

Observations, projections and impacts of climate change on water resources in Arabian Peninsula: current and future scenarios

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Abstract This study investigated the effects of climate change on water resources in the Kingdom of Saudi Arabia (KSA) using observational data and climate models. Data from 1950 to 2013 were analysed and modelled to provide a comprehensive reference document on the status of climate change in KSA. Climate predictions up to 2050 and 2075 were performed using seven climatic models, and the Standardised Precipitation Index was used to assess droughts over the past 64 years to avoid uncertainty in the form of inadequate precipitation records. The central-northern region received moderate rainfall (70–100 mm/year), while the central, north-eastern and south-western regions received the highest mean annual rainfall, ranging from 150 to 300 mm/year. Over time, the climate has become hotter, and rainfall has decreased slightly each year. The north-western and south-eastern regions received the lowest mean annual rainfall (4–50 mm/year). In terms of rainfall seasonality [coefficient variation (CV)], the central-northern region and the coastal regions had moderate annual rainfall variability (27–83 %); the central-western region had high variability (89–100 %). The eastern regions and Al-Riyadh had the highest variability, with CV values exceeding 100 % due to anomalies in the amount of precipitation over the years. The projection models predicted a declining trend in the mean annual

precipitation for most regions of KSA under all of the studied scenarios. Models also showed a slight increase in the mean annual precipitation around the coastline of the Red Sea and in the southern regions. The drought analysis revealed that the whole of KSA has experienced long and extreme droughts presenting an alarming risk as most of these are agricultural regions. The risk will become extremely dangerous if the declining trend in rainfall continues, causing increasingly severe droughts.

Keywords Climate change · Climate models · Drought · KSA · Rainfall seasonality · Standardised Precipitation Index · Water resources

Introduction

The Kingdom of Saudi Arabia (KSA) does not lack land for food production; what is missing is water. Agricultural development has increased the demand for water resources throughout the country, leading to their partial depletion, particularly in the case of non-renewable fossil water, which is the main source of freshwater according to the FAO (2008). The lack of permanent rivers or lakes means that water is scarce and extremely valuable. The country is facing decreasing water per capita, but continuously increasing water consumption due to population growth, economic development, household consumption patterns and the ever-increasing production sectors. This, in turn, has led to a rapid increase in the demand freshwater (Al-Zahrani 2009). Rainfall is extremely important for the natural replenishment of aquifers for fresh renewable water. Population growth, industrial development and irrigation for agriculture have increased dramatically over the past century, raising the demand for water. Furthermore, large-scale environmental challenges,

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such as the recent droughts in the Middle East (including the Arabian Peninsula), are straining the already scarce water resources (Ragab and Prudhomme 2002; Sen et al. 2013). The pressure on water resources worldwide is driven by demographic, economic and social factors. Similarly, lifestyle changes, individual perceptions of water resources, consumption rates and life patterns are all social drivers in water resource issues (World Water Assessment Programme 2009).

The International Water Management Institute (a research centre of the Consultative Group on International Agricultural Research; CGIAR 2000) conducted a study to examine the water supply and demand for 118 countries over the 1990–2025 period. KSA was highlighted as one of the most “water scarce” countries, and by 2025 it will not have enough water to maintain 1990 levels of per capita food production from irrigated agriculture or to meet industrial, household and environmental needs. The country is already facing water supply shortages in both urban and rural areas, despite the abundance of land. With increasing water demand, rainwater collection for non-potable or irrigation uses, as well as groundwater recharge, is now being considered in many urban areas (Ashworth 2005; Leggett and Shaffer 2002; Peters 2006; Mahmoud et al. 2016; Mahmoud and Alazba 2016). Rainwater harvesting is an ancient technology that has been used throughout history to supply water to human settlements and, more recently, to urbanised areas (Gould and Nissen-Petersen 2000). Globally, millions of such systems are currently in use (ABS 1998; Heggen 2000; Lye 1992), and a wide variety of both potable and non-potable applications are functioning (Cooper 2001; Fewkes 1999; Gould and Nissen-Petersen 2000; Ratcliffe 2002).

The Standardised Precipitation Index (SPI) has gained wider acceptance worldwide in several studies to detect historical drought events (Leavesley 1994; Christensen et al. 2004; Iglesias et al. 2007; Vicente-Serrano et al. 2010; Piao et al. 2010). However, there are no such studies in KSA. On the other hand, few studies have investigated climate change in KSA. Alyamani and Sen (1993) studied seasonal rainfall variability over a 15-year period using a monthly rainfall dataset derived from 29 stations in KSA. The study revealed that the maximum rainfall over the south-western region was in January, while in the central provinces, it was in February and October. Similarly, Abdullah and Al-Mazroui (1998) studied the distribution of annual rainfall for the south-west of KSA over the 1970–1992 period. Their findings revealed that rainfall distributions in KSA fit better with normal and gamma distribution functions than with an exponential distribution, depending upon the selected domain within the region. Subyani (2004) conducted a study using data from 63 rainfall stations in south-western KSA for the 1971–1990 period to assess seasonal and regional rainfall variations. Kotwicki and Al Sulaimani (2009) projected the state of the future climate on the Arabian Peninsula (for the 2050s

relative to 1961–1990). This study reported that temperature and rainfall extremes seem to be increasingly likely in the Arabian Peninsula, again emphasising the importance of a detailed assessment of the recent climate in the region. Moreover, their study found that climate change in KSA is dominated by large and abrupt changes with millennial spacing, many of which have occurred on annual to decadal timescales.

The climate of a region can be determined by the long-term average, frequency and extremes of several meteorological variables, including precipitation. In an arid region such as KSA, aridity is the dominant climatic feature (Al-Taher 1994) and rainfall is quite variable and is becoming a precious natural resource. Therefore, it is important to study and investigate past, current and future climate change in the country and its effects on hydrology, agriculture, human activities and drought or flood. Meteorological drought is the earliest and most explicit event in the occurrence and progression of drought conditions. Rainfall is the primary driver of meteorological drought. Numerous indicators based on rainfall are used for drought monitoring (Smakhtin and Hughes 2007).

The availability of up-to-date climatic information for a region improves the effectiveness of any assessment of climate change and climate impact studies, especially in relation to global warming and changes in climate (IPCC 2007a). A hindrance in obtaining climate information for KSA is the sparseness and/or unavailability of surface observation datasets for most of the country. Thus, the use of available gridded datasets is invaluable in previous studies and highly appropriate in these circumstances. The present study provides an inclusive reference document on the status of climate change in KSA. The study analysed and modelled data from the past 64 years (1950–2013) through the interpolation of several gridded datasets and ground observation datasets. In addition, the climate status in 2050 and 2075 was predicted using seven climatic models. The overall purpose of this study was to provide up-to-date information on the status of the climate in KSA and to provide an indication of the future situation. Drought was also assessed by calculating the SPI for the entire country over the past 64 years, from 1950 to 2013. The SPI is a way of measuring drought that is different from other drought indicators. Negative values indicate drought, and positive values indicate wet conditions.

Data and methodology

Data pre-processing and analysis

The study focused on KSA, which has an area of 2.15 million square kilometres and a mean annual rainfall of 112 mm/

year (Mahmoud et al. 2014). The monthly average rainfall is 12 mm; April is the wettest month (with an average rainfall of 21 mm), and June to October are the driest months. KSA is a tropical and subtropical desert region with notable spatial variability in rainfall. In the northern region, annual rainfall ranges from 100 to 200 mm. In contrast, in the south, except near the coast, annual rainfall is generally lower than 100 mm. The higher land areas of the west and south experience the highest rainfall, with some parts receiving about 500 mm a year (Mahmoud et al. 2014).

The rainfall variation in KSA was explored from 1950 to 2013, and seven climatic models namely NorESM1-M, IPSL-CM5A-LR, MRI-CGCM3, MIROC5, HadGEM2-ES, GISS-E2-R and BCC-CSM1-1 were used to provide climate predictions up to 2050 and 2075, according to four climate change scenarios. This analysis is very important for estimating the volume of rainwater that can be harvested, which depends on the amount of rainfall, its temporal pattern, losses (represented by runoff coefficients), storage capacity and subsequent uses. In this study, 64 years of monthly rainfall data (1950–2013) collected from 29 weather stations located across the country (Fig. 1) were interpolated with climate data obtained from the World Data Center for Meteorology and the NASA Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al. 2000). The interpolation approach combined the available rainfall from weather stations and several satellite sources into a final merged product, taking advantage of the strengths of each data type. The final merged data were then used to estimate the rainfall pattern, average monthly and annual rainfall, wet and dry months of the year, and seasonal precipitation, which is the coefficient of the variation in annual rainfall.

