabian Peninsula except in GFDL. In ECHAM, the southern parts of the Peninsula have fewer cold days while in the HADGEM northern parts have fewer cold days.

Changes in TX10p (days) (2036-2065) from base period (1976-2005)



Changes in TX10P (days) (2071-2100) from base period (1976-2005)

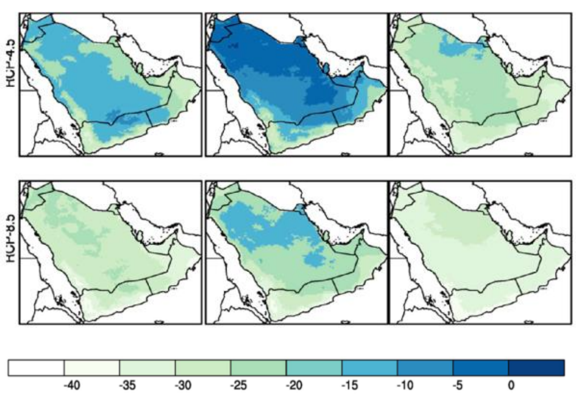


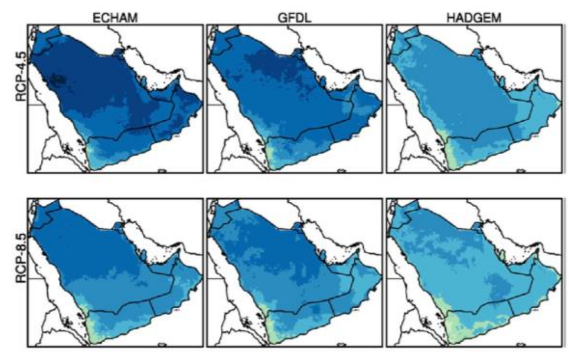
Fig. 7: as in Fig. 4 but for cold days (%).

At the end of the century, both ECHAM and HADGEM models seem to have very similar patterns under the high emission scenario where the cold days are projected to decrease by 35% over most of the Arabian Peninsula. It is remarkable that GFDL has different patterns than the other two models. It is also worth noting that the number of cold days does not drop to half while the number of warm days exceeds a double as shown above.

3.2.5 Cold nights

The projected spatial changes of cold nights (%) in the mid- and end-century with respect to the base period are shown in Fig. 8. Similar to the cold day projections, the cold nights are also projected to decrease over the Arabian Peninsula. The projected signals are more pronounced under high emission scenarios. Moreover, these changes are higher towards the end of the 21st century. HADGEM shows a remarkable decrease by the end of the century in both scenarios especially for RCP8.5 that tends to reach 40%.

Changes in TN10p (days) (2036-2065) from base period (1976-2005)



Changes in TB10P (days) (2071-2100) from base period (1976-005)

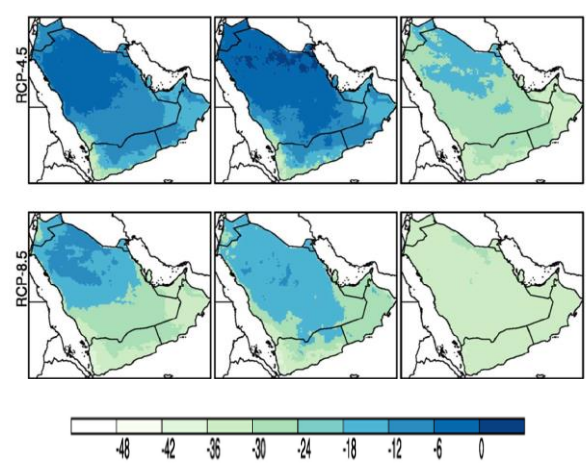
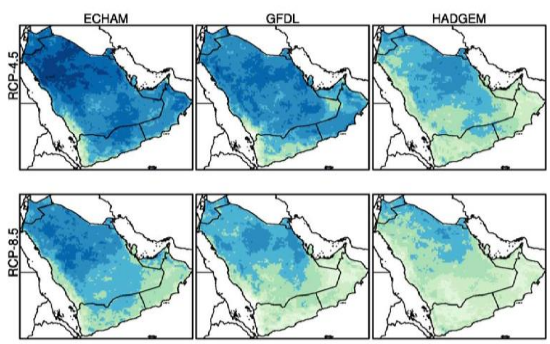


Fig. 8: as in Fig. 4 but for cold nights (%).

