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Review

Changes in climate extremes in the Arabian Peninsula: analysis of daily data

Said Hamed AlSarmi* and Richard Washington
Climate Research Lab, Oxford University Centre for the Environment, University of Oxford, Oxford, UK

ABSTRACT: This article presents an analysis of observed climate extremes over the Arabian Peninsula (AP); a region for which little such analysis has been available. A set of climate extremes indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) were computed and analysed for trends including the periods 1970–2008 and 1986–2008 at 23 stations covering six countries (Bahrain, Qatar, Kuwait, Oman, Saudi Arabia and UAE) and for Bahrain (1950–2008), Kuwait (1962–2008), Masirah and Salalah (1943–2008). The results indicate a general decreasing trend of cold temperature extremes and increasing trends of the warm temperature extremes during the periods of analysis. Over the whole region, a remarkable and highly significant increase in very warm nights during 1986–2008 has occurred. In general higher temperature trends (magnitudes/significance) are reported over the northern AP in the day-time extremes while for the night-time extremes the trends are higher and significant for the southern region especially during the recent decades. The precipitation indices trends are weak and insignificant except for the annual count of days when precipitation exceeds 10 mm which shows a significant decrease during 1986–2008.

KEY WORDS extremes; Arabia; trends

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1. Introduction

Alexander *et al.* (2006) notes that most analyses of long-term climate change using observational temperature and precipitation data have focused on changes in monthly mean values. If the change in mean, however, were related to a shift in distribution, particularly in the extremes, then this could have a major impact on society and ecosystems (Frich *et al.*, 2002). Because analysis of changes in extremes depends on daily data, which are generally difficult to access, there have been gaps in such analysis for many parts of the world (Frich *et al.*, 2002; Alexander *et al.*, 2006). To tackle this issue, the Joint World Meteorological Organisation Commission for Climatology (CCl)/World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDI) coordinated workshops in regions where analyses of daily data had not yet been undertaken with ensuing workshops in numerous regions, e.g. the central and south Asia (Klein Tank *et al.*, 2006), South America (Vincent *et al.*, 2005), the south east Asia and south Pacific (Manton *et al.*, 2001), the Caribbean region (Peterson *et al.*, 2002), southern and west Africa (New *et al.*, 2006), South America (Haylock *et al.*, 2006), the Middle East (Zhang *et al.*, 2005), the western central Africa, Guinea Conakry, and Zimbabwe (Aguilar *et al.*, 2009) and, Central America and northern South America (Aguilar *et al.*, 2005), the Indo-Pacific region (Caesar *et al.*, 2011) and recently the Arab region (Donat *et al.*, 2013).

Important findings have emerged from this and similar research. Klein Tank *et al.* (2006), in the case of central and south Asia, found that the indices of temperature extremes are increasing in both the cold tail and the warm tail of the daily minimum and maximum temperature over the period 1961–2000. Similar trends patterns were observed over South China during 1961–2007 (Fischer *et al.*, 2011) and over southwestern China during 1961–2008 (Zongxing *et al.*, 2012). For Hong Kong, Wong *et al.* (2011) found that extreme daily maximum and minimum temperature and warm spell duration have increased significantly during the period 1885 to 2008 while the frequency of cold days and cold spell duration had decreased.

Zhang *et al.* (2005) were responsible for the first region-wide analysis of the Middle East extreme indices for 1950–2003, examining 52 stations from 15 countries. In earlier work, Hulme (1996) and Jones and Reid (2001) demonstrated that warming may have contributed to a reduction in the P/PE ratio in many of these dryland regions. Nasrallah *et al.* (2004) studied the

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* Correspondence to: S. H. AlSarmi, Climate Research Lab, Oxford University Centre for the Environment, University of Oxford, Oxford OX1 3QY, UK. E-mail: said.alsarmi@ouce.ox.ac.uk

summer extreme temperature events over Kuwait during 1958–2000, finding that the most significant heat wave events, as far as both their duration and intensity are concerned occurred in the last decade of the 20th century. Almazroui *et al.* (2012a) have pointed to a decrease in rainfall over Saudi Arabia of 35.1 mm (5.5 mm) per decade during the wet (dry) season over the years 1994–2009 while temperature has increased at 0.72 °C per decade during the dry season. The authors report that maximum, mean and minimum temperatures have increased significantly at a rate of 0.71, 0.60 and 0.48 °C per decade, respectively. Recently Donat *et al.* (2013) examined the temporal changes in climate extremes in the Arab region with regard to long-term trends, they found consistent warming trends across the region where the increased frequencies of warm days and warm nights, higher extreme temperature values, fewer cold days and cold nights and shorter cold spell durations are all evident since the early 1970s.

This article builds on previous climate extremes studies in the region such as Zhang *et al.* (2005) and Almazroui *et al.* (2012a, 2012b) by evaluating the trends in indices of daily temperature and precipitation for stations located in the Arabian Peninsula (AP). While Zhang *et al.* (2005) used daily data from nine stations covering two countries located in the AP (Oman and Saudi Arabia) and Almazroui *et al.* (2012a,2012b) concentrated on Saudi Arabia only (though not based on daily data), this paper uses data from 24 stations covering 6 countries to analyze trends of 21 climate extreme indices. The objective of this study is to document the spatial distribution and temporal trends of extreme temperature and precipitation parameters over the AP, following the examples set for many regions by the ETCCDI. Two periods are considered: 1970–2008, and 1986–2008 and a long-term assessment with some stations beginning in 1943. Annual and seasonal indices are investigated (not monthly). As the stations cover a wide geographical area, we also study two sub regions namely the non-monsoonal region (north of 20 °C) and monsoonal region (south of 20 °C).

The AP is characterized by unique topography which varies between deserts and high mountains. It is well known for containing the world's largest continuous sand desert (Rub Al-Khali) - a region of extreme aridity and extreme temperatures. In general, the Arabian Peninsula is dominated by two air masses, namely, the Polar Continental that occurs from December to February and Tropical Continental that occurs in summer from June to September. Both systems are affected by minor incursions of Polar Maritime and Tropical Maritime air (Fisher and Membery, 1998).

2. Data

Stations records of daily precipitation, maximum temperature and minimum temperature were provided by the Meteorological Services of most of the AP countries. Oman provided 24 stations, Saudi Arabia 11, UAE 4 with 1 station from each of Qatar, Bahrain and Kuwait. The station's data have different starting dates where the longest continuous data is from Bahrain (1950–2008). Salalah and Masirah, stations located in Oman, have the longest daily precipitation record (1943–2008) although the record is not continuous. Longer daily precipitation data (1943–1976) for Salalah and Masira stations were kindly provided by the Climatic Research Unit, University of East Anglia (P. Jones, personal communication, 2010).

To make the best use of the available data and to maximise the number of stations used in the analysis, stations which have a data period of equal to or more than 20 years formed the core of the analysis which covers two key periods 1970–2008 and 1986–2008. A separate trend analysis will focus on the limited stations which have data prior to 1970 (Bahrain, Kuwait, Masirah and Salalah).

The seasonal definition follows AlSarmi and Washington (2011) namely winter (DJF), spring (MA, 1st transitional period), early summer (MJ, pre-monsoon), late summer (JAS, monsoon) and autumn (ON, 2nd transitional period or post-monsoon).

2.1. Quality control (QC)

First, data were quality controlled for false values and outliers using RClimDex software, which is developed and maintained by Xuebin Zhang and Feng Yang at the Climate Research Branch of Meteorological Service of Canada. Software and documentation are available online (http://cccma.seos.uvic.ca/ETCCDI/). Specifically, the following tests were conducted: (1) Identification of erroneous values such as negative precipitation or daily maximum temperature less than the daily minimum temperature. Instances of false values were identified and removed. (2) Identification of outliers where the outlier threshold is defined as the mean of the value for the day plus or minus four times the standard deviation of the value for the day, following Zhang *et al.* (2005) and Alexander *et al.* (2006). The standard deviations of the stations were taken from the base period 1986–2008; these outliers were checked to determine if the values marked as outliers were really outliers. The unreasonable outliers were removed. (3) Visual inspection of the data through a series of plots as histograms, enabling additional checks.

In the case of Seeb station (Oman), a unique cooling trend in all seasons was detected which is anomalous in comparison with its neighbouring stations of Sohar (180 km) and Sur (420 km) and the region as a whole (AlSarmi and Washington, 2011). Figure 1 shows clear differences between Seeb station relative to Sohar and Sur especially in the night-time minimum temperature indices. Higher values of night time temperature indices at Seeb station relative to Sohar and Sur are evident before 1994. The higher night-time temperature values of Seeb are also evident in the warmest nights (TNx) and warm night frequency (TN90p). The variance in

