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Assessment of meteorological droughts over Saudi Arabia using surface rainfall observations during the period 1978–2017

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Abstract
This paper discusses the preliminary results of meteorological drought analysis over Saudi Arabia for the period 1978–2017. In conjunction with meteorological observations, datasets from the Climate Prediction Center (CPC), the Merged Analysis of Precipitation (CMAP), the Climatic Research Unit (CRU), and the Tropical Rainfall Measuring Mission (TRMM) are utilized to understand the impact of the spatial distribution of rainfall on drought events. Applying precipitation thresholds allows rainfall classifications such as deficit, scanty, and surplus. Precipitation thresholds are also used to define meteorological droughts in the country, which are categorized as usual, moderate, and severe. It is found that drought events occur in Saudi Arabia due to shortfalls in the dry season, even though there is above normal rainfall in the wet season. There is no case of a shortfall in both the wet and dry seasons causing drought. Saudi Arabian droughts of all categories occurred mostly in the dry season, with fewer in the wet season. Results show that in Saudi Arabia, the last month of the wet season (April) is less prone to drought while the first and last months of the dry season (June and September respectively) are more prone to drought. Spatial distribution of drought climatology is obtained by calculating the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI). Further application-driven studies of projections are needed based on drought indices and climate model output.

Keywords Drought · Rainfall · Saudi Arabia · Precipitation threshold · Observed and gridded datasets

Introduction

Drought is a recurrent characteristic feature of climate variability and is manifest by prolonged and continuous periods of dry weather along with an abnormal deficient of rainfall. Droughts have significant impacts on the infrastructure, socio-economic activity, and the environment. They cause drying of the earth and water shortages, dry wells, depletion of groundwater and soil moisture, stream flow reduction, crop failure, and a lack of fodder for livestock. These impacts are particularly severe on already semi-arid and arid regions (Abdullah and Al-Mazroui 1998; Ragab and Prudhomme 2000) such as the Arabian Peninsula, and in particular on Saudi Arabia, which covers 80% of the Peninsula (Almazroui et al. 2012a, 2012b). Saudi

Arabia contains the world's largest continuous sand desert, the Rub Al-Khali (Empty Quarter). Despite the fact that both the onset and the ending of droughts are usually slow processes, their cumulative effect can be far more disastrous than other climate phenomena, (Bhalme and Mooley 1980). The total impact of large-scale droughts may be far more disastrous than other short time scale natural phenomena even catastrophic ones such as floods (Bhalme and Mooley 1980). Cumulatively, droughts have direct negative impacts on various socio-economic sectors including agriculture, food production, infrastructure, biodiversity, tourism, and water storage.

Precipitation is the single most influential meteorological variable on the persistence and ending of drought, although drought can manifest itself in different ways, e.g., food shortages, water scarcity, and difficulties with power generation. Other variables, both meteorological (e.g., surface temperature, moisture and cloud cover) and hydrological (e.g., soil moisture, evapotranspiration, runoff and underground water table), are of secondary importance in the characterization of drought. Both meteorological and hydrological variables are non-stationary in historical records due to climate change and global warming. The

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Intergovernmental Panel for Climate Change (IPCC) has declared that the warming of our climate, observed since the beginning of the 20th century, is unequivocal (IPCC 2007, 2013). The consequences of this warming have been observed in the recent decades. For example, changes in atmospheric circulation and rainfall patterns and the widening of the tropical belt are commonly accepted as consequences of global warming (Seidel et al. 2008). It is expected that climate change will continue to affect rainfall patterns and hence the frequency and intensity of droughts in the future. Therefore, understanding drought situations in the present climate is a prerequisite to the analysis of any future scenarios.

The Arabian Peninsula, like many other places, is experiencing changes in temperature and rainfall patterns in response to climate change which will significantly affect the frequency and spatial characteristics of droughts. Unprecedented changes in the climate of Saudi Arabia have been reported by Almazroui et al. (2012a) in recent years. The trend of increasing global surface temperature is also observed regionally in the various districts of Saudi Arabia (Almazroui et al. 2012b). The observed surface temperatures in Saudi Arabia have been analyzed by Almazroui et al. (2012a) and were found to display a significant increasing trend. They also report a significant trend of decreasing rainfall for the recent past (1994–2009). It is expected that this warming trend will also have an impact on rainfall and probably on drought (Almazroui et al. 2012b). Rainfall climatology, particularly in an arid environment, is strongly governed by the topography (Lioubimtseva 2004). From analysis of rainfall climatology, Almazroui et al. (2012a) concluded that there is great spatial and temporal diversity of rainfall over the Arabian Peninsula.

Although many research centers have conducted drought studies in various locations worldwide, to the best of our knowledge, very little research has been done in this field for Saudi Arabia. For example, the Red Cross/Red Crescent Climate Centre in the Netherlands reported on East African drought (Shongwe et al. 2011), the European Drought Center (http://europeandroughtcentre.com/about-us/edc/), the Queensland Drought Mitigation Centre in Australia (http://www.droughtmanagement.info/wp-content/uploads/2017/08/1_9_International-Drought-Mitigation-Research-Center_2017.pdf), and the North Central Climate Science Center and NOAA's Physical Sciences Division in USA (https://casc.usgs.gov/content/eddi-new-drought-index-provides-early-warning-flash-droughts) all work locally and internationally on this topic. To comply with the Water and Environment National Programs proposed by the King Abdulaziz City for Science and Technology (KACST), to face the challenges posed by future climate change and to contribute to timely and evidence-based decision-making, we have undertaken research to fill this knowledge gap, and specially to identify drought characteristics over Saudi Arabia. Therefore, the main goal of this paper is to identify the principal characteristics of drought events in Saudi Arabia using observed and gridded datasets for the present climate and to improve understanding of seasonal impacts on the identified events.

Data and methodology

There are three types of droughts: namely meteorological, hydrological, and agricultural. In this study, we focus on meteorological drought over Saudi Arabia by analyzing the observed rainfall and its distribution patterns. It is possible to diagnose meteorological drought by analyzing the rainfall time series. For this purpose, the following datasets are used:

a) Observations of available monthly surface rainfall collected by the General Authority of Meteorological and Environmental Protection (GAMEP; hereafter referred to as observed) for the period 1978–2017. The observation locations in Saudi Arabia are shown in Fig. 1 (open circles). The GAMEP data have the advantage of being quality controlled (Islam et al. 2015).

b) Gridded datasets from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; see Xie and Arkin 1997), the Climatic Research Unit (CRU; see Harris et al. 2014; Mitchell et al. 2004; New et al. 2000), and the Tropical Rainfall Measuring Mission (TRMM; see Kummerow et al. 2000).
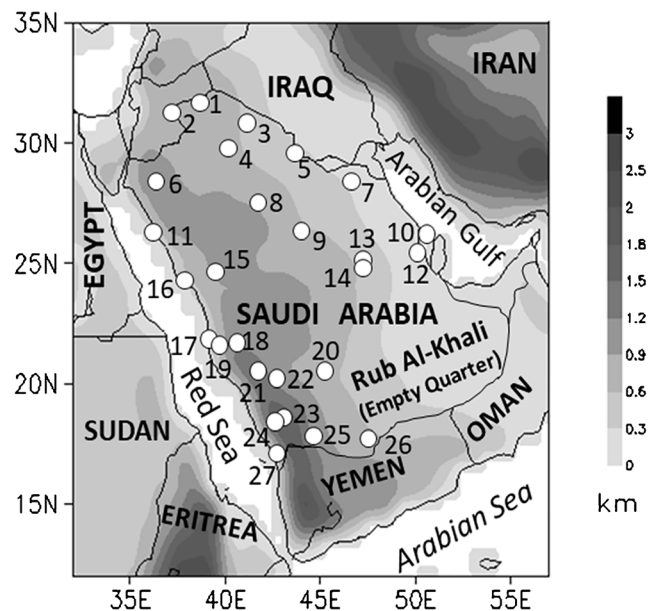
Fig. 1 The map of Saudi Arabia and its surroundings with elevation (km). The surface observation sites throughout Saudi Arabia are shown with open circle marks. The numeric represents station ID from north to south across the country and stations names can be seen in Almazroui et al. (2012a)

While various definitions of drought have been formulated in the literature over the past 30 to 50 years, there is still no single universal definition of drought. In this study, the focus is mainly on meteorological drought based on a percent or proportion of normal rainfall (the long-term mean is taken to be 100%). In meteorological terms, drought is in general associated with a prolonged and abnormal regional moisture deficit (Palmer 1965) or a sustained period of significantly below normal rainfall (Oladipo 1985). The definition of drought is also dependent on the region of interest, for example, as pointed out by Oladipo (1985), a dry period of several weeks in the mid-latitudes in the summer can be considered to be a drought, whereas in other areas, such as parts of the subtropics, drought is normally defined as two or more consecutive rainy seasons without rain. Similar definitions aligned with rainfall thresholds are used in different parts of the world, e.g., in India, South Africa, and USA (Smakhtin and Hughes 2004).

