RICCAR

Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-economic Vulnerability in the Arab Region

Regional climate modelling outputs for Saudi Arabia: Key findings

TECHNICAL REPORT

UNITED NATIONS
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Shared Prosperity **Dignified Life**

Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR)

E/ESCWA/CL1.CCS/2023/RICCAR/TECHNICAL REPORT.18

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United Nations Economic and Social Commission for Western Asia (ESCWA)

TECHNICAL REPORT

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PREFACE

The Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) is a joint initiative of the United Nations and the League of Arab States.

RICCAR was launched under the auspices of the Arab Ministerial Water Council in 2010 and derives its mandate from resolutions adopted by this council as well as the Council of Arab Ministers Responsible for the Environment, the Arab Permanent Committee for Meteorology and the ESCWA Ministerial Session.

RICCAR is implemented through a collaborative partnership involving 11 regional and specialized organizations. The RICCAR Regional Knowledge Hub (RKH) is managed by the Economic and Social Commission for Western Asia (ESCWA) and the Arab Centre for the Studies of Arid Zones and Dry Lands (ACSAD) with the Food and Agriculture Organization of the United Nations (FAO) hosting the Arab/Middle East and North Africa (MENA) Domain data portal and ESCWA hosting the Mashreq Domain data portal. ESCWA coordinates the regional initiative under the umbrella of its Arab Centre for Climate Change Policies.

This technical report was prepared by ESCWA based on the RICCAR regional climate modelling outputs generated by the Swedish Meteorological and Hydrological Institute (SMHI).

ABBREVIATIONS AND ACRONYMS

AR5	Fifth Assessment Report
AR6	Sixth Assessment Report
CDDs	consecutive dry days
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
DTR	diurnal temperature range
ESCWA	Economic and Social Commission for Western Asia
GCM	global climate model
IPCC	Intergovernmental Panel on Climate Change
MIDAS	MultI-scale bias AdjuStment
RCM	regional climate model
RCP	representative concentration pathway
RH	relative humidity
RICCAR	Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region
RS	shortwave radiation
SSP	shared socioeconomic pathway
SU40	maximum daily temperature threshold of 40°C
Tmax	maximum temperature
Tmin	minimum temperature
UHI	urban heat islands

EXECUTIVE SUMMARY

The Intergovernmental Panel on Climate Change (IPCC) and the Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) both conclude that parts of Saudi Arabia will experience increased climate risks over the coming decades, specifically as follows:

With regard to temperature:

- Between 1975 and 2000, temperatures in Saudi Arabia increased by 0.5°C, higher than the global mean (0.3°C).
- By 2030, the annual temperature rate will increase to about 0.6°C per decade.
- By mid-term (2041–2060), the average temperature in Saudi Arabia will have risen by 2°C on average, compared to the recent historical period (1995–2014) under the "business-as-usual" scenario (SSP5-8.5). Some areas will increase by > 2.4°C.
- Nightly minimum temperatures are increasing at a faster rate than daytime maximum temperatures, particularly during the cooler months (November-April). This phenomenon is known as diurnal temperature range (DTR) reduction and is linked to increased cloud cover and aerosols from sand and dust storms.
- By mid-term, nearly half of the population will experience days > 40°C at least four months of the year.
- By mid-term, Saudi Arabia will experience nearly 20 heat waves annually (including during winter), each lasting about 10 days.

With regard to precipitation:

- Precipitation variability is projected to widen, particularly after 2030, varying as much as 60 per cent annually from one year to the next, raising the risk of both droughts and floods.
- Extreme precipitation events in Saudi Arabia are expected to occur up to three or four times per year by mid-term.
- Increased drought is most likely in the Rub' al-Khali, reaching up to 283 consecutive dry days (CDDs) per year by mid-term.
- Starting in 2030, the annual evaporation rate will be 40 per cent higher than the precipitation rate, resulting in increased groundwater losses and higher salinity.

Other indicators show the following:

- A projected decline in downwelling shortwave radiation (RS) is likely due to an increase in dust and aerosol concentrations in the atmosphere, a concern for sand and dust storms.
- Strong wind days (> 32.3 kph) are increasing during the summer months (+4.7 days/season by mid-term) in central-eastern Saudi Arabia, affecting cities like Medina and Bisha, raising the risk of sand and dust storms.

CONTENTS

FIGURES

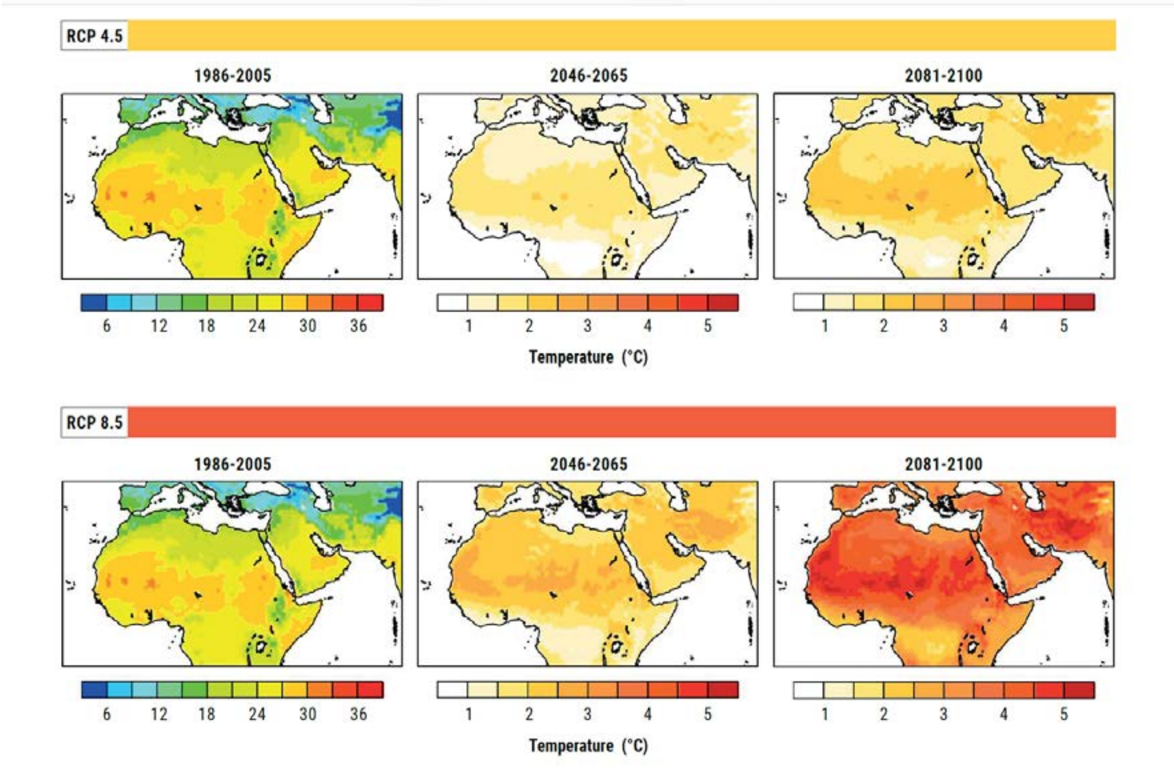
TABLES

1 CHARACTERIZING THE GLOBAL AND REGIONAL CLIMATE UNDER CURRENT AND FUTURE CONDITIONS

Signatories to the United Nations Framework Convention on Climate Change Paris Agreement pledge to keep the increase in the global average temperature well below 2°C while pursuing efforts to keep temperature increases under 1.5°C by the end of the twenty-first century compared to pre-industrial levels (in the 1850s). However, the Intergovernmental Panel on Climate Change (IPCC) projects that global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate in the absence of ambitious climate mitigation measures.[1]

In tandem, the Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) found that the change in the average temperature in the Arab region is happening faster than the global average. The average temperature in the Arab region increased by 0.8°C over the last 20 years alone, with the mean temperature projected to increase by 2.6°C by mid-term (2041–2060) and up to 4.8°C by the end of this century compared to the start of this century[2] under the higher emissions "business-as-usual" scenario (RCP 8.5) used in the IPCC Fifth Assessment Report (AR5), as shown in figure 1. RICCAR projections also show that precipitation signals are increasing variability and are giving rise to more frequent extreme climate events.

FIGURE 1: Mean change in annual temperature (˚C) for mid- and end-term for ensemble of three RCP 4.5 and RCP 8.5 projections compared to the reference period



Source: Economic and Social Commission for Western Asia (ESCWA) and others, 2017.

The IPCC Sixth Assessment Report (AR6) issued by Working Group I in 2022 presents findings on observed and projected climate change across the globe and in selected regions. One of the regions identified in the IPCC Interactive Atlas is the Arabian Peninsula.[3] The analysis shows that over the last 40 years, the average temperature in the Arabian Peninsula has been increasing at a faster rate than the global trend. During this same period, anthropogenic warming has amplified observed droughts across the region, while extreme rainfall has been increasing in elevated areas. Such precipitation variability is projected to increase further with a warmer climate.

More specifically, the observed average temperature across Saudi Arabia is increasing at a rate of 0.6°C per decade,[4,5] with a higher rate witnessed in early spring (March and April).[6] The daily minimum temperature (Tmin) has been rising at a more rapid rate than the daily maximum temperature (Tmax), resulting in a recent reduction in the diurnal temperature range (DTR).[7,8] Detected temperature trends have been amplified in urban areas, particularly during the summer months, due to elevated solar heat storage in urban structures and roadways. For instance, Riyadh has exhibited a higher temperature than the average in recent years and is at an increased risk of heat waves and urban heat island effects, as well as droughts and escalating water scarcity. Riyadh was specifically referenced as being subject to climate risks by IPCC Working Group II, which assesses climate change impacts, adaptation and vulnerability.

Characterizing climate in the Arabian Peninsula

Weather patterns across the Arabian Peninsula are affected by the following:

- Arid landmasses and the desert belt in the north
- North-westerly winds due to a high-pressure ridge extending southward into central Saudi Arabia
- Low-pressure ridge over the east

Advection has occasionally resulted in limited visibility stemming from sandstorms, dust storms, haze, mist and fog. Precipitation is confined to sporadic winter rainfall, generally originating from warm Gulf waters.

Local boundary fronts between the warm, moist air adjacent to the coast and cooler, drier continental air has produced convergence zones resulting in heavy precipitation and thunderstorms. Such conditions generate extremely high summer temperatures, high evaporation rates and limit freshwater resource availability.