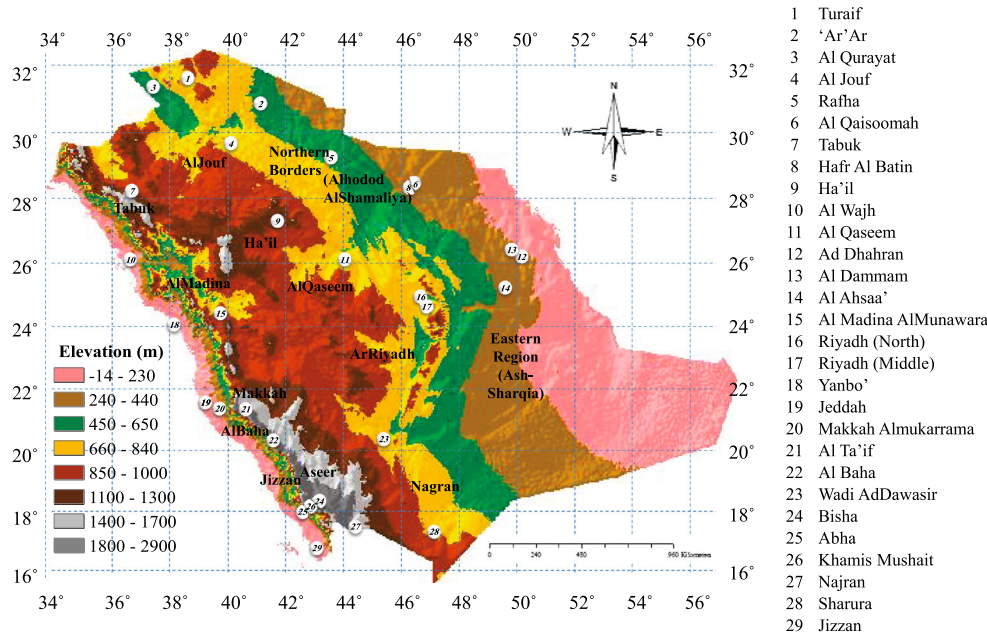
The TRMM is a joint space mission between NASA and Japan’s National Space Development Agency, designed to monitor and study tropical and subtropical precipitation, and the associated release of energy. The mission uses five instruments: Precipitation Radar, TRMM Microwave Imager, Visible Infrared Scanner, Clouds & Earth’s Radiant Energy System and Lightning Imaging Sensor. Many products are available on various grids and temporal resolutions. The TRMM Microwave Imager is the main instrument used for precipitation.

The Global Precipitation Climatology Project was established by the World Climate Research Program to address the problem of quantifying the distribution of precipitation around the globe over many years. The microwave estimates are based on Special Sensor Microwave/Imager data from the Defense Meteorological Satellite Program (USA) satellites that fly in sun-synchronous low-Earth orbits. The infrared precipitation estimates are computed primarily from geostationary satellites (USA, Europe, Japan), and secondarily from polar-orbiting satellites (USA). Additional low-Earth orbit estimates include the Atmospheric Infrared Sounder data from NASA Aqua, and Television Infrared Observation Satellite Program Operational Vertical Sounder and Outgoing Longwave Radiation Precipitation Index data from the NOAA series satellites.

Future climate change projection

In the late 1960s, NOAA’s Geophysical Fluid Dynamics Laboratory developed the first general circulation climate model that combined both oceanic and atmospheric processes. Since then, future climate data have often been

Fig. 1 Map of KSA showing elevation and weather stations



generated using Global Climate Models (GCMs, also known as General Circulation Models). There are various GCMs with different outputs. The weather simulated by these models depends in part on the assumed atmospheric concentration of greenhouse gasses. In the present study, the climate projections were generated by the IPSL-CM5 Earth System Model using four representative concentration pathways (RCPs) (RCP = 2.6, 4.5, 6 and 8.5).

The climate projections from seven climatic models used four RCPs (RCP = 2.6, 4.5, 6 and 8.5). These are the most recent GCM climate projections that are currently in use. Each RCP is a result of different combinations of economic, technological, demographic, policy and institutional factors. For instance, the second-to-lowest RCP is considered a moderate mitigation scenario. However, it is also consistent with a baseline scenario that assumes that global development will focus on technological improvements and a shift to service industries, but does not aim to reduce greenhouse gas emissions as a goal in itself. More detailed information on the further development steps of these scenarios in the RCP process is available elsewhere (Riahi et al. 2007; Hijjoka et al. 2008; Wise et al. 2009; van Vuuren et al. 2006, 2007).

The Standardised Precipitation Index

Drought is a natural local or regional phenomenon that is basically caused by a lack of precipitation over a period of time, which is a common issue in KSA. McKee et al. (1993; 1995) devised the SPI for the definition of meteorological drought; it is a valuable tool for estimating the intensity and duration of drought events. The Standardised Precipitation Index (SPI) has been increasingly used for the assessment of drought intensity in many countries (Wu et al. 2001, 2005, 2006; Vicente-Serrano et al. 2004, 2010; Wilhite et al. 2005; Cancelliere et al. 2007; Zhang et al. 2009; Pai et al. 2011; Dutra et al. 2013). Li et al. (2007) conducted a study in the southern Amazon region using a time series analysis of the SPI. The results indicated a decrease in SPI values from 1970 to 1999, reflecting an increase in dry conditions. The interpretation of drought at different timescales using the SPI has also been proven to be superior to the Palmer Drought Severity Index (Guttman 1998). Goodrich and Ellis (2006) used both the SPI and annual Palmer Drought Severity Index values to rank the years according to drought severity.

The SPI is a probability index that is based solely on precipitation and was designed to quantify the precipitation deficiency for multiple timescales. These timescales reflect the impact of drought on the availability of different water resources. The SPI has various advantages, including quantification of the precipitation deficit and the ability to apply it in areas with different climates over various

timescales. For instance, it has been used over a short timescale in agricultural studies, and over a longer timescale for the assessment of underground waters, river flows and lake water levels (Edwards and McKee 1997; Hayes et al. 1999). The SPI is also able to identify emerging droughts months sooner than the Palmer Index, as reported by Hayes (2000). The use of a long timescale is recommended for the estimation of the SPI to obtain independent results. Guttman (1991, 1993, 1998, 1999) reported that data for at least 50 years are necessary for the definition of the SPI over timescales of less than 12 months, while longer datasets are required for 24-, 36- or 48-month periods. Agnew (2000) reported that in some regions, the use of datasets longer than 40 years for estimating the mean precipitation ensures that the computation of the SPI is independent of the average base period.

In the present study, the spatial and temporal variations in monthly precipitation over KSA were calculated using monthly rainfall data for 64 years (1950–2013) from 29 weather stations, together with gridded satellite rainfall data, to detect the drought frequency, drought intensity and drought duration for the whole country. The SPI was calculated on 1-, 2-, 3-, 4-, 5-, 6-, 7-, 8-, 9-, 10-, 11- and 12-month timescales, corresponding to the observed total rainfall for each of the past 12 months. These timescales reflect the soil moisture conditions (short timescale) or the underground water, river flow and lake water levels (long timescale).

The SPI was defined for each of the above timescales as the difference between the monthly precipitation for the relevant month (x_i) and the mean value (\bar{x}), divided by the standard deviation (σ), and was calculated using the following Eq. (1):

$$\text{SPI} = \frac{x_i - \bar{x}}{\sigma} \quad (1)$$

where x_i is the monthly rainfall amount and \bar{x} and σ are the mean and standard deviation of rainfall calculated from the whole time series of monthly values.

McKee et al. (1995) and Komuscu (1999) defined various drought intensities, for all timescales, together with their corresponding probabilities. However, Agnew's (2000) classification scheme for drought classes adopted slightly different thresholds (Table 1). Thus, the SPI is a tool for the assessment of drought, which takes into account its intensity and duration. Because the SPI values fit a normal distribution, its thresholds can be combined with the corresponding probabilities. Based on the criteria proposed by Edwards and McKee (1997), values < -2.0 (extreme drought) are expected to occur two or three times in 100 years. In this study, we used the classification of McKee et al. (1995) and Komuscu (1999) to estimate the drought conditions for KSA.

Table 1 Classification scale for the SPI values

SPI	Komuscu (1999) and McKee et al. (1995) drought classes	Agnew (2000) drought classes
<-2.00	Extreme drought	Extreme drought
<-1.65		
<-1.50	Severe drought	
<-1.28		Severe drought
<-1.00	Moderate drought	
<-0.84		Moderate drought
<-0.50		No drought
<-0.00	Mild drought	No drought

Results and discussion

Impacts and response of climate change on water resources in KSA

With less than 2 % of the total area of KSA suitable for cultivation, the future of the nation depends on its natural resources and climate change. In the early 1990s, the population distribution varied greatly among the towns of the eastern and western coastal regions, the densely populated areas, and most of the land is empty desert. The changing climate has had extreme and dramatic effects in KSA; for instance, until the 1980s, there were lakes in the Layla Aflaj region and deep waterholes in the Al-Kharj region, fed by huge deep aquifers that were formed in prehistoric times and are considered as non-renewable resources. The Al-Kharj region was an extremely valuable source of drinking water in a barren land. Recently, these aquifers have been heavily consumed for both domestic purposes and agricultural activities, and no freshwater currently remains in the lakes or waterholes. In the absence of permanent rivers or streams, the country’s water needs must be met through the extraction of groundwater, the desalination of seawater and very scarce surface water. This is an example of the power of nature and the human survival response. In eastern KSA and the Jabal Tuwayq, artesian wells and springs are plentiful. In Al Ahsa, a number of large, deep pools are constantly replenished by artesian springs supplied by underground water from the eastern watershed of the Jabal Tuwayq. Such springs and wells allow extensive irrigation in agriculture areas. In the Hijaz, wells are abundant and springs are common in the mountainous areas. In Najd and the great deserts, watering places are comparatively fewer and scattered over a wide area. Water must be hoisted or pumped to the surface, and even where water is plentiful, its quality is very poor.

The analysis of more than 60 years of climate data revealed that KSA has a semi-arid to hyper-arid climate, characterised by very low rainfall (annual average of 112 mm) and extremely high evapotranspiration, resulting

in water scarcity and reduced vegetation cover. The south-western region of KSA has the highest average annual rainfall. Summer rainfall occurs over the south-west mountains due to the easterly jet stream and the monsoon. However, the climate becomes hotter and rainfall decreases slightly each year. Ragab and Prudhomme (2002) predicted climate change in KSA up to the 2050s. Their results indicated a decrease in precipitation of 20–25 % and an increase in temperature of 1.5–2.5 °C, confirming the results obtained in this study. In response to the changing climate and the absence of renewable water resources, the Saudi government has taken various measures to ensure the sustainability of water resources, including assessments of water availability and the construction of more than 360 dams, mostly located in the south-west of the country, to ensure each drop of rainfall counts (Mahmoud et al. 2016; Mahmoud and Alazba 2016). Most of these dams were established to recharge groundwater supplies, which had been depleted before construction of the dams commenced. Such depletion over the years has hindered the area’s agricultural activities because groundwater wells are the main source of water. The effects of changing climate patterns on water resources are creating social and political tensions at both local and national levels worldwide. In KSA, for example, the shift towards agriculture has generated a number of changes in the structure and function of the ecosystem, resulting in the overall degradation of the ecological services provided by the country’s natural ecosystem.

Climate change in KSA will affect all aspects of life, including water resources, food and agricultural production, biodiversity, forest and shrubland. The government is raising awareness of the extreme effects of climate change through many channels, including the private sector, with strong emphasis on energy conservation and domestic and agricultural water use. For instance, there are many national projects currently underway in institutions and research centres around the country, involved in the development of water conservation regulations, the promotion of wastewater collection and treatment, the

development of advanced desalination techniques and the design and eventual implementation of water saving policies for agriculture. A survey conducted in 2008 in 128 countries by Pugliese and Ray (2009) revealed that 49 % of the surveyed individuals in KSA were aware of climate change, 40 % perceived it as a threat to the country, and 39 % believed that it was caused by human activities. These results are due to government programmes designed to raise awareness of climate change and its associated problems.

Spatio-temporal distribution of rainfall over KSA

Monthly rainfall distribution over KSA

Figure 1 shows the altitude of the 29 stations representing the area ranged from sea level up to 2900 m (Fig. 1). The developed rainfall distribution maps (Fig. 2a, b) indicate that the lowest rainfall occurs in June and October, with 21 and 20 mm, respectively, whereas the highest rainfall occurs in March and April, with 67 and 70 mm, respectively (Fig. 2a). The spatio-temporal distribution of rainfall (mm) over the studied period (1950–2013) is shown in Fig. 2. The average monthly rainfall was calculated from 64 years of monthly rainfall data (1950–2013) collected from 29 weather stations located over KSA. These data were interpolated with climate data obtained from the World Data Center for Meteorology and the NASA TRMM using the inverse distance-weighted method. The interpolation approach combined the available rainfall from the weather stations and several satellite sources into a final merged product, taking advantage of the strengths of each data type. The final merged data were then used to estimate the rainfall patterns, average monthly and annual rainfall, wet and dry months of the year and precipitation seasonality, which is the coefficient of the variation in annual rainfall.

Rainfall in KSA can vary significantly in a given month and across different months and from one region to another. During the studied period, the northern region received most of its rainfall from November to April, which is critical for groundwater resources and the agricultural sector in the region. The main source of groundwater recharge in this region is from rainwater harvesting. For instance, the spatial distribution of January rainfall is shown in Fig. 2a; the amount ranged from 1 to 40 mm, most of which occurred in the northern border and coastal regions, including Jizzan and Al-Baha with an average of 40 mm, while some locations in other regions had an average of 20 mm or less. The maximum rainfall (Fig. 2a, b) fell in the central, north-eastern and south-western areas.

The north–north-eastern regions of KSA receive most of their rainfall from November to April, which are

considered wet months. This trend continues towards the centre of KSA. During the wet season, more rainfall occurs over the northern than the southern sub-region. The south and south-western regions receive most of their rainfall from June to September. However, these are considered dry months because no rain falls in the northern and south-eastern regions during these months, which is clearly indicated by the January and July rainfall in Fig. 2a, b, respectively. Moreover, in the south and south-western regions little rainfall occurs during this period. Therefore, this season is considered the dry season in KSA.

Annual rainfall distribution over KSA

The analysis of rainfall data revealed that the mean annual rainfall in KSA (Fig. 3) over the 64-year period ranged from 4 to 300 mm/year, which is extremely low compared with the global mean annual rainfall. Thus, KSA is classified as an arid and hyper-arid region. The problem is exacerbated by the lack of water conservation plans and the absence of surface water. Exploitation of groundwater accumulated as a result of annual rainfall has not been possible for decades. In this severely arid zone, the lack of available water resources is aggravated during drought periods. The analysis of annual rainfall and its variations is very important for the development of water balancing approaches and water conservation plans. In the present study, we analysed the long-term mean annual rainfall over KSA for the 1950–2013 period (Fig. 3).

The north-western and south-eastern regions had the lowest mean annual rainfall of 4–50 mm/year. Al-Rub Al-Khali also had a low annual rainfall of 60–80 mm/year. However, the central-northern region had moderate rainfall of 70–100 mm/year. The central, north-eastern and south-western regions received the highest mean annual rainfall of 150–300 mm/year. The regions of Hail, Tabuk, Al-Qaseem and Makkah received a mean annual rainfall of 100–200 mm/year. The regions of Asir, Jizzan and Al-Baha along the western coast are influenced by the Indian Ocean monsoons, which usually occur between October and March. These regions had an annual rainfall of 300 mm/year. Similarly, the northern borders received a mean annual rainfall of 100–300 mm/year. Over the rest of KSA, the annual rainfall was extremely low (Table 2).