Annual rainfall of 25% or monthly rainfall of 40% below normal is suggested to define drought in the USA (Bates 1935). Droughts in South Africa are defined as rainfall below 50% of the normal amount (Bruwer 1990). In some states of India, seasonal (or even weekly) rainfall below 50% of normal is accepted to constitute drought conditions (Banerji and Chabra 1964; Ramdas 1950). However, the Indian Meteorological Department (IMD) defines a deficit as 20–60% less rain than normal while scanty is defined as more than 60% below normal. In general, meteorological droughts in India are defined (Smakhtin and Hughes 2004) as follows: usual or common drought (rainfall in a month/season is ≥ 25% below normal), moderate drought (between 26 and 50% below normal), and severe drought (≥ 50% below normal). However, the question arises as to how to define and analyze meteorological drought for a semi-arid to arid climate region such as Saudi Arabia? To answer this question, we first analyze dry conditions based on rainfall thresholds. Next, drought indices are calculated, and a few drought cases are studied in detail for better understanding any seasonal factors behind drought in Saudi Arabia. The final goal is to calculate drought indices from climate model output data, which will be documented separately.

In this analysis, categories of rainfall are defined as follows: average (simple average from all stations used), deficit (≥ 20% below normal), and scanty (≥ 60% below normal). The categories of surplus (≥ 20% above normal) and usual (within ± 20% of normal) are also used. Monthly rainfall data are used for annual and seasonal analyses, and the national average is based on data from all 27 stations across the country. The annual rainfall duration is defined as the ratio of rainy years to the total analysis period expressed as a percentage and trend significance is obtained using F test.

To better understand the drought situation in Saudi Arabia, drought indices (for instance see Dash et al. 2012; Gidey et al. 2018a,b; Mustafa and Rahman 2018) were calculated for the long-term over the country. Among various drought indices, we selected the Standardized Precipitation Index (SPI, Mckee et al. 1993) and the Palmer Drought Severity Index (PDSI, Palmer 1965) to be calculated using observed rainfall from 27 stations, along with other variables for the current climate. The drought events may be categorized using the SPI values as follows: mild (0 to − 0.99), moderate (− 1.00 to − 1.49), severe (− 1.50 to − 1.99), and extreme (− 2.00 and less). In PDSI, drought events are categorized as mild drought (− 1.0 to − 1.99), moderate drought (− 2.0 to − 2.99), severe drought (− 3.0 to − 3.99), and extreme drought (− 4.0 or less).

The topography of Saudi Arabia and its surroundings is shown in Fig. 1. A northwest-southeast–oriented mountain range with heights reaching about 1.5 km or more above sea level is located on the southwestern side of Saudi Arabia crossing through to Yemen (Fig. 1). This complex mountainous region receives the highest annual mean rainfall in Saudi Arabia (Almazroui 2011).

The observed data currently available over Saudi Arabia is mainly from stations along the western and eastern coasts and the northern and central areas of the country. There are no station data available from the southeastern region where Rub Al-Khali or the Empty Quarter is situated. In this paper, the definition of wet (November to April) and dry (June to September) seasons are adopted following Almazroui (2011), consistent with the climatology of Saudi Arabia. This study used May and October as transition periods from wet to dry and dry to wet, respectively.

We first analyzed the observed rainfall time series data to identify drought years using rainfall thresholds. Then, the re-analysis gridded datasets were examined to understand the influence of seasonal rainfall on the drought events. The higher resolution (0.25°×0.25°) gridded rainfall dataset Tropical Rainfall Measuring Mission (TRMM) starting from 1998 was available for analysis. A relatively coarse resolution (2.5°×2.5°) gridded rainfall dataset was available from CMAP, starting in 1979 (both over land and the ocean), as well as from CRU (0.5°×0.5°) for land only. In this study, the CMAP, CRU, and TRMM datasets are employed to investigate the causes of drought in the rain-deficit years identified by the time series analysis mentioned earlier. Note that these gridded datasets are already calibrated against the observed rainfall and good agreement was found among the datasets (Almazroui et al. 2012a).

Results

Rainfall categories for Saudi Arabia

Annual rainfall duration (defined as rainy year divided by total 40 analyzed year expressed as a %) varies from category to

Fig. 2 Annual rainfall duration (percent of the rainy year to the analysis period) associated to different categories at each station location across Saudi Arabia for the period 1978–2017. Different categories are identified based on rainfall threshold. Station IDs are followed according to Fig. 1
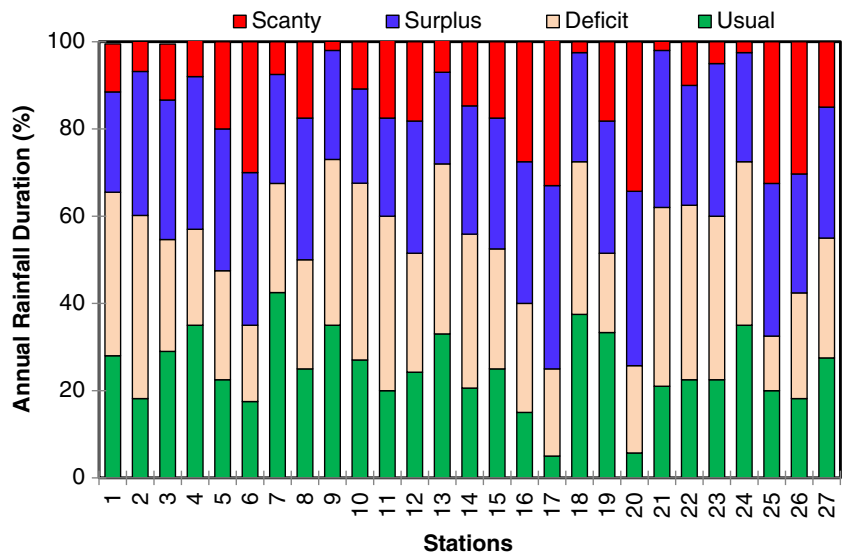
category and station to station (Fig. 2). Large variations in annual rainfall duration are found between stations for the

categories of usual and scanty rainfall. The category of usual rainfall is the most frequent one for the northeast station 7

Fig. 3 Time sequences of the number of stations (in percent) associated with different rainfall classes in Saudi Arabia for the period 1978–2017
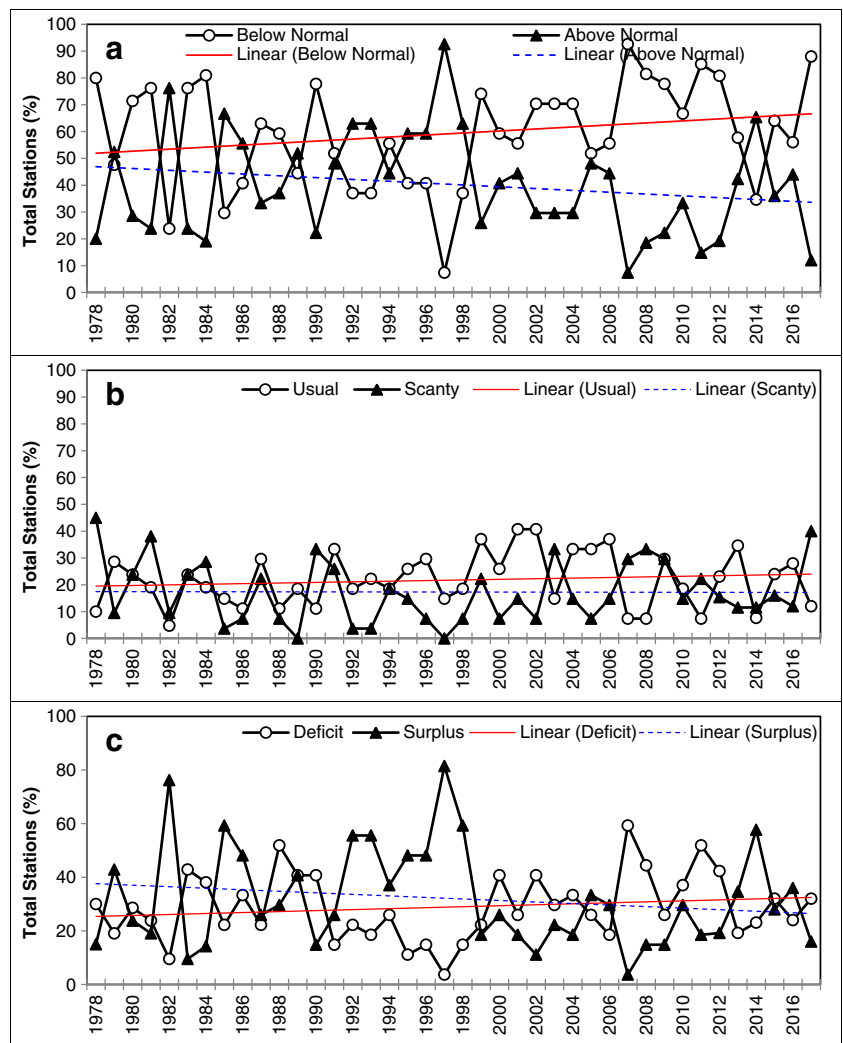
Fig. 4 The time sequences of **a** annual, **b** wet season, and **c** dry season rainfall (mm) with their classes obtained from the observed dataset. The normal (country average from 27 stations), deficit (20% below normal), scanty (60% below normal), and surplus (within ± 20% of normal) are used to identify drought year over the country
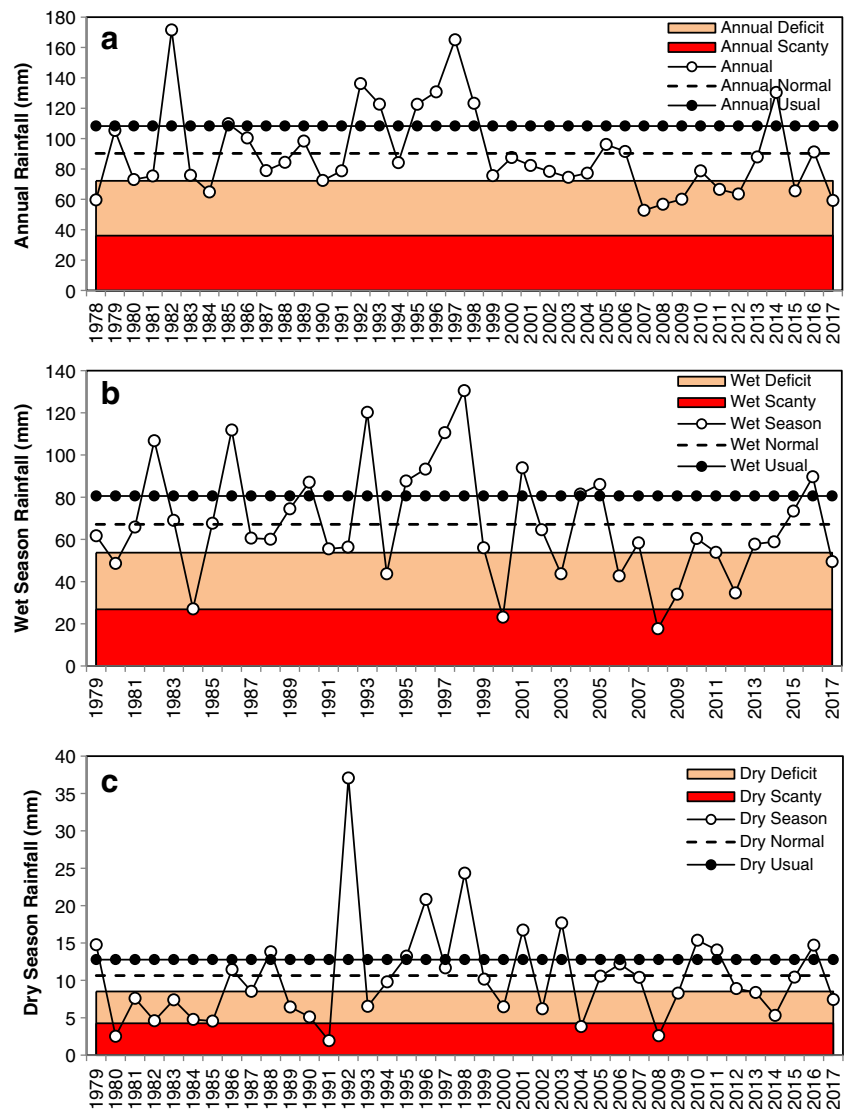

(AlQuasumah) (43%, 17 years out of 40), whereas it is least frequent for the western station 17 (Jeddah) (5%, 2 years out of 40). In contrast, the category of scanty rainfall duration is found to be most common for station 17 (37%) and least usual (3%) for stations 9, 18, and 24. The abundance of the category of deficit rainfall duration is almost the same for all stations except for a few, the lowest being 13% for the southern station 25 (Najran). In general, the deficit rainfall category is rarer for those stations with many surplus and scanty years, e.g., stations 6 and 25.

Time sequences of the stations (in %) across Saudi Arabia associated with different rainfall categories are shown in Fig. 3. As shown in Fig. 3a, the stations with below and above annual normal rainfall years mirror each other: an increase of below-normal rainfall in a year follows a decrease of above-normal in the same year and vise versa. The number of stations with above normal annual rainfall years decreases insignificantly, just as the number

with below-normal rainfall increases. Over the analysis period 1978–2017, 58% of the stations show below-normal rainfall while 42% show above-normal rainfall. The number of stations showing scanty rainfall decreases insignificantly, while those showing normal or usual rainfall increase (Fig. 3b). Similarly, the number of stations showing a surplus decreases insignificantly, while the number showing a deficit is significantly increases (Fig. 3c) (at the 90% level). Altogether, this is an indicator of decreased rainfall over the country in recent decades.

The time sequences of annual and seasonal rainfall averaged from all 27 stations over Saudi Arabia are displayed in Fig. 4. In some years, annual rainfall is below normal (dashed line), indicating the possibility of a drought year. Figure 4 a shows that annual rainfall is below normal for 25 years and in deficit for 10 (1978, 1984, 1990, 2007, 2008, 2009, 2011, 2012, 2015, and 2017) of the 40 years from 1978 to 2017. None of the years fall into the scanty rainfall category at the
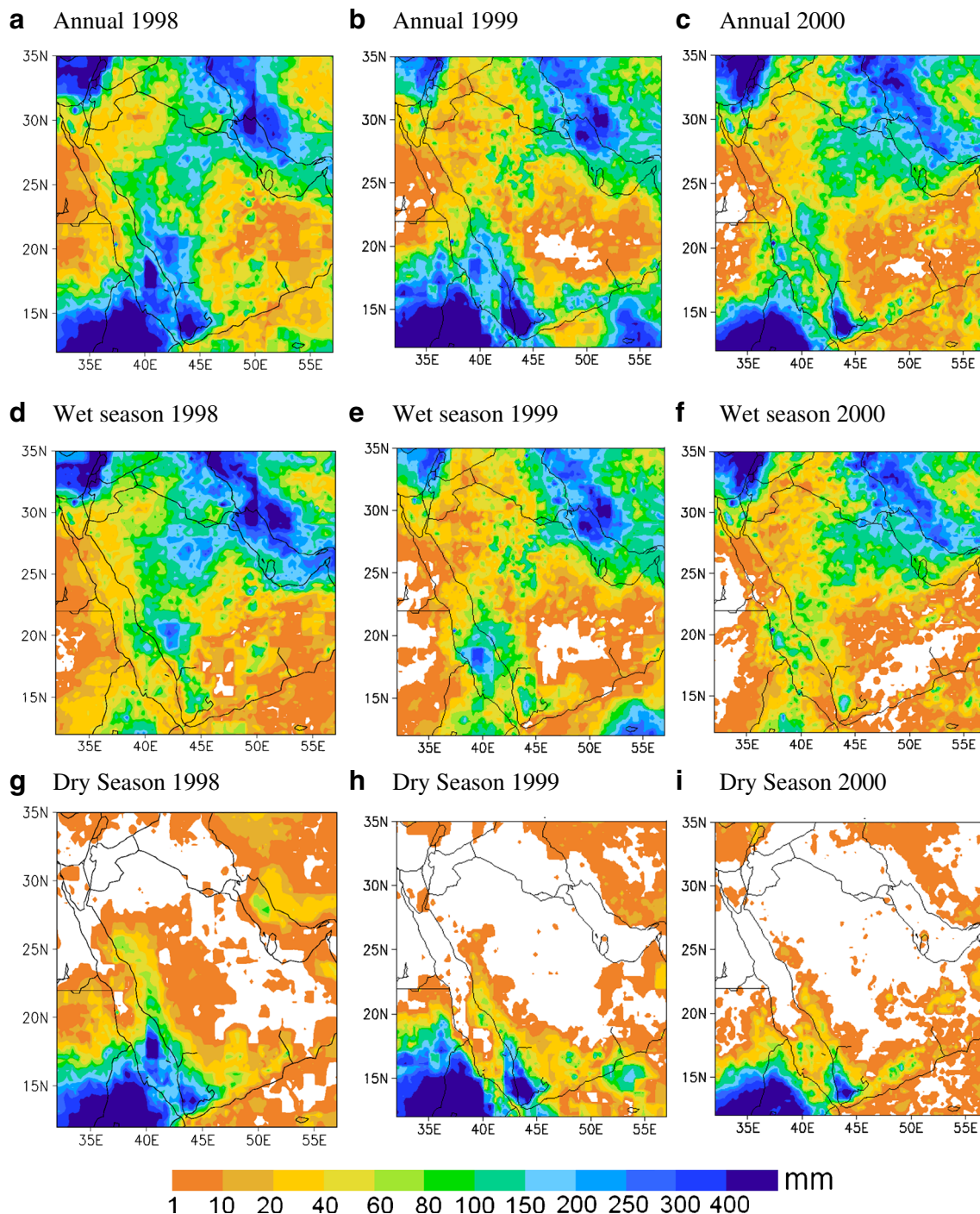
Fig. 5 Rainfall obtained from the TRMM dataset for annual (top panels), wet season (middle panels), and dry season (bottom panels) for surplus year 1998 (**a**, **d**, g), normal year 1999 (**b**, **e**, **h**) and shortfall year 2000 (**c**, **f**, **i**). Rainfall amount below 1 mm is not shown in the legend