IPCC also reports that precipitation has exhibited spatio-temporal variability in the region.[9] This has been witnessed in Saudi Arabia where, approximately every 10 years, the general trend moves from increasing to decreasing rainfall.[10] Precipitation has demonstrated a correlation with temperature such that warmer years are drier than relatively cooler years.[11] This phenomenon is also paralleled in seasonal effects; the warmer season from May to October is relatively dry and most precipitation occurs during the cooler, wetter season from November to April.[12] Moreover, precipitation spatially varies across the country and is generally highest in the Asir Highland climatic region (figure 2). Rainfall in the Rub' al-Khali is nearly nil; low rainfall has also been detected in the northern/An Nafud and coastal Red Sea regions.[13]

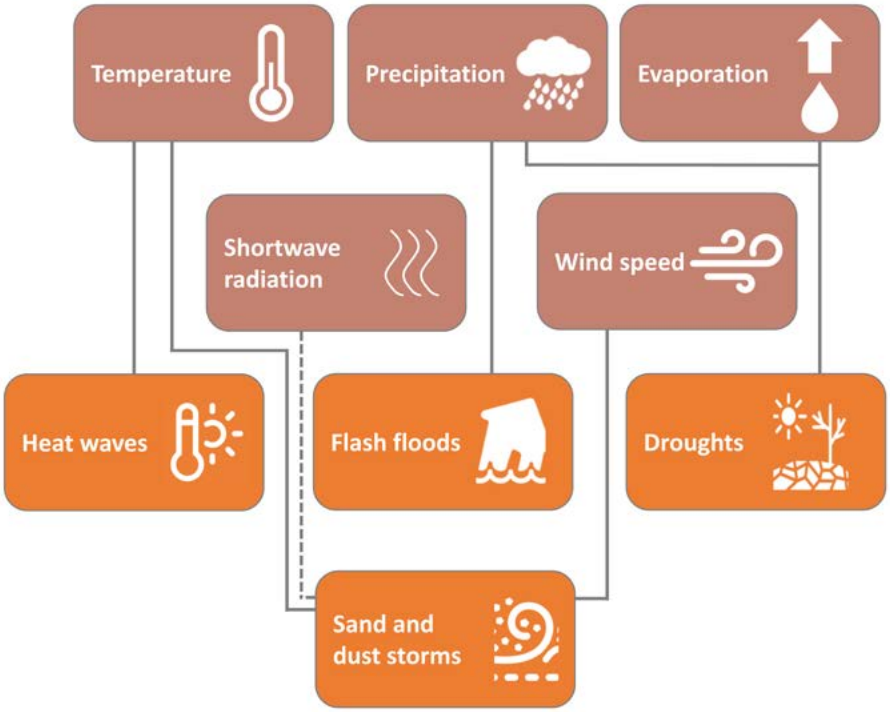
FIGURE 2: Climatic regions of Saudi Arabia and selected rainfall stations

Source: Adapted from Almazroui and others, 2015.

Results from the Arab Domain generated under RICCAR reveal that climate change across the region projects a nonlinear increase in temperature, with a sharp increase towards the end of the twenty-first century, particularly for the higher emissions "business-as-usual" scenario (RCP 8.5). In addition, precipitation signals increasing variability, giving rise to extreme climate events.[14] Advances in regional climate modelling provide more detailed analysis at a subregional level. Recently, fine resolution datasets were made available for the Mashreq Domain under RICCAR.

Climate modelling outputs obtained from the Mashreq Domain include several parameters. This report presents a selected few that are most relevant for Saudi Arabia with related extreme events indices to highlight potential impacts (figure 3). The resultant climate risks can have severe impacts on human health, agriculture and livestock, water availability, forests, biodiversity and infrastructure.

FIGURE 3: Selected climate change parameters and their potential risks

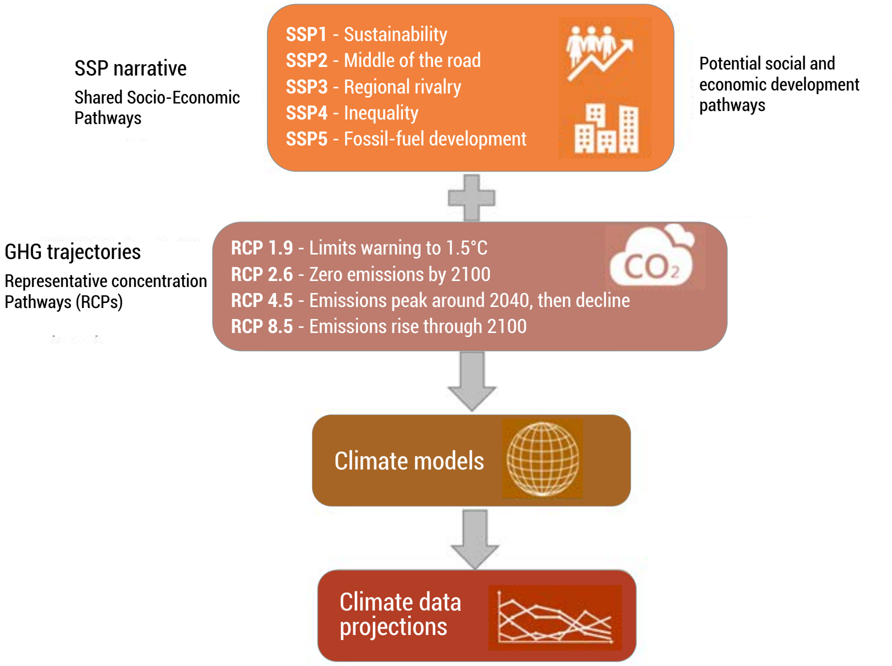


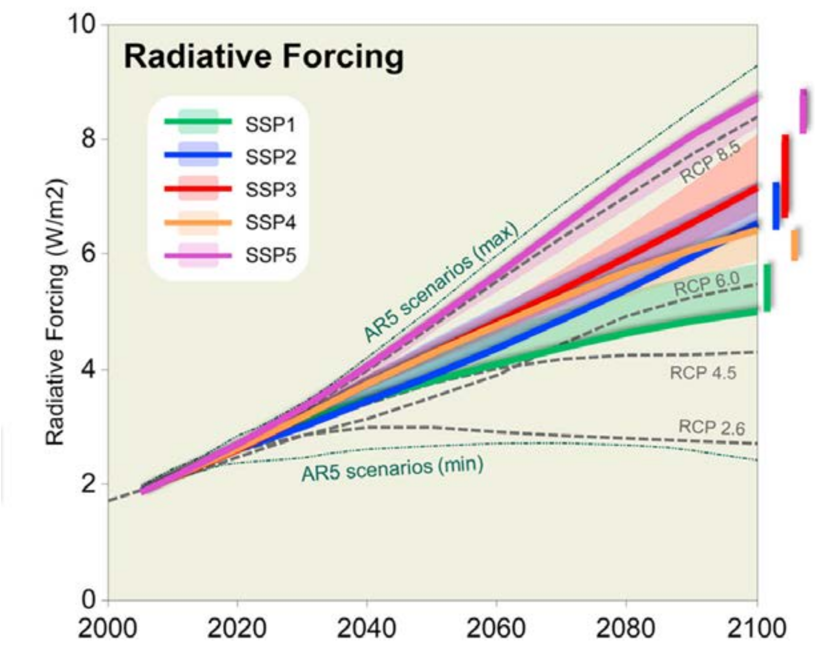
Source: Authors.

2 REGIONAL CLIMATE MODELLING METHODOLOGY

Global assessments of projected climate change are typically derived from ensembles of global climate models (GCMs), which are comprised of numerical models developed by different research institutions. Such GCMs simulate physical processes in the land surface, ocean, atmosphere and cryosphere to project the response of the global climate to increasing greenhouse gas emissions. The latest generation of GCMs is based on the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) with results presented in the IPCC AR6.

FIGURE 4: (a) SSPs and RCPs and their linkage to climate models and projections (left) - (b) global average change in radiative forcing over time including SSP baseline marker scenarios (and ranges of SSP non-marker baseline scenarios) compared to the RCPs and the full range of the IPCC AR5 scenarios (right)





Source: Adapted from Riahi and others, 2016.

To describe the future climate, IPCC has developed differing scenarios, which have evolved over time. CMIP6 models use a matrix framework that combines potential greenhouse gas trajectories, known as representative concentration pathways (RCPs), with a range of shared socioeconomic pathways (SSPs) that examine how global society, demographics and economics might change through to the year 2100. Scenarios range from SSP1-1.9, which most closely portrays a 1.5°C target under the Paris Agreement, to SSP5-8.5, which describes high radiative forcing in a fossil fuel development world (figure 4).[15,16] SSP5-8.5 is closest to a "business-as-usual" scenario based on high challenges for mitigation but low challenges for adaptation and is thus well suited for providing the upper boundary for policymaking. For this reason, results from SSP5-8.5 are presented herein.

To minimize uncertainties, climate scientists generally present data from three or more models, obtaining the mean from a 20-year period. IPCC in AR6 described a historical reference period based on the range spanning the period 1995-2014. Future periods typically describe projected changes in climate compared to the reference period; AR6 used near term (2021–2040), mid-term (2041–2060) and end term (2081–2100).

Despite the ongoing evolution of GCMs, important gaps remain when evaluating climate projections at a smaller scale. GCMs are known to have coarse horizontal resolutions with feedback and simulation biases. To better understand climate processes at a smaller scale, scientists conduct spatio-temporal downscaling using regional climate models (RCMs) with a specific domain, which are nested within the GCMs.

Projections from the Mashreq Domain (figure 5) are among the few RCM outputs currently available based on CMIP6. The Mashreq Domain was established as part of RICCAR to frame the set-up of regional climate projections for Western Asia, including Saudi Arabia.[17] The projections are generated at 10 km grid resolution with results covering the period from the year 1961 to 2070. Results from the Mashreq Domain entail a single RCM (HCLIM-ALADIN)[18] nested in six GCMs (table 1) based on the SSP5-8.5 scenario at 10 km resolution.

Raw RCM precipitation and temperature outputs obtained from the ensemble exhibit strong seasonal biases over Saudi Arabia that can lead to skewed interpretations of the results if not reviewed against observed datasets. Thus, it is important to present bias-adjusted data for precipitation; the minimum, maximum and mean temperature; and their associated extreme events indices. Bias-adjustment was conducted using the MultI-scale bias AdjuStment (MIdAS) bias adjustment methodology.[19] Bias-adjustment was not conducted for remaining climate variables.

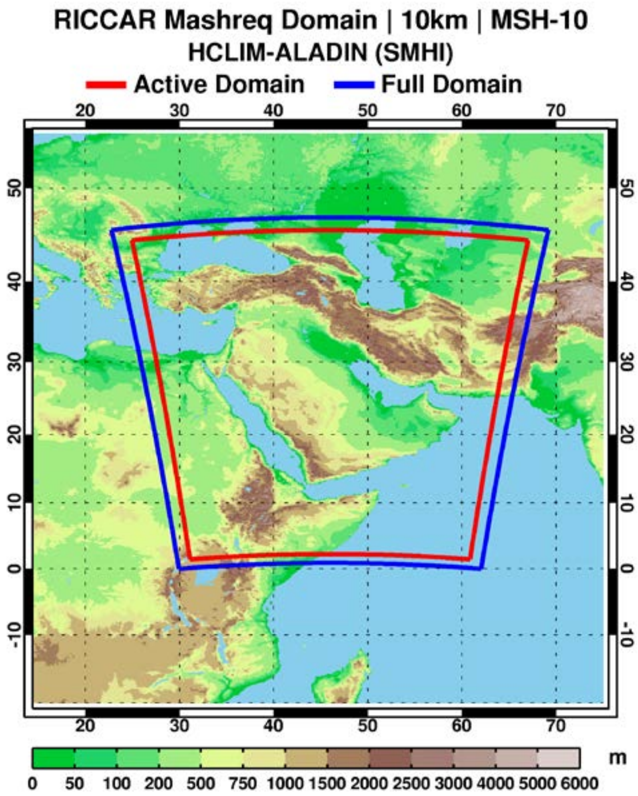
TABLE 1: GCMs selected for the Mashreq Domain

Driving GCM	Institute
CMCC-CM2-SR5[20]	Euro-Mediterranean Centre on Climate Change
CNRM-ESM2-1[21]	Centre National de Recherches Météorologiques and Centre Européen de Recherche et Formation Avancée en Calcul Scientifique
EC-Earth3-Veg[22]	European Consortium
MPI-ESM1-2-LR[23]	Max Planck Institute
MRI-ESM2-0[24]	Meteorological Research Institute
NorESM2-MM[25]	Norwegian Meteorological Institute

Source: Adapted from SMHI and ESCWA, 2021.

