



# Coupled Model Inter-comparison Project Database to Calculate Drought Indices for Saudi Arabia: A Preliminary Assessment

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## Abstract

The objective of this paper is to present how the Coupled Model Inter-comparison Project phase 3 (CMIP3) multi-model datasets might be used to calculate drought indices for Saudi Arabia. Widely used drought indices such as the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI) are constructed and analyzed using observed rainfall from 27 stations as well as data from best performing CMIP3 models along with other variables for the present climate. Of the 22 CMIP3 models, the Canadian (CC: CCCMA-CGCM3.1) and the Australian (CS: CSIRO-Mk3.0) models were used in estimating the annual rainfall over Saudi Arabia while the German/Korean (MI: MIUB-ECHO-G) and the Japanese (MM: MIROC3.2 and MR: MRI-CGCM2.3.2) models were used in estimating the annual temperature. Results show that the CS model is superior to the other 21 CMIP3 models in calculating both SPI and PDSI. As for drought indices, PDSI (76% and 65% for CS and CC, respectively) performs well in assessing the spatial distribution of drought conditions as well as in determining the number of events (63% and 26% for CS and CC, respectively) within the different drought categories when compared to observations. Therefore, further use of PDSI is recommended for drought diagnosis in future climate for the disaster management purposes for Saudi Arabia, however, the use of the latest climate models datasets e.g. AR5 or AR6 may need further investigation.

**Keywords** Drought · Drought indices · Saudi Arabia · CMIP3 multi-models

## 1 Introduction

Large-scale droughts are acknowledged to be the most important cause of global natural disasters. Although floods and other natural phenomena occurring over a shorter time-scale can also be catastrophic, the overall impact of large-scale droughts is far more disastrous (Bhalme and Mooley 1980). Drought impacts are particularly severe in arid and semi-arid regions across the world including the Arabian Peninsula and Saudi Arabia which contains the world's largest continuous sand desert, the Rub Al-Khali (Almazroui et al. 2012a, b). Drought has significant negative impacts on agriculture, food production and storage, infrastructure, power generation, society and the environment. Altogether, knowledge of drought is important in disaster management.

In Saudi Arabia, although there is some reliance on agriculture in the southern and eastern states, water resources are scarce in the other parts of the country. A wise strategy of the management, storage, and usage of water resources is, therefore, extremely important for the country. In addition, demand for and production of electricity is an issue of immense concern for Saudi Arabia, particularly during the summer because of its dry climate and natural extreme temperature.

Since the beginning of the twentieth century, warming of the global climate has been observed and unequivocally confirmed by the Intergovernmental Panel for Climate Change (IPCC) (IPCC 2007, 2013). Over the last 100 years, it has been observed that the global surface temperature has increased by  $0.6 \pm 0.2$  °C and that the rising trend became undeniably apparent after the 1980s when compared to the base-period 1961–1990. Studies also report that rainfall has likely decreased by about 0.3% per decade over much of the subtropical (10°N–30°N) land areas of the northern hemisphere during the twentieth century (IPCC 2001). The significant increase in temperature and decrease in rainfall

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of recent times is observed in the local climate of Saudi Arabia as reported by Almazroui et al. (2012a, b). Rainfall first increased insignificantly in the period 1979–1993, and then significantly decreased in the second period, 1994–2009. Rainfall decreased at a rate of 35.1 mm (5.5 mm) per decade during the wet (dry) season (Almazroui et al. 2012b). The maximum, mean and minimum temperatures have increased significantly by 0.71, 0.60, and 0.48 °C per decade, respectively (Almazroui et al. 2012a). These data suggest that Saudi Arabia is facing drier conditions that could result in prolonged drought. In this context, the study of drought diagnosis is essential for the policymakers and stakeholders of the country. In Saudi Arabia, the network of surface observations is of low density and observations are unavailable for remote places such as over the Rub Al-Khali desert. Furthermore, surface observations are limited in their ability to predict beyond real time and this implies the necessity to include climate model data in the study of drought over the country.

General Circulation Models (GCMs) and Regional Climate Models (RCMs) are increasingly used in many meteorological and climate research centres across the world to study climate variability. Because of the high levels of complexity of the climate system, climate models (GCMs and RCMs) are the tools available to scientists to simulate the behavior of the climate system besides Earth System Dynamics and Earth Systems modelling, and to study, in particular, past and future drought patterns (Gao and Giorgi 2008; Blenkinsop and Fowler 2007; Mpelasoka et al. 2008; Busby et al. 2007). There are also hydrological models in studying drought phenomena in a region. More than 18 coupled GCMs have been made available by the Program for Climate Model Diagnosis and Inter-comparison for the fourth IPCC Assessment Report (AR4) (Cook and Vizy 2006). In the past decade, CMIP3 models constitute the latest technology in climate science and are used by numerous scientists to study changes in climate and in precipitation and drought (Cook and Vizy 2006; Shongwe et al. 2009, 2010). However, later on, Coupled Model Inter-comparison Project phase 5 (CMIP5) dataset are available to the scientists to analyze and the Coupled Model Inter-comparison Project phase 6 (CMIP6) data are on the way to publish by 2022. To date, there have very limited attempts to apply climate model outputs to the assessment of drought scenarios due to recent and likely-to-continue warming and climate change over Saudi Arabia.