annual scale. In the wet season, there are many years with below-normal rainfall of which 7 (1980, 1994, 2003, 2006, 2009, 2012, and 2017) are identified as being in deficit (Fig. 4b). The rainfall analysis of the wet season identified that 3 years (1984, 2000, and 2008) as scanty. This indicates that there was very little rainfall in the wet season over the country for these 3 years and that the country was experiencing meteorological drought, especially in the northern and central parts of the country, where wet season rainfall is the main supply of renewable water resources. In the dry season, rainfall over the country was found to be in deficit for 15 years (1981, 1982, 1983, 1984, 1985, 1987, 1989, 1990, 1993, 2000, 2002, 2009, 2013, 2014, and 2017) (Fig. 4c). Hence, 1980, 1991, 2004, and 2008 were identified as scanty years in the dry season due to the lack of rainfall in the south and southwestern parts of the country.

Table 1 Drought classes in Saudi Arabia in different months for 40 years period (1978–2017). In this tabulation, symbols for usual drought = U, moderate drought = M and severe drought = S are used

Year	Drought classes											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1978	U M			U	U M	U M S		U M	U M S	U M S	U M S	U M S
1979			U M S			U M S	U M S		U M S		U M S	
1980	U M					U M S	U M S	U M S	U M S	U M S		U M
1981	U M			U M S		U M S	U M	U M S	U M S	U M S	U M S	U M S
1982						U M S	U M S	U M S	U M S			
1983						U M S	U M S	U M S	U M S	U M S	U M S	U M S
1984	U M S	U M S		U M		U M S	U M S	U M S	U M S	U M S		U M
1985		U M S	U M			U M S	U M S	U M S	U M S	U M S		
1986	U M				U M S	U M S	U M S	U M S	U M	U M S		
1987	U M S	U M S				U M S	U M S		U M S		U M S	
1988			U M		U M S	U M S		U M S	U M S	U M S	U M S	
1989	U M S				U M S	U M S	U M S	U M S	U M S	U M S		
1990				U M		U M S	U M S	U M S	U M S	U M S	U M S	U M S
1991				U M		U M S	U M S	U M S	U M S		U M	U M S
1992				U M		U M S	U M S		U M	U M S		
1993						U M S	U M S	U M S	U M S		U M S	
1994		U M S				U M S	U M	U M S	U M			
1995	U M S					U M S		U M	U M S	U M S	U M S	
1996		U M					U M S	U M S	U M S	U M S		U M
1997		U M S		U		U M	U M S	U M S	U M S			
1998		U M S				U M S	U M		U M S	U M S	U M S	U M S
1999				U M S	U M S	U M S	U M S	U M S	U M	U M S	U M S	
2000		U M S	U M S	U M		U M S	U M S	U M S	U M S	U M		
2001		U M S			U M S	U M S	U M		U M S	U M	U M S	
2002		U M			U M S	U M S	U M S	U M S	U M S	U M S		
2003	U M	U M S	U M		U M	U M S	U M S		U M S	U M S		
2004		U M S	U M S		U M S	U M S	U M S	U M S	U M S	U M	U M	
2005						U M S	U M S		U M S	U M S	U M	U M S
2006	U M S		U M			U M S	U M S		U M S			
2007			U M		U M	U M	U M S	U M S	U M S	U M S	U M S	U M S
2008		U M S	U M S	U M		U M S	U M S	U M S	U M S			U M S
2009	U M S	U M S	U M S			U M S	U M S	U M	U M S	U M S		
2010						U M S		U M S	U M S	U M S	U M S	
2011		U M S			U M	U M S	U M	U M	U M S	U M S		U M S
2012	U M S	U M S	U M S		U M S	U M S	U M S	U M S	U M S	U M		
2013		U M S				U M S	U M S	U M S	U M S	U M S		
2014		U M S				U M S	U M S	U M S	U M S			
2015	U M S	U M S		U M S	U	U M S	U M S	U	U			
2016	U M S	U			U	U M S			U M S	U M S		U M S
2017	U M S					U M S	U M S	U M S	U M S	U M S	U M S	U M S

As shown in Fig. 4b, three consecutive years from 1998 to 2000 belong to different rainfall categories: 1998 is in surplus, 1999 is almost in deficit, and 2000 is scanty. To understand in detail the status of these three consecutive years, the spatial distribution of rainfall in and around Saudi Arabia obtained from relatively high-resolution TRMM data is displayed in Fig. 5. In general, Saudi Arabia received less rainfall as compared with neighboring countries to the northeast and southwest, particularly in the dry season that also appears in the annual amount. The annual total rainfall was high in the

southwestern and central parts of Saudi Arabia in 1998 but was then reduced in 1999 and 2000. It is mainly the wet season rainfall which contributes to surplus rain in 1998 for the abovementioned regions (Fig. 5d). In 1998, heavy rainfall was also observed in the southwest region during the dry season (Fig. 5g). Although relatively heavy rainfall occurred in the center of the Arabian Gulf during the wet season of 2000, reduced rain in the southwest (Fig. 5e) as well as little rain in the dry season (Fig. 5i) caused this year to be classified as scanty. Overall, annual rainfall patterns in 1998, 1999, and 2000 show a similar distribution over the region (Almazroui et al. 2012b). The annual low rainfall (below 80 mm) was in the very dry area of Rub Al-Khali, moderate rainfall (above 80 mm to below 150 mm) was in the dry area over central to north of Saudi Arabia, and heavy rainfall (above 150 mm) was in the wettest area in the southwest of the Peninsula.

Drought categories for Saudi Arabia

Meteorological drought categories in Saudi Arabia obtained based on rainfall thresholds (Smakhtin and Hughes 2004) are discussed here.

As a first step, the national average rainfall for each month for the 40-year analysis period was obtained. The data was then categorized into usual ($\geq$ 25% below average), moderate (between 26 and 50% below average), and severe ($\geq$ 50% below average) droughts as presented in Table 1. In most years, drought occurs in Saudi Arabia during the dry season (June–September). The transition month of October also experienced a drought situation for 29 years (73%) of the 40. In the wet season (November–April), only a few years present a drought situation. Because the amount of monthly rainfall in Saudi Arabia is very low, once a drought is identified for any month, it qualifies almost always for all three categories (usual, moderate, and severe).