Note: The regional climate modelling outputs are nested within these models.

FIGURE 5: The Mashreq Domain



Source: Adapted from SMHI and ESCWA, 2021.

Note: The active domain (red) includes the area where RCM results are considered usable. The full domain (blue) indicates the actual area needed for the RCM (HCLIM-ALADIN in this case) to perform properly within the active domain. The area between the active and the full domains is a transition zone between the GCM driving boundaries and the RCM; using results from this zone should be avoided.

3 REGIONAL CLIMATE MODELLING OUTCOMES FOR SAUDI ARABIA

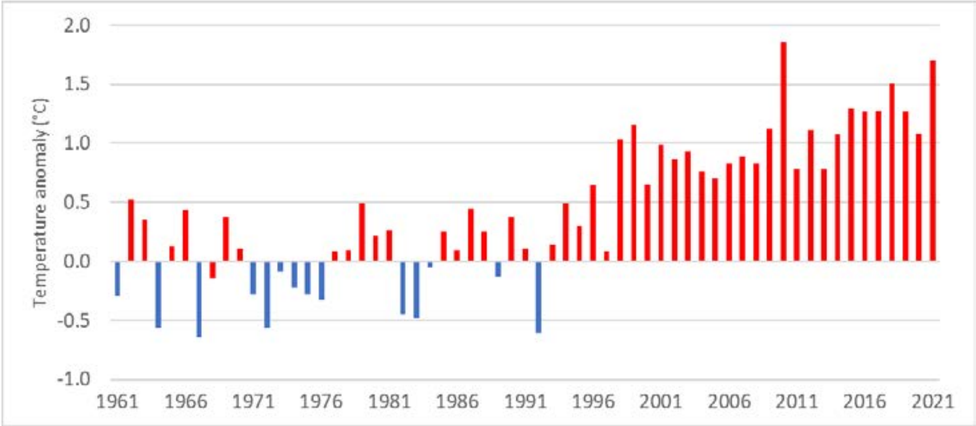
A. Temperature, very hot days and heat waves

1. Mean temperature

In AR6, IPCC emphasizes that there is an anthropogenic link between carbon dioxide being released into the atmosphere, rising global temperatures and accelerating climate impacts.[26] However, it acknowledges that the temperature increases unevenly due to oceanic effects, variable surface albedo and other factors. At the start of the twenty-first century (1995–2014), the mean annual temperature in the Arabian Peninsula increased by 0.8°C since the pre-industrial period (1850s), which was higher than the global mean (0.6°C). The rate has accelerated in recent decades (figure 6), reaching a 0.5°C increase just between 1975 and 2000 in Saudi Arabia (compared to 0.3°C globally).[27]

Between 1975 and 2000, temperatures in Saudi Arabia increased by 0.5°C, higher than the global mean (0.3°C).

FIGURE 6: Observed mean temperature anomaly in Saudi Arabia, 1961–2021, compared to the historical mean (1961–1990)

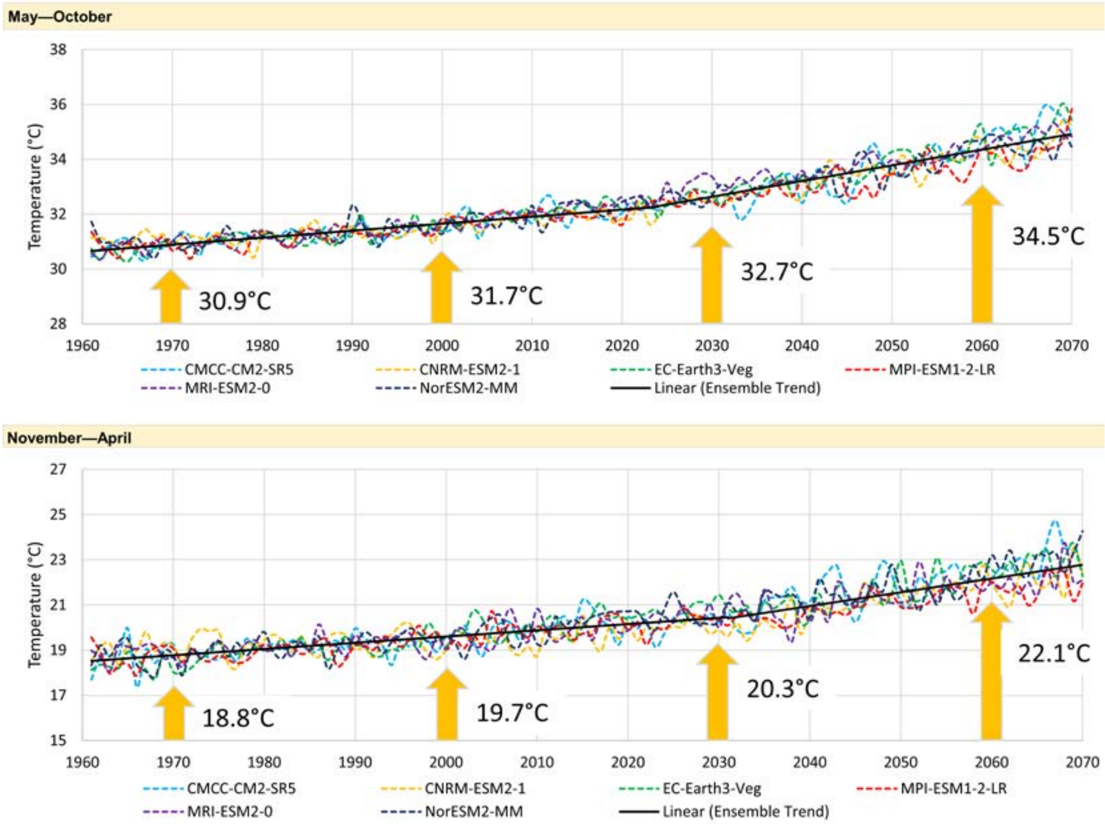


Source: Analysis from CRU TS dataset from Harris and others, 2020.

By 2030, the annual temperature rate will increase to about 0.6°C per decade.

Results from the Mashreq Domain climate models reveal the increase in temperature across Saudi Arabia since 1961, which has been rising at a rate of 0.26°C and 0.28°C per decade for the May-October and November-April seasons, respectively (figure 7). These values obtained from the Mashreq Domain outputs are mid-range between the IPCC estimates obtained from GCMs [28], observed data [29,30] and reanalysis data (figure 6).[31] Differences are attributed to the coarseness of the GCMs when compared to the IPCC estimates and the few selected stations for the observed data. By around 2030, the rate of temperature increase will double, compared to the present, based on a fossil fuel development future scenario (SSP5-8.5). Across Saudi Arabia, the rate of temperature rise will increase to 0.57°C per decade during the May-October season and 0.61°C per decade during the November-April season. The greater increase during the cooler months is consistent with the general trend for northern mid and high latitudes.[32]

FIGURE 7: Seasonal temperature time series for Saudi Arabia based on the bias-adjusted Mashreq Domain RCM outputs, SSP5-8.5

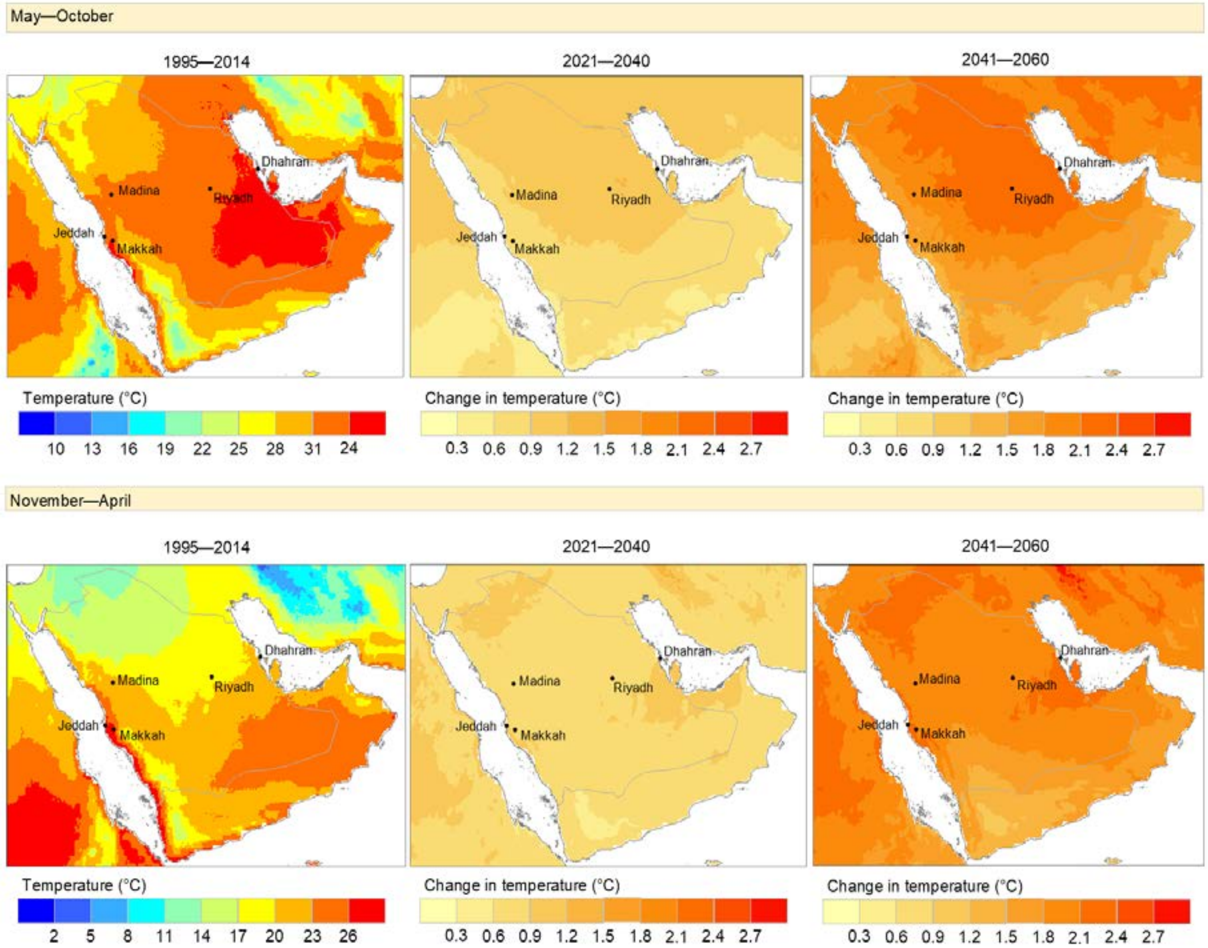


Source: Authors.

Temperature intensification is not uniform across Saudi Arabia, however (figure 8). The spatial pattern presented during the RCM reference period (1995–2014) matches observed data.[33,34] During the May-October season, higher temperatures prevailed over Saudi Arabia, extending north-eastward towards Kuwait, Iraq and Iran. During the November-April season, seasonal higher temperatures shift southward and are limited to Rub' al-Khali and the southern Red Sea coast.

Proximity to the sea, topography and land use/land cover can impact the projected rise in temperature. In general, the incremental temperature increase exhibits an increasing gradient from the south-west to the north-east. By mid-term (2041–2060), the mean temperature will have risen by 2°C compared to the recent historical reference period (1995–2014) (table 2), with some areas in the eastern Najd interior region increasing by > 2.4°C.

FIGURE 8: Mean seasonal change in temperature for the near term (2021–2040) and the mid-term (2041–2060) compared to the reference period (1995–2014) based on the bias-adjusted Mashreq Domain RCM outputs, SSP5-8.5



Source: Authors.

2. Diurnal temperature range

DTR, which is the net difference between the daily maximum and minimum temperatures, can often provide more climate change insight than the mean temperature alone. Increases in cloud cover, elevated aerosol concentrations, rising greenhouse gases and humidity have resulted in a global DTR reduction.[35]

Globally, a general decrease in DTR has been observed, mostly due to increased cloud cover. During the day, clouds act as a shield to prevent shortwave radiation (RS) and sunlight from reaching the ground. Clouds also prevent radiative cooling at night by trapping heat near the earth's surface. Thus, on cloudy days and nights, the daily maximum and minimum temperatures are nearly the same as the mean temperature, reducing the temperature range. Elevated aerosol concentrations, rising greenhouse gases and higher humidity from increased water vapour are also causing DTR reduction.

During the reference period, Tmax and Tmin averaged 32.5°C and 18.5°C annually, which is similar to the observed data during the period spanning the years 1978 to 2010.[36] Seasonally, the reported differences in mean Tmax were greater than Tmin (12.5°C and 11°C, respectively). During the warmer months (May-October), temperatures are influenced by monsoon-desert atmospheric circulation resulting in a wider DTR. Conversely, during the cooler months (November-April), the range is diminished due to effects from the subtropical Middle East jet streams and temperature moderation from the sea.

DTR reduction is linked to increased cloud cover and aerosols from sand and dust storms.

The projected rise in Tmax and Tmin generally exhibits an increasing gradient from south to north (figures 9 and 10), with a greater increment for Tmin.

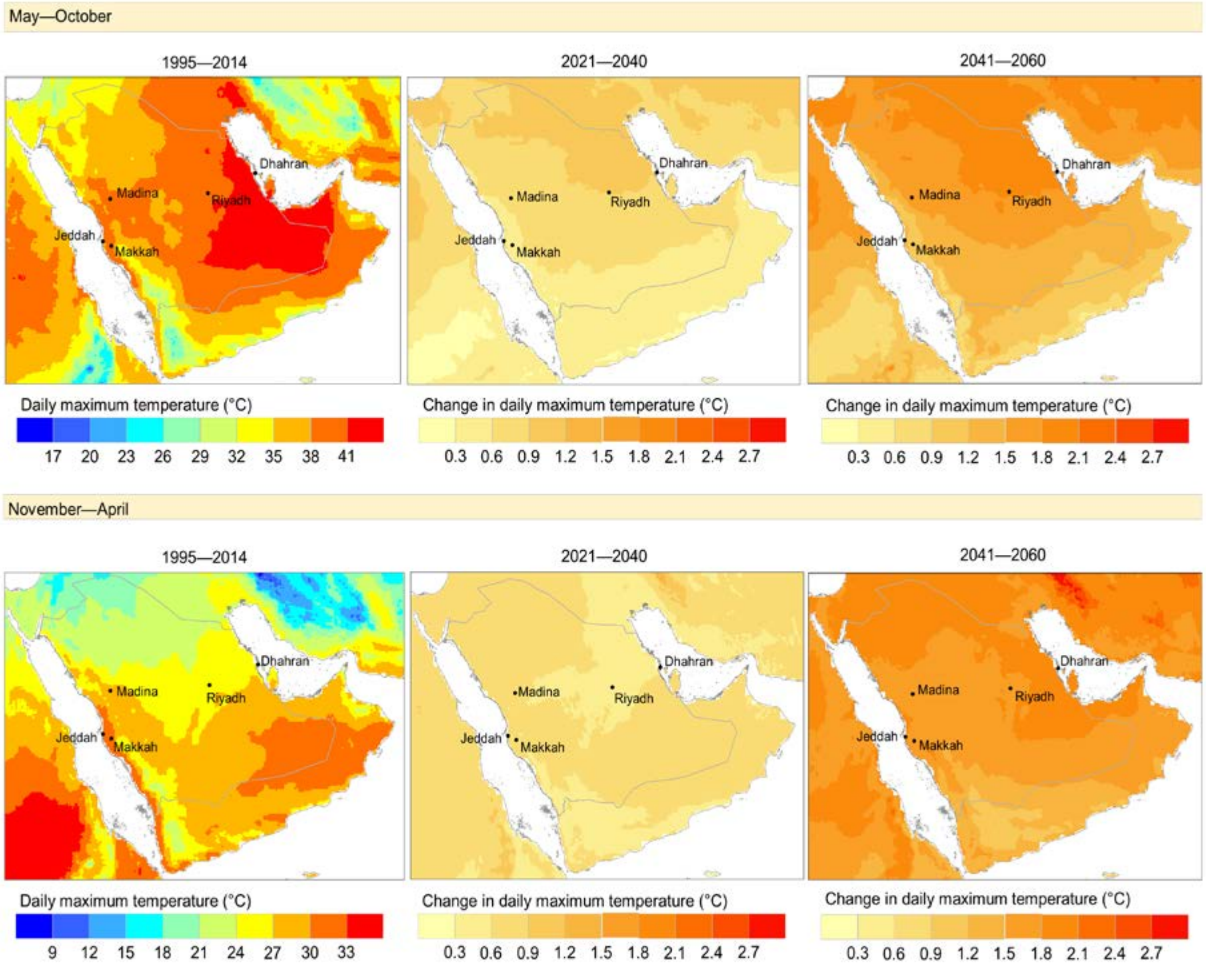
Seasonally, the intensification is greater during the May-October season for the near term (2021–2040) but switches to the November-April season for the mid-term (2041–2060) (table 2). This oscillating trend has been observed in recent years, attributed to temperature-related extreme events.[37] The Tmax and Tmin fluctuating trends have resulted in variable DTR projections. Globally, variable DTR has been linked to human health and mortality,[38] changes in crop yield[39] and bird impermanence.[40] During the warmer dry season (May-October), DTR is projected to decrease for the near term but then increase by mid-term to match the reference period (table 2). However, DTR reduction is the prevailing trend during the cooler wet season (November-April). These changes are most likely linked to other climate variables. DTR is closely related to cloud cover (affecting about 60 per cent of regional annual variance), followed by changes in soil moisture, precipitation and atmospheric dipole phenomena.[41] As seen later in this report, DTR variability is consistent with changes in the hydrological cycle and downwelling shortwave radiation.

TABLE 2: Comparison of the mean change in maximum, minimum and mean seasonal temperature for the near term (2021–2040) and the mid-term (2041–2060) compared to the reference period (1995–2014) based on the bias-adjusted Mashreq Domain RCM outputs, SSP5-8.5, Saudi Arabia mean

Season	Variable	C°		
		1995–2014	2021–2040	2041–2060
May–October	Temperature	31.8	32.8 (+0.9)	33.8 (+2.0)
	Tmax	38.7	39.4 (+0.8)	40.3 (+1.6)
	Tmin	24.0	25.1 (+1.1)	25.6 (+1.6)
	DTR	14.7	14.3	14.7
November–April	Temperature	19.7	21.7 (+0.9)	22.7 (+2.0)
	Tmax	26.2	26.8 (+0.7)	27.9 (+1.7)
	Tmin	13.0	13.9 (+0.9)	15.0 (+2.0)
	DTR	13.2	12.9	12.9

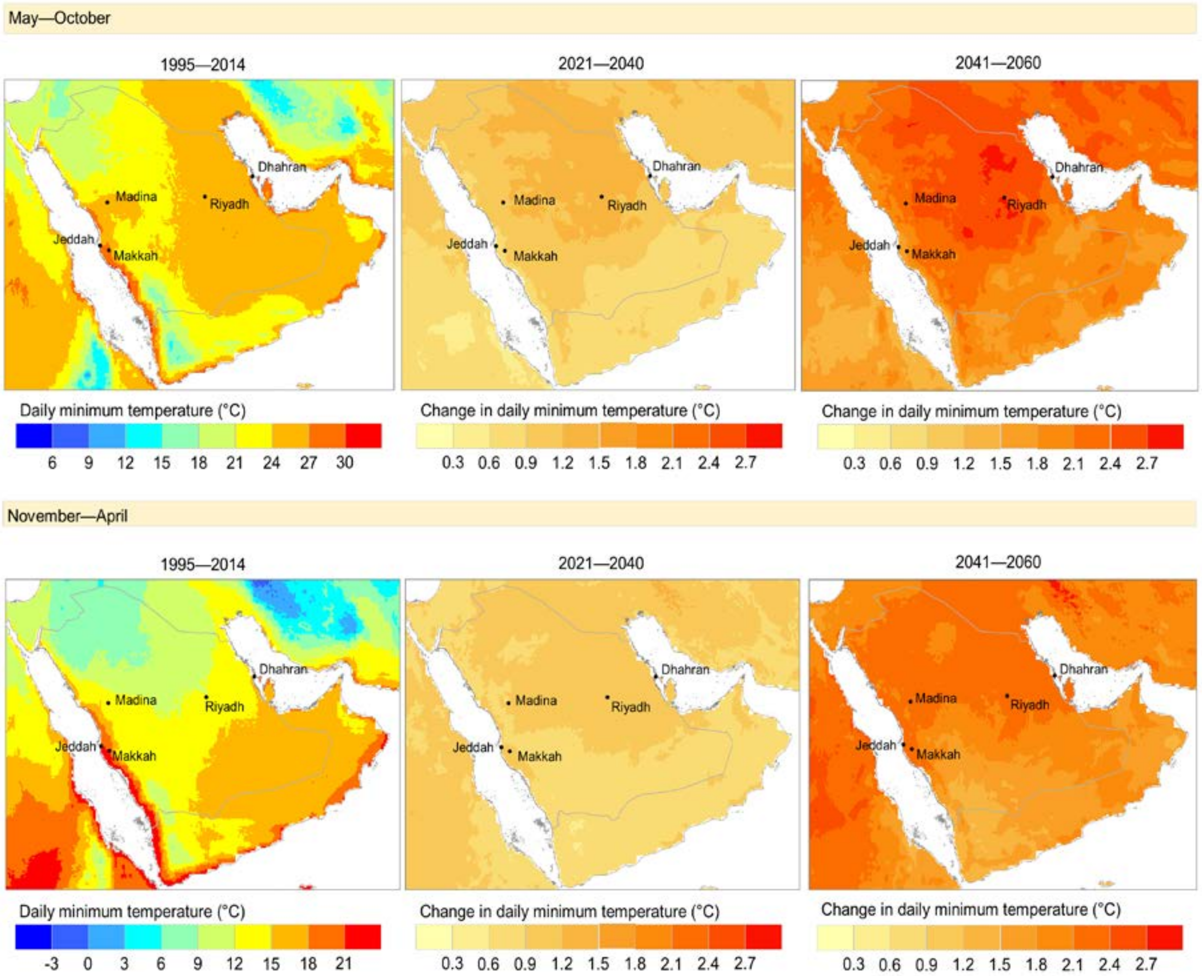
Source: Authors.

FIGURE 9: Mean seasonal change in Tmax for the near term (2021–2040) and the mid-term (2041–2060) compared to the reference period (1995–2014) based on the bias-adjusted Mashreq Domain RCM outputs, SSP5-8.5



Source: Authors.

FIGURE 10: Mean seasonal change in Tmin for the near term (2021–2040) and the mid-term (2041–2060) compared to the reference period (1995–2014) based on the bias-adjusted Mashreq Domain RCM outputs, SSP5-8.5



Source: Authors.

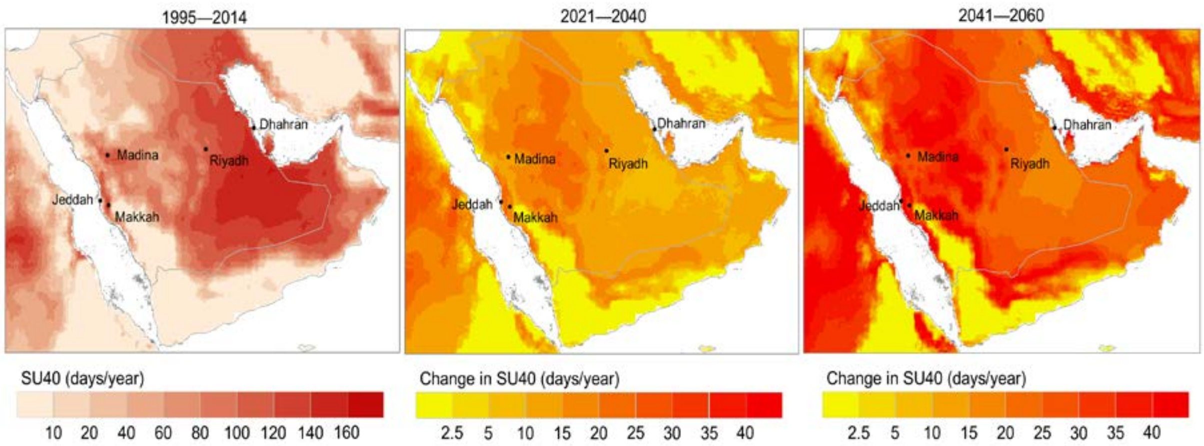
3. Very hot days and heat waves

IPCC has identified heat waves as a growing high risk for Saudi Arabia.[42] An increasing number of very hot days and heat waves can provoke adverse impacts on human health, agricultural and livestock productivity, infrastructure and the environment. Identification of the most vulnerable areas to temperature-related extreme events is important for policymakers to help allocate necessary resources and implement adaptive measures.

Days which exceed the maximum daily temperature threshold of 40°C (SU40) have been defined by RICCAR as a "very hot day".[43] Temperatures which exceed this value render the likelihood of heat exhaustion among the population. For the reference period (1995–2014), very hot days were detected about 80 days/year (< 3 months) on average (figure 11); the highest SU40 values were in Rub' al-Khali, exceeding 160 days/year (5.3 months). Such days are projected to increase, correlating with the projected rise in temperature. Values are expected to increase 13.5 days/year by near term (2021–2040) and 27.7 days/year by mid-term (2041–2060). The rise by mid-term means that 56 per cent of the land area of the country will experience temperatures exceeding 40°C for at least four months out of the year, which will affect 48 per cent of the population. This is a significant increase compared to 10 per cent of the surface area and 29 per cent of the population experiencing SU40 days during the reference period.

By mid-term, almost half the population of Saudi Arabia will experience days above 40°C at least four months per year.

FIGURE 11: Mean annual change in the number of very hot days (days when Tmax > 40 °C) for the near term (2021–2040) and the mid-term (2041–2060) compared to the reference period (1995–2014) based on the bias-adjusted Mashreq Domain RCM outputs, SSP5-8.5



Source: Authors.

A heat wave is an extended period of excessive temperatures relative to the normal conditions. However, there is no universally accepted methodology to quantify the number of heat wave events and their duration. One widely accepted approach is the number of consecutive days when the maximum temperature exceeds a certain threshold. Here, a similar approach is adopted that was used for other recent studies across the Arab Domain: a heat wave is a period in which at least three consecutive days exceed the 95th percentile of Tmax obtained from a historical control period (1981–2010), over a 31-day window.[44,45] Heat waves are not limited to summer months; based on the definition used herein, a relative heat wave can occur during winter.

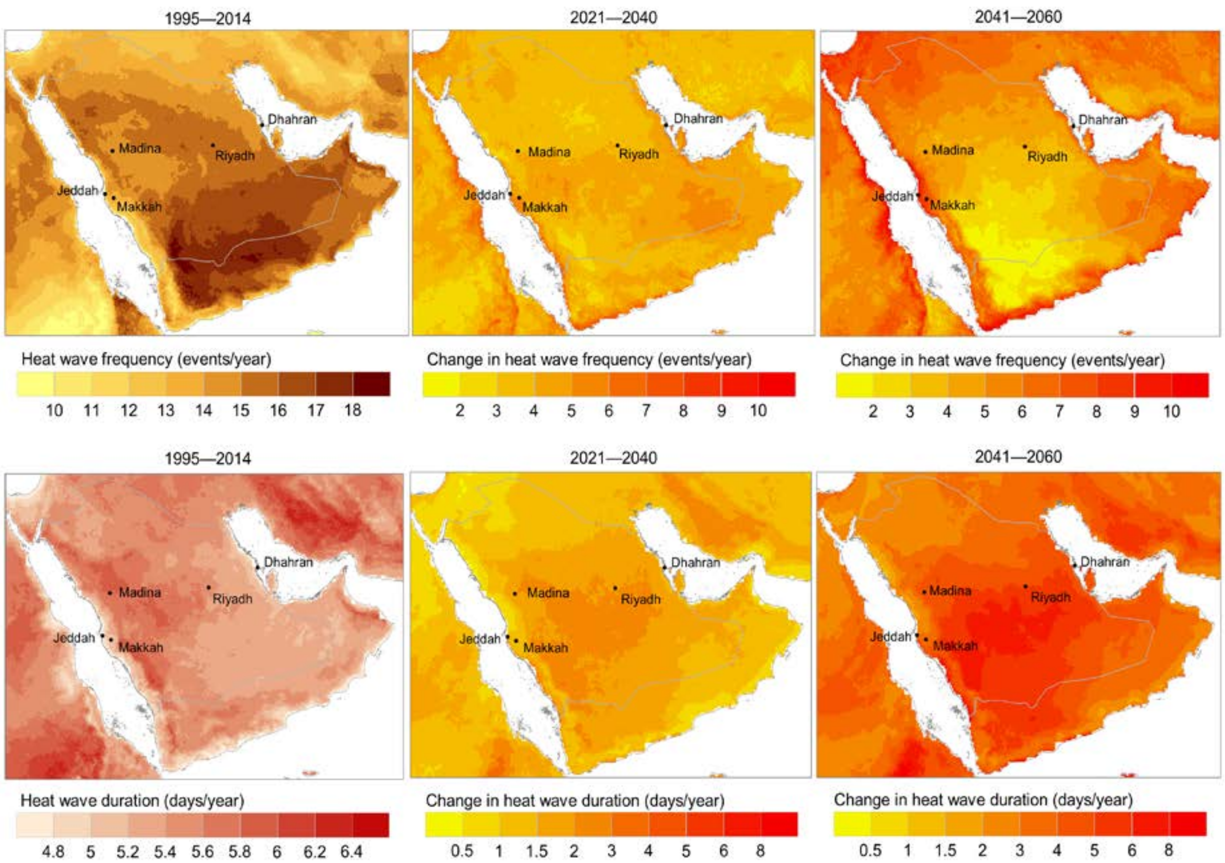
By mid-term, Saudi Arabia will experience nearly 20 heat waves annually (including during winter), each lasting about 10 days.

During the reference period (1995–2014), about 15 heat wave events occurred annually lasting 5.5 days (figure 12). This is comparable to the reported number of days of extreme temperatures in Saudi Arabia.[46] Both the heat wave frequency and duration are expected to rise. By mid-term (2040–2060), heat waves will occur nearly 20 times per year (+4.6 events/year compared to the reference period) and will last approximately 10 days.

It should be noted that these projections do not consider urban heat island nor relative humidity effects, which can affect temperature. Urban heat islands (UHI) are caused by radiative properties of urban infrastructure, dense building configurations and adjacent heat sources and sinks. Cities in Saudi Arabia have exhibited temperatures 1°C –1.5°C higher than nearby peri-urban areas, particularly at night.[47] Moreover, UHI effects can increase extreme temperature indices, causing them to rise; a study revealed that heat wave duration in urban landscapes increased by 2.3 days compared to rural areas.[48]

The heat index, or apparent temperature, considers the combined effects of relative humidity (RH) with temperature. Temperatures can feel higher than the reported air temperature when RH is ≥ 40 per cent and air temperature is ≥ 26.6°C; the relationship between the two variables is nonlinear.[49] Relative humidity averages about 32 per cent annually across Saudi Arabia and is not projected to change significantly. However, in coastal areas, the average RH exceeds 74 per cent, particularly along the southern Red Sea.[50] The combination of this RH with the average annual air temperature (27°C) in this locale results in an annual average heat index of 30°C.

FIGURE 12: Mean annual change in heat wave frequency (top) and duration (bottom) for the near term (2021–2040) and the mid-term (2041–2060) compared to the reference period (1995–2014) based on the bias-adjusted Mashreq Domain RCM outputs, SSP5-8.5



Source: Authors.

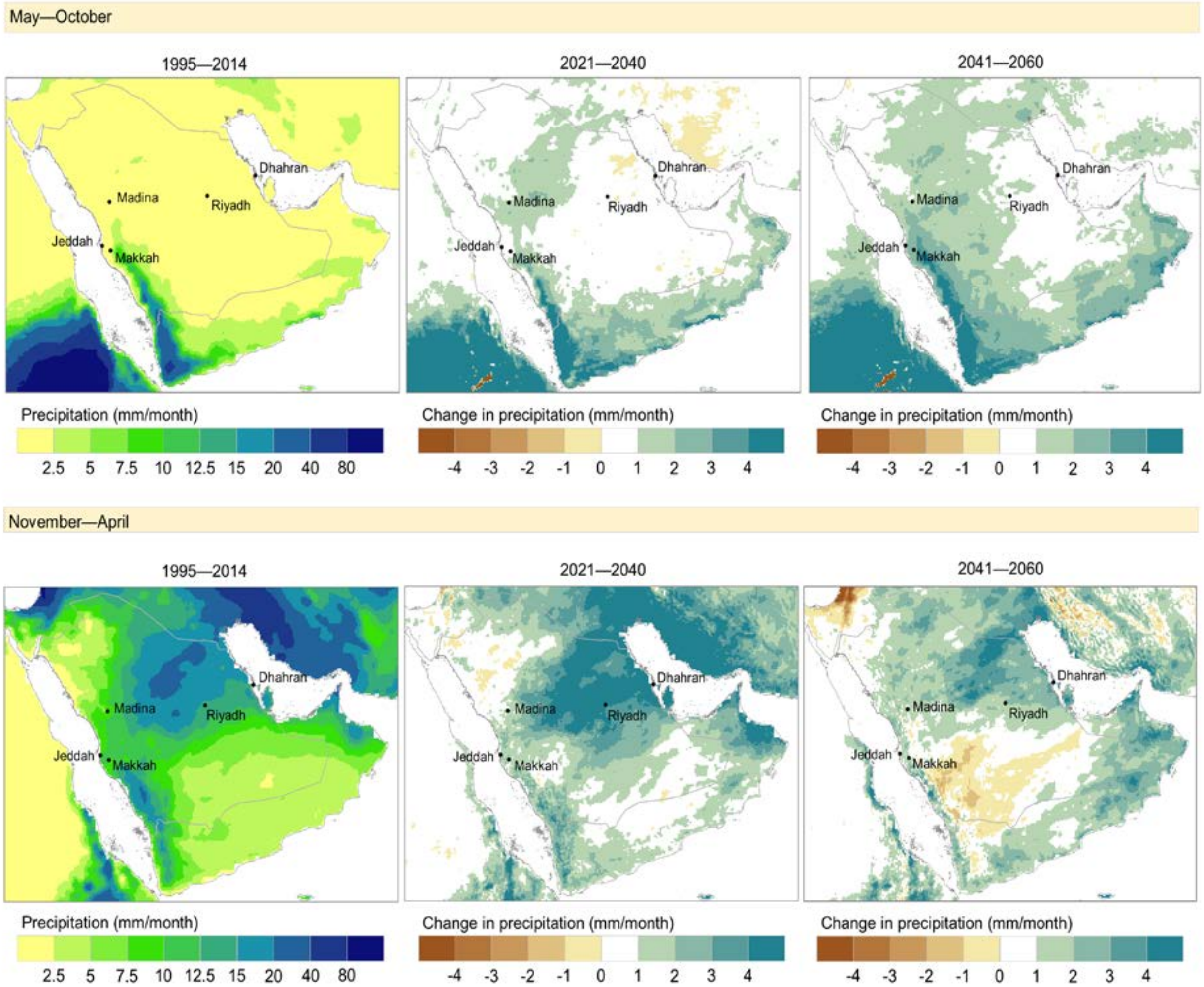
B. Precipitation, droughts and flash floods

Precipitation in Saudi Arabia has been generally limited to the six-month period from November to April, influenced by the positive Indian Ocean Dipole and warm El Niño–Southern Oscillation phenomena.[51] During the reference period (1995–2014), model outputs indicate an average precipitation of 10.2 mm/month, concurring with the long-term observed mean (figure 13).[52] Projected precipitation signals a general increase but will remain variable. During the wet season, the largest projected increases will occur in the Najd interior region, increasing by 45 per cent in the near term (2021–2040) compared to the reference period. Conversely, in the Rub' al-Khali, precipitation is projected to decline during the mid-term (2041–2060).

During the winter season, precipitation may occur in the form of snowfall in the northern mountainous regions of Turaif, Tabuk, Arar and Rafha; more rarely, snow can occur in the Asir Highlands.[53] Most recently, in 2022, snow and hail fell near the town of Badr (coastal Red Sea) in January[54] and measurable snowfall occurred in the Tabuk area near the Jordanian border in December.[55]

Rainfall during the dry season (May-October) is nearly negligible. During the reference period, model outputs revealed a mean precipitation of 1.6 mm/month, which is less than the long-term observed mean (2.9 mm/month).[56] Precipitation is largely confined to the southern Red Sea coastal and Asir Highland regions, influenced by orographic convection and the Indian monsoon.[57] Projections suggest a slight increase in future precipitation. However, towards the mid-term, inter-annual variability will greatly widen.

FIGURE 13: Mean seasonal change in precipitation for the near term (2021–2040) and the mid-term (2041–2060) compared to the reference period (1995–2014) based on the bias-adjusted Mashreq Domain RCM outputs, SSP5-8.5

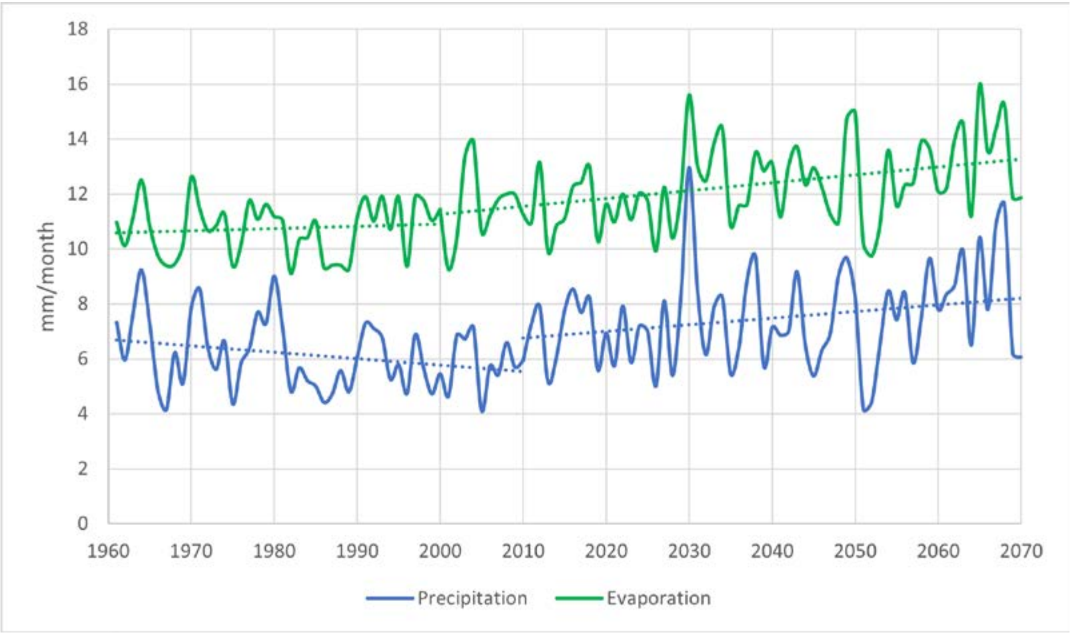


Source: Authors.

Precipitation variability is projected to widen particularly after 2030, varying as much as 60 per cent annually from one year to the next.

Through the year 2010, Saudi Arabia was in a period of generally decreasing precipitation (figure 14). Since then, generally increasing precipitation has been observed[58] and is projected to continue through mid-term. However, inter-annual variability will widen, particularly after 2030, varying as much as 60 per cent from one year to the next. Rapid transitions between wet and dry periods (known as hydroclimate whiplash) are more likely globally, including in Saudi Arabia.[59] These shifts often result in extreme events including droughts and floods. Thus, although the average precipitation volume is projected to increase, the rainfall pattern is changing and may include one or more extreme precipitation events followed by a period of drought.

FIGURE 14: Time series comparison of precipitation and evaporation (based on ensemble from six Mashreq Domain climate models, SSP5-8.5 for Saudi Arabia)



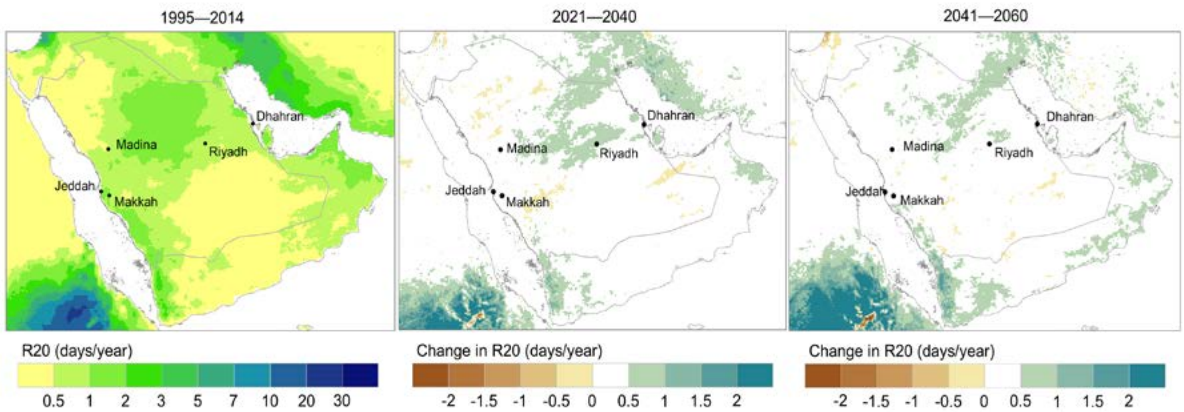
Source: Authors.

Recent flash floods across Saudi Arabia due to extreme precipitation, topography, urbanization and other factors have resulted in adverse economic impacts.[60] A November 2009 flood event in Jeddah following 74 mm of rainfall resulted in loss of life and extensive infrastructure and property damage. A subsequent event measured even greater precipitation (111 mm) and occurred in the same area less than 14 months later (January 2011).[61,62] Along the opposite coast, extreme precipitation events occurred in both 2017 and 2018 in Dammam, resulting in transportation disruptions, including train derailment, and widespread infrastructure damage.[63] Recurrent flooding has also occurred in the north, near Tabuk, including the January 2019 event, which reported 52 mm of rainfall in 24 hours.[64]

Extreme precipitation events in Saudi Arabia are expected to occur up to three or four times per year by the mid-term (2041–2060).

Extreme precipitation in Saudi Arabia can be defined by days on which it exceeds 20 mm, approximately equal to the 90th percentile for precipitation.[65] During the reference period (1995–2014), one could expect a 20 mm precipitation event to occur about once every 1.4 years in Saudi Arabia and as much as twice annually in the Najd interior region (figure 15). Such extreme precipitation is expected to happen annually in the future, occurring up to three or four times per year by mid-term (2041–2060).

FIGURE 15: Mean annual change in very heavy rain days (days when precipitation ≥ 20 mm; R20) for the near term (2021–2040) and the mid-term (2041–2060) compared to the reference period (1995–2014) based on the bias-corrected Mashreq Domain RCM outputs, SSP5-8.5

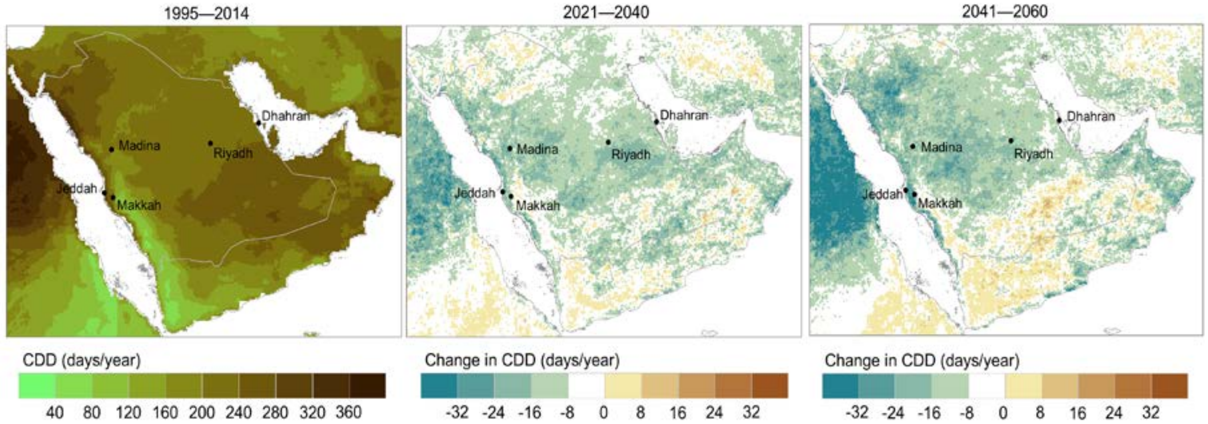


Source: Authors.

Drought is most likely in the Rub' al-Khali, reaching up to 283 CDDs per year by the mid-term (2041–2060).

Flood events can transpire after a period of drought. Drought risk is assessed by one or more indices proposed in literature. One of the simplest methods is by the maximum length of a dry spell, also known as consecutive dry days (CDDs), proposed by the Expert Team on Climate Change Detection and Indices.[66] During the reference period (1995–2014), the maximum period without measurable rainfall was about 224 days/year across Saudi Arabia (figure 16). This period will shorten by 10.5 days/year, on average, by near-term (2021–2040); this means that Saudi Arabia (with the exception of Rub' al-Khali) will be generally less dry in the future, consistent with recent observations. However, by mid-term (2041–2060), some lengthening is expected in the south (up to 20.7 days/year in Rub' al-Khali). This increase in the maximum length of a dry spell is concurrent with a rise in 20 mm precipitation days, mounting the risk for future hydroclimate whiplash.

FIGURE 16: Mean annual change in maximum length of CDDs for the near term (2021–2040) and the mid-term (2041–2060) compared to the reference period (1995–2014) based on the bias-corrected Mashreq Domain RCM outputs, SSP5-8.5



Source: Authors.

C. Evaporation

Evaporation is generally positively correlated with temperature. However, in the Arab region, this relationship is not necessarily the case due to the limited availability of water resources.[67] In general, the annual evaporation trend was unchanged through 2000 but since then has been increasing and is projected to continue to rise through mid-term (2041–2060) (figure 14). Across Saudi Arabia, there are 449 dams used to collect, store and recharge runoff and for flood protection. Water availability in reservoirs is threatened by high evaporation rates, over abstraction and limited precipitation, particularly in the Rub' al-Khali.[68]

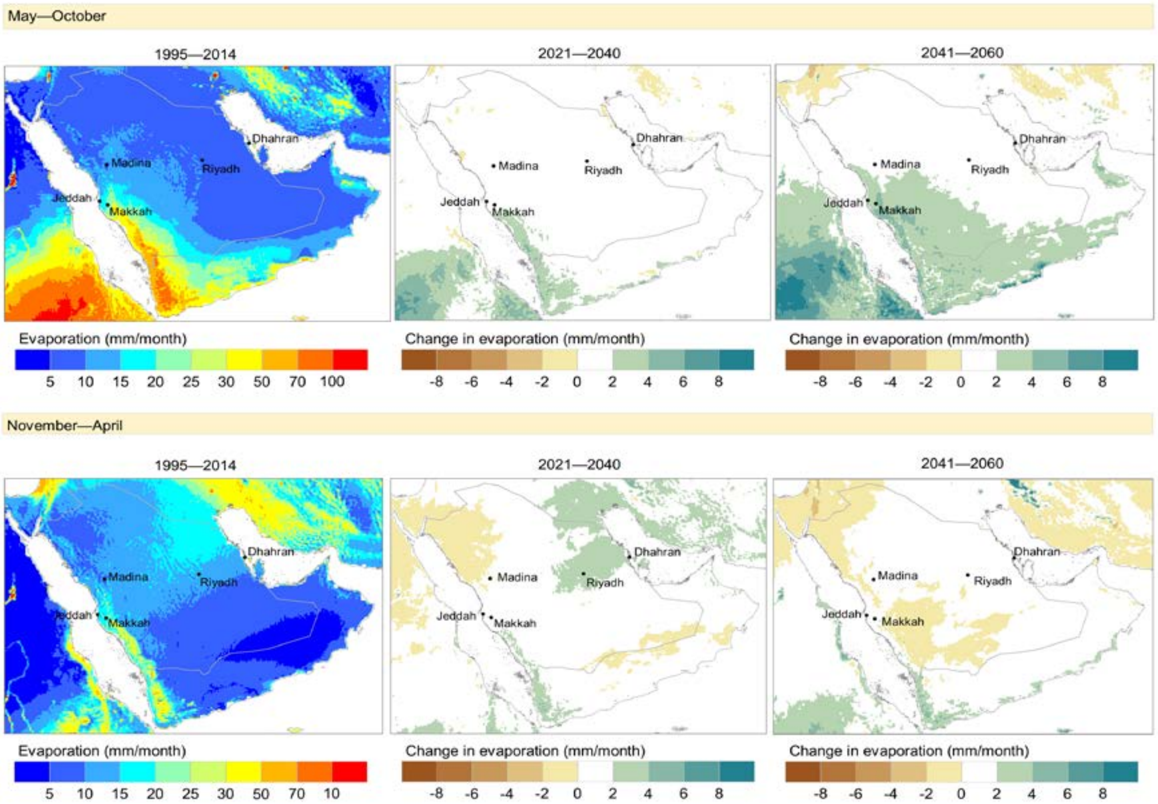
The mean evaporation rate during the reference period was nearly the same for both seasons (approximately 11 mm/month) but differed spatially (figure 17). During the May-October season, the highest evaporation rates are in the south coastal Red Sea and Asir Highland regions and exhibit a gradual decreasing gradient from the south-west towards the north-east. This pattern is similar to precipitation during the same season. During the wetter November-April season, precipitation is more widespread and, thus, evaporation rates are more evenly distributed.

Starting in 2030, the annual evaporation rate will be 40 per cent higher than the precipitation rate, resulting in increased groundwater losses and higher salinity.

Evaporation rates are projected to increase during the May-October season, particularly during the mid-term (2041–2060). Rates will increase, on average, by 1.6 mm/month for the mid-term. In general, the highest evaporation rates will be in the coastal Red Sea and Asir Highland regions, averaging 27 and 31 mm/month, respectively, by mid-term. However, localized evaporation rates may be higher; up to 137 mm/month are expected in the northern/An Nafud region by mid-term. These high evaporation rates are greater than the projected precipitation and can result in increased groundwater losses and higher salinity,[69] emphasizing the need to secure non-conventional water resources.

For the November-April season, evaporation rates are decreasing in some areas. However, evaporation rates are projected to still exceed precipitation rates in much of Saudi Arabia (figure 14). Although precipitation rates are expected to increase, rising temperatures affecting evaporation rates will result in disruption in the water cycle. To maintain balance, other water resources, namely, soil moisture and reservoirs, must compensate for the rise in atmospheric water.

FIGURE 17: Mean seasonal change in evaporation for the near term (2021–2040) and the mid-term (2041–2060) compared to the reference period (1995–2014) based on the Mashreq Domain RCM outputs, SSP5-8.5



Source: Authors.

D. Downwelling shortwave radiation

Downwelling RS measures the direct energy from the sun as the sum of all wavelengths in the range of ~300–3000 nm, including near-ultraviolet, visible light and near-infrared radiation. It can vary according to the distance from the equator, cloud cover, elevation, and natural and man-made obstructions that block the sun from reaching the earth's surface. The significance of downwelling RS in Saudi Arabia is twofold: the variable can be used to estimate solar energy potential and as a proxy to estimate airborne dust and other aerosols.

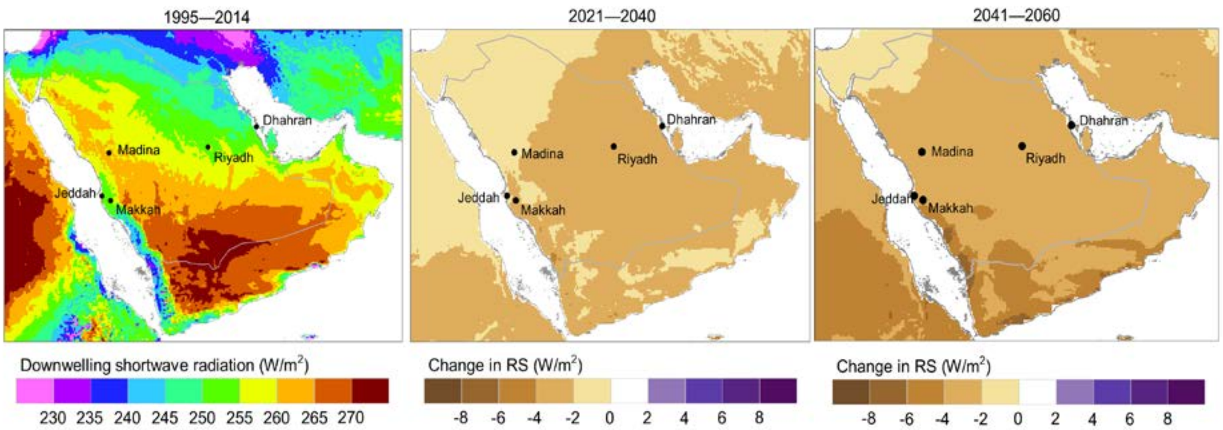
Saudi Arabia is well suited for developing solar energy due to its estimated 3,000 hours of sunshine per year and reported average annual solar radiation of 2,200 kWh/m^2.[70] Results from the climate modelling outputs are nearly the same; for the reference period (1995–2014), the average RS was 258 W/m^2 (2,261 kWh/m^2). Values vary slightly, exhibiting a decreasing gradient from the south-west to the north-east, with the exception of the coastal Red Sea region (figure 18).

Decreasing downwelling RS is linked to aerosols from sand and dust storms.

A projected decline in RS, known as global dimming, is due to the increased presence of particulate matter in the atmosphere. This phenomenon can hinder the development of solar energy. Although RS is expected to decrease (about 1 per cent by mid-term), the impacts on solar energy potential are not significant.

Global dimming due to dust and aerosol concentrations is a concern for sand and dust storms. Sand and dust storms occur frequently in Saudi Arabia, which has exhibited an increasing trend.[71] Assessing climate change impacts on sand and dust storms faces challenges due to complex linkages between climate parameters, environmental factors and aerosols. A projected value has been implemented by ESCWA, in conjunction with other partners, to evaluate climate change impacts on sand and dust storms. In this context, projected changes in RS can be used as a proxy for aerosols and sand and dust storm analysis. A severe dust storm in West Asia in March 2012 reduced RS to a maximum daily average value of 134 W/m^2.[72]

FIGURE 18: Mean annual change in downwelling RS for the near term (2021–2040) and the mid-term (2041–2060) compared to the reference period (1995–2014) based on the Mashreq Domain RCM outputs, SSP5-8.5

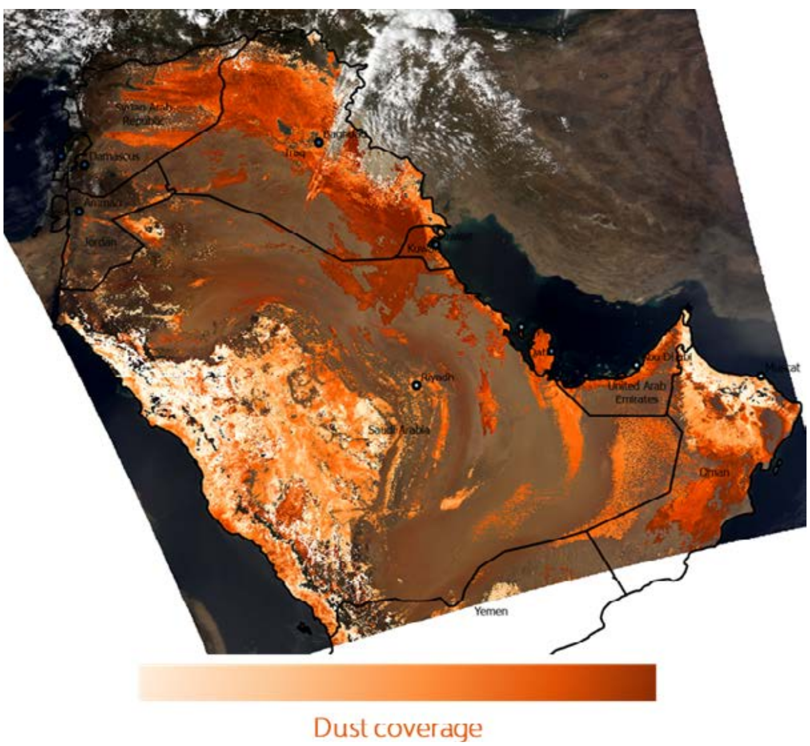


Source: Authors.

E. Strong wind days

Sand and dust storms (figure 19) can happen during any season in Saudi Arabia, but the highest number of storms occurs during the spring and summer months. The reported seasonal mean (1985–2014) was 46 and 18 storms, respectively.
Storms are caused by shifts in temperature and wind speed, environmental factors, the presence of aerosols and other parameters.

FIGURE 19: Global dust detection index analysis, 23 May 2022



Source: ESCWA analysis.

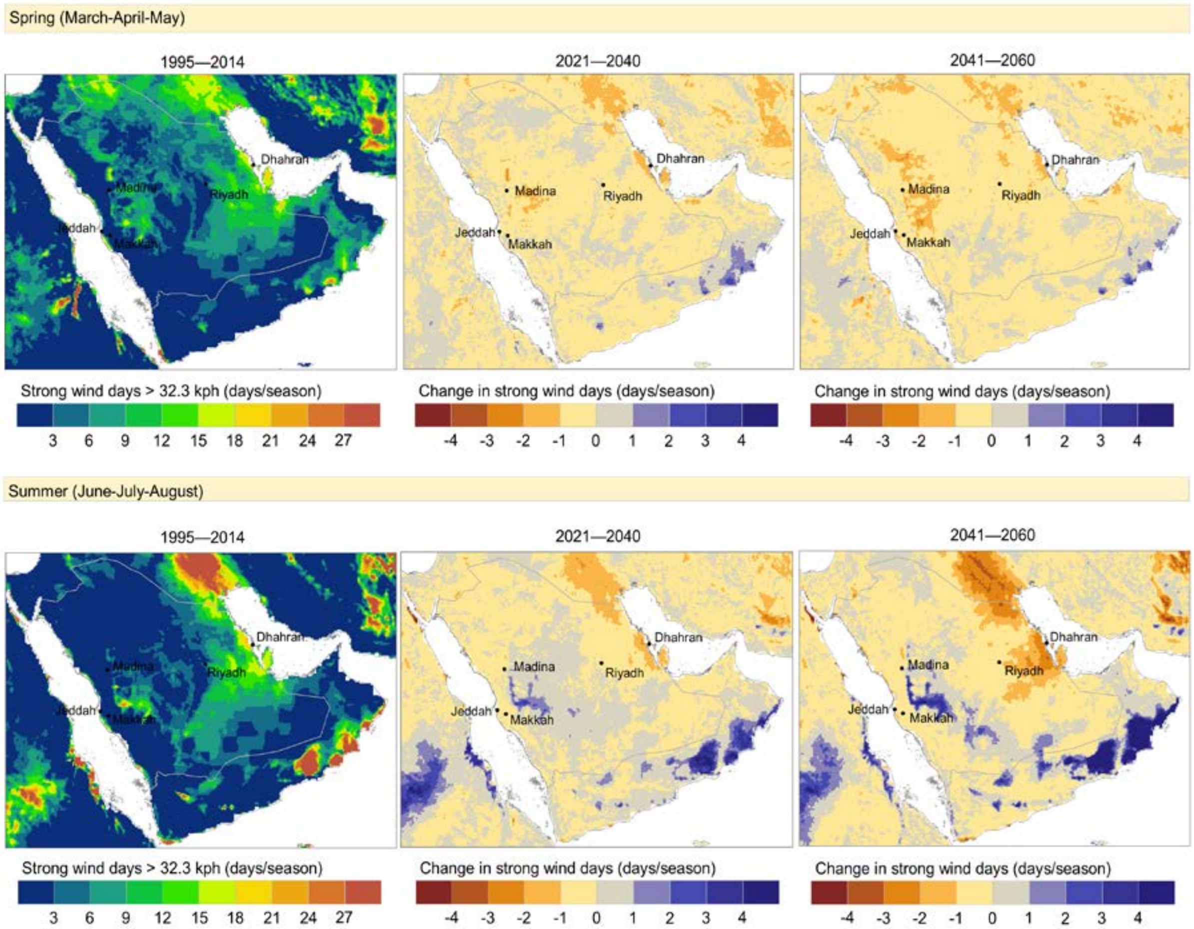
Differing wind speed thresholds have been determined as the minimum velocity necessary to lift suspended sediment in various desert environments. For fine material in desert flats, similar to landscapes across Saudi Arabia, the threshold ranges from 32.3–40.2 kph (9–11.2 m/s).[74] An analysis of the number of days, which exceed this 32.3 kph threshold during the spring and summer seasons is one of the parameters to consider for projected sand and dust storms.

The spring strong wind days for the reference period (1995–2014) follow a consistent pattern with reported sand and dust storm events. Most events occurred in Qaisumah, Al Ahsa and Rafha, near the Arabian Sea (figure 20).[75] Many historical summer sand and dust storms events also occurred in Ahsa. However, summer storms likewise occurred in Gizan and Yanbu along the Red Sea coast,[76] indicating that other parameters dominated in sand and dust storm development.

Strong wind days (> 32.3 kph) are increasing during the summer months (+4.7 days/season by mid-term) in central-eastern Saudi Arabia, affecting cities such as Medina and Bisha.

Projected changes in strong wind days do not reveal a significant pattern during the spring season. However, projected changes are more evident for the summer season, particularly for the mid-term (2041–2060). Increasing strong wind days are exhibited near the convergence of the Najd interior, Asir Highland and West Rub' al-Khali climate regions. Cities such as Bisha, which reported sand and dust storms twice over five years during the summer season,[77] may be at an increased risk. Conversely, areas near the Arabian Sea signal a decrease in strong wind days during the summer season, affecting cities such as Al Ahsa.

FIGURE 20: Mean seasonal change in strong wind days (> 32.3 kph) for the near term (2021–2040) and the mid-term (2041–2060) compared to the reference period (1995–2014) based on the Mashreq Domain RCM outputs, SSP5-8.5



Source: Authors.

4 CONCLUSION

Rising temperatures are of great concern across the Arab region, including Saudi Arabia. Temperatures exceeding 50°C have already been witnessed in the country.[78] As warming continues, days that surpass the 50°C threshold will occur with greater frequency. Such extreme conditions will have detrimental impacts on human health, the agricultural sector, infrastructure and socioeconomic development.

The projected upward temperature trend also has adverse impacts on other climatic factors. This temperature uptick is likely to amplify droughts and floods, including rapid changes from one extreme to the other (hydroclimate whiplash).[79] Precipitation-related extreme events have already been observed in Saudi Arabia. Flash floods, adversely affecting populated areas and infrastructure, have occurred, often after a period of drought. Moreover, amplified drought risk has been identified as an area of concern, which can also have adverse impacts on society.

The country is additionally prone to sand and dust storms that stem from varying climatic and environmental factors. Projected changes in downward shortwave radiation, diurnal temperature range and other parameters suggest an expected rise in aerosols in the atmosphere, to include dust and other particulate matter. A study is currently in progress to evaluate climate change effects on the frequency and intensity of sand and dust storms, which will consider this projected uptick in aerosols.

Climate variables affecting Saudi Arabia are not limited to those described herein. Other parameters include wind speed, relative humidity and sea level rise. Each parameter is interlinked and should not be evaluated in a vacuum.

These climate projections can help to target adaptation measures and positions on the shift to a just and inclusive sustainable energy transition. Structural and non-structural adaptation measures are needed to cope with potential impacts. Vulnerability assessments can be used as evidence-based tools to target areas most benefitted by adaptation. Investments in solar and wind energy can be informed based on projected changes in the climate over the coming decade. In this manner, the scientific findings drawn from the climate change projections described in this report can help to bridge the knowledge gap and inform sound policies and actions.

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This report provides a summary of mid and end-century climate change projections for Saudi Arabia. The Intergovernmental Panel on Climate Change (IPCC) and the Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR) both conclude that parts of Saudi Arabia will experience increased climate risks over the coming decades. These risks include temperature increases, precipitation variability and extremes (droughts and floods), and an increase in strong wind days that could contribute to sand and dust storms.

23-00244