3.2.6 Cold spell duration

Contrary to the warm spell duration index, the cold spell duration index (CSDI) decreases in the high-emission scenario in the mid-century very little except over the southern Arabian Peninsula, most notably, in the HADGEM model (Fig. 9). By the end of the 21st century, little change happens in the moderate scenario but for the high-emission scenario the number decreases considerably everywhere over the Arabian Peninsula in GFDL and HADGEM and over the southern and eastern parts of the Peninsula in ECHAM.

Changes in CSDI (days) (2036-2065) from base period (1976-2005)



Changes in CSDI (days) (2071-2100) from base period (197-2005)

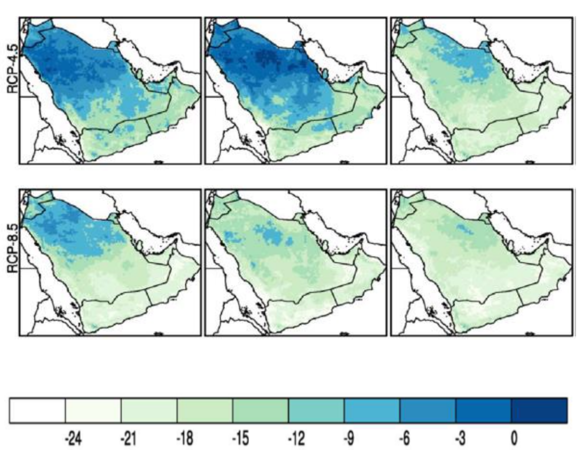


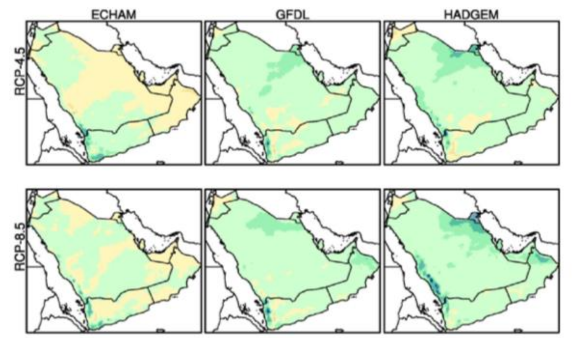
Fig. 9: as in Fig. 4 but for the cold spell duration (days).

3.3 Precipitation extreme indices

The extreme precipitation is often associated with catastrophic floods that may have huge implications on both the human and natural systems. This section analyzed the projected changes in the precipitation climate extremes over the Arabian Peninsula. Here we will discuss the changes in precipitation in terms of the extreme indices defined in the data and methodology section (Table 2). It is worth mentioning that the Asir Mountains in the southwestern Arabian Peninsula receive most of the rain during the dry season (June-September; Almazroui 2020b). The amount and pattern of rain in this region is different from the central and coastal regions. Asir Mountains have orographic rainfalls where moisture from the Arabian Sea and Red Sea is transported vertically to condense. In the central parts, the troughs of the passing Mediterranean cyclones are responsible for the rain in the rainy season (November to April). It is difficult to account for changes in the rainfall over the Empty Quarter Rub Al-Khali which receive very low rainfall whatsoever because if we notice an increase that would mean a substantial change in the circulation pattern to lead to this change.

In Fig. 10, we noticed an increase in the very wet days rainfall over the whole Arabian Peninsula for GFDL and HADGEM under both scenarios, and little increase observed only in central and eastern Arabian Peninsula for ECHAM in the mid-century. Towards the end of the century, we noticed a decrease in the very wet days rainfall in the central and southern regions under both scenarios for ECHAM and GFDL. There is a very large increase projected over the north-eastern Peninsula that extends to the central region. Asir Mountains and the coastal region along the Red Sea have projected an increase in the very wet days rainfall for all models under both scenarios.

Changes in R95p (mm) (2036-2065) from base period (1976-2005)



Changes in R95p (mm) (2071-2100) from base period (1976-2005)