The analysis of the mean annual satellite and stations rainfall data shows the overestimation of the satellite rainfall values for most of the stations, as seen in Table 2. Only few numbers of stations have similar amounts of satellite and station rainfall values. The average correction factor is shown in Table 2 for each station in KSA. The analysis also revealed that the mean annual rainfall in KSA is equal to 89.52 % of the mean annual rainfall derived from the satellite data.

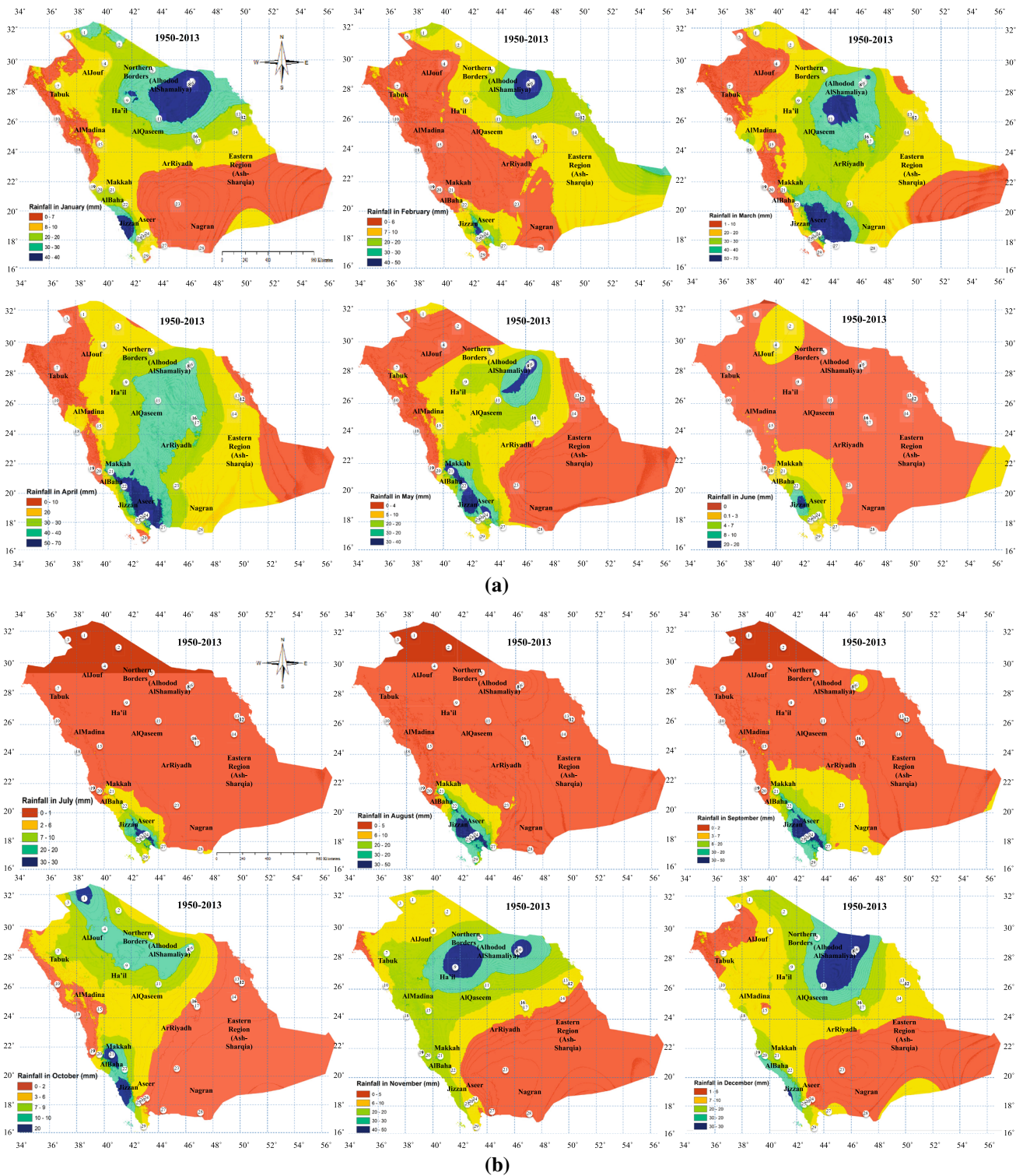
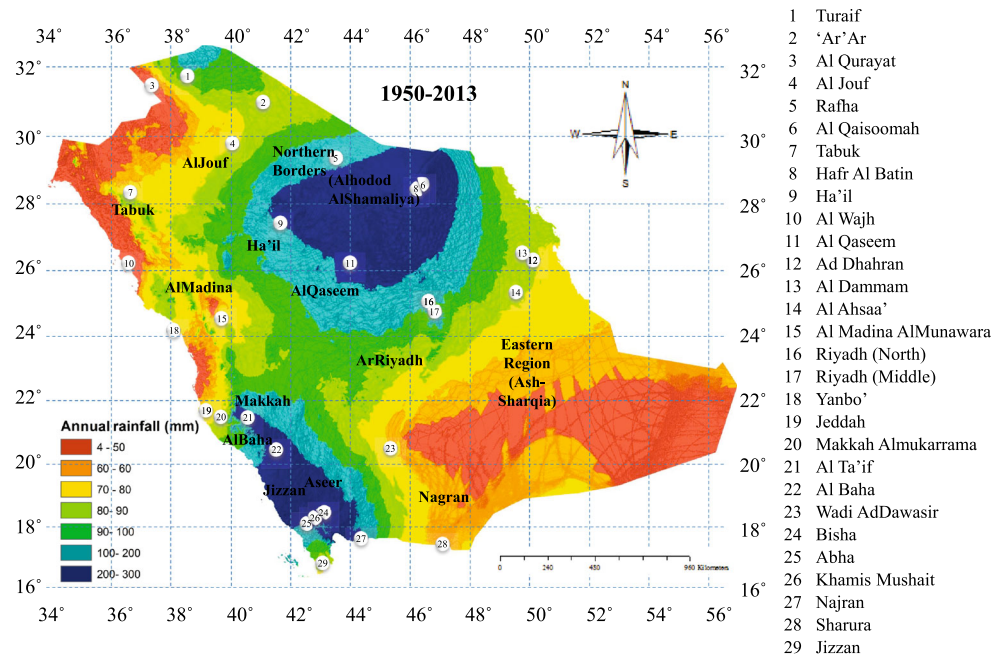


Fig. 2 a Average monthly rainfall distribution from January to June. b Average monthly rainfall distribution from July to December

Rainfall Seasonality Index, i.e. CV %

This index is the ratio of the standard deviation of the monthly total precipitation to the mean monthly total

precipitation and is expressed as a percentage. To calculate the index, the first step is to calculate the standard deviation of the 12-monthly precipitation values, then divide the result by the mean monthly precipitation. To avoid unusual

Fig. 3 Mean annual rainfall (1950–2013)

CV values, 1 is added to the denominator where the mean rainfall is less than 1. Finally, the output of the previous step is multiplied by 100.

Figure 4 shows the percentage of precipitation variability. The central-northern region of KSA, including Al-Jouf, the northern borders, Tabuk and Hail, and the coastal regions (Al-Baha, Jizzan) had moderate annual rainfall variations (27–83 %). The central-western region had large annual rainfall variability (89–100 %). The highest percentage was observed in the Nagran, eastern regions (Ash-Sharqia), Asir and Al-Riyadh, where the CV values exceeded 100 %. On average, the CV values for these regions were 155, 105, 135 and 120 %, respectively. Values larger than 100 % indicate extremely large variability in annual precipitation. In these regions, the standard deviation of the precipitation throughout the year exceeded the average precipitation, which can be explained by precipitation anomalies throughout the course of the year in these regions.

Quarterly rainfall distribution over KSA

Precipitation in the coldest quarter This index (Fig. 5a) approximates the total precipitation during the coldest quarter. The coldest regions in KSA are mainly located in the north-west and south-west of KSA. The highest rainfall in the coldest quarter was in Jizzan, Asir, Al-Baha, the northern borders, Al-Qaseem and Hail, respectively. The amount of rainfall in these six regions ranged from 17 to 110 mm/W_{3 months}. The previous four indices are very useful for different applications in KSA, such as for identifying the water requirements for different crops using the water

balance approach, and for identifying the driest and wettest regions, which is essential for drought forecasting, the natural replenishment of aquifers and flood management.

Precipitation in the driest quarter This index (Fig. 5b) is the sum of the three consecutive months with the lowest cumulative precipitation. The value of this index ranged from 0 to 57 mm/W_{3 months}. This index clearly showed that there was no rainfall during the driest quarter in each year, except for a limited amount in Jizzan, Asir and Al-Baha. The Rub Al-Khali region and the central-northern sub-region are classified as extremely dry according to this index.

Precipitation in the warmest quarter This index (Fig. 5c) calculates the precipitation values for the hottest 3 months of the year. This index revealed that there was no rainfall in KSA during the hottest months of the summer except for Jizzan, Asir and Al-Baha, due to the topographic characteristics of these regions and their coastal locations. The previous two indices showed that no rain fell for 6 months of each year (the driest and warmest quarters), which led to extra discharge of groundwater potential in these regions to meet agricultural water requirements. This indicates that in the near future, there will be no groundwater in KSA due to the impact of climate change and the increase in annual temperature. Possible solutions to this problem include reducing the cultivated area, especially for crops with high water consumption, and setting up more artificial recharge wells in areas with high rainfall. More wastewater treatment plants could also be constructed, although this is particularly difficult in Arab countries due to public attitudes towards wastewater reuse.

Table 2 Accuracy of satellite-derived rainfall data and variation with annual rainfall for different weather stations and drought classification

ID	Station name	Latitude	Longitude	Altitude (m)	Station rainfall (mm/year)	Satellite-derived rainfall (mm/year)	Variation (Sat. -Sta)	Accuracy (%)
1	Turaif	31.41	38.4	818	84.17	85	0.83	99.02
2	'Ar'Ar	31	41	600	62.8	75	12.2	83.73
3	Al-Qurayat	29.38	43.29	447	46.7	50	3.3	93.40
4	Al-Jouf	31.5	37.5	560	54.63	60	5.37	91.05
5	Rafha	29.47	40.06	671	85.6	100	14.4	85.60
6	Al Qaisoomah	28.32	46.13	358	125.53	150	24.47	83.69
7	Tabuk	28.22	36.38	776	28.8	27	-1.8	106.67
8	Hafr Al Batin	28.2	46.07	360	123.1	146.9	23.8	83.80
9	Ha'il	27.26	41.41	1013	113.72	114	0.28	99.75
10	Al Wajh	26.12	36.28	21	25	26	1	96.15
11	Al-Qaseem	26.18	43.46	650	143.9	150	6.1	95.93
12	Ad Dhahran	26.16	50.1	17	90.3	90.1	-0.2	100.22
13	Al Dammam	26.42	50.12	1	80.3	83.7	3.4	95.94
14	Al Ahsaa'	25.3	49.48	179	84.8	87.2	2.4	97.25
15	Al Madina AlMunawara	24.33	39.42	636	63.7	65.6	1.9	97.10
16	Riyadh (north)	24.42	46.44	611	110.6	112.6	2	98.22
17	Riyadh (middle)	24.63	46.77	624	86.79	91.2	4.41	95.16
18	Yanbo'	24.09	38.04	6	30.3	55	24.7	55.09
19	Jeddah	21.3	39.12	17	52.1	67.8	15.7	76.84
20	Makkah Almukarrama	21.4	39.85	213	110.65	115	4.35	96.22
21	Al Ta'if	21.29	40.33	1454	172.17	180.6	8.43	95.33
22	Al-Baha	20.3	41.63	1652	142.61	202.88	60.27	70.29
23	Wadi AdDawasir	20.5	45.16	652	25.47	55	29.53	46.31
24	Bisha	19.59	42.37	1163	88.68	111	22.32	79.89
25	Abha	18.14	42.39	2093	229.14	230	0.86	99.63
26	Khamis Mushait	18.18	42.48	2057	190.55	201	10.45	94.80
27	Najran	17.37	44.26	1210	60.43	100	39.57	60.43
28	Sharura	17.47	47.11	725	70.29	60.9	-9.39	115.42
29	Jizzan	16.54	42.35	3	128.64	135.25	6.61	95.11
	Country mean				225.9	252.4	-26.4	89.52

Precipitation in the wettest quarter This quarterly index (Fig. 5d) approximates the total precipitation during the wettest quarter, which is the sum of the three consecutive months with the highest cumulative precipitation (W_3 months). This index is very important for studies related to environmental factors that affect the seasonal distributions of species. Precipitation in the wettest quarter ranged from 30 to 170 mm. Based on in this index, the wettest region in KSA is located in the south-west. Asir, Jizzan, Al-Baha, the northern borders, Al-Qaseem and Hail are the wettest regions in KSA. The precipitation values for the wettest quarter in these regions ranged from 60 to 170 mm/ W_3 months. During the field survey, we found that these six regions contained 116 rainwater harvesting dams

and groundwater recharge dams, representing 32 % of the total number of constructed dams in KSA.

Future climate projection based on seven climatic models

The climate projections from seven climatic models used four RCPs (RCP2.6, RCP4.5, RCP6 and RCP8.5). The average annual precipitation projections from the seven GCMs are shown in Figs. 6 and 7 for each scenario. Under the RCP2.6 scenario, the average annual precipitation shows a slight increase in 2050 (Fig. 6a) and 2075 (Fig. 7a). The predicted annual rainfall increase is 10 % in the central region (Al-Qaseem, Al-Riyadh) and 7 % in

Fig. 4 Precipitation seasonality (coefficient of variations)

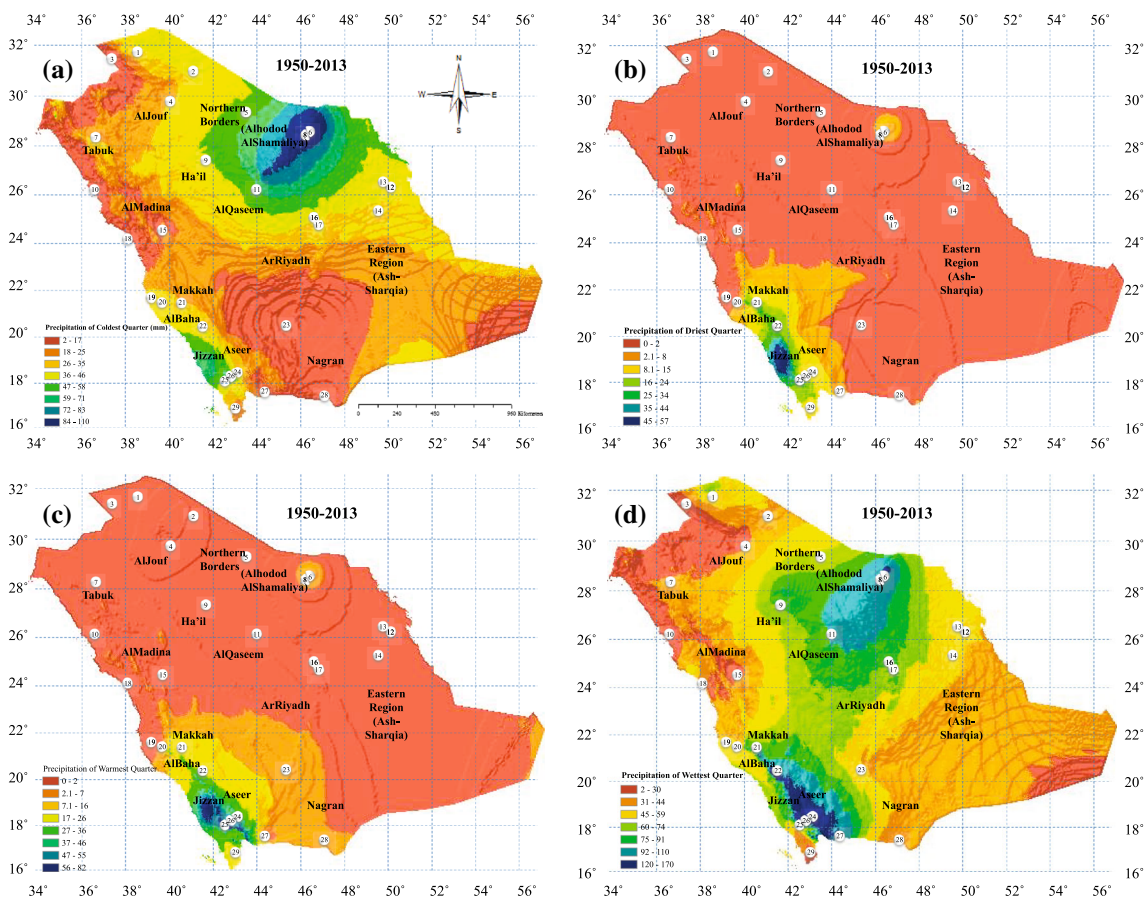
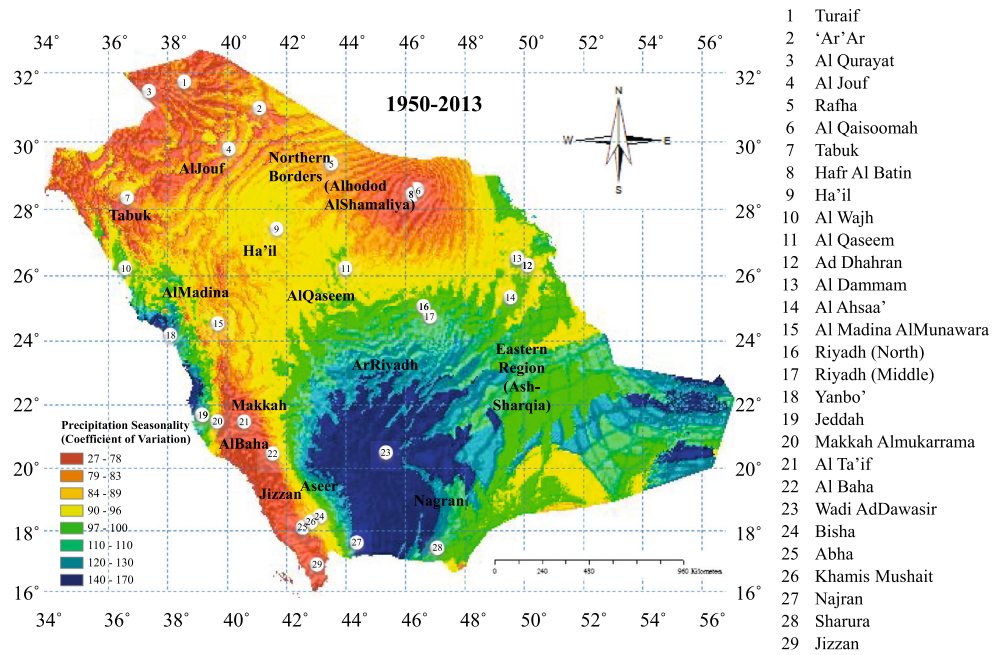


Fig. 5 Quarterly rainfall classification- precipitation of coldest, driest, warmest and wettest quarter

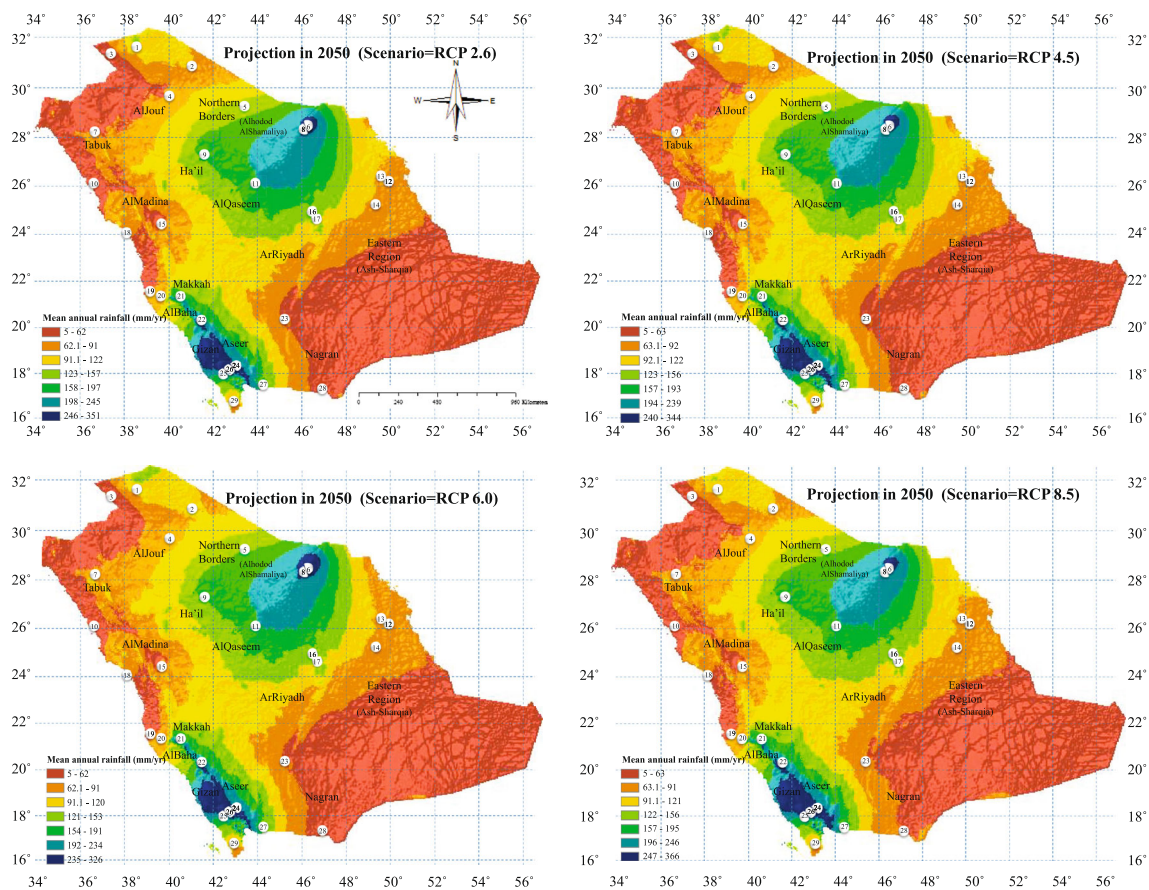


Fig. 6 Mean future climate projection in 2050 under four scenarios

Jizzan, which is a coastal region. Moreover, the results under the first scenario confirm the results of a previous study of the area, which predicted a slight increase during the 2050s (Meehl et al. 2007). General warming all over the country is predicted, especially in the northern border and central regions, including Al-Riyadh, varying from 0.15 to 0.75 °C, with an average of 0.40 °C (PME 2005). On average, there will be an increase of 11.5 % in the mean annual temperature over Al-Qaseem and Tabuk, a 10.5 % increase in Riyadh, and a 6 % increase in Jeddah. This increase in the mean annual temperature is due to increasing greenhouse gases and emissions, combined with decreasing forest and shrubland areas, which are being replaced by irrigated cropland and urban areas.

Under the second scenario (RCP4.5), by 2050, the mean annual rainfall will decrease by 1.5 % over the whole KSA, except for the northern borders, Al-Jouf and Ar'Ar, which will face a decrease of 20 %. Up to 2050, according to the projection models, there will be a warming trend everywhere except for the coastal regions (Jizzan Al-Baha, Asir). However, under the third scenario (RCP6), by 2050, the mean annual rainfall will moderately decrease by 2 % over the whole country except for the northern borders,

which will face a decrease of 5–11 % across the entire region. Al-Jouf, Ar'Ar and Al-Qurayat, and Turaif will face a decrease in annual rainfall ranging from 9 to 24 %. Under the fourth scenario (RCP8.5), the decreasing trend will expand to other areas, with an average 12–24 % decrease in annual rainfall by 2050 in the northern border region, Al-Jouf, Ar'Ar and Al-Qurayat, Turaif, Hail, Al-Qaseem and Guriat. In addition, there will be an annual temperature increase of between 1.8 and 4 °C all over the country. The maximum increase in annual temperature will be in the north, south and south-west of KSA.

Similarly, for the year 2075, all seven models show a slight increase under the first scenario (RCP2.6, the similar trend is shown for 2050). However, under the second scenario (RCP4.5), a declined trend in annual rainfall continues as the mean annual rainfall decreases by 1.95 % over the whole KSA, except for the northern borders (Al-Jouf and Ar'Ar) which will face a decrease of 25 %. Moreover, under the third scenario (RCP6), the mean annual rainfall will decrease by 9.5 % over the whole country except for the northern borders (Tabouk, Al-Jouf and Jizan) which will face a decrease of 18–27 % across the entire region. Under the fourth scenario (RCP8.5), the

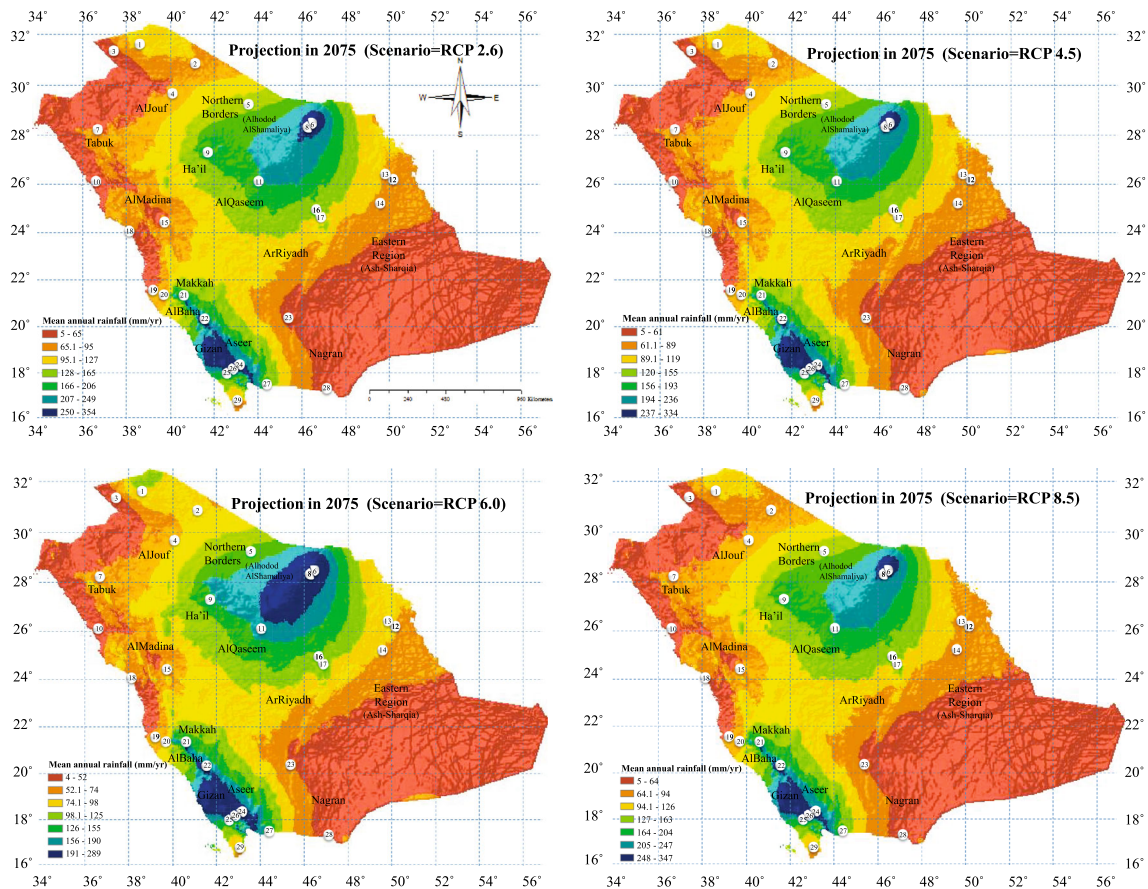


Fig. 7 Mean future climate projection in 2075 under four scenarios

decreasing trend will expand to other areas with an average decrease of 15–27 % in annual rainfall by 2075 in the northern border region including Al-Jouf, Ar'Ar and Al-Qurayat, Turaif, Hail, Al-Qaseem and Guriat (Fig. 7).

In general, the projection models predicted a declining trend in the mean annual precipitation in most regions of KSA under all of the studied scenarios. The models also showed a slight increase in the mean annual precipitation around the coastline of the Red Sea and southern regions. These predictions highlight the extreme effects of climate change in KSA and its natural resources, which may be due to the sensitivity of its ecosystems. The only possible solutions are to develop various mitigation and adaptation measures to cope with the adverse impacts of climate change. This can be done by ensuring the effective use of rainfall for groundwater recharge, rooftop rainwater collection for domestic use to make each drop of rainfall count, increasing wastewater treatment plant capacities and increasing public awareness about the impact of climate change.

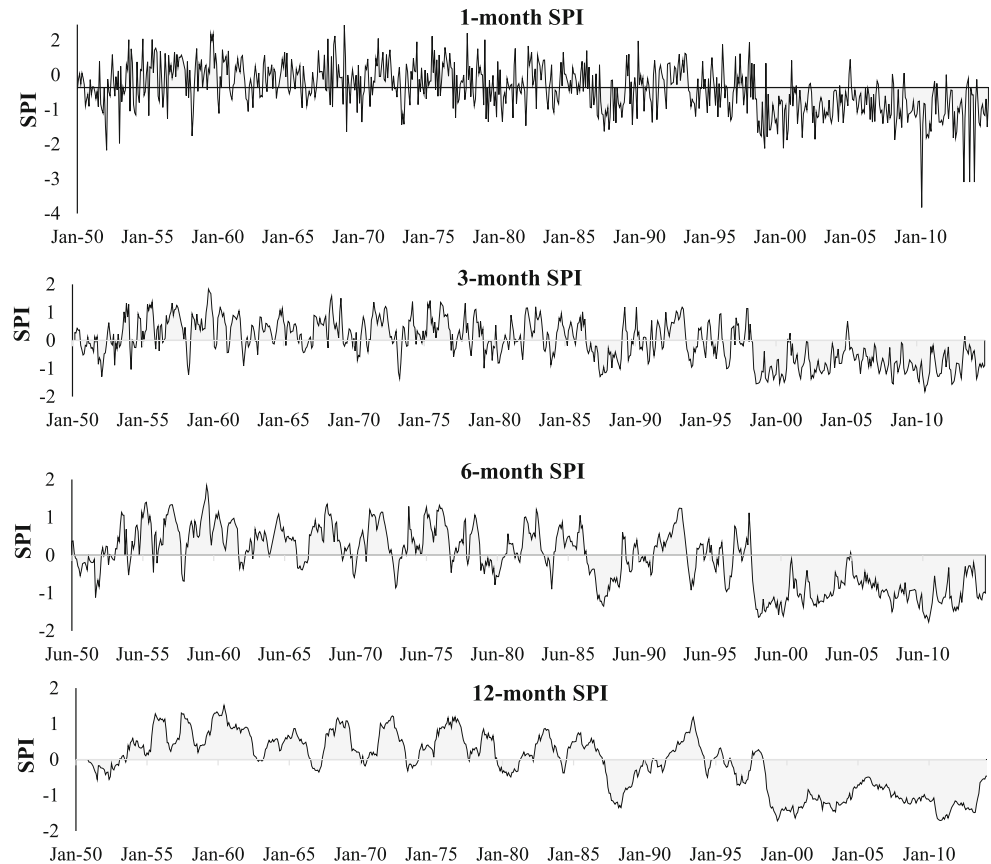
Spatial and temporal analysis of drought in KSA

The resulting SPI represents standard deviations the precipitation deficit deviates from the normalised average. Using the

SPI score, drought can be categorised using Table 1 (McKee et al. 1993; Agnew 2000). For example, if the score is less than -2 ($SPI \leq -2$), the year is categorised as extreme drought with a cumulative probability between 0 and 2.3 %.

The climate projection results in the previous section indicate that there will be less rainfall and increasing drought across large areas of KSA in the future. To confirm this phenomenon, four drought categories were used in line with Komuscu (1999), McKee et al. (1995) and Agnew (2000). We developed a time series of the monthly values of the SPI for each timescale for the years 1950–2013, as shown in Fig. 8. The analysis of the time series of these monthly values showed that drought events change as the timescale changes. The 1-month SPI varies frequently above and below zero. In 1950, the monthly value of the SPI ranged from as low as -0.6 in November, which is classified as a moderate drought event according to the drought classifications of Komuscu (1999) and McKee et al. (1995), and up to 0.46 in May 1950. From 1950 to 1980, the monthly SPI values varied frequently from mild to moderate drought and from moderate to severe drought. However, from 1980 to 2013, the situation totally changed and droughts became more severe due to the decrease in annual precipitation during this period.

Fig. 8 Time series of the monthly values of SPI for each timescale in the years 1950–2013



The analysis of the time series of the monthly SPI values indicated that the longer the timescale, the slower the SPI changes due to changes in rainfall. Periods with negative or positive SPI values were less frequent, but longer in duration. When using the 6- to 12-month timescale, droughts were more concentrated and longer than the 1-, 2- or 3-month drought events. This provides a clearer classification of historically significant drought events. The 12-month SPI values in Fig. 8 show that in 1950, 1951, 1952 and 1953, there were mild droughts, as the SPI values were < -0.6 , and from 1954 to 1980, there were no droughts according to Agnew’s (2000) drought classification. During this period, the highest 12-month SPI values were observed in 1960, 1970 and 1975. The lowest 12-month SPI values (-0.7 to -2) were observed over the 1980–2013 period. There was an extreme drought lasting for 13 years ($SPI < -2$), as determined by the monthly values from January 2000 until July 2013.

Climate change already understood to alter the atmospheric circulation changes the precipitation and drought regimes (IPCC 2007b). In statistical indices, such as SPI, these distribution functions characterise variability, where drought refers to precipitation events occurring at low extreme of precipitation distribution. Shifts in climate normals (including in precipitation mean and distribution)

are understood to affect the precipitation variability and hence the drought frequency, as shown in Fig. 4. In addition, if a large precipitation record is used, as in this study (1950–2013), the precipitation distribution will approach the true distribution (gamma distribution in case of the original SPI model (McKee et al. 1993). That was done to avoid the uncertainty in the form of inadequate precipitation records which may cause a heterogeneity and inconsistency in SPI results.

Over the past 20 years, the whole of KSA has generally faced long, severe and extreme droughts. For instance, Al-Riyadh, Al-Baha, Jizzan, Asir, Al-Qaseem, Makkah and Al-Jouf are classified as extreme drought regions (Table 3), thus presenting an alarming risk as most of these are agricultural regions.

The risk will become extremely dangerous if the declining trend in rainfall continues, causing increasingly severe droughts. Among the previous regions, Asir, Al-Baha and Jizzan have the highest annual rainfall in KSA, yet at the same time are facing extreme drought. Moreover, these results confirm the output of the predication model that there will be a general decrease in annual rainfall in KSA.

In terms of climate trends in KSA with regard to the scenarios adopted in the present study, there is a general

Table 3 Drought classification and SPI values in KSA

ID	Station name	Annual rainfall (mm/year)	SPI	Drought classification		
1	Turaif	84.17	<−2 to −1.65	Extreme drought		
2	'Ar' Ar	62.8				
3	Al-Qurayat	46.7				
4	Al-Jouf	54.63				
5	Rafha	85.6				
6	Al Qaisoomah	125.53				
11	Al-Qaseem	143.9	<−1.5 to −1	Severe drought		
20	Makkah Almukarrama	110.65				
22	Al-Baha	142.61				
27	Najran	60.43				
28	Sharura	70.29				
29	Jizzan	128.64				
9	Ha'il	113.72				
23	Wadi AdDawasir	25.47				
7	Tabuk	28.8			<−1 to −0.5	Moderate drought
8	Hafr Al Batin	123.1				
10	Al Wajh	25				
12	Ad Dhahran	90.3				
13	Al Dammam	80.3				
14	Al Ahsaa'	84.8				
15	Al Madina AlMunawara	63.7				
18	Yanbo'	30.3				
19	Jeddah	52.1				
21	Al Ta'if	172.17				
25	Abha	229.14	−0.5 to 0	Mild drought		
24	Bisha	88.68				
26	Khamis Mushait	190.55				

warming all over KSA and there are vast areas of rainfall deficits covering all northern parts of the Kingdom and the Asir mountains. In order to cope with adverse impacts of climate change in the region, various measures have to be taken to ensure the sustainability of water resources such as assessments of water resources availability, construction of more rainwater harvesting dams, building more desalination plants to supply support the domestic water supplies in the KSA, and promotion of wastewater treatment and reuse.

Conclusions and recommendations

This study investigated climate change and its impact on water resources in KSA using observational data and climate models. The findings provide an inclusive reference document on the status of climate change in the country, with analysis and modelling of the past 64 years (1950–2013) and projections of the state of the climate in 2050 using seven climatic models, and the SPI was used to

assess droughts over the past 64 years to avoid uncertainty in the form of inadequate precipitation records. The analysis of more than 60 years of climate data revealed that KSA has a semi-arid to hyper-arid climate, characterised by very low rainfall (annual average of 112 mm) and extremely high evapotranspiration, resulting in water scarcity and reduced vegetation cover. The south-western region of KSA had the highest average annual rainfall. Summer rainfall occurred over the south-west mountains due to the easterly jet stream and the monsoon. Over time, the climate is becoming hotter, and rainfall is decreasing slightly each year.

During the studied period, the northern region received most of its rainfall from November to April. The north—north-eastern regions of KSA received most of their rainfall during the wet months of November to April, and this trend continued towards the centre of the country. The south and south-western regions received most of their rainfall during June to September. However, these are considered dry months because during this season, no rainfall occurred in the northern and south-eastern regions,

while little rainfall occurred in the south and south-western regions. The north-western and south-eastern regions had the lowest mean annual rainfall of 4–50 mm/year. Al-Rub Al-Khali also had low annual rainfall of 60 to 80 mm/year. However, the central-northern region had moderate rainfall (70–100 mm/year); the central, north-eastern and south-western regions received the highest mean annual rainfall ranging from 150 to 300 mm/year. The largest annual rainfall variability was observed in Nagrah, the eastern regions (Ash-Sharqia), Asir and Al-Riyadh, where the CV values were 155, 105, 135 and 120 %, respectively. Values over 100 % indicate extremely high variability in annual precipitation. In these regions, the standard deviation of the precipitation throughout the year exceeded the average precipitation, due to precipitation anomalies throughout the course of the year in these regions. The RCP 2.6 scenario predicted a slight increase in the average annual precipitation. Annual rainfall will increase by 10 % in the central region (Al-Qaseem, Al-Riyadh) and by 7 % in Jizzan. Under the second scenario, the mean annual rainfall in 2050 will decrease by 1.5 % over all of the country except for the northern borders, Al-Jouf and Ar'Ar, which will face a decrease of 20 %. Under the third scenario, the mean annual rainfall by 2050 will moderately decrease by 2 % over the entire KSA except for the northern borders, where the decrease will range from 5 to 11 % across the entire region. Al-Jouf, Ar'Ar, Al-Qurayat and Turaif will face a decrease in annual rainfall ranging from 9 to 24 %. Under the fourth scenario (RCP8.5), the decreasing trend expands to other areas, with an average 12–24 % decrease in annual rainfall by 2050 in the northern border region, Al-Jouf, Ar'Ar, Al-Qurayat, Turaif, Hail, Al-Qaseem and Guriat. In addition, the annual temperature will generally increase by 1.8–4 °C. According to the model, the north, south and south-west of the country will face the highest increase in annual temperature.

During the past 20 years, KSA has experienced long, severe and extreme droughts, and Al-Riyadh, Al-Baha, Jizzan, Asir, Al-Qaseem, Makkah and Al-Jouf are classified as extreme drought regions. This presents an alarming risk as most of these are agricultural regions. The risk will become extremely dangerous if the declining trend in rainfall continues, causing increasingly severe droughts. Among the previous regions, Asir, Al-Baha and Jizzan have the highest annual rainfall in KSA, yet at the same time are facing extreme drought. Moreover, these results confirm the output of the prediction model that there will be a general decrease in annual rainfall in KSA. The impact of climate change in KSA will affect all aspects of life including water resources, food and agricultural production, biodiversity, forest and shrubland.

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