Time sequences of the number of drought occurrences (in a month) under different drought categories for the period 1978–2017 are shown in Fig. 6. All drought categories show an insignificant increase in the number of drought

occurrences. On average, usual or moderate drought occurred for 7 months (continuous horizontal line) while severe drought occurred for 6 months (dashed horizontal line) in a year. Both usual and moderate droughts occur for 14 (35%) years (1978, 1981, 1984, 1990, 1999, 2000, 2003, 2004, 2007, 2008, 2009, 2011, 2012, and 2017) with above an average number of drought months (7). In contrast, severe drought occurs for 11 (28%) years (1981, 1983, 1984, 1989, 1990, 1999, 2004, 2008, 2009, 2012, and 2017) with an above average number of drought months (6). Both usual and moderate droughts occur for a maximum number of drought months (9) for the years 1981, 1984, 2004, 2007, and 2012. Therefore, to understand the seasonal dependency of rainfall, drought years were identified from the time series analysis and investigated in detail using different datasets to construct the spatial distribution of rainfall patterns for the four example years of 1981, 1984, 2004, and 2007.
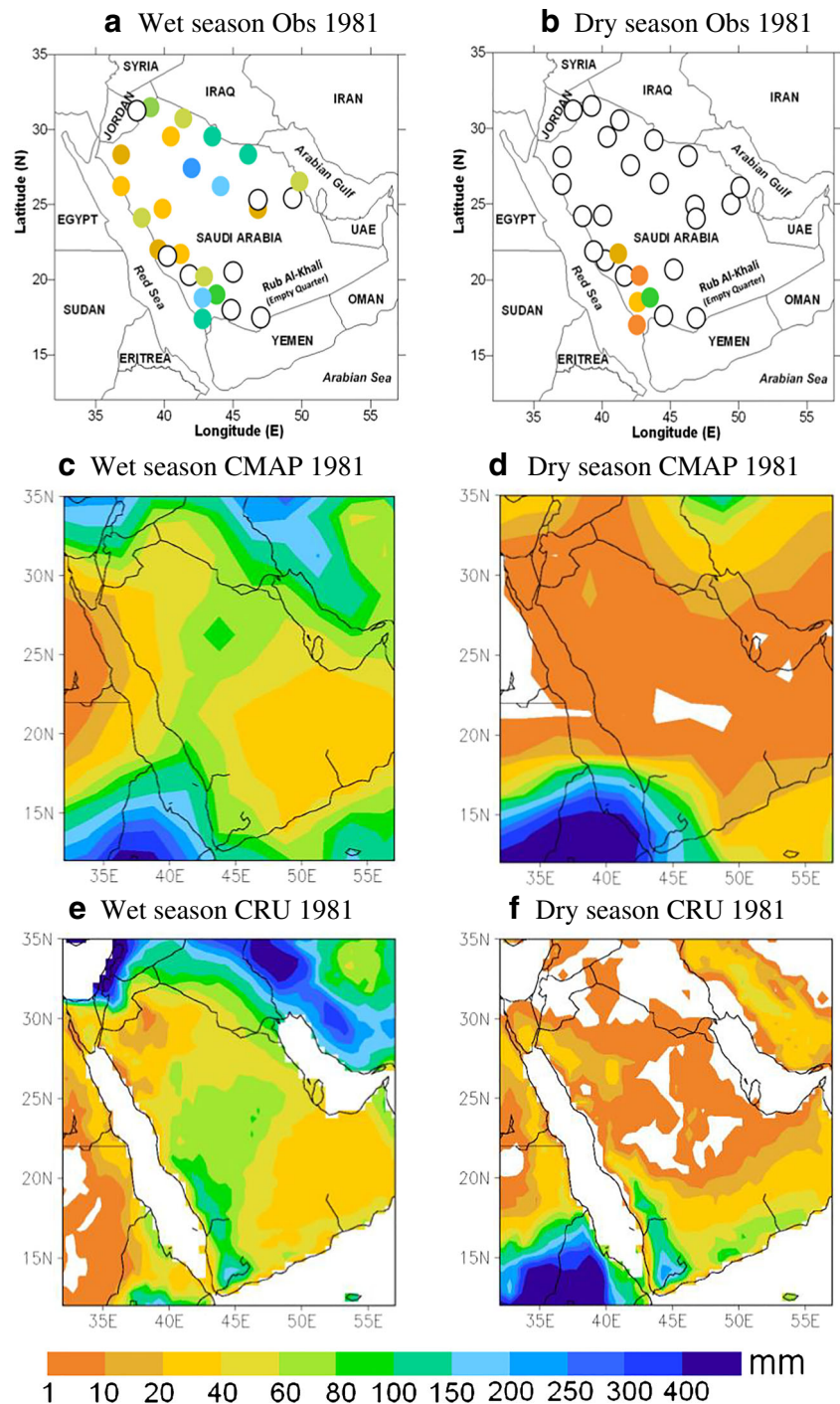
Case-1 (1981) To highlight the drought situation in the year 1981, the spatial distribution of seasonal rainfall obtained from the observed, CMAP, and CRU data is displayed in Fig. 7. The rainfall in 1981 was low in Saudi Arabia as compared to the neighboring countries of Eretria and Iran. In that year, in Saudi Arabia, the annual average rainfall was close to the lower limit of the deficit range (~ 20% below normal) and a deficit was detected in the dry season (see Fig. 4). In the wet season, the CMAP and CRU data show large rainfall amounts in the southwest and central to northern regions compared to the normal year of 1999 (see Fig. 5). The observational data show a very similar distribution to that obtained from the CMAP and CRU data. Therefore, due to the wet season rainfall distribution, 1981 cannot be identified as a drought year. The dry season rainfall distribution obtained from observations shows less rainfall in the southwest region of the country in 1981. A similar result is obtained from CMAP and CRU data. In this year, severe drought occurs for 7 months (see Fig. 6). Hence, it is concluded that the lack of dry season rainfall in the southwest region in 1981 is

Fig. 6 Time sequences of drought frequency (in months) under different classes in Saudi Arabia for the period 1978–2017. Then, usual ($\geq$ 25% below normal), moderate ($\geq$ 26 and < 50% below normal), and severe ($\geq$ 50% below normal) droughts are used to identify drought class over the country
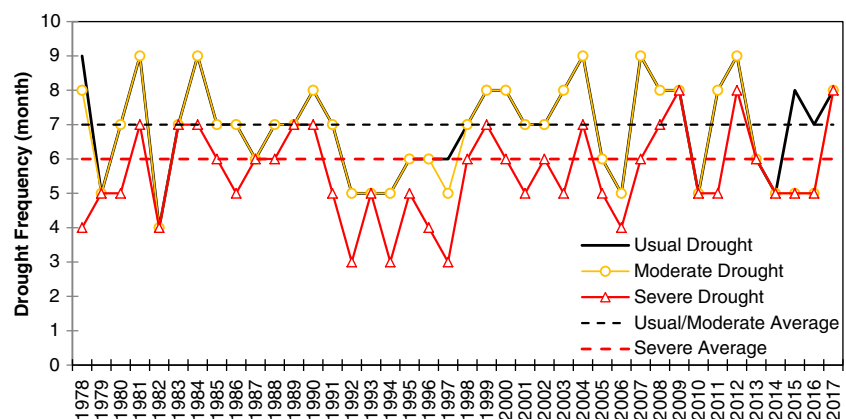
Fig. 7 The wet (left panels) and dry (right panels) season rainfalls obtained from the observed (top panels) CMAP (2nd row), and CRU (bottom panels) datasets for the year 1981. Rainfall amount below 1 mm is not shown in the legend


a Wet season Obs 1981

b Dry season Obs 1981

c Wet season CMAP 1981

d Dry season CMAP 1981

e Wet season CRU 1981

f Dry season CRU 1981

responsible for the meteorological drought that year over Saudi Arabia. This is consistent with the deficit rainfall discussed earlier (see Fig. 4c).

