RECENT CLIMATE CHANGE OVER THE ARABIAN PENINSULA: TRENDS AND MECHANISMS

A thesis submitted to the University of Oxford for the degree of Doctor of Philosophy in Geography and the Environment

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Say, “Indeed, my prayer, my rites of sacrifice, my living and my dying are for Allah, Lord of the worlds.

Quran Al Anam 162

Abstract

The global climate is changing. Compared with many parts of the world, especially North America and Europe, relatively little is known about how climate has changed over the Arabian Peninsula (AP) in recent decades. Quantifying the climate change in the mean and extreme temperature and precipitation variables and understanding the mechanisms behind these changes are essential for establishing adequate and proper adaptation strategies to ensure sustainability, reduce vulnerability and safeguard livelihoods. Four papers in this thesis contribute to that objective, utilising a combination of in situ high quality meteorological station data and high resolution regional climate model data.

The first paper quantifies the trends in monthly, seasonal and annual mean, maximum, minimum temperatures and Diurnal Temperature Range (DTR) variables and total precipitation. The station dataseries are tested for quality control and homogeneity. A non-parametric test is used to calculate the trends and evaluate the trend significance for individual stations, subregions (Non-monsoonal and Monsoonal) and for the whole area average. There is a high significant increase in the temperature variables especially the minimum temperature (during 1980-2008 and over all the AP the trend of annual minimum temperature is 0.55℃ decade^{-1} while the annual maximum temperature trend is 0.32℃ decade^{-1}) which leads to significant decrease in the DTR. The precipitation is decline but insignificantly. The non-monsoonal region located north of 20° N has experienced higher rates of warming than the monsoonal region. Spring and summer seasons witness the highest significant warming. The interannual variability of the AP temperature and precipitation shows marked negative association after 1998.

The second paper utilises the AP daily data of maximum temperature, minimum temperature and precipitation to calculate climate extremes indices, evaluate the regional/subregional trends of these indices and assess the trend significance. There is a clear significant decrease of cold temperature extremes and a significant increase in the warm temperature extremes. The increase in the nighttime temperature extremes is remarkable in the last two decades (the rate of increase of the warm night frequency is 3.6% decade-^{1} during 1986-2008). The spatial trend patterns reveal a latitudinal distinction whereby the northern AP experiences an increase associated with day-time extremes while for the night-time extremes the trends are higher and significant for the southern region. Precipitation indices trends are weak and although they show general decrease in the last two decades they are insignificant. The changes in the Dew Point (Td) and the Mean Sea Level Pressure (MSLP) indicate possible changes in the regional dynamics.

The third paper uses the Providing Regional Climates for Impact Studies (PRECIS) regional climate model forced by the European Centre for ERA-Interim re-analysis (ERA-Interim) to simulate the AP climate during 1990-2008. PRECIS simulation is validated based on climate mean and trends. The model simulation captures the mean climatic conditions and patterns, the increasing temperature tendency, as well as the decreasing precipitation observed in the last two decades. However, PRECIS has cold bias especially with the minimum temperature and it overestimates the precipitation over the high lands or regions close to them over the southwestern mountains and underestimates the precipitation over the southeastern mountains. The model products provide indications on the reasons behind the highest daytime spring warming (decrease of specific humidity) and significant nighttime summer warming (increase of Sea Surface Temperature (SST)). The model fails to simulate the recent increase of the nighttime temperature parameters over AP.

The final paper addresses the possible local atmospheric circulations, SST and remote modes of variability associated with the recent AP climate extreme changes. Using the PRECIS simulation, composite difference maps for some surface, upper atmospheric

circulation maps and SSTs between two period 1990-1997 and 1998-2008 have been calculated. The composite difference maps reveal significant local changes in these atmospheric and oceanic variables which possibly partly explain the recent regional warming and drying conditions during the last two decades. In addition, relationships of the regional/subregional extremes indices timeseries have been calculated with some known remote modes of variability. There is a clear, strong relation of El Niño Southern Oscillation (ENSO) with the AP climate in all the seasons except in winter. The North Atlantic Caspian Sea Pattern (NCP) influences the regional climate in winter especially the temperature variables.

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List of Acronyms

AOGCMs	Atmospheric Oceanic General Circulation Models
AP	Arabian Peninsula
AG	Arabian Gulf
AS	Arabian Sea
CCL	Commission for Climatology
CDD	Consecutive Dry Days
CLIVAR	Climate Variability and Predictability
CORDEX	Coordinated Regional Climate Downscaling Experiment
CRUTS3.2	Climatic Research Unit Time Series 3.2
CWD	Consecutive Wet Days
DJF	December, January and February
DTR	Diurnal Temperature Range
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA	ECMWF Reanalysis
ENSO	El Niño-Southern Oscillation
ESCWA	Economic and Social Commission for Western Asia
ETCCDI	Expert Team on Climate Change Detection and Indices
GoO	Gulf of Oman
IPCC	Intergovernmental Panel on Climate Change
IOD	Indian Ocean Diploe
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JAS	July, August and September
LBC	Lateral Boundary Condition
MA	March and April
MENA	Middle East North Africa
MON	MONsoon
MJ	May and June
MSL	Mean Sea Level
MSLP	Mean Sea Level Pressure
NAO	North Atlantic Oscillation
NCDC	National Climate Data Center
NCP	North Atlantic Caspian Sea Pattern

NE	NorthEast
NMON	Non- MONsoon
NMSs	National Meteorological Services
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
ON	October and November
PRECIS	Providing Regional Climates for Impact Studies
QC	Quality Control
RCMs	Regional Climate Models
RS	Red Sea
SE	SouthEast
SOI	Southern Oscillation Index
SST	Sea Surface Temperature
SW	SouthWest
STH	Sub-Tropical High
W	West
WCRP	World Climate Research Programme
UAE	United Arab Emirates
UK	United Kingdom
USSR	Union of Soviet Socialist Republics

Chapter 1: Introduction

1.1. Preface

The study of climate on all scales (meso, synoptic or planetary), its variability, trends, and extremes is important for human welfare in many regions of the globe. *Dash et al*. [2007] state that the study of climate changes and the search for robust evidences are issues of concern specifically when it is known that poor people are very vulnerable to climate change. Knowledge of climate helps to reduce the impacts of climate extremes and to ensure early adaptation measures for adverse future changes. The Fourth assessment Report of the IPCC confirms changes in the atmosphere, cryosphere and ocean show unequivocally that the world is warming [*Solomon et al*., 2007] and this has again been asserted in the recently released Fifth Assessment report [*Hartmann et al*., 2013]. *Goddard* [2001] has indicated that many of climate studies focus on temperature and precipitation parameters because of their societal links. An important step in developing countries is to tap into local resources and expertise to enhance current observational datasets [*Coppola and Giorgi*, 2010].

There is a high consensus in the literature that the planet Earth is warming. According to the IPCC fifth assessment report [*Hartmann et al*., 2013], It is certain that global mean surface temperature has increased since the late 19^{th} century. Each of the past three decades has been successively warmer at the Earth's surface than all the previous decades in the instrumental record, and the first decade of the 21^{st} century has been the warmest. The globally averaged combined land and ocean surface temperature data as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06] °C, over the period 1880–2012. There is a notable regional increase in intense rain events with accompanying flash floods and hail. Comparisons between observations and models suggest that changes in monsoons and storm intensities are related at least in part to changes in observed Sea Surface Temperature (SST) [*Solomon et al*., 2007]. The SST of Arabian Sea and Bay of Bengal shows positive trends and there is increase in the number of severe cyclonic storms crossing the Indian coast [*Dash et al*., 2007]. It is unlikely that the mean climate could warm without altering climate extremes [*Aguilar et al.*, 2008]. If the change in mean, however, was related to a shift in distribution then this could have a major impact on society and ecosystems [*Frich et al*., 2002]. Claiming whether the recent global climate change is a consequence of natural or anthropogenic source involves huge scientific effort. *Hurrell* [2000] reported that natural climate variability could easily be misinterpreted as anthropogenic and the strength of the link between atmospheric indices and climate variability has added to the debate over our ability to detect and distinguish between natural and anthropogenic climate change. However, in spite of all the information gleaned to date about global climate change, the overall picture of climate change over Arabia is surprisingly under-developed.

The abundance of natural resources in the Arabian Gulf (AG) countries makes this region quite important for navigation, oil drilling and other socio-economic activities [*Luis and Kawamura*, 2002]. The AG area, with its vast petroleum resources, should have an enormous interest in policies that are intended, or may be proposed, to deal with climate change issues [*Nasrallah and Balling Jr*., 1993]. Whereas climate change studies have received much attention in most of the countries less is known about the recent climate change in the Arabian Peninsula (AP). As *Economic and Social Commission for Western Asia* [2010] postulates, Arab countries should be made aware of and provide more inputs to the IPCC deliberations, and the IPCC should give more attention to guidelines on vulnerability and adaptation issues [*Kotwicki and Al-Sulaimani*, 2008]. High spatial and temporal studies are essential nowadays to help decision makers to take appropriate measures. This is because of the fact that there are different mechanisms of climate variability based on location and topographical factors. Precipitation climatology varies considerably from one place to another in the region [*Zhang et al*., 2005].

From the above it is essential for the AP countries to raise their interest in climate change issues and to invest in climate education, awareness and societal participation. The recent AP temperature and precipitation trends during the last 2-4 decades [*AlSarmi and Washington*, 2011; *AlSarmi and Washington*, 2013] are an alarming signal of high near-future impacts which should involve quick and strategic policies to reduce the risk and increase the profit. Studying the mechanisms behind such changes needs the use of numerical models. Before models are used for generating future climate scenarios, they require verification based on their ability to simulate not only the mean climate but also observed changes in variables such as temperature and rainfall and extremes [*Dash et al*., 2007]. *Solomon et al.* [2007] state that understanding temperature and precipitation anomalies associated with the dominant patterns of climate variability is essential to understanding many regional climate anomalies and why these may differ from those at the global scale.

Arabia is essentially a vast plateau, bordered in the west and south by mountains that rise steeply from the Red Sea. In the east, the peninsula slopes gently to the Arabian Gulf. It contains some of the world's largest sandy desert areas, notably the Rub‘ al Khali (“Empty Quarter”) in the south and An Nafūd in the north. The deserts of the AP and the Middle East sit astride of the Tropic of Cancer and extend from the Mediterranean seaboard to the coasts of the Sultanate of Oman and Yemen, almost all of the area lies within the arid zone of the Afro-Arabian old world desert belt [*Bray and Stokes*, 2004]. *Zhu and Atkinson* [2004] state that over Arabia, from November to February the whole area is dominated by the winter monsoon system with a low-level cold high-pressure overlain by upper-level westerly flow. From June to September, a warm trough extended from the Indian monsoon low with a subtropical high governing upper-level flow. The other periods, March to May, and October, were not so dominated by one major circulation.

The vast desert areas of the AP [*AlSarmi and Washington*, 2011; *AlSarmi and Washington*, 2013] and the poor data availability, quality and consistency [*Nasrallah and Balling Jr*., 1993; *Zhang et al*., 2005; *Kwarteng et al*., 2009], have led to the region being under-researched. To date however, limited research has been carried out using meteorological data and few of these studies have discussed detailed quality control and homogeneity tests of data. Furthermore earlier research has focused on climate change studies over single countries rather than the whole AP region, for example over Saudi Arabia [*Almazroui et al*., 2012; *Almazroui, Nazrul Islam et al*., 2012], over Kuwait [*Nasrallah et al*., 1990; *Nasrallah et al*., 2001; *Nasrallah et al*., 2004], over Bahrain [*Elagib and Addin Abdu*, 1997; *Elagib*, 2008] and over Oman [*Kwarteng et al*., 2009; *Charabi and Al-Hatrushi*, 2010]. *Haylock et al.* [2006] emphasise the need for more regional analyses and, in particular, the need to include results from regions lacking in published studies. Developing countries tend to head this list because of insufficient resources to undertake such analyses, limited access to data, fewer digitized records, and reduced data quality to which extreme analyses are very sensitive. Nevertheless, climate data quality and availability is sufficient to support research, given a substantial and focused effort. This work proposes to compile up-to date and historical meteorological data, carry tests to determine the extent of climate changes and to find the regions of most extreme change and vulnerability.

This present study demonstrates that climate change is evident over the AP during the last few decades. Significant temperature increases and precipitation decreases will lead to severe impacts on society if the observed trends continue in the future. Therefore a concerted effort is needed in the case of the AP to address the knowledge deficit in climate. Central to this thesis therefore is the evaluation of observed temperature parameters and total precipitation trends using an updated data series which includes several new stations compared with previous efforts, evaluation of the trends in the climate extremes indices based on daily data sets and investigation of the controls on AP climate variability using high resolution model. To my knowledge and for some countries (as Qatar, UAE and Yemen) this was the first observed data analysis of climate change for the complete AP.

1.2. Research aims

This thesis focuses on the AP recent climate change during the last 3 to 4 decades. In addition some specific analysis has been carried out for some stations which have longer data records as Salalah and Masirah (1943-2008), Bahrain (1950-2008) and Kuwait (1962-2008). Furthermore, the mechanisms behind the recent climate change have been revealed and studied.

The first aim of this thesis is to quantify the trends and their statistical significance for monthly, seasonal and annual mean, maximum and minimum temperature and total precipitation records. The second aim is to assess the trends and significance of the regional extremes indices based on daily data. A high resolution Regional Climate Model RCM (PRECIS) simulation of 25 km was validated in terms of mean and trends using CRU reanalysis and station data. The simulation was used to analyse and identify potential links to atmospheric and oceanic variables connecting with change in the region (aims 3 and 4).

The specific aims/research questions addressed in this thesis are:

1. What are the monthly, seasonal and annual observed trends in mean, maximum and minimum temperature and total precipitation in recent decades over the AP? What temperature parameters show the largest trends? What seasons are the largest trends found in? Where do the significant changes occur?
2. How do the temperature and precipitation extremes change during the last few decades? What are the spatial and temporal extremes change patterns?

3. How accurate is the simulation of the AP mean climate, trends and variability in a high resolution regional climate model (25km) using quasi-observed boundary condition (ERA-Interim)?

4. What are the controls which influence the recent AP climate extremes variability and change?

1.3. Thesis structure

This thesis comprises six main chapters. Chapter 2 is a literature review, which is intended to provide a background for the aims proposed above and further context for the thesis. This is followed by four research chapters, each of which is a paper that has been published in or submitted to a peer-reviewed journal. These address the four main research aims/questions listed above:

- Chapter 3 (Recent Observed Climate Change over the Arabian Peninsula) examines the trends of monthly, seasonal and annual mean, maximum, minimum temperatures, Diurnal Temperature Range (DTR) and the precipitation over the AP' 7 countries during the period 1980-2008. Ground-based observations from 31 stations will be tested for quality control and homogeneity then the trends will be calculated for all the individual stations in addition to regional and subregional (Non-Monsoonal (NMON) and Monsoonal (MON)) averages. Results of this chapter provide clear evidence that significant changes in climate have occurred over Arabia during the last 3-4 decades.

- Chapter 4 (Changes in Climate Extremes in the Arabian Peninsula: analysis of daily data) provides an evaluation of 21 climate extreme indices trends over the AP during the recent decades. The climate daily timeseries of 42 stations have been tested for quality control and homogeneity. Then the climate extremes indices have been calculated for all the individual stations passing the quality and homogeneity tests. Trends and significant have been calculated for all the stations in additional to regional and subregional averages. The results of this chapter support the findings in Chapter 3.

- Chapter 5 (An RCM-based simulation assessment of annual and seasonal temperature and precipitation climate and trends of means and extremes in the Arabian Peninsula during 1990-2008) uses high resolution (25 km) regional climate model (HadRM3P) to simulate the recent AP recent climate during 1990-2008. The simulation was then validated against the gridded observed CRU and the stations data in two ways; first the mean climate and seconds the trends (in the mean and the extreme). The validation was based on both annual and seasonal timescales.

- Chapter 6 (Circulation changes over the Arabian Peninsula associated with recent climate change) identifies atmospheric/oceanic controls on interannual and seasonal variability in the AP extremes. Annual and seasonal maps of composite mean difference between two periods, 1990-1997 and 1998-2008, are derived to assess changes in the local atmospheric/oceanic variables. Then links to atmospheric/oceanic controls have been calculated. The possible physical mechanisms of the strong statistical links identified earlier have been outlined on a seasonal basis.

- Chapter 7 reviews the results of the research chapters with reference to each aim outlined in section 1.2, it presents general conclusions with regards to these aims and the broader research field, discusses the limitations of the research presented in this thesis and finally proposes logical next steps for the further progression of the work.

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Chapter 2: Literature Review and sources of data

2.1. Overview and climate change definition

This literature review provides a background for the aims proposed in section 1.2 and further context for the thesis that could not be developed fully in section 1.1. It is not intended to be an exhaustive review of the current state of the scientific field. It begins by summarising the recent findings of global climate change (means and extremes). It then moves on to focus on the recent regional status of the climate covering Asia including the AP, before considering controls on climate variability and change. The second half of the literature review focusses on the AP, starting with a brief overview of the AP topography and climate. Finally the sources of data available for the study of recent climate change and drivers of changes are outlined and limitations therein highlighted.

The *Intergovernmental Panel on Climate Change (IPCC)* [2012] defines climate change as “change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings or to persistent anthropogenic changes in the composition of the atmosphere or in land use”.

2.2. The recent global Climate changes

The globally averaged combined land and ocean surface temperature data as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06] °C over the period 1880–2012, and about 0.72°C [0.49°C to 0.89°C] over the period 1951–2012 [*Hartmann et al*., 2013]. Over Eurasia, *Dai* [2006] found that spatial patterns of long-term trends during 1976–2004 are characterized by the largest observed warming (0.2° to 0.7°C decade^{-1}) for the planet. *Jones and Moberg* [2003] reported that the rate of annual warming for global land areas over the 1901–2000 period is estimated to be 0.07˚C decade^{-1} (significant at better than the 99.9%

level). They noted that the warming is not continuous but occurs principally over two periods (about 1920–1945 and since 1975).

According to the *IPCC fourth assessment report* [*Solomon et al.*, 2007], the surface temperatures over land regions have warmed at a faster rate than over the oceans in both hemispheres. Significantly faster rates of warming are reported for land areas compared with oceans over the past two decades (about 0.27°C vs. 0.13°C per decade). Recently *Klotzbach et al.* [2009] investigate surface and satellite temperature trends over the period from 1979 to 2008. They found that surface temperature data sets from the National Climate Data Center (NCDC) [*Smith and Reynolds*, 2005] and the Hadley Center (HadCRUT3v) [*Brohan et al*., 2006] show larger trends over the 30-year period than the lower-tropospheric data. For land trends, the results are as follows 1- NCDC 0.31℃/decade; 2- CRUTEM3v 0.22℃/decade. They also found that the NCDC data set indicates nearly three times as much warming over land areas as over ocean areas during the past 30 years. *Solomon et al.* [2007] indicates that warming is typically larger in arid than in moist regions and that the 21st century temperature change is positive everywhere and increases going from the coasts into the continental interiors. *Yang* [2009] reported that the rate of rising temperature north of 35°N was obviously higher than that south of 35°N. *Solomon et al.* [2007] reported that surface air temperature trends since 1979 are now consistent with those at higher altitudes. Furthermore, *Jones and Moberg* [2003] concluded that over the recent period, 1977–2001, warming clearly dominates and there is a tendency for it to be greater over land areas, although only in some seasons.

The *IPCC Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)* [*Simon et al*., 2012] states that it is very likely that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights, at the global scale, that is, for most land areas with sufficient data. There have been statistically significant trends in the number of heavy precipitation events in some regions. It is likely that more of these regions have experienced increases than decreases, although there are strong regional and subregional variations in these trends. *Alexander et al.* [2006] reported that changes in all the extreme percentile-based indices seem to have occurred around the mid-1970s. Indeed every year since 1979 has been above the long-term average (1961-1990) for the annual occurrence of warm nights and every year since 1977 has been below the long-term average for the annual occurrence of cold nights. This indicates a shift toward warmer conditions in the most recent decades. *Weber et al.* [1997] reported that after 1980, a strong increase is evident in all temperature records, in maximum, minimum and mean temperatures. A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events. Changes in extremes can be linked to changes in the mean, variance, or shape of probability distributions, or all of these [*Simon et al*., 2012].

Global-scale trends in a specific extreme may be either more reliable (e.g., for temperature extremes) or less reliable (e.g., for droughts) than some regional-scale trends, depending on the geographical uniformity of the trends in the specific extreme [*Simon et al*., 2012]. *Solomon et al.* [2007] reported that more intense and longer droughts have been observed over wider areas, particularly in the tropics and subtropics since the 1970s, this leads to significant increase of the daytime temperature extremes. In the drylands, there is a clear link between drought and extreme high temperature [*Nasrallah et al*., 2004]. In addition, *Frich et al*. [2002] found a globally upward trend in Heat Wave Duration Index (HWDI). *Alexander et al*. [2006] found that the magnitude of the trends is generally greater for minimum temperature related extremes. Annually the largest change in extremes corresponding to an increase in minimum temperature is over Eurasia where the minimum daily minimum temperature (TNn) increased by nearly 5˚C between 1951 and 2003, the greatest change in the absolute temperature indices. *Manton et al.* [2001] reported that minima had increased more rapidly than maxima. *Peterson et al*. [2002] indicates that during the last few decades, mean monthly minimum temperatures have generally been warming faster than mean monthly maximum temperatures. *Weber et al*. [1997] have presented evidence that over mountain regions of Central Europe in the last decades the daily minimum temperature has increased in relation to the daily maximum temperature.

The warming in the last 30 years is widespread over the globe, and is greatest at high northern latitudes. The greatest warming has occurred in the NH winter (DJF) and spring (MAM) [*Solomon et al*., 2007]. *Alexander et al.* [2006] found that MAM has the most widespread significant change in the temperature indices with the least change usually occurring during SON. *Dai* [2006] found that RH–T is negative over many arid areas where atmospheric subsidence and soil wetness play an important role. More common in the dry land regions has been a negative association between precipitation and temperatures, such that warmer (colder) years have been drier (wetter) [*Hulme*, 1996]. *Solomon et al*. [2007] reported that spring drying of the land surface over Europe was an important factor in the occurrence of the extreme 2003 temperatures.

Aguilar et al. [2005] reported that Sea Surface Temperatures (SSTs) likely play a key role in the temporal evolution of temperature and precipitation. *Solomon et al*. [2007] reported that the world's oceans have warmed since 1955, accounting over this period for more than 80% of the changes in the energy content of the Earth's climate system. The subtropical latitudes in both hemispheres are characterized by an increase in salinity in the upper 500 m [*Solomon et al*., 2007]. The patterns are consistent with a change in the Earth's hydrological cycle, in particular with changes in precipitation and inferred larger water transport in the atmosphere from low latitudes to high latitudes and from the Atlantic to the Pacific. The increase of global SSTs will enhance the evaporation process which leads to an increase of the water vapour content at the lower atmosphere. *Klotzbach et al*. [2009] reported that increased atmospheric humidity can increase downward longwave radiation due to water vapor absorption and reemission. Hence increase of night time temperature. Furthermore, an atmosphere with higher concentrations of the greenhouse gases, CO_2 and water vapour, also reduces the cooling at night. Consequently if, for instance, there is a long-term positive trend in greenhouse gas concentrations or cloudiness over the observing site, it may introduce an upward bias in the observational record of minimum temperatures that necessarily will result in an upward bias in the long term surface temperature record.

2.3. Recent Climate changes over Asia and the Arabian Peninsula

There is a need for focused regional studies on climate change trends and variability. Regional climate change can be very different from the global average, reflecting changes in the circulations and interactions of the atmosphere and ocean and other components of the climate system [*Solomon et al*., 2007; *Lu et al*., 2009]. Looking into drylands only, *Hulme* [1996] found that all dryland regions have warmed, however, with the majority of the warming probably being unrelated to regional dryland effects, the greatest warming of more than 1° C per 100 years has occurred over central-east Asia then SW Asia. This warming may have contributed to a worsening of the P/PE ratio in many of these dryland regions [*Hulme*, 1996].

Table 2-1 summarises some recent finding of country specific climate change analysis over Asia continent.

Area	**Period**	**Trends**	**Data**
China arid regions	since the 1980s	Rising temperatures and precipitation in most areas. The average temperature in China rose by 1.1°C during the last 50 years, i.e., 0.22°C for every 10 years	*Yang* [2009]
Taklimakan Desert	1960-2005	temperature has an increasing trend	*Xiao et al.* [2008]
SW Iran	1950-2007	precipitation series indicated insignificant trends in annual and seasonal series while temperature trends revealed a significant increase during summer and spring seasons	*Zarenistanak et al.* [2014]
Hulunbeier sandy land	Recent 45 years	There had been a warming and drying trend	*Zhao* [2007]
India	1901-1987	Mean temperature has increased and is almost solely determined by increases in maximum temperature	*Kumar et al.* [1994]
India	1901-2003	Annual mean temperature has increased by about 0.7°C and the maximum temperature has increase by 0.8°C. The annual minimum temperature over India does not show any appreciable increase	*Dash et al.* [2007]
Inner Mongolia	1955-2005	Significant warming and drying trends during the last 30 years compared with the preceding 20 years with the most significant trends of Tmean (0.54–0.71 ˚C/10 yr) occurring in the desert	*Lu et al.* [2009]
Middle East	Recent decades	warming trend in long-time series of surface temperature	*Sivakumar et al.* [2005]
Turkey	1950–2004	the last decade significant warming trend is observed leading to 2000–2002 temperatures to be recorded as maximums in record history	*Tayanç et al.* [2009]

Table 2-1 Recent climate change analysis findings in some countries of the Asian continent.

Nasrallah and Balling [1996] found a linear temperature increase of 0.63℃ during the period 1891-1990 over the AP, most warming occurred 1911-1935 while the recent 50 years (1951-1990) show slight cooling trend. The trends show that despite the rapid buildup of greenhouse gases during 1951 to 1990 time period, the AP region has not warmed, and in fact, the region has cooled slightly. It is important to point out that the authors had included many countries located further north of the AP such as Iraq, Syria, Lebanon, Israel and Jordan. However, when *Nasrallah and Balling* [1993] calculated the average near surface temperature trend for the same period (1951-1990) over the AG area, they found a highly statistically significant trend of 0.65°C/100 years. The authors state that for any reason, the AG area appears to have been warming over the past century at a statistically significant rate. The observed temperature and precipitation trends are unlike those observed for the entire Northern Hemisphere (NH) over the same period; because (a) the NH warmed only 0.44°C while AG 0.65°C; (b) the NH warmed more in the first half of the period than the second half, as opposed to the tendency in the Gulf area to warm in the most recent 40 years; (c) the NH warmed three times as much in winter as in summer, whereas the Gulf warming was entirely in the summer season.

There is medium confidence in a warming trend in daily temperature extremes in much of Asia [*Simon et al.*, 2012]. *Manton et al.* [2001] found statistically significant warming trends over Southeast Asia and South Pacific during the period between 1961 and 1998. There was a dramatic increase in hot days and warm nights across the region in the 1998, coinciding with the globe's warmest year in the period of instrumental records. More intense and longer droughts have been observed over wider areas, particularly in the tropics and subtropics since the 1970s. *Lu et al.* [2009] reported that with latitude increasing, the rate of change in Tmax in Inner Mongolia is increasing. *Kumar et al.* [1994] found that during the period 1901-1987 the increase of mean temperature is solely contributed by the maximum temperature which increased by 0.6°C/100 year. *You et al.* [2008] investigated the extreme temperature indices in the eastern and central Tibetan Plateau during 1961-2005. They found statistically significant increasing trends. *Shrestha et al.* [1999] indicated that the distributions of seasonal and annual temperature trends show high rates of warming in the high-elevation regions of Naipal (Middle Mountains and Himalaya), while low warming or even cooling trends were found in the southern regions. This is attributed to the sensitivity of mountainous regions to climate changes. The seasonal temperature trends and spatial distribution of temperature trends also highlight the influence of monsoon circulation. Over India and during the last 40-50 years, *Dash et al.* [2007] found that maximum temperatures show positive trends over most parts of the country.

Zhang et al. [2005] studied changes in extremes over the Middle East region for the period 1950–2003, it was found that the frequency of warm days has significantly increased while the frequency of cold days has significantly decreased. The reduction in the number of cold days is gradual and started in the 1970s, but the increase in warm days exhibits a sudden increase toward the 1990s. Over Kuwait, *Nasrallah et al.* [2004] found a gradual increase in the number of hot days was observed since 1980. Since 1977, there have been record breaking years the 1990s is the warmest decade of the record. However, *Nasrallah and Balling* [1996] found insignificant trends in the average maximum or minimum temperature data of the three stations (Doha, Riadh, Dhahran) during 1951-1990. This shows the impact of the high anomalous temperatures of the 1990s decade on the recent significant warming over the AP.

Nasrallah and Balling [1995] found that over the Middle East during 1950-1990, the greatest warming is occurring in the spring, and the least warming is occurring in the winter. On a seasonal basis winter months (DJF) warmed 0.01 °C/decade, spring months (MAM) warmed 0.13°C/decade, summer months (JJA) warmed 0.08°C/decade, and autumn warmed 0.05°C/decade. The trend results are influenced by the sampling periods (*Haylock* [2006], *Manton et al.* [2001], *Elagib and Mansell* [2000]) and the area of study.

Conflicting results are produced due to the use of different time periods. This is true over AP, *El Gindy* [1994] found no regional warming was detected in the study area from the present data whose length reach 35 years ((Doha 1962-1992), (Seeb 1974-1990), (Sur 1977-1990), (Masira 1956-1990)). *Nasrallah and Balling* [1996] used 57 satellite grid cells time series (2.5°x2.5°) to calculate the trends cover the AP from 1979 to 1990. They found that the satellite-based annual temperature measurements for AP show a slight warming trend that is not statistically significant. While over the AG *Nasrallah and Balling* [1993] found a 0.14 ^{o}C warming (not statistically significant) over the 1979-1991 time period.

In the drylands there is a clear link between drought and extreme high temperature [Nasrallah et al., 2004]. *Elagib and Mansell* [2000] reported that the period of greater warmth in Sudan appears to coincide with that of rainfall depletion reported post mid-1960s. *Kafle and Bruins* [2009] reported that over Israel during the period 1970-2002, the relationship between the temperature and precipitation in this study showed a negative correlation. Over the desert stations the relationships between a 1 ℃ increase in annual temperature and the decline in precipitation are 120 and 126 mm for Kefar Blum and Har Kena’an, respectively.

2.4. Controls on climate variability and change

Changes in atmospheric circulation are important for local climate change since they could lead to greater or smaller changes in climate in a particular region than elsewhere. Analysis of atmospheric and climate variability has shown that a significant component of change can be described in terms of fluctuations in the amplitude and sign of indices of a relatively small number of preferred patterns of variability some of the best known of these are: El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Northern Annular Mode (NAM), Southern Annular Mode (SAM), Pacific-North American (PNA) and Pacific Decadal Oscillation (PDO) [*Solomon et al*., 2007]. The *IPCC SREX* [*Simon et al*., 2012] indicates that it is likely that there has been a poleward shift in the main Northern and Southern Hemisphere extratropical storm tracks. The observed climate changes can be expressed as a shift of atmospheric/oceanic patterns towards the structure associated with one sign of these preferred patterns. The increased mid-latitude westerlies in the North Atlantic can be largely viewed as resulting of NAO changes. Over Turkey, *Tayanç et al.* [2009] suggest that the decreasing precipitation rates in the Aegean part of Turkey in the period of 1950–2004 can be related to the positive phase of the NAO in the recent years. Since about 1985, the NAO has tended to remain in a strong positive phase, though with substantial interannual variability. This recent upward trend in the NAO accounts for much of the regional precipitation increase in northern Europe and precipitation decrease in the Mediterranean Basin.

ENSO is the dominant mode of global-scale variability on interannual timescale although there have been times when it is less apparent. The 1976-1977 climate shift, related to the phase change in the Pacific Decadal Oscillation (PDO) towards more El Niño events and changes in the evolution of ENSO, has affected many regions, including most tropical monsoons [*Solomon et al.,* 2007]. *Galvin* [2007] reported that relatively strong westerlies are associated with the development of the El-Niño anomalies in the eastern Pacific and their formation mechanism seems to be directly linked with the El-Niño phenomenon. In view of the mass transport associated with such a change in wind velocity, accompanied by the vast amount of water vapour that can be carried by such tropical winds, it is easy to see how El Niño has global consequences. La Niña is an amplification of the westward flow of the Trade Winds and associated increased warmth of the western Pacific. It is measured as an increase from the normal pressure difference Tahiti–Darwin. Its consequences are an increase in west Pacific tropical storm activity and copious additional rainfall across South-East Asia and north-eastern Australia. *Nasrallah and Balling* [1993] found that the correlation between the Gulf-area temperature data and three large-scale potential predictors namely (1) solar sunspot cycle-length as measure of solar input, (b) the Southern Oscillation Index (SOI) as a measure ocean-atmosphere interaction and (c) the stratospheric turbidity index as a measure of volcanic dust in the high atmosphere, were not statistically significantly different than zero. *Krichak et al.* [2000] demonstrates the importance of the Red Sea (RS) which appears to be important as a corridor for transporting the air masses from the Arabian Sea and tropical Africa into the Mediterranean region. Overall, conclude that a number of the observed 20th century climate changes can be viewed in terms of changes in the patterns of variability [*Solomon et al.*, 2007]. Therefore, it is therefore important to test the ability of climate models to simulate them and to consider the extent to which observed changes related to these patterns are linked to internal variability or to anthropogenic climate change.

The climate related research findings discussed earlier point to the fact that little work has been done so far over the AP. Arabia needs to plan for more research in all aspects of the climate system especially the atmosphere and the hydrosphere, it needs to focus more on increasing the climate data quality and availability (this includes digitizing projects) and to raise the awareness of its communities of the global climate change reality, possible impacts and the need for strategic adaptation policies.

2.5. The Arabian Peninsula

2.5.1. Location

Tropical Asia, including arid and semi-arid tropics, has a unique climatological distinction because of the pervasive influence of the monsoons. The summer southwest monsoon influences the climate of the region from May to September, and the winter northeast monsoon controls the climate from November to February [*Sivakumar et al*., 2005]. *Galvin* [2007a] reported that the most commonly used definition of the tropics is the zone within which the sun is directly overhead at some time during the year, i.e. the zone between the tropics of Cancer and Capricorn (23.45°N and 23.45° S). *Parker* [2006] defines the areas north of 20°N as the extratropical Northern Hemisphere. The Arabian Peninsula is located in the Southwest region of Asia (the sub-tropical belt between 12°N, 32°N). It is a vast terrain characterized by its aridity, scarcity of fresh water resources and an ever-increasing demand on fresh water supplies. It is probably the largest surface (about 3 X 10^6 km^2) on Earth not traversed by a perennial stream. The climate of the AP is classified as arid to semi-arid. It is affected, mainly, by two contrasting and conflicting systems of climate: a cyclonic system, which moves in from the north during winter and the monsoon from the southwest in summer [*Nouh*, 2006]. These regions are found beneath the sinking air at the sub-tropical latitudes of about 30° N and 30° S which produces divergence and drying in the lower troposphere [*Elagib and Addin Abdu*, 1997]. The AP could be divided climatically into extratropical (north of 20°N or Non-monsoonal (NMON)) and tropical (south of 20°N or Monsoonal (MON)) subregions. The NMON subregion is characterized by a cyclonic system which moves in from the north during winter and spring while the MON subregion is affected by the monsoon system. Monsoons are generally characterized by a reversal of winds near the surface twice per year and the development of largescale deep circulation systems. As a result, for most places within the area of the monsoon circulation, one season is wet (summer) and the other dry (winter). There are many variations, however, and this generalization hides important local weather variations [*Galvin*, 2008d].

Most AP regions are under the zonal axis of the subtropical high pressure belt where large-scale descent or air subsidence is dominate preventing cloud formation and causing dry weather. Although the monsoon trough (the Inter Tropical Convergence Zone (ITCZ)) crosses southern parts of south-west Asia in summer but embedded convection is usually restricted to the mountains of Yemen, Oman and south-western Saudi Arabia, this is because in the ITCZ deep convection can only occur where warm air can ascend through a weakened sub-tropical inversion, usually in the presence of divergence in the upper-tropospheric easterlies, which causes dynamical ascent and also because of the relative dryness of the atmosphere in depth [*Galvin*, 2008a].

2.5.2. Seasonal climates

Zhu and Atkinson [2004] summarise the seasonal AP regional synoptic climate as follows. From November to February, the whole area is dominated by the winter monsoon system with a low-level cold high-pressure overlain by upper-level westerly flow. From June to September, a warm trough extends from the Indian monsoon low with a subtropical high governing upper-level flow. The other periods, March to May, and October, are not dominated by any local synoptic pressure system.

Many of the AP regional climate studies (*Al-Maskari* [2006]; *AlBrashdi* [2008], *Membery* [1985], *Fleitmann et al*.[2003] and *Takahashi* [1981]) have used the standard four seasons. However, in general there are two main seasons winter and summer and two transition seasons first transition (MA) and second transition (ON). At the same time, there are researchers who consider MJ as a pre-monsoon season and ON as a post-monsoon season. Summer season studies such as *Murtugudde et al*. [2007] and *Fleitmann et al*. [2007] use JAS as the summer season months while *Miller et al.* [2008] has defined an early summer season MJ and late summer season JAS. Based on the previous studies definitions, the seasonal definition in this work will follow a modified version of *Fisher and Membery* [1998] over AP, namely winter (DJF), spring (MA) (1st transitional period), early summer (MJ, premonsoon), late summer (JAS) and autumn (ON) (2nd transitional period or postmonsoon). A short description for each season follows.

Winter (DJF)

As Asia cools, the subtropical high becomes re-established over the south of the continent and northeasterly winds bring dry weather across all areas north of about 10 °N [*Galvin*, 2008d]. The dry cool northeasterly winds affect mostly the AP southern areas which then veer to southerly over the southwestern and western areas. The Mediterranean cyclones, which migrate from west to east in association with upper troughs and active phases of subtropical and polar jets, are considered the main rain-producing synoptic systems. Their potential generally decreases from north to south except for the mountainous areas, where uplift motion act as a regional factor [*Abdullah and Al-Mazroui*, 1998]. *Galvin* [2008c] reported that over the tropics the upper troughs, in particular when they sharpen, are a major trigger for cumulonimbus development.

Spring (MA, 1st transitional season)

In spring, there is no major dominating pressure system affecting the region and the mean sea level pressure is described as slack. The AP atmosphere is very sensitive to upper troughs where the water (or land) is warm; the ingredients are present to form large areas of embedded cumulonimbus [*Galvin*, 2008b]. Short-wave upper troughs can also trigger the development of severe weather almost anywhere in the tropics, in particular in spring. Over the deserts, additional forcing, such as sea- or lake-breeze convergence, can assist in the development of such short-lived storms [*Galvin*, 2008c]. *Membery* [1983b] describes the mechanisms of the formation of thunderstorms in spring as when a low pressure area moved out of the desert ‘empty quarter’ onto the coastal strip. Fed by a moist, warm, low level inflow from the Arabian Sea/Indian Ocean, considerable instability is attained from very cold air in the middle levels of the atmosphere which had tracked across Europe where it had caused icy conditions a week before. Through late in the season, storms do occur in in April and early part of May from time to time. Another contributed factor is the moisture transport ahead of troughs in southern branch of westerlies [*Yihui and Zunya*, 2008].

Early summer (MJ, premonsoon).

Early summer season marks the start of the summer when the solar insolation is overhead at latitude 23.5° N which leads to the development of the thermal low that extends from northern India along to southern Pakistan and south Arabia. This season is known for the Shamal winds. *Membery* [1983a] reported that the Shamal from the Arabic word for north is a wind which blows with particular persistence in summer, from late May until early July, over Iraq and the Arabian Gulf. It occurs as a result of the Gulf area being strongly influenced by the heat low over Pakistan and Afghanistan and a consequent trough to the lee of Zagrous Mountains. The topographical features of central Saudi Arabia, with gradual upsloping terrain to the west and the presence of a semi-permentant high pressure cell over northern Saudi Arabia tend to create an enhancement of the low-level flow particularly below 1500m. *Murtugudde et al.* [2007] indicates that there is a potential nonstationarity of the correlation between Oman precipitation and Indian summer monsoons. Answering such details will require coupled climate experiments which are beyond the scope of this investigation. *Yang et al.* [2004] studied the influence of the subtropical upper westerlies on the strength of the South Asia monsoon; they show that before a strong (weak) Asian summer monsoon, the 200-mb westerlies over subtropical Asia are weak (strong) during the previous winter and spring. A significant feature of these signals is represented by the variability of the Middle East jet stream whose changes are linked to the Arctic Oscillation, North Atlantic Oscillation, El Niño–Southern Oscillation, and other climate phenomena.

Late summer (JAS)

During late summer the Asian summer monsoon is at its peak. Moist southwesterlies are a feature of the Arabian Sea (AS) and they blow towards India, Pakistan and southern Arabian coasts. However air is subsidising over the south Asian areas stretching from the desert or semidesert climate from northwest India, through southwest Pakistan and Iran, across the AP. Due to stability and the influence of surrounding mountain chains, rainfall is at very low levels in coastal Yemen, Oman, Iran and Pakistan [*Galvin*, 2008d]. Over the AP land, higher values of mean temperatures are observed from May to September relative to rest of the year [*Rehman*, 2010]. Taking Kuwait as a typical example, using a daytime screen temperature of 40 °C and a dew point of –15 °C, the air is highly turbulent, often to the 500 hPa (5500 m) level, but with marked dryness and subsidence prevailing, there is normally little or no low or medium-level cloud. There is, however, relatively poor visibility right up to the 500 hPa level and clean air/good visibility above [*Galvin*, 2008c].

Due to the strong southwesterly monsoon winds over the Arabian Sea, the coasts of southern AP (Oman and Yemen) are affected by upwelling which cause SST to cool to around 16-18℃ bringing moist air to its condensation point. A restricted fringe of the southern coast of Oman is exposed to the inflow of moisture from the Arabian Sea resulting in topographically induced precipitation [*Charabi and Al-Hatrushi*, 2010]. A unique aspect of the summer monsoon along the south coast of the AP is the effect of upwelling cool water along this coast. As well as promoting a good fishery, the upwelling water cools the overlying air. This causes condensation from the moist flow to be trapped close to the surface and, in some places; in particular the bay between Al Ghaydah, Yemen and Şalālah, Oman, there is persistent low cloud and drizzle, associated with the Khareef wind [*Galvin*, 2008d].

Autumn (ON, 2nd transitional season or postmonsoon).

This season is the transition between summer and winter. The pressure starts to build over central Asia which initiates the northeasterly trade winds over the AS and the land areas located over southern AP. Most of the rain is caused by early advanced westerly upper troughs especially if there is a lower level easterly moisture transport. Over Arabia, middle latitude disturbances begin to affect the northern part and local circulation weakened due to stability of lower atmosphere during autumn [*Takahashi and Arakawa*, 1981].

2.5.3. Arabian Sea Surface Temperature (SST)

The Gulf is located in a subtropical, hyper-arid region where temperatures are high in summer and winds dry in winter. This leads to 1–2 m potential evaporation per year, added to which is the general lack of precipitation. High saline water of >39 Practical Salinity Units (psu) occurs in most Gulf waters Air and water temperature tracks each other closely. Combined with atmospheric dynamics driven by cold winds (the Shamal) from the nearby Anatolian and Iranian highlands, these result in marked amplitude of summer/winter temperature differences [*Sheppard et al*., 2010]. Due to this unusual physical environment, the AG experiences marked temperature extremes atypical of seas at similar latitude, with hot, dry, tropical conditions during the summer and temperate conditions during the winter. In addition to extreme variations in temperature, the AG also experiences substantial fluctuations in salinity levels, which can exceed 70 psu in some embayments. *Jackson* [1988] reported that the highest SST in the world are found in the AG with summer maxima of 36.0℃ or more, however, in the Gulf of Oman (GoO) the influence of the monsoon is strong and in general the sea temperatures are lower than the AG. The RS and AG are notable areas that can trigger the development of small, but intense, clusters of cumulonimbus clouds, especially during the summer. Convection is only inhibited by the subsidence inversion and the dry air above it. When the air at higher levels is moistened somewhat (in particular near the base of an upper trough) and when the inversion is weak, deep convection is often the result and may be seen across the width of either sea [*Galvin*, 2009].

2.6. Sources of data for the study of AP climate change

There is a relative paucity of data availability in the AP with additional concern over quality and consistency [*Nasrallah and Balling Jr.*, 1993; *Zhang et al.*, 2005; *Kwarteng et al*., 2009]. This is in addition to the fact that much of the area is desert and there are very few sites with instrumental data. The communication to obtain these data is problematic. The confidence in observed changes in mean and extreme climate variables depends heavily on the quality and quantity of data and the availability of these data for analysis [*Simon et al*., 2012]. Therefore it was crucial to use a blend of data sources in this thesis which covers observations from meteorological stations, observed gridded data, reanalysis and model data. For the first two core results chapters (chapters 3 and 4), observed data from the available in situ climate data of the AP meteorological stations have been used. Observed gridded data, reanalysis and model data have been utilised in the last 2 core chapters (chapters 5 and 6).

2.6.1. Meteorological stations data

Monthly and daily mean temperature, maximum temperature, minimum temperature and precipitation data have been obtained from the National Meteorological Services (NMSs) of the AP, namely Oman, UAE, Qatar, Bahrain, Saudi Arabia, Kuwait and Yemen for a total of 44 stations. 24 stations were provided from Oman and 4 from UAE, 11 from Saudi Arabia, 2 from Yemen and 1 station from each of Qatar, Bahrain and Kuwait. The majority of the stations have data records since 1980s, however, there are some stations have longer data record beginning in the 1970s (Saudi Arabia), 1960s (Kuwait), 1950s (Bahrain) and 1940s (Oman). 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). Many of the Omani stations have been excluded from the analysis because of their short data period while other stations did not have data for the complete period as the Yemini stations. Table 2-1 presents details of all the meteorological station name, WMO number, location, elevation and data period from which climate data have been obtained for this work.

Table 2-2: Lists the Arabian Peninsula National Meteorological Services (NMSs) used in this work

Country	Station	WMO	Latitude	Longitude	Elevation(m)	Period	
						Monthly	Daily
Oman	Khasab	41240	26 20	56 23	33.0	1980-2008	1986-2008
	Sohar	41246	24 28	56 38	3.6	1980-2008	1986-2008
	Saiq	41254	23 04	57 38	1755.0	1980-2008	1986-2008
	Seeb	41256	23 35	58 17	8.4	1980-2008	1986-2008
	Sur	41268	22 32	59 28	14.0	1980-2008	1986-2008
	Masirah	41288	20 40	58 54	19.0	1943-2008	1943-2008
	Thumrait	41314	17 40	54 01	467.0	1980-2008	1986-2008
	Salalah	41316	17 02	54 05	22.0	1943-2008	1943-2008
	Adam	41264	22 23	57 31	285.0	1998-2008	1998-2008
	Bahla	41263	22 59	57 18	589.0	1998-2008	1998-2008
	Samail	41257	23 18	57 56	414.0	1998-2008	1998-2008
	Diba	41242	25 37	56 15	20.0	2000-2008	2000-2008
	Doqum	41290	19 37	57 38	40.0	2004-2008	2004-2008
	Fahud	41262	22 20	56 29	170.0	1985-2008	2000-2008
	Ibra	41265	22 44	58 30	469.0	1998-2008	2000-2008
	Ibri	41252	23 25	56 31	244.0	1985-2008	1985-2008
	Jabal Shams	41259	23 07	57 09	3009.0	2003-2008	2003-2008
	Ras Alhad	41270	22 18	59 48	10.0	2005-2008	2005-2008
	Marmul	41304	18 08	55 10	269.0	1985-2008	1999-2008
	Mina Qaboos	41258	23 37	58 34	4.0	1982-2008	2005-2008
	Nizwa	41255	22 51	57 32	460.0	1991-2008	2000-2008
	Qarn Alam	41275	21 22	57 03	139.0	2000-2008	2000-2008
	Qiroon Hirrity	41315	17 15	54 05	878.0	1984-2008	2000-2008
	Rustaq	41253	23 24	57 25	322.0	1998-2008	2006-2008
UAE	Ras Alkhaimah	41184	25 37	55 56	31.0	1979-2008	1979-2008
	Dubai	41194	25 15	55 20	5.0	1979-2008	1979-2008
	Sharjah	41196	25 20	55 31	33.0	1979-2008	1979-2008
	Al Ain	41218	24 16	55 36	262.0	1994-2007	1994-2007
Bahrain	Bahrain	41150	26.16	50.39	2.0	1950-2008	1950-2008
Qatar	Doha	41170	25.15	51.34	11.0	1980-2008	1986-2008
Kuwait	Kuwait	40582	29.22	47.59	6.1	1962-2008	1962-2008
Saudi Arabia	Tabuk	40375	28 23	36 36	768.1	1985-2008	1986-2008
	Hail	40394	27 26	41 41	1001.5	1970-2008	1970-2008
	Dhahran	40416	26 16	50 10	16.8	1970-2008	1970-2008
	Al-Madinah	40430	24 33	39 42	635.6	1970-2008	1970-2008
	Riyadh	40438	24 42	46 44	619.6	1970-2008	1970-2008
	Jeddah	41024	21 42	39 11	16.9	1970-2008	1970-2008
	Al-Taif	41036	21 29	40 33	1452.8	1970-2008	1970-2008
	Bisha	41084	19 59	42 38	1162.0	1970-2008	1970-2008
	Khamis Mushait	41114	18 18	42 48	2055.9	1985-2008	1986-2008
	Gizan	41140	16 53	42 35	7.2	1985-2008	1986-2008
	Dammam	40417	26.27	49.49	12. 0	2000-2008	2000-2008
Yemen	Sana'a	41404	15.31	44.11	2190.0	1996-2005	Nil
	Aden	41480	12.5	45.02	3.0	1996-2005	Nil

In cases of low stations density and less details of stations history information (‘metadata’) associated with the data, it is essential to check the data homogeneity. There is a need to start of the project with the observations checking for inhomogeneities before using them for climate analysis [*Böhm et al.*, 2001]. The homogeneity test enables the detection of 95% (or more) confidence level change points in the temperature and precipitation series. High significance threshold is used for statistically-identified inhomogeneities that are not supported by metadata [*Peterson et al*., 1998]. In many cases these change points appear to be regionally widespread (detected in many countries) and coincide with real climate shifts. *Peterson et al.*[1998] state that a change in a station's time series may indicate inhomogeneities or may simply indicate an abrupt change in the regional climate. To isolate the effects of station discontinuities from regional climate change, many techniques use data from nearby stations as an indicator of the regional climate. Any significant variation from that regional climate signal is assumed to be due to inhomogeneities. For example the highest number of significant temperature discontinuities occurred in 1997 and 1998 years. *Solomon et al.* [2007] indicated that surface temperatures were enhanced by the major 1997–1998 El Niño. The warmth of the exceptional year 1998 was clearly related to the record-breaking 1997/98 El Niño event. Estimates of the influence from the Southern Oscillation Index (SOI) would suggest that 0.15–0.20°C of the warmth was due to this cause. The rate of recent global temperature rise means that the next El Niño event is likely to lead to a new record, even if the event were only of moderately strong intensity [*Jones and Moberg*, 2003]. *Nasrallah et al.* [2004] state that in August 1998, Kuwait had struck by the most severe and longest heat wave, the daily maximum temperature exceeded 50°C on consecutive days. Saudi Arabia has recently experienced such extreme climatic events, where 2010 was considered the warmest year of the instrumental observational period of Saudi Arabia, 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 [*Almazroui et al*., 2012]. Over Israel *Kafle and Bruins* [2009] found that over all meteorological stations the year 1998–1999 was the warmest year during the period 1970–2002. *Haylock et al.* [2006] indicates that over South America the homogeneity test lead to detection of significant jumps in the record that coincide with wet El Niño years also the test was much more powerful in detecting jumps in the temperature record.

2.6.2. Climatic Research Unit (CRU) time-series datasets

Due to the low density of meteorological observations at the AP, the Climatic Research Unit (CRU) TS3.2 data [*Harris et al*., 2014] has also been used. This dataset offers the most complete, consistent and updated compilation of gridded precipitation and temperature data at the global scale. The data are stored at a spatial resolution of 0.5° latitude/longitude, and cover the period 1901-2011. These datasets are month-by-month variations in climate over the last century or so. These are calculated on high-resolution (0.5x0.5 degree) grids, which are based on an archive of monthly mean temperatures provided by more than 4000 weather stations distributed around the world. They allow variations in climate to be studied, and include variables such as cloud cover, diurnal temperature range, frost day frequency, precipitation, daily mean temperature, monthly average daily maximum temperature, vapour pressure and wet day frequency. Station anomalies (from 1961 to 1990 means) were interpolated into 0.5° latitude/longitude grid cells covering the global land surface (excluding Antarctica), and combined with an existing climatology to obtain absolute monthly values. Secondary variables (frost day frequency and potential evapotranspiration) have been estimated from the six primary variables using well-known formulae. The new dataset compares very favourably, with the major deviations mostly in regions and/or time periods with sparser observational data. The new CRU dataset includes diagnostics associated with each interpolated value that indicates the number of stations used in the interpolation, allowing determination of the reliability of values in an objective way [*Harris et al.*, 2014].

2.6.3. Regional climate model (PRECIS) and ERA-Interim reanalysis data

The AP climate station density is low. Understanding the climate, particularly in the desert areas is therefore difficult. To overcome this, climate models are used to fill the gap and provide the climate data series needed for analysis. Furthermore, the AP topography is complex where it covers coasts, steep terrains and deserts. This justifies the need for Regional Climate Model (RCM) rather than Global Climate Model (GCM) as the former has higher resolution than the latter, hence, the representations of the local processes are more reasonable such as sea breeze, convergence zones and mountains interactions. The Middle East (including the AP) has unique feature of the combination of a sea coast and mountain range which are difficult, if not impossible, to capture and perhaps a higher resolution regional climate model would be necessary to address these features [*Evans*, 2009]. The RCM used is the Providing Regional Climates for Impact Studies (PRECIS) regional climate model to assess how well PRECIS can simulate the AP climate during the recent past. PRECIS is driven, not by output from a GCM, but by a re-analysis namely the European Centre for Medium range Weather Forecasting (ECMWF) ERA-Interim re-analysis (ERA-Interim) of actual global observations over the period 1989-2008 [*Jones et al.*, 2004]. Recently, *Lelieveld et al.* [2012] have run PRECIS to study the recent and future climate change and impacts in the Eastern Mediterranean and the Middle East for the 21st century.

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Chapter 3: Recent Observed Climate Change over the Arabian Peninsula

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Abstract

We have examined trends in temperature and precipitation parameters for the Arabian Peninsula (AP) during the last 2 to 3 decades. The data set has been carefully quality controlled and checked for homogeneity. Although of low density (21 stations) and relatively short time period, a clear picture of climate change in the region has emerged. The general pattern of the AP mean annual temperature trend is one of warming, with 14 of 21 stations show statistically significant warming at 0.05 level and most at 0.01 level and only one (Seeb) showing statistically significant cooling. The highest statistically significant mean annual warming trends are found in Oman (Sur=1.03°C decade^{-1}) and Emirates (Dubai=0.81°C decade^{-1}). The season of maximum warming in mean temperature is March to April. The highest monthly mean temperature trend in the AP occurs in Sur in May (1.47°C decade^{-1}). There is a broad statistically significant increase in mean annual maximum temperature in AP in 12 out of 21 stations with the highest trends in central and eastern/southeastern AP. Only SW AP and the Gulf of Oman do not show warming. The highest monthly maximum temperature trend in the AP occurs in Bahrain in March (2. 27°C decade^{-1}). The second highest significant warming trends are reported in Doha in February (1.54°C decade^{-1}). For minimum temperature, 16 out of 21 stations show statistically significant warming trends, with the highest annual trends observed in the Emirates (Dubai=1.24°C decade^{-1}), northwest Oman (Sohar=1.17°C decade^{-1}) and Qatar

(Doha=1.13°C decade^{-1}). The highest monthly minimum temperature warming rate occurred in October. Both Dubai and Kuwait reported the highest significant rate of 2.00°C decade^{-1}. The general mean annual diurnal temperature range trend is negative in the AP with 6 out of 21 stations show statistically significant negative trends while 3 stations show statistically significant positive trends. Trends in mean annual precipitation are significant at only two stations which show a decrease in precipitation.

3.1. Introduction

Many parts of the world and especially developed countries have benefitted from assessments of observed climate changes, especially in relation to temperature and precipitation owing to the societal importance of these parameters [*Goddard et al.*, 2001]. According to the IPCC fourth assessment report [*Solomon et al.,* 2007], the surface temperatures over land regions have warmed at a faster rate than oceans in both hemispheres with land based warming trends of about 0.27°C vs. 0.13°C per decade over the past two decades. Climate change studies have, in the past, been largely restricted to North America, Europe and Australia as a result of data availability [*Freiwan and Kadioglu,* 2008]. Less is known about trends in temperature and precipitation in the Arabian Peninsula (AP). To some extent, this is because the region covers a broad range of countries, some of which have poor data availability, quality and consistency [*Zhang et al.,* 2005; *Kwarteng et al.,* 2009; *Nasrallah and Balling Jr.,* 1993]. This is in addition to the fact that much of the area is desert and there are very few sites with instrumental data. The region, located in the southwestern Asia, is characterized by unique topography which varies between deserts and high mountains. It is a dry environment with very high temperature especially in summer. It is vast with several contrasting climate zones, the northern part of which is considered to be subtropical (north of 20˚N) while the southern is a tropical (monsoonal) type.

Zhang et al. [2005] were responsible for the first region-wide trend analysis of the Middle East extreme indices for 1950-2003 at 52 stations covering 15 countries. The study shows statistically significant, spatially coherent trends in temperature indices that indicate temperature increase in the region. In a broader study covering all dryland regions, *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. Over the Middle East, *Zhang et al.* [2005] concluded that trends in precipitation are weak in general and do not show spatial coherence while over Oman during 1977 to 2003, *Kwarteng et al.*[2009] reported that in general, the monthly and yearly patterns of precipitation are stable and no significant trends were observed over the study period.

Economic and Social Commission for Western Asia [2010] urges Arab countries to demonstrate commitment and preparation in relation to emerging international climate change frameworks and that these countries should provide more inputs to the IPCC negotiations. Additionally, climate change projections for the AP shows little agreement amongst the models, particularly with regards to the sign of precipitation change. A concerted effort is therefore needed in the case of the AP to address the knowledge deficit in climate. The aim of this paper is to evaluate observed temperature parameters and precipitation trends over the relatively neglected AP region using an updated data series which includes several new stations compared with previous efforts. To our knowledge, this is the first trend analysis of climate parameters for several countries in the AP especially Oman, Qatar, Emirates and Yemen. Previous studies focus on one or a few stations per country using only one variable [*Elagib*, 2008; *Nasrallah et al.*, 2004] or use coarse gridded data with few stations [*Nasrallah and Balling Jr.*, 1993]. This paper uses data for 21 stations covering AP's 7 countries to analyze trends of 5 climate variables.

3.2. Data

Monthly mean temperature, maximum temperature, minimum temperature and precipitation data have been provided by the National Meteorological Services NMSs of the AP, namely Oman, UAE, Qatar, Bahrain, Saudi Arabia, Kuwait and Yemen for a total of 21 stations (Figure 3-1).

17 stations were provided from Oman and 4 from UAE, 5 from Saudi Arabia, 2 from Yemen and 1 station from each of Qatar, Bahrain and Kuwait. Station data which is included have the following characteristics: 1- less than 5% missing values in the whole period. 2- they have passed the homogeneity and quality control tests. 3- Bahrain, Masirah and Salalah have the longest data record of more than 50 years (1943-2008) while most of the remaining stations have data from 1980-2008. To maximize the number of stations used in the analysis, stations which have at least 24 years of data during the period 1980-2008 were selected to form the bulk of the study. A small proportion of stations did not have data for the complete period (Table 3-1) but have been included because no data from these regions has been previously available. Approximately 70% of the stations have no missing values in the period 1980-2008 for the temperature and precipitation variables while the remaining stations have between 0.3% to 4.9% missing values.

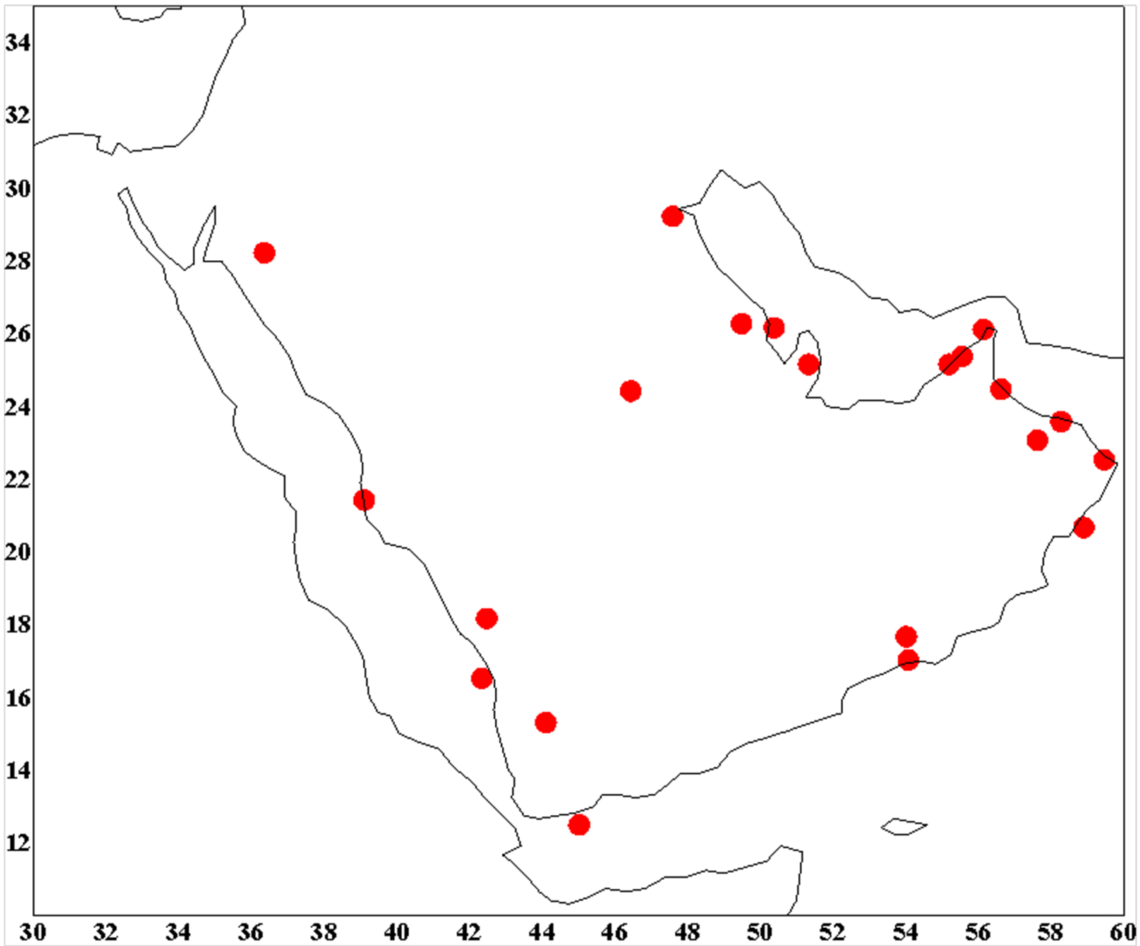

Figure 3-1: The distribution of 21 stations used in this study in the Arabian Peninsula.

Table 3-1: Stations List

Country	Station	WMO	Latitude	Longitude	Elevation(m)	Period Temperature Mean	Maximum	Minimum	Period Precipitation
Oman	Salalah	41316	17.03	54.08	22.0	1943-2008	1948-2008	1943-2008	1943-2008
	Masirah	41288	20.67	58.91	19.0	1956-2008	1943-2008	1943-2008	1956-2008
	Saiq	41254	23.07	57.63	1755.0	1980-2008	1980-2008	1980-2008	1980-2008
	Seeb	41256	23.58	58.28	8.4	1980-2008	1980-2008	1980-2008	1980-2008
	Sur	41268	22.53	59.47	14.0	1980-2008	1980-2008	1980-2008	1980-2008
	Thumrait	41314	17.67	54.02	467.0	1980-2008	1980-2008	1980-2008	1980-2008
	Khasab	41240	26.11	56.14	33.0	1980-2008	1980-2008	1980-2008	1980-2008
	Sohar	41246	24.47	56.63	3.6	1980-2008	1980-2008	1980-2008	1980-2008
UAE	Dubai	41194	25.15	55.2	5.0	1980-2008	1980-2008	1980-2008	1980-2008
	Ras Alkhaimah	41184	25.37	55.56	31.0	1980-2008	1980-2008	1980-2008	1980-2008
Bahrain	Bahrain	41150	26.16	50.39	2.0	1955-2008	1955-2008	1955-2008	1955-2008
Qatar	Doha	41170	25.15	51.34	11.0	1980-2008	1980-2008	1980-2008	1980-2008
Kuwait	Kuwait	40582	29.22	47.59	6.1	1980-2008	1980-2008	1980-2008	1985-2008
Saudi Arabia	Tabuk	40375	28.22	36.36	768.1	1985-2008	1985-2008	1985-2008	1985-2008
	Riyadh	40438	24.42	46.44	619.6	1985-2008	1985-2008	1985-2008	1985-2008
	Jeddah	41024	21.42	39.11	16.9	1985-2008	1985-2008	1985-2008	1985-2008
	Khamis Mushait	41114	18.17	42.48	2093.4	1986-2008	1986-2008	1986-2008	1985-2008
	Gizan	41140	16.53	42.35	7.2	1985-2008	1985-2008	1985-2008	1985-2008
	Dammam	40417	26.27	49.49	12. 0	2000-2008	2000-2008	2000-2008	2000-2008
Yemen	Sana'a	41404	15.31	44.11	2190.0	1996-2005	1996-2005	1996-2005	1996-2005
	Aden	41480	12.5	45.02	3.0	1996-2005	1996-2005	1996-2005	1996-2005

The seasonal definition will follow a modified version of *Fisher and Membery* [1998] over AP, namely winter (DJF), spring (MA) (1^{st} transitional period), early summer (MJ, premonsoon), late summer (JAS) and autumn (ON) (2^{nd} transitional period or postmonsoon).

3.2.1. Quality Control

Data supplied by the region's NMSs were quality controlled in two stages: 1) a check for physically implausible data (e.g. negative rainfall or maximum temperature < minimum temperature) and 2) analysis of outliers which are identified by numerical and visual checks. These were evaluated by comparing their values to nearest stations in order to determine whether the flagged values were associated with real or anomalous weather events. A few physically implausible values have been set to missing.

3.2.2. Homogeneity Checks

A homogeneous climate time series is defined as one where variations are caused only by variations in climate [*Conrad and Pollak*, 1950]. It is important, therefore, to remove the inhomogeneities. Data homogeneity is assessed using the RHtestV3 software which uses a two-phase regression model applied to monthly data in order to check for multiple stepchange points that could exist in a time series [*Wang*, 2008; *Wang*, 2003].

Identified step changes are checked against the station history (if available). Significant change points (5% level) were identified in 8 stations for mean temperature, 10 for maximum temperature, 8 for minimum temperature and 3 for precipitation. Most of these change points were regionally widespread (detected in many countries) and were found to be physically real, which concurs with other similar studies [*Alexander et al.*, 2006; *Peterson et al.*, 1998] (Table 3-2).

Table 3-2: Details of significant detected changepoints showing years, stations, variables and dates

Year	Station	Variable	Date (year.month)
1995	Khasab	precipitation	1995.11
	Rasalkhaima	precipitation	1995.11
1997	Doha	max T	1997.07
	Masira	max T	1997.06
	Sanaa	meanT	1997.06
	Aden	meanT	1997.07
	Aden	minT	1997.07
1998	Bahrain	mean T	1998.01
	Bahrain	max T	1998.01
	Bahrain	min T	1998.05
	Doha	mean T	1998.01
	Dubai	max T	1998.01
	Dubai	mean T	1998.01
	Rasalkhaima	max T	1998.02
	Riadh	max T	1998.05
1998	Doha	precipitation	1998.01
	Khasab	precipitation	1998.03
	Rasalkhaima	precipitation	1998.03
1999	Dubai	mean T	1999.06
	Dubai	max T	1999.08
	Bahrain	min T	1999.06

For example the highest number of significant temperature discontinuities occurred in 1997 and 1998. It is apparent from the spatial (not shown) and temporal signal that these changepoints are linked to heating associated with the 1997/8 El Niño . Most changepoints occurred in the southern AP stations earlier (mid 1997) than those detected in the north (Bahrain, Qatar, Emirates and Saudi Arabia) which followed several months later. The heating anomalies are evident in several reanalysis data sets (not shown).

Figure 3-2 shows an example from Bahrain monthly mean temperature. The station shows a large inhomogeneity in 1998, which corresponds to the exceptional region-wide warming, associated with the 1998 El Niño year. Historical explanations for the cause of the change points, such as station relocation, are found for only two stations namely Khasab and Sur. Therefore, we use the adjusted monthly time series of these stations where the changepoints are significant and supported by metadata.

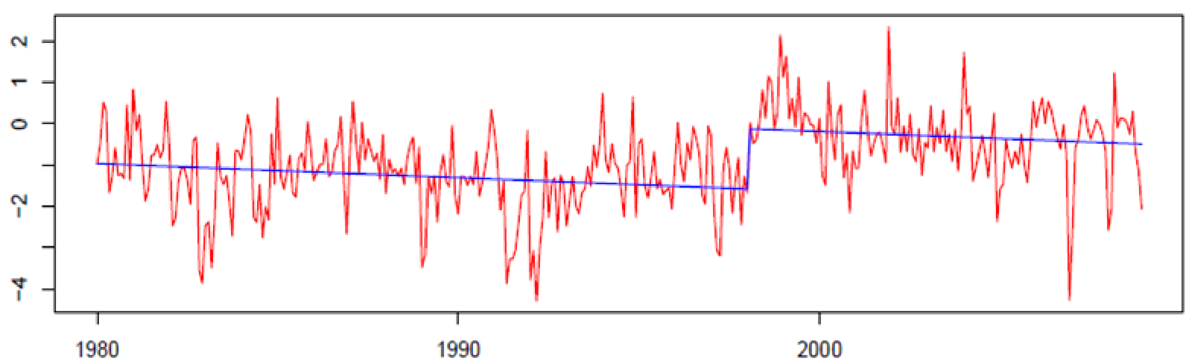

Figure 3-2: Bahrain station monthly mean temperature changepoint of 1998.

After quality control and homogeneity testing, 8 stations were retained for Oman, 2 from UAE, 6 stations from Saudi, 2 from Yemen and 1 station from Qatar, 1 from Bahrain and 1 from Kuwait. The final list of stations is summarized in Table 3-1.

3.3. Methods

3.3.1. Trends

Linear trends are computed for the following variables: mean temperature, maximum temperature, minimum temperature, diurnal temperature range (DTR) and precipitation series using the nonparametric approach by *Sen* [1968] modified by Wang and Swail [2001] to account for time series autocorrelation. This is a robust approach which is resistant to outliers and can be computed when data are missing. Annual missing values are excluded from the analysis when calculating the linear trend. The method has been widely used to compute trends in climate studies [*Aguilar et al.,* 2009; *Alexander et al.,* 2006; *Butt et al.,* 2009; *Zhang et al.,* 2005].

The significance of the trend is determined using Mann-Kendall's test for which data need not conform to any particular distribution. A similar method was adapted by *Manton et al.* [2001]. The 5% level of statistical significance is used. Monthly, seasonal and annual trends are calculated for all the 21 stations based on the stations time period. Two trends analyses were carried out; the first used station data with a period equal or more than 24 years during 1980-2008 (18 stations) while the second analysis used stations data with a period more than 50 years during 1943-2008 (Bahrain, Marisah, Salalah).

3.3.2. Area Averaging

The AP regional average time series for the 5 variables were calculated following *Aguilar et al's.* [2009] method which avoids the domination of stations with high mean values by averaging the stations time series anomalies. A base reference of 1985-2005 was used to calculate the station normals and anomalies following *Jones and Moberg* [2003] who used at least 20 years of data within the 30-yr period to calculate the normals. Data for the base period 1985 through 2005 were used in the calculation of the anomalies; at least 18 years needed to be available in this base period for the station to be used. In addition, the regional standardized time series of all the variables have been calculated and regional trends obtained. Both the anomaly and standardized averaged time series lead to similar trend shape, sign and significance. The standardized time series are not used and the results are based on the anomaly time series. No adjustments for the varying number of stations during some years have been made but it is important to note that the first 5 years (1980-1984) did not include Saudi Arabia's stations. *New et al.* [1999] state that monthly anomalies tend to be more a function of large-scale circulation patterns and are relatively independent of physiographic control. We assume the network studied here is sufficient to describe the month-to-month departures from the mean climate.

The area average time series have been computed for 3 areas: the all AP, the monsoonal area (stations south of 20°N under the direct influence of the monsoon which comprise 5 stations located over Oman and Saudi Arabia namely Masirah, Thumrait, Salalah, Gizan and Khamis Mushait) and the non-monsoonal stations located at north of 20°N covering the remaining 13 stations excluding the short period stations.

3.4. Results

3.4.1. Stations

Trends of mean, maximum and minimum temperature, diurnal temperature range and precipitation are presented in this section. Trends for individual stations precede regional trends.

3.4.1.1. Trends during the period 1980-2008

3.4.1.1.1. Mean temperature

The general pattern of the Arabian Peninsula (AP) mean annual temperature trend is warming, with 14 of 21 stations show statistically significant warming at 0.05 level and most at the 0.01 level. One station (Seeb-Oman) shows significant cooling (Figure 3-3) while the remaining 6 station trends are not statistically significant.

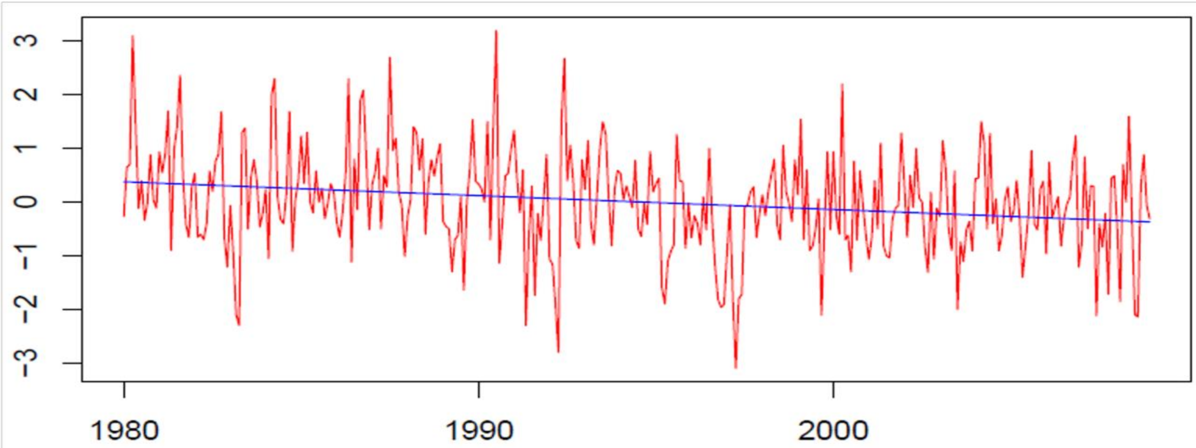

Figure 3-3: Muscat monthly anomalies time series with linear regression line showing the cooling.

The highest statistically significant warming trends are found in Oman (Sur=1.03°C decade^{-1}) and UAE (Dubai=0.81°C decade^{-1}) (Figure 3-4). Both countries are located in the eastern/southeastern parts of the AP. Other stations showing statistically significant high rates of warming are Doha (0.65°Cdecade^{-1}), Khamis Mushait (0.60°C decade-^{1}) and Kuwait (0.57°C decade^{-1}).

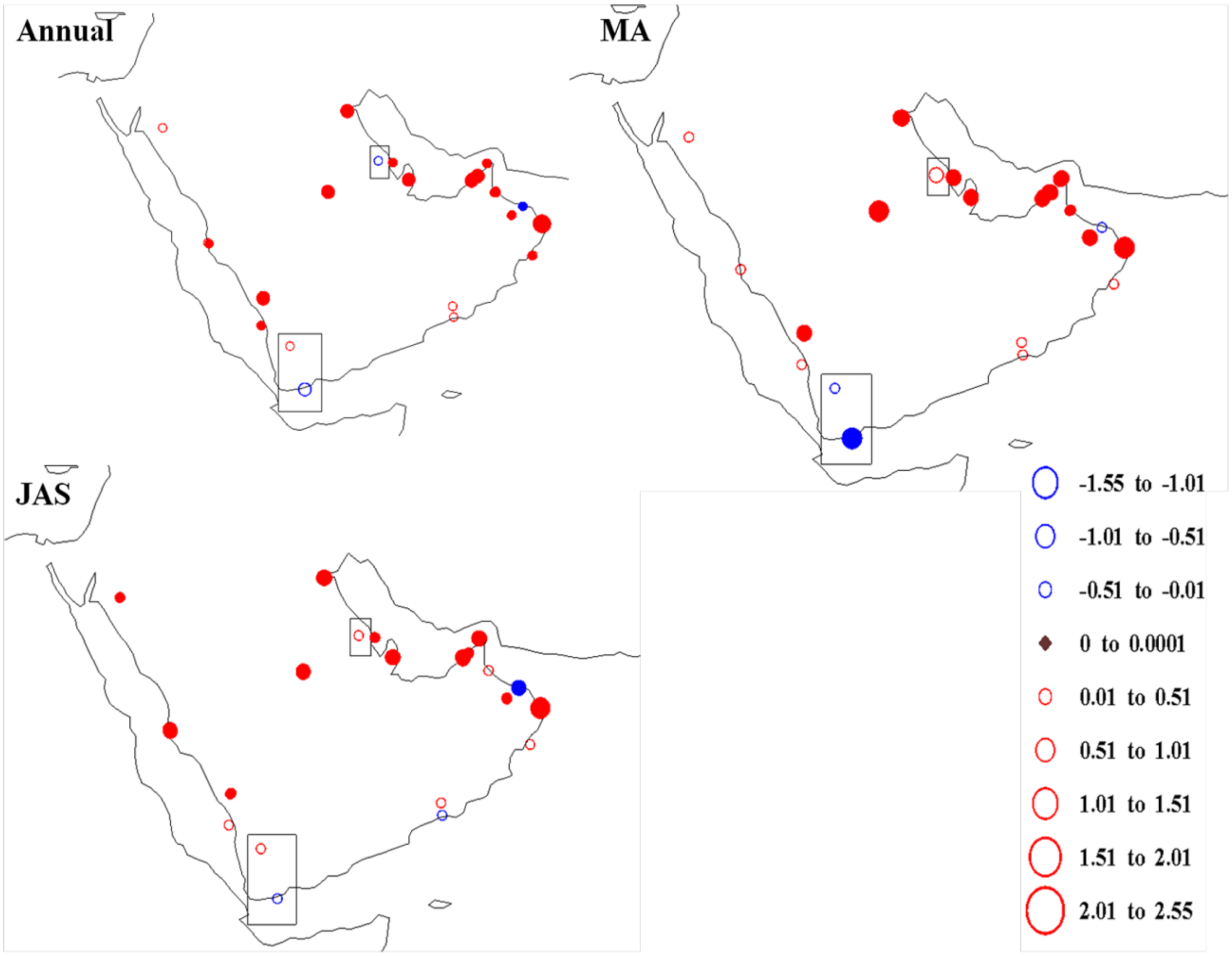

Figure 3-4: Mean temperature trends in the Arabian Peninsula in degrees °C per decade for the period 1980-2008(except Saudi Arabian stations 1985-2008). The slope of the warming trend is proportional to the diameter of the circles. Shaded circles are statistically significant at the 0.05 level. Warming is shown in red and cooling in blue. Stations enclosed by the rectangle have a much shorter record.

The lowest trend values are observed on the south and southwest coast of AP (Masirah and Gizan, (0.22°C decade^{-1}).Trends in annual temperature at the rest of the southern AP stations are not statistically significant. We start the seasonal analysis with the March-April trends which have three notable features 1)- the highest significant warming trend is in central AP (Riyadh =1.22°C decade^{-1}) 2)- 8 stations in the Arabian Gulf (AG) have warming in excess of 0.55°C decade^{-1} and 3)- there are no statistically significant trend along the southern AP coast (Figure 3-4).

The western areas of AP have higher statistically significant warming in JAS season compared with MA season (Figure 3.4). The warming extends from Sur in east Oman to Jeddah in west Saudi Arabia (the line of largest warming) while Seeb shows significant cooling (-0.55°C decade^{-1}), as is evident also in the mean annual trends. The warming pattern in MJ season is closer to MA season with Sur station at the eastern Oman reporting the highest statistically significant monthly mean temperature warming trend in all AP in May (1.47°C decade^{-1}).

In the DJF season, the areas of most rapid warming are generally the same as for the mean annual temperature (i.e. eastern and southeastern AP). In this season, 10 of 21 stations show statistically significant trends. Surprisingly, the highest rate of warming is observed over the mountains in northern Oman (Saiq=0.85°C decade^{-1}) at around 2 km above mean sea level and distant from large settlements. Sur, Dubai and Khamis Mushait have significant trends of more than 0.70°C decade^{-1}). In the DJF season, warming trends in the northern stations are not as steep as those for the mean annual trends. In contrast, some of the eastern and southern trends are larger during DJF. It is also striking that Khamis Mushait (2 km above MSL) reported the highest statistically significant warming in January (0.80°C decade^{-1}).

3.4.1.1.2. Maximum temperature:

There is a broad statistically significant increase (at 0.05 level) in mean annual maximum temperature in AP with 12 out of 21 stations showing statistically significant warming. The exception is southwest AP and Gulf of Oman (Figure 3-5).

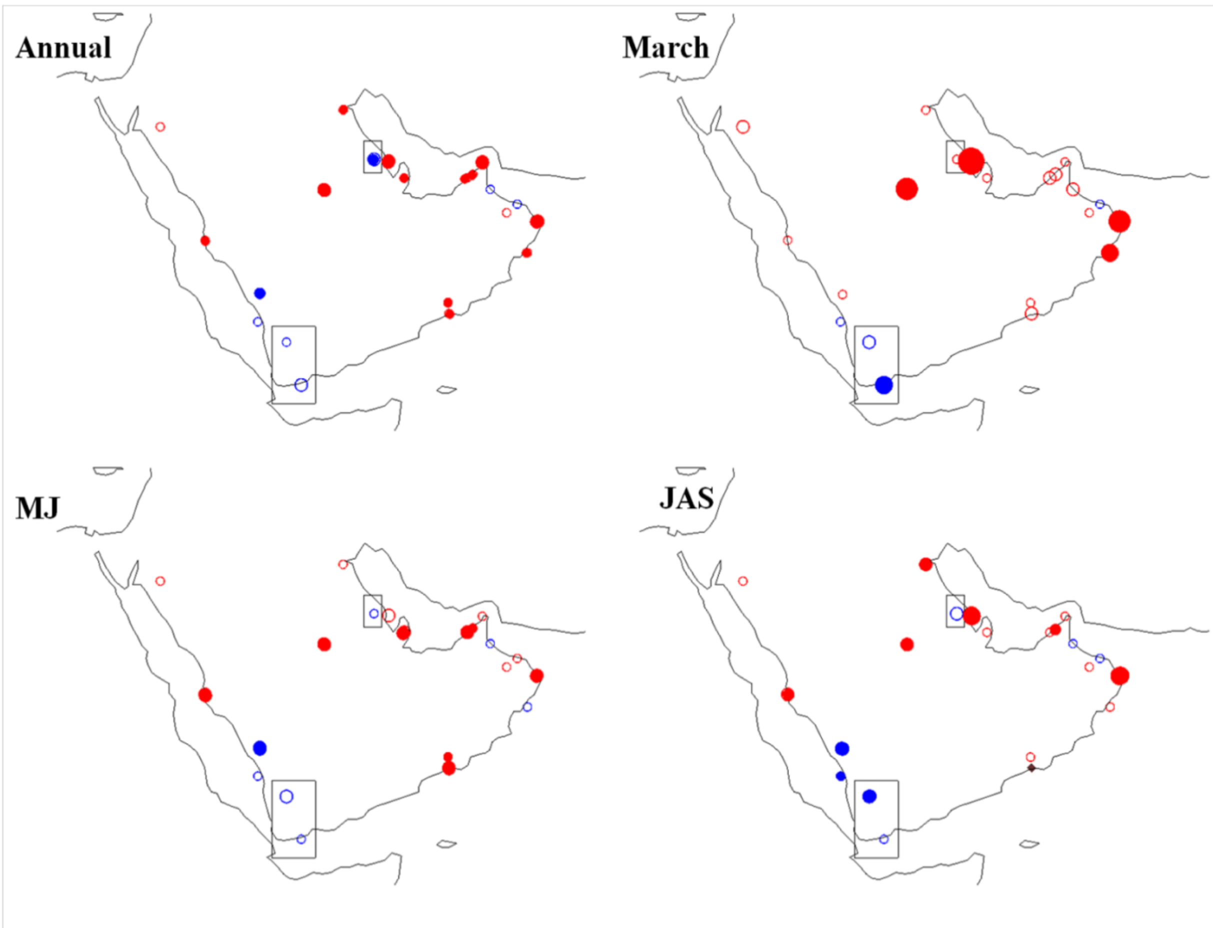

Figure 3-5: As in figure 3-4 but for maximum temperature.

The highest mean annual trends are observed in the central and eastern/southeastern areas where Sur and Khasab (Oman) reported the values of 0.93 and 0.88°C $decade^{-1}$

respectively. Bahrain shows a similarly high trend of 0.81 °C decade^{-1}. Both Saiq over the Northern Oman Mountains and Masirah over Oman's east coast reported the lowest statistically significant trend (0.27°C decade^{-1}). The cooling in the southwest AP is not statistically significant except in Khamis Mushait (-0.40°C decade^{-1}).

The MA season shows the highest number of stations with high trend values. Riyadh and Kuwait reported the highest MA season significant warming of 1.50 and 1.25 °C decade^{-1} respectively. The month of March witnessed the highest monthly maximum temperature trend value in the AP of 2.27°C decade^{-1} (at Bahrain see Figure 3-5). The second highest significant warming trend is reported at Doha in February (1.54°C decade^{-1}). In MJ a line of significant warming trends appeared from Dubai (UAE to Jeddah in west Saudi Arabia) with warming trends ranging from 0.52 to 0.76°C decade^{-1}. This line also appeared in the mean temperature MJ and JAS seasons (Figure 3-5). A line of intense significant warming is seen in central AP in the JAS season (Bahrain=1.10°C decade^{-1}) but intense significant cooling occurred in the southwest areas (Khamis Mushait = -0.75°C decade^{-1}) (Figure 3-5). In ON season most of the statistically significant trends are observed in Oman and UAE while significant cooling persists in the southwest AP.

3.4.1.1.3. Minimum Temperature:

From the data in Figure 3-6, it is apparent that the warming trends of the mean annual minimum temperature in AP are statistically significant and these are more spatially coherent at more of the stations compared with those for the annual mean and annual maximum temperature.

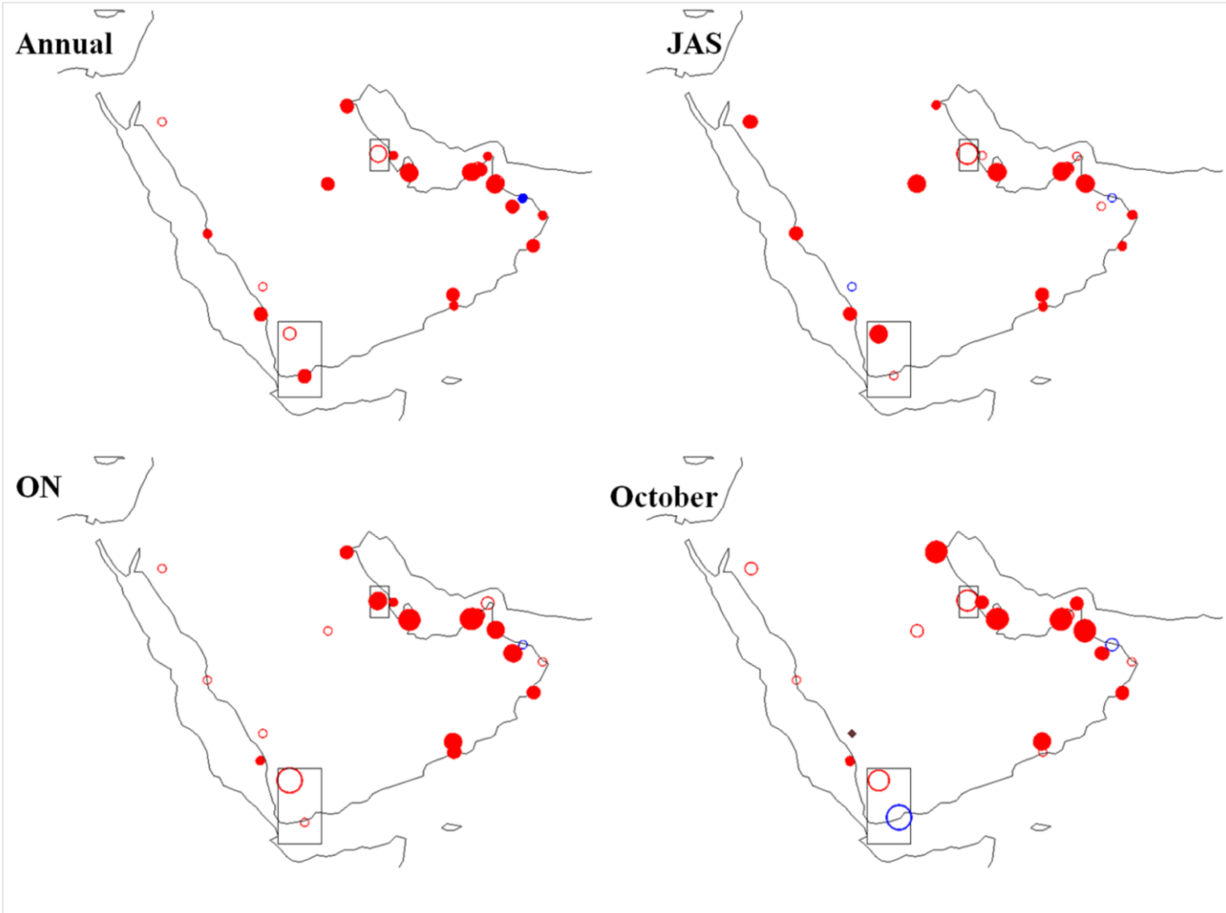

Figure 3-6: As in figure 3-4 but for minimum temperature.

16 out of 21 stations show statistically significant warming trends, the highest trend values are observed in the UAE (Dubai=1.24°C decade^{-1}), northwest Oman (Sohar=1.17°C decade^{-1}) and Qatar (Doha=1.13°C decade^{-1}). One single striking difference with the other variables is that the trend of the mean annual minimum temperature is statistically significant even over the south AP coast. There is only one statistically significant cooling trend (Seeb, -0.32°C decade^{-1}).

Widespread and significant warming trends are evident in MJ and JAS with many stations reporting high trend values in excess of (1.00°C decade^{-1}). The line of intense warming from east to west AP apparent in the MJ season is even more marked in the JAS season (Figure 3-6). This line is seen from February through to September (not shown). ON season witnessed the highest significant trends which cover all the eastern AP. Dubai reported the highest trend of 1.61°C decade^{-1}. Other stations reporting trends higher than 1.00°C decade^{-1} include: Sohar, Saiq, Thumrait and Doha (Figure 3-6). In October both Dubai and Kuwait reported the highest significant rate of 2.00°C decade^{-1}.

The statistical significant warming in DJF covers most of central and southern AP (Doha=1.23°C decade^{-1}, Saiq=1.20°C decade^{-1}) while significant cooling is observed over Seeb(-0.63°C decade^{-1}). Interestingly in the MA season the statistically significant trends are limited to AG stations as Kuwait (1.22°C decade^{-1}), Doha (1.19°C decade^{-1}) and Dubai (1.00°C decade^{-1}).

3.4.1.1.4. Diurnal Temperature Range

The general mean annual DTR trends pattern is negative in the AP (Figure 3-7) with 6 out of 21 stations show statistically significant negative trends.

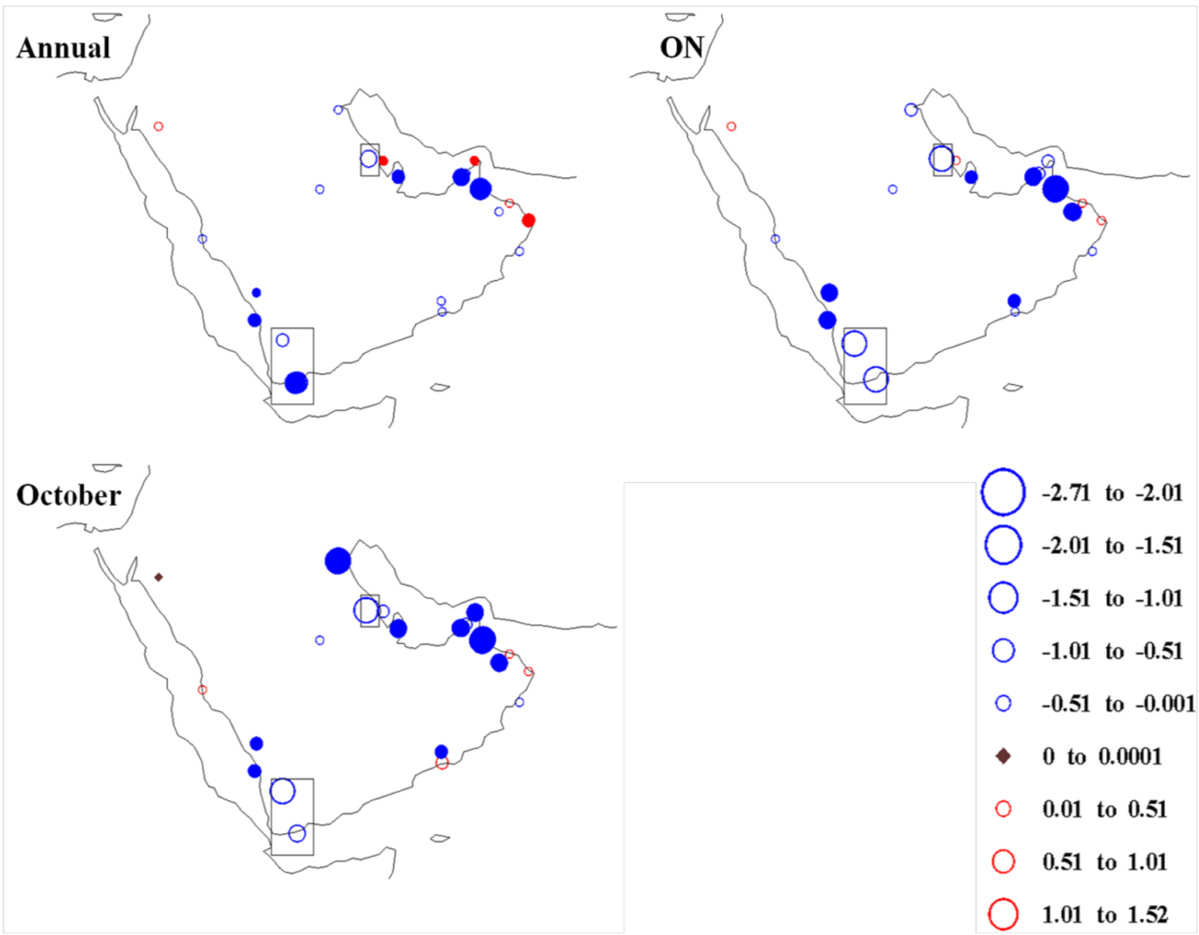

Figure 3-7: As in figure 3-4 but for Diurnal Temperature Range (DTR).

The highest negative rate occurred in the northwest Oman (Sohar=-1.45°C decade^{-1}), Qatar (Doha=- 0.79°C decade^{-1}) and UAE (Dubai=-0.71°C decade^{-1}). Sur, Khasab and Bahrain stations show statistically significant positive trends with values 0.58°C decade^{-1}, 0.47°C decade^{-1}and 0.44°C decade^{-1} respectively. The results show few statistically significant trends in the first half of the year but the negative trends increase significantly in the second half of the year i.e. MJ, JAS and ON seasons especially over eastern, southeastern and the southwest AP (e.g. ON Figure 3-7). October witnessed the highest monthly statistically significant trends (Figure 3-7) with values exceeding -2.00°Cdecade^{-1} as in Sohar (Oman) and Kuwait (Kuwait).

3.4.1.1.5. Precipitation

The total annual precipitation trends values show only 2 stations with statistically significant trends. Both stations show negative trends: (Saiq =-67.71 mm decade^{-1} which is-59% of the base mean and Tabuk= -20.90 mm decade-^{1}(-163% of the base mean). Most of the remaining stations trends are negative and not statistically significant (Figure 3-8).

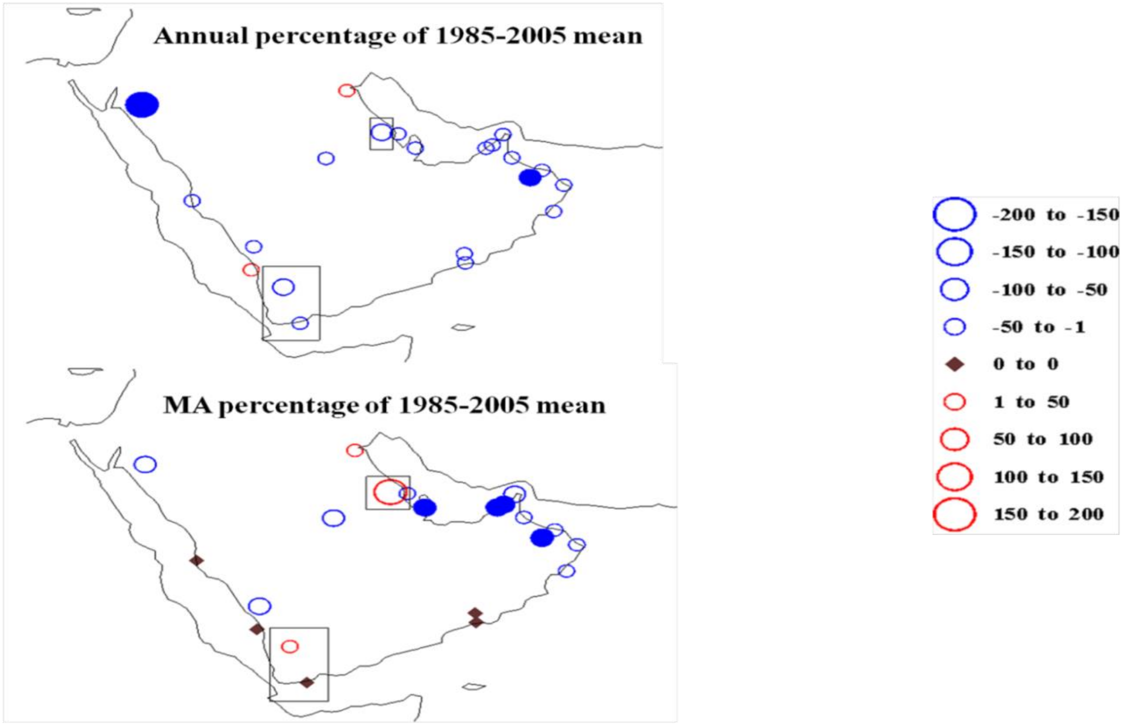

Figure 3-8: Precipitation percentages from 1985-2005 mean in the Arabian Peninsula per decade for the period 1980-2008 (except Saudi Arabian stations 1985-2008) The slope of the drying/wetting trend is proportional to the diameter of the circles. Shaded circles are statistically significant at the 0.05 level. Drying is shown in blue and wetting in red. Stations enclosed by the rectangle have a much shorter record.

Of the rainy seasons, the largest number of negative statistically significant trends occurs in MA (Figure 3.8), covering northern Oman (Saiq=-10.23 mm decade^{-1}, -94% of the base mean), Qatar (Doha=-3.87 mm decade^{-1}, -85% of the base mean) and Emirates (Dubai=-3.52 mm decade^{-1}, -67% of the base mean). In the DJF season the trend values shows 1 negative statistically significant trend over Thumrait (south Oman) and 1 positive statistically significant trend over Kuwait (6.94 mm decade^{-1}, 82% of the base mean). In January there is a widespread increase of precipitation over AG and west of AP but it is statistically insignificant. The AlKhareef summer rain over Salalah (south Oman) shows statistically significant negative trend (-3.72 mm decade^{-1}, -53% of the base mean).

3.4.1.2. Trends during the period 1943-2008:

Analysis of trends for stations with a record of more than 50 years (See Table 3-3) was done for Salalah, Masirah and Bahrain. The results show that the mean annual mean temperature is increasing significantly at 0.01 level over all the stations. Salalah and Bahrain warmed at similar rate of 0.15°C decade^{-1} while Masirah warmed at a lower rate of 0.08°C decade^{-1}. Over Salalah all the seasons are warming significantly (0.001 level) except JAS. Masirah cooled in early summer (MJ) with the remaining seasons warming significantly. Most of the seasonal warming over Bahrain is in early and late summer (significant at 0.001 level). The highest significant warming month over Salalah, Masirah and Bahrain are October, November and June respectively.

Table 3-3: Regional Trends and Significance (a) and Overall Change of Mean, Maximum, and Minimum Temperatures, DTR, and Precipitation Over the Arabian Peninsula for Long-Term Data for Salalah, Masirah and Bahrain

Mean Temperature (°C $decade^{-1}$)						
	Salalah		Masirah		Bahrain	
	Trend	α	Trend	α	Trend	α
DJF	0.19	0.001	0.23	0.001	0.03	
MA	0.23	0.001	0.11	0.05	0.12	
MJ	0.12	0.001	-0.09	0.01	0.39	0.001
JAS	0.04		-0.05		0.24	0.001
ON	0.26	0.001	0.18	0.001	0.13	0.05
Annual	0.15	0.001	0.08	0.01	0.16	0.01
Minimum temperature (°C $decade^{-1}$)						
DJF	0.25	0.001	0.10		-0.05	
MA	0.30	0.001	0.16	0.1	0.08	
MJ	0.30	0.001	0.17	0.01	0.27	0.01
JAS	0.18	0.001	0.13	0.01	0.01	
ON	0.33	0.001	0.25	0.001	-0.05	
Annual	0.27	0.001	0.14	0.001	0.03	
Maximum Temperature (°C $decade^{-1}$)						
DJF	0.16	0.01	0.24	0.001	0.08	
MA	0.36	0.001	0.24	0.05	0.42	0.05
MJ	0.20	0.05	0.15		0.71	0.001
JAS	0.05		0.11		0.68	0.001
ON	0.35	0.01	0.31	0.001	0.42	0.01
Annual	0.21	0.001	0.20	0.001	0.46	0.001
DTR (°C $decade^{-1}$)						
DJF	-0.14	0.1	0.13		0.10	
MA	0.04		0.08		0.34	0.1
MJ	-0.13		-0.02		0.46	0.05
JAS	-0.13	0.05	0.01		0.62	0.001
ON	-0.07		0.05		0.44	0.01
Annual	-0.11	0.05	0.05		0.42	0.001
Precipitation (percentage of the base mean 1971-2000)						
DJF	0.00		5.76		29.26	
MA	0.745		0.00		0.172	
MJ	10.87		0.00		0.00	
JAS	-22.11		0.00		0.00	
ON	0.00		0.00		0.00	
Annual	-4.33		-10.73		27.40	

The mean annual maximum temperature is increasing significantly (at 0.001 level) with similar trends (0.20°C decade^{-1}) over Salalah and Masirah. The warming is large by a factor of two at Bahrain (0.46°C decade^{-1}) with similar significance. Most of the significant warming is in DJF, MA and ON in Salalah and Masirah while all the seasons are warming significantly over Bahrain except DJF season. May reported the highest warming month in Salalah, November in Masirah and July in Bahrain.

Both Salalah and Masirah reported statistically significant (at 0.001 level) increase in mean annual minimum temperature with higher trends reported over Salalah (0.27°C decade^{-1}). The mean annual DTR is increasing over Bahrain (0.42° Cdecade^{-1}) but is decreasing significantly over Salalah station with rate of -0.11°Cdecade^{-1}.

3.4.2. Arabian Peninsula Regional Trends

An area-average time series of the AP was constructed based on monthly station anomalies. The contribution of the station data to the area average was weighted to remove the effect of the domination of the regional time series by the higher density of stations in some regions. The trends were calculated following the methods described in section 3.3.1 The resulting annual cycle of regional AP trends is shown in Figures 3-9 and 3-10. As was clear from the discussion of station trends, there are generally higher values in the north and lower values on the coastal margin in the south where smaller trends occur. As a result, the AP region was divided into 2 sub-regions: (1) stations south of 20°N under the direct influence of the monsoon and (2) non-monsoon stations located north of 20°N. The monsoonal area consists of 5 stations located over Oman and Saudi Arabia (Masirah, Thumrait, Salalah, Gizan and Khamis Mushait). The non-monsoonal area covers the remaining 13 stations (excluding the short period stations).

3.4.2.1. Mean temperature

The all AP annual mean temperature increased at a rate of 0.40°C decade^{-1} (0.001 significance level) during the period 1980-2008 while the non-monsoonal annual mean temperature increased at a rate of 0.46°C decade^{-1} (0.001 significant level). In contrast to the all AP and the non-monsoonal regions, the temperature increases over the monsoonal subregion is lower (0. 20°C decade^{-1}which is almost half of the all AP).

The warming is significant over all AP in almost all seasons and months except January (see Table 3-4). The annual cycle (Figure 3.9) of the mean temperature trends peaks in MA season with a minimum in JAS in both all and non-monsoonal regions. The mean temperature trend in the non-monsoonal subregion is 6 times higher than the monsoonal subregion in MJ season. However, in the Monsoonal area, the mean temperature is increasing significantly in DJF and MA seasons with other peak in ON season.

Table 3-4: Regional Trends for the Period 1980–2008 and Significance (a) and Overall Change of Mean, Maximum, and Minimum Temperatures, DTR, and Precipitation Over the Arabian Peninsula[a]

	Mean Temperature									Maximum Temperature								
	All			NMon			Mon			All			NMon			Mon		
Month	Trend	α	°C	Trend	α	°C	Trend	sig.	°C	Trend	α	°C	Trend	α	°C	Trend	α	°C
Jan	0.24		0.7	0.21		0.6	0.21		0.6	-0.03		-0.1	-0.07		-0.2	0.17		0.5
Feb	0.64	0.001	1.9	0.70	0.001	2.0	0.46	0.01	1.3	0.69	0.01	2.0	0.90	0.01	2.6	0.39	0.05	1.1
Mar	0.53	0.01	1.5	0.63	0.01	1.8	0.21		0.6	0.55		1.6	0.54		1.6	0.42	0.1	1.2
Apr	0.50	0.05	1.5	0.59	0.05	1.7	0.28	0.05	0.8	0.36		1.0	0.51		1.5	0.13		0.4
May	0.52	0.001	1.5	0.68	0.001	2.0	0.16		0.5	0.50	0.001	1.4	0.44	0.01	1.3	0.63	0.05	1.8
Jun	0.37	0.001	1.1	0.51	0.001	1.5	0.00		0.0	0.17		0.5	0.31	0.1	0.9	-0.09		-0.3
Jul	0.33	0.001	1.0	0.39	0.01	1.1	0.22		0.6	0.11		0.3	0.08		0.2	0.16		0.5
Aug	0.38	0.001	1.1	0.54	0.001	1.6	-0.12		-0.4	0.29	0.1	0.8	0.41	0.05	1.2	-0.21		-0.6
Sep	0.44	0.001	1.3	0.48	0.001	1.4	0.22	0.1	0.6	0.27	0.05	0.8	0.28	0.1	0.8	0.25	0.1	0.7
Oct	0.40	0.001	1.2	0.51	0.001	1.5	0.24	0.05	0.7	0.13		0.4	0.10		0.3	0.23		0.7
Nov	0.44	0.01	1.3	0.44	0.01	1.3	0.31	0.01	0.9	0.25		0.7	0.26	0.05	0.7	0.04		0.1
Dec	0.47	0.05	1.3	0.49	0.05	1.4	0.45	0.01	1.3	0.12		0.3	0.02		0.1	0.24	0.1	0.7
DJF	0.49	0.01	1.4	0.47	0.05	1.4	0.34	0.001	1.0	0.29	0.1	0.8	0.26	0.1	0.8	0.32	0.05	0.9
MA	0.56	0.01	1.6	0.64	0.01	1.8	0.27	0.01	0.8	0.44	0.1	1.3	0.60	0.1	1.7	0.26		0.7
MJ	0.44	0.001	1.3	0.60	0.001	1.7	0.10		0.3	0.32	0.01	0.9	0.39	0.01	1.1	0.30		0.9
JAS	0.38	0.001	1.1	0.47	0.001	1.4	0.13		0.4	0.23	0.01	0.7	0.31	0.05	0.9	0.08		0.2
ON	0.41	0.001	1.2	0.48	0.001	1.4	0.25	0.01	0.7	0.10		0.3	0.15		0.4	0.11		0.3
ANN	0.40	0.001	1.1	0.46	0.001	1.3	0.20	0.001	0.6	0.32	0.01	0.9	0.37	0.01	1.1	0.21	0.05	0.6

Table 3-4 continued.

	Minimum Temperature									Diurnal Temperature Range								
	All			NMon			Mon			All			NMon			Mon		
Month	Trend	α	^{o}C	Trend	α	^{o}C	Trend	α	^{o}C	Trend	α	^{o}C	Trend	α	^{o}C	Trend	α	^{o}C
Jan	0.31		0.9	0.22		0.6	0.35	0.1	1.0	-0.31		-0.9	-0.34	0.1	-1.0	-0.25		-0.7
Feb	0.77	0.01	2.2	0.76	0.05	2.2	0.85	0.05	2.5	-0.03		-0.1	0.09		0.2	-0.61		-1.8
Mar	0.56	0.05	1.6	0.65	0.01	1.9	0.34		1.0	0.05		0.1	0.06		0.2	0.01		0.0
Apr	0.83	0.01	2.4	0.96	0.05	2.8	0.47	0.05	1.4	-0.24		-0.7	-0.27		-0.8	-0.22		-0.6
May	0.71	0.01	2.1	0.81	0.01	2.3	0.39	0.05	1.1	-0.18		-0.5	-0.33		-1.0	0.44		1.3
Jun	0.68	0.001	2.0	0.76	0.001	2.2	0.39	0.01	1.1	-0.47	0.01	-1.4	-0.41	0.01	-1.2	-0.53	0.05	-1.5
Jul	0.50	0.001	1.4	0.60	0.001	1.7	0.25	0.05	0.7	-0.39	0.05	-1.1	-0.50	0.01	-1.4	-0.07		-0.2
Aug	0.59	0.001	1.7	0.67	0.001	1.9	0.46	0.001	1.3	-0.37	0.05	-1.1	-0.22		-0.6	-0.56	0.001	-1.6
Sep	0.59	0.001	1.7	0.63	0.001	1.8	0.55	0.001	1.6	-0.42	0.05	-1.2	-0.44	0.1	-1.3	-0.35	0.1	-1.0
Oct	0.85	0.001	2.5	1.00	0.001	2.9	0.58	0.01	1.7	-0.78	0.001	-2.3	-0.95	0.001	-2.8	-0.18		-0.5
Nov	0.59	0.01	1.7	0.53	0.05	1.5	0.74	0.001	2.2	-0.35		-1.0	-0.19		-0.5	-0.77	0.01	-2.2
Dec	0.42	0.1	1.2	0.41		1.2	0.61	0.05	1.8	-0.30		-0.9	-0.42		-1.2	-0.20		-0.6
DJF	0.51	0.01	1.5	0.45	0.05	1.3	0.67	0.01	1.9	-0.20		-0.6	-0.09		-0.3	-0.40	0.1	-1.2
MA	0.53	0.01	1.5	0.66	0.01	1.9	0.39	0.1	1.1	-0.12		-0.3	-0.10		-0.3	-0.15		-0.4
MJ	0.74	0.001	2.1	0.83	0.001	2.4	0.37	0.01	1.1	-0.25	0.1	-0.7	-0.31	0.1	-0.9	-0.16		-0.5
JAS	0.57	0.001	1.6	0.63	0.001	1.8	0.44	0.001	1.3	-0.36	0.001	-1.0	-0.35	0.01	-1.0	-0.37	0.01	-1.1
ON	0.70	0.001	2.0	0.73	0.001	2.1	0.64	0.001	1.8	-0.57	0.01	-1.6	-0.61	0.01	-1.8	-0.49	0.1	-1.4
ANN	0.55	0.001	1.6	0.61	0.001	1.8	0.44	0.001	1.3	-0.26	0.01	-0.7	-0.21	0.05	-0.6	-0.25	0.05	-0.7

Table 3-4 continued.

	Precipitation								
	All			NMon			Mon		
Month	Trend	α	%	Trend	α	%	Trend	α	%
Jan	2.93		54.7	3.60		53.7	-0.22		-12.0
Feb	-5.21		-106.2	-6.58		-102.1	-0.68	0.05	-74.6
Mar	-4.35		-64.2	-4.26		-55.3	-1.01		-23.2
Apr	-1.39		-35.4	-1.66		-51.9	-0.31		-5.3
May	-0.10		-6.3	-0.24		-23.7	0.93		30.4
Jun	0.17		17.9	0.46	0.05	94.3	-0.20		-9.8
Jul	-0.20		-7.6	0.25		13.6	-0.55		-11.6
Aug	-0.50		-18.3	-0.52		-32.6	-1.20		-20.8
Sep	-0.11		-10.8	0.00		0.0	-0.72		-38.6
Oct	-0.01		-0.5	-0.04		-4.0	0.06		2.5
Nov	0.40		14.9	0.51		16.4	0.00		0.0
Dec	1.28		25.4	1.45		23.1	-0.03		-1.5
DJF	-0.36		-7.2	0.29		4.5	-0.63		-43.3
MA	-3.14		-58.7	-2.96		-54.4	-1.50		-29.4
MJ	-0.01		-0.5	0.14		18.7	-0.16		-6.4
JAS	-0.11		-5.2	-0.20		-14.5	-0.60		-14.6
ON	0.19		9.3	0.24		11.8	0.14		7.5
ANN	-6.59		-16.9	-8.72		-21.7	-1.91		-5.3

[a]Regions: All, all Arabian Peninsula; NMon, nonmonsoonal subregion; Mon, monsoonal subregion. Precipitation given as percentages of the base mean.

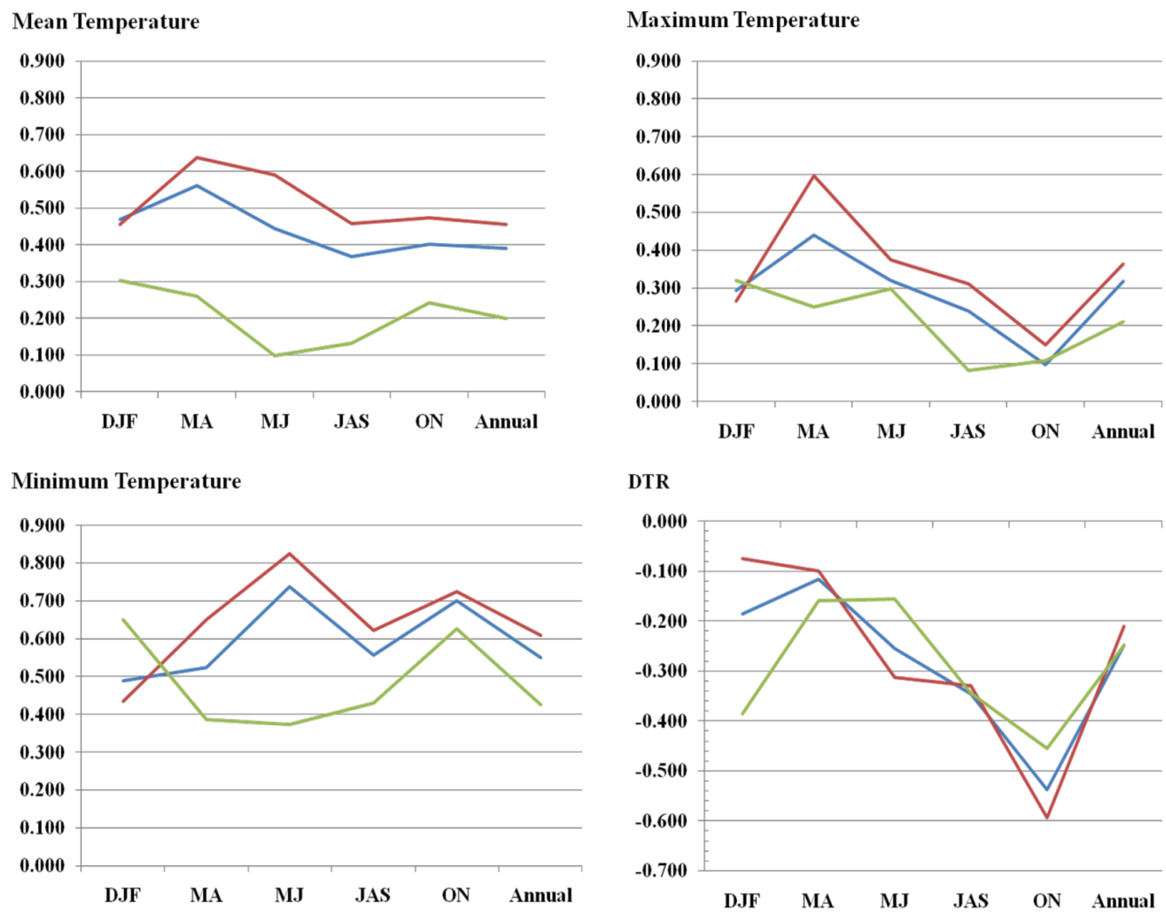

Figure 3-9: Seasonal and annual cycle trends in degrees °C per decade for the period 1980-2008 (except Saudi stations 1985-2008) of mean, maximum and minimum temperatures for all Arabian Peninsula (blue), non-monsoonal subregion (red) and monsoonal subregion (green).

3.4.2.2. Maximum temperature

The all AP annual mean maximum temperature is increasing significantly at a rate 0.32 C decade^{-1} which is less than the mean temperature. The rate of the annual mean maximum temperature for the monsoonal and non-monsoonal region is 0.21°C decade^{-1} and 0.37°C decade^{-1} respectively.

Over all AP, the maximum temperature warming is significant in February, May and September and in MJ and JAS. In the JAS season, the non-monsoonal area warming was 4 times higher than the monsoonal area. For the monsoonal area, the maximum temperature trends have the highest values in the first half of the year (only significant in DJF season) with a minimum in the second half of the year (Figure 3-9).

3.4.2.3. Minimum temperature

The warming rate of annual mean minimum temperature is higher than the mean and maximum temperatures over all AP and the 2 subregions. The annual mean minimum temperature trend is 0.55°C decade^{-1} over all AP. It is 0.61°C decade^{-1} over the non-monsoonal subregion. Over the monsoonal subregion the annual warming rate is 0.44°C decade^{-1}.

Similar to the mean temperature, the warming over all AP is significant in all seasons and months except January and December. Minimum temperature peaks significantly (at 0.05 level) in MJ and ON at both all and non-monsoonal regions. There is also a DJF peak in the monsoonal region (Figure 3-9).

3.4.2.4. DTR

As a result of higher warming trends of annual mean minimum temperature relative to annual mean maximum temperature, there is a significant decrease of the annual mean DTR over all regions. The trend values reported over all AP, the non-monsoonal and monsoonal subregions are as follow -0.26°C decade^{-1}, -0.21°C decade^{-1} and -0.25°C decade^{-1} respectively.

The DTR trend is insignificant in DJF and MA at all and the non-monsoonal regions but the highest reduction in DTR occurs significantly in ON season (Figure 3-9). In the monsoonal subregion, the lowest significant reduction occurred in JAS season.

3.4.2.5. Precipitation

The general trend for precipitation is drying over all the regions with overall decrease of annual total around 19.1 mm (-16.9% of the base mean) over all AP although this trend is not significant (Figure 3-10).

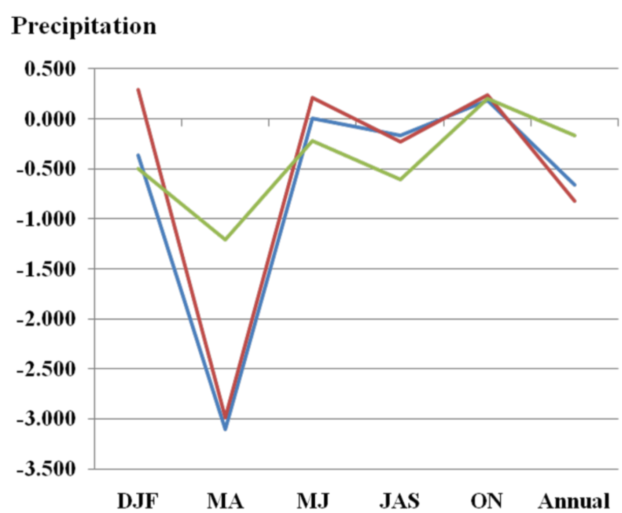

Figure 3-10: As in figure 3.9 but for precipitation in mm decade^{-1}.

3.4.3. Sensitivity to missing data

Trends for all AP and the two subregions (non-monsoon and monsoon) have been recalculated without the Saudi Arabian stations to assess the impact of the missing data (1980-1984) for the Saudi Arabian stations. Excluding Saudi Arabian stations yields almost identical trends of the mean, maximum and minimum temperatures and DTR in all AP, non-monsoon and monsoon subregions. Some differences do exist, notably the maximum temperature in the monsoon subregion where the trends are higher when excluding the Saudi Arabian stations relative to the trends when including of Saudi Arabian stations. The following values are the difference between the trends for Monsoon region without the Saudi Arabian stations and the monsoon region with all stations included: 0.24˚ C decade^{-1} in May, 0.38˚C decade^{-1} in October, 0.23˚C decade^{-1} in MJ season and 0.30˚C decade^{-1} in ON season. The precipitation results are insensitive to the exclusion of the Saudi Arabian stations.

3.5. Discussion

3.5.1. For the period 1980-2008:

3.5.1.1. Precipitation

Observed precipitation trends are generally less spatially coherent and of lower level of statistical significance than temperature changes [*Alexander et al.,* 2006]. This is true also of the AP. *Nasrallah and Balling* [1996] suggested some possible reasons for the lack of clear trends in AP including: (a) the low rainfall totals that dominate the region, (b) the great temporal and spatial variability of precipitation in such an arid and topographicallydiverse environment. Most of the drying in all AP and the subregions occurred in MA season. Most of the AP rainfall mechanisms occur during winter and spring westerly upper air troughs [*Fisher and Membery*, 1998; *Galvin*, 2009]. The AP precipitation anomalies time series was correlated with the North Atlantic Oscillation (NAO) and El Niño-Southern Oscillation (ENSO) indices (Table 3-5). The indices time series were extracted from the NCEP/NCAR website (http://www.esrl.noaa.gov/psd/data/climateindices/list/). AP rainy seasons (DJF and MA) have higher and significant correlation with ENSO (Nino3.4 and SOI indices) than NAO. Correlation is insignificant with NAO.

Table 3-5: Arabian Peninsula precipitation anomalies correlation (and significance) with ENSO and NAO indices

	correlation	p value
	DJF	
NAO	-0.19	0.32
Nino3.4	0.38	0.04
SOI	-0.45	0.02
	MA	
NAO	0.15	0.47
Nino3.4	0.47	0.01
SOI	-0.42	0.04

A noticeable result of the precipitation analysis is that the annual total data from years 1995–1997 for many AP stations include record high levels of precipitation. Further analysis of daily rainfall totals and the mechanisms associated with these events is required before a fuller picture can emerge.

3.5.1.2. Mean Temperature

During the past two decades the surface temperatures over land regions have warmed at about 0.27°C vs. 0.13°C over oceans per decade [*Solomon et al.,* 2007]. The rate over land is faster than over the oceans in both hemispheres. *Klotzbach et al.* [2009] found a closer global trend of 0.31^{o}C/decade over the period 1979-2008 using surface temperature data sets from the National Climate Data Center (NCDC). Comparison of individual station mean annual temperature trends within AP with global trends (Figure 3-11) allows the distinction of four types of station trends. First Bahrain, Sohar, Tabuk and Jeddah are all similar to global land trends. Second, trends at Doha, Riyadh, Khamis Mushait, Dubai, Kuwait, Khasab, Saiq, Ras Alkhaimah and Sur are 1.5 to 3.5 times higher than the global land mean trends. Third stations which located further south in the AP (Masirah, Salalah, Thumrait and Gizan) report lower trends. Fourth, one station Seeb reported a significant cooling trend (Aden and Dammam are also negative but over a much reduced period).

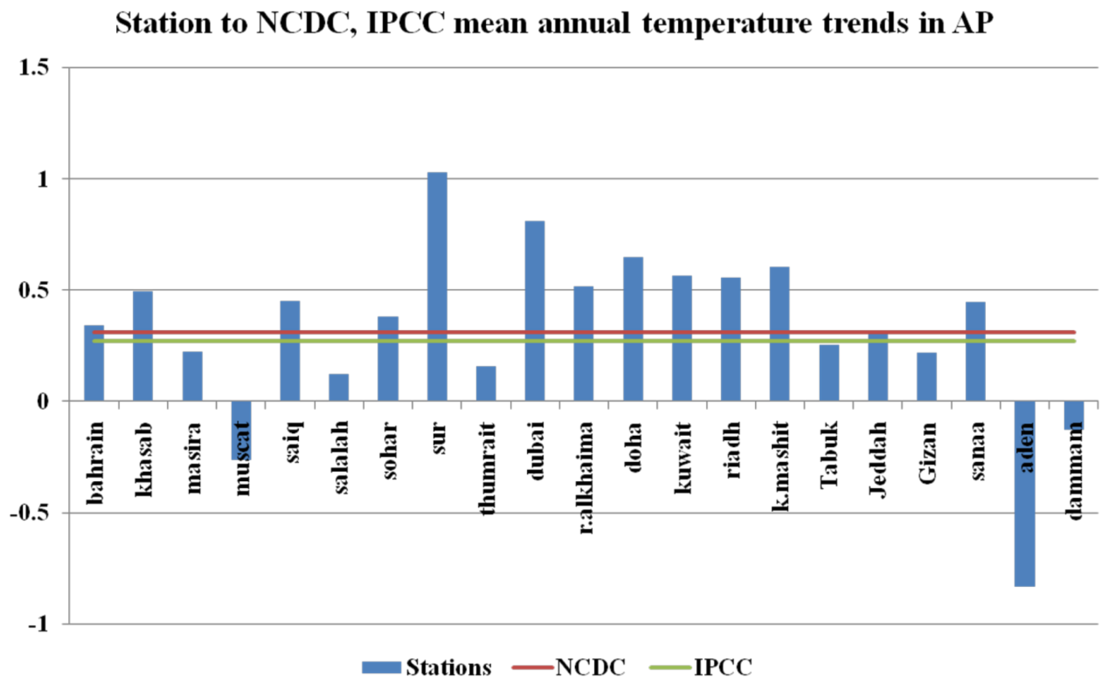

Figure 3-11: Arabian Peninsula stations mean annual temperature trends for the period 1980-2008 (except Saudi Arabian stations 1985-2008) in degree ˚C per decade relative to global mean annual temperature according to *IPCC* [*Solomon et al.*, 2007] and *Klotzbach et al.* [2009].

The recent significant warming over AP during the last few decades is in agreement with several other dryland or AP region studies. *Hulme* [1996] reported that all dryland regions have warmed. This study shows that the non-monsoonal region located north of 20^{o}N has experienced higher rates of warming. This is in line with *Solomon et al.* [2007] who reported greater increases in the interior compared with coastal regions. Temperature trends are specific to sampling periods [*Manton et al.*, 2001; *Haylock et al.*, 2006; *Elagib and Mansell*, 2000] and the area of study and this is true over AP. *El Gindy* [1994] found no regional warming for Doha (1962-1992), Seeb (1974-1990), Sur (1977-1990), or Masira

(1956-1990). Analysis by .*Nasrallah and Balling* [1996] over the period 1979 to 1990, found similar results to the earlier ground-based assessments, namely a slight warming trend that is not statistically significant. The additional years available to this study change this picture substantially, pointing to the importance of recent years in leading to a statistically significant warming trend.

The AP mountainous stations are located at around 2000m above mean sea level. Saiq station is located within a diffuse settlement of 2km width while Khamis Mushait is larger. Over Khamis Mushait the rate of warming is 10 times higher than Gizan in MA seasons while the trend at Saiq is 5 times higher than Sohar in JAS season. These stations merit further attention.

Dry lands have experienced a negative association between precipitation and temperatures, such that warmer (colder) years have been drier (wetter) [*Hulme,* 1996; *Jones and Reid,* 2001]. The temperature and precipitation regimes appear to be very closely coupled (r=-0.456, p=0.01) over the AP region (Figure 3-12). Sustained negative precipitation anomalies are matched by sustained positive temperature anomalies since 1998.

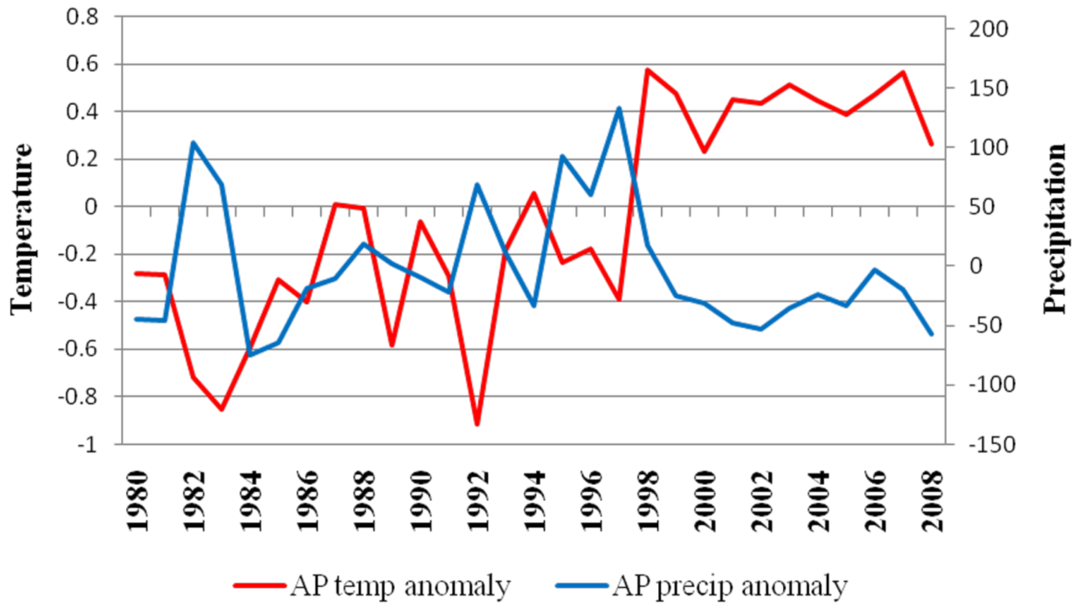

Figure 3-12: All Arabian Peninsula annual anomalies time series for both temperature and precipitation for the period 1980-2008.

For all AP the highest significant warming occurs in MA season, then DJF and MJ. Some AP regions have experienced cooling, notably the monsoonal subregion in JAS season and the cooling at Seeb of -0.27°C decade^{-1} (with a July peak of -0.58°C decade^{-1}). Possible reasons for this cooling include the enhancement of the SW monsoon and strengthened upwelling regimes over the western Arabian Sea since 1997 where average summertime phytoplankton biomass has increased more than 350% [*Goes et al.*, 2005]. In addition, *Sultan and Ahmad* [1993] have demonstrated that during the southwest monsoon (summer) the upwelled cold water from the southern coast of Arabia appears to compensate the heat gain in the Gulf of Oman.

3.5.1.3. Maximum Temperature

For all AP the maximum temperature is increasing significantly (0.032°C $decade^{-1}$), but at a lower rate than the mean temperature. The AP mountain maximum temperature trends are striking in that the two stations Saiq and Khamis Mushait, show no significant warming (the latter shows significant cooling) even though the mean annual temperatures here are increasing (1.3-1.5°C) as a result of changes to minimum temperatures. Reasons for the behavior of maximum temperature are unclear.

The warming of maximum temperature over AP is significant, largest and most widespread during late winter and spring. For example in February, 15 stations reported an overall increase more than 1.5°C and 5 stations more than 3°C. This might be due to the sensitivity of maximum temperature to the decrease of precipitation in the highest rainy months as in February (Doha reported overall increase of 4.5°C) and March (Bahrain reported 6.6°C). This is also true for the MA season. The large increase of maximum temperature in the monsoon area during DJF could be related to the weakening of the Sub-Tropical High (STH) over Asia and associated circulation changes such as a reduction in temperature advection by the northerly trade winds [*deMenocal and Rind*, 1993].

Salalah is an example of how the maximum temperature trends may be sensitive to the start and retreat of the monsoon season. Over this monsoonal station the warming trend is significant and reaches its highest value on May (1.11°C $decade^{-1}$) prior to the onset of the cooler monsoon season. After the retreat of the monsoon in October the warming trend changes to more positive (relative to summer months) over Salalah (1.00°C $decade^{-1}$).

3.5.1.4. Minimum Temperature

For the all AP and the subregions, the increasing trend in mean temperature is matched and derives partly from an increase in the minimum temperature. Minimum temperature is increasing faster than maximum temperature – which is a widespread finding [*Aguilar et al.,* 2005; *You et al.,* 2008; *Zhang et al.,* 2005; *Labraga and Villalba,* 2009; *Manton et al.,* 2001].

3.5.1.5. DTR

Solomon et al. [2007] reported that the global average DTR has stopped decreasing. Widespread (but not ubiquitous) decreases in continental DTR have coincided with increases in cloud amounts and the trends are highly variable from one region to another. This is not the case in AP. During 1980-2008 the DTR shows a significant reducing trend at a rate of -0.26°C decade^{-1}. Due to the uniform high and significant rate of warming of the mean annual minimum temperature over the north and south AP, the mean annual DTR trends do not show high variation between the subregions. Both AP Mountain’s stations reported reduction in DTR. Khamis Mushait is reducing at -0.50°Cdecade^{-1} (significant at 0.01 level) while Saiq is reducing at -0.40°Cdecade^{-1} (significant at 0.1 level). There are some seasonal and monthly variations in the DTR trends. In winter, the monsoonal region witnessed high and significant (at 10% level) DTR reduction. This could be due to the expected RH increase in the monsoonal area and weakening of NE monsoon [*deMenocal and Rind,* 1993].

3.5.2. Urban Influence on temperature

In order to investigate urban influence on temperature, which has recently been studied by *Parker* [2010], we define two categories of stations: large cities and smaller towns/rural settings using a cutoff population of 100,000 inhabitants. A similar approach was adopted by *Tayanç et al.* [2009]. The population data were derived from the United Nations Demographic Yearbook 2007 (http://unstats.un.org/unsd/demographic/). The large cities category comprise 11 stations (Bahrain, Salalah, Sohar, Dubai, Ras Alkhaimah, Doha, Riyadh, Khamis Mushait, Tabuk, Jeddah and Gizan) while the small towns comprise 6 stations (Khasab, Masirah, Saiq, Sur, Thumrait and Kuwait). Time series for each category were computed for mean, minimum, maximum temperature and DTR.

Mean annual mean temperature trends from large and small/rural cities both show statistically significant warming (at 0.001 level), the larger cities reported 0.43°C decade^{-1} while the smaller/rural towns reported 0.50 °Cdecade^{-1}. For the rest of the seasons and months the difference are small except in September and ON seasons where surprisingly the smaller/rural cities reported higher significant warming relative to large cities by ≥ 0.20°Cdecade^{-1}. In the case of minimum temperature, the larger cities reported higher and significant trends in minimum temperature during late summer (0.77°C decade^{-1}) relative to small cities (0.40°C decade^{-1}). As the maximum temperature trend (0.22°C decade^{-1}) is less than the minimum temperature over the large cities during late summer, this leads to sharp significant (at 0.001 level) decrease in DTR. Any urban warming signal should be most evident in summer, when urban heat islands are stronger owing to greater storage of solar heat in urban structures [*Parker*, 2004].

3.5.3. For the period 1943-2008:

Mean annual warming for Bahrain (0.16°C decade^{-1}) and Salalah (0.15°C decade^{-1}) is similar though slightly lower than the global land temperature increases for the same period (0.18°C decade^{-1} based on National Climatic Data Centre). Masirah is warming at a still lower rate (0.08°C decade^{-1}). Analyses of extended periods from earlier studies which ended in the 1990s show the importance of warming in more recent years. For example *Nasrallah and Balling* [1993] found an insignificant mean annual temperature increase over the Arabian Gulf (1950-1990) although warming was significant in the summer months.

Nasrallah and Balling [1996] also analyzed trends in minimum temperature (1951-1990) for 3 stations (Doha, Dhahran and Riyadh), finding no statistically significant trends. Furthermore they report a small increase in the DTR. The new results from this study show that both Salalah and Masira report significant warming. The annual DTR is decreasing significantly over Salalah but increasing significantly over Bahrain. Recently *Elagib* [2010] found significant urban influence on DTR over Khartoum. Using data during 1941-2005 he observed rising night-time temperature at a higher rate than daytime temperature leading to significant reduction in DTR with greater effect on the hot season. The additional years (to 2008) therefore leads to a revised view of temperature trends. Additionally, the extended period study shows that Bahrain is warming significantly in summer months not in winter but it is the reverse over Salalah and Masirah, pointing to the importance of the monsoon in modulating the temperature response. Precipitation trends remain insignificant (as in *Nasrallah and Balling* [1996]) even with the additional years available in this study.

3.6. Conclusion

During the last 2-3 decades 14 out of 21 stations in the AP reported significant warming in the mean annual temperatures. This warming is mainly derived from the minimum temperature (16 out of 21 stations reported statistically significant warming) where the warming rate was higher, more spatially coherent and more statistically significant than for maximum temperature (12 out of 21 stations reported statistically significant warming). This leads to a general decrease of the DTR (6 out of 21 stations reported statistically significantly negative trends with 3 stations reporting significant positive trends) while the precipitation decreases significantly only in two stations. In general, most of warming occurred over the eastern/southeastern areas. The trends show considerable spatial consistency within countries and across regions (subregions) even though the climate varies across the region. Some site specific stations reported significant mean temperatures warming at more than 1.5-3.5 times the global rate. Minimum temperature increases reach approximately 3-6˚C in October in both urban and rural stations over the period 1980 to 2008.. Overall, these observational data underscore the concerns about global climate change with the projections, as summarized by IPCC, having not exaggerated but may in some respects actually underestimated the change [*Rahmstorf et al.*, 2007]. Regional climate change attribution experiments are much needed for the AP region. These changes need attention by the AP communities to enable planning and adaptation.

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Chapter 4: Changes in Climate Extremes in the Arabian Peninsula: analysis of daily data

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Abstract

This paper 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 6 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 10mm which shows a significant decrease during 1986-2008.

4.1. 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]. Since 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, A. M. G. 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*, *Mok & Lee* [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 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*. [2012] 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 0.72oC 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 degrees oC 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 paper builds on previous climate extremes studies in the region such as *Zhang et al*. [2005] and *Almazroui et al*. (2012a,b) 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 9 stations covering two countries located in the AP (Oman and Saudi Arabia) and *Almazroui et al*. (2012a,b) 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°N) and monsoonal region (south of 20°N).

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].

4.2. 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, premonsoon), late summer (JAS, monsoon) and autumn (ON, 2nd transitional period or postmonsoon).

4.2.1. 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 4-1 shows clear differences between Seeb station relative to Sohar and Sur especially in the nighttime minimum temperature indices.

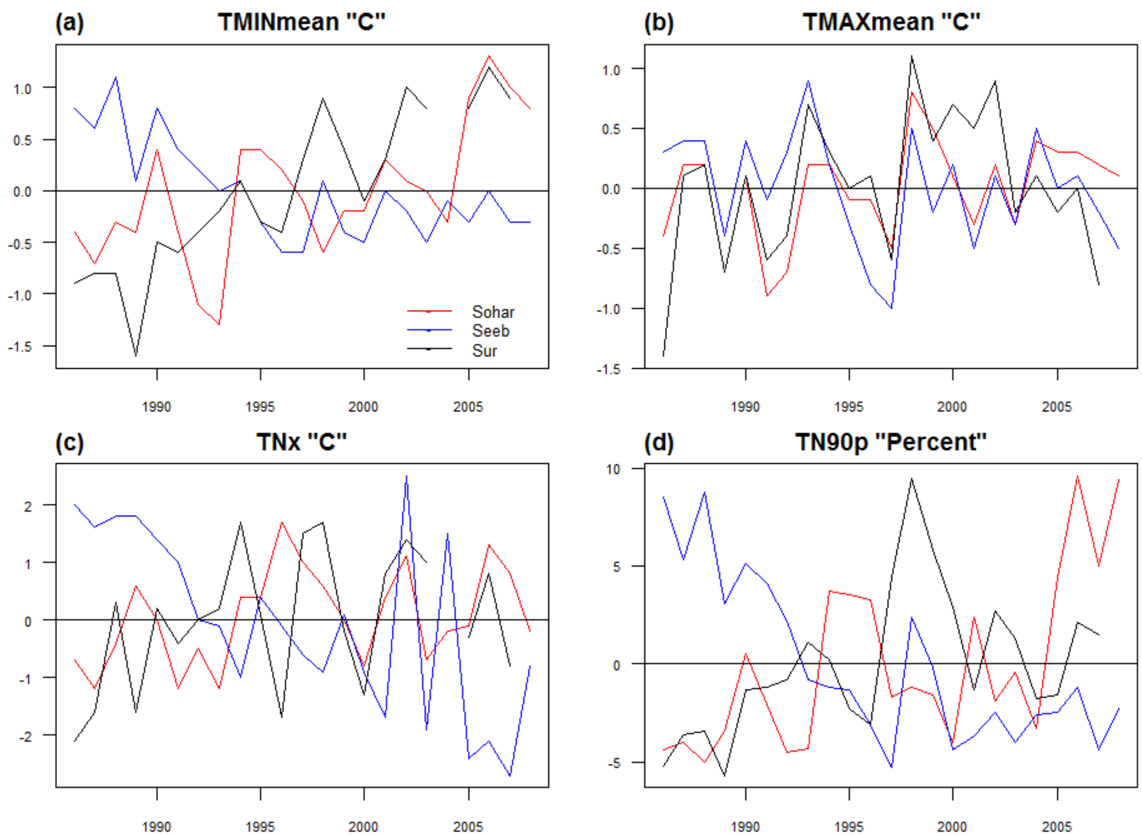

Figure 4-1: Seeb station annual timeseries (blue) relative to neighbouring stations Sohar (red) and Sur (black) for TMINmean, TMAXmean, TNx and TN90p extreme indices.

Higher values of night time temperature indices at Seeb station relative to Sohar and Sur are evident before 1994. The higher nighttime temperature values of Seeb are also evident in the warmest nights (TNx) and warm night frequency (TN90p). The variance in 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.

4.2.2. 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 stepchange 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 changepoints 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 Niño years 1982, 1997 and 1998. Table 4-1 summarizes some of these significant changepoints showing the station, the date and the variable. Several stations share potential common change point dates.

Table 4-1: Details of significant detected changepoints showing years, stations, variables and dates

Year	Station	Variable	Date (year.month.day)
1982	Al-Madinah	maxT	19820130
	Dhahran	maxT	19820204
	Riyadh	maxT	19820203
	Al-Taif	minT	19820131
	Jeddah	minT	19820131
	Sharjah	maxT	19820208
1997	Gizan	maxT	19970519
	Sohar	maxT	19970516
	Salalah	maxT	19970614
	Sharjah	minT	19970614
	Salalah	maxT	19970612
	Masirah	maxT	19970704
	Saiq	minT	19970708
	Salalah	minT	19970703
1998	Bahrain	maxT	19980323
	Bisha	maxT	19980312
	Hail	maxT	19980409
	Riyadh	maxT	19980310
	Dubai	precipitation	19980308
	Ras Alkhaimah	maxT	19980314
	Sharjah	maxT	19980313
	Doha	maxT	19980312
	Khasab	maxT	19980316
	Khamis Mushait	maxT	19980312
	Kuwait	maxT	19980407
	Saiq	maxT	19980316
	Sohar	maxT	19980321

The RHtestV3 detected 2 significant (at 0.05 level) changepoints of the original daily maximum temperature of Sur station. These changepoints have been confirmed with the station metadata and coincide with station relocation dates. The dates of the 2 significant changepoints are 20030414 and 20070516 which are clear from the plot in Figure 4-2.

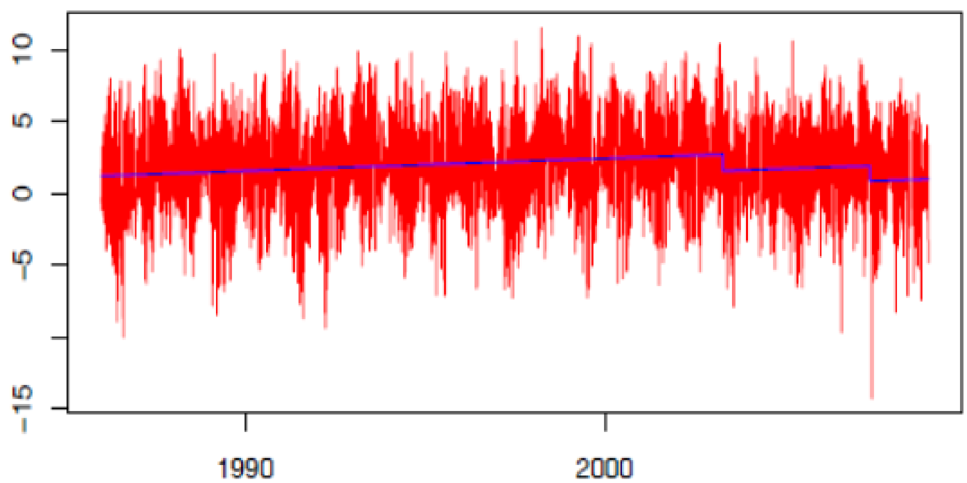

Figure 4-2: Sur station daily maximum temperature changepoints.

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 4-3 shows Sur mean annual maximum temperature of the original (red) and the adjusted (blue) values. In general the variability of both annual timeseries look similar with lower values (by 2.0℃) in the adjusted timeseries from the beginning of the period until 2002.

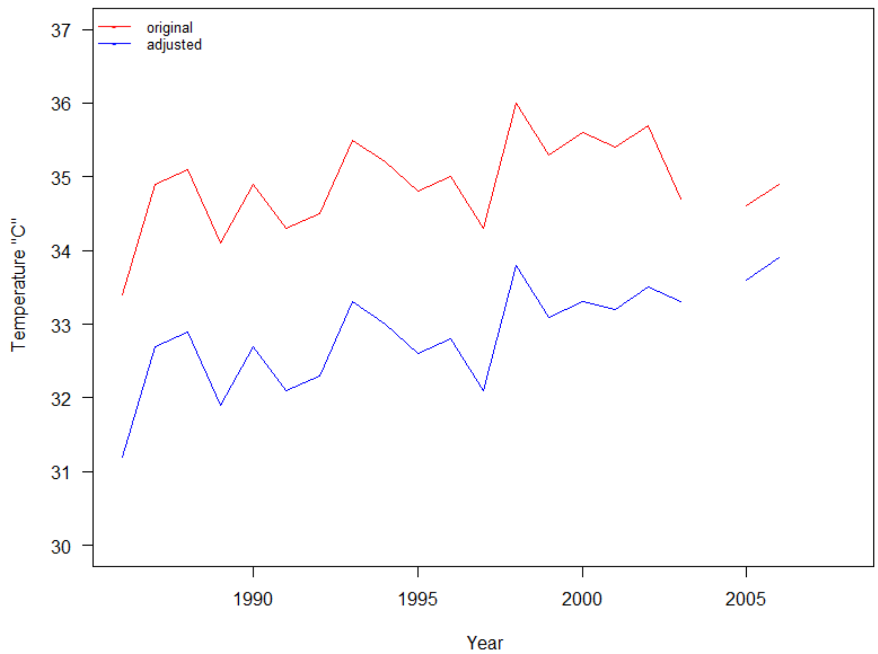

Figure 4-3: Sur mean annual maximum temperature of the original (red) and the adjusted (blue) timeseries.

The reduction in temperature between 2002 and 2003 is lower in the adjusted timeseries (0.2℃) than the original timeseries (1.0℃). After quality control and the homogeneity testing evaluations, 10 stations were retained from Saudi Arabia, 8 stations from Oman (the remaining 16 stations were mainly excluded because of their short record), 3 from UAE, and 1 station from Qatar, 1 from Bahrain and 1 from Kuwait. The final list of stations is summarized in Table 4-2 where details of station locations, name, period and missing percentage (%) are listed. As the analysis will cover 3 periods, the period longer than 1970-2008 will use data from 4 stations (each of different length); the period 1970-2008 will use data from 9 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 4-4.

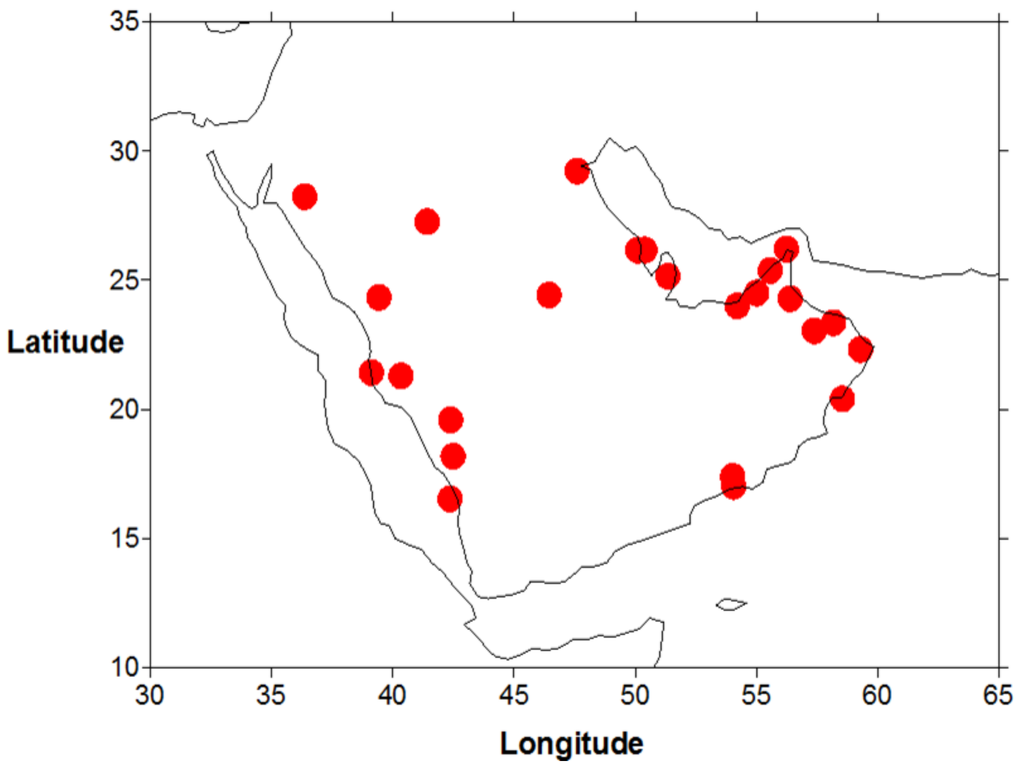

Figure 4-4: The distribution of 24stations used in this study in the Arabian Peninsula.

Table 4-2: Stations 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)

4.3. Methods

4.3.1. 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 4-3 summarizes the temperature and precipitation climate extreme indices used in this study. These 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.

Table 4-3: List all the ETCCDI climate indices calculated by RClimDex used in this study

ID	Descriptive name	Definitions	UNITS
SU40	Very warm days	Annual count when TX(daily maximum)>40ºC	Days
TR25	Very warm nights	Annual count when TN(daily minimum)>25ºC	Days
TXx	Warmest day	Monthly maximum value of daily maximum temperature	^{o}C
TNx	Warmest night	Monthly maximum value of daily minimum temperature	^{o}C
TXn	Coldest day	Monthly minimum value of daily maximum temperature	^{o}C
TNn	Coldest night	Monthly minimum value of daily minimum temperature	^{o}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	^{o}C
TMINmean	Mean minimum	Monthly mean value of daily minimum temperature	^{o}C
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	^{o}C
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
R10	Number of heavy precipitation days	Annual count of days when PRCP>=10mm	Days
CDD	Consecutive dry days	Maximum number of consecutive days with RR<1mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR>=1mm	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>=1mm)	mm

4.3.2. 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 nonmonsoonal region (north of 20°N) and the monsoonal region (south of 20°N) following *AlSarmi and Washington* [2011].

4.3.3. Trend Calculation

Trends for stations and regional timeseries 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 timeseries 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.

4.4. Results

Table 4-4 summarises all the AP regional (subregions) annual temperature and precipitation extreme indices 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.

Table 4-4: 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)

4.4.1. 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 nighttime 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. 4-5(a)-(l)).

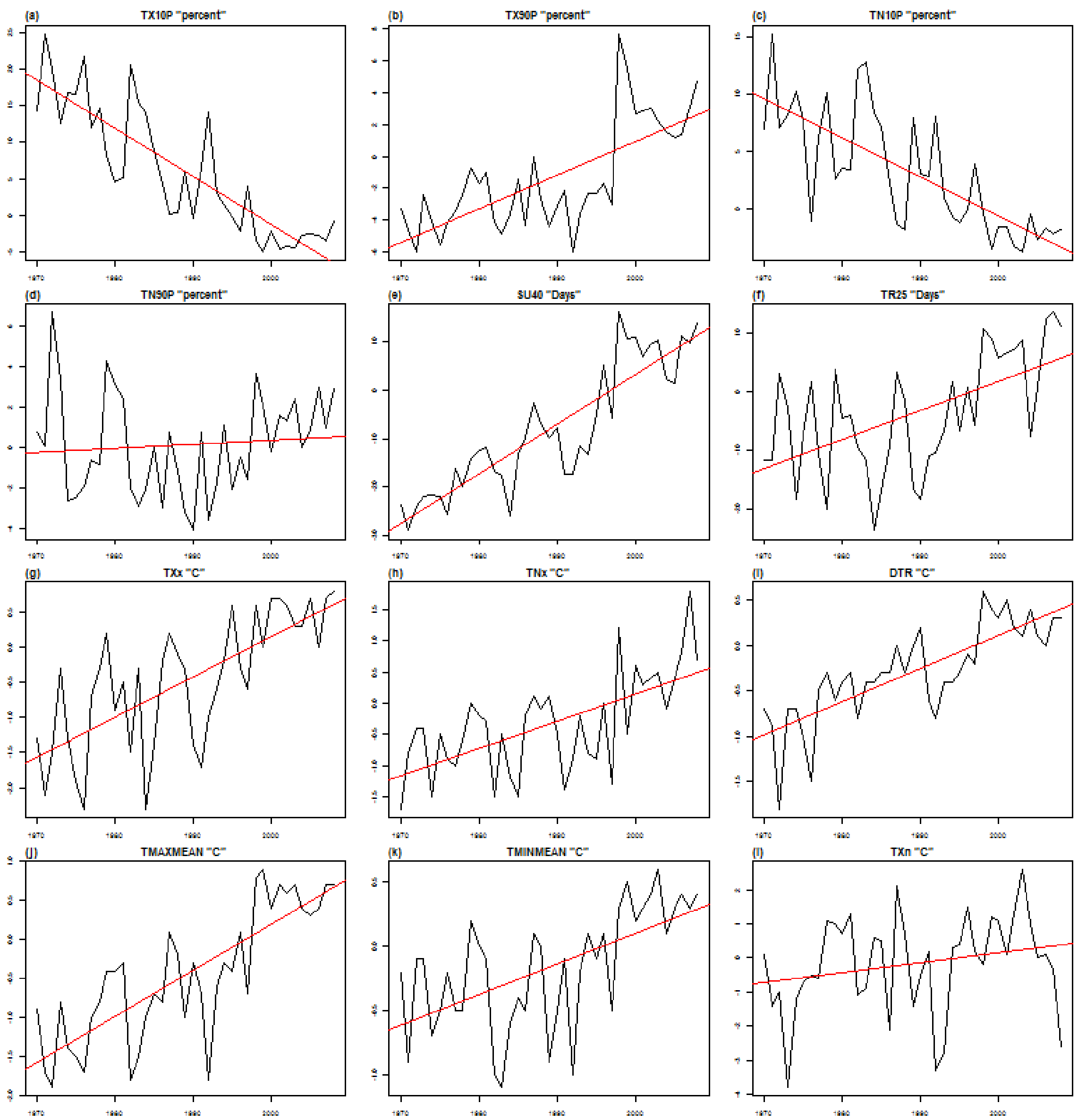

Figure 4-5: All AP regionally averaged anomaly series (relative to the mean for 1986-2008) of temperature extreme indices with linear trends for 1970-2008 (red).

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 4-6) pointing to the region-wide decrease in occurrence of cold extremes.

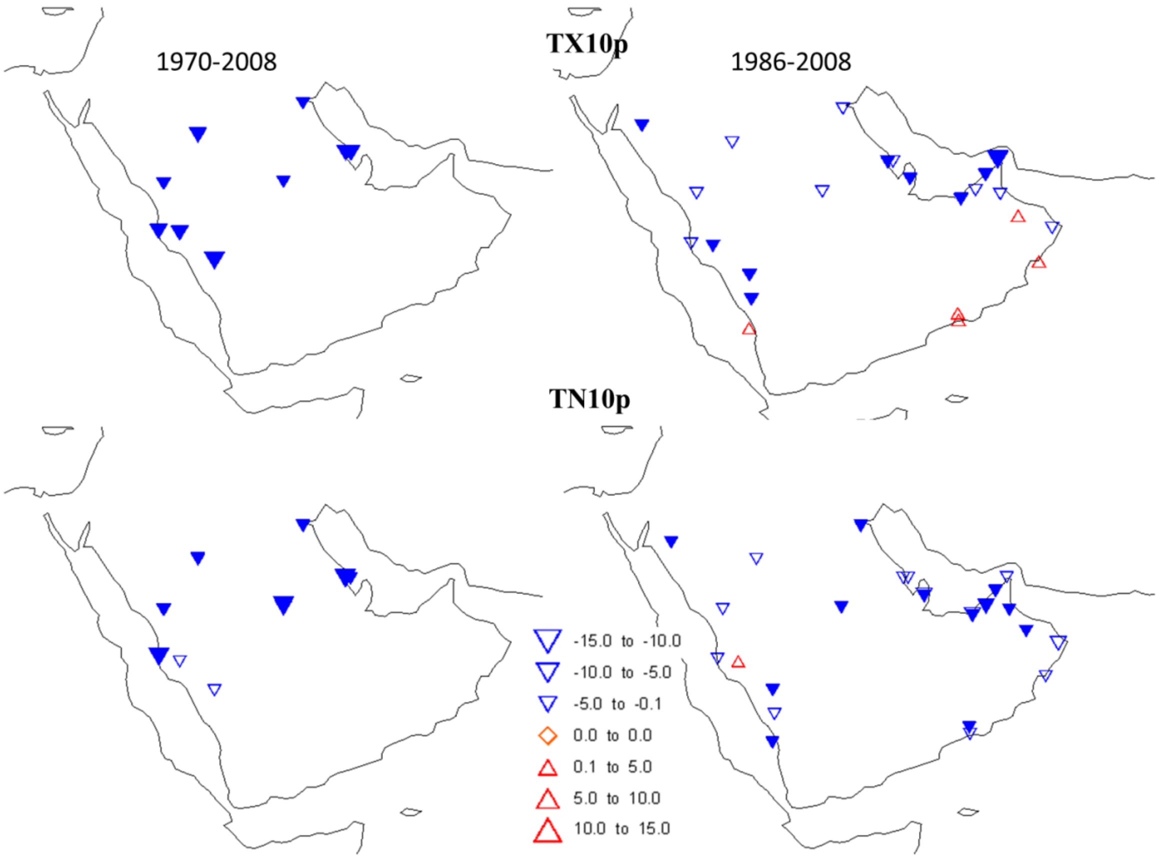

Figure 4-6: Annual TX10p (top row) and TN10p (bottom row) trends in the Arabian Peninsula in percentage per decade for the period 1970-2008 (left column) and 1986-2008 (right column). Upward red triangles represent increasing trends while downward blue triangles decreasing trends. The slope of the increasing/decreasing trend is proportional to the size of the triangles. Shaded triangles are statistically significant at the 5 % level.

There were also large significant reductions in the frequency of cold nights (TN10p) over the 39 years (Figure 4-6). 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 4-7).

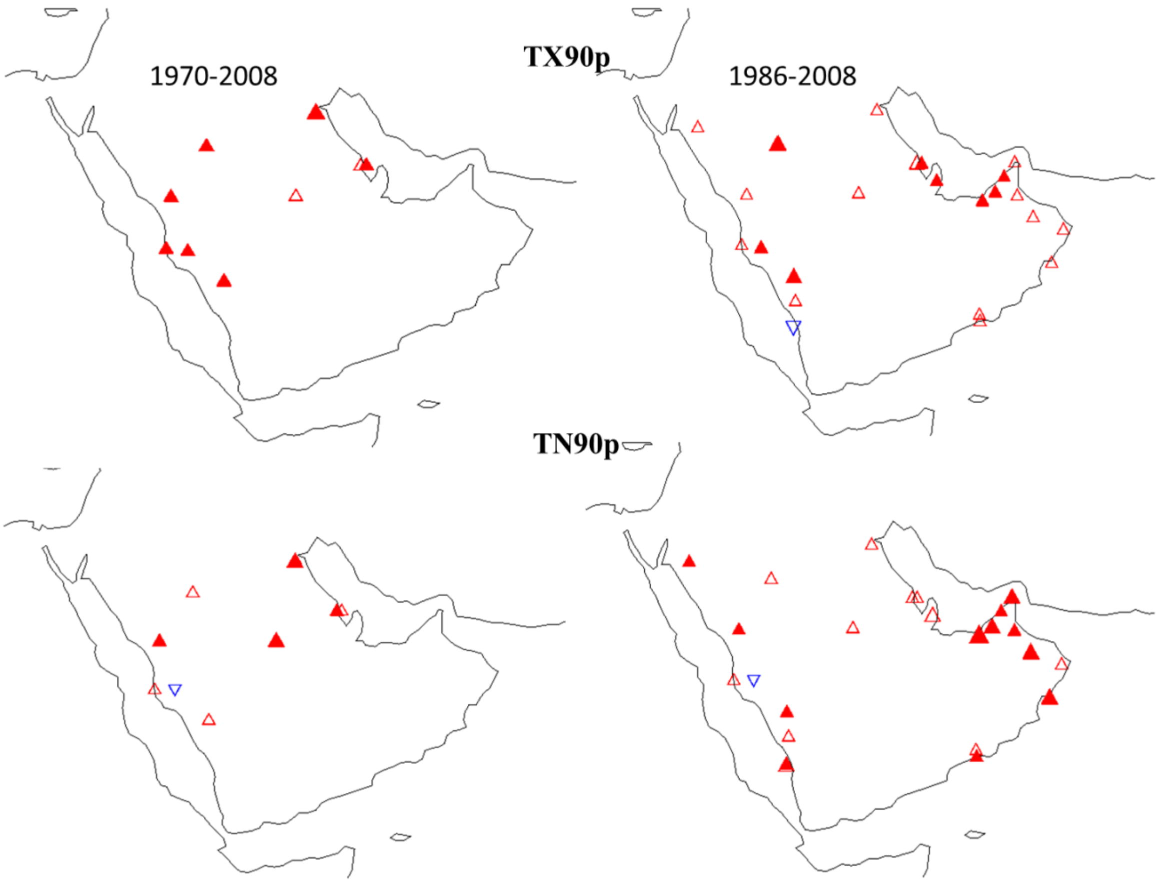

Figure 4-7: Same as Figure 4-6, but trends for TX90p and TN90p.

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 4-8).

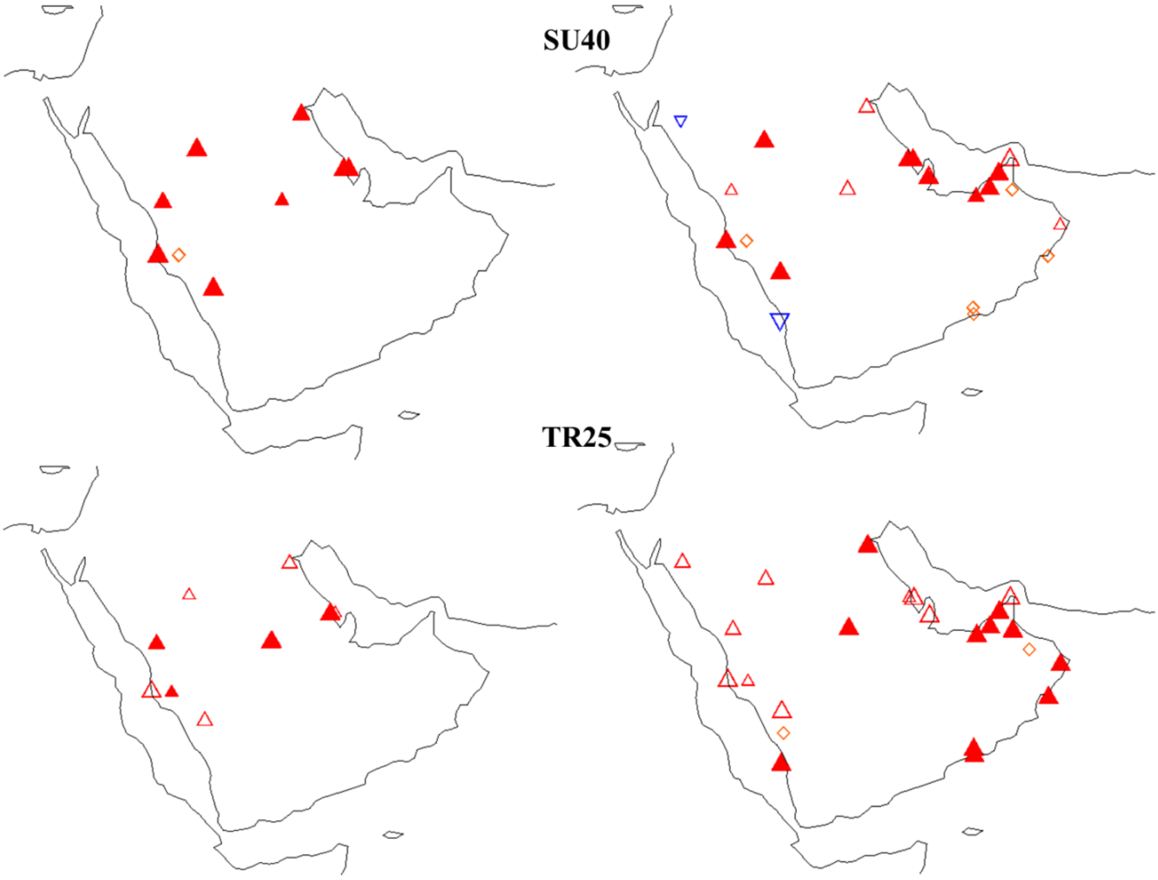

Figure 4-8: Same as Figure 4-6, but trends for SU40 and TR25.

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 4-9).

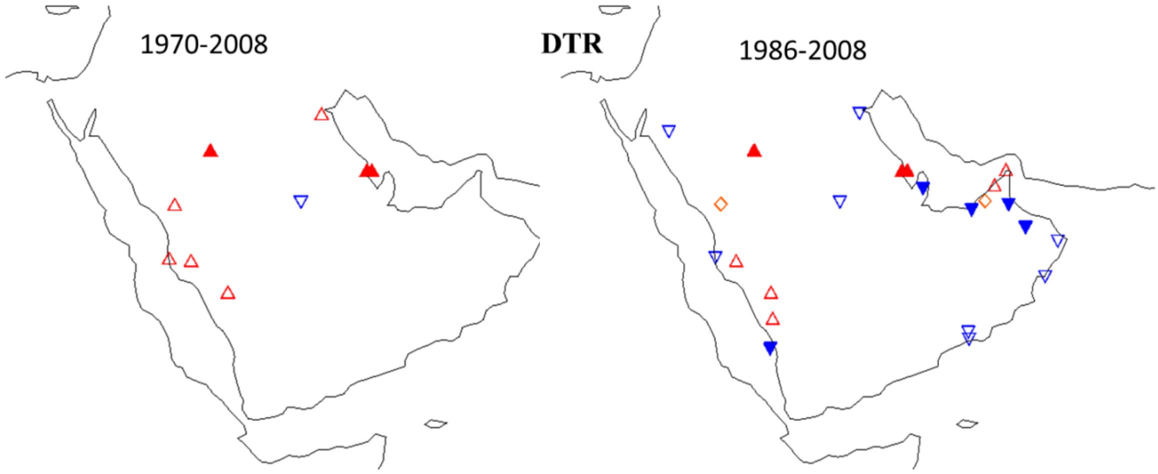

Figure 4-9: Same as figure 4-6, but trends for DTR.

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 4-4). The AP region is characterized by large interannual variability in comparison to trends. Figure 4-10 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.

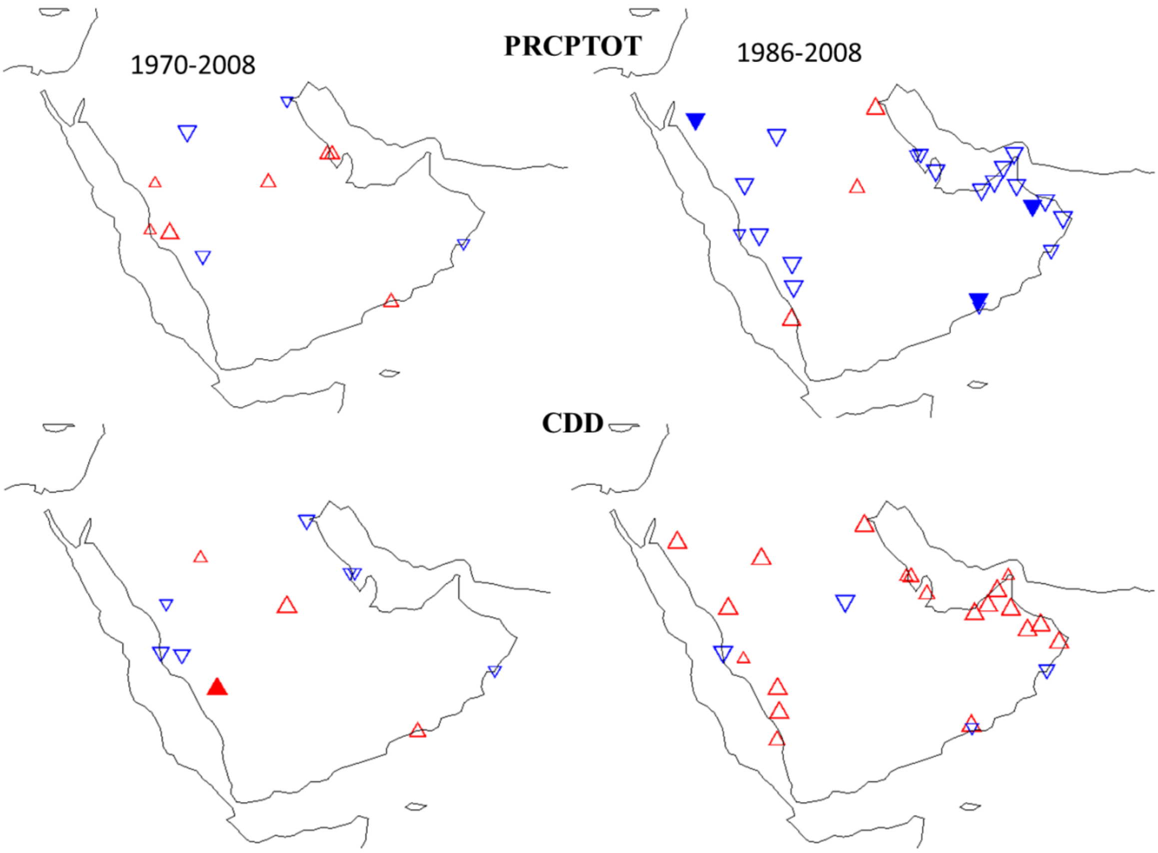

Figure 4-10: Trends in the annual total precipitation (PRCPTOT) (top row) and the maximum number of consecutive days with RR<1mm (CDD) (bottom row) for 1970-2008 (left column) and 1986-2008 (right column). Upward triangles (red) represent increasing trends and downward triangles (blue) decreasing trends. Shaded triangles indicate the statistically significant trends at 0.05 level.

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-day 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.

4.4.2. Period 1986-2008

The regional annual average results for the period 1986-2008 are shown in Table 4-4. 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 nighttime 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). 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 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.

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 4-4). 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.

4.4.3. Longer Period

The results for the stations with available records longer than 1970-2008 period are shown in Table 4-5.

Table 4-5: 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. (2008)

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 nighttime extremes of TR25, TNn, TN10p and TMINmean. No significant trends in the indices of the precipitation extremes are reported.

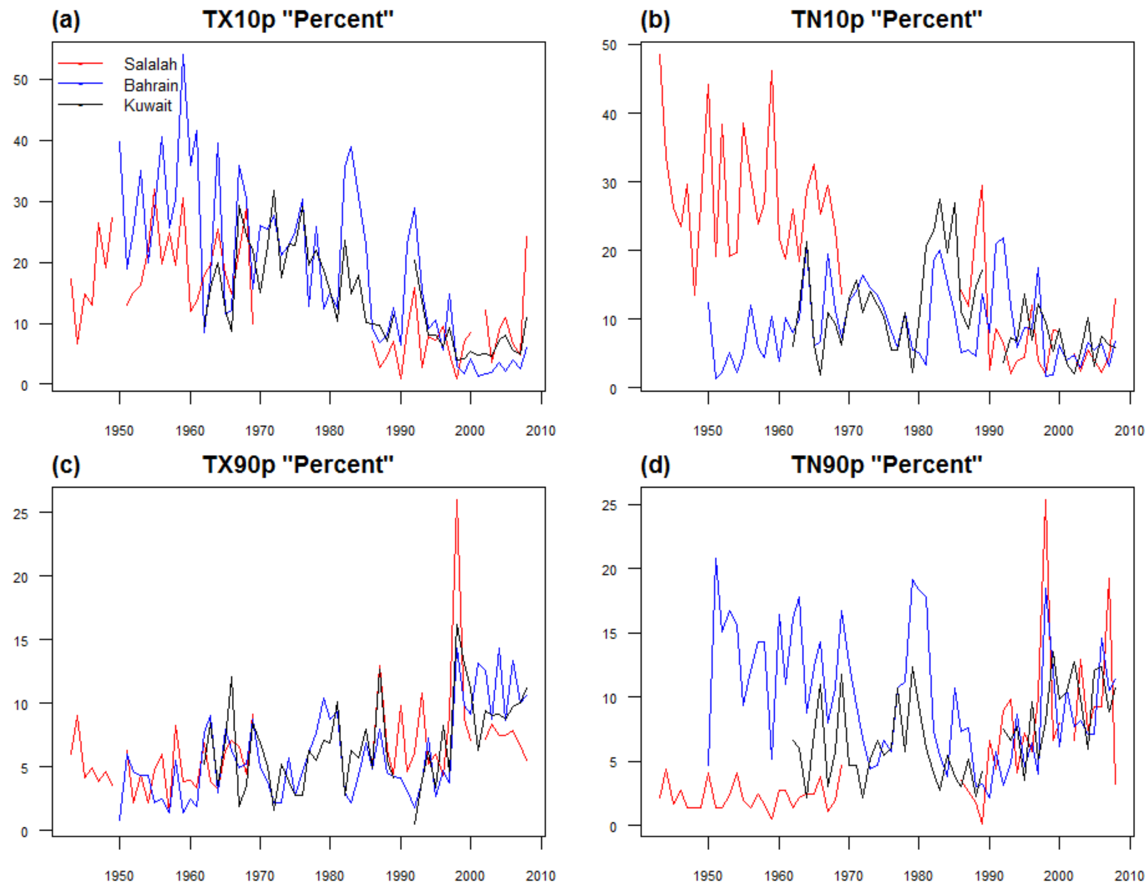

Figure 4-11: Timeseries of the annual percentile-based temperature indices (TX10p, TN10p, TX90p, TN90p) for the stations with data longer 1970-2008, Salalah (red), Bahrain (blue) and Kuwait (black).

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 (Figure 4-11). Unlike TX10p, the stations timeseries of the TX90p index show an abrupt jump in 1998. For the nighttime 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 (Figure 4-11).

4.4.4. Comparisons with previous studies

4.4.4.1. 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 4-6). 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 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.

Table 4-6: 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 Index	All AP	Global (1971-2005)	Middle East (1970-2003)	Central and South Asia (1961-2000)	Southwestern China (1961-2008)	Indo-Pacific (1971-2005) (All)	Indo-Pacific (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. (2012)	Zhang et al. (2005)	Klien Tank et al. (2006)	Li Zongxing et al. (2012)	Caesar et al. (2012)	Caesar et al. (2012)

4.4.4.2. 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.

4.5. 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 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 nighttime 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 4-12 and 4-13 show the PDFs for 6 stations located in different parts of the AP.

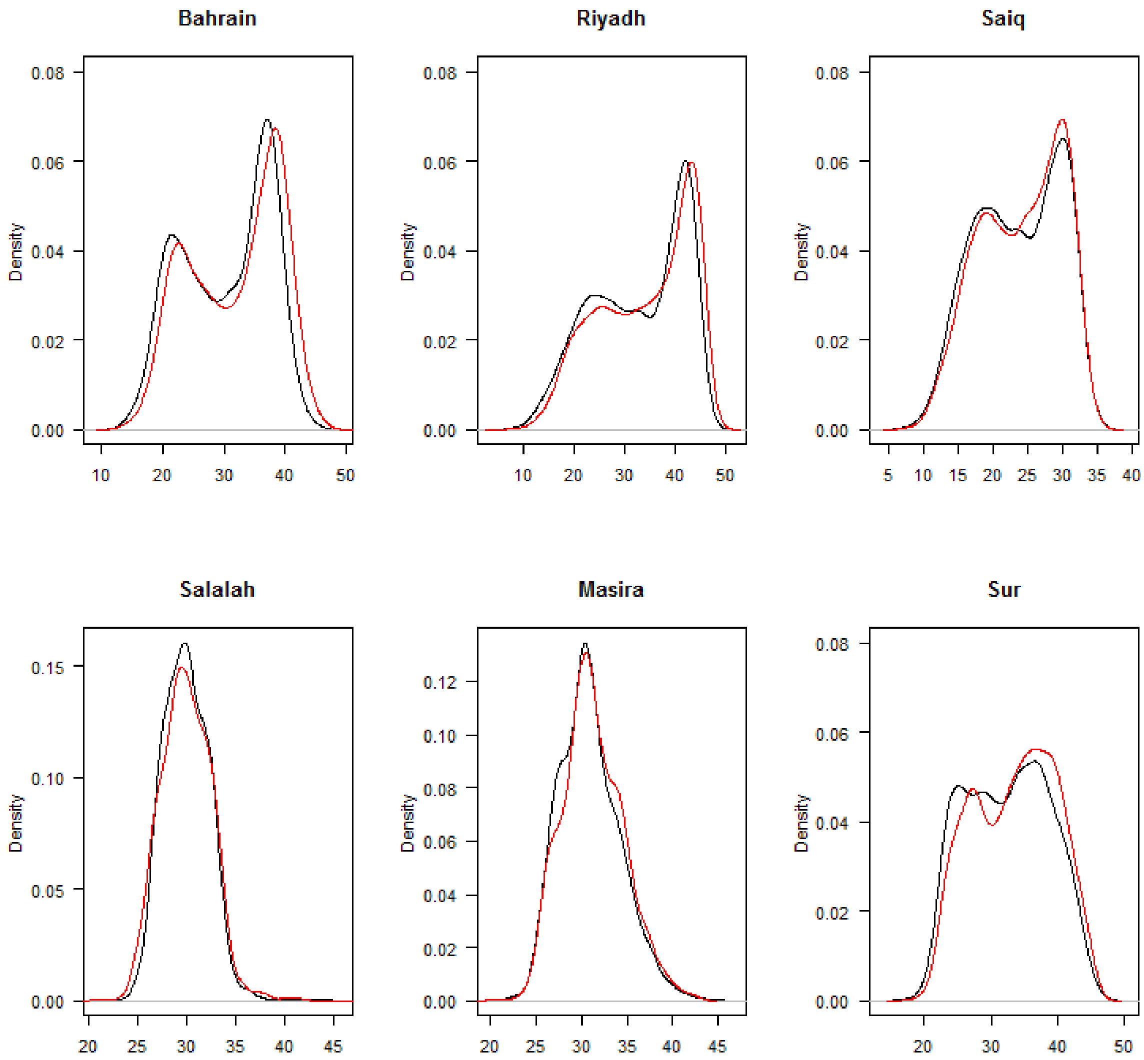

Figure 4-12: Probability density functions showing change in distribution of the maximum temperature (horizontal axis) of 6 stations during two periods 1986-1997(black) and 1998-2008(red).

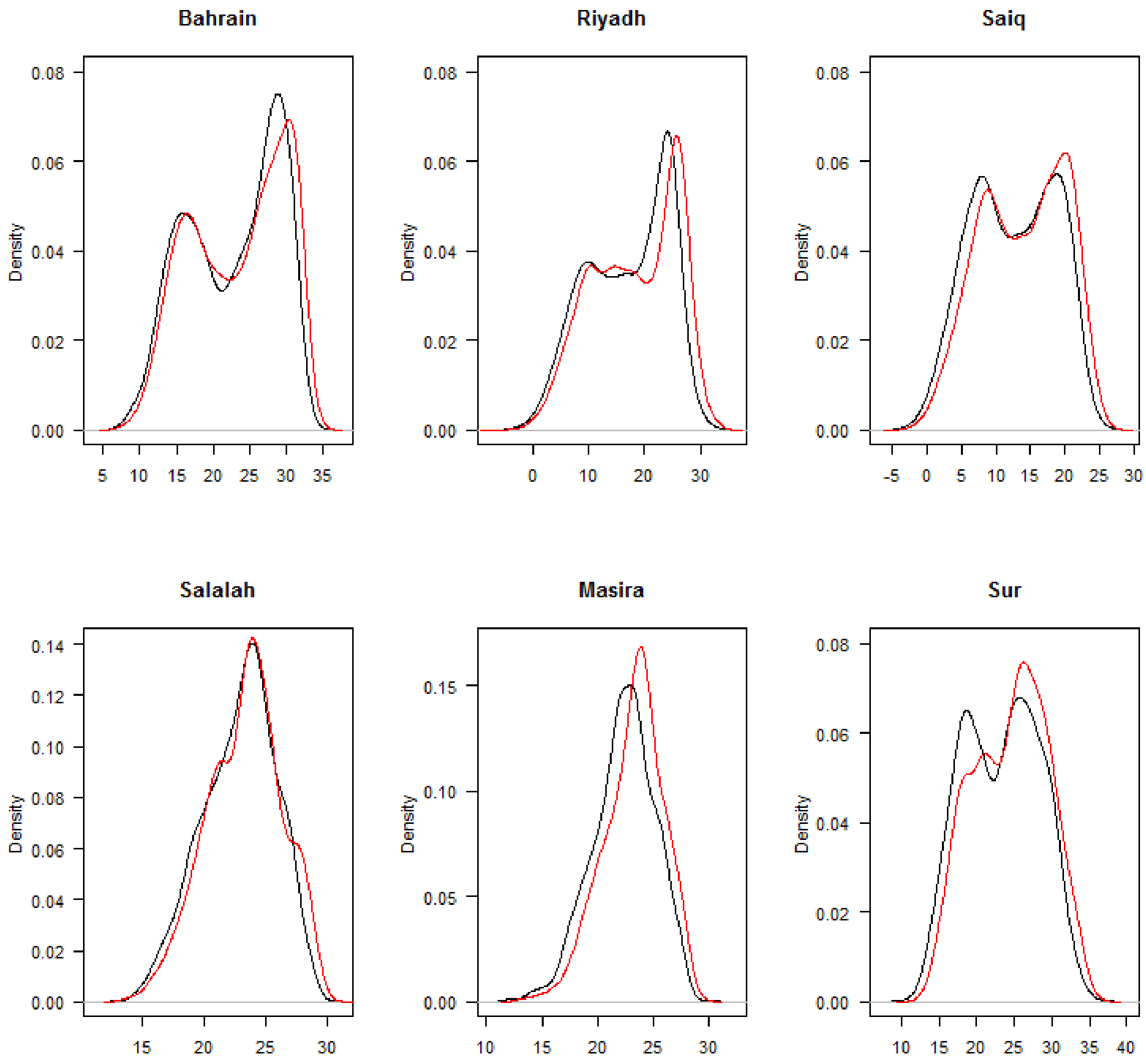

Figure 4-13: Similar to Figure 4-12 but for minimum temperature.

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 nonmonsoonal 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 4-14).

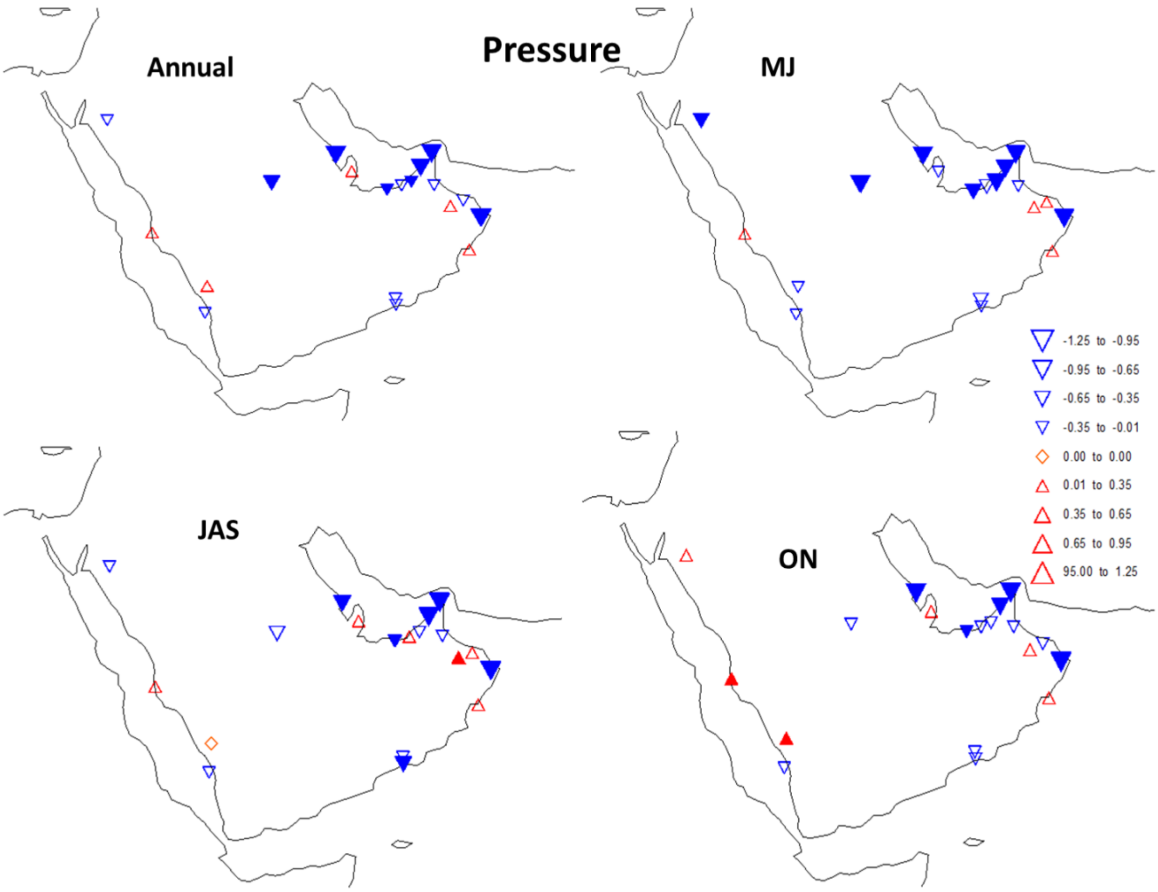

Figure 4-14: Same as Figure 4-6, but trends for Mean Sea Level Pressure.

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 4-15 reveals 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.

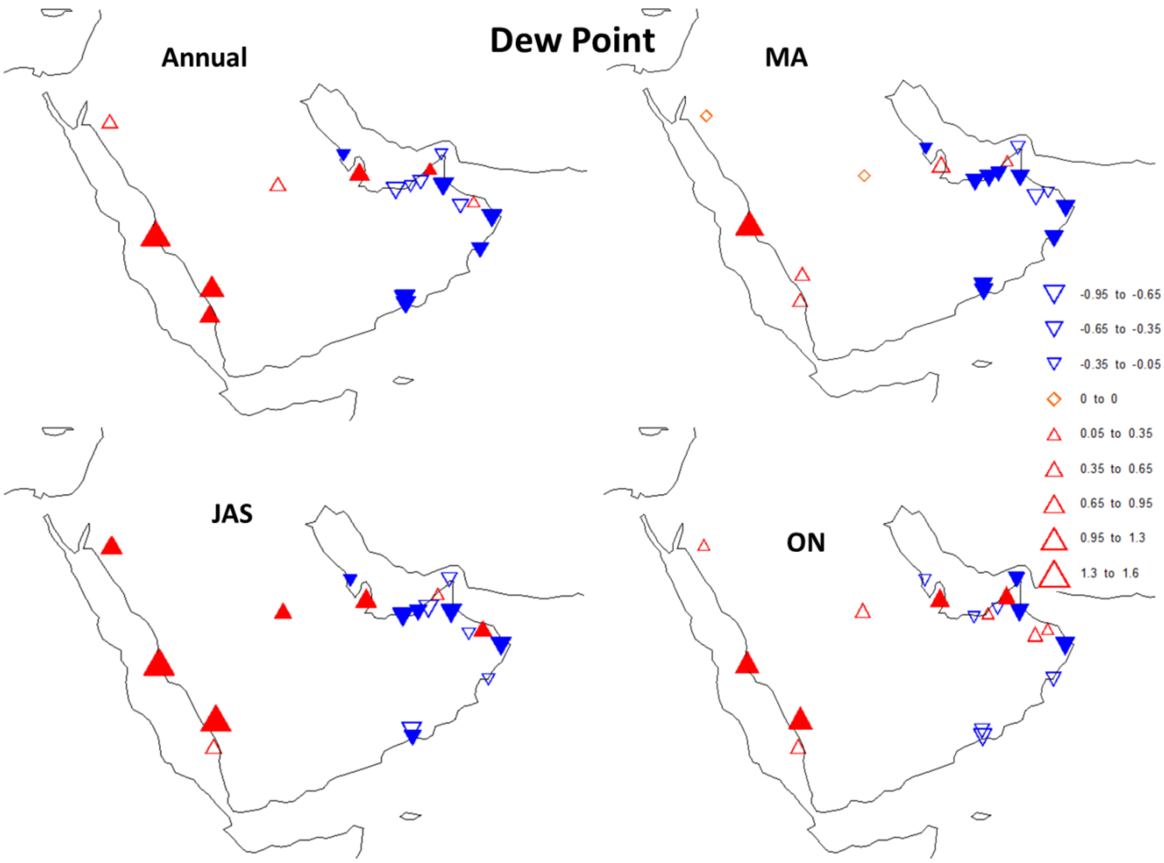

Figure 4-15: Same as Figure 4-6, but trends for Dew Point temperature.

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.

4.6. 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 paper 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

We wish to express our gratitude to all the AP NMSs for providing the climate data. Special thanks to the Ministry of Transport and Communication in the Sultanate of Oman for sponsoring the lead author's research on the Arabian climate trends, variability and change. The authors encourage the research community to contact directly the relevant AP NMSs in order to obtain the data.

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Chapter 5: An RCM-based simulation assessment of annual and seasonal temperature and precipitation climate and trends of means and extremes in the Arabian Peninsula during 1990-2008

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Under review in *Journal of Geophysical Research*

Abstract

This study examines the ability of a regional climate model, based on Providing Regional Climates for Impact Studies (PRECIS), to simulate the climate of the Arabian Peninsula (AP) during the period 1990-2008 using ERA-Interim boundary conditions. Despite a negative temperature bias over the southwestern, western and northwestern areas and the positive bias in the southeast and south areas, the model simulation captures the mean climatic conditions and patterns, the increasing temperature tendency, as well as the decreasing precipitation observed in the last two decades. PRECIS overestimates the precipitation over the high lands or regions close to them over the southwestern mountains. However, it underestimates the precipitation over the southeastern mountains. Although the model trends for temperature and precipitation agree with the observed gridded dataset and the meteorological stations dataset, differences were observed in magnitudes and spatial distribution over the domain. For the daytime means and extremes in surface temperature over the AP, PRECIS replicates the Nonmonsoon (NMON) region trends better than the Monsoon (MON) trends, although the latter are not as spatially coherent in the observed either. The model

matches the magnitude of the observed trends well in the spring but during late summer the trends are 50% relative to the stations data set trends. Most of the model discrepancies occurred in the night time temperature. Although the model shows good agreement with the stations when reporting significant trends during spring and summer (early and late), it underestimates the trends magnitude by nearly 50 % over the AP region and the NMON region. The model fails to simulate the large increase of nighttime temperature over the MON region. The results show that seasons have strong influence on the temperature and precipitation trends and most high and significant changes have occurred in spring and summer seasons.

5.1. Introduction

Projections of future climate resulting from the anthropogenic effects such as increasing greenhouse gas concentrations depend on the integration of climate models. According to the *IPCC Fifth Assessment Report AR5* [*Flato et al*., 2013], the horizontal resolution of most present-day Atmospheric Oceanic General Circulation Models (AOGCMs) which are key to climate projections is still of the order of a few hundred kilometers. There is very high confidence that models reproduce observed large scale mean surface temperature patterns (pattern correlation of ~0.99), though systematic errors of several degrees are found in some regions, among these regions over high topography and over regions of ocean upwelling.

Resolving features of the climate system such as land-surface feedbacks and the way topography interacts with the atmosphere is difficult to achieve realistically at coarse resolution typical of global models. For impact studies there is a need for regional details of how climate might change, including variability and extremes events [*Arnell et al.*, 2003]. The ongoing Coordinated Downscaling Experiment (CORDEX) has set out a framework for generating climate information using regional climate models (RCMs) with grid-spacing of the order of 50km [*Coppola and Giorgi*, 2010]. In many cases RCM resolution has increased from around 50 km to around 25 km [*Christensen et al*., 2010]. RCMs are full climate models and as such are physically based. They are typically forced by coarse resolution information from a global model and then compute temporally and spatially fine-scale information consistent with the forcing using their higher resolution representation of the climate system [*Jones et al*., 2004]. RCMs are thought to be potentially better at simulating and projecting changes to extremes of weather. Regional models have been argued to be useful to a variety of problems relating to future climate change, such as water resources management, analysis of extreme events and land cover change [*Pal et al*., 2007; *Flato et al.*, 2013].

Giorgi et al. [2009] has argued that the credibility of the models, in turn, can be measured by the model's ability to reproduce observed climate conditions or different climate states. Studies of historical periods are therefore important in order to assess the model capability. There has been substantial progress since the IPCC AR4 in the assessment of model simulations of extreme events. *Flato et al.* [2013] note that the inter-model range of simulated climate extremes is similar to the spread amongst observationally based estimates in most regions. In addition, changes in the frequency of extreme warm and cold days and nights over the second half of the 20th century are consistent between models and observations. However, the majority of models underestimate the sensitivity of extreme precipitation to temperature variability or trends, especially in the tropics, which implies that models may underestimate the projected increase in extreme precipitation in the future [*Flato et al*., 2013].

The climate of the Middle East (including the AP) with its combination of land/sea contrasts, topography and the degree of surface heating [*Evans*, 2009], presents a challenge for climate models, particularly so at the coarse resolution of global models and therefore lends itself to the regional modeling approach. There has been little analysis of regional model simulations and performance over the Arabian Peninsula (AP). There is a need to validate such model simulations, particularly if these models are to prove useful for climate change adaptation. West Asia is at the fringes of the influence of different drivers of European, Asian and African climates and remains poorly analysed in the peer-reviewed literature with respect to climate model performances [*Flato et al*., 2013].

The broad aim of this paper is to assess the ability of a regional climate model to simulate annual and seasonal mean climate (temperature and precipitation) and trends in the means and the extremes over the AP. The European Centre for Medium Range Weather Forecasts ERA-Interim re-analysis covering the period 1989-2008 is used as initial and Lateral Boundary Condition (LBC) to force a regional climate model from the Providing Regional Climates for Impact Studies (PRECIS) suite. Focus will be given to the simulated extremes because of the importance of extremes in climate impacts and given that there have recently been a number of studies on observed changes in extremes in the AP [*Lelieveld et al.*, 2012; *S. H. AlSarmi and Washington*, 2013; *Donat et al*., 2013]. Trends in climate means and extreme indices from meteorological stations in the AP over the period 1990-2008 will be compared with the regional model simulations. The seasonal definition will follow *AlSarmi and Washington* [2011] namely winter (DJF), spring (MA, 1st transitional period), early summer (MJ, premonsoon), late summer (JAS, monsoon) and autumn (ON, 2nd transitional period or postmonsoon). Figure 5-1 shows the geographical domain of the study.

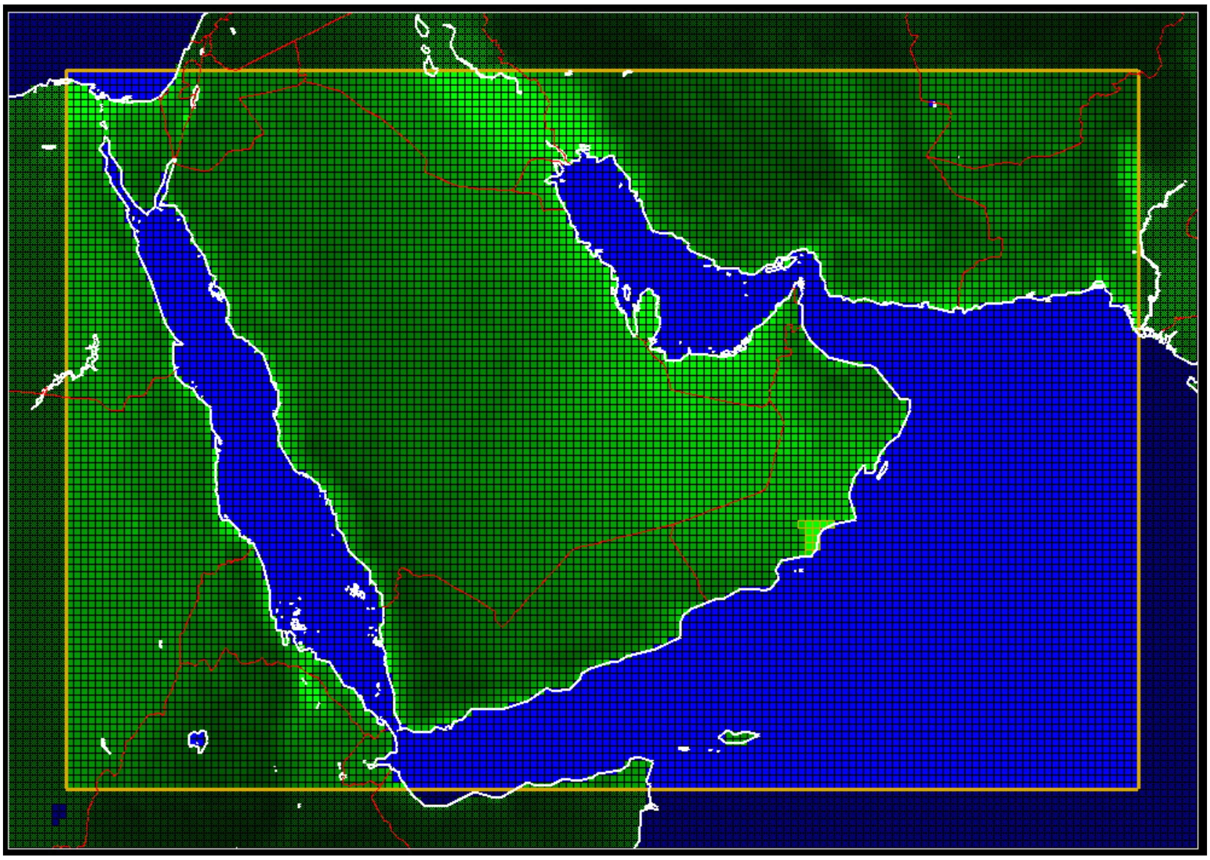

Figure 5-1: Geographic area and 0.22° latitude/longitude (~25 km) grid coordinates of the PRECIS regional climate model, applied for the period 1990-2008. The outer eight rows of grid cells are a "buffer zone"- not included in the analysis.

5.2. Data

The AP meteorological stations records of daily and monthly precipitation and temperature (maximum, minimum and mean) over the period 1990-2008 were provided by the Meteorological Services of most the AP countries. Oman provided 24 stations, Saudi Arabia 11, UAE 4 with 1 station from each of Qatar, Bahrain and Kuwait. These data have recently been analysed by *Alsarmi and Washington* [2011; 2013].

Simulation was performed using the PRECIS regional climate model, based on the United Kingdom (UK) Meteorological Office Hadley Centre HadRM3P model [*Jones et al.*, 1995] for the period 1990-2008. The reason behind selecting the 1990-2008 period is much to do with the daily data period available from the meteorological stations. As most of these stations have daily data during 1986-2008, a common period data of 1990-2008 has been selected. In order to investigate the state of the regional climate, the length of the simulation should be at least 10 years to give a reasonable idea of the mean climate change, although 30 years is preferable to better determine changes in higher order statistics [*Jones et al.*, 2004]. The model will be forced using the ERA Interim reanalysis data which is a result of a weather forecasting (NWP) model, taking in observational data and assimilating it to provide the optimum estimate of the state of the atmosphere on any given day (or shorter time interval, e.g. 6 hours), needless to say, no model will give a perfect validation against climatology or observations [*Jones et al.*, 2004].

PRECIS applies the same formulation of the climate system as its parent AOGCM which is HadCM3. The PRECIS climate model is an atmospheric and land surface model of limited area and high resolution which can be run over any part of the globe.

More details about the model are found in *Jones et al.* [2004]. HadRM3P is set up with horizontal grid spacing of 25 km with 19 levels in the atmosphere (from the surface to 30 km in the stratosphere) and four levels in the soil. At 25km, the model topography fields show the key features of the main AP mountain chains (the W/SW and SE) and shape, although this is still generally smoothed especially over Oman Mountains (Figure 5-2). Table 5-1 summarizes the elevation differences of the model grid boxes relative to the actual meteorological stations elevations. Most of the elevations difference is in the range from 10 to 100 meters with the greatest differences occurring over the highest elevations. The highest positive elevation difference with a value more than 200 meters occurred over Oman (Salalah and Sur) and over Saudi (Al-Taif and Bisha) while the highest negative elevation difference occurred over Oman mountains (Saiq, -623.1 meters).

Table 5-1: Elevation bias of the PRECIS model and CRU data relative to the actual stations elevations in meters

Country	Station	PRECIS	CRU
Oman	Khasab	61.219	245
	Sohar	81.339	85.37
	Saiq	-623.1	-1268
	Seeb	57.784	45.6
	Sur	324.35	42
	Masirah	-19	6
	Thumrait	34.43	58
	Salalah	232.34	-7
UAE	Ras Alkhaimah	-9.594	-14
	Dubai	16.189	17
	Sharjah	-11.811	-11
Bahrain	Bahrain	-2	3
Qatar	Doha	28.172	-8
Kuwait	Kuwait	133.65	40.91
Saudi Arabia	Tabuk	142.58	514.89
	Hail	-28.31	42.5
	Dhahran	-3.163	-0.8
	Al-Madinah	18.3	182.4
	Riyadh	197.49	40.37
	Jeddah	47.509	21.12
	Al-Taif	239.7	-21.8
	Bisha	453.6	175
	Khamis Mushait	140.2	-1187.9
	Gizan	-7.24	12.76

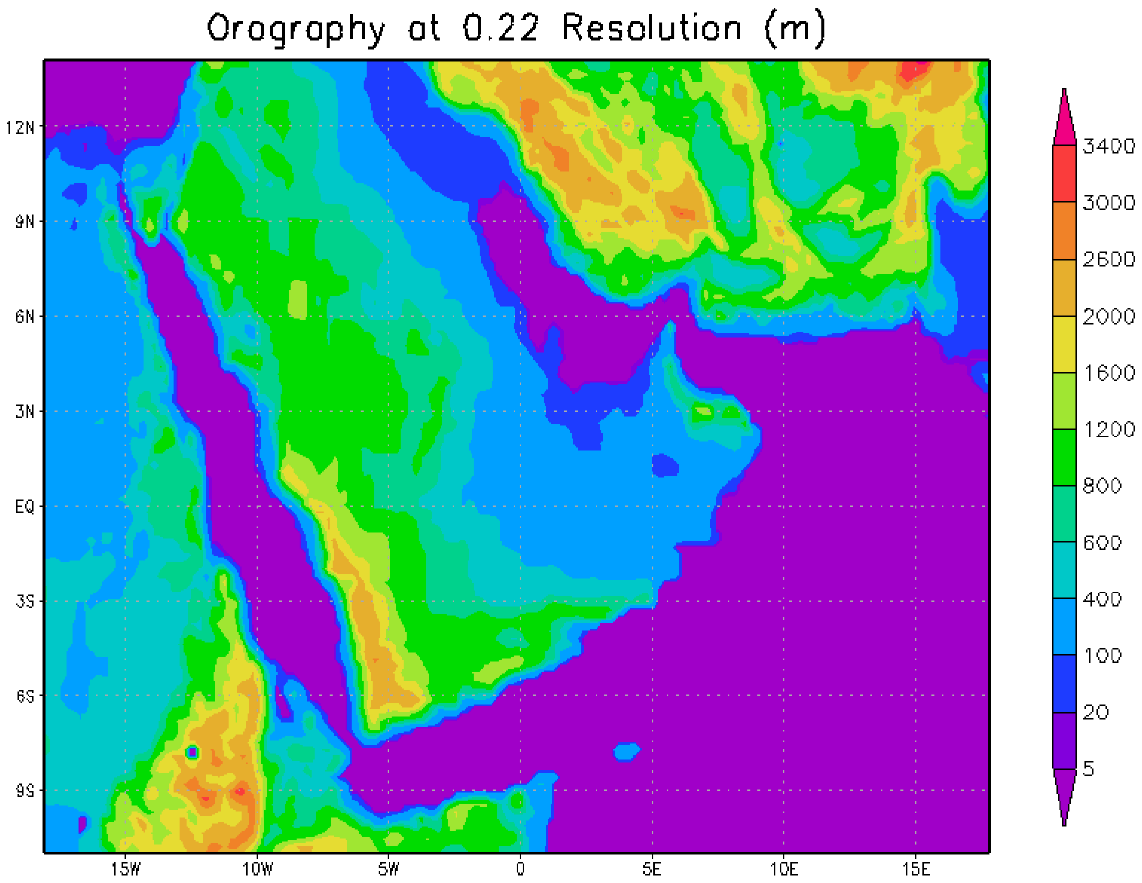

Figure 5-2: PRECIS topography of the Arabian Peninsula at 25 km resolution.

Due to the low density of meteorological observations over the AP, we use the Climatic Research Unit (CRU) TS3.2 data [*Harris et al*., 2014] to assess the model climatology. These data have been used over the AP and the Middle East region by, amongst others, *Almazroui et al*. [2012] and *Lelieveld et al*. [2012]. This dataset offers the most complete, consistent and updated compilation of gridded precipitation and temperature data at the global scale. The data are available at a spatial resolution of 0.5° latitude/longitude, and cover the period 1901-2011 [*Mitchell and Jones*, 2005]. The monthly time series of air temperature (mean, maximum and minimum) and precipitation have been used for the period 1990-2008. Although CRU TS3.2 datasets have been chosen for their global, quality controlled and their temporal coverage they are however of low spatial resolution and as such do not capture the structure in fields such as precipitation [*Evans*, 2009]. In addition CRUTS datasets have major deviations mostly in regions and/or time periods with sparser observational data [*Harris et al.*, 2014]. One area that might suffer such deviations is the Arabian Peninsula due to its limited number of observing sites.

5.2.1. Quality Control of Station Data (QC)

Station 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. Threshold values were similarly defined by *Zhang et al.* [2005] and *Alexander et al.* [2006]. The standard deviations of the stations were taken from the base period 1990-2008; (3) visual inspection of the data through a series of plots such 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 and Sur [*S. AlSarmi and Washington*, 2011] and the region as a whole. We decided to exclude Seeb station due to the station relocation in 1994 following *AlSarmi and Washington* [2013]. Although Seeb temperature variables have been excluded from the analysis but we used Seeb precipitation data as they deemed to be correct and homogeneous.

5.2.2. Homogeneity

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 stepchange points that could exist in a time series [*X. L. Wang*, 2003; *X. L. Wang*, 2008]. The two-phase regression model was applied to daily maximum, minimum temperatures as well as the daily precipitation. Most changepoints 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 Niño years 1998. Table 5-2 summarizes these significant changepoints showing the station, the date and the variable. Several stations share potential common change point dates.

The RHtestV3 detected 1 significant (at 0.05 level) changepoints of the original monthly mean temperature of Sur station on March 2003 and 1 significant changepoint of the original minimum temperature on January 2000. Possible cause of these changepoints is the station relocation as implied from the station metadata. The decision was made to use the adjusted Sur temperature timersires – an approach adopted in other studies (e.g. *Frich et al.* [2002] Australia; *Alexander et al.* [2006]).

Table 5-2: Details of significant detected changepoints during the year 1998 showing stations, variables and dates

Year	Station	Variable	Date (year.month)
1998	Dubai	maxT	19980100
	Ras Alkhaimah	maxT	19980200
	Sharjah	maxT	19980200
	Riyadh	maxT	19980500
	Al-Taif	maxT	19980400
	Hail	maxT	19980400
	Khamis Mushait	maxT	19980200
	Bahrain	meanT	19980100
	Dubai	meanT	19980100
	Hail	meanT	19980500
	Bahrain	minT	19980500
	Khasab	Precip	19980300
	Ras Alkhaimah	Precip	19980300
	Doha	Precip	19980100

After quality control and the homogeneity testing evaluations, 10 stations were retained from Saudi Arabia, 8 stations from Oman (the remaining 16 stations were mainly excluded because of short record), 3 from UAE, and 1 station from Qatar, 1 from Bahrain and 1 from Kuwait. The final list of stations is summarized in Table 5-3 where details of stations location, name and missing percentage (%) during the period 1990-2008 are listed. The total number of used for this analysis is 23 (24 for precipitations including Seeb). The stations locations are shown in Figure 5-3. Furthermore, in addition to the calculation of all the region time averages, two more subregional time series were produced, namely the nonmonsoonal region (north of 20°

N) and the monsoonal region (south of 20° N) following *AlSarmi and Washington* [2011].

Table 5-3: Stations location, name, elevation and missing percentage (%) during the period 1990-2008

Country	Station	WMO	Latitude	Longitude	Elevation(m)	Variable			
						MaxT	MinT	MeanT	Precipitation
Oman	Khasab	41240	26 20	56 23	33	3.5	3.5	1.8	2.2
	Sohar	41246	24 28	56 38	3.6	0	0	0	0
	Saiq	41254	23 04	57 38	1755	0.4	0.4	1.3	0.4
	Seeb	41256	23 35	58 17	8.4	nil	nil	nil	0
	Sur	41268	22 32	59 28	14	0	0	0	0
	Masirah	41288	20 40	58 54	19	0	0	0	0
	Thumrait	41314	17 40	54 01	467	0	0	0	0
	Salalah	41316	17 02	54 05	22	0	0	0	0
UAE	Ras Alkhaimah	41184	25 37	55 56	31	0	0	0	0
	Dubai	41194	25 15	55 20	5	0	0	0	0
	Sharjah	41196	25 20	55 31	33	0	0	0	0
Bahrain	Bahrain	41150	26.16	50.39	2	0	0	0	0
Qatar	Doha	41170	25.15	51.34	11	0	0	0	0
Kuwait	Kuwait	40582	29.22	47.59	6.1	5.3	0	4.8	5.7
Saudi Arabia	Tabuk	40375	28 23	36 36	768.1	0	0	0	0
	Hail	40394	27 26	41 41	1001.5	0	0	0	0
	Dhahran	40416	26 16	50 10	16.8	0	0.9	0	0
	Al-Madinah	40430	24 33	39 42	635.6	0.9	1.8	0.9	0.9
	Riyadh	40438	24 42	46 44	619.6	0	0.4	0.4	0.4
	Jeddah	41024	21 42	39 11	16.9	0.4	0.4	0.4	0.4
	Al-Taif	41036	21 29	40 33	1452.8	0.9	0.9	0.9	0.9
	Bisha	41084	19 59	42 38	1162	0	0	0	0
	Khamis Mushait	41114	18 18	42 48	2055.9	0	0	0	0
	Gizan	41140	16 53	42 35	7.2	0.4	0.4	0.4	0.4

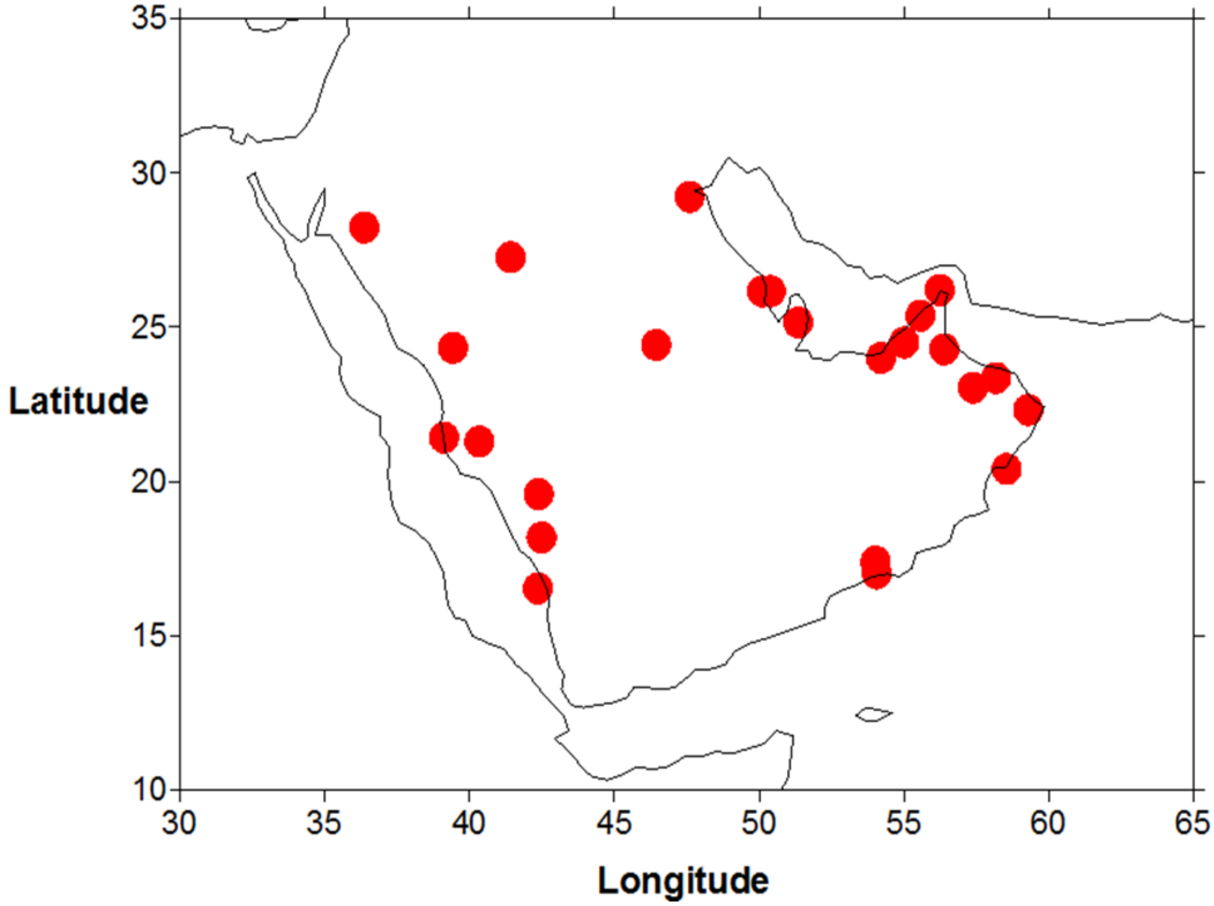

Figure 5-3: The distribution of 24 stations used in this study in the Arabian Peninsula.

5.3. Method

Analysis in this study focuses on surface air temperature and precipitation, and two different statistical moments mean (climatology) and trends (monthly data and extremes). Focus is given to the annual and seasonal timeframes but not monthly. Using a model grid spacing of 25 km will allows, in several cases, for comparison of model results to observations at meteorological stations. The annual and seasonal climatology maps are generated for both PRECIS simulation and CRU data. The bias of temperature (mean, maximum and minimum) and precipitation of PRECIS simulation run are generated using the CRUT3.2 gridded data and the stations data set for the period 1990-

2008. We re-grid the PRECIS 0.22° to 0.5° CRUTS3.2 grid resolution to ensure both data sets have the same common grid resolution for model evaluation. The regrid work has been executed by using the Climate Data Operator software (CDO). The interpolate function is used which is based on PINGO (Procedural INterface for GRIB formatted Objects) grid interpolation, it interpolates fields from one longitude/latitude grid to another.

Trends for stations and regional timeseries 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; *S. 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 timeseries residuals using the technique described in *Zhang et al.* [2005]. Details of this method are given by *Wang and Swail* [2001]. The majority of the stations have no missing data during 1990-2008 except over Khasab and Kuwait where missing varies from 3-6%. The 5% level of statistical significance is used. Annual and seasonal trends are calculated for all the stations and regions (subregions).

RClimDex software was used to calculate climate indices from the daily data with emphasis given to high temperatures, heavy rainfall and drought conditions [*Lelieveld et al*., 2012]. These are mixed of core and locally defined thresholds indices which are robust and dependent on the AP local climate. Six precipitation indices and 11 temperature indices were calculated. Table 5-4 summarizes the temperature and precipitation climate extreme indices used in this study. A base period of 1990-2008 has been used for calculating the percentile based indices. Stations to be included in the analysis have at least 18 years of data within this base period and pass the QC and homogeneity tests.

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 1990-2008) and the anomalies from this mean were computed. The regional averaged series were calculated by averaging all the anomalies. Similar methods 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 stations anomaly time series were obtained relative to the 19 years base period of 1990-2008.

Table 5-4: List all the ETCCDI climate indices calculated by RClimDex used in this study

ID	Descriptive name	Definitions	UNITS
SU40	Very warm days	Annual count when TX(daily maximum)>40ºC	Days
TR25	Very warm nights	Annual count when TN(daily minimum)>25ºC	Days
TXx	Warmest day	Monthly maximum value of daily maximum temperature	^{o}C
TNx	Warmest night	Monthly maximum value of daily minimum temperature	^{o}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	^{o}C
TMINmean	Mean minimum	Monthly mean value of daily minimum temperature	^{o}C
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	^{o}C
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
R10	Number of heavy precipitation days	Annual count of days when PRCP>=10mm	Days
CDD	Consecutive dry days	Maximum number of consecutive days with RR<1mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR>=1mm	Days
R95p	Very wet days	Annual total PRCP when RR>95th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR>=1mm)	mm

5.4. Results

The PRECIS simulated annual and seasonal precipitation and temperature over the AP will be evaluated relative to the CRU data set and the meteorological stations data in two ways; the characteristics of the mean climate and the trends of monthly data and the climate extreme indices.

5.4.1. Mean Climate

The following sections discuss the climatological patterns of the temperature (mean, maximum and minimum) and precipitation over the AP using PRECIS and CRU data sets. In general the climatological patterns simulated by PRECIS match the CRU data reasonably well although there are some notable biases. However, PRECIS shows more detailed patterns owing to its higher grid-spacing (25 km) than the gridded CRU data (50 km).

5.4.1.1. PRECIS climatolgy and bias relative to CRU data

The annual and seasonal maximum temperature patterns obtained from PRECIS and CRU data are shown in Figure 5-4. According to the PRECIS simulation, the highest mean annual maximum temperatures reach 40-44℃ over Rub Al-Khali while over the highlands in southwestern AP, the temperatures drop to 22-26℃. During DJF, the maximum temperature in the north is between 18-24℃ while in the south it reaches 28-32℃. The heat low intensifies from MA to JAS when it reaches its peak temperature of around 44-48℃ over the Rub Al-Khali. PRECIS locates the centre of the heat low (taken as the highest temperature) further south relative to CRU in MJ and JAS seasons. The mean maximum temperature bias (PRECIS minus CRU) indicates that PRECIS is some 2-5℃ colder than CRU over north/northwestern Saudi Arabia and there is a warm bias of 2-10℃ over the area extending from the AG to the south AP coasts (Figure 5-5).

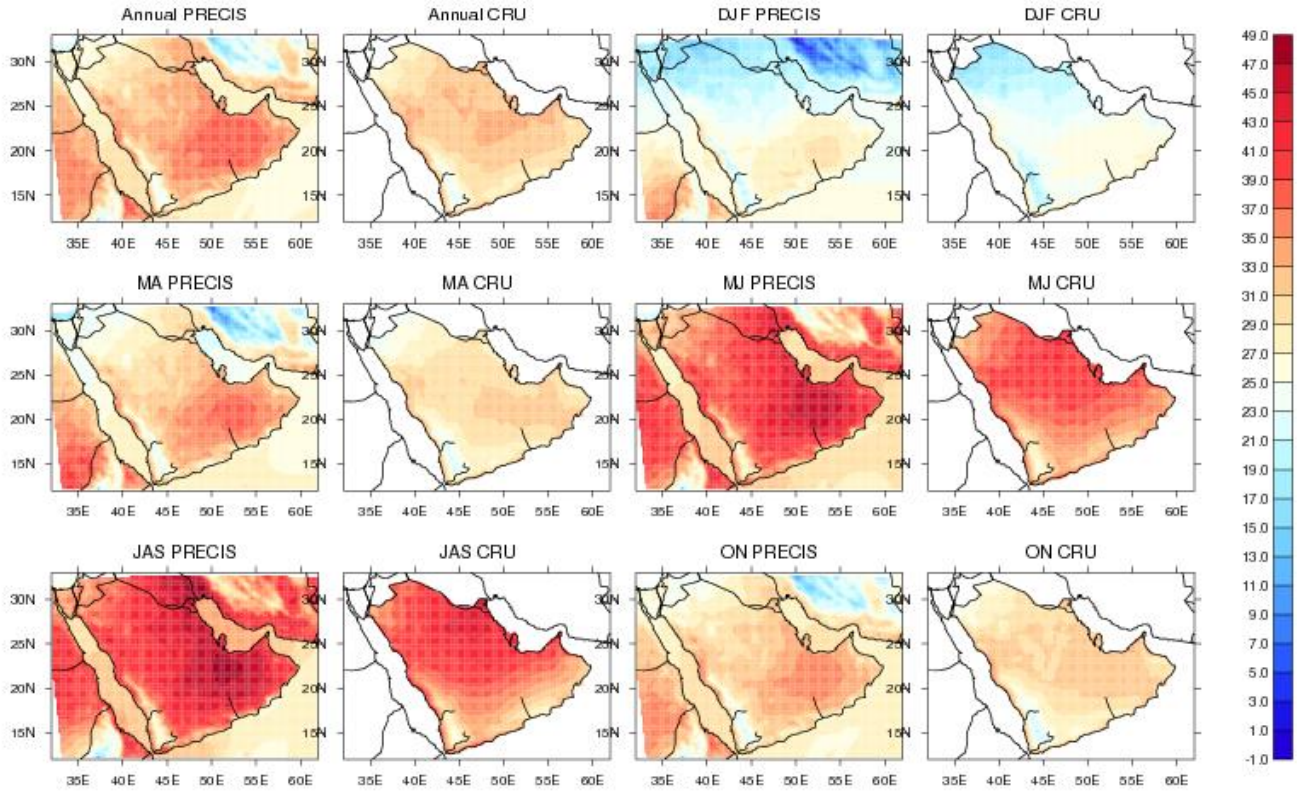

Figure 5-4: Maximum temperature (℃) annual and seasonal climatology of PRECIS and CRU datasets for the period 1990-2008.

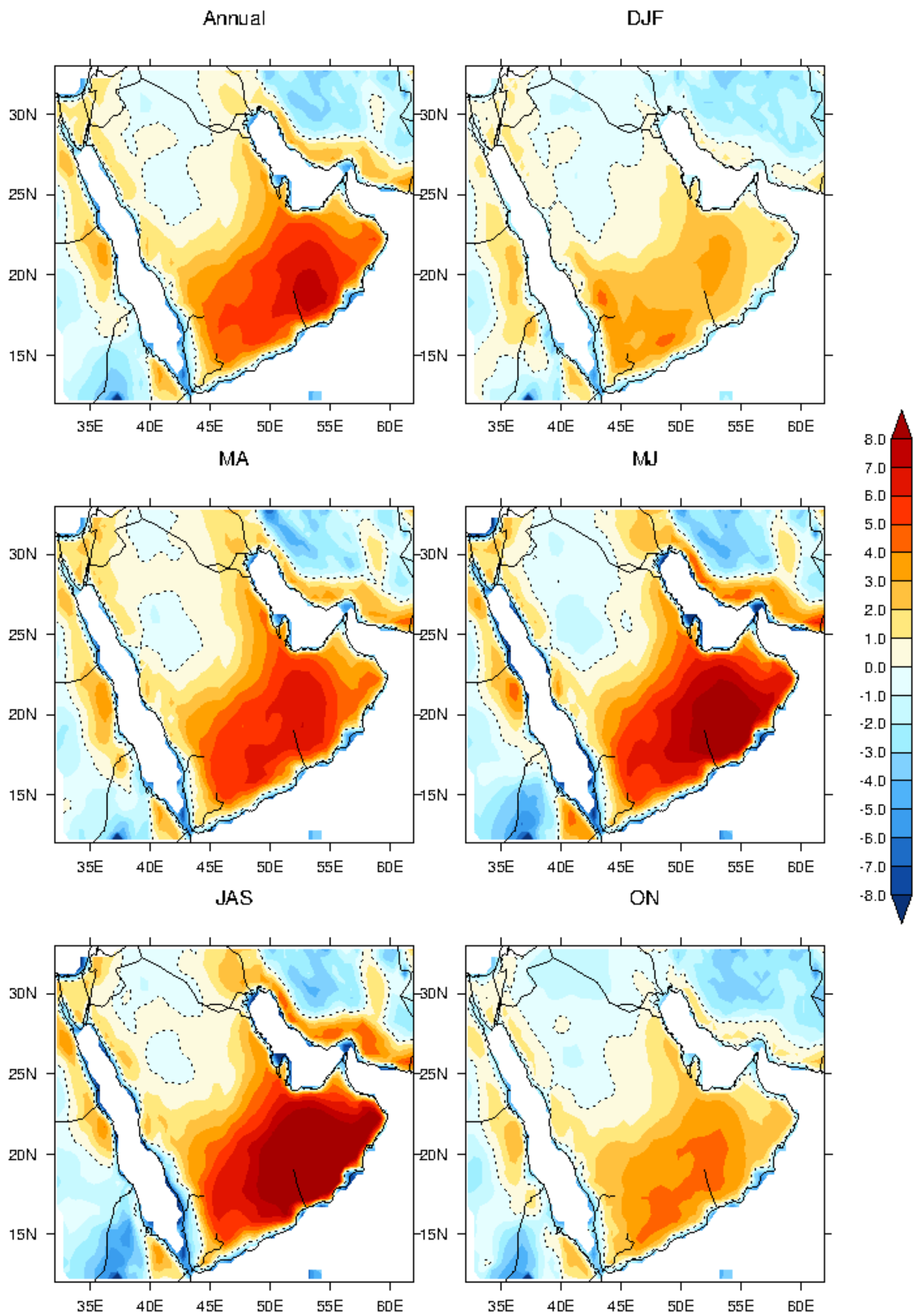

Figure 5-5: Maximum temperature bias (℃) maps of PRECIS minus CRU annual and seasons' means during 1990-2008. The dashed line represents the zero value.

In order to locate the heat low in terms of Mean Sea Level Pressure (MSLP), the MSLP annual and seasonal climatology plots have been obtained from the PRECIS simulation (Figure 5-6). During MJ season, most of the AP areas are influenced by the Indian monsoon trough while the heat low is remarkably developed over southeast areas during JAS season.

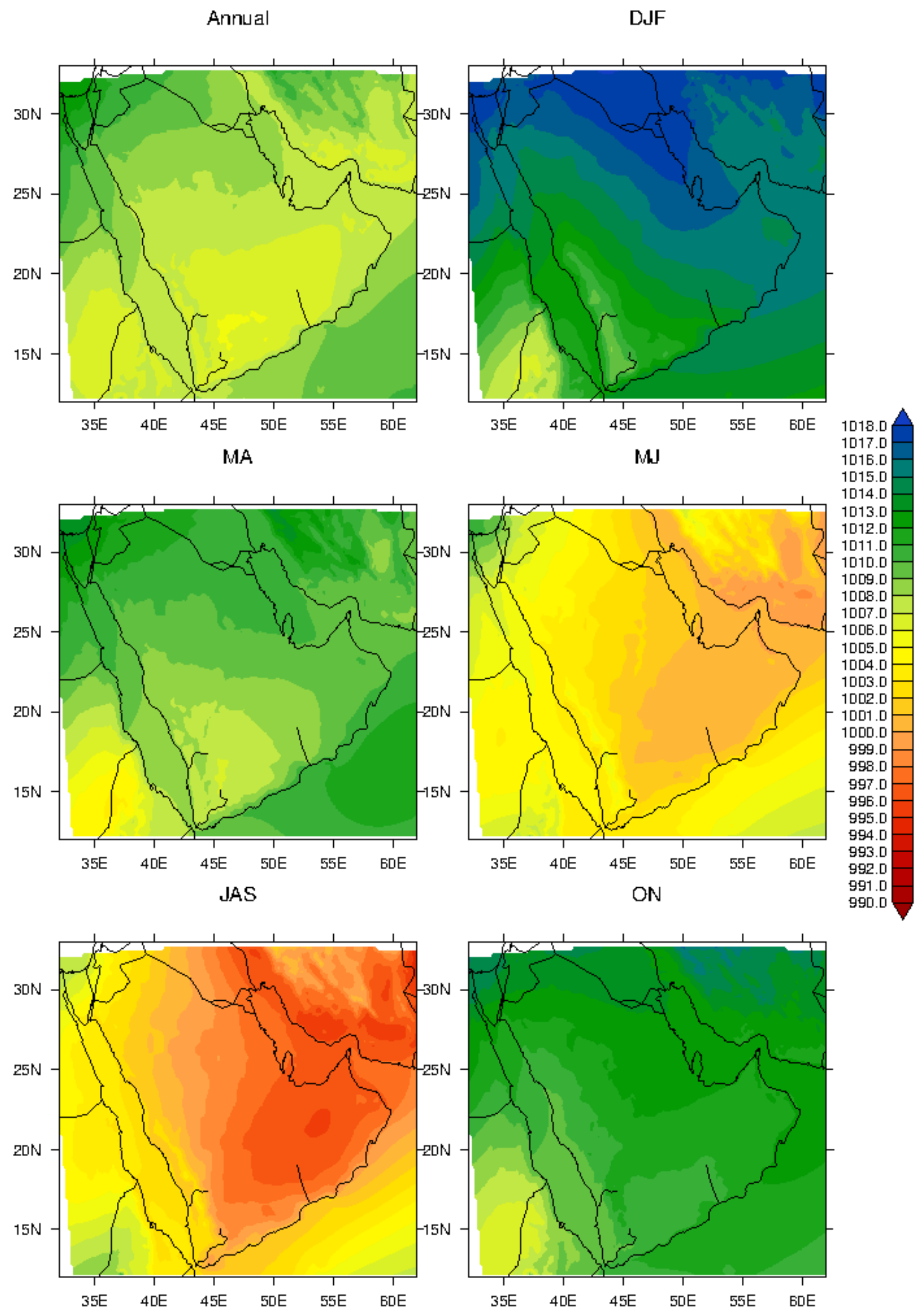

Figure 5-6: Mean Sea Level Pressure (hpa) annual and seasonal climatology of PRECIS dataset for the period 1990-2008.

The PRECIS annual mean temperature shows a northwest to southeast gradient with maxima located over the Rub Al-Khali of 30-32℃ (not shown). The lowest annual mean temperature is observed over the northwest and southwest AP with a mean temperature range of 12-16℃. Similar temperature patterns occur in winter (DJF) with lowest temperature reaching 4-8℃ in the northwest AP and over the mountains at the southwest and southeast AP. The MA, MJ and JAS maps reveal the annual cycle of the heat low over south AP. PRECIS simulates the heat low structure clearly in the JAS season where temperatures reach the peak at around 40-44℃. The heat low structure is less defined in the ON season.

There is a model cold bias of around 2-4℃ in the north and northwest AP. Most of the bias occurs in the DJF and MA seasons. However PRECIS has a warm bias over the area extending from the AG to the southern AP coasts. The bias exceeds 7℃ over south Oman.

Based on PRECIS simulation the mean annual and seasonal minimum temperature patterns are characterized by a northwest to southeast gradient (not shown). The areas reporting the lowest mean minimum temperatures are the northwestern and southwestern AP during winter where lowest temperature at around -4.0 to 0.0℃. During summer the minimum temperature in the northern areas ranges between 18 and 24℃, while in the south it is 26℃ and higher. In comparison with CRU data, the model is colder in all the seasons especially during winter and autumn. The largest bias (in excess of -5℃) occurs over the north/northwestern AP and along the south coast. The mean and maximum temperature bias pattern is similar. The Rub Al-khali region experienced a warm model bias between 2 and 4℃. The spatial distribution of the mean temperature bias matches the spatial distribution of the maximum and minimum temperature bias closely.

Most precipitation in the AP occurs in winter and spring due to mid-latitudes synoptic weather systems while in summer precipitation occurs over the mountains due to the orographic uplift of the moist monsoonal or onshore sea breeze flow. PRECIS simulations show a range in precipitation from approximately 25 mm in the south to 150 mm and higher in the north. The influence of topography is clearly evident with heavy precipitation in the AP over the southwestern areas where more than 400 mm a year is accumulated (Figure 5-7). In the summer, the precipitation is confined to the higher areas located at the south of the AP (southwestern, south and southeast mountains). This is most likely due to the influence of the South Asia monsoon inflow and the topographical uplift to which it is subjected. During late summer (JAS), PRECIS simulates 20-30 mm/year of precipitation over Yemen and south Oman with approximately 100-150 mm over the southwestern Mountains. Comparisons of PRECIS data set with CRU show that the model overestimates precipitation especially over the mountains. The model provides much greater spatial detail than CRU especially over the northwestern and southern high lands. A wet bias of more than 100 mm and higher occurs over the high lands in the region especially over the southwestern mountains range during late summer.

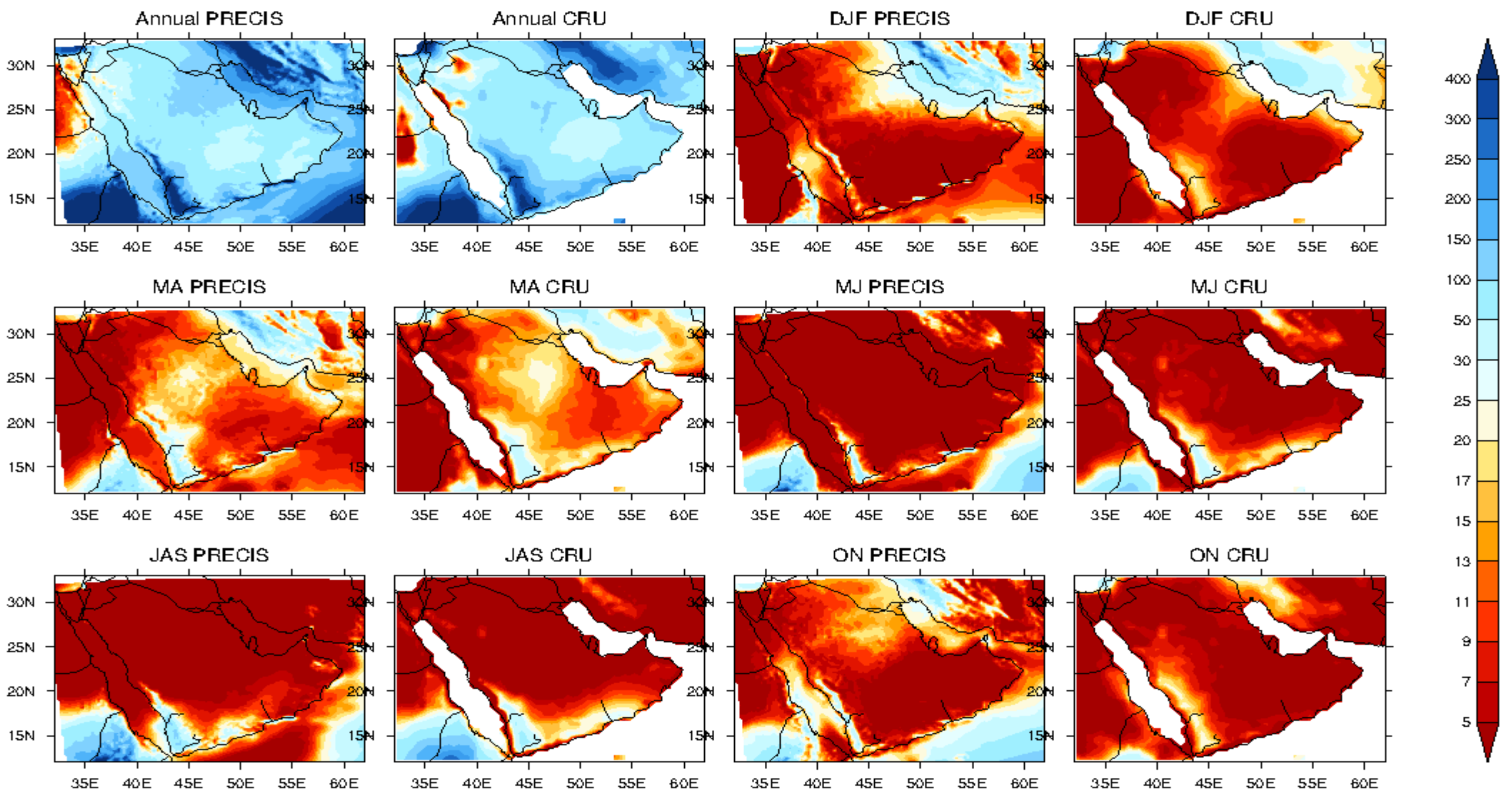

Figure 5-7: Precipitation (mm) annual and seasonal climatology plots of PRECIS and CRU datasets for the period 1990-2008.

5.4.1.2. PRECIS to ERA-Interim reanalysis bias

In order to assess whether the ERA-Interim boundary condition which force PRECIS has its own limitation over the region, annual and seasonal for mean temperature and precipitation bias plots have been obtained for a common grid resolution of 0.75 degree. The same regrid method as in section 5.3 has been adapted

5.4.1.2.1. Mean Temperature

The annual and seasonal mean temperature bias patterns obtained from PRECIS relative to ERA-Interim data are shown in Figure 5-8. The bias pattern looks similar to Figure 5-5 but cold bias are located over mostly western and northwestern areas whereas the areas extending from the AG to the south AP coasts especially Rub Al-khali region witness warm bias of around 1-2℃. However the bias magnitude of PRICIS minus CRU in Figure 5-5 is larger than the magnitudes of PRECIS minus ERA-Interim in Figure 5-8.

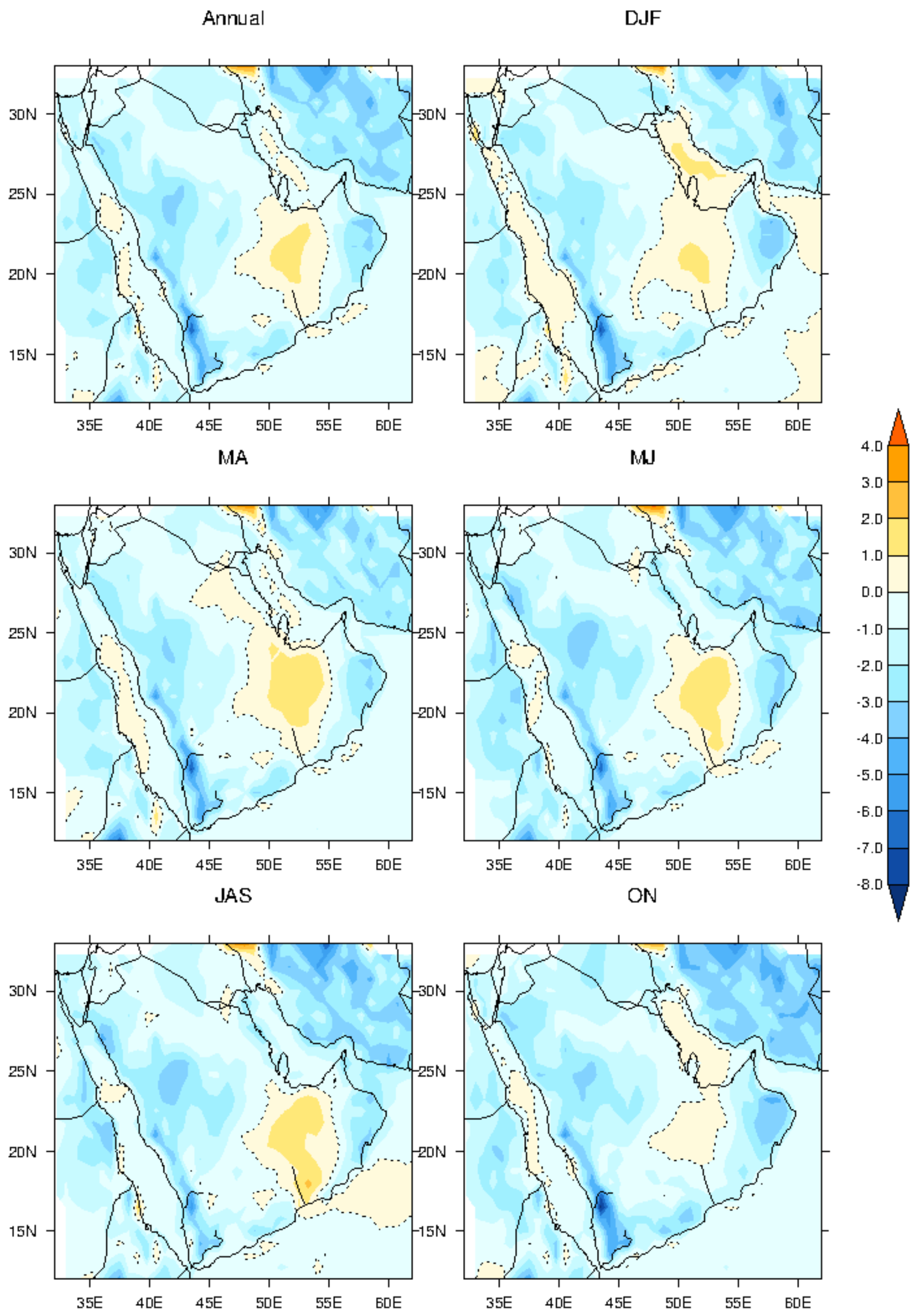

Figure 5-8: Mean temperature bias (℃) maps of PRECIS minus ERA-Interim annual and seasons' means during 1990-2008 (resolution 0.75 degree).

5.4.1.2.2. Precipitation

The annual and seasonal mean temperature bias patterns obtained from PRECIS relative to ERA-Interim data are shown in Figure 5-9. The bias pattern looks similar to the precipitation bias patterns of PRECIS minus CRU (not shown) especially over the SW mountains where the overestimation is the dominant pattern especially over the annual and JAS season.

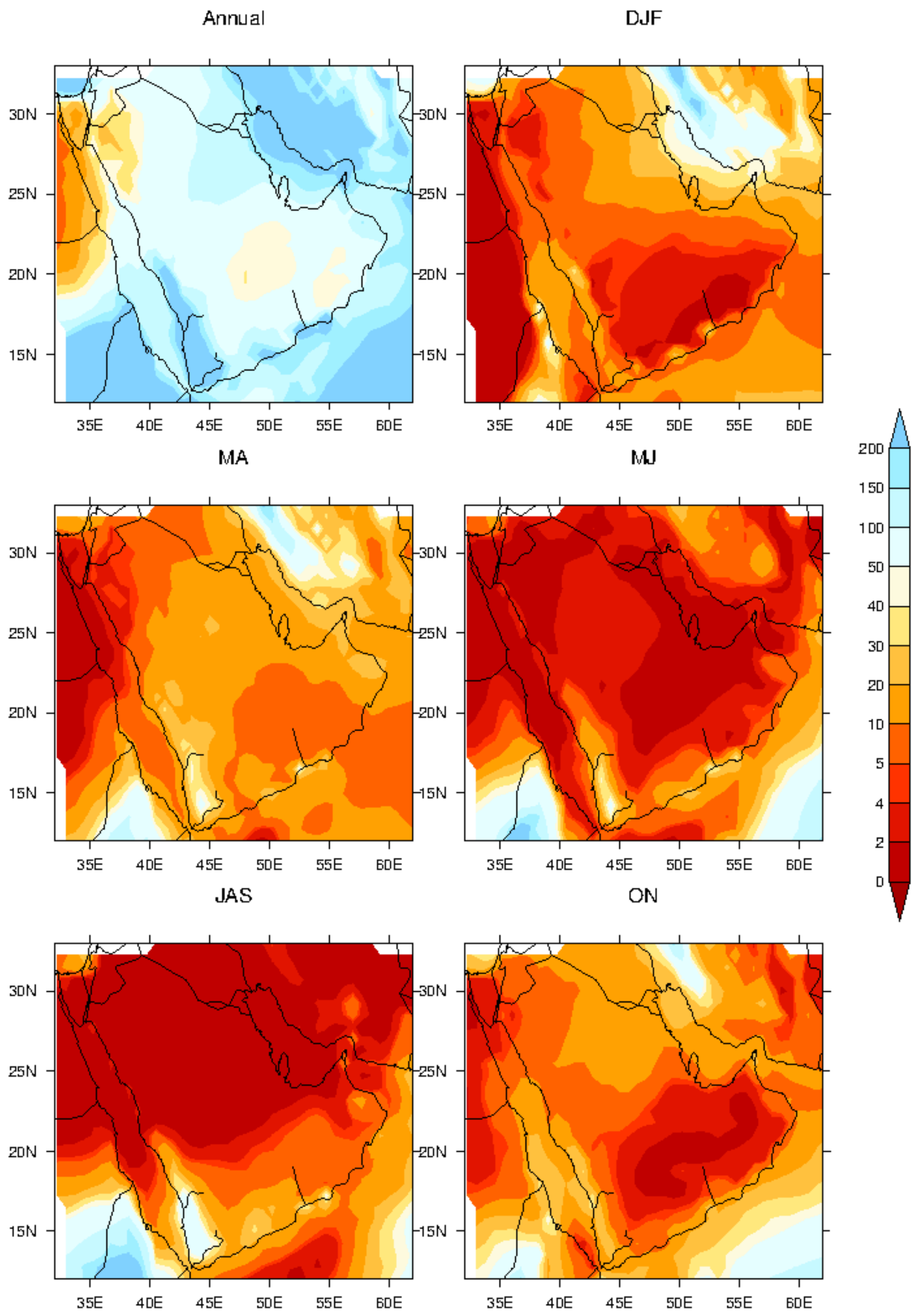

Figure 5-9: Mean precipitation bias (mm) maps of PRECIS minus ERA-Interim annual and seasons' means during 1990-2008 (resolution 0.75 degree).

In summary the bias plots of mean temperature and precipitation suggest that ERA-Interim driving force data are representing the regional climate better in temperature relative to precipitation variable.

5.4.1.3. PRECIS and CRU to meteorological stations bias

Given the large bias, particularly in the monsoon region, between PRECIS and CRU temperatures, this section investigates the agreement between PRECIS, CRU and the meteorological station data. It may be the case that the bias between the station data and PRECIS is smaller than the bias between CRU and PRECIS. For the temperatures, the range of biases is -6.4 to 9.9 in PRECIS and -10.3 to 6.2 in CRU. The lowest PRECIS negative bias of -6.4 occurs in the maximum temperature in the JAS season over Bisha station (southwest Saudi) while the lowest negative reported in CRU -10.3 which occurs also in the maximum temperature in JAS season over Thumrait (south of Oman). The highest PRECIS positive bias of 9.9 occurs in the maximum temperature in MJ season over Saiq (Oman Mountains) while the highest positive CRU bias of 6.2 occurred in DJF season over Saiq (Oman Mountains). The bias patterns of the precipitation look similar to the temperature in the sense that both variables biases occur over the high lands. The annual lowest negative observed bias in PRECIS is -156.0 mm over Saiq station (Oman) while the highest positive reported over 380.4 mm Gizan (southwest Saudi). For CRU the annual lowest negative bias observed over -195.0 mm observed over Saiq while the highest positive of 168.3 mm over Bisha (southwest Saudi).

The bias results summarised earlier either when comparing the model data (PRECIS) to the observed gridded data (CRU) or to the meteorological stations data indicate large bias especially in the deserts and mountains areas. This mean that caution needs to be taken when interpreting and comparing the trends results which will be discussed in the next section.

5.4.2. Trends

5.4.2.1. Area average mean climate trends (temperature and precipitation)

Table 5-5 summarises the regional average anomaly trends obtained from the meteorological stations and from the matching locations for the PRECIS simulation and CRUTS3.2 datasets for the temperature (maximum, mean and minimum) and precipitation percentage change during the period 1990-2008. The analysis is conducted for all regions in the AP as well as the non-monsoon and monsoon regions.

Table 5-5: Trends per decade for the regional average anomaly of temperature (maximum, minimum and mean) and precipitation percentage change during 1990-2008 (values for trends significant at 5% level are shown in bold). Regions: All (all Arabian Peninsula), MNOM (non-monsoonal subregion), MON (monsoonal subregion)

Variable		All			NMON			MON		
		PRECIS	CRU	stations	PRECIS	CRU	stations	PRECIS	CRU	stations
MaxT	Annual	**0.6**	**0.6**	**0.6**	**0.6**	**0.7**	**0.6**	**0.3**	**0.4**	0.1
	DJF	0.4	0.4	0.2	0.5	0.5	0.3	0.3	0.3	0.3
	MA	**1.3**	**1.1**	**1.3**	**1.4**	**1.3**	**1.5**	**0.7**	**0.7**	**0.5**
	MJ	0.5	**0.8**	**0.7**	0.7	**1.0**	**0.9**	0.3	0.3	0.0
	JAS	**0.3**	**0.6**	**0.6**	0.4	**0.7**	**0.9**	0.1	0.3	0.1
	ON	0.1	0.5	**0.5**	0.2	0.3	**0.6**	0.2	0.1	-0.1
MinT	Annual	**0.3**	**0.4**	**0.6**	**0.4**	**0.5**	**0.7**	0.2	0.1	**0.5**
	DJF	0.0	0.0	0.3	0.1	0.1	0.3	0.0	-0.1	0.3
	MA	0.3	**0.8**	**0.9**	**0.5**	**1.0**	**1.1**	0.2	0.3	0.5
	MJ	0.4	**0.8**	**1.0**	**0.5**	**0.9**	**1.2**	0.1	0.2	**0.6**
	JAS	**0.4**	**0.6**	**0.9**	**0.5**	**0.7**	**1.0**	0.1	**0.3**	**0.7**
	ON	0.0	0.2	**0.7**	0.0	0.3	**0.7**	0.2	-0.1	0.5
MeanT	Annual	0.3	**0.5**	**0.6**	**0.3**	**0.6**	**0.6**	0.2	**0.3**	**0.3**
	DJF	0.3	0.3	0.3	0.3	0.4	0.5	0.2	0.0	0.3
	MA	**0.8**	**0.9**	**1.2**	**1.0**	**1.2**	**1.4**	0.4	**0.6**	**0.4**
	MJ	**0.4**	**0.8**	**0.9**	**0.6**	**0.9**	**1.0**	0.3	0.3	0.3
	JAS	**0.3**	**0.6**	**0.7**	**0.4**	**0.6**	**0.9**	0.1	**0.3**	**0.4**
	ON	0.2	**0.4**	**0.4**	0.3	**0.4**	**0.6**	0.0	0.1	0.1
Precipitation (%)	Annual	**-36.4**	-16.6	-21.0	**-42.6**	-25.6	**-33.2**	-31.0	0.7	-20.7
	DJF	-43.9	-18.1	-23.3	**-36.9**	-28.7	-34.5	-31.0	18.6	-29.2
	MA	-48.2	-15.3	**-63.5**	-56.6	-10.9	**-69.1**	-13.8	-12.3	-30.3
	MJ	-24.3	-25.6	-8.9	-3.3	-42.4	-24.0	-10.5	**20.0**	-1.4
	JAS	-2.8	6.4	-3.0	-1.3	8.0	-9.3	2.9	12.5	-8.5
	ON	0.3	23.5	7.3	-6.1	-2.4	-4.9	8.2	71.2	5.5

Over the AP as a whole, there are statistically significant positive trends for all three data sets (PRECIS, CRU, stations) for the annual, MA and JAS maximum temperature. The slope of the trends matches exactly in the case of the annually averaged data (0.6℃ decade^{-1}) and are within 15% (1.1 to 1.3℃ decade^{-1}) during MA. PRECIS underestimates the observed data sets by 50% during the JAS season (trends of 0.3℃ compared with 0.6 °C). PRECIS does not simulate a significant trend to match the observed station increase in maximum temperature in MJ or ON. Results are similar for minimum temperature where PRECIS simulates statistically significant increasing trends which match the observed in the annual mean data as well as the summer data. As with the maximum temperature, PRECIS is only able to simulate half the observed trend in the JAS season. Significant observed minimum trends are not simulated by PRECIS in MA, MJ or ON. Significant mean temperature trends are matched across the data sets in MA, MJ and JAS, although again PRECIS underestimates the size of the trend typically by 50%.

The non-monsoon region shares many similarities with the All region trends. Significant trends are found across all data sets for the annual and MA maximum temperature. There is agreement in the case of significant minimum trends across all three data sets for the annual mean, MA, MJ and JAS seasons. PRECIS generally underestimates the size of the trends in the summer seasons by 50% or more in comparison with the station trends. Only the seasons from October to February do not see matching significant trends in minimum temperature across all data sets.

The monsoon region has by far the fewest trends that show significance across the data sets. In fact only the MA season for maximum temperature shows agreement across all three. Whereas station trends are increasing significantly in 7 of possible seasonal and temperature classes (MA max temperature, annual, MJ and JAS minimum temperature and annual, MA and JAS mean temperature, the PRECIS model simulates significant trends in only annual and MA maximum temperatures. The model therefore has significant difficulties in the monsoon region. Significant precipitation trends are only evident in annual model rainfall for all and NMON regions. In the observed data, significant negative trends occur over the NMON in the annual and MA season. Overall there are too few matching trends in the precipitation data for meaningful report.

5.4.2.2. Gridded data (PRECIS and CRU) and stations trends

While there is generally good agreement in the case of area average trends across the three data sets, particularly for all regions and non-monsoon maximum, minimum and mean annual, MA and JAS temperature, a more exacting test for the model is whether the spatial distribution of trends within the area averages presented in the section above match with the observed. These have been calculated for the period 1990-2008. Figures 5-10 and 5-11 show the spatial distribution of the annual and seasonal mean temperature trends obtained from PRECIS, CRU and the stations during 1990-2008. In general the trend patterns (magnitude and significance) of CRU data are much closer to the stations than PRECIS. This is not surprising since CRU is derived from station data.

The best match between the data sets for mean temperature occurs in the MA season when widespread warming is simulated in the model across a broad swath of the interior of AP. The model misses the northern most extent of the significant warming and also underestimates the trends everywhere except for the far north-eastern part of the domain. Warming in mean temperature for JAS in the model matches the CRU distribution well but again underestimates the strength of the trend substantially.

During ON, station warming is confined to Oman coast and UAE with the highest significant trend reported by Sur station over Oman (1.7℃ decade^{-1}). Over these areas both PRECIS and CRU underestimate the trends significance and magnitude by nearly 50%. Over the entire the region, trends are insignificant during winter when PRECIS simulates an exaggerated cooling pattern apart from a small area south of Red Sea which is supported by the stations (Gizan, 0.7℃ decade^{-1}).

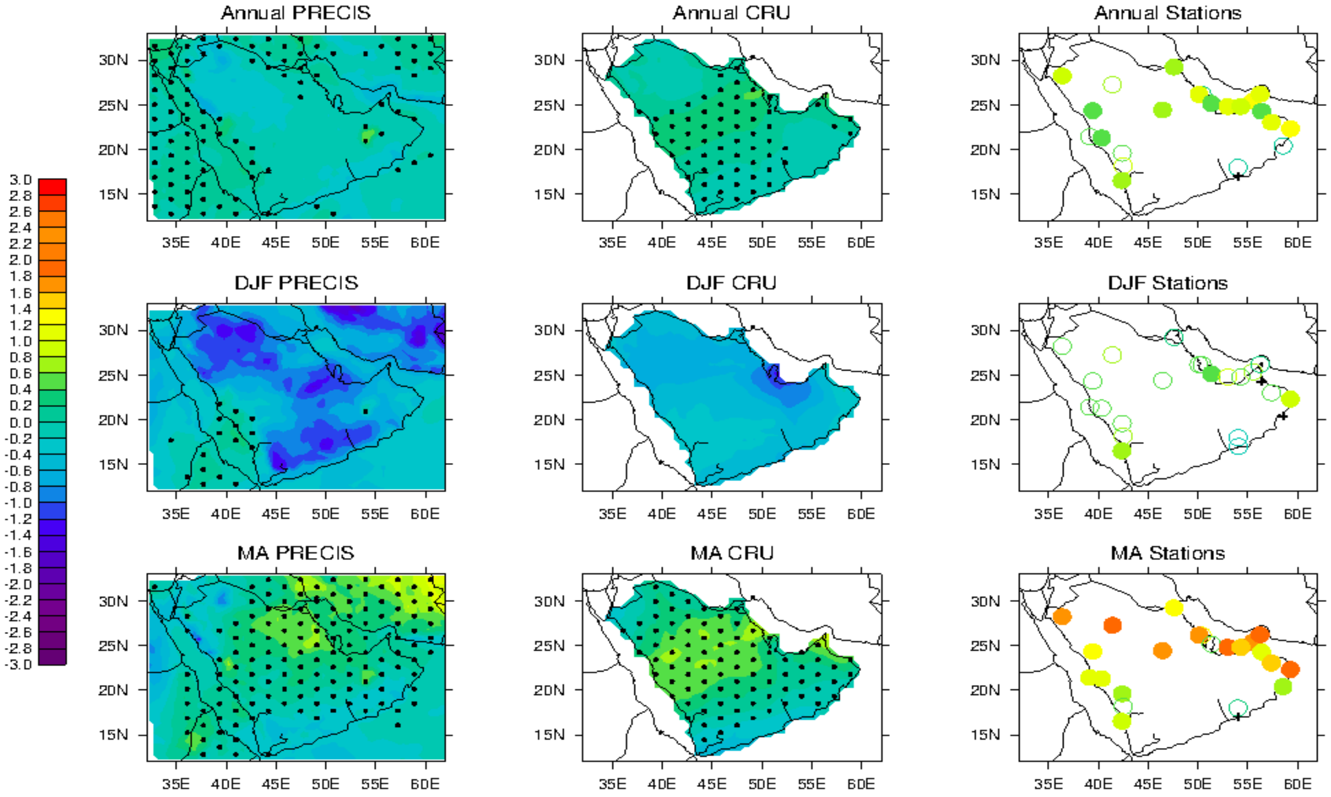

Figure 5-10: Mean temperature annual, DJF and MA trends plots of PRECIS, CRU and stations for the period 1990-2008 (grids of trends significant at 5% level are shown with black dots. For the stations trends the shaded circles are significant at 5%). The plus symbol (+) represents stations with zero trends.

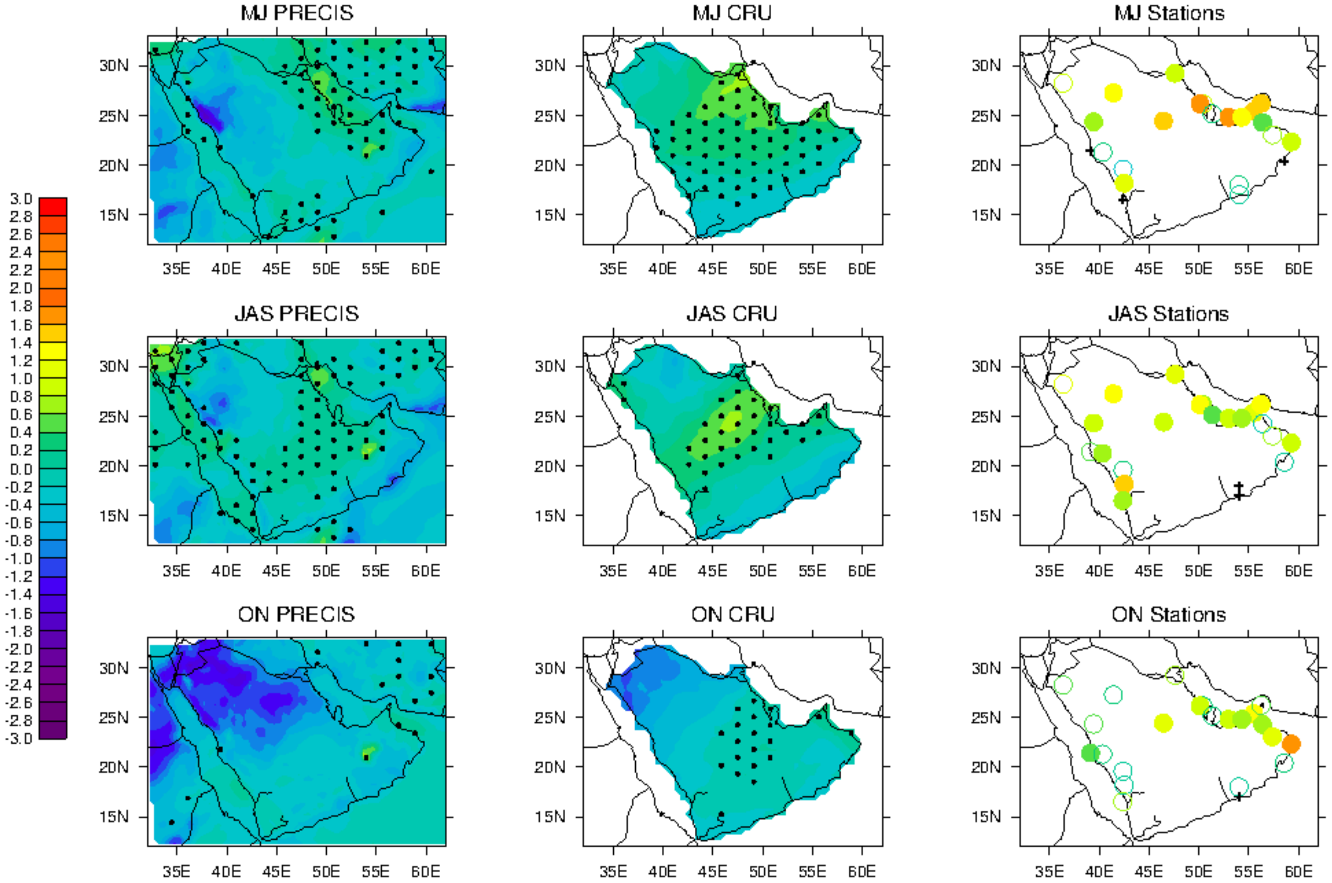

Figure 5-11: Mean temperature MJ, JAS and ON trends plots of PRECIS, CRU and stations for the period 1990-2008 (grids of trends significant at 5% level are shown with black dots. For the stations trends the shaded circles are significant at 5%). The plus symbol (+) represents stations with zero trends.

The spatial distribution of maximum temperature trends (Figures 5-12 and 5-13) is similar to mean temperatures, apart from the annual mean where PRECIS simulates widespread significant trends in the north of the domain which are not matched by CRU. The station trends in MA which are strongly positive and significant are well simulated by PRECIS although the degree of warming is still rather muted. Generally the pattern of warming in MJ and JAS matches well. There are some important differences during spring and summer (MJ and JAS) especially over Oman coastal stations and west/northwest AP. For example in the stations data set, the highest trend values range between 2.2 to 2.7 ℃ decade^{-1} especially over central, eastern and southeastern AP. PRECIS captures the MA spatial trends very well although of relatively lower magnitudes whereas CRU confines the highest trends to the central and western AP. In MJ season the highest significant warming occurred over the AG as seen from the stations data set (Dhahran 2.2℃ decade^{-1}). Again, PRECIS detects this very well although with lower magnitude. In ON, the warming of the maximum temperature is high and significant only over south AG, UAE and Oman coast which is similar to the mean temperature. Some indication of significant warming appears in PRECIS and CRU data sets over Oman coast in ON season but with much lower magnitude. During winter, PRECIS tends to exaggerate the cooling over north AP but simulate well the warming in the south Red Sea which is supported by Gizan station (0.6℃ decade^{-1}).

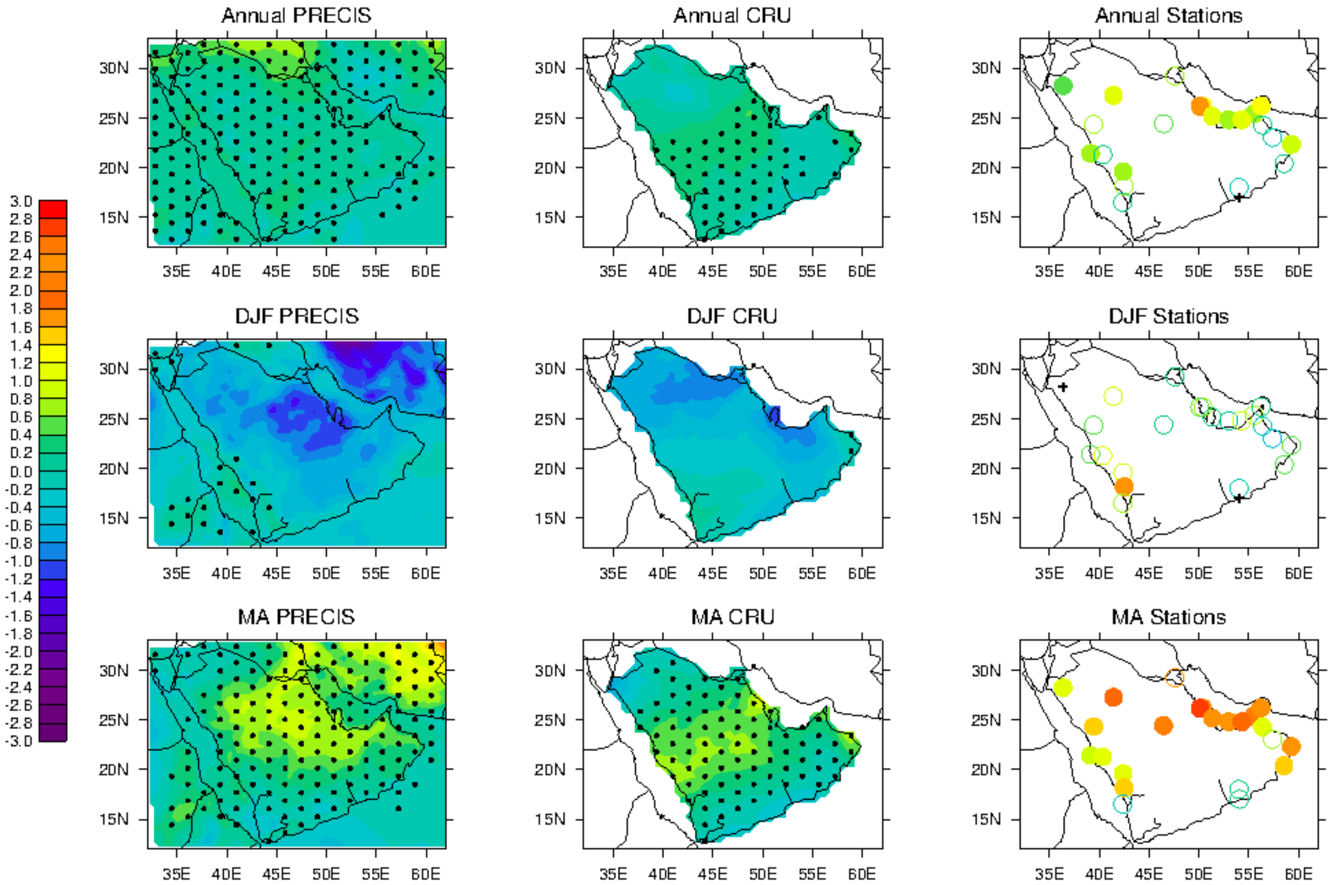

Figure 5-12: Maximum temperature annual, DJF and MA trends plots of PRECIS, CRU and stations for the period 1990-2008 (grids of trends significant at 5% level are shown with black dots. For the stations trends the shaded circles are significant at 5%). The plus symbol (+) represents stations with zero trends.

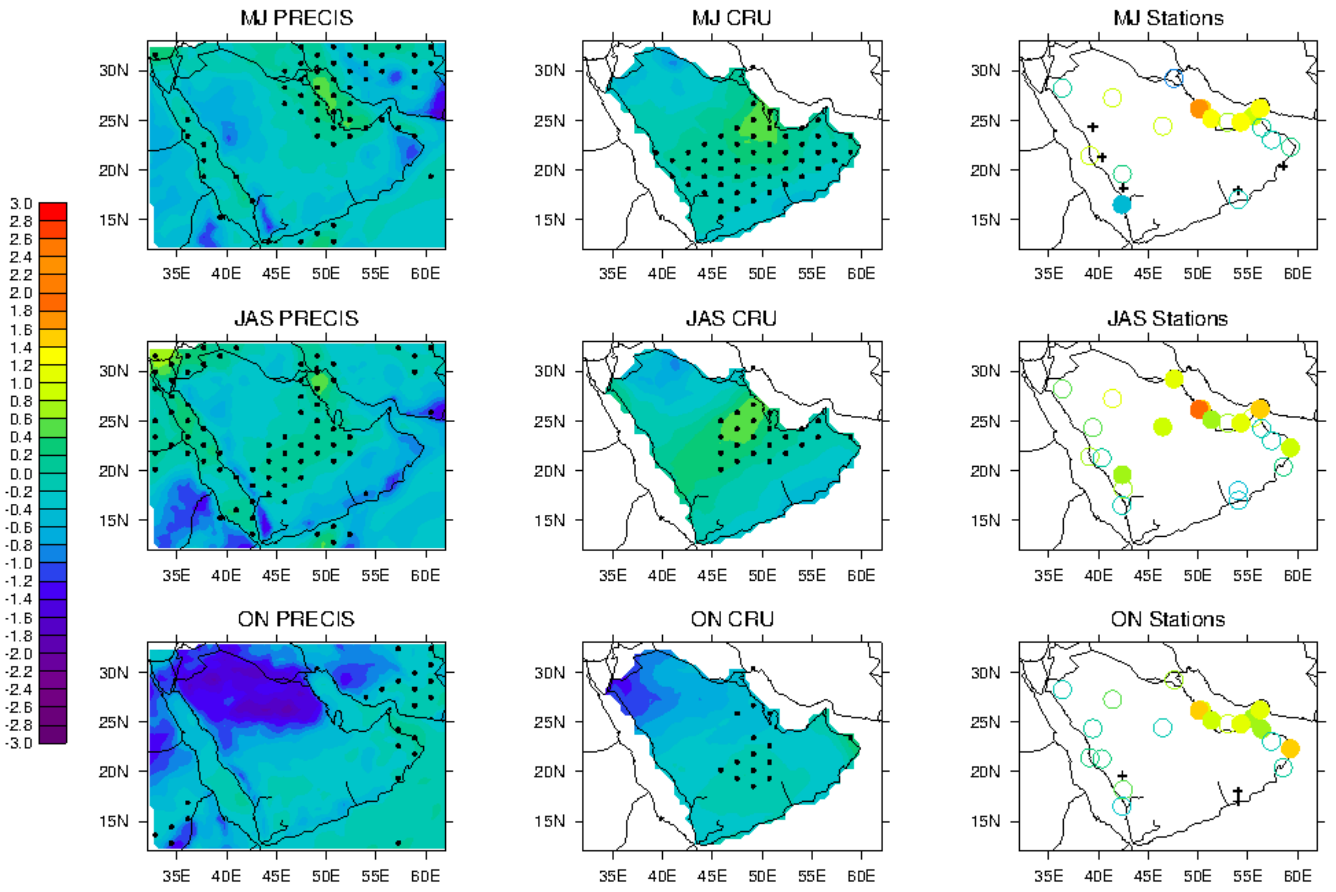

Figure 5-13: Maximum temperature MJ, JAS and ON trends plots of PRECIS, CRU and stations for the period 1990-2008 (grids of trends significant at 5% level are shown with black dots. For the stations trends the shaded circles are significant at 5%). The plus symbol (+) represents stations with zero trends.

Figures 5-14 and 5-15 presents the spatial distribution of trends for the annual and seasonal minimum temperature for PRECIS, CRU and the stations. The annual stations data set shows that the highest warming occurs over the AG and Oman coast. Around 70% of the stations have statistical significant trends with magnitudes varying between 1.0 and 1.6℃ decade^{-1}. The CRU data shows the highest significant trends area to the central AP while PRECIS confined the warming to the eastern/southeastern areas. Most of the warming is in spring and summer in the CRU and the stations data sets. The highest significant trends observed in eastern/southeastern areas (1.4 to 2.2℃ decade^{-1}) according to the stations data while the central/northern areas witness the highest warming in the CRU data. The line of intense warming is clear in the JAS seasons in the stations and to lesser extent in the CRU data. However, PRECIS shows low significant warming (0.3 – 0.8℃ decade^{-1}) which is confined to the eastern AP (AG) in MA and MJ while in JAS season the significant warming appeared along central AP and northern AG. The mean minimum trends patterns in ON season look similar to the mean and maximum temperature with clear underestimation of the trends significance and magnitude in the PRECIS and CRU data sets. During winter both CRU and PRECIS miss the warming in the southeast AP.

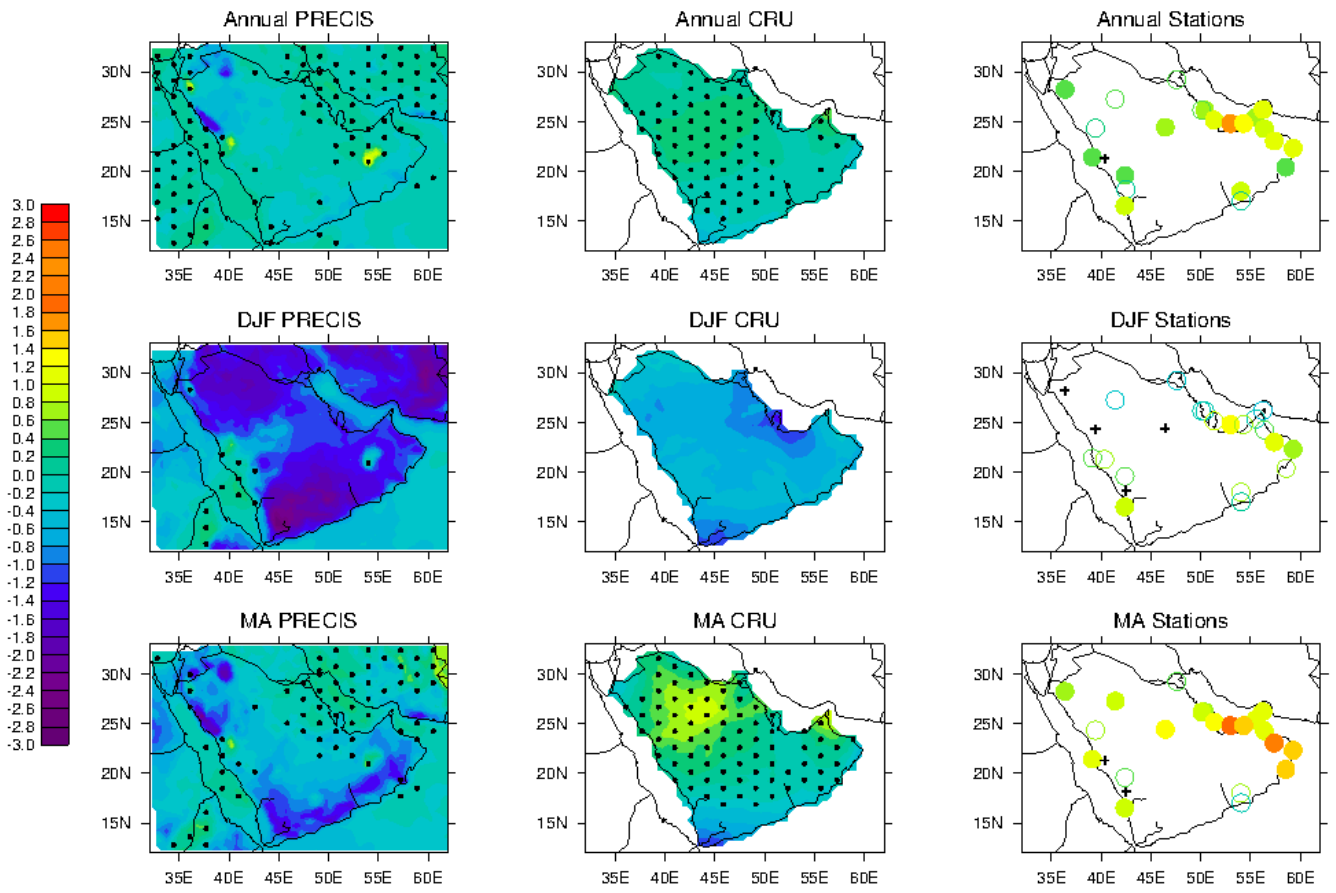

Figure 5-14: Minimum temperature annual, DJF and MA trends plots of PRECIS, CRU and stations for the period 1990-2008 (grids of trends significant at 5% level are shown with black dots. For the stations trends the shaded circles are significant at 5%). The plus symbol (+) represents stations with zero trends.

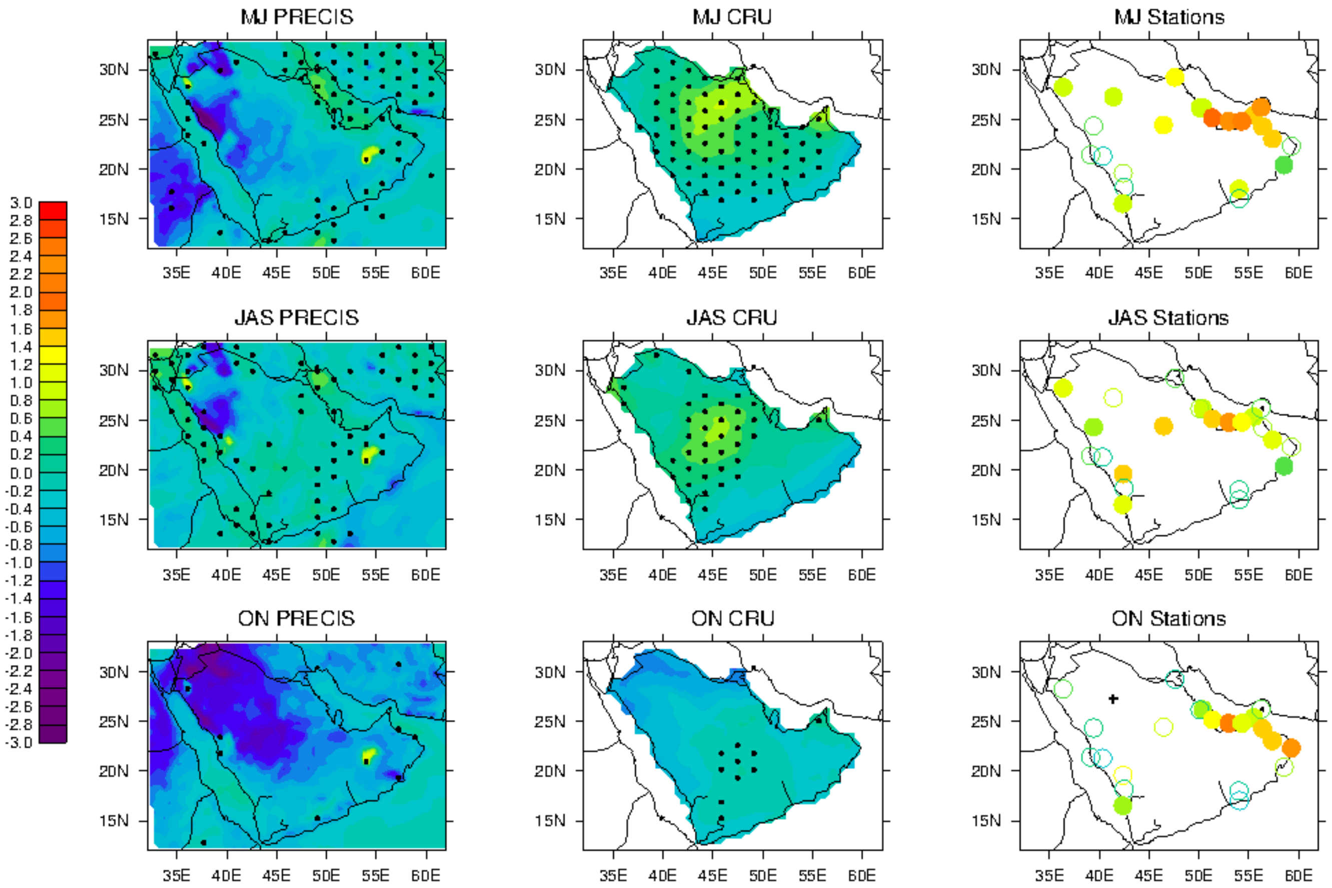

Figure 5-15: Minimum temperature MJ, JAS and ON trends plots of PRECIS, CRU and stations for the period 1990-2008 (grids of trends significant at 5% level are shown with black dots. For the stations trends the shaded circles are significant at 5%). The plus symbol (+) represents stations with zero trends.

The spatial distribution of the annual and seasonal change in precipitation (%) obtained from PRECIS, CRU and the stations, relative to the base period 1990-2008, is displayed in figures 5-16 and 5-17. Overall, the precipitation reduces in the all the data sets but with few grids/stations reporting significant trends. However, CRU data set shows significant increasing trends in the area extending from south to the central AP during summer and autumn. PRECIS agrees well with the stations trends especially in locating the significant reduction areas in the annual, MA and ON seasons. The highest annual percentage change reduction reported in Al-Madinah station (-93.8%) while seasonally Sharjah station reported the highest reduction of -97.2% in MA season. The maps of spatial distribution of precipitation are more informative than the area average trends which tend to show little useful information.

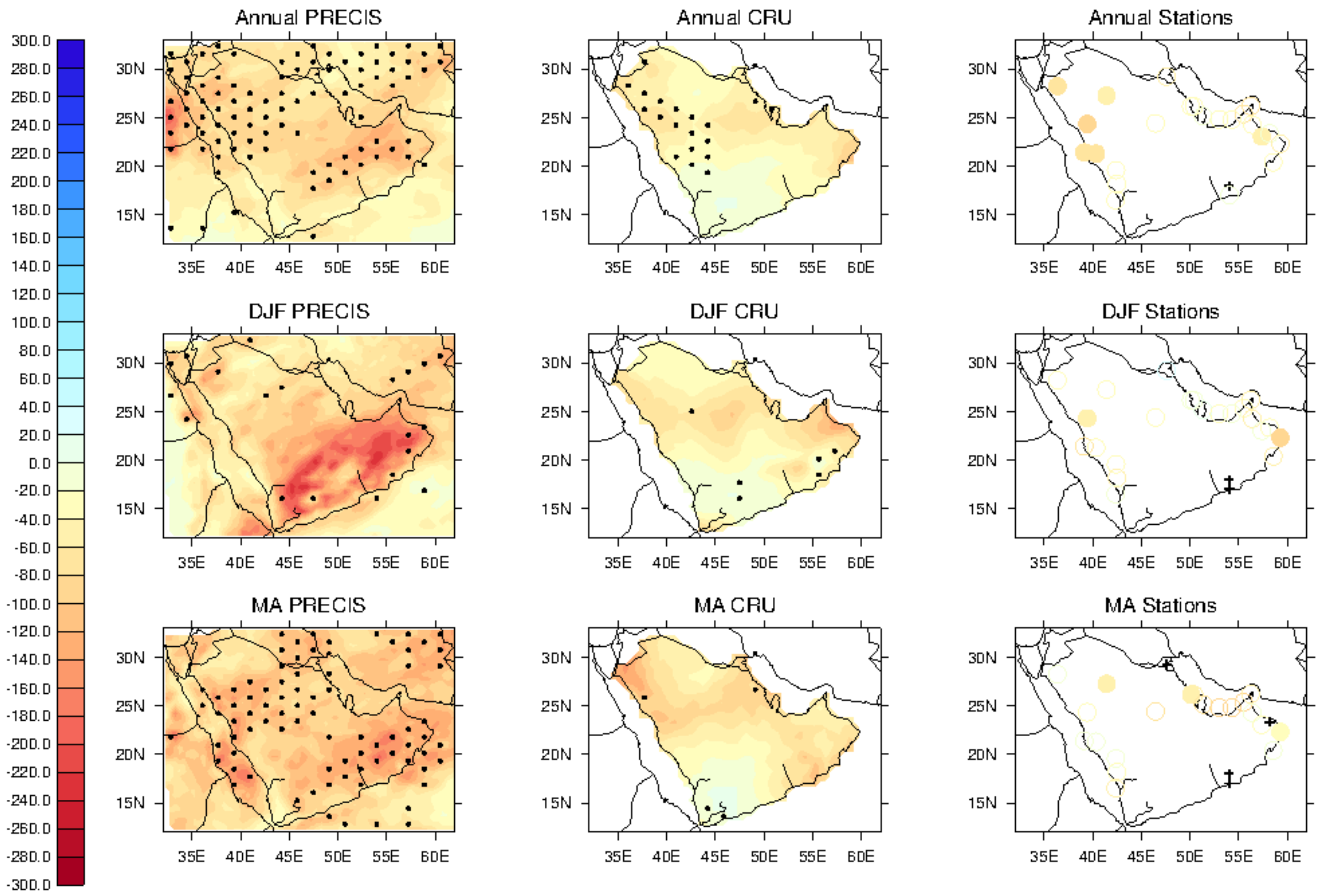

Figure 5-16: Precipitation (percentage change) annual, DJF and MA trends plots of PRECIS, CRU and stations for the period 1990-2008 (grids of trends significant at 5% level are shown with black dots. For the stations trends the shaded circles are significant at 5%). The plus symbol (+) represents stations with zero trends.

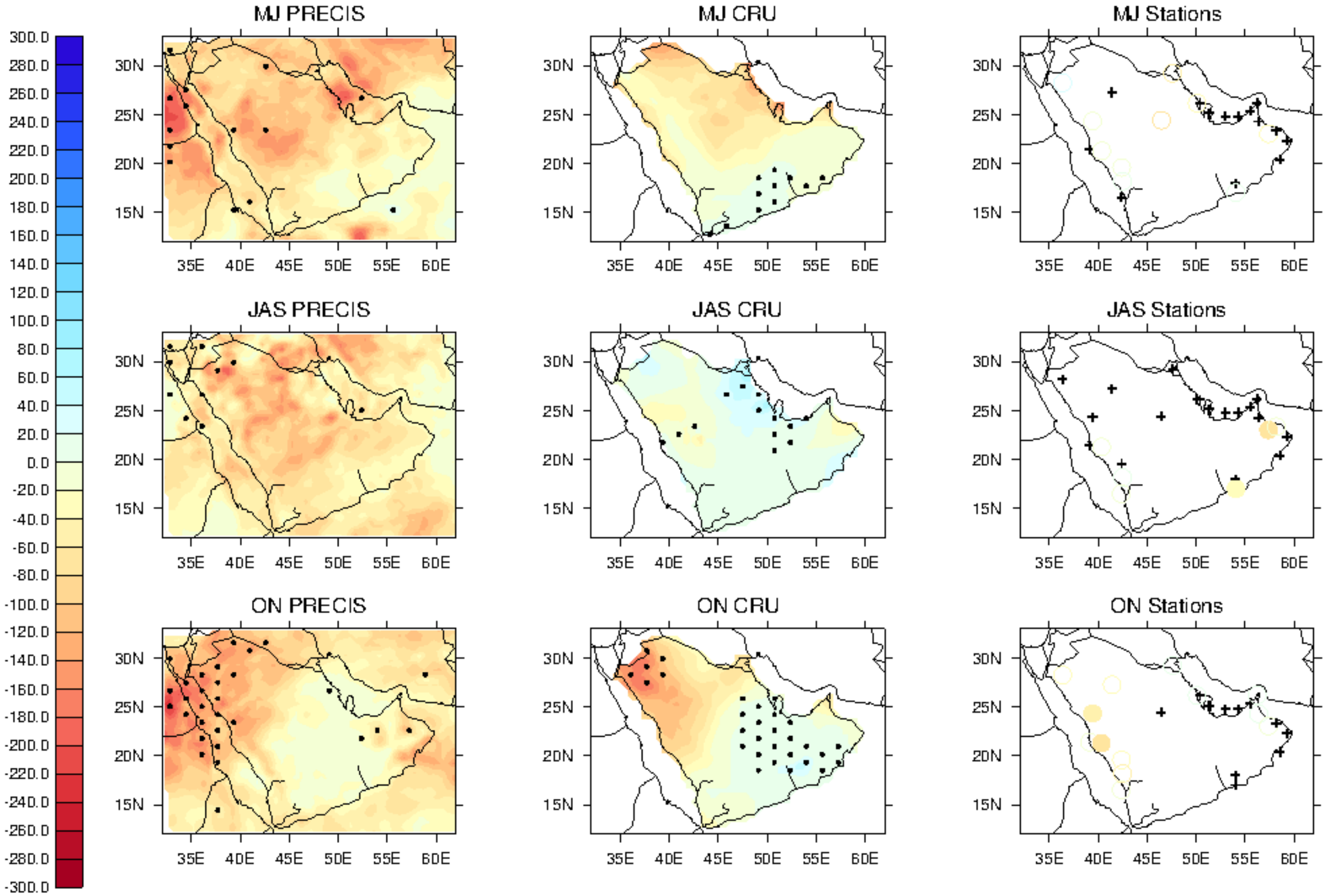

Figure 5-17: Precipitation (percentage change) MJ, JAS and ON trends plots of PRECIS, CRU and stations for the period 1990-2008 (grids of trends significant at 5% level are shown with black dots. For the stations trends the shaded circles are significant at 5%). The plus symbol (+) represents stations with zero trends.

5.4.2.3. Extremes trends

Table 5-6, 5-7 and 5-8 summarises for the three AP regional (subregions) annual and seasonal average anomaly temperature and precipitation extreme indices trends during 1990-2008 for the meteorological stations and the stations sites points of the PRECIS simulation. Taking into account all the seasons, regions and indices, there are 201 possible matching pairs of station and PRECIS values for extreme trends (3 regions, 6 seasons and >10 extremes). Of these, 97 are statistically significant for station data and of these 97, there are 42 cases (roughly 50%) where PRECIS and the station indices are both statistically significant. Agreement is generally highