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Recent climate change in the Arabian Peninsula: Seasonal rainfall and temperature climatology of Saudi Arabia for 1979–2009

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ABSTRACT

Attempts are made to study the seasonal climatology of the Arabian Peninsula, including the regional to station level information for Saudi Arabia for the period 1979–2009. The wet (November to April) and dry (June to September) season rainfall and temperature climatology are obtained from various data sources, namely, surface observations, CPC Merged Analysis of Precipitation (CMAP), Climatic Research Unit (CRU) and Tropical Rainfall Measuring Mission (TRMM). These gridded datasets detect the dry zone over the Rub Al-Khali, the world's largest sand desert, during the wet season. In this season, large rain belts exist north of 30°N and south of 15°N. During the dry season, the Arabian Peninsula is almost entirely dry north of 15°N but rain belts exist below this latitudinal boundary. Irrespective of the season or dataset used, a relatively heavy-rain area is obtained for the southwest of the Peninsula. The wet (dry) season temperature is highest over the western (middle to the northern) parts of the Peninsula.

Surface observations indicate that, irrespective of season, rainfall insignificantly increased in the first period (1979–1993), and then significantly decreased in the second period (1994–2009). The decrease rate is 35.1 mm (5.5 mm) per decade during the wet (dry) season. The temperature over Saudi Arabia has increased significantly, and the increase rate is faster (0.72 °C per decade) in the dry season compared to the wet season (0.51 °C per decade).

1. Introduction

The purpose of this work is to gain insight into the recent-past and present climate as well as climate change in the Arabian Peninsula, in particular over Saudi Arabia, on a seasonal basis. Any long-term (30 years or greater) climatological changes in rainfall and temperature are considered as a measure of climate change in a given region (Elagib and Mansell, 2000; Lazaro et al., 2001; Moonen et al., 2002; Islam, 2009; Islam et al., 2010), and therefore, an in-depth analysis of the climate parameters, i.e., rainfall and temperature, is essential for gaining an understanding of the recent-past and present climate of a region. The final goal of the detailed and up-to-date climatic information presented here is to provide a reference document for climate impact studies, including those for assessment, adaptation and mitigation, for the Arabian Peninsula and Saudi Arabia in a changing climate, and to enhance and sharpen the disaster management plans for the many and various stakeholders.

Season-based climate information has considerable implications for impact studies, especially for a semi-arid region (Köppen, 1936; Shepered, 2006) such as Saudi Arabia (Abdullah and Al-Mazroui, 1998), where the annual average rainfall was only 82.4 mm during the period 1998–2009 (Almazroui, 2011a); annual average rainfall over Saudi Arabia was 93.5 mm during the period 1979–2009 (current analysis, Table 1). Almazroui et al. (2012) showed that the distribution of annual rainfall over the Peninsula varies greatly from place to place and from time to time. Usually, a large amount of rainfall is observed toward the northern edge of the Peninsula

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Table 1
The surface observation station information and the corresponding rainfall amounts (mm) over Saudi Arabia during the period 1979–2009. The wet season is November to April and the dry is June to September. In the first column, the asterisk (*) after the station name indicates that the dataset is available from 1985. The last row provides the national average rainfall values averaged over all the stations.

	Station Information			Rainfall (mm)		
Station name	Lat (°N)	Lon (°E)	Altitude (m)	Annual	Wet season	Dry season
Turaif	31.68	38.73	852	85.5	73.9	0.4
Guriat*	31.40	37.28	504	46.7	40.5	0.1
Arar	30.90	41.14	550	58.6	51.1	0.1
Al-Jouf	29.78	40.10	670	56.4	45.9	0.9
Rafha	29.62	43.49	445	86.9	75.9	0.1
Tabuk	28.37	36.60	770	29.3	20.7	1.0
Hail	27.44	41.69	1000	116.4	95.3	0.5
Wejh	26.20	36.47	20	25.3	24.1	0.1
Gassim	26.30	43.77	648	145.6	125.6	0.3
Madina	24.54	39.70	630	64.7	49.8	4.5
Yenbo	24.14	38.06	8	31.0	24.9	0.1
Al-Qaysumah	28.33	46.12	360	126.5	115.1	0.3
Dhahran	26.26	50.16	22	92.5	89.8	0.0
Al-Ahsa*	25.30	49.49	180	84.8	79.8	0.8
Riyadh New*	24.92	46.72	612	110.6	104.6	0.0
Riyadh Old	24.71	46.73	610	88.9	81.2	0.3
Jeddah	21.71	39.18	18	51.2	47.8	0.5
Makkah*	21.43	39.79	273	110.6	81.6	11.5
Taif	21.48	40.55	1455	174.6	87.2	31.7
Al-Baha*	20.29	41.64	1655	142.6	79.4	29.8
Bisha	19.99	42.61	1167	88.5	62.4	6.6
Wadi-Aldawasser	20.30	45.12	617	26.1	24.2	2.8
Abha	18.23	42.66	2100	230.3	144.8	50.3
Khamis Mushait	18.29	42.80	2047	189.3	85.1	67.0
Najran	17.61	44.41	1213	60.1	36.8	13.1
Sharurah*	17.47	47.12	727	70.3	43.0	20.4
Gizan	16.90	42.58	4	131.8	66.7	40.5
Country normal				93.5	66.8	10.6

during the wet season and over the southern parts during the dry season; a result obtained based on the short-term climatology of rainfall from the TRMM 3B42 dataset during the period 1998–2009 (Almazroui, 2011a). The seasonal rainfall distribution in a limited area over south-western Saudi Arabia is described by Subyani (2004), including the details of the possible mechanisms for rainfall in this region. Rainfall in south-western Saudi Arabia is characterized by precipitation events throughout the whole year because of topographically-driven convective events (Abdullah and Al-Mazroui, 1998; Al-Mazroui, 1998). However, the details of the seasonal rainfall distribution for the Arabian Peninsula using long-term datasets (including gridded analyses such as the CMAP and CRU datasets) are not available within the literature. Moreover, the seasonal temperature climatology of Saudi Arabia has not been studied in detail except through using a single station (Dhahran) dataset by Rehman (2010). Therefore, in this paper, a detailed investigation is presented for the recent-past and present seasonal climate, which might be useful in application-oriented tasks.

The Middle East countries, including those on the Arabian Peninsula, are characterized by large variations in their climatic conditions, and these variations can be significant within a single country like Saudi Arabia (Ragab and Prudhomme, 2000). From north to south, Saudi Arabia exhibits a large variation of climatic conditions in terms of temperature. However, for rainfall, apart from the south-western region, most parts of the country are considered to be an arid climate and Saudi Arabia is well known for containing the world's largest continuous sand desert, which is called Rub Al-Khali (Empty Quarter). Any increase in temperature, particularly when accompanied by a decrease in precipitation over Saudi Arabia, could have a major impact on agriculture and water supplies (Alkolibi, 2002). Lindner (2006) reported widespread changes in the amount of precipitation, with a tendency for humid areas to become more humid and for dry and arid areas to become even drier. These may be the preconditions for flash floods caused by heavy rainfall and drought caused by a deficit of rain.

Any change in climate produces changes in extreme weather events, such as heavy rainfall, heat and cold waves, in addition to prolonged drought occurrences (Kotwicki and Al Sulaimani, 2009). For instance, Saudi Arabia has recently experienced such extreme climatic events, where 2010 was considered the warmest year of the instrumental observational period of Saudi Arabia (Almazroui, 2012a), and the classic example marking this extremely hot year is the national record-breaking 52 °C that was measured in Jeddah on the 22 June 2010. Extreme rainfall events have also struck this region (in 2009 and 2011), which resulted in the loss of many lives in Jeddah (Almazroui, 2012b). These extreme events occurred on 25 November 2009 with 74 mm of rain recorded by the Presidency of Meteorology and Environment (PME) and on 26 January 2011, with 111 mm within 4 h by the Department of Meteorology, King Abdulaziz University (KAU). These examples of such extremes may be considered as indirect effects of climate change (Almazroui, 2011b). On a positive note, the Arabian Peninsula climate and heavy rainfall events in western

Saudi Arabia have been successfully simulated using regional climate models (see for example, Almazroui, 2011b; Almazroui, 2012c).

For other parts of the Arabian Peninsula, Nasrallah et al. (2004) studied temperature extremes, such as heat waves, hot days, very hot days and extremely hot days, over Kuwait during the period 1958–2000. The hot–dry and cool–wet events over Bahrain were studied by Elagib and Addin (1997). Temperature extremes over Jordan were studied by Freiwana and Kadioglu (2008). The arid land ecosystems of these and other countries on and adjoining the Arabian Peninsula are among the most vulnerable to the threat of climate change (FAO, 2010).

According to the Intergovernmental Plan on Climate Change (IPCC) Fourth Assessment Report (AR4), most scenarios show increases of more than 2 °C in annual temperature by 2080, as compared with the base period temperature of 1961–1990 (Lindner, 2006). Using the UK Hadley Centre's global climate model (HadCM2), Ragab and Prudhomme (2000) concluded that by the year 2050, some parts of Saudi Arabia will experience reduced rainfall amounts by up to 20–25%, compared with present mean values during the dry season, while temperatures will rise by 2.0–2.75 °C inland, and by about 1.5 °C in coastal areas. In the winter season, rainfall will decrease by 10–15%, while temperatures will rise by 1.75–2.5 °C inland, and by about 1.5 °C in coastal areas. These indications of a decrease in rainfall and an increase in temperature are crucial for regional disaster management programs such as for water scarcity, food crises, and associated population migration.

Despite decreases in total values, Alpert et al. (2008) obtained an average increase in temperature of 1.5–4 °C throughout the Mediterranean region in the last 100 years, a dominant negative trend in rainfall (i.e. reduction) over the last 50 years, and a tendency toward an increase in extreme daily rainfall, although it was mentioned that these trends differ across sub-regions and periods. Alpert et al. (2004) showed that the frequencies of occurrence of the mostly dry Red Sea trough systems (Krichak et al., 1997; Tsvieli and Zangvil, 2005; Ziv et al., 2005) have nearly doubled since the 1960s, from 50 to about 100 days per year; a fact that explains a dominant decreasing trend in rainfall in most of the eastern Mediterranean. Therefore, the main aim of this paper is to generalize the complete seasonal climatology of the Arabian Peninsula by examining the region through rainfall and temperature trends, including a station-level dataset for Saudi Arabia, and to provide a reference document for disaster management studies.

2. Data and methodology

The historical norms for observed rainfall (mm) in the wet and the dry seasons at 27 different observation sites for a 31-year period (1979–2009), obtained from the Presidency of Meteorology and Environment (PME), Saudi Arabia, are presented in Table 1. In this paper, the definition of wet (November to April) and dry (June to September) seasons are adopted following Almazroui (2011a), which are consistent with the climatology of Saudi Arabia, which covers about 80% of the Arabian Peninsula. The spatial distribution of seasonal rainfall and temperature are obtained from the observed, CMAP (2.5°×2.5°; Xie and Arkin, 1997), CRU TS3.1 (0.5°×0.5°; updated version of Mitchell and Jones, 2005) and TRMM (0.25°×0.25°; Kummerow et al., 2000) datasets.

The standard CMAP dataset used in this study consists of monthly averaged precipitation values obtained from 5 kinds of satellite estimate, viz: GPI, OPI, SSM/I scattering, SSM/I emission and MSU for the period 1979 onwards. Precipitation events are sporadic and few over the Arabian Peninsula, and just a small number of them can dramatically affect the monthly value. Low Earth Orbit satellites could have missed some of them and/or some sensor over the years could have overestimated or underestimated rainfall with respect to other sensors. In addition, the probability of observing such infrequent precipitation events changes year by year also due to the number of reliable satellite overpasses over the Arabian Peninsula.

The CRU TS3.1 dataset is the University of East Anglia gridded climate dataset interpolated using the original information from stations around the world for the period 1901 to 2009. In the interpolation records, the anomaly with respect to the average for the period 1961–1990 is calculated. The anomaly is interpolated using thin-plate splines as a function of latitude/longitude. The gridded values of the CRU dataset are obtained by applying a smooth fitting in 3D space to the available surface station observations (New et al., 2000). New et al. (1999) described how this interpolation technique changes the spatial autocorrelation of data and introduces a known bias in the results. The CRU dataset may exhibit large differences between observed and interpolated data over a particular region if the observation locations are sparse. However, for Saudi Arabia the number of observation sites used in the CRU dataset is the same as utilized in the current study.

In TRMM, the precipitation radar (PR) is the first onboard orbital radar for estimating precipitation, and has been providing good quality estimates for the tropical regions since 1998. This analysis uses the TRMM 3B42 product, which is the merging of the TRMM Microwave Imager (TMI) radiometer and the PR instrument data with other microwave (MW) sources. The Multi-satellite Precipitation Analysis (TMPA) algorithm provides 3-hourly 0.25°×0.25° latitude/longitude gridded precipitation data for the latitude band 50°N–50°S over the period 1998–present (Huffman et al., 2007). The 3B42 product uses the combined TMI-PR estimates (TRMM product 2B31) for calibration purposes (Haddad et al., 1997a, 1997b). The various passive microwave (PMW) estimates are inter-calibrated for large global regions and then the PMW datasets are merged in 3-hourly windows centered on the nominal observation time. In the TMPA, infrared (IR) brightness temperature is calibrated with the combined PMW estimates. Thereafter, the combined PMW-IR estimates are used to fill gaps in the PMW for each 3-hourly image. Finally, the multi-satellite field is adjusted to reduce bias using the monthly Global Precipitation Climatology Centre (GPCC) monitoring gauge analyses. The TRMM 3B42 product is the basic input of seasonal accumulations, which is useful for climate change impact studies. Note that the TRMM rainfall dataset is found to overestimate by only 8% the station data in Saudi Arabia (Almazroui, 2011a).

During the period analyzed, the climatology was obtained for the phases 1979–2009 (available observed, CMAP and

CRU datasets) and 1998–2009 (available observed, CMAP, CRU and TRMM datasets). In obtaining the spatial distribution of the seasonal climatic parameters from the surface observations, the datasets are displayed directly (maintaining ratios) without using any re-gridding techniques in order to avoid interpolation errors. For the trend analysis of the observation-based seasonal rainfall over Saudi Arabia, the entire analysis period (1979–2009) is divided into two halves: the first half is from 1979 to 1993 and the second is from 1994 to 2009. The linear trends of mean, maximum and minimum temperature are obtained to estimate the variations of observed temperature in the changing climate. The station-level seasonal rainfall and temperature datasets for the different observational sites are obtained from across Saudi Arabia (see Table 1 for location details).

3. Results

3.1. Seasonal rainfall climatology

Fig. 1 displays the wet season rainfall obtained from CMAP, CRU and the observed datasets averaged over the period 1979–2009. The observed dataset is displayed for each station site to avoid any interpolation (Fig. 1c). The CMAP dataset shows two east-to-west extended heavy-rain belts in the Arabian Peninsula region: one in the north that occurs above 30°N and the other in the south that exists below 15°N (Fig. 1a). A tongue from the northern belt extends from the northern Arabian Gulf into central Saudi Arabia. On the other hand, a similar tongue from the southern feature also extends from Ethiopia/Eritrea into western and central Saudi Arabia. Two light-rain areas can be clearly seen: one is over Egypt and its surroundings extending into north-western Saudi Arabia, whereas the other one is over the Rub Al-Khali. Similarly, heavy-rain belts can also be seen in the CRU dataset (Fig. 1b), however, the southern belt is narrower, resulting in a wider light-rain belt over Egypt that covers most of Sudan. The light-rain area over the Rub Al-Khali is also very clear even though in the CRU dataset the values are quite different. Note that rainfall amounts <1 mm are not displayed either for CMAP or for CRU.

Over Saudi Arabia, the CMAP and CRU datasets show two light-rain areas, which are located in the northwest and the southeast of the country. As mentioned earlier, the north-western dry zone over Saudi Arabia is an extension of the Egyptian dry zone, and the south-eastern one is over the Rub Al-Khali, the world's largest sand desert. Within Saudi Arabia, the relatively heavy-rain areas are along the south-western coast and the southwest-to-northeast inclined rain band that passes over the middle of the country. The station datasets confirm the low rainfall amounts in the northwest and the relatively higher amounts over the south-western coast and in the middle of the country (Fig. 1c). The maximum observed rainfall for the wet season is 144.8 mm in the south-western region, which was recorded at Abha station (location in Table 1). There are no observational facilities in the south-eastern region, however the station nearest to that region indicates a small amount of rainfall. It appears that Mediterranean climate conditions as well as the Sudan low influence the wet season rainfall climatology of Saudi Arabia (Abdelmola, 2009).

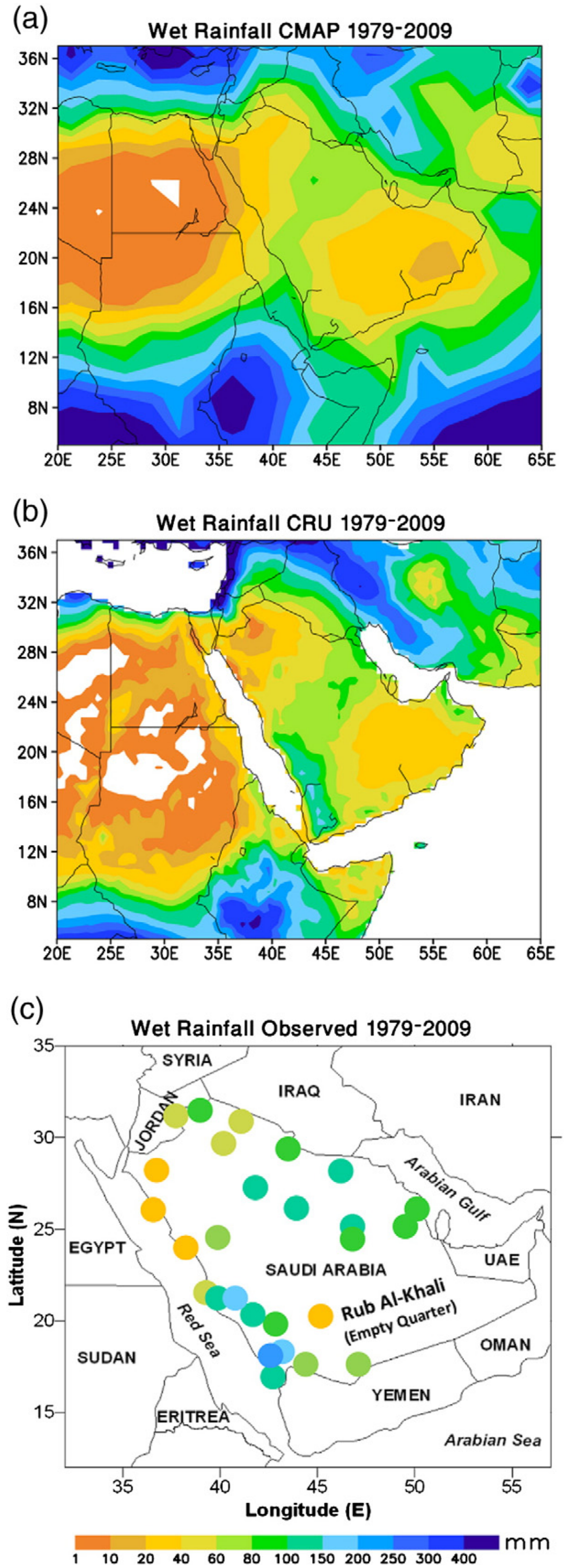

Fig. 1. Spatial distribution of the wet season rainfall (mm) averaged for the period 1979–2009 obtained from the (a) CMAP, (b) CRU, and (c) station datasets.

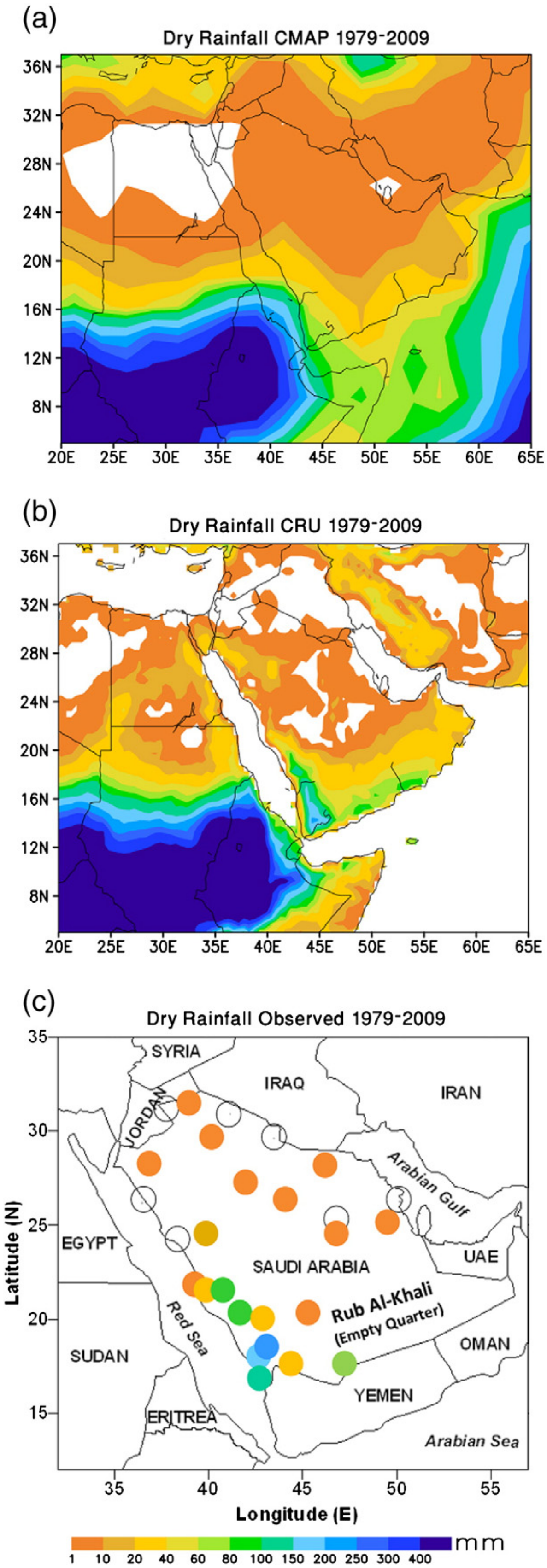

Fig. 2. Spatial distribution of the dry season rainfall (mm) averaged for the period 1979–2009 obtained from the (a) CMAP, (b) CRU, and (c) station datasets. In panel c the open circles indicate rainfall amounts less than 1 mm.

The dry season rainfall averaged over 1979–2009 is displayed in Fig. 2. The CMAP dataset shows essentially no rain over most parts of Egypt and an east-to-west dry zone (rainfall <20 mm) between 20° and 33°N (Fig. 2a). The presence of this dry zone is also clearly visible in the CRU dataset (Fig. 2b). Over Saudi Arabia, the CMAP and CRU datasets show little rainfall except in the south-western coastal area. A similar situation is evident in the observed dataset (Fig. 2c). In Fig. 2c, the open circles represent rainfall below 1 mm during the dry season. Hence, the dry season rainfall over Saudi Arabia is dominated by the Sudan low and is influenced by the Indian monsoon. The Mediterranean weather conditions do not influence the dry season rainfall climatology of the country (Abdelmola, 2009).

Because the rainfall varies considerably in space and time (Subyani, 2004; Islam et al., 2010), we discuss in more detail the period 1998–2009 when the high resolution (0.25°×0.25°) TRMM dataset became available. The TRMM dataset is more authentic in terms of obtaining the rainfall climatology because of its high resolution and the availability of the dataset both over the land and the ocean.

Fig. 3 displays the wet season rainfall distribution averaged over the period 1998–2009 obtained from the CMAP, CRU, TRMM and observed datasets. Almazroui (2011a) used the TRMM dataset for the same duration, however he did not use any other gridded dataset. Similar to the rainfall climatology for the period 1979–2009 discussed earlier (see Fig. 1), there are again two light-rainfall zones in the CMAP (Fig. 3a), CRU (Fig. 3b) and TRMM (Fig. 3c) datasets during the period 1998–2009 over the Arabian Peninsula: one over Egypt extending to north-western Saudi Arabia and the other over the Rub Al-Khali. A southwest-to-northeast inclined relatively heavy-rain zone lies across Saudi Arabia. The existence of the northern Arabian Peninsula heavy-rain belt above 28°–30°N remains the same, however the southern Arabian Peninsula rain belt is shifted to the south and it lies below 10°N for this short-term climatology. A similar distribution obtained from the station dataset (Fig. 3d) supports this distribution of wet season rainfall. The spatial distribution of rainfall over Saudi Arabia is more or less similar to that obtained for the period 1979–2009 for both the CMAP and CRU datasets (see Fig. 1). This implies that the acquired rainfall distribution persisted during the wet season in this region; however amounts might differ due to the differing lengths of the analysis period.

The dry season rainfall short-term climatology averaged over the period 1998–2009 is displayed in Fig. 4. In this season, the no-rain belt discussed earlier (see Fig. 2a) extends up to the Arabian Gulf for CMAP (Fig. 4a), with a similar situation evident in the TRMM data (Fig. 4c). The heavy-rain belt in the southern Arabian Peninsula remains the same as obtained earlier for the duration 1979–2009. The relatively heavy-rain in the south-western coastal area is a unique characteristic of that region, as obtained from the observed, CMAP, CRU and TRMM datasets, and consistent with the long-term observed, CMAP and CRU datasets. This implies

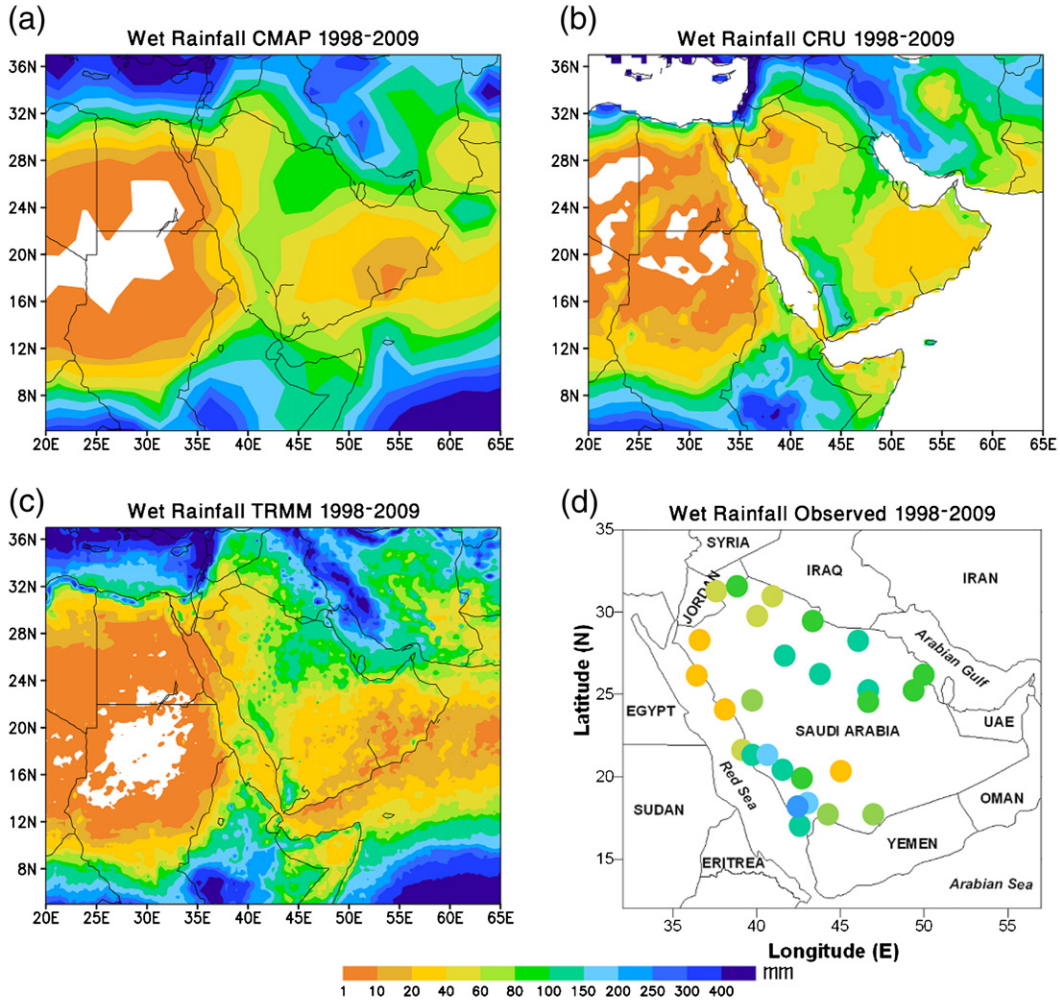

Fig. 3. Spatial distribution of the wet season rainfall (mm) averaged over the period 1998–2009 obtained from the (a) CMAP, (b) CRU, (c) TRMM, and (d) station datasets.

that irrespective of the length of analysis period, the spatial distribution patterns of the rainfall remain similar over Saudi Arabia. Therefore, it is concluded that the present rainfall distributions for the wet and dry seasons represent the rainfall climatology of the country.

It is evident from Fig. 1 through Fig. 4 that the CRU dataset over Saudi Arabia represents well the observed station data, however slight differences exist because the CRU dataset is a re-gridded product of the station data. On the other hand, TRMM performs better than CMAP, compared with the observed station data, because of TRMM's high resolution, whereas CMAP is coarse resolution, missing small-scale event details.

3.2. Seasonal temperature climatology

Temperature is an important parameter for any vulnerability assessment in a changing climate and its analysis depends on the variations in its mean, maximum and minimum values. Therefore, the details of the seasonal mean, maximum and minimum temperatures are taken into consideration for this discussion.

The spatial distribution of the wet season mean temperature averaged over the period 1979–2009 is displayed in Fig. 5. The CRU dataset shows that mean temperature is low (below 15 °C) in the northern Arabian Peninsula; it is very low over Iran but this feature extends across northern Iraq into the northern edge of the domain. Low temperatures also exist in the south-western coastal zone of Saudi Arabia, these extend into Yemen and also over Ethiopia/Eritrea. The highest temperature (above 27 °C) is observed over Sudan. The temperature over the Rub Al-Khali is above 21 °C. Within Saudi Arabia, the highest temperature (more than 24 °C) is observed on the west coast (along the Red Sea). The station dataset also represents similar characteristics to the CRU dataset (Fig. 5b). The station dataset is displayed at the site level to avoid the interpolation of the site values.