Case-2 (1984) As discussed above, the annual rainfall for 1984 is classed as in deficit, even though both wet and dry seasons were close to the scanty classification (Fig. 4). Therefore, to highlight the drought situation during 1984, the spatial distribution of seasonal rainfall obtained from the observed, CMAP,

and CRU data is shown in Fig. 8. In 1984, the wet season rainfall over Iran and both the wet and dry season rainfalls over Eretria are much higher than over Saudi Arabia. In this year, the annual average rainfall in Saudi Arabia is within the deficit range (~ 20% below normal) and a deficit is detected in the wet season (see Fig. 4). Figure 8 a shows clear evidence of a lack of wet season rainfall in the observed data for 1984. In the wet season, the CMAP and CRU data both show small rainfall amounts in the southwest and central-to-northern regions
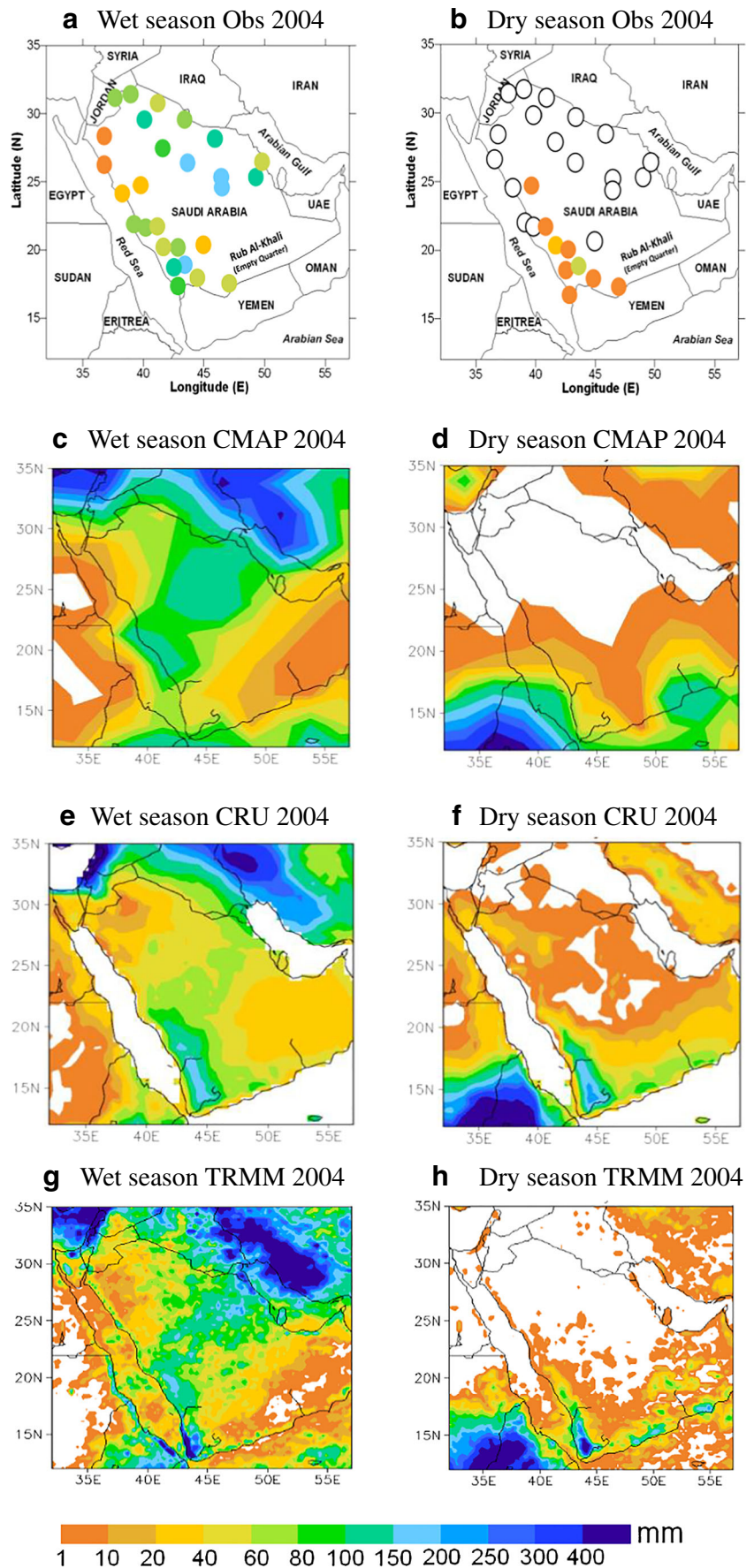
Fig. 8 The wet (left panels) and dry (right panels) season rainfalls obtained from the observed (top panels), CMAP (2nd row), and CRU (bottom panels) datasets for the year 1984. Rainfall amount below 1 mm is not shown in the legend
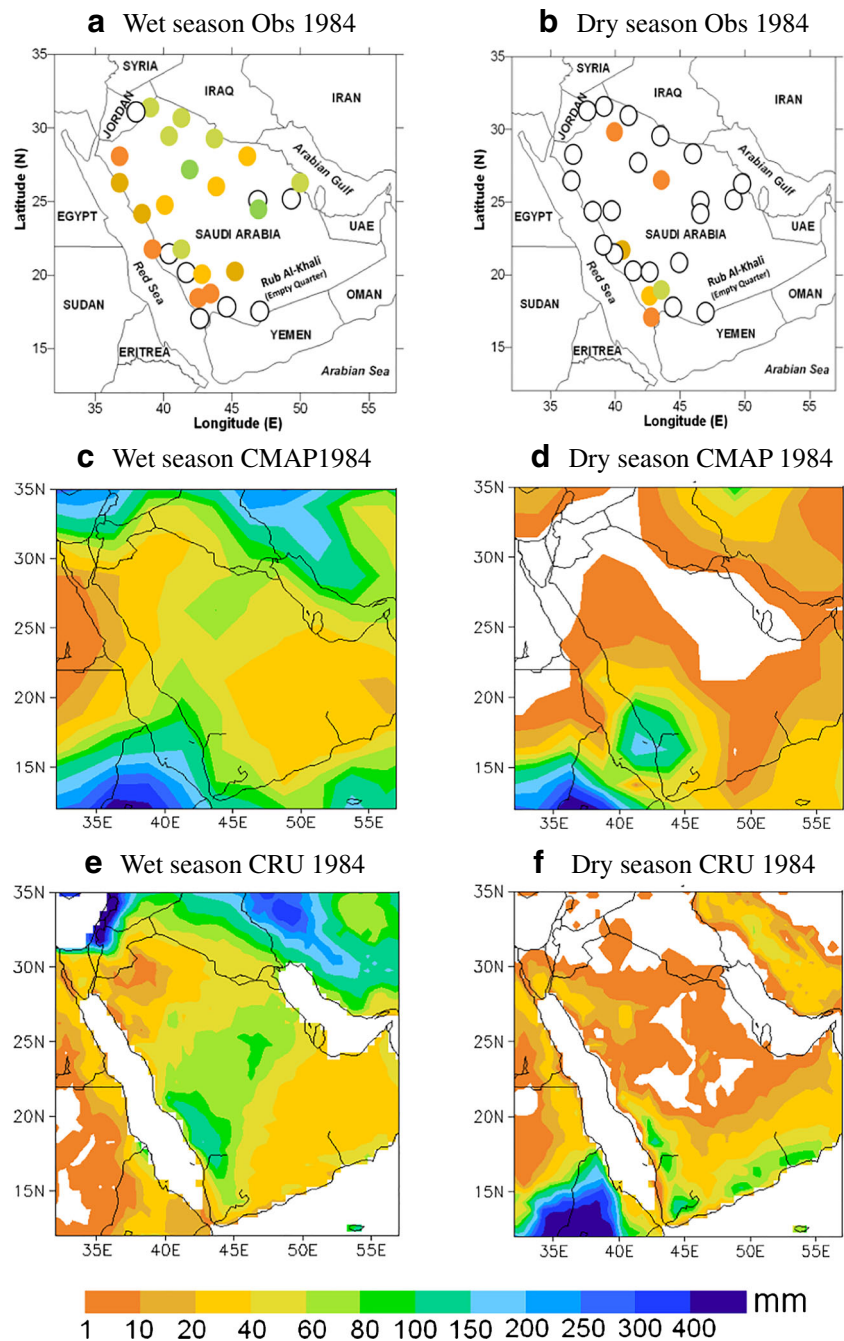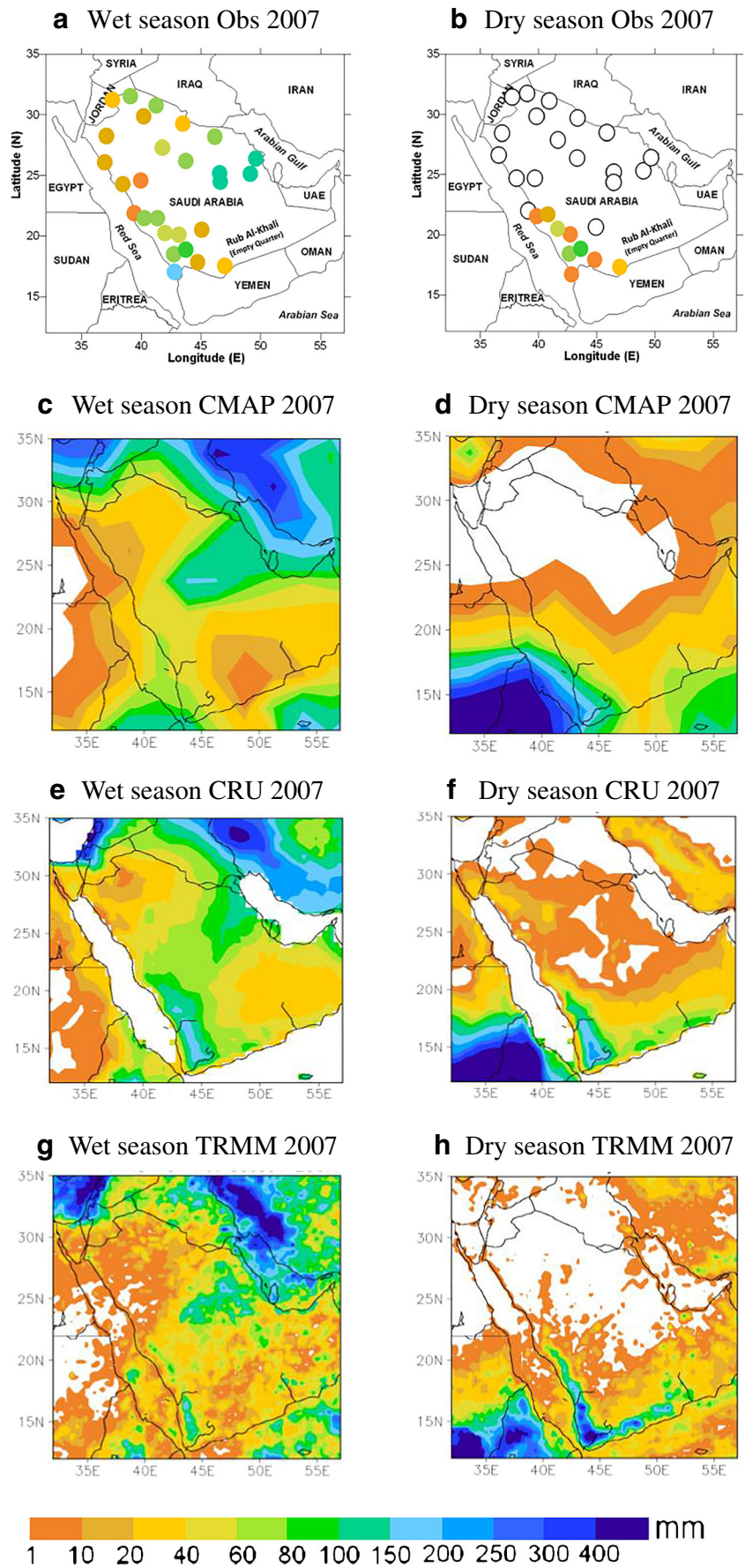
compared to the normal year, 1999 (see Fig. 5). The coarse resolution CMAP data cannot detect this very well, but the relatively high-resolution CRU clearly captures the lack of wet season rainfall for 1984 in the data. Analysis of dry season gridded rainfall data shows a very similar distribution to observations in 1984 (Fig. 8b). The CMAP data show larger rainfall amounts in the southwest region, and the CRU data shows very similar totals to CMAP. Severe drought occurs for 7 months during this year (see Fig. 6). Therefore, it is concluded that the 1984 drought over Saudi Arabia was due to a lack of wet season rainfall as discussed earlier (see Fig. 4b).