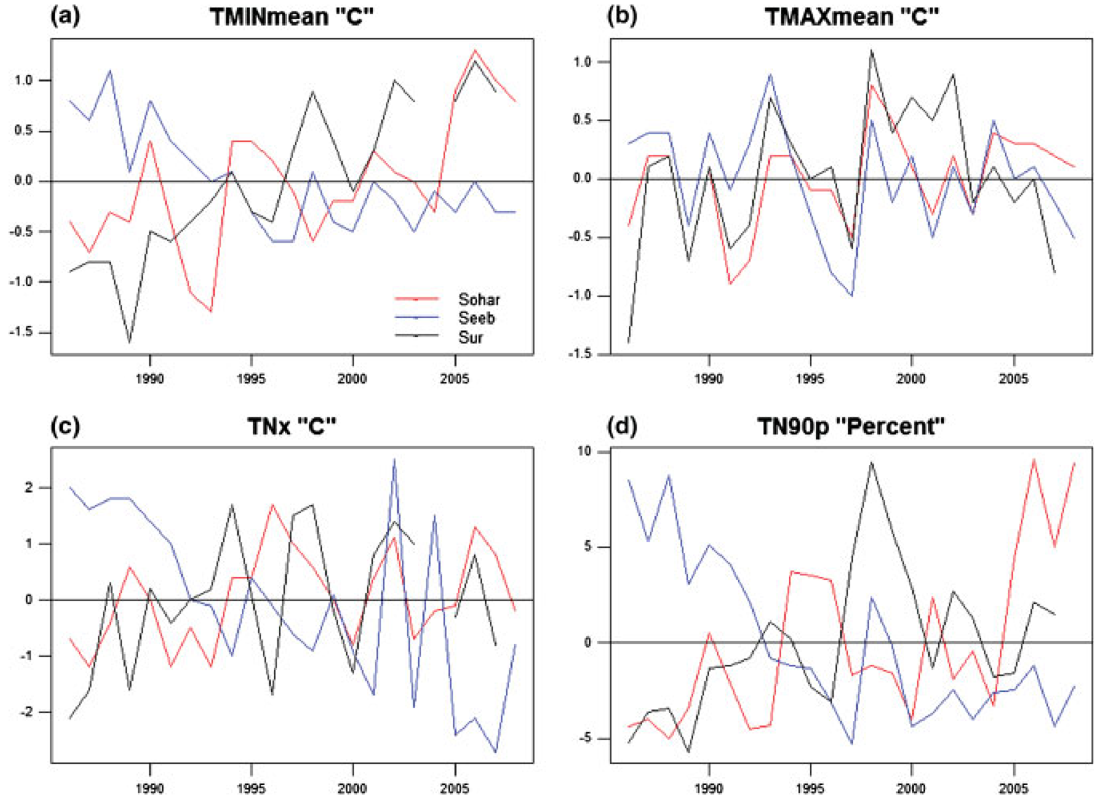

Figure 1. Seeb station annual time series (blue) relative to neighbouring stations Sohar (red) and Sur (black) for (a) TMINmean, (b) TMAXmean, (c) TNx and (d) TN90p extreme indices.

temperature at Seeb is also lower post 1994. A probable reason for such variation is the relocation of the station to a new site at the aerodrome approximately 1.5 km from the old site in 1994 (the station relocation is not documented in the station metadata). We decided to exclude Seeb station given this background. Although Seeb temperature variables have been excluded from the analysis we use Seeb precipitation data as they are deemed to be correct and homogeneous.

2.2. Homogeneity checks

A homogeneous climate time series is defined as one where variations are caused only by variations in climate (Conrad and Pollak, 1950). Data homogeneity is assessed using the RHtestV3 software (available from http://cccma.seos.uvic.ca/ETCCDI/), which uses a two-phase regression model to check for multiple step change points that could exist in a time series (Wang, 2003; Wang, 2008). The two-phase regression model was applied to daily maximum, minimum temperatures as well as the daily precipitation. Most change points were found to be physically real, as with similar studies (Peterson *et al.*, 1998; Alexander *et al.*, 2006; AlSarmi and Washington, 2011). For example most of the jump points are detected in the strongest El Nino years 1982, 1997 and 1998. Table 1 summarizes some of these significant change points showing the station, the date and the variable. Several stations share potential common change point dates.

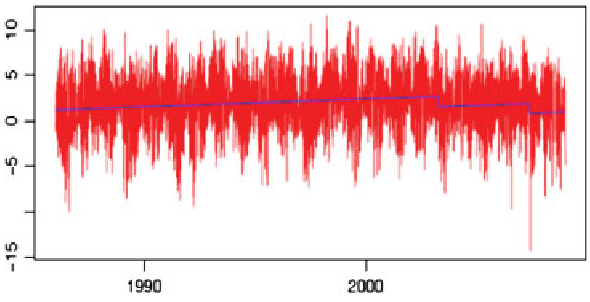

Figure 2. Sur station daily maximum temperature changepoints.

The RHtestV3 detected two significant (at 0.05 level) change points of the original daily maximum temperature of Sur station. These change points have been confirmed with the station metadata and coincide with station relocation dates. The dates of the two significant change points are 20030414 and 20070516 which are clear from the plot in Figure 2.

The decision was made to use the adjusted Sur daily maximum temperature – an approach adopted in other studies (e.g. Frich *et al.* (2002) Australia; Alexander *et al.* (2006) former USSR). Figure 3 shows Sur mean annual maximum temperature of the original (red) and the adjusted (blue) values. In general the variability of both annual time series look similar with lower values (by 2.0 °C) in the adjusted time series from the beginning of the period until 2002. The reduction in temperature

Table 1. Details of significant detected changepoints showing years, stations, variables and dates.

Year	Station	Variable	Date (year.month.day)
1982	Al-Madinah	MaxT	1982.01.30
	Dhahran	MaxT	1982.02.04
	Riyadh	MaxT	1982.02.03
	Al-Taif	MaxT	1982.01.31
	Jeddah	MaxT	1982.01.31
	Sharjah	MaxT	1982.02.08
1997	Gizan	MaxT	1997.05.19
	Sohar	MaxT	1997.05.16
	Salalah	MaxT	1997.06.14
	Sharjah	MinT	1997.06.14
	Salalah	MaxT	1997.06.12
	Masirah	MaxT	1997.07.04
	Saiq	MinT	1997.07.08
	Salalah	MinT	1997.07.03
1998	Bahrain	MaxT	1998.03.23
	Bisha	MaxT	1998.03.12
	Hail	MaxT	1998.04.09
	Riyadh	MaxT	1998.03.10
	Dubai	Precipitation	1998.03.08
	Ras Alkhaimah	MaxT	1998.03.14
	Sharjah	MaxT	1998.03.13
	Doha	MaxT	1998.03.12
	Khasab	MaxT	1998.03.16
	Khamis Mushait	MaxT	1998.03.12
	Kuwait	MaxT	1998.04.07
	Saiq	MaxT	1998.03.16
	Sohar	MaxT	1998.03.21

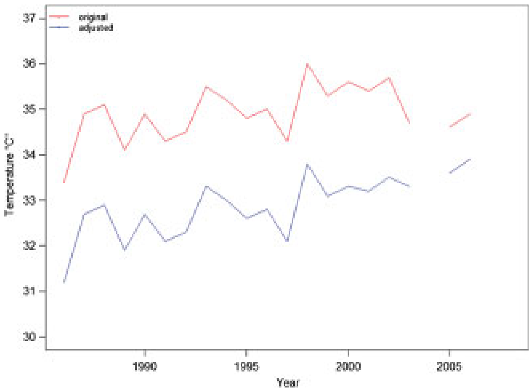

Figure 3. Sur mean annual maximum temperature of the original (red) and the adjusted (blue) time series.

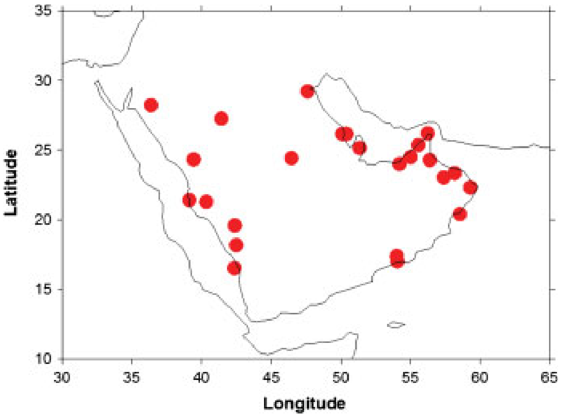

Figure 4. The distribution of 24 stations used in this study in the Arabian Peninsula.

between 2002 and 2003 is lower in the adjusted time series (0.2 °C) than the original time series (1.0 °C). After quality control and the homogeneity testing evaluations, ten stations were retained from Saudi Arabia, eight stations from Oman (the remaining 16 stations were mainly excluded because of their short record), three from UAE and one station from Qatar, Bahrain and Kuwait. The final list of stations is summarized in Table 2 where details of station locations, name, period and missing percentage (%) are listed. As the analysis will cover three periods, the period longer than 1970–2008 will use data from four stations (each of different length); the period 1970–2008 will use data from nine stations (11 stations for precipitation) while 1986–2008 will use data from 23 stations (24 for precipitation which includes Seeb). The station locations are shown in Figure 4.

3. Methods

3.1. Indices calculations

RClimDex software was used to calculate climate indices from the daily data. The ETCCDI recommend a total of 27 core indices, 11 precipitation and 16 temperature indices. Table 3 summarizes the temperature and precipitation climate extreme indices used in this study. These

Table 2. Station location, name, period and missing percentage (%).

Country	Station	WMO	Latitude	Longitude	Elevation(m)	Variable (period, missing)		
						MaxT	MinT	Precipitation
Oman	Khasab	41240	26.20	56.23	33.0	1986–2008 (5.3)	1986–2008 (5.4)	1986–2008 (6.1)
	Sohar	41246	24.28	56.38	3.6	1986–2008 (0.0)	1986–2008 (0.0)	1986–2008 (0.0)
	Saiq	41254	23.04	57.38	1755.0	1986–2008 (1.1)	1986–2008 (1.1)	1986–2008 (2.1)
	Seeb	41256	23.35	58.17	8.4	Nil	Nil	1986–2008 (1.1)
	Sur	41268	22.32	59.28	14.0	1986–2008 (0.7)	1986–2008 (0.7)	1986–2008 (0.7)
	Masirah	41288	20.40	58.54	19.0	1986–2008 (1.0)	1986–2008 (1.0)	1943–2008 (1.2)
	Thumrait	41314	17.40	54.01	467.0	1986–2008 (0.2)	1986–2008 (0.2)	1986–2008 (0.2)
	Salalah	41316	17.02	54.05	22.0	1943–2008 (24.2)	1943–2008 (24.2)	1943–2008 (13.6)
UAE	Ras Alkhaimah	41184	25.37	55.56	31.0	1979–2008 (0.0)	1979–2008 (0.0)	1979–2008 (0.8)
	Dubai	41194	25.15	55.20	5.0	1979–2008 (0.0)	1979–2008 (0.0)	1979–2008 (0.0)
	Sharjah	41196	25.20	55.31	33.0	1979–2008 (0.0)	1979–2008 (0.0)	1979–2008 (10.0)
Bahrain	Bahrain	41150	26.16	50.39	2.0	1950–2008 (0.0)	1950–2008 (0.0)	1950–2008 (0.0)
Qatar	Doha	41170	25.15	51.34	11.0	1986–2008 (0.0)	1986–2008 (0.0)	1986–2008 (1.1)
Kuwait	Kuwait	40582	29.22	47.59	6.1	1962–2008 (2.2)	1962–2008 (2.2)	1962–2008 (4.0)
Saudi Arabia	Tabuk	40375	28.23	36.36	768.1	1986–2008 (0.0)	1986–2008 (0.0)	1986–2008 (0.0)
	Hail	40394	27.26	41.41	1001.5	1970–2008 (5.2)	1970–2008 (5.2)	1970–2008 (5.2)
	Dhahran	40416	26.16	50.10	16.8	1970–2008 (2.6)	1970–2008 (2.6)	1970–2008 (2.6)
	Al-Madinah	40430	24.33	39.42	635.6	1970–2008 (5.4)	1970–2008 (5.4)	1970–2008 (5.4)
	Riyadh	40438	24.42	46.44	619.6	1970–2008 (5.4)	1970–2008 (5.4)	1970–2008 (5.1)
	Jeddah	41024	21.42	39.11	16.9	1970–2008 (3.4)	1970–2008 (3.4)	1970–2008 (2.6)
	Al-Taif	41036	21.29	40.33	1452.8	1970–2008 (5.3)	1970–2008 (5.3)	1970–2008 (5.2)
	Bisha	41084	19.59	42.38	1162.0	1970–2008 (5.2)	1970–2008 (5.2)	1970–2008 (5.2)
	Khamis Mushait	41114	18.18	42.48	2055.9	1986–2008 (0.4)	1986–2008 (0.0)	1986–2008 (0.0)
	Gizan	41140	16.53	42.35	7.2	1986–2008 (0.4)	1986–2008 (0.4)	1986–2008 (0.4)

Table 3. List all the ETCCDMI climate indices calculated by RClimDex used in this study.

ID	Descriptive name	Definitions	Units
SU40	Very warm days	Annual count when TX (daily maximum) > 40 °C	Days
TR25	Very warm nights	Annual count when TN (daily minimum) > 25 °C	Days
TXx	Warmest day	Monthly maximum value of daily maximum temperature	°C
TNx	Warmest night	Monthly maximum value of daily minimum temperature	°C
TXn	Coldest day	Monthly minimum value of daily maximum temperature	°C
TNn	Coldest night	Monthly minimum value of daily minimum temperature	°C
TN10p	Cold night frequency	Percentage of days when TN < 10th percentile	%
TX10p	Cold day frequency	Percentage of days when TX < 10th percentile	%
TN90p	Warm night frequency	Percentage of days when TN > 90th percentile	%
TX90p	Warm day frequency	Percentage of days when TX > 90th percentile	%
TMAXmean	Mean maximum	Monthly mean value of daily maximum temperature	°C
TMINmean	Mean minimum	Monthly mean value of daily minimum temperature	°C
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C
RX1day	Max 1-d precipitation amount	Monthly maximum 1-d precipitation	mm
R10	Number of heavy precipitation days	Annual count of days when PRCP > =10 mm	Days
CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR > =1 mm	Days
R95p	Very wet days	Annual total PRCP when RR > 95th percentile	mm
R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR > =1 mm)	mm

include core and locally defined thresholds indices which are robust and dependent on the AP local climate. Seven precipitation indices and 13 temperature indices were calculated. One additional index has been calculated which is not directly computed by RClimdex, the annual contribution from wet days (R95pT) following Alexander *et al.* (2006).

As more than 60% of the stations have data starting in the mid-1980s and in order to maximize the number of stations available for study, a base period of 1986–2008 has been used for calculating the percentile based indices. Stations to be included in the analysis have at least 20 years of data within this base period and pass the QC and homogeneity tests.

3.2. Area averaging

The trends were calculated for individual stations and for regionally average anomaly series for each index. The area average time series for all AP, non-monsoonal/monsoonal sub-regions were created as follows: first an arithmetical base period mean was calculated for all the stations (the base period 1986–2008) and the anomalies from this mean were computed for each station. The regional averaged series were calculated by simple averaging of all the anomalies. Similar methods have been adapted by Aguilar *et al.* (2009), New *et al.* (2006) and AlSarmi and Washington (2011) to avoid the domination of stations with high mean values. The station anomaly time series were obtained relative to the 23-year base period of 1986–2008, this is following Jones and Moberg (2003) who used at least 20 years of data within the 30-year period to calculate the normal.

It is important to emphasize that the regional average indices time series during the period 1970–2008 were obtained from 9 stations located further north in the AP, namely Bahrain, Kuwait, Riyadh, Hail, Dhahran, Al-Madinah, Jeddah, Al-Taif and Bisha (in addition to Salalah and Masirah for precipitation), so these are less representative of the whole region. However during the period 1986–2008 the spatial distribution of the stations allows better representation of the whole region since an additional 14 stations are added mainly from locations located further south in the AP, namely Ras AlKhaimah, Dubai, Sharjah, Doha, Tabuk, Khamis Mushait, Gizan, Khasab, Sohar, Saiq, Sur, Masirah, Salalah and Thumrait. Furthermore in addition to the calculation of all the regional time averages, two more subregional time series were produced for the period 1986–2008, namely the non-monsoonal region (north of 20 °N) and the monsoonal region (south of 20 °N) following AlSarmi and Washington (2011).

3.3. Trend calculation

Trends for stations and regional time series are computed using the Kendall's slope estimator which is proposed by Sen (1968). This method is based on Kendall's rank correlation and is defined as the median of the slopes obtained from all joining pairs in the series. This is a robust approach which is resistant to outliers and does not assume any underlying probability distribution of the data series. The method has been widely used to compute trends in climate studies (Zhang *et al.*, 2005; Alexander *et al.*, 2006; Aguilar *et al.*, 2009; Butt *et al.*, 2009; AlSarmi and Washington, 2011).

The significance of the trend is determined using Mann–Kendall's test but with a modification to account for lag-1 autocorrelation in the time series residuals using the technique described in Zhang *et al.* (2005). Details of this method are given by Wang and Swail (2001). The trends were computed only if less than 25% of the values were missing. The 5% level of statistical significance is used. Annual and seasonal trends are calculated for all the stations and regions (subregions) and for all the time periods.

4. Results

Table 4 summarizes all the AP regional (subregions) annual temperature and precipitation extreme indices

Table 4. Trends per decade for the regional indices of temperature and precipitation extremes (values for trends significant at 5% level are shown in boldface).

	1970–2008	1986–2008		
Index	All AP	All AP	NMON	MON
SU40	**10.4** (5.4, 18.2)	**6.9** (−10.7, 23.9)	**9.5** (−1.2, 22.3)	1.5 (−10.7, 23.9)
TR25	**6.1** (3.3, 17.7)	**15.1** (0.0, 35.9)	**14.7** (0.0, 35.9)	**15.3** (0.0, 25.7)
TXx	**0.6** (0.2, 0.8)	**0.4** (−0.3, 1.2)	**0.5** (−0.1, 1.2)	0.4 (−0.3, 0.7)
TXn	0.2 (−0.1, 0.6)	0.0 (−0.9, 1.3)	0.1 (−0.9, 1.3)	−0.1 (−0.7, 0.8)
TNx	**0.4** (0.1, 0.7)	**0.7** (−0.2, 1.2)	**0.6** (−0.2, 1.2)	**0.8** (−0.1, 0.9)
TNn	0.0 (−0.3, 0.6)	0.2 (−1.4, 1.3)	0.1 (−1.4, 1.3)	0.6 (0.1, 1.3)
TN10p	**−3.3** (−5.8, −0.2)	**−3.0** (−6.8, 1.1)	**−3.0** (−6.8,1.1)	**−3.3** (−4.3, −1.3)
TX10p	**−6.1** (−8.5, −3.7)	−1.2 (−5.6, 1.9)	−1.5 (−5.6, 0.2)	−0.2 (−3.6, 1.9)
TN90p	0.7 (−0.4,2.4)	**3.6** (−1.2, 12.7)	**3.7** (−1.2, 12.7)	**2.7** (1.1, 5.9)
TX90p	**2.2** (0.8,3.7)	**1.9** (−8.6, 5.7)	**3.0** (0.8, 5.7)	0.6 (−8.6, 5.7)
DTR	**0.3** (−0.3,0.6)	−0.1 (−1.1, 0.6)	0.1 (−0.9, 0.6)	−0.4 (−1.1, 0.3)
TMAXmean	**0.6** (0.3,0.9)	**0.3** (−0.5, 1.3)	**0.4** (−0.2, 1.3)	0.0 (−0.5, 0.8)
TMINmean	**0.3** (−0.1,0.6)	**0.5** (−0.3, 1.4)	**0.6** (−0.3, 1.4)	**0.5** (0.1, 0.8)
RX1day	0.6 (−1.3,3.4)	−6.4 (−21.7, 8.7)	−4.8 (−21.7, 7.5)	−4.6 (−6.9, 8.7)
R10	0.1 (−0.4,0.4)	**−0.6** (−5.6, 0.9)	−0.7 (−5.6, 0.9)	0 (0, 0)
CDD	1.9 (−8.6,20.0)	16.9 (−28.0, 33.3)	5.7 (−28.0, 33.3)	7.7 (−9.7, 30.0)
CWD	−0.1 (0.0,0.0)	−0.2 (−1.2, 0.1)	−0.2 (−1.2, 0.1)	−0.2 (0.0, 0.0)
R95p	−0.1 (−2.7,1.6)	−7.0 (−18.1, 13.3)	−2.5 (−18.1,13.3)	−4.9 (−13.3, 0.0)
R95pT	1.7 (0.0,0.6)	−2.2 (−4.6, 3.1)	−0.1 (−4.6, 3.1)	−0.7 (−4.6, 0.0)
R99p	−0.4 (0.0,0.0)	0.8 (0.0,0.0)	0.6 (0.0, 0.0)	0 (0.0, 0.0)
PRCPTOT	1.5 (−15.8,12.3)	−20.4 (−153.0, 17.3)	−19.8 (−153.0, 17.3)	−8.1 (−34.9, 12.6)

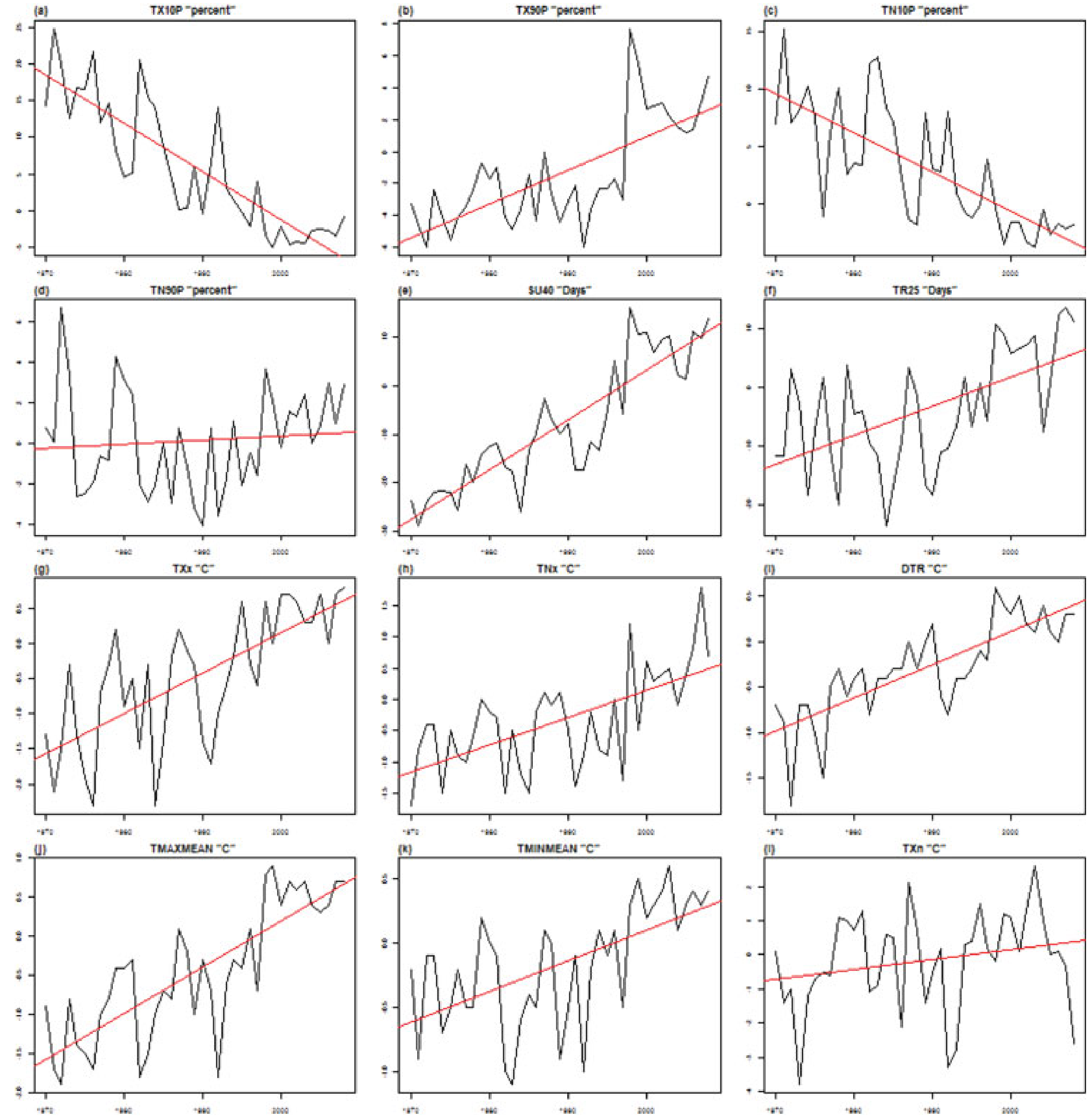

Figure 5. All AP regionally averaged anomaly (a–l) series (relative to the mean for 1986–2008) of temperature extreme indices with linear trends for 1970–2008 (red).

trends during 1970–2008 and 1986–2008. Trends in temperature extremes in the two periods are consistent in sign and significance although magnitude varies. However the precipitation extreme trends show some changes in sign especially in the latter period where more negative trends are reported. Most of the precipitation trends are not significant in the two periods except the number of heavy precipitation days (R10) in the 1986–2008 period.

4.1. Period 1970–2008

Trends for the temperature indices revealed significant changes associated with warm extremes increasing and cold extremes decreasing. These results clearly indicate significant warming. The warming trend is greater for daytime indices than for those of night-time indices. Regional averages of cold day frequency (TX10p), warm day frequency (TX90p), cold night frequency (TN10p), warm night frequency (TN90p), very warm days (SU40), very warm nights (TR25), warmest day (TXx), warmest night (TNx), diurnal temperature range (DTR), mean maximum temperature (TMAXmean), mean minimum temperature (TMIN mean) and coldest day (TXn) all display trends consistent with warming (Figure 5(a)–(l)).

For the percentile-based temperature indices (TX10p, TN10p, etc.), the individual stations show most spatial coherence in the cold day frequency (TX10p). All the stations indicate a significant decrease over the 1970–2008 period (Figure 6) pointing to the region-wide decrease in occurrence of cold extremes. There were also large

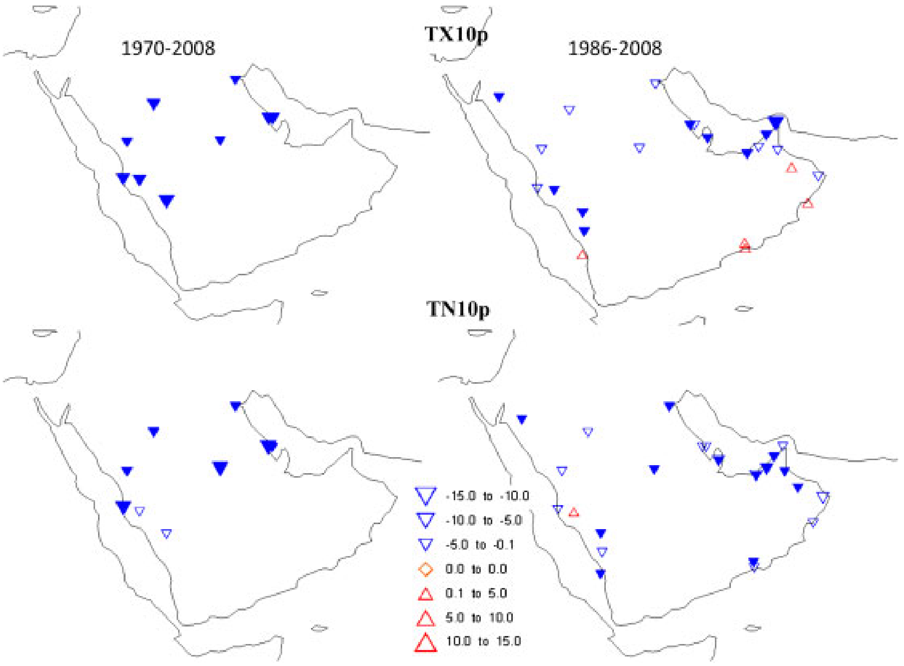

Figure 6. Annual TX10p (top row) and TN10p (bottom row) trends in the Arabian Peninsula in percentage per decade for the period 1970–2008 (left column) and 1986–2008 (right column). Upward red triangles represent increasing trends while downward blue triangles decreasing trends. The slope of the increasing/decreasing trend is proportional to the size of the triangles. Shaded triangles are statistically significant at the 5% level.

significant reductions in the frequency of cold nights (TN10p) over the 39 years (Figure 6). The frequency of warm days (TX90p) relative to 1986–2008 has increased significantly and this rate of increase is higher than that of warm nights (TN90p). All the stations reported positive trends in the TX90p with 78% significant while of the TN90p, 89% reported positive trends with 44% significant (Figure 7).

Both annual counts of days with very warm days (SU40) and annual counts of nights with very warm nights (TR25) show strong significant increasing trends with a greater increase of warm days compared with warm nights. All stations reported significant trends in the SU40 (Figure 8). For the absolute temperature indices (TXx, TNx, etc.), the trend is positive and significant in the warm tail of the daily maximum and minimum temperature while the cold tail shows insignificant to zero trends. The trend in mean maximum temperature (TMAXmean) has increased significantly and is twice the mean minimum temperature (TMIN mean) which leads to a significant positive increase in the diurnal temperature range (DTR); 89% of the stations show positive trends in the DTR while none of the stations reported significant negative trends (Figure 9).

During 1970–2008, the trend magnitudes and the percentage of stations with statistically significant trends are highest in summer (MJ and JAS) and autumn (ON). The trends are lower with fewer significant stations in the DJF season.

In contrast to the temperature indices, no significant trends in any of the precipitation indices over the period 1970–2008 are found (Table 4). The AP region is characterized by large interannual variability in comparison to trends. Figure 10 shows the annual station trends map of the total precipitation (PRCPTOT) and the consecutive dry days (CDD) as an example of lack of spatial coherence. Almost no significant changes occurred. There is an increasing trend in the regional annual total precipitation (PRCPTOT) but this is insignificant. In agreement with the increase of the total precipitation, the consecutive dry days (CDD), the max 1-d precipitation amount (RX1day) and the number of heavy precipitation days (R10) also all increase. The percentile measures of heavy precipitation (i.e. rainfall >95th (very wet) percentile and >99th (extremely wet)) are decreasing but the trends are not significant.

4.2. Period 1986–2008

The regional annual average results for the period 1986–2008 are shown in Table 4. The trend pattern is broadly similar to the period 1970–2008 with notable significant changes in temperature extremes associated with warm extremes increasing and cold extremes decreasing which indicates significant warming. However unlike the period 1970–2008, the warming trend for the period 1986–2008 is higher for night-time indices than for those of daytime indices.

For the percentile-based temperature indices, over all the AP, increases in frequency of warm nights (TN90p) shows the most spatial coherence. About 96% of the stations reported increases in the TN90 with 61% having statistically significant increases at 0.05 level (Figure 7).

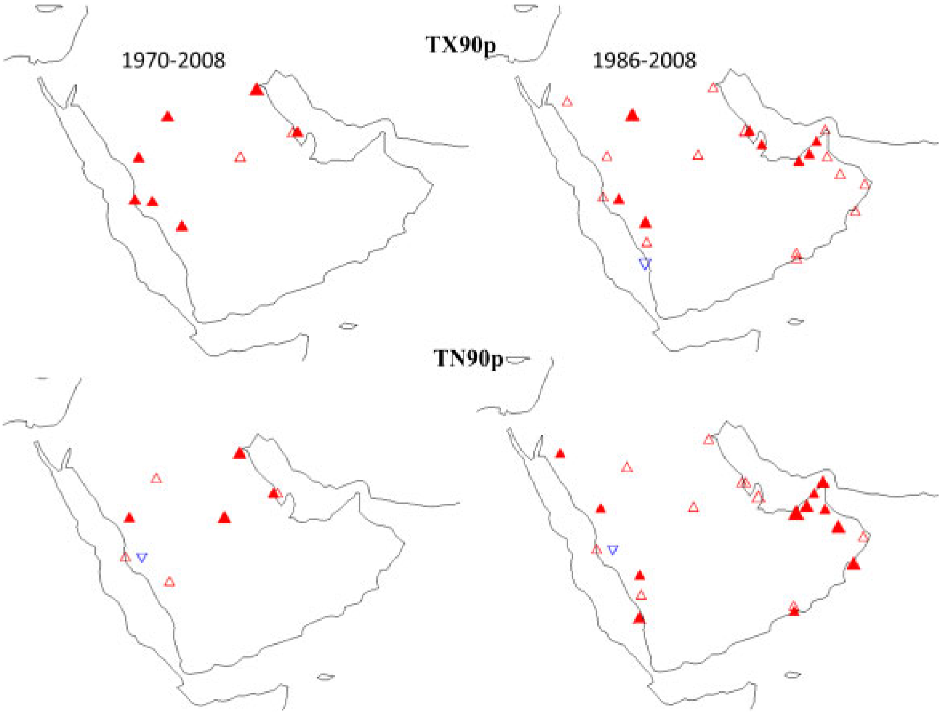

Figure 7. Same as Figure 7, but trends for TX90p and TN90p.

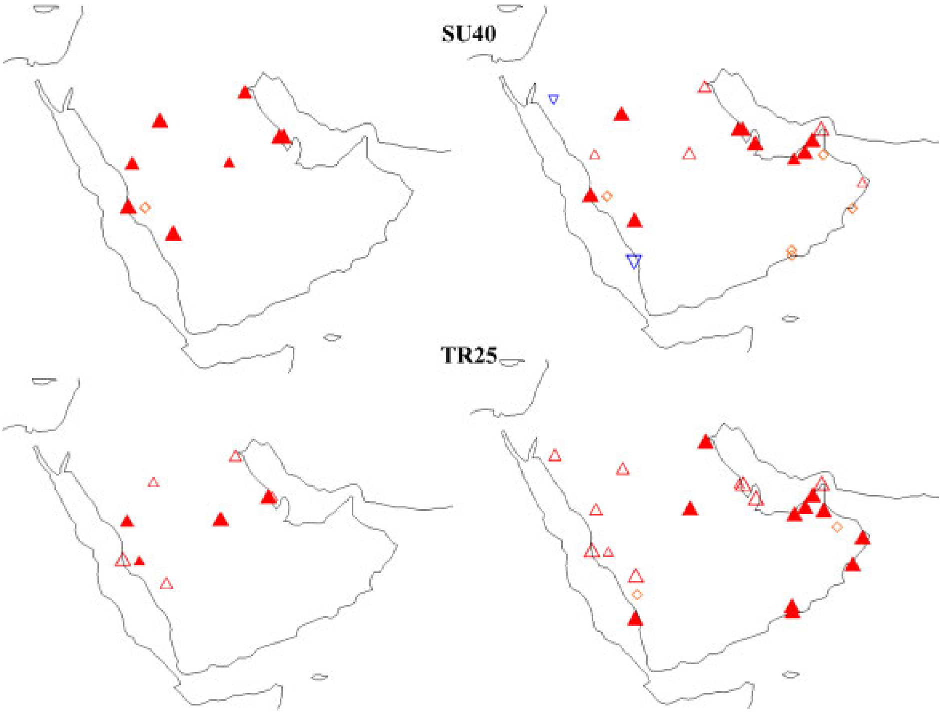

Figure 8. Same as Figure 7, but trends for SU40 and TR25.

The TN90p shows a similar pattern of trends in both the non-monsoonal and monsoonal subregions with the largest increase for the former. The frequency of warm days (TX90p) has increased significantly but at a lower rate than the warm nights frequency (TN90p). The non-monsoonal region shows the largest increase in TX90p. While there were similar significant reductions in the frequency of cold nights (TN10p) over all the regions, interestingly the cold day frequency (TX10p) shows no trend.

The increase of the very warm nights (TR25) relative to the very warm days (SU40) is large and significant over all the regions especially over the monsoon region

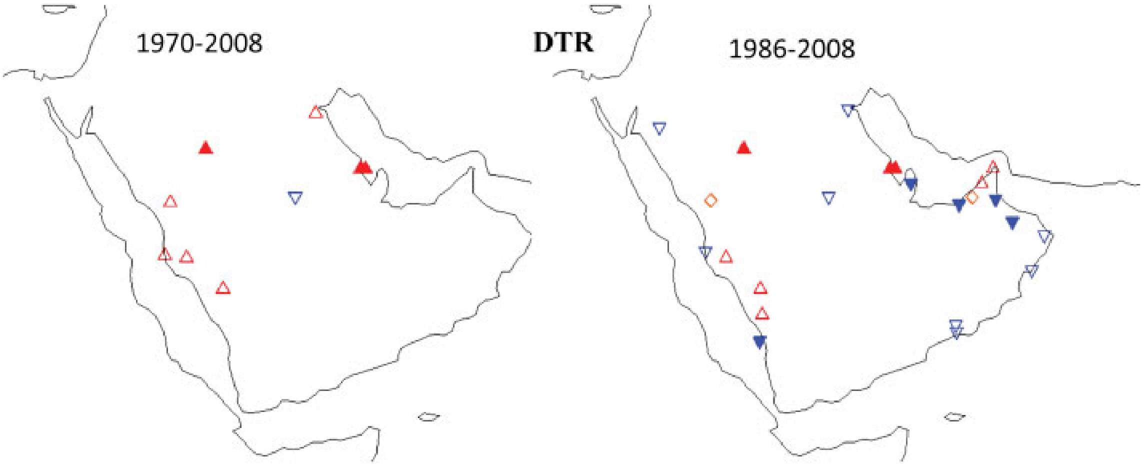

Figure 9. Same as Figure 7, but trends for DTR.

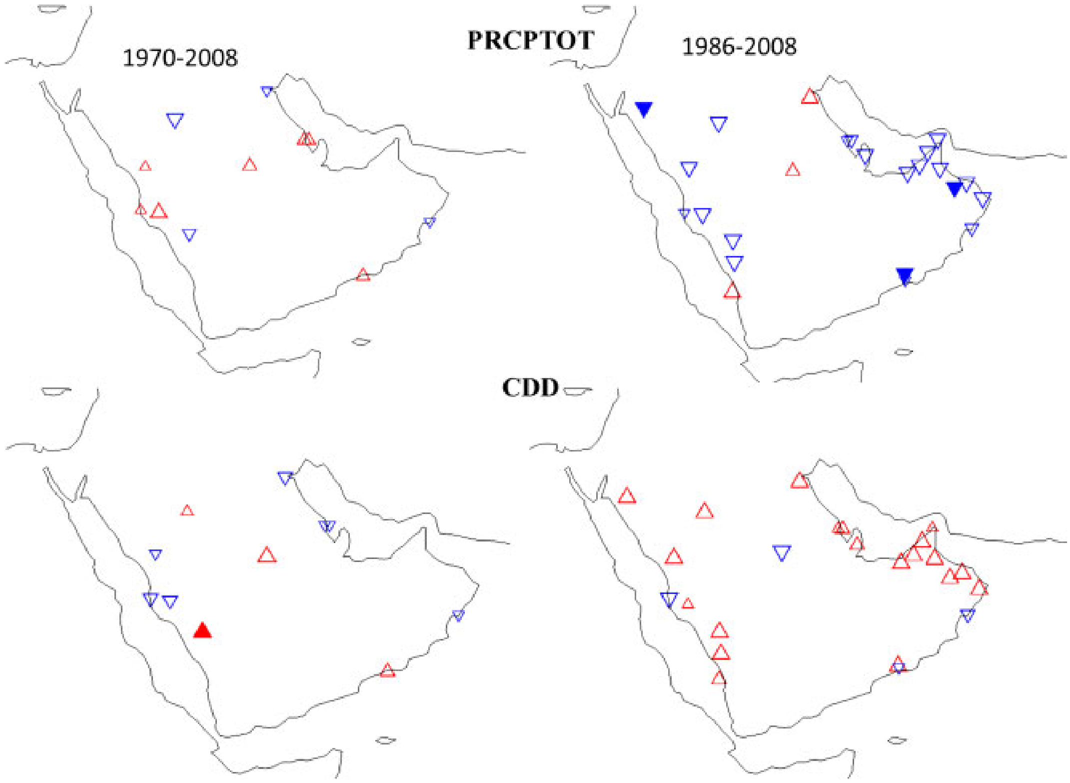

Figure 10. Trends in the annual total precipitation (PRCPTOT) (top row) and the maximum number of consecutive days with RR < 1 mm (CDD) (bottom row) for 1970–2008 (left column) and 1986–2008 (right column). Upward triangles (red) represent increasing trends and downward triangles (blue) decreasing trends. Shaded triangles indicate the statistically significant trends at 0.05 level.

where TR25 is 10 times higher than the SU40. For the absolute temperature indices, the trend is similar to the 1970–2008 period where the regional average is positive and significant in the warm tail of the daily maximum and minimum temperature while the cold tail shows insignificant to zero trend. Over the subregions, the non-monsoonal region has higher trends in both tails for daily maximum temperature relative to the monsoonal region while it is the reverse for daily minimum temperature.

The mean minimum temperature (TMINmean) has increased significantly over all the regions while the mean maximum temperature (TMAXmean) has increased significantly over all and the non-monsoonal regions. The DTR trend is low and insignificant over the AP region and the non-monsoonal regions, however, as the increase of the mean minimum is higher than the mean maximum over the monsoon region, leading to negative though insignificant DTR trends there.

During 1986–2008 the seasons of highest trend magnitude are spring (MA) and summer (JAS, MJ). The winter (DJF) season experiences the weakest trends with the fewest significant stations.

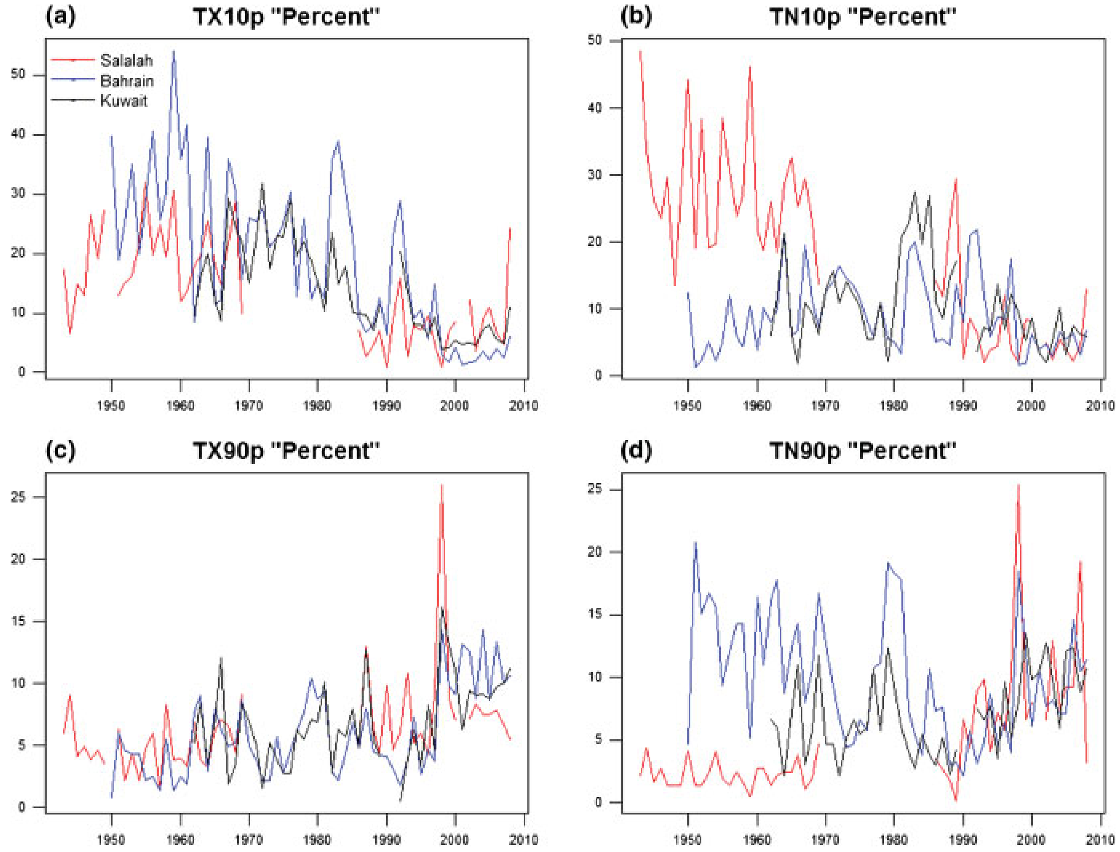

Figure 11. Time series of the annual percentile-based temperature indices [(a) TX10p, (b) TN10p, (c) TX90p, (d) TN90p] for the stations with data longer 1970–2008, Salalah (red), Bahrain (blue) and Kuwait (black).

The only significant trend reported in the precipitation indices over the period 1986–2008 is the number of heavy precipitation days (R10) over all AP region (Table 4). The trends of the precipitation extremes are insignificant with no spatial coherence. The annual station trends map of the total wet-day precipitation (PRCPTOT) and the consecutive dry days (CDD) are shown in Figure 10. As expected from the negative regional annual total precipitation (insignificant), 89% of the stations reported negative trends although only 13% have significant negative trends. Both the consecutive dry days (CDD) and the extremely wet days (i.e. rainfall >99th (very wet) percentile) are increasing but the trends are not significant.

4.3. Longer period

The results for the stations with available records longer than 1970–2008 period are shown in Table 6. For stations located further north in the AP (Bahrain and Kuwait), the highest reported statistically significant trends are observed in the daytime extremes (SU40, TXx, TX10p and TMAXmean). However for Salalah station, located in the south of AP, trends are large and statistically significant in the night-time extremes of TR25, TNn, TN10p and TMINmean. No significant trends in the indices of the precipitation extremes are reported.

Figure 11 shows the variability of the annual percentile-based temperature indices (TX10p, TN10p, TX90p, TN90p) for the stations with data longer than 1970–2008. For the TX10p index all the stations indicate that the decrease started in 1970 and this variation is part of longer-term variations with opposite trends in this index before the middle of last century. Unlike TX10p, the stations time series of the TX90p index show an abrupt jump in 1998. For the night-time percentile-based temperature indices, the pattern is different between north and south AP. For Salalah (south AP), the recent decrease of the TN10p and increase of the TN90p is part of a long-term trend while for Bahrain and Kuwait (north AP) the variability has been decreased markedly over the last 2 decades with a clear decrease in the TN10p and increase in the TN90p.

4.4. Comparisons with previous studies

4.4.1. Period 1970–2008

Trends of extreme indices over the AP during the 1970–2008 period are generally comparable to global and regional studies for a similar period of investigation (Table 5). However, the regional trend for cold day frequency (TX10p) over the AP is notably higher than elsewhere. While changes in warm night frequency (TN90p) in the globe and other regions show a strong statistically increasing trend, the increase over this region

Table 5. Trends of temperature and precipitation extremes from this study (1970–2008) and other sources (trends significant at 0.05 level are in bold).

1970–2008		Global	Middle East	Central and South Asia	Southwestern China	Indo-Pacific	Indo-Pacific
Index	All AP	(1971–2005)	(1970–2003)	(1961–2000)	(1961–2008)	(1971–2005) (All)	(1971–2005) (Indian Ocean)
SU40	**10.4**						
TR25	**6.1**						
TXx	**0.6**	**0.29**	**0.30**	**0.17**	**0.11**	0.02	**0.78**
TXn	0.2	−0.02	**0.60**		**0.13**	0.04	**0.74**
TNx	**0.4**	**0.33**	**0.50**		**0.17**	0.04	**0.94**
TNn	0.0	0.25	**0.60**	**0.73**	**0.29**	0.36	**0.77**
TN10p	**−3.3**	**−1.42**	**−2.50**	**−5.70**	**−0.37**	**−2.14**	**−2.11**
TX10p	**−6.1**	**−0.95**	**−0.20**	**−2.60**	**−0.13**	**−1.44**	**−2.04**
TN90p	0.7	**2.95**	**2.60**	**6.86**	**0.36**	**2.46**	**3.85**
TX90p	**2.2**	**1.64**	**2.40**	**4.72**	**0.22**	**2.30**	**4.36**
DTR	**0.3**	−0.08	−0.01	**−0.12**	**−0.18**	0.11	**0.26**
TMAXmean	**0.6**						
TMINmean	**0.3**						
RX1day	0.6	0.26	0.00	1.02	**0.05**	−1.12	1.12
R10	0.1	0.03	0.00	0.11	0.00	−0.14	2.09
CDD	1.9	**−1.19**	3.60		−0.05	−1.01	0.66
CWD	−0.1	**−0.07**			**−0.08**	−0.13	0.10
R95p	−0.1	**4.68**	−6.00	**6.46**	0.04	12.24	22.66
R95pT	1.7						
R99p	−0.4	**3.38**	−3.30	3.01	**0.05**	4.98	−12.61
PRCPTOT	1.5	5.91	**−24.00**	6.87	0.03	−2.86	**81.84**
Data	This study	Caesar *et al.* (2011)	Zhang et al. (2005)	Klein Tank et al. (2006)	Zongxing et al. (2012)	Caesar *et al.* (2011)	Caesar *et al.* (2011)

Table 6. Trends of temperature and precipitation extremes from this study (longer 1970–2008) and other sources (trends significant at 0.05 level are in bold).

Index	Kuwait (1962–2008)	Bahrain (1950–2008)	Salalah (1943–2008)	Masirah (1943–2008)	Global (1950–2003)	Middle East (1950–2003)	Western central Africa (1955–2006)
SU40	**5.9**	**6.6**	0.00				
TR25	3.5	1.1	**12.0**				
TXx	**0.5**	**0.6**	0.5		**0.21**	0.07	**0.25**
TXn	0.5	0.1	0.0		0.37	0.20	**0.13**
TNx	**0.6**	0.0	**0.2**		**0.30**	**0.23**	**0.21**
TNn	0.1	**−0.3**	**0.2**		**0.71**	**0.28**	**0.23**
TN10p	−1.5	−0.2	**−4.1**		**−1.26**	**−1.30**	**−1.71**
TX10p	**−3.9**	**−5.1**	**−2.2**		**−0.62**	−0.40	**−1.22**
TN90p	**1.1**	**−1.2**	**1.1**		**1.58**	**1.20**	**3.24**
TX90p	**1.1**	**1.0**	**0.5**		**0.89**	**0.66**	**2.87**
DTR	0.2	**0.4**	**−0.1**		**−0.08**	**−0.12**	0.00
TMAXmean	**0.4**	**0.4**	**0.1**				
TMINmean	0.2	−0.1	**0.3**				
RX1day	2.6	0.6	0.2	0.4	**0.85**	0.00	−0.87
R10	0.0	0.0	0.0	0.0	**0.29**	−0.03	−0.67
CDD	−4.5	−2.1	4.8	−11.6	−0.55	**−5.00**	−0.06
CWD	0.0	0.0	−0.2	0.0	−0.02		−0.35
R95p	1.4	0.0	0.0	0.0	**4.07**	−0.30	−12.19
R95pT	0.7	0.0	0.0	0.0			
R99p	0.0	0.0	0.0	0.0	**2.52**	−1.60	−3.66
PRCPTOT	10.1	4.6	−1.0	0.3	**10.59**	−0.30	**−31.13**
Data					Alexander et al (2006)	Zhang et al. (2005)	Aguilar et al. (2009)

is low and insignificant. The significant increase of the DTR in this region is similar to the Indian Ocean region (Caesar *et al.*, 2011). As none of the regional average precipitation extreme indices shows significant change in this region over 1970–2008, the comparison with the globe and other regions is difficult.

4.4.2. Period longer than 1970–2008

In comparison with the global or regional results, the trends of the stations over north AP over the longest period of analysis have larger significant trends than elsewhere in many daytime temperature indices as TXx, and TX10p. Over the south AP, the TN10p is notably higher than elsewhere. The significant increase of the DTR over Bahrain in the north of the AP is in contrast to the global and other regions (Table 6).

5. Discussion

Compared with temperature extremes, the trends of the precipitation extremes over the AP are low and not significant. This is in line with AlSarmi and Washington (2011), Zhang *et al.* (2005) and Kwarteng *et al.* (2009). Precipitation is dominated by large interannual variability (Almazroui *et al.*, 2012b). Only the number of heavy precipitation days (R10) has a statistically significant decreasing trend over all the AP during 1986–2008. The recent decreasing trend in the total annual rainfall over the AP which is supported by a recent study by Almazroui *et al.* (2012a) is associated with a significant decrease in the number of heavy precipitation days (R10), an increase in the consecutive dry days (CDD) and an increase in the extremely wet days (R99). These trends suggested that the rainfall in the AP has become more intense with longer dry spells between the more intense events. There is some indication of total precipitation increase over the Red Sea coast during 2000–2009 at Gizan station (insignificant) which is in line with Almazroui *et al.* (2012b).

The regional trends for cold day frequency (TX10p) over the AP (especially over the northern areas) during 1970–2008 and the longer period is markedly higher than the globe and other regions for almost the same period. However over Salalah station during 1943–2008 (south AP), the TN10p is notably higher than elsewhere. While changes in warm night frequency (TN90p) for the globe and other regions show strong statistically increasing trend during 1970–2008, the increase over this region is low and insignificant. In contrast to the global trend and most other regions, the DTR is significantly increasing over this region during the 1970–2008 period. One similar region reporting significant DTR increases during an almost a similar period (1971–2005), is the

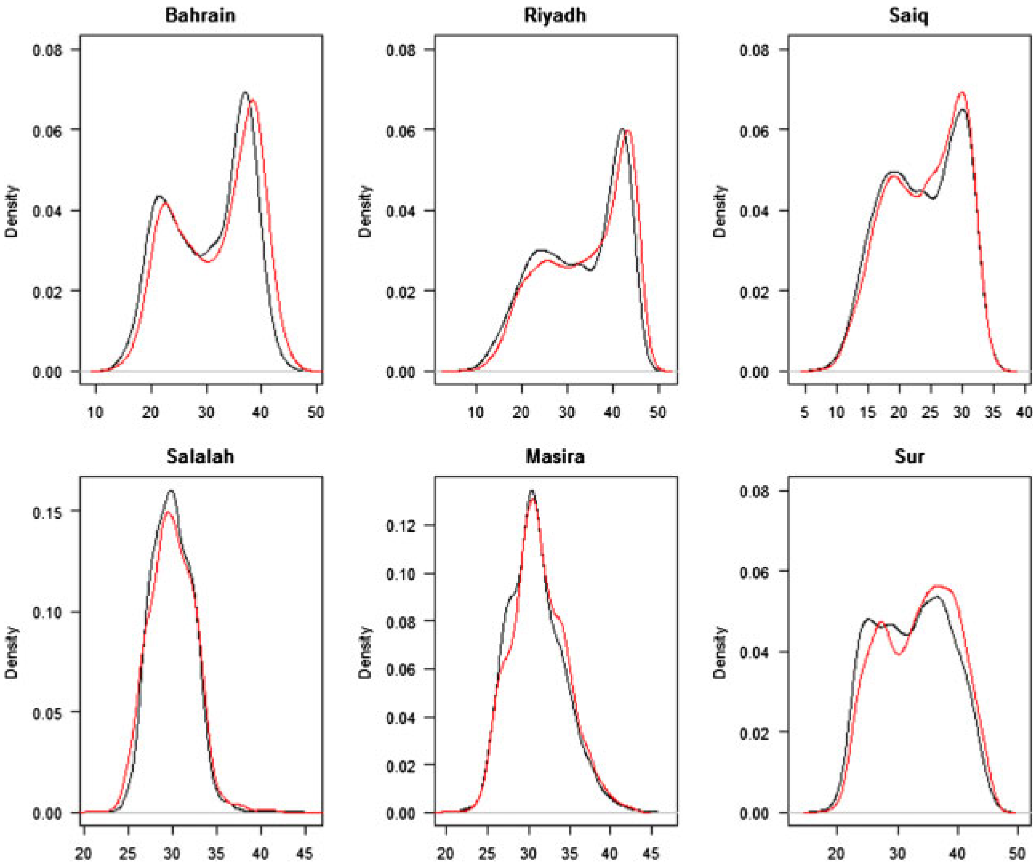

Figure 12. Probability density functions showing change in distribution of the maximum temperature (horizontal axis) of six stations during two periods 1986–1997(black) and 1998–2008(red).

Indian Ocean region (Caesar *et al.*, 2011). An important step in diagnosing this interesting feature of AP climate change is the role of cloudiness. This is, however, beyond the scope of the current study.

In general for the night-time temperature extremes, the regional trend, declining from south to north, potentially indicates the influence of Indian Ocean sea surface temperature on the nearby coastal stations. This spatial difference of the trend pattern between north and south AP is in line with the monthly temperature results by AlSarmi and Washington (2011).

To investigate further the shift in distribution of maximum and minimum temperature over the AP, we compare the Probability Density Functions (PDFs) of selected stations for two different time periods 1986–1997 and 1998–2008. Figures 12 and 13 show the PDFs for six stations located in different parts of the AP. They represent the distribution of maximum and minimum temperatures respectively. Both figures confirm the distribution shift to a warmer pattern during the most recent decade 1998–2008. The minimum temperature shows the most marked shifts towards more warm nights at all the stations. The shift is pronounced over both non-monsoonal and monsoonal areas and covers land, coastal and mountainous stations

The percentage of stations with statistically significant trends in the temperature extremes are higher in summer than in winter, this is in line with Zhang *et al.*(2005). In addition this study shows that during the period 1986–2008, Spring (MA) has a high percentage of stations with statistically significant trends. The change of the regional average DTR trend from positive (significant) during the longer period to negative (insignificant) during 1986–2008, especially in the summer season, is consistent with the increase of the minimum temperature and the lower increase (decrease) of the maximum temperature especially over the monsoon region. One potential component of this change is a possible increase in upwelling in association with strengthening of the southwest monsoon winds (AlSarmi and Washington, 2011). The increase of the southwest monsoon winds may result from the increasing pressure gradient over southern AP due to the summer heat low deepening in the interior of AP, itself a response to warming. To test this, Mean Sea Level pressure (MSLP) trends over the AP were calculated during the period 1986–2008 (Figure 14). In general the pressure is falling over most of the stations particularly in the early summer (MJ) season which reported to have the highest number of stations with large and significant MSLP decreases, as might be expected from a deepening of the heat low. This alone would change the pressure gradient over southern Arabia coast.

To investigate if the recent significant increase of minimum temperature over the AP is related to increasing humidity, the dew point (Td) temperature trends were calculated during the period 1986–2008. Figure 15 reveals

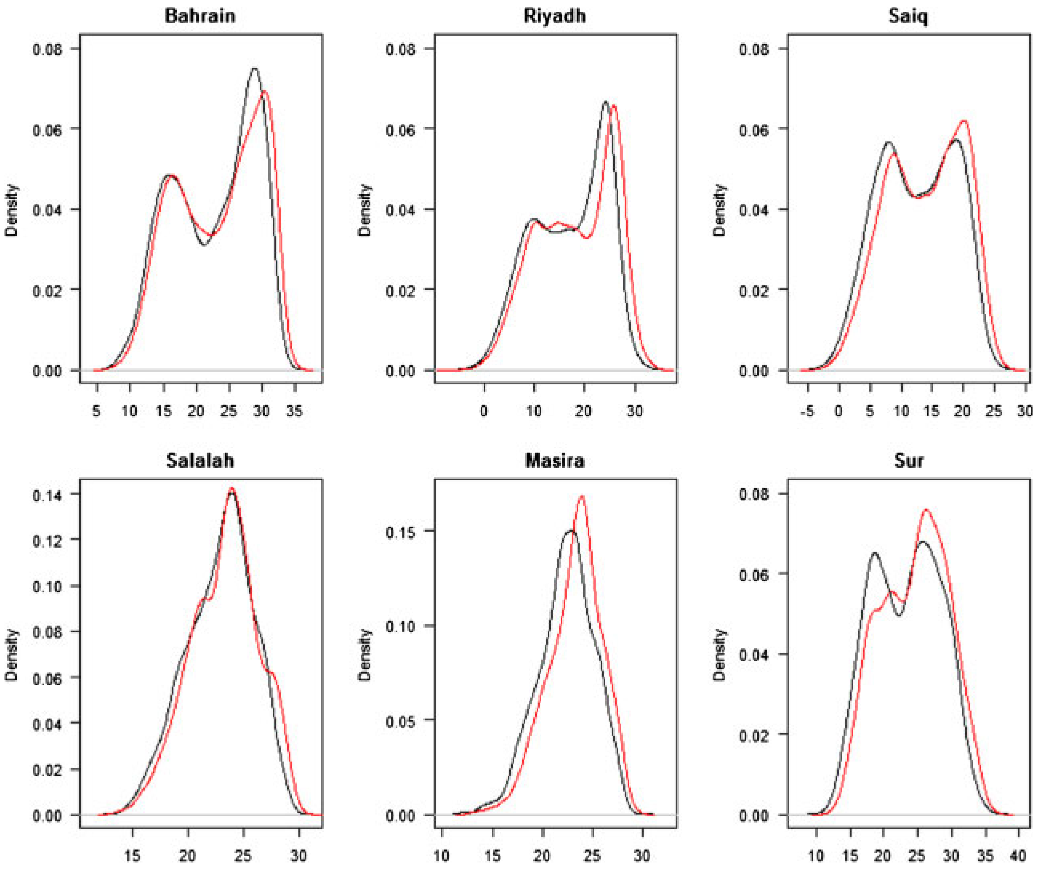

Figure 13. Similar to Figure 13 but for minimum temperature.

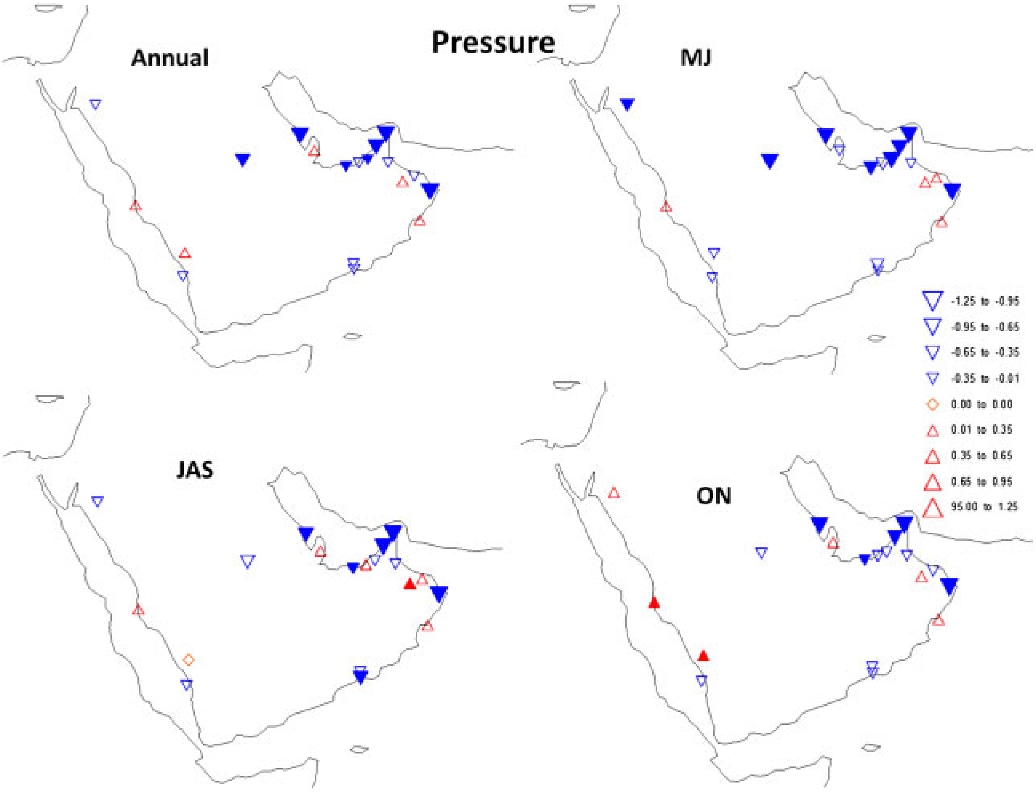

Figure 14. Same as Figure 7, but trends for mean sea level pressure.

significant decreasing Td in the southeast/south AP while the central/southwest AP witnesses significant increasing trends. Such patterns are more pronounced in the annual and late summer season suggesting some possible change has already occurred to the atmospheric circulation/dynamics over central/south AP. The increasing Td over central/southwest AP could accelerate the increase of minimum temperature in these areas. It also supports the recent findings of rainfall increasing along the Red Sea coast during 2000–2009 by Almazroui *et al.* (2012b). However more investigations are needed to explain the increase in the minimum temperature over southeast/south AP in addition to the changes in Td.

6. Conclusion

We have examined a set of temperature and precipitation extreme indices for the Arabian Peninsula derived from daily maximum and daily minimum temperature and daily precipitation amounts. The daily data were obtained for 23 stations for temperature and 24 for precipitation covering 6 countries with different data periods, the longest being from 1943 to 2008. This paper contributes to the evaluation of new trend results for the AP region which has suffered from a dearth of available daily data. The data set has been tested for quality control and carefully assessed for homogeneity.

Although the data coverage is low density (24 stations) and a relatively short time period, a clear picture of climate change in the region has emerged. There is a consistent pattern of trends in daily temperature extremes over the AP that is related to significant warming, with cold extremes decreasing and warm extremes increasing. Annual mean maximum temperature, annual mean minimum, annual highest minimum temperatures as well as annual highest maximum temperatures all had statistically significant increasing trends over AP as a whole. In conjunction, the annual number of very warm days (SU40) and very warm nights (TR25) increased significantly, Furthermore, the annual percentage of days with daily minimum temperature lower than the 10th percentile (TN10p) has a statistically significant decreasing trend, whereas the annual percentage of days with daily minimum temperature higher than the 90th percentile (TN90p) and the annual percentage of days with daily maximum temperature higher than the 90th percentile (TX90p) has statistically significant rising trends in the 3 analysed periods. Trends in precipitation indices are weak and insignificant in general except for the annual count of days when precipitation exceeds 10mm which shows a significant decrease during 1986–2008.

These results generally agree with what has been observed in other parts of the world during the second half of the 20th century (Frich *et al.*, 2002; Alexander *et al.*, 2006). Inspection of trends in dew point temperature show a dipole with increasing humidity in the west AP and decreasing humidity in eastern AP, pointing to the potential for significant dynamical controls on climate change in the region. The findings of this article

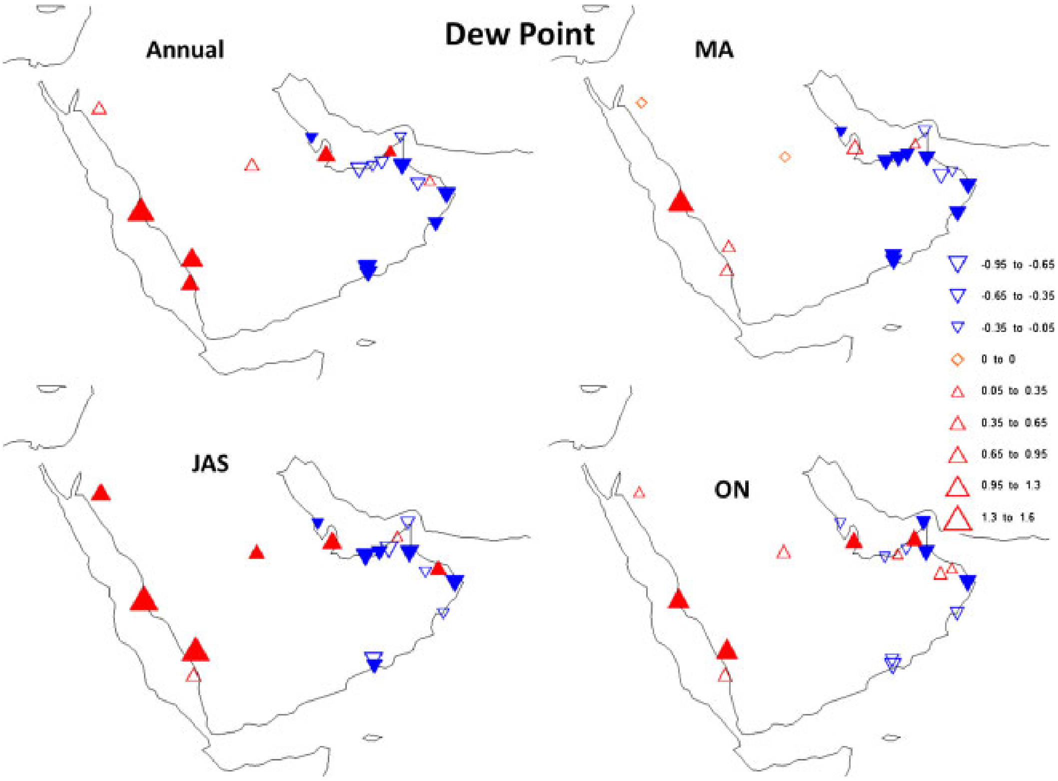

Figure 15. Same as Figure 7, but trends for dew point temperature.

reveal the paramount need to assess how climate extremes will change in the future. The combination of complex ocean–atmosphere interaction and the topography of the region mark the AP out as an important arena for climate model evaluation. A phase of work on regional climate models is underway.

Acknowledgements

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