Analyzing the mean temperature climatology is important for any region but the assessment of maximum temperature in particular is necessary for many application-oriented tasks, such as the study of extremes and power generation. The spatial distribution of the wet season maximum temperature averaged over the period 1979–2009 is displayed in Fig. 6. The structure is similar to the mean temperature (see

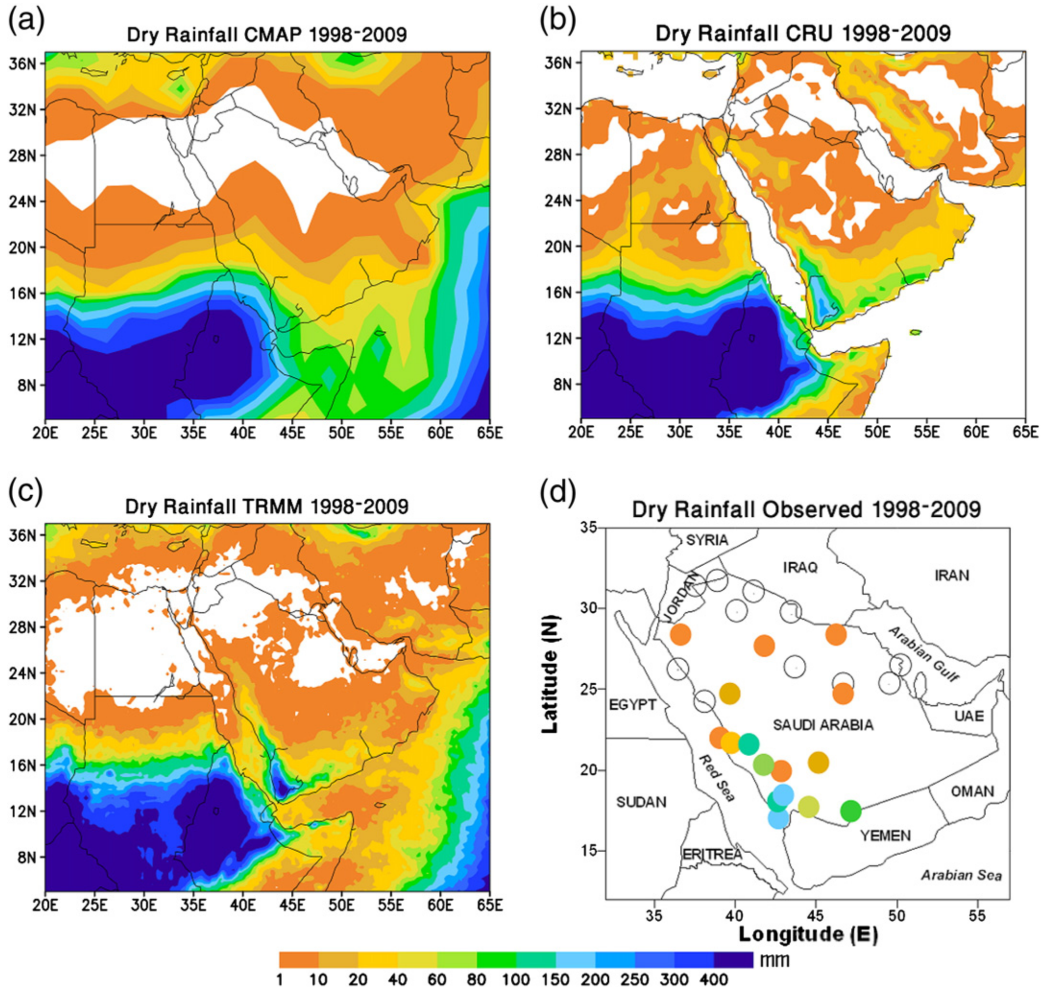

Fig. 4. Spatial distribution of the dry season rainfall (mm) averaged over the period 1998–2009 obtained from the (a) CMAP, (b) CRU, (c) TRMM, and (d) station datasets. In panel d the open circles indicate rainfall amounts less than 1 mm.

Fig. 5); values are high in all the regions. In the analysis domain, the highest maximum temperature (>36 °C) occurs over south-eastern Sudan. Over the Rub Al-Khali, it is between 27 °C and 30 °C, and along the Red Sea coast of Saudi Arabia, the highest temperature, of more than 30 °C, is obtained. The observed dataset (Fig. 6b) supports this distribution of maximum temperature.

As with the maximum temperature, the spatial distribution of wet season minimum temperature averaged over the period 1979–2009 is displayed in Fig. 7. The minimum temperature is below 9 °C (mostly over Egypt, Jordan, Iraq, Iran and the north-western quadrant of Saudi Arabia). Low temperatures are also apparent over Ethiopia/Eritrea and western Yemen, extending into south-western Saudi Arabia. The minimum temperature is between 18 °C and 24 °C over the Rub Al-Khali and the west coast of Saudi Arabia. The spatial distribution of minimum temperature obtained from the observations (Fig. 7b) again supports the results derived from the CRU dataset. Similarly, Fig. 8 displays the dry season mean temperatures averaged over the period 1979–2009. In this season, the structure of temperature distribution is different from the distribution for the wet season; a high temperature zone (above 33 °C) exists over northern Sudan and central Saudi Arabia that extends up to Kuwait, Iraq and south-western Iran (Fig. 8a). The high temperature zone is shifted to the north compared with the wet season. In the dry season, low mean temperatures are evident over western Yemen and the Ethiopia/Eritrea region. Overall, the dry season mean temperature over the Arabian Peninsula region is high, relative to the wet season. Within Saudi Arabia, the highest temperature zone (33–36 °C) stretches from the Arabian Gulf inland toward the center of the country instead of over the western side (i.e. associated with the Red Sea) discussed earlier for the wet season. The relatively low temperature zones are toward the north-western and south-western quadrants, whereas the lowest temperature (below 24 °C) occurs along the south-western parts of the country. The observed dataset (Fig. 8b) fully supports this distribution obtained from the CRU dataset.

The spatial distribution of dry season maximum temperature averaged over the period 1979–2009 is displayed in Fig. 9. The CRU dataset shows very high temperatures

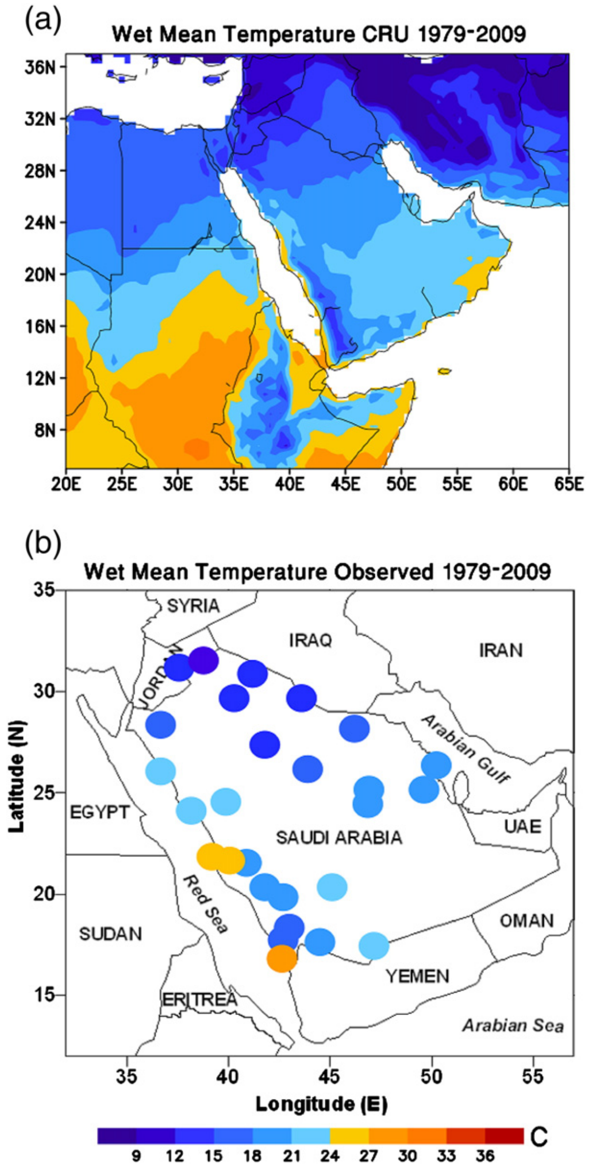

Fig. 5. Spatial distribution of the wet season mean temperature (°C) averaged over the period 1979–2009 obtained from the (a) CRU, and (b) station datasets.

(above 42 °C) confined to a pocket over northern Sudan and from northern Saudi Arabia extending into central Iraq (Fig. 9a). A pocket of low temperature (below 27 °C) is evident over south-western Yemen. High temperatures are also recorded at most of the stations over Saudi Arabia (Fig. 9b).

Fig. 10 displays the dry season average minimum temperature obtained from the CRU and observed datasets averaged over the period 1979–2009. The CRU dataset shows the highest temperatures (above 27 °C) confined to a pocket over Sudan and in a small area in eastern Saudi Arabia along the coast of the Arabian Gulf. Low temperatures (below 18 °C) exist over Ethiopia/Eritrea and the south-western quadrant of Saudi Arabia that extends into western Yemen. The minimum temperature over the north-western parts of Saudi Arabia, which extends northwards, is also relatively low. The observed dataset (Fig. 10b) fully supports the minimum temperatures distribution obtained from the CRU dataset, which also provides better authentication of our reported climatology results, not reported hitherto for this region.

3.3. Seasonal change in recent–past climate

The spatial distribution of the change in rainfall (%) obtained from CRU, relative to the base period of 1979–2009, is displayed in Fig. 11. The top panels are for the decade 1980–1989, the middle panels are for the decade 1990–1999, and bottom panels are for the decade

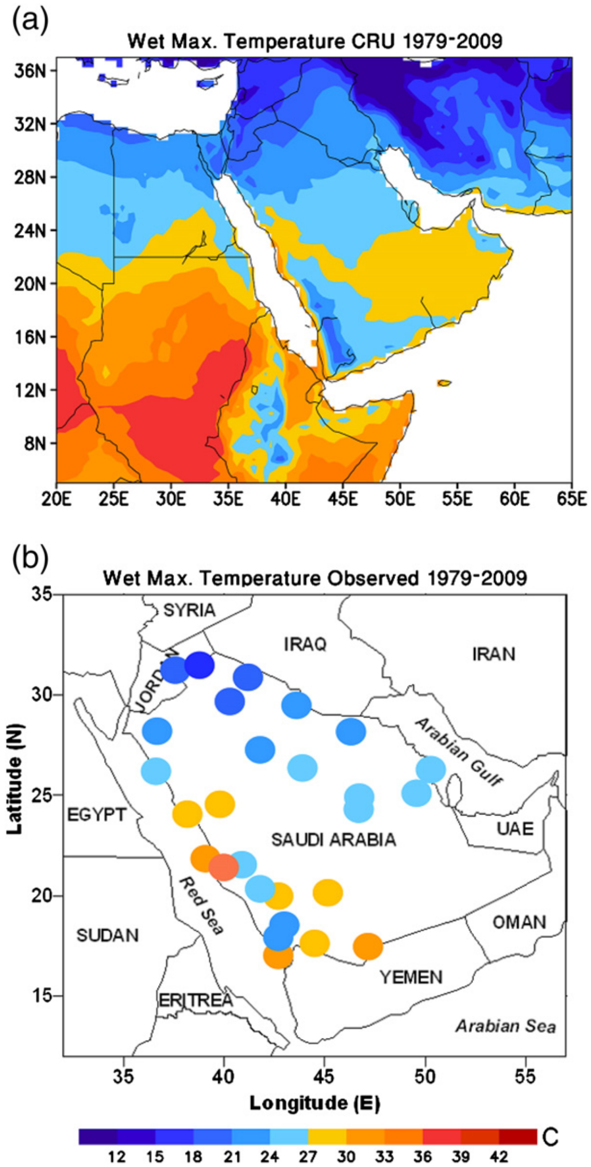

Fig. 6. Spatial distribution of the wet season maximum temperature (°C) averaged over the period 1979–2009 obtained from the (a) CRU, and (b) station datasets.

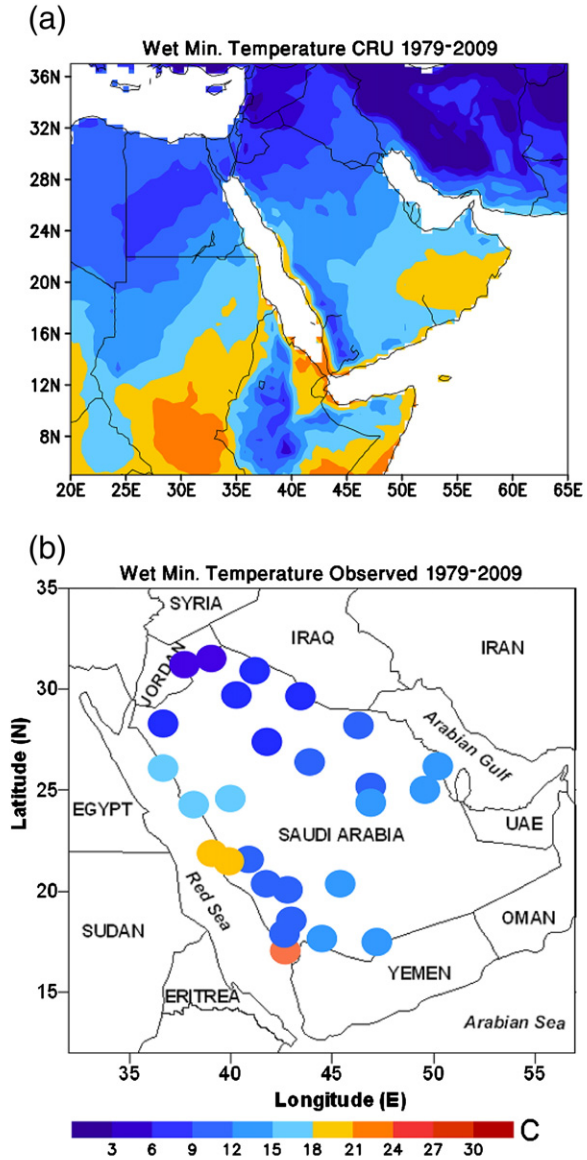

Fig. 7. Spatial distribution of the wet season minimum temperature (°C) averaged over the period 1979–2009 obtained from the (a) CRU, and (b) station datasets.

2000–2009, respectively. The left panels are for the wet seasons, whereas the right panels are for the dry seasons. During 1980–1989, the wet season rainfall was below the 31-year average over almost all parts of the Arabian Peninsula but above average over central and north-western Saudi Arabia, which extends to the northern edge of the domain (Fig. 11a). In this decade, the deficit of rainfall is below 10% over Oman, southern Sudan and Somalia. The surplus of above 10% is also noticeable over north-western Saudi Arabia, eastern Sudan and Ethiopia/Eritrea. The wet season rainfall change is almost the opposite during 1990–1999: rainfall above average over the Arabian Peninsula but below average in the inclined southeast-to-northwest zone over Saudi Arabia, which extends up to Jordan and western Iraq (Fig. 11c). During the decade 2000–2009, rainfall is below the 31-year average over central Saudi Arabia, which extends to all Gulf countries, while the above average values are maintained over south-western Peninsula, particularly over Yemen (Fig. 11e). This implies variation of rainfall on the decadal scale, even though spatial distribution remains almost the same when averaged over the periods 1979–2009 and 1998–2009, as discussed earlier. It is interesting to note the rainfall surplus along the Red Sea coast for both the 1990–1999 and 2000–2009 decades, which is also evident for the southern Peninsula (Fig. 11c and e).

In the dry season, the relative decadal percentage change of rainfall follows the same patterns obtained for the wet season only for the southern Peninsula because there are almost no rains for the middle to northern Peninsula. In the dry

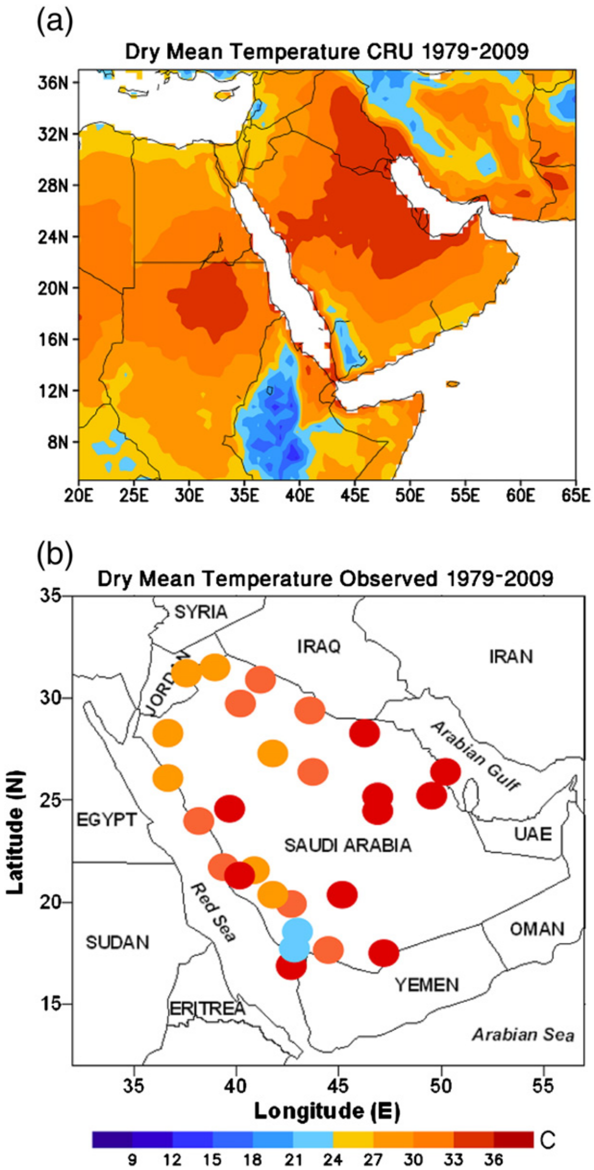

Fig. 8. Spatial distribution of the dry season mean temperature (°C) averaged over the period 1979–2009 obtained from the (a) CRU, and (b) station datasets.

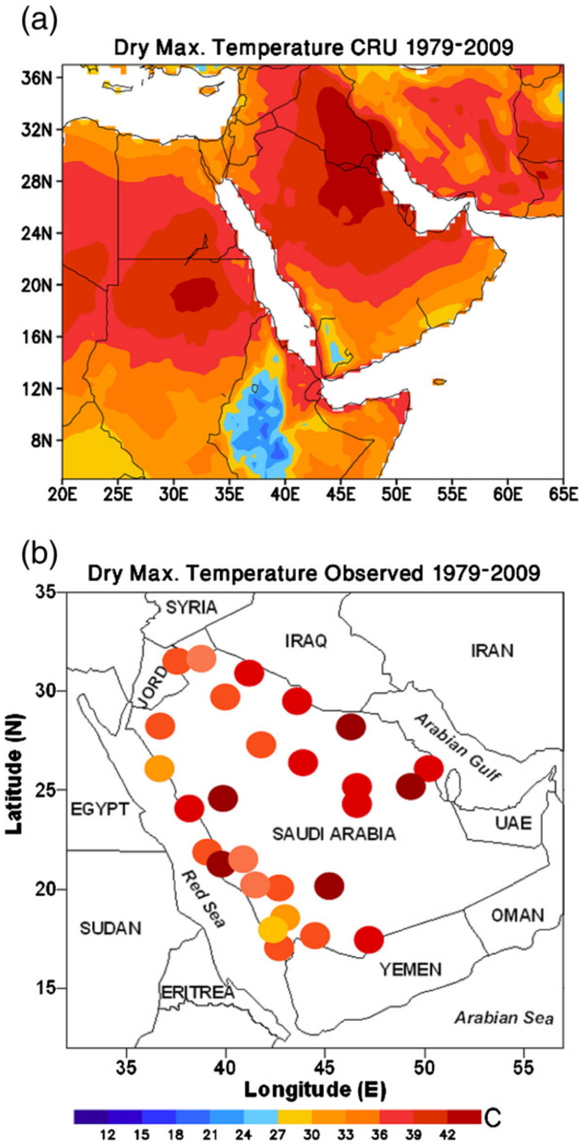

Fig. 9. Spatial distribution of the dry season maximum temperature (°C) averaged over the period 1979–2009 obtained from the (a) CRU, and (b) station datasets.

season, there is a rainfall deficit over Yemen, which extends into southern Saudi Arabia and Oman during the period 1980–1989 (Fig. 11b). During the decade 1990–1999, there is a rainfall surplus over all of the southern Arabian Peninsula except for a deficit in a small pocket over eastern Oman (Fig. 11d). During the decade 2000–2009, rainfall was above average over the entire Arabian Peninsula. It should be noted that rainfall in this dry season is important for the southern Peninsula because the northern parts are almost rainless. Thus, Fig. 11 signifies the seasonal and regional variation of rainfall over the Peninsula, which is important for the full and appropriate utilization of application-oriented tasks.

In previous discussion (see Fig. 11), it was found that over the Arabian Peninsula, rainfall increased in the relatively heavy-rain areas during both the wet and the dry seasons in 1990–1999 and 2000–2009 compared with 1980–1989. However, the change of rainfall for any particular year was not clear from the average picture for these three decades. Therefore, the time sequences of the observed station rainfall for Saudi Arabia during the period 1979–2009 for both the wet and dry seasons are displayed in Fig. 12, along with results of a linear trend analysis. Overall, rainfall has an insignificant decreasing trend of 6.3 mm per decade during the wet season, with a relatively large standard deviation of 29 mm (not shown). Careful inspection indicates that the wet season rainfall trend is increasing in the first few years and decreasing in the last few. As mentioned in Section 2, in this study, the total analysis period is divided into two

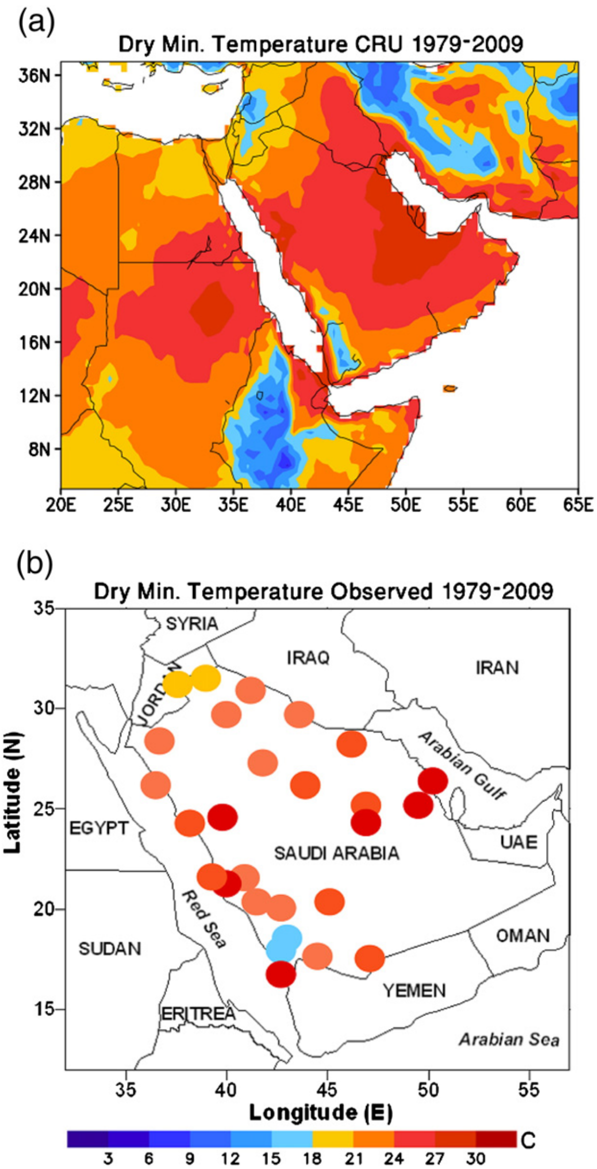

Fig. 10. Spatial distribution of the dry season minimum temperature (°C) averaged over the period 1979–2009 obtained from the (a) CRU, and (b) station datasets.

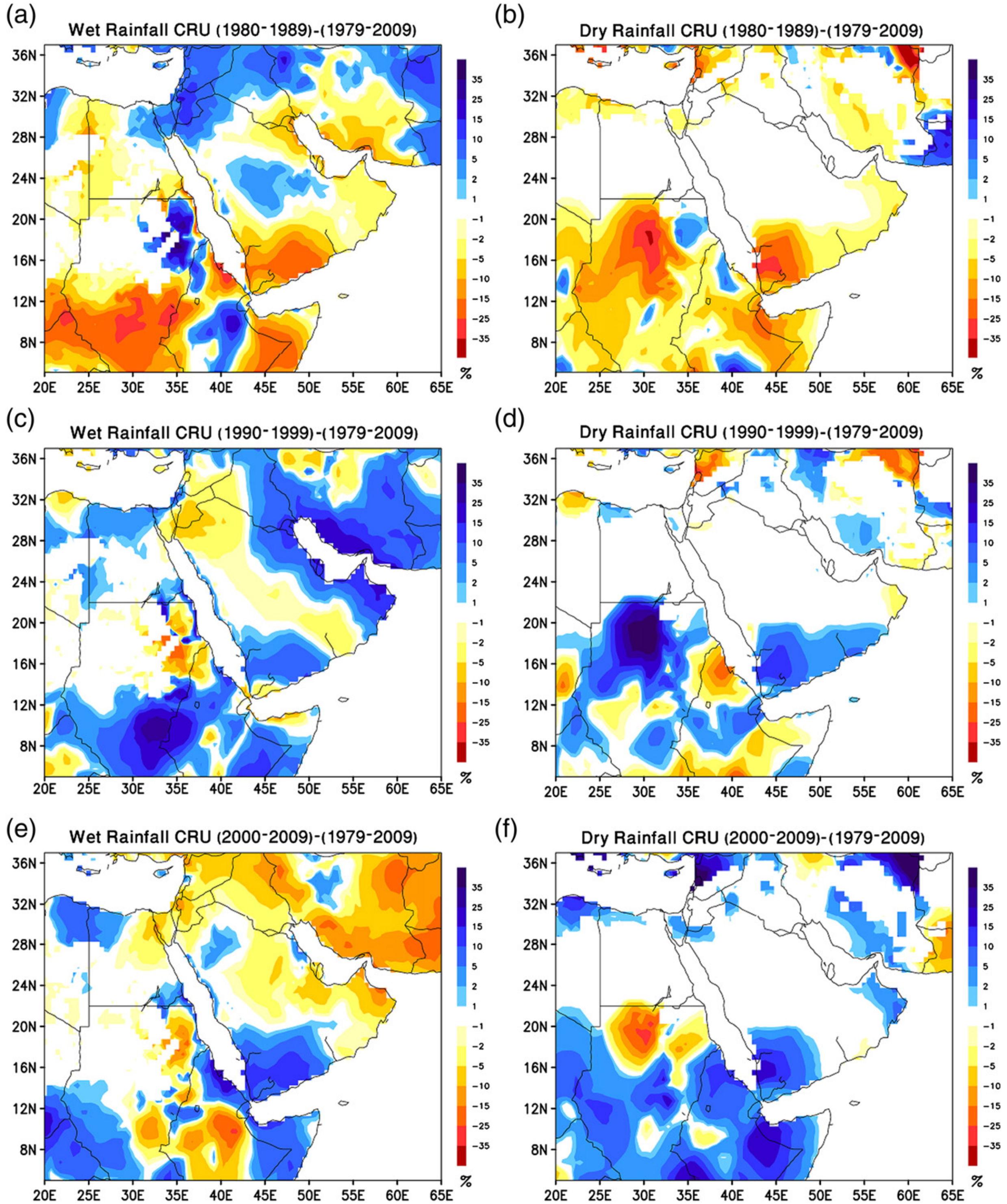

Fig. 11. Spatial distribution of the wet (left panels: (a), (c) and (e)) and the dry season (right panels: (b), (d) and (f)) rainfall change (%) for the decade 1980–1989 (top panels), 1990–1999 (middle panels), and 2000–2009 (bottom panels) with respect to the base period (1979–2009) for the CRU dataset.

halves: the first half is the period 1979–1993 and the second is 1994–2009. The wet season rainfall shows an insignificant increasing trend at a rate of 12.6 mm per decade during the first half-period 1979–1993 (with the standard deviation value of 4.7 mm) and it shows a significant decreasing trend (at 95% level) at a rate of 35.1 mm per decade during the second half-period 1994–2009 (with a standard deviation value of 34.0 mm). This clearly indicates the influence

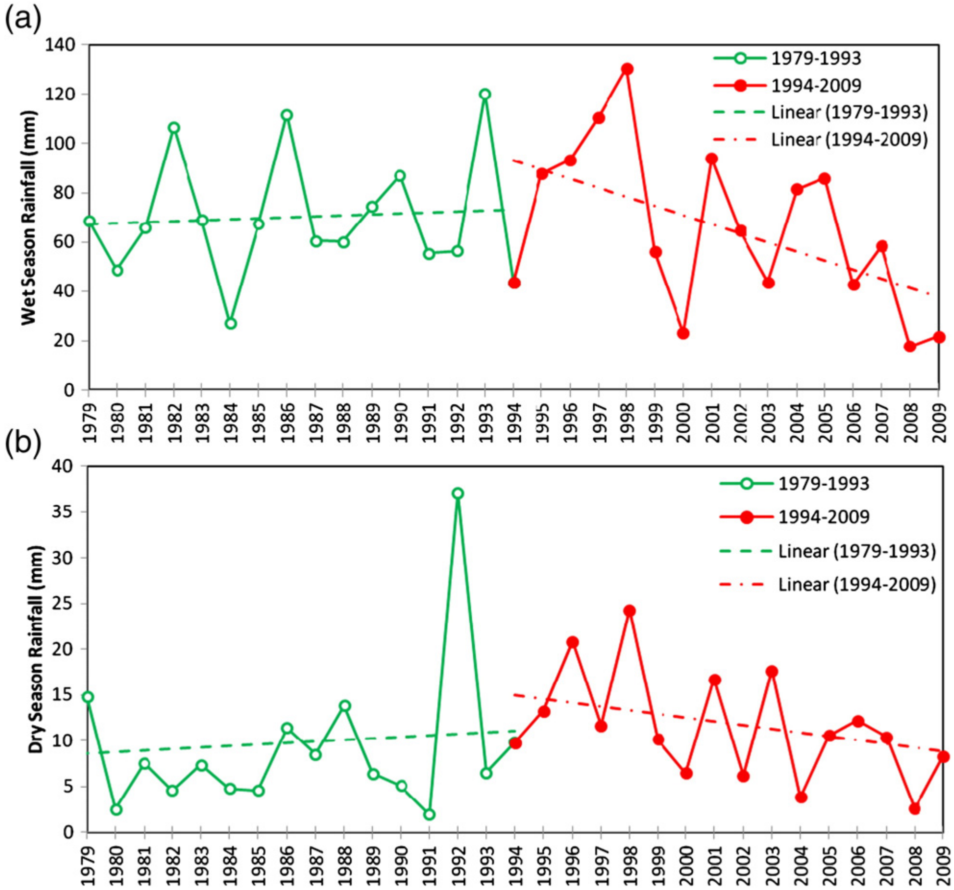

Fig. 12. Time sequences of the observed (a) wet season and (b) dry season rainfall (mm) during the period 1979–2009 over Saudi Arabia. The seasonal trends are displayed for the first (1979–1993) and second (1994–2009) periods. For the wet season, the first/second period indicates insignificant/significant increase/decrease in rainfall (12.6/35.1 mm per decade). For the dry season, the first/second period indicates insignificant/significant increase/decrease in rainfall (2.0/5.5 mm per decade).

of the choice of the beginning and the end years on the trend estimates, as discussed by Liebmann et al. (2010).

In contrast with the wet season, rainfall during the dry season over Saudi Arabia is low and mostly confined to the southwest, as depicted earlier. During the dry season, the rainfall is insignificantly increasing at a rate of 0.4 mm per decade for the entire period 1979–2009, with a standard deviation value of 7.4 mm (not shown). Although the dry season increasing trend is small, it is opposite in nature compared with the wet season trend. The nature of the trends is mostly determined by the extreme year of 1992 (37.1 mm). The results show that rainfall is insignificantly increasing at a rate of 2.0 mm per decade during the first period (1979–1993), with a standard deviation value of 8.4 mm, whereas it is significantly (above 90% level) decreasing at 5.5 mm per decade during the second period (1994–2009), with a standard deviation value of 5.9 mm. Irrespective of season, the decreasing trends in the second half of the analysis period are greater compared with the increasing trends in the first half. This provides a clear indication that the recent rainfall trends over Saudi Arabia have decreased; these might be linked to the prolonged droughts that have occurred across the whole of the Arabian Peninsula in the last decade.

For many application-oriented tasks related to climate change, the nature of any temperature variation is important. The spatial distributions of the mean temperature change (°C) for the decades 1980–1989, 1990–1999 and 2000–2009 relative to the base period (1979–2009) during the wet and dry seasons are displayed in Fig. 13. For both the wet and dry seasons, temperature warmed during the decade 2000–2009 compared with 1980–1989 and 1990–1999 over the Arabian Peninsula. The dry season temperature cooled over Sudan during 2000–2009 compared with the decade 1980–1989 (Fig. 13b and f). The cooling of temperature over Sudan is prominent during the dry season, which may be related to the Sudan low, which is one of the climate-controlling mechanisms of this region (Abdelmola, 2009). Hence, temperatures changing with time in both the wet and dry seasons are evidence of global warming at the local level, which is of significance for the agriculture, water and power generation sectors of the country. This change in temperature over Saudi Arabia encourages a detailed investigation of the seasonal trends for mean, maximum and minimum temperature, discussed next.

Figs. 14 and 15 display the time sequences of temperature change for the mean, maximum and minimum temperatures, obtained from the observed station data for the wet and the

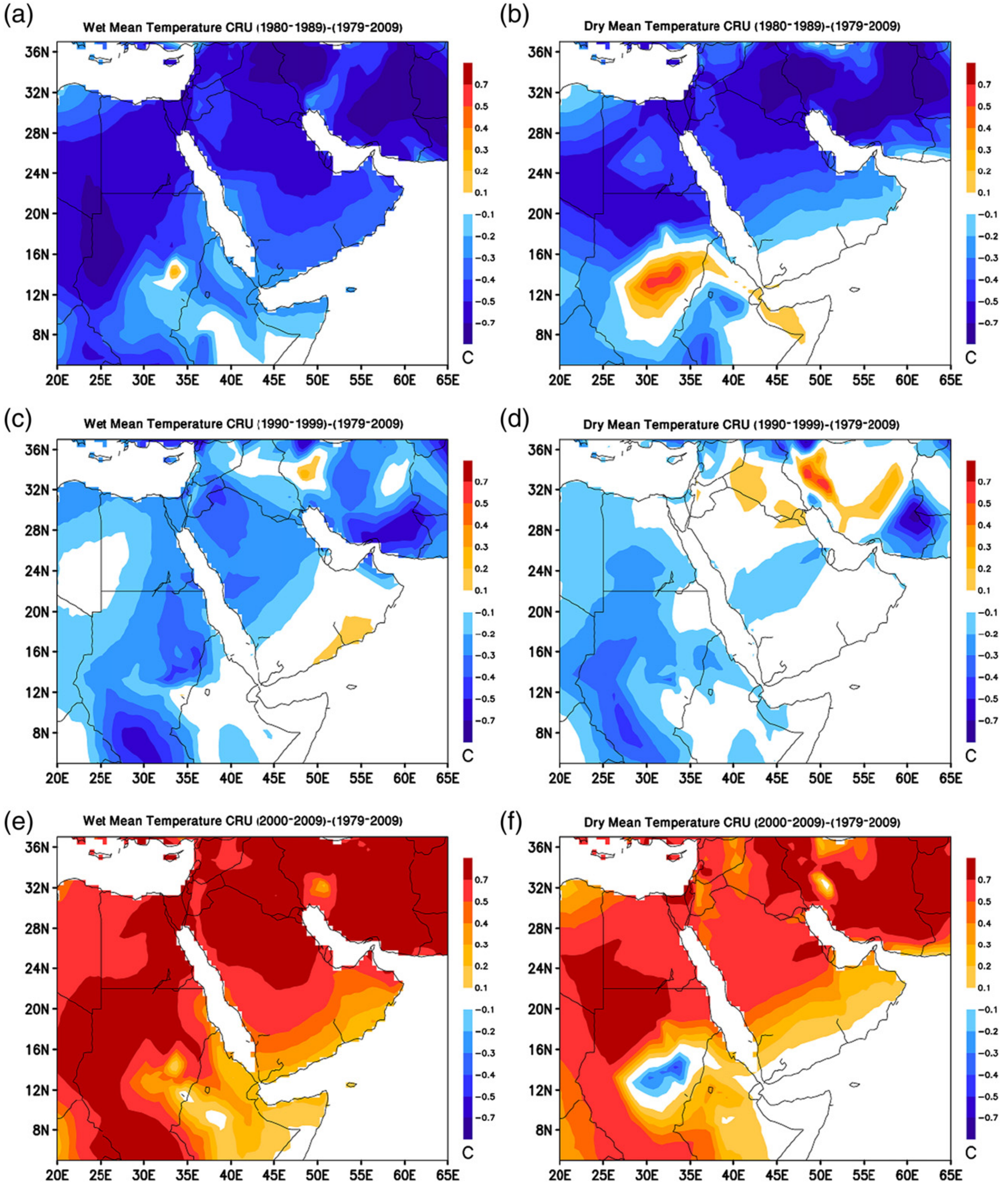

Fig. 13. Spatial distribution of the wet (left panels: (a), (c) and (e)) and the dry season (right panels: (b), (d) and (f)) mean temperature (in °C) for the decade 1980–1989 (top panels), 1990–1999 (middle panels), and 2000–2009 (bottom panels) with respect to the base period (1979–2009) for the CRU dataset.

dry seasons, respectively, during the period 1979–2009. Because of the lower variability of temperature relative to the rainfall, the trend analyses are performed for the entire analysis period without any time division. During the wet season, the increasing trend of temperature is 0.51, 0.67 and 0.34 °C per decade for the mean, maximum and minimum temperatures, with $R^2 = 0.32$, 0.33, 0.23, respectively. This indicates that maximum temperature is increasing at a faster rate

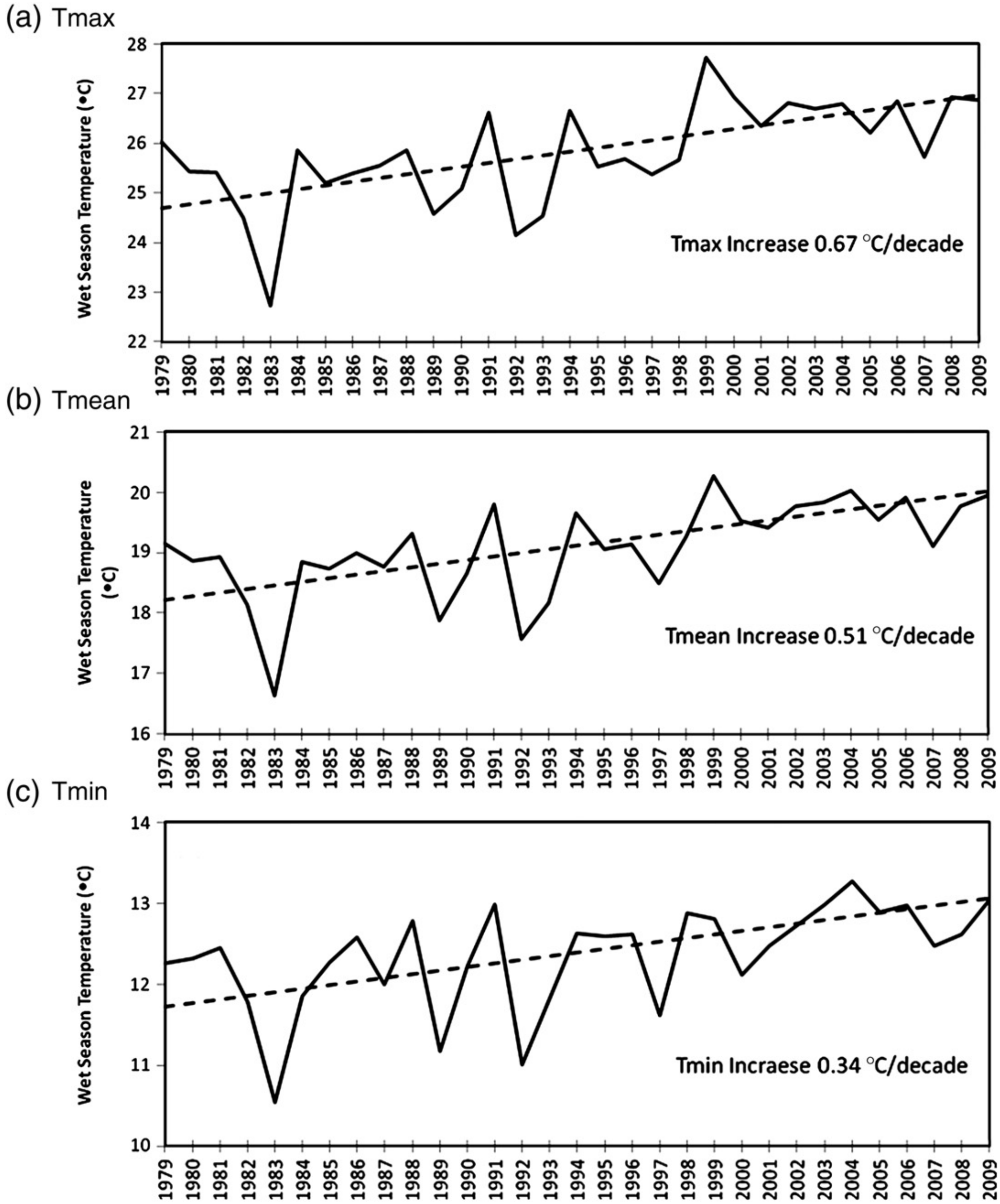

Fig. 14. The time sequences of the observed wet season temperatures (°C) during the period 1979–2009 over Saudi Arabia. The trends of the (a) maximum, (b) mean, and (c) minimum temperature are also displayed. All the trends are statistically significant at 99% level.

compared with the minimum temperature. Note that all the increasing trends in the wet season are statistically significant at the 99% level.

During the dry season, the statistically significant (99% level) increasing rate of temperature is 0.72, 0.80 and 0.63 °C per decade for the mean, maximum and minimum temperatures, with $R^2 = 0.71$, 0.71, and 0.65, respectively, obtained from the observed station datasets (Fig. 15). Again, the rate of increase for maximum temperature is higher than that for minimum temperature. However, the rate of increase for the dry season mean temperature (0.72 °C per decade) is consistent with the value of 2.00–2.75 °C by 2050 (Ragab and Prudhomme, 2000). The definition of the dry season (June to September) in this study is slightly different from that used by Ragab and Prudhomme (2000), who used April to September. Overall, the increasing trend for temperature during dry season is large, compared with the wet season. This may indicate the possibility of more dryness over the country, which may be linked to the impact of climate change in this region, particularly for Saudi Arabia. This vital information is missed in the annual temperature climatology as reported by Almazroui et al. (2012), and this

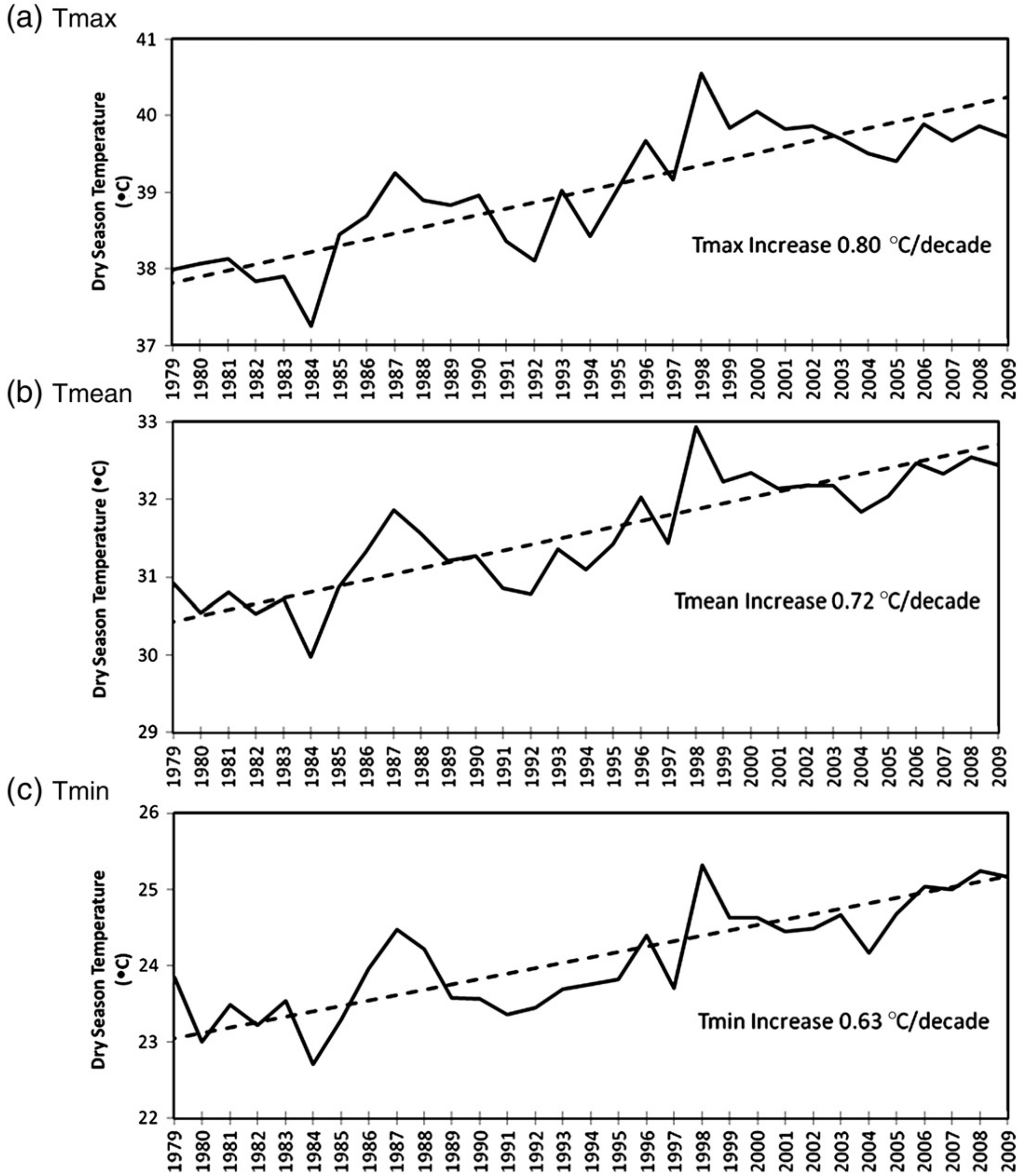

Fig. 15. The time sequences of the observed dry season temperatures (°C) during the period 1979–2009 over Saudi Arabia. The trends of the (a) maximum, (b) mean, and (c) minimum temperature are also displayed. All the trends are statistically significant at 99% level.

reinforces the importance of generalizing a seasonal climatology for application-oriented tasks in a changing climate environment.

4. Summary and conclusions

Using the observed and gridded datasets (CMAP, CRU and TRMM), the seasonal rainfall and temperature (minimum, mean, and maximum) climatologies have been studied for a 31-year period (1979–2009) over the Arabian Peninsula. The intention has been to present a reference document on the recent–past and present climatic variations for use in projection and application-oriented studies. The spatial distributions for both temperature and rainfall climatic variables were obtained. Interannual and decadal trends were calculated to estimate the magnitude of change in climate over the Arabian Peninsula, in particular over Saudi Arabia.

The spatial distributions of the wet season (November through April) rainfall during the periods 1979–2009 and 1998–2009 indicate that the area of lightest rain in the Arabian Peninsula is located over the Rub Al-Khali. Over Saudi Arabia, the relatively heavy-rain zone is inclined southwest-to-northeast. In contrast, the dry season (June through September) rainfall distribution for these two time periods indicates that the north of the Arabian Peninsula is almost rainless. In this season, very low rainfall totals were observed in the north of the Arabian Peninsula but higher totals were observed in the south. Irrespective of season, significant amounts of rain persist in the south-western area of Saudi Arabia, consistent with earlier results.

The wet season highest temperatures are evident over the west of the Peninsula, whereas in the dry season, they are over the central and northern parts. The lowest temperatures in the wet season occur mostly in the north of the Arabian Peninsula, and within Saudi Arabia they are in the north-western quadrant, with a small region in the southwest that extends into Yemen. During the dry season, a high temperature zone rests over the whole of Saudi Arabia; the low temperature areas are reduced relative to the wet season.

Using the observed dataset for Saudi Arabia during the period 1979–2009, it is noticed that during the analysis period, the wet (dry) season rainfall amount was 66.8 mm (10.6 mm), whereas the annual rainfall was 93.5 mm. During the recent past (1994–2009), the significant decrease of rainfall is 35.1 mm (5.5 mm) per decade during the wet (dry) season. Overall, the temperature has a significant increasing linear trend; the mean temperature is increasing at a rate of 0.51 °C (0.72 °C) per decade in the wet (dry) season. It is important to note that rainfall has increased in the south of the Peninsula and in particular along the Red Sea coast in recent decades, compared with the 1980s. This picture is different to the situation evident over inland parts of the Peninsula. Therefore, care should be taken in the utilization of rainfall information for application-oriented tasks because it varies greatly from place to place and from time to time.

This analysis represents the first complete documentation of the long-term (more than 30 years) seasonal climatology of rainfall and temperature (for spatial distribution) over the Arabian Peninsula and at the station level over Saudi Arabia, which may have relevance for local climate impact studies due to climate change.

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