Case-3 (2004) As discussed above, the time series obtained from the observed data identified 2004 as falling in the usual category of rainfall for the wet season and the scanty category for the dry season (see Fig. 4). Figure 9 displays the wet and dry season rainfall obtained from the observed, CMAP, CRU, and TRMM datasets for 2004. The highest rainfall in 2004 is observed to the northeast in the wet season and to the southwest in the dry season while very little rain falls over Saudi Arabia. The observed data shows that the wet season rainfall in 2004 is close to average. The TRMM dataset shows rainfall all over the country. The dry season rainfall in 2004 was very

Fig. 9 The wet (left panels) and dry (right panels) season rainfalls obtained from the observed (top panels), CMAP (2nd row), and CRU (bottom panels) datasets for the year 2004. Rainfall amount below 1 mm is not shown in the legend

Fig. 10 The wet (left panels) and dry (right panels) season rainfalls obtained from the observed (top panels), CMAP (2nd row), and CRU (bottom panels) datasets for the year 2007. Rainfall amount below 1 mm is not shown in the legend

a Wet season Obs 2007

b Dry season Obs 2007

c Wet season CMAP 2007

d Dry season CMAP 2007

e Wet season CRU 2007

f Dry season CRU 2007

g Wet season TRMM 2007

h Dry season TRMM 2007

Table 2 Rainfall classes in Saudi Arabia obtained from 27 stations for 40 years (1978–2017). In this tabulation, total station locations are counted 1080 (27 × 40) individual stations

	Annual	Wet season	Dry season
Below normal	606	636	833
Above normal	418	388	191
Total	1024	1024	1024
Usual	221	208	63
Deficit	298	288	80
Scanty	174	223	721
Surplus	331	305	160
Total	1024	1024	1024
Missing stations	56	56	56
Total stations	1080	1080	1080

low all over Saudi Arabia, as determined from all the data sources. In the dry season, the CMAP and TRMM data show low rainfall amounts in the southwest region compared to the normal year of 1999 (see Fig. 5). This is consistent with the scanty classification identified for 2004 from the time series analysis (see Fig. 4c). In this year, severe drought occurs for 7 months (see Fig. 6). So, it is evident that the lack of dry season rainfall is responsible for the drought situation in 2004 over the country.

Case-4 (2007) The time series analysis identified a deficit of rainfall in 2007, 2008, and 2009 at the annual scale (see Fig. 4a). However, 2007 was identified as usual during the wet and dry seasons (see Fig. 4b, c). The spatial distribution of seasonal rainfall obtained from all data sources used is shown in Fig.

10. The distribution of rainfall in 2007 shows a common phenomenon that rainfall over Saudi Ara is lower than over neighboring Iran and Eretria. The wet season rainfall obtained from the observed data shows average rainfall over the country for 2007. Similar results were obtained from the CMAP and TRMM datasets. Both the datasets agree on average rainfall in 2007, as discussed above (see Fig. 4b, c). The dry season rainfall distribution obtained from the observed data shows almost no rain over the country except for small patches in the southwest area in 2007 (Fig. 10b). In this season, the northern regions are completely dry. In the southwestern regions, there was also very little rain in the dry season except for only two stations. The CMAP, CRU, and TRMM data are in agreement with this condition over the country. In this year, severe drought occurs for 6 months (see Fig. 6). Therefore, the lack of rainfall during the dry season is the cause of drought in 2007 over Saudi Arabia.