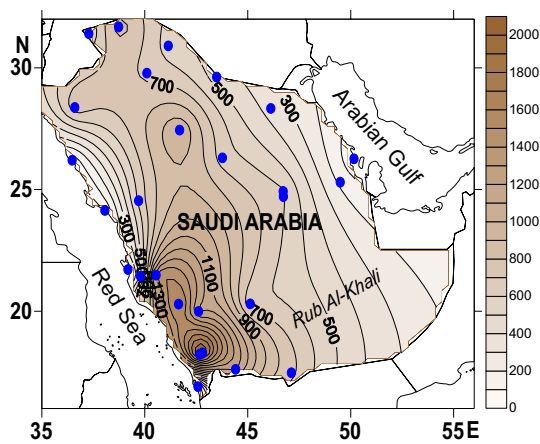
Surface temperature and rainfall are among the meteorological variables used to study the spatio-temporal characteristics of droughts. Meteorological drought can be deduced from rainfall data. However, rainfall information alone is sometimes not enough to define drought for a region. In this context, various indices are used to characterize droughts using various climate variables including rainfall. Although

none of the major indices is inherently superior to the others in all circumstances, some indices are better suited for certain uses. One of the earliest drought indices, the Palmer Drought Severity Index (PDSI; Palmer 1965) has been used in various places, particularly in the United States. PDSI is associated with a prolonged and substantial deficiency in moisture (Karl 1983). The USA National Drought Mitigation Center uses the Standardized Precipitation Index (SPI, McKee et al. 1993) to monitor moisture supply conditions. The SPI is a widely used drought index based on the probability of precipitation over multiple time scales. Several studies have demonstrated (McKee et al. 1995; Guttman 1998; Hayes et al. 1999) that the SPI is a good tool for detecting and monitoring drought events. A comprehensive study (Lloyd-Hughes and Saunders 2002) proves that the SPI value is as efficient at characterizing drought phenomena as the PSDI index, which requires many more parameters.

As previously mentioned, the role of climate models in the study of drought is irreplaceable since they constitute the tool that can simulate present and future climate. The World Climate Research Programme's Coupled Model Inter-comparison Project (WCRP's CMIP) multi-model simulations have been made available to the climate community to support understanding of past climates and to investigate future climate change. There is no one particular model able to represent the exact climatology of a region and which can be used to calculate drought indices, for example in Saudi Arabia. Therefore, in the current study, the WCRP's CMIP phase 3 (CMIP3) best performing model(s) data are used in the calculation of drought indices for the present climate (1978–2000). This study is the first step and the success of this study is encouraging for the application of WCRP's CMIP phase 5 (CMIP5) multi-model datasets in subsequent studies.

## 2 Data and Methodology

In this study, we are interested in determining meteorological drought through the calculation of SPI and PDSI from the selected CMIP3 multi-model outputs. Climate parameters such as rainfall, temperature and evaporation are required in the calculation of the drought indices mentioned above. Here, surface observations collected by the Presidency of Meteorology and Environment (hereafter referred to as observed) over the period 1978–2000 for 27 stations (Fig. 1) are utilized. This work uses data from 22 models for the past climate available from the WCRP's CMIP3 multi-models (Table 1). To achieve homogeneity of datasets, this study used re-gridded  $1^\circ \times 1^\circ$  products of the datasets of all 22 models.



**Fig. 1** The map of Saudi Arabia with elevation (m). The observation sites across Saudi Arabia are shown with filled circle marks

The location of the ground observation sites across Saudi Arabia, along with the topography is shown in Fig. 1. The observed data currently available for Saudi Arabia is mainly from stations along the coasts, the north and the central areas of the country. There are no station data available from the

southeastern region mainly over the Rub Al-Khali. Climatic conditions, particularly rainfall and temperature in the arid environment, are governed by the topography (Lioubimtseva 2004). In Saudi Arabia, a north–south oriented mountain range with heights reaching 2000 m or above is located on the southwestern side of the country. The peaks slope downward to the eastern and northern sides of the country. This mountain range plays an important role in the rainfall mechanism of the region and in temperature variations.