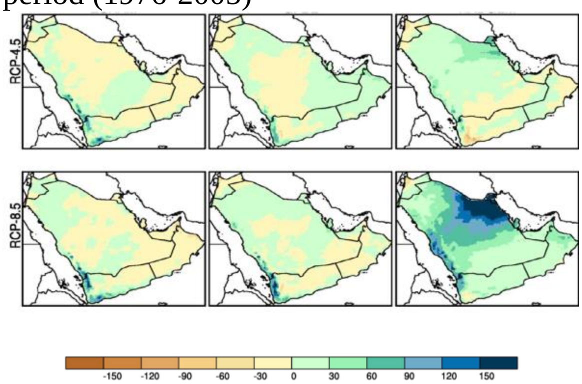
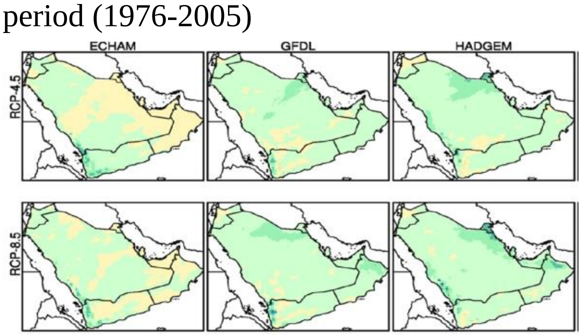


Fig. 10: as in Fig. 4 but for the very wet days (mm)

3.3.1 Extremely wet days

The patterns of the projected changes in the extremely wet days rainfall are very similar to those of the very wet days (Fig. 11).

Changes in R99p (mm) (2036-2065) from base period (1976-2005)



Changes in R99p (mm) (2071-2100) from base period (1976-2005)

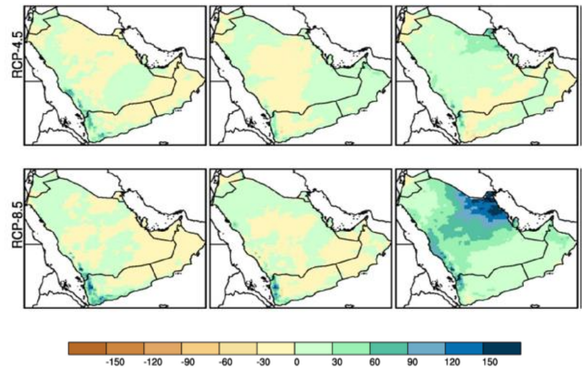
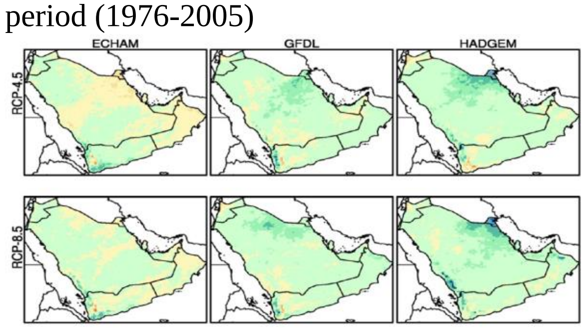


Fig. 11: as in Fig. 4 but for the extremely wet days (mm)

3.3.2 Heavy rainfall

Heavy rainfall days are projected to increase over the Arabian Peninsula in general and especially over central, north-eastern, and south-western parts in the mid-century (Fig. 12).

Changes in R10 (days) (2036-2065) from base period (1976-2005)



Changes in R10 (days) (2071-2100) from base period (1976-2005)

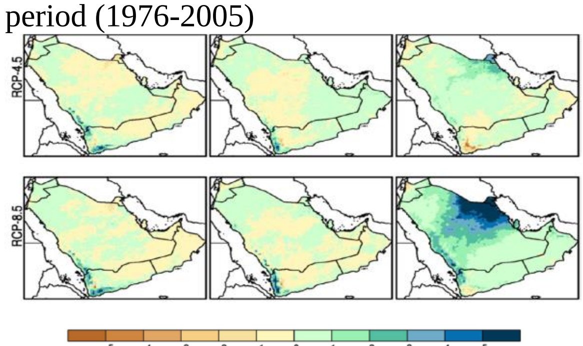
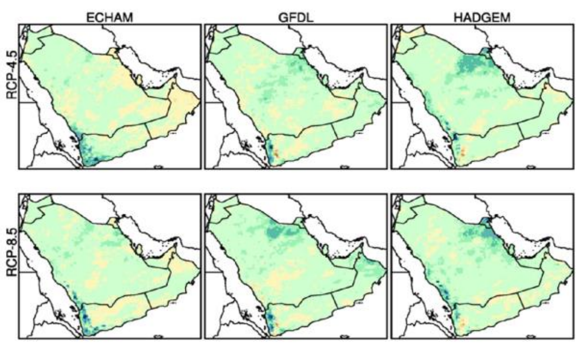


Fig. 12: as in Fig. 4 but for the heavy precipitation days (days/yr).

Similar to the wet and very-wet-days pattern discussed earlier, by the end of the century the number of heavy-precipitation days decrease almost everywhere and for all models except for HADGEM where the number of days increase considerably over large parts of the Peninsula under the high-emission scenario (Fig. 13). It is already obvious that the patterns of very wet day, extremely wet days, and heavy precipitation days are very similar but the extreme precipitation days are projected to increase rather than decrease in the last third of the century under both scenarios for the three models.

Changes in R20 (days) (2036-2065) from base period (1976-2005)



Changes in R20 (days) (2071-2100) from base period (1976-2005)

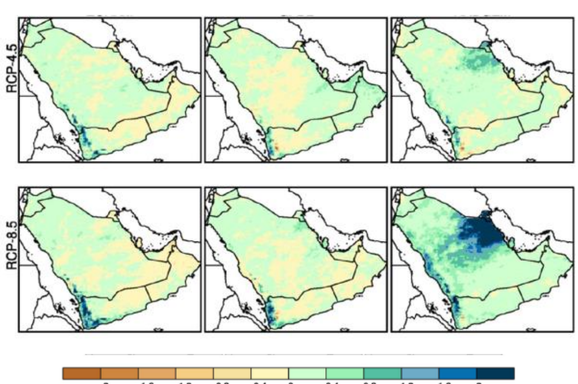
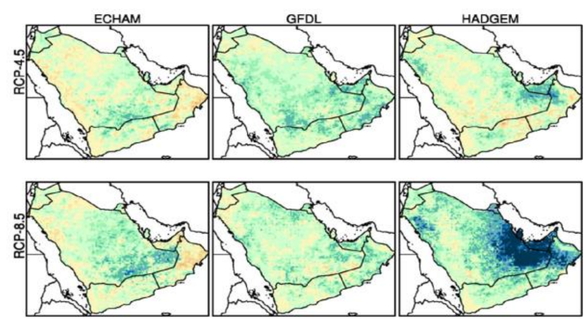


Fig. 13: as in Fig. 4 but for the very heavy precipitation days (days/yr).

3.3.3 Consecutive dry days

The number of consecutive dry days increases over a large area of central and western Arabian Peninsula for HADGEM and ECHAM under the moderate scenario in the mid-century where it decreases under the high-emission scenario (Fig. 14). On the other hand, the decrease for GFDL changes to increases at the end of the century while a pattern of diminishing dry days happens in the eastern Arabian Peninsula in the Empty Quarter for the other two models, raising a question; whether a particular dominant change in the circulation patterns will change under the high emission scenario to allow for such a dramatic change or not.

Changes in CDD (mm) (2036-2065) from base period (1976-2005)



Changes in CDD (mm) (2071-2100) from base period (1976-2005)

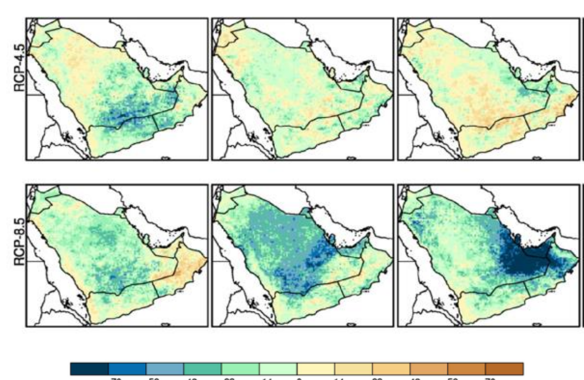


Fig. 14: as in Fig. 3 but for the consecutive dry days (days)

3.4 Climate change at selected cities in Saudi Arabia

The low-resolution data is not able to well represent the local climatic features. We are already aware of this limitation. However, to examine future change at local scale, we chose five cities that represent different climatic regions and have economical weight in the Arabian Peninsula.

3.4.1 Najran

The changes in the annual mean, minimum and maximum temperature for the three downscaled CMIP5 models along with their mean with respect to the reference period for Najran are shown in Fig. 15. The annual temperatures show generally a monotonous increase under the RCP4.5. However, they tend to diverge starting 2030 where the changes for HADGEM temperature are more than the other two models, while GFDL temperature are lower than both HADGEM and ECHAM5. The maximum temperature increase never exceeds 3 °C. The changes in daily precipitation of the annual mean at Najran for GFDL are lower than the other two models, fluctuating around 0, the other two models reached peak changes at various points. ECHAM5 reached 1.5 mm change around 2015, 0.5 mm change around 2035 and 1 mm around 2060 under RCP4.5. This model also shows remarkable decrease around 2020 and around 2080. The changes in the annual temperature in the RCP8.5 are more for all mean temperatures and rise to reach 6 °C above the reference period. The change in the precipitation under RCP8.5 is less than the RCP4.5 generally up to mid-century and HADGEM shows two peaks around 1.5 mm increase in 2060 and another smaller peak at the end of the century.

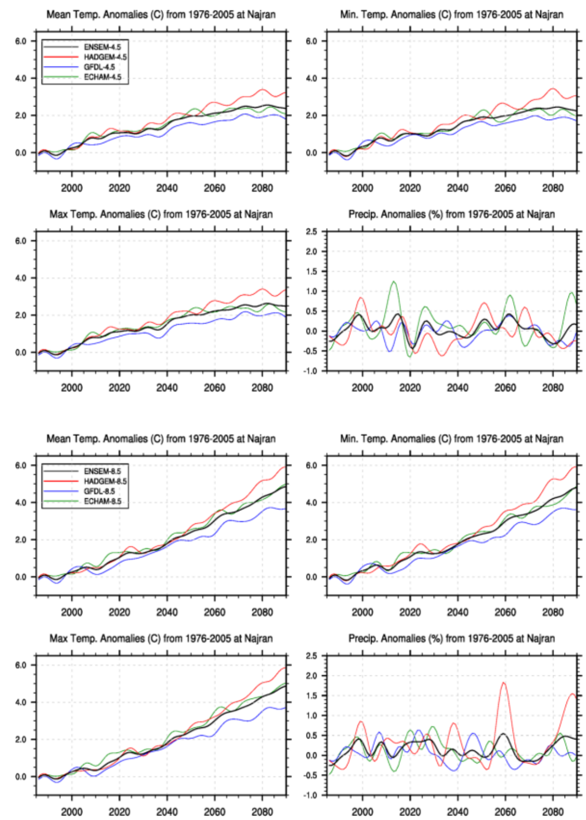


Fig. 15: Temperature and precipitation anomalies from the reference period for Najran. The first two rows from the top are under RCP4.5. Top row: mean temperature anomaly (left), minimum temperature anomaly (right). The second row: maximum temperature anomaly (left) and precipitation anomaly (right). The last two rows show the same variables in the same order but under RCP8.5. The models names are in the legend.

3.4.2 Jeddah

Jeddah is a major economic city in Saudi Arabia, located at the southwestern side of the country along the coast of the Red Sea. The changes in the annual mean, minimum and maximum temperature in the three CMIP5 models along with their mean with respect to the reference period for Jeddah are shown in Fig. 16. Under the RCP4.5 the annual mean, minimum, and maximum temperature shows a similar trend as in Najran but at a slower rate (Fig. 16). The changes in the temperature are generally less at Jeddah than Najran. The changes in daily precipitation of the annual mean at Jeddah (Jeddah receives a yearly amount of rainfall of about 50 mm). For GFDL, changes are higher than the other two models until mid-century, exceeding 1 mm change around 2025. In the second half of the century, HADGEM is higher, reaching a similar peak around 2060. For ECHAM5, changes in the precipitation are generally lower than the other two models. The changes in the annual temperature under the RCP8.5 are more for all mean temperatures and rise to about 5 °C above the reference period. The changes in the precipitation are generally higher than the RCP4.5 after 2040 for the three models.

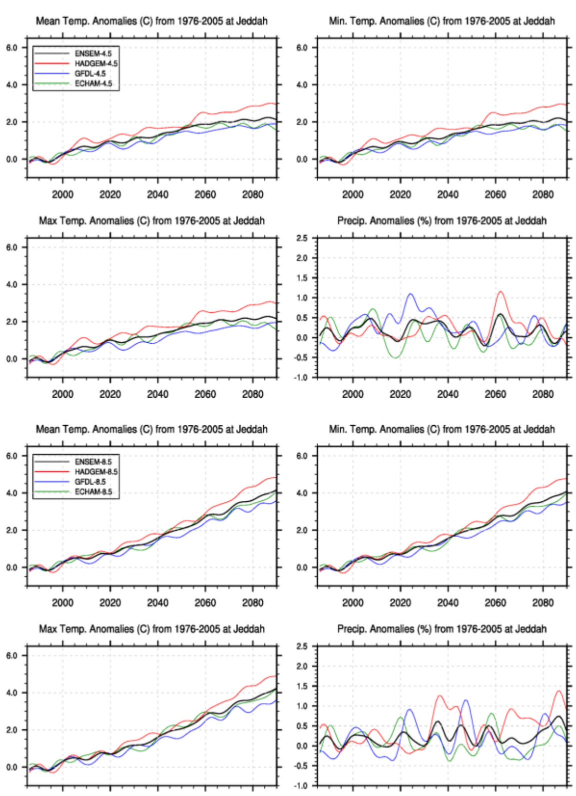


Fig. 16: As in Fig. 15 but for Jeddah.

3.4.3 Gassim

In the case of another important city Gassim (Fig. 17), annual mean, minimum and maximum temperatures increase monotonously at varying rates under the RCP4.5 scenario; HADGEM and ECHAM5 have higher rates then GFDL, with HADGEM reaching 4 °C above the annual mean of the reference period at the end of the century while GFDL model, increase does not exceed 2 °C.

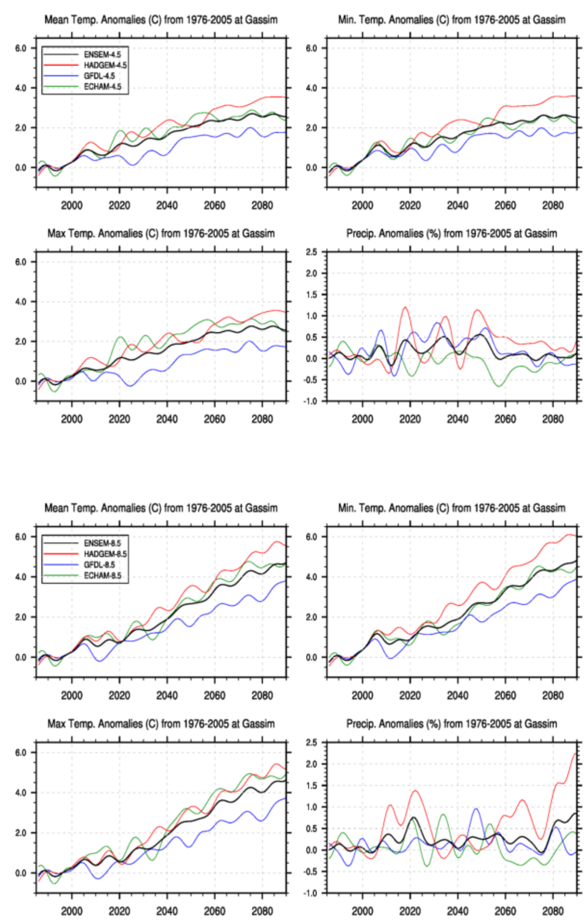


Fig. 17: the same as Fig. 14 but for Gassim+

For the precipitation, an overall increase in both GFDL and HADGEM, and an overall decrease for ECHAM are noticed. All three models tend to have less rain by the end of the century. The changes in the annual temperature under the RCP58.5 happen at a fast rate under RCP8.5 scenario starting in 2020 and reach to 6 °C by the end of the century for HADGEM. For GFDL and ECHAM, changes are generally lower than HADGEM, though converging from mid-century both reach an increase of 4 °C by the end of the century. The precipitation pattern for HADGEM is higher in most of the century, reaching 1.5 mm peak around 2025 and exceeds 2 mm by the end of the century. For ECHAM, it is lower in many years of this century and precipitation drops below the reference period average in almost one third of the century.

3.4.4 Al-Jouf

Al-Jouf is one of the northwest cities of the Arabian Peninsula and considered a temperate region in terms of precipitation and temperature. The changes in the annual mean, maximum and minimum temperature in the RCP4.5 are shown in Fig. 18. Temperatures increase but a reasonable rate reaching about 3.5 °C increase by the end of the century for HDGEM and 3 °C for ECHAM, and less than 2 °C for GFDL. The change in the precipitation is not much for ECHAM, with GFDL and HADGEM increase is much more than the ECHAM and it is difficult to correlate among the models. Under the RCP8.5, the annual mean, minimum and maximum temperatures seem to increase at a fast rate to reach 6 °C by the end of the century for HADGEM and 4 °C for ECHAM, and only 3 °C for GFDL. The precipitation changes are generally low except for two remarkable peaks for HADGEM around 2025 and 2070 to exceed 1 mm change of the mean. Variation of precipitation for the ECHAM model is much lower than the other two models in most years of the century after 2020.