Discussion

Analysis of these four cases showed that drought events over Saudi Arabia occur mostly due to a deficit of rainfall in the dry season. All rainfall categories in Saudi Arabia, at annual and seasonal scales for 1978–2017, are summarized in Table 2 taking into account the distribution of the 27 stations over 40 years, i.e., 1080 (= 27 × 40) individual station points. At the annual scale, there are the 298 (29%) of station points in deficit and 331 (32%) in surplus. The usual rainfall category was obtained for a relatively small number of station points (221 = 22%), whereas the scanty category was found only for 174 (17%) station points. During both wet and dry seasons,

Fig. 11 Annual cycle of drought frequency (in year) associated to different classes obtained based on rainfall threshold in Saudi Arabia for 40 years analysis period (1978–2017)
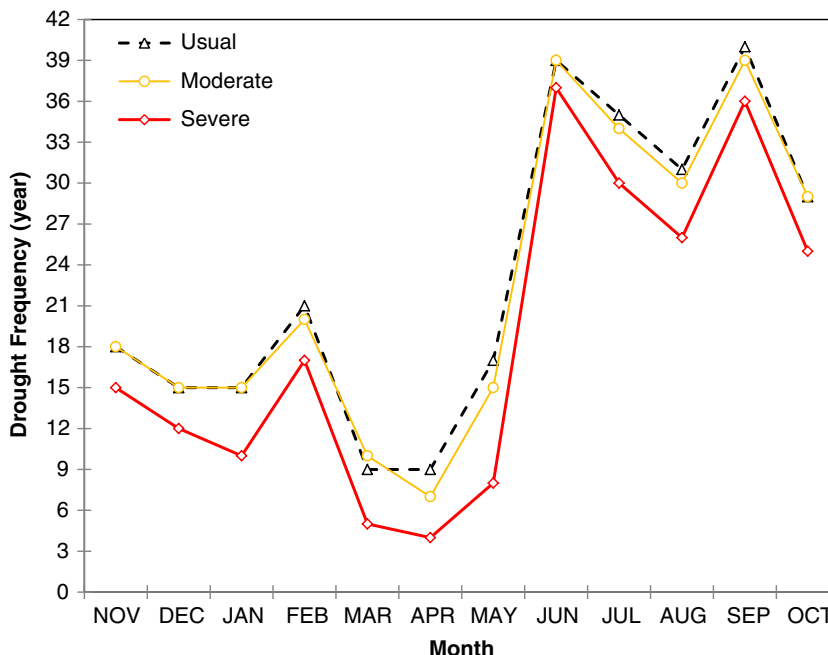
Table 3 Summary of the four cases of meteorological drought years in Saudi Arabia analyzed during 1978–2017

Case	Drought year	Season	Region	Remark
1	1981	Dry	Southwest	Dry season rainfall causes drought
2	1984	Wet	Southwest	Wet season rainfall causes drought
3	2004	Dry	Southwest	Dry season rainfall causes drought
4	2007	Dry	Country	Dry season rainfall causes drought

the number of stations below normal rainfall increased and those with above normal decreased greatly. In the dry season, the scanty category applied to the highest number (721 = 70%) of station points, while in the wet season, a surplus was found at the highest number (305 = 30%) of station points. This implies that in Saudi Arabia, drought mainly occurred due to a shortfall in the dry season, and surpluses were due to heavy rainfall in the wet season.

The annual cycle of drought frequency associated with different drought categories in Saudi Arabia is displayed in Fig. 11. Both the usual and moderate categories show the same number of drought years for all months, except that the moderate category has 2 years less for April, the last month of the wet season. The severe category also follows the patterns of usual and moderate droughts. November, the beginning of the wet season, shows a decreasing trend in, the number of drought years in all categories. Next in rank is April, the end of the wet season. February is an exception, being ranked higher than both in January and March. After the transition month of May, the number of drought years sharply increased for all categories in June, the beginning of the dry season. In June, both usual and moderate drought categories occurred in 39 years (98%), while the severe category occurred in 37 years (93%), out of 40. In July and August, the number of drought years slightly declined, although at the end of the dry season, the usual category reached the maximum number of 40 years (100%), while severe also reached 90%. The tendency in the transition month of October is towards a reduction in all categories. Overall, lower rainfall during the dry season is seen to

be responsible for drought conditions in Saudi Arabia, supporting the previous conclusion. Results show that for the last months of the wet season, April is less prone, while the first and last months of the dry season (June and September) are more prone to drought.

The cause of meteorological drought over Saudi Arabia analyzed for four cases between 1978 and 2017 is summarized in Table 3. Of the four cases analyzed, the drought situation in three of them is due to dry season shortfall while wet season shortfall is responsible for the fourth. The combination of shortfalls in both wet and dry seasons is not found in any of the four cases studies. Hence, it is concluded that the rainfall time series obtained from the station observation accurately represents the meteorological drought conditions over Saudi Arabia and these conclusions are supported by the CMAP, CRU, and TRMM datasets.

In order to demonstrate the drought situation in Saudi Arabia, commonly used drought indices such as SPI and PDSI are calculated from observations at 27 station locations across Saudi Arabia (Fig. 12). More information about the drought indices may be seen in some literaures, for instance Dash et al. (2012), Gidey et al. (2018a, b), and Mustafa and Rahman (2018). The spatial distributions of SPI- and PDSI-based drought indices show that drought is pervasive in the southern and northeast regions of Saudi Arabia. However, the situation may change in the future because climate model simulations show a likely increase in precipitation over the south and southeast and a decrease in the northwest of the Peninsula in the projection period (Almazroui et al. 2017b,
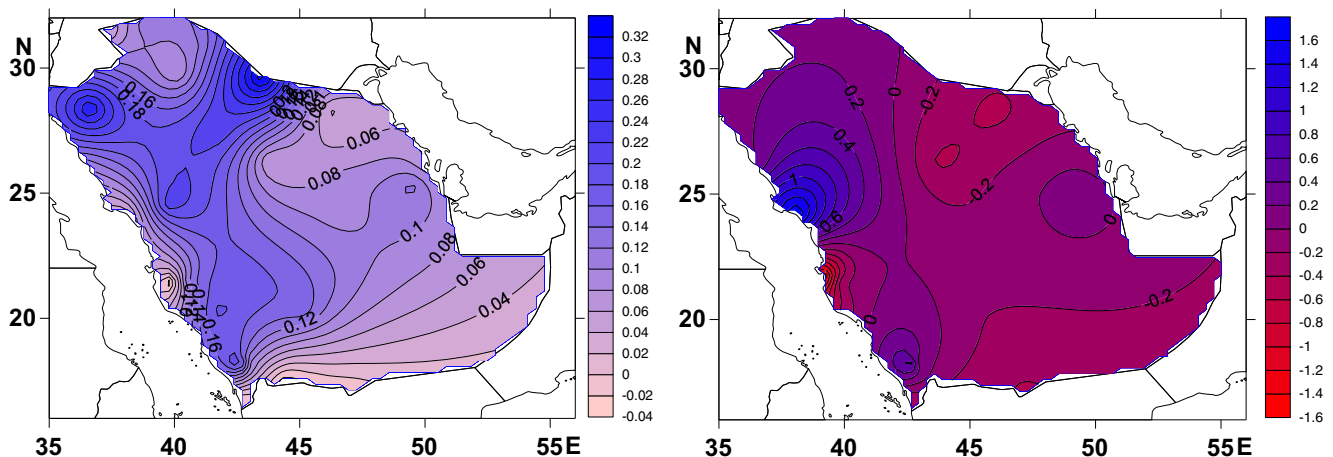
Fig. 12 Spatial distributions of drought indices SPI (left panel) and PDSI (right panel) obtained from observed data

c). The results of the current study may not apply because detailed analyses for mild drought, moderate drought, severe drought, and extreme drought were not performed here. Also to better understand and project the drought situation in Saudi Arabia, it is suggested that drought indices be calculated using climate model output, for example, with Saudi-KAU GCM data (Almazroui et al. 2017a; Ehsan et al. 2017). So far, the use of climate model data in calculating drought indices has been a challenging task because of the limitations of climate simulations. Therefore, the utility of climate model output, along with some validation work, will be presented in a separate document.

Conclusions

The purpose of this paper is to identify drought conditions for Saudi Arabia using observed data for the present climate (1978–2017). Rainfall data is helpful for understanding meteorological drought phenomena and their characteristics in the region. Using rainfall thresholds, the categories of deficit, scanty, and surplus were applied to data at both annual and seasonal scales. Based on monthly data of rainfall thresholds, the drought categories of usual, moderate, and severe were identified. Results show that for the 40-year analysis period, annual rainfall was below normal for 25 years, of which 10 years show deficit rainfall at the annual scale. The wet season experienced 7 deficit and 3 scanty years while the dry season had 15 deficit and 4 scanty years. Usual and moderate droughts occur for almost same number of months in a year. Patterns of the monthly distribution of severe drought cases follow almost the same distribution pattern as usual/moderate droughts. Four drought cases (1981, 1984, 2004 and 2007) within the country are discussed in detail. Of the four, three were due to a deficit in rainfall in the dry season. A combined shortfall in both wet and dry seasons causing drought phenomena was not found. Considering the distribution of 27 stations over 40 years ($1080 = 27 \times 40$) individual station points), we found that the dry season is responsible for the scanty category and the wet season for the surpluses throughout the country. All of the drought categories in Saudi Arabia occurred mostly during the dry season, with fewer during the wet season. The drought index calculations show the current pattern of drought over the region. The next step is to obtain drought indices for the near future (e.g., 2021–2050) and far future (2071–2100) using climate model simulations, and this will be documented in a separate paper.

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