Of the available drought indices, the current study took the widely used SPI (Moldovan et al. 2002) and PDSI (Palmer 1965) into consideration. The SPI is a well-known measurement method to characterize the severity of drought and lack of moisture at different time scales (3-month, 6-month, and 12-month). Mathematically, the SPI is based on the cumulative probability of a given rainfall event occurring at a station (Edwards and McKee 1997).

The SPI is defined for various timescales as the difference between monthly precipitation ( $x_i$ ) and the mean value ( $\bar{x}$ ), divided by the standard deviation ( $s$ ) of the values followed by Gamma distribution:

$$SPI = \frac{x_i - \bar{x}}{s}, \tag{1}$$

**Table 1** CMIP3 multi-models used for the drought indices analyses

Model index	Model ID	Country of origin	Acronym used	Atmospheric resolution	References
1	MRI-CGCM2.3.2	Japan	MR	2.8°×2.8°	Yukimoto et al. (2001)
2	ECHAM5/MPI-OM	Germany	EC	1.9°×1.9°	Jungclaus et al. (2006)
3	BCC-CM1	China	BC	1.9°×1.9°	Dong (2001)
4	CCCMA-CGCM3.1(T47)	Canada	CC	2.8°×2.8°	Flato et al. (2000)
5	CSIRO-Mk3.0	Australia	CS	1.9°×1.9°	Gordon et al. (2002)
6	MIROC3.2(hires)	Japan	MH	1.1°×1.1°	Hasumi and Emori (2004)
7	MIROC3.2(medres)	Japan	MM	2.8°×2.8°	Hasumi and Emori (2004)
8	GFDL-CM2.1	USA	G1	2.0°×2.5°	Delworth et al. (2006)
9	GFDL-CM2.0	USA	G0	2.0°×2.5°	Delworth et al. (2006)
10	MIUB-ECHO-G	Germany/Korea	MI	3.9°×3.9°	Legutke and Voss (1999)
11	GISS-AOM	USA	GA	3°×4°	Russell et al. (1995)
12	GISS-ER	USA	GR	4°×5°	Schmidt et al. (2006)
13	GISS-EH	USA	GH	4°×5°	Schmidt et al. (2006)
14	IAP-FGOALS-g1.0	China	IF	2.8°×2.8°	Yu et al. (2004)
15	UKMO-HadGEM1	UK	HG	1.3°×1.9°	Jones et al. (2004)
16	UKMO-HadCM3	UK	HC	2.5°×3.75°	Jones et al. (2004)
17	INM-CM3.0	Russia	IN	4°×5°	Diansky and Volodin (2002)
18	BCCR-BCM2.0	Norway	BB	1.9°×1.9°	Furevik et al. (2003)
19	NCAR-CCSM3	USA	NC	1.4°×1.4°	Collins et al. (2006)
20	NCAR-PCM	USA	NP	2.8°×2.8°	Washington et al. (2000)
21	IPSL-CM4	France	IC	2.5°×3.75°	Marti et al. (2005)
22	CNRM-CM3	France	CN	1.9°×1.9°	Salas-Méliea et al. (2005)

where  $x$  is the precipitation amount variable, which is fitted to the Gamma distribution, and  $s$  is the standard deviation of the precipitation variable. It follows from Eq. (1) that SPI is dimensionless. An approximation of SPI by Abramowitz and Stegun (1965) is used in the SPI program source code.

$$Z = \text{SPI} = -\left(t - \frac{c_0 + c_0t + c_1t^2}{1 + d_1t + d_2t^2 + d_3t^3}\right) \quad \text{for } 0 < H(x) \leq 0.5, \tag{2}$$

$$Z = \text{SPI} = +\left(t - \frac{c_0 + c_0t + c_1t^2}{1 + d_1t + d_2t^2 + d_3t^3}\right) \quad \text{for } 0.5 < H(x) \leq 1, \tag{3}$$

where  $t = \sqrt{\ln\left(\frac{1}{H(x)}\right)}$  for  $0 < H(x) \leq 0.5$   
 $t = \sqrt{\ln\left(\frac{1}{(1.0-H(x))^2}\right)}$  for  $0.5 < H(x) \leq 1.0$ .

$$C_0 = 2.515517, d_1 = 0.010328$$

$$C_1 = 0.802853, d_2 = 0.189269$$

$$C_2 = 0.010328, d_3 = 0.001308$$

The drought events may be categorized using the SPI values as follows: mild drought (0 to -0.99); moderate drought (-1.00 to -1.49); severe drought (-1.50 to -1.99); and extreme drought (-2.00 and less). In this study, SPI values for 12-month runs are analyzed.