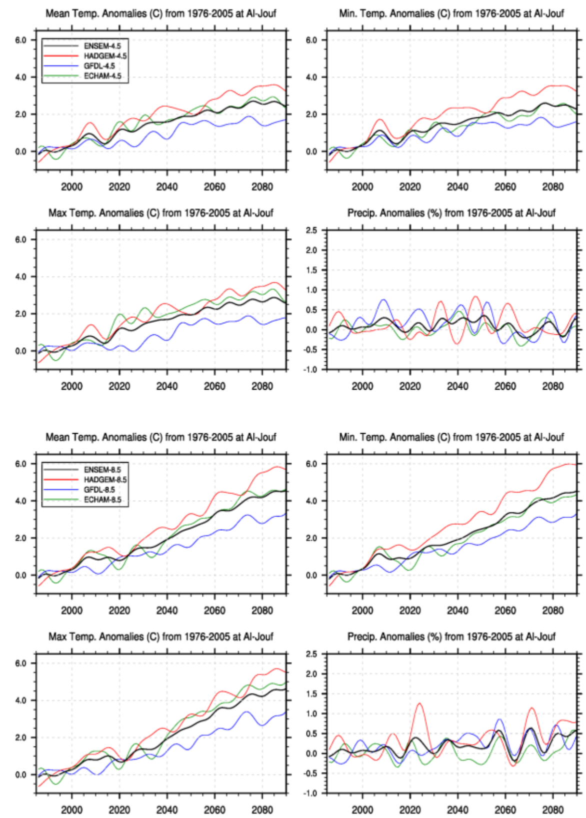


Fig. 18: the same as Fig. 14 but for Al-Jouf

4. Summary and conclusions

A regional climate model (RegCM4) was used to downscale the three CMIP5 GCMs to calculate precipitation and temperature extremes for the Arabian Peninsula in the twenty-first century. With reference to the current climate (1976-2005), changes in temperature and precipitation extremes were obtained for two future time-slices, 2036-2065 and 2071-2100, under two RCP scenarios (RCP4.5 and RCP8.5). The warm days (TX90p) are increased more than 50% over many portions of the Arabian Peninsula, particularly southern regions, and double over Asir Mountains. Additionally, at the end of the century, both scenarios' models tend to have very substantial increases in the frequency of warm days. Conversely, warm nights (TN90p) have a trend like that of warm days. There will be more warm nights in the southern regions of the Arabian Peninsula. Warm spell durations (WSDI) over the Arabian Peninsula indicate a rise in warm spell frequency. Under the high emission scenario, the increase is more noticeable. Long-lasting heat waves and drought-like conditions are typically linked to the rise in warm spells. In contrast, especially over the southern Arabian Peninsula, the cold spell duration index (CSDI) dropped relatively little under the high-emission scenario by the middle of the century.

Over the majority of the Arabian Peninsula in the middle of the twenty-first century, the number of cold days (TX10p) is decreasing. The patterns under the high emission scenario reveal that over the majority of the Arabian Peninsula, the number of cold days is predicted to fall by 35% by the end of the century. Over the Arabian Peninsula, cold nights (TN10p) are also expected to become less frequent. Under a high emission scenario, the expected signals are stronger. Additionally, these shifts are more pronounced as we approach the end of the 21st century. There is a very significant growth of extremely wet days across the central and the north-eastern regions of the Peninsula. Under all scenarios, there is an increase in the number of very wet days in the Asir Mountains and the area near the Red Sea coast for rainy days. The expected changes in extremely wet day patterns are remarkably similar to those of extremely wet day patterns.

In the middle of the century, it is anticipated that there will be an increase in the number of heavy rainfall days across the Arabian Peninsula, particularly in its central, northern, and southwestern regions. It is clear that the patterns of very wet days, extremely wet days, and heavy precipitation days are similar, but under both scenarios for the three models, it is predicted that extreme precipitation days will increase rather than decrease by the end of the century. Under the moderate scenario in the middle of the 21st century, the frequency of consecutive dry days will increase over a significant portion of the central and western Arabian Peninsula, whereas it will fall under the high-emission scenario.

Although the present study analyzed for the first time the bias corrected data to study climate change over the Arabian Peninsula. The coarse resolution of the downscaled data implies a limitation to study in-detail the climate change conditions at local/city scale. For realistic planning, the behavior of temperature and precipitation across other Saudi Arabian cities has to be studied further, using more model simulations with high-resolution information. The use of downscaled high-resolution datasets from the latest CMIP6 models is recommended. According to the current study, careful interpretation of climate projections is required for studies pertaining to climate change effect and adaptation as well as for policy considerations.

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تحليل الظواهر المناخية المتطرفة في شبه الجزيرة العربية باستخدام بيانات المحاكاة المصغرة لنموذج المناخ الإقليمي (RCM)

منصور المزروعي، أسماء يعقوب، عمران نديم، نذر الإسلام، سجاد سعيد، كامل شهزاد، محمد إسماعيل، طلال العويبدي، حسني حسانين

مستخلص. من المرجح أن يؤثر تغير المناخ بشدة على اقتصاديات البلدان في شبه الجزيرة العربية، ويجعل سكانها عرضة لظواهر الطقس المتطرفة. تتسبب نوبات هطول الأمطار الغزيرة والفيضانات في خسائر في الأرواح، بالإضافة إلى خسائر اقتصادية فادحة. هدفت هذه الدراسة إلى استكشاف أنماط درجات الحرارة والهطول المستقبلية في شبه الجزيرة العربية باستخدام نماذج محاكاة المناخ الإقليمي للفترة الزمنية المستقبلية ٢٠٣٦–٢٠٦٥ و٢٠٧١–٢١٠٠ مع اعتبار الفترة المرجعية ١٩٧٦–٢٠٠٥. تناولت الدراسة كذلك بعض المؤشرات المناخية لمدن مختارة في المملكة العربية السعودية. لهذا الغرض، تم محاكاة ثلاثة نماذج مناخية عالمية من البرنامج العالمي لأبحاث المناخ في المرحلة الخامسة لمشروع النموذج المتقارن (CMIP٥) شبه الجزيرة العربية باستخدام نموذج المناخ الإقليمي للمركز الدولي للفيزياء النظرية النسخة المطورة الخامسة (ICTP RegCM٥).

تظهر نتائج مؤشرات المناخ المتوقعة أن الأيام الدافئة والليالي الدافئة تزداد بأكثر من ٥٠٪ في معظم أجزاء شبه الجزيرة العربية، وتحديداً في الأجزاء الجنوبية وتتضاعف تقريباً فوق منطقة جبل عسير. يُظهر مؤشر مدة الفترة الدافئة زيادة في الفترة الدافئة في منطقة شبه الجزيرة العربية بينما يظهر مؤشر مدة موجة البرد انخفاض في مدة فترة موجة البرد في منتصف القرن بشكل ضئيل للغاية، باستثناء منطقة جنوب شبه الجزيرة العربية في ظل سيناريو الانبعاثات عالية الدقة. بدرجات متفاوتة تنخفض عدد الأيام الباردة والليالي الباردة في معظم أنحاء شبه الجزيرة العربية في منتصف القرن الحادي والعشرين. كما تشير المؤشرات القصوى المتوقعة لهطول الأمطار إلى زيادة في عدد الأيام شديدة الأمطار في شبه الجزيرة العربية بأكملها في ظل كلا السيناريوهيين (RCP٤,٥ و RCP٨,٥)، وزيادة طفيفة فقط في وسط وشرق شبه الجزيرة العربية بالنسبة لنموذج المناخ العالمي (ECHAM٥) في منتصف القرن. قرب نهاية القرن، نلاحظ انخفاضًا في عدد الأيام شديدة الأمطار في المناطق الوسطى والجنوبية وفقًا لكلا السيناريوهيين لنماذج المناخ العالمية (ECHAM٥) و (GFDL). كما أنه من المتوقع أن تزداد أيام هطول الأمطار الغزيرة في شبه الجزيرة العربية بشكل عام في منتصف القرن. بحلول نهاية القرن، ينخفض عدد أيام هطول الأمطار الغزيرة في كل مكان تقريبًا وفي جميع النماذج باستثناء النموذج المناخي (HADGEM) حيث تزداد عدد الأيام بشكل كبير على أجزاء كبيرة من شبه الجزيرة في ظل سيناريو الانبعاثات عالية الدقة. من المتوقع أن يزداد هطول الأمطار الشديد بدلاً

من الانخفاض في نهاية القرن في ظل كل السيناريوهيات للنماذج الثلاثة. كما تزداد عدد أيام الجفاف المتتالية على مساحة كبيرة من وسط وغرب شبه الجزيرة العربية في ظل السيناريو المعتدل في منتصف القرن بينما يتناقص في ظل سيناريو الانبعاثات عالية الدقة. تشير النتائج الحالية إلى أن هناك حاجة إلى تفسير دقيق لإسقاطات المناخ لأغراض السياسة وكذلك لتأثير تغير المناخ والدراسات ذات الصلة بالتكيف مع التغيرات المناخية.

الكلمة الرئيسية: المناخ المتطرف؛ شبه الجزيرة العربية؛ نموذج المناخ الإقليمي (RegCM)؛ إسقاط المناخ؛ مؤشرات المناخ المتطرفة