The PDSI was developed by Palmer in the 1960s and uses information on temperature and rainfall in a formula to determine dryness (Palmer 1965). According to Palmer’s scheme (Palmer 1965), the occurrence of a drought is an accumulative process, and a current PDSI value  $X_i$  for month  $i$  can be computed as a weighted (i.e., duration factors) sum of the precedent PDSI value  $X_{i-1}$ , and the current moisture anomaly  $Z_i$ , expressed as follows:

$$X_i = pX_{i-1} + qZ_i.$$

The  $p$  and  $q$  can be calculated following Liu et al. (2017).

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). To calculate PDSI, evaporation is required, which is not available from the surface observations for the present study. In these circumstances, proxy data from a regional climate model is used to represent evaporation at each observation site. For simplicity and because of the scarcity of observed data in Saudi Arabia, this study calculates SPI and PDSI from 1978 to 2000 from the observed and CMIP3 selected best models’ datasets.

### 3 Results and Discussion

#### 3.1 Best Performing CMIP3 Models

Before applying CMIP3 datasets to the calculation of drought indices, the selection of suitable models is

necessary because different climate models will yield different results on the simulation of rainfall and temperature in Saudi Arabia that is then used to analyze the drought behaviour. The main reason for assessing all the CMIP3 models is to reduce uncertainties and identify suitable models for the region. Moreover, we had no prior knowledge of which model would perform better for this region of the world although some models perform better than others in simulating the present climate. In addition, all these models are used by the IPCC for its Fourth Assessment Report (AR4) in 2007. The final reason is that a much larger model-based ensemble database is created using all these models.

Monthly rainfall is essential for the calculation of drought indices for a particular location or region. For this purpose, monthly rainfall obtained from CMIP3 models are used along with the observed data collected across Saudi Arabia. The annual cycle of monthly rainfall obtained from all 22 CMIP3 models compared with the surface observations is available in Almazroui et al. (2017a). It is observed that many models largely overestimate rainfall in the dry season (June–September) and most of them underestimate rainfall during the wet season (November–April). Results indicated that ensemble of two models (CC and CS) show the best performance when compared to the observed data. In this study, these two models (CC and CS) were finally selected as the best models among the CMIP3 models for use in estimation of rainfall and to calculate drought indices.

Temperature is another climate parameter used in the calculation of certain drought indices such as PDSI. The annual temperature cycle obtained from all 22 CMIP3 models compared to observations is available in Almazroui et al. (2017a). Results showed that the three-model (MI, MM and MR) ensemble is closer to the observations. In this study, these 3 models (MI, MM and MR) were selected as the best among the CMIP3 models for the estimation of temperature for use in the calculation of drought indices.

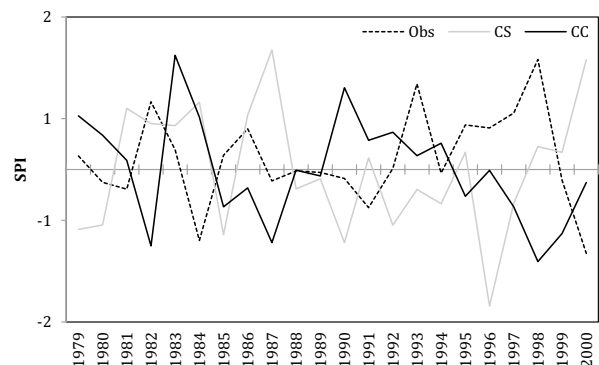


Fig. 2 SPI calculated from the observed and CMIP3 best models (CC and CS) data. SPI is obtained from rainfall at 27 stations across Saudi Arabia

### 3.2 Drought Indices from Observations and Data from the Best CMIP3 Models

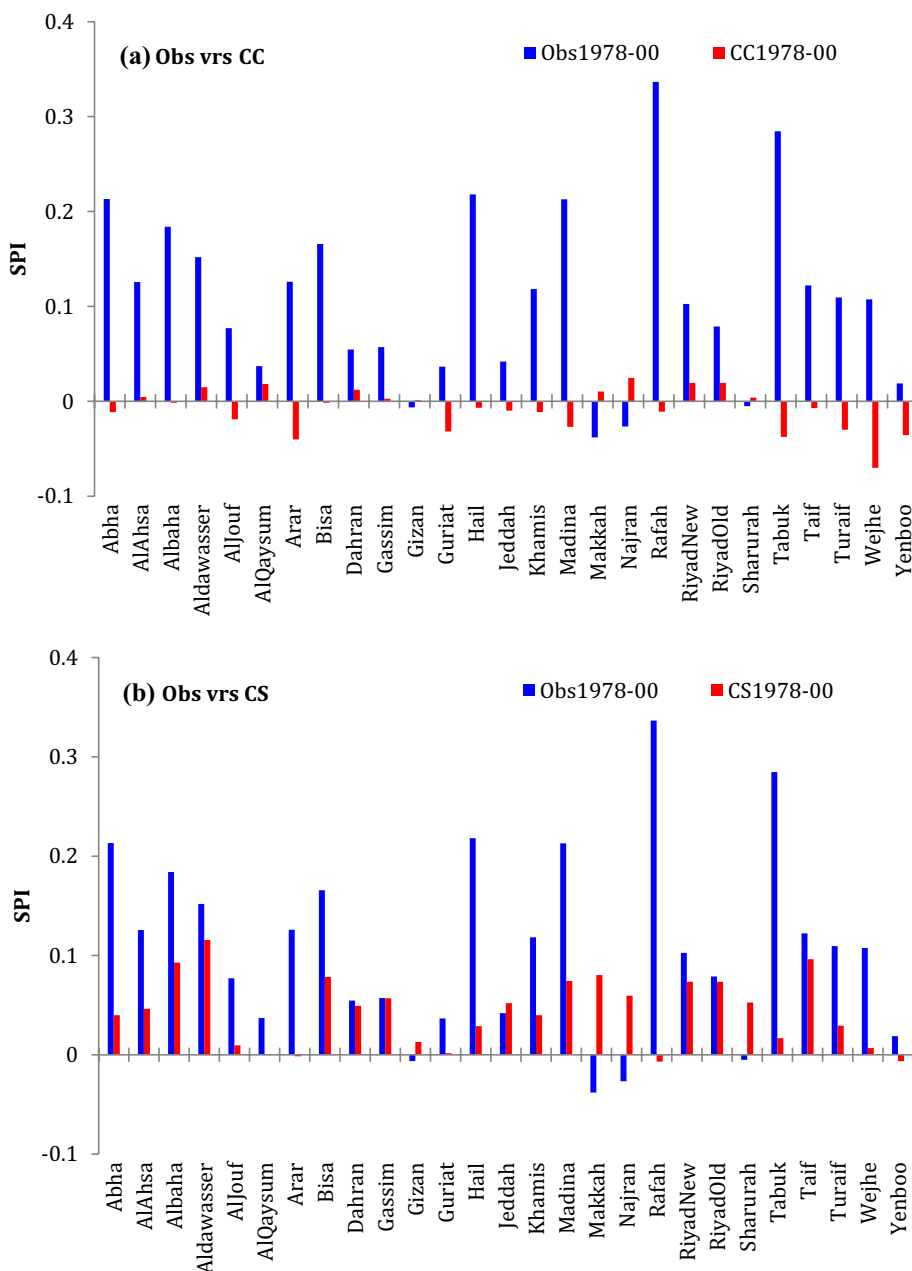
The drought indices such as SPI and PDSI are obtained from observations and data from the best CMIP3 models (CC and CS) as discussed here. Note that model temperature is the average of the best three models.

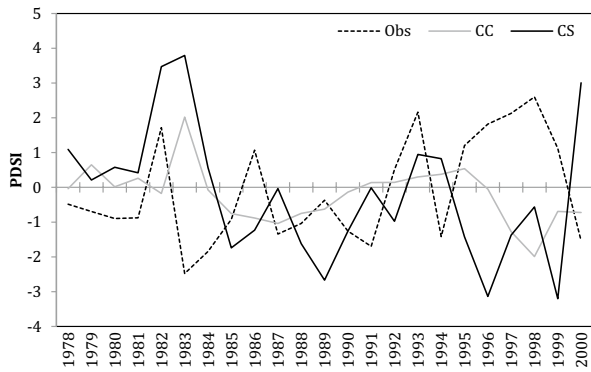
The SPI time sequences calculated from the CMIP3 best models and observations are shown in Fig. 2. The national average of rainfall is generated from all stations using a simple arithmetic average before calculating SPI. SPI patterns obtained from CMIP3 best models match with observations for only 36% of events. Both CC and CS data show some differences in capturing drought events over

Saudi Arabia. For greater transparency, the SPIs obtained from the two data sources at each station site are displayed in Fig. 3. Careful inspection shows that for 63% (26%) of stations the SPI, for CS (CC) are in line with observations. This suggests that among the selected models, CS is best at calculating the SPI for Saudi Arabia, at least in our analysis.

The PDSI time sequences obtained from observations, and from CC and CS for the period 1978–2000, are shown in Fig. 4. Country-average rainfall and temperature generated from a simple average of all stations are used in the calculation of PDSI. Of the 23 years analyzed, 14 drought years (1978, 1979, 1980, 1981, 1983, 1984, 1985, 1987, 1988, 1989, 1990, 1991, 1994 and 2000) were identified as such

**Fig. 3** Comparison of SPI for different stations obtained from observed and CMIP3 models data



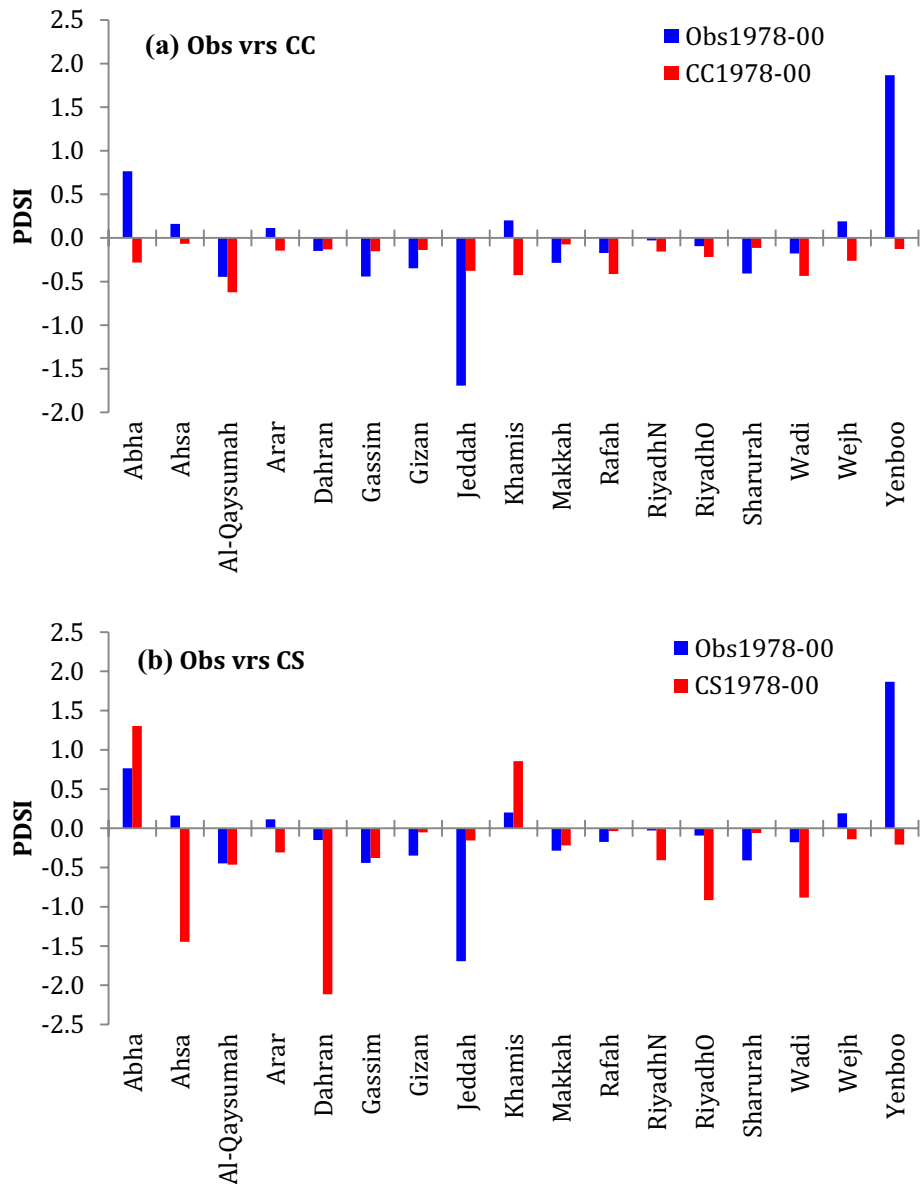


**Fig. 4** PDSI calculated from the observed and CMIP3 best models (CC and CS) data. PDSI is obtained using rainfall at 27 stations across Saudi Arabia

by observed PDSI over Saudi Arabia. There are some agreements as well as discrepancies between the observed PDSI and the PDSI obtained from the best CMIP3 models. Of the 23 years, the CC matches 11 (48%) of these years (1978, 1984, 1985, 1987, 1988, 1989, 1990, 1992, 1993, 1995 and 2000) with the observed PDSI. On the other hand, the CS matches 8 (35%) of these years (1982, 1985, 1987, 1988, 1989, 1990, 1991 and 1993) with observed PDSI.

To better understand the utility to obtain drought characteristics using CMIP3 data, PDSI is examined at individual stations using both observations and best models (Fig. 5). For many stations both CC and CS are better at capturing the observed drought events. In the case of CC, the model and observed events are in phase for about 65% of the stations; however, for CS they are in phase for about 76% of the stations. This indicates that PDSI can be used to monitor

**Fig. 5** Comparison of PDSI for different stations obtained from observed and CMIP3 models data



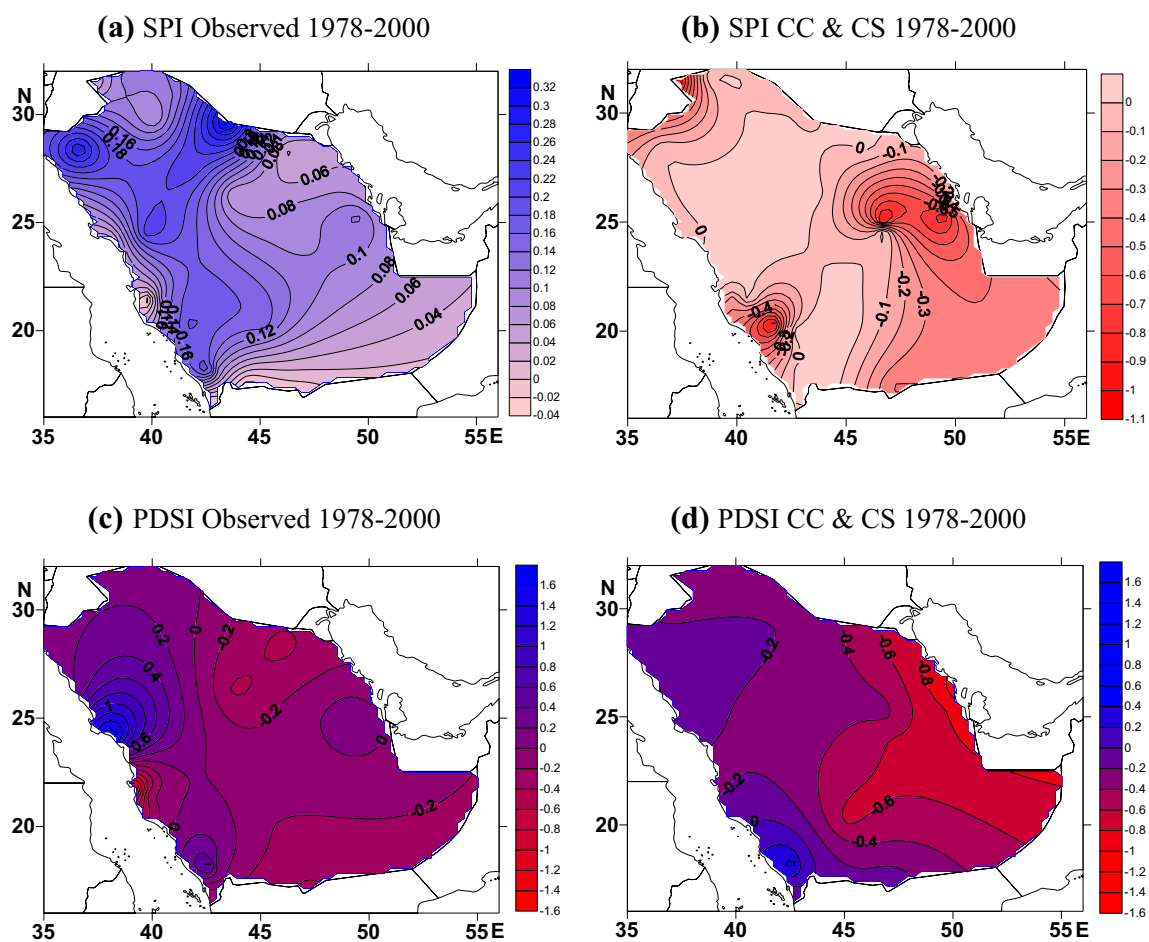


drought phenomena for Saudi Arabia and that of all the CMIP3 models, CS is the best one for the calculation of PDSI.

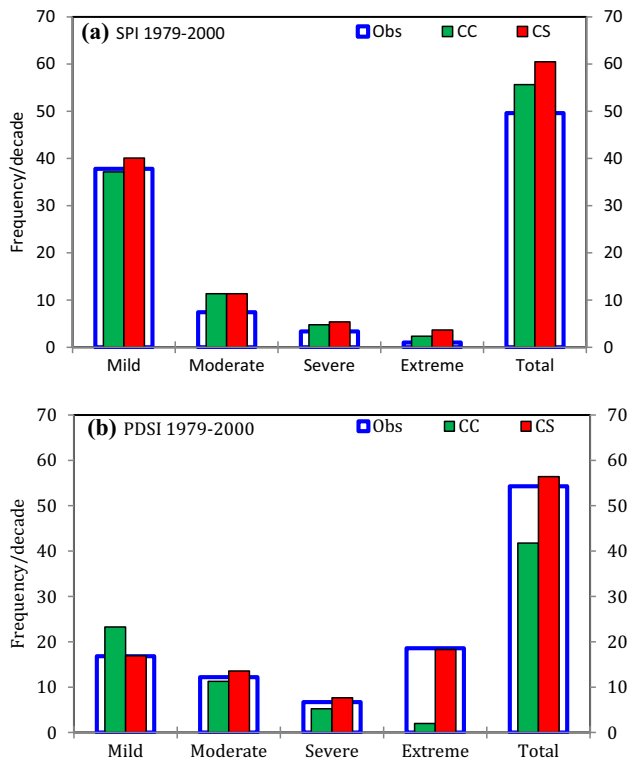
The spatial distributions of drought indices obtained from observed and averaged CMIP3 best models ensemble for the period 1978–2000 are displayed in Fig. 6. Model-based SPI shows more droughts over Saudi Arabia than observations. Drought seems severe in the southwest part which is one of the heavy rainfall region in Saudi Arabia. It is also severe in the eastern region near the Arabian Gulf. These two regions are very important for the economy of the country. In contrast, the PDSI from the two data sources show comparable results, with quite similar patterns although with different magnitudes. Model simulated PDSI also shows severe drought in the eastern side of the country. These information are valuable to understand the changes in drought condition over the country in the projection period, which has to be calculated and presented in a separate documentation.

Finally, the frequency of each drought category, obtained from observations and CMIP3 best models, is analyzed. In

the case of SPI, CS over-calculates drought frequency for all categories resulting in an overestimate in 22% of events by CMIP3 (Fig. 7a). CC overestimates drought frequencies for all categories except for mild drought where almost the same number were determined. The results from the CMIP3 overestimate total SPI events by about 12%. The PDSI shows encouraging results for the determination of drought frequency. The number of events calculated for all drought categories is very close with only 4% overestimation for total events in the case of CS (Fig. 7b). The discrepancy can be attributed to the fact that temperature and evaporation data, as well as rainfall, are used in PDSI calculation whereas for SPI, only rainfall is used to determine drought status. The CC estimate of the number of moderate and severe drought events was quite accurate, although mild events were overestimated and severe events were grossly underestimated, resulting a total underestimation of 23% for all PDSI events. It is apparent that CC and CS underestimate drought frequencies by less than 10% using PDSI. Hence, we can conclude that CS is the best of all the CMIP3 models in the



**Fig. 6** Spatial distributions of drought indices SPI (top panels) and PDSI (bottom panels) obtained from observed (left panels) and CMIP3 best models ensemble (right panels) averaged for the period 1978–2000



**Fig. 7** Drought frequency under different categories obtained for **a** SPI (12-month) and **b** PDSI averaged for the period 1978–2000

calculation of drought indices over Saudi Arabia and PDSI is found to be the more suitable of the two indices in this analysis. The usefulness of other climate models such as CMIP5 and newly developed Saudi-KAU GCM (Almazroui et al. 2017b; Ehsan et al. 2017) is under consideration for a subsequent next study.

## 4 Conclusions

Best performing model data from the 22 models in the Coupled Model Inter-comparison Project Phase 3 (CMIP3) for the period 1978–2000 are used to calculate the widely accepted drought indices, SPI and PDSI, for Saudi Arabia. Results were then compared with those obtained from the surface observations at 27 sites across the country. Of the 22 CMIP3 multi-models, the Canadian (CC: CCCMA-CGCM3.1) and the Australian (CS: CSIRO-Mk3.0) models were used as those producing the best estimates of the annual rainfall in Saudi Arabia. On the other hand, the German/Korean (MI: MIUB-ECHO-G) and the Japanese (MM: MIROC3.2 and MR: MRI-CGCM2.3.2) models were used in estimating the annual temperature for Saudi Arabia. Using these best performing models, the SPI and PDSI drought

indices are calculated for the current climate. Results show that PDSI can determine drought conditions for 76% (65%) of the stations in phase with observations for CS (CC), while SPI identified 63% (26%) of stations in phase with observations for CS (CC). PDSI overestimates (underestimates) drought frequency by 4% (23%) for CS (CC) compared to observations, whilst SPI is greatly overestimated by both CS and CC. Moreover, PDSI with drought frequency determined by CS is closer to observations for all categories, implying that the CS model is superior to the other 21 CMIP3 models in its ability to calculate drought phenomena over Saudi Arabia. Therefore, the calculation of PDSI with CS model data is recommended for further investigation using CMIP3 model projections as well as CMIP5 data. In the case where a multi-model ensemble is used to calculate drought indices for Saudi Arabia, PDSI along with CC and CS data are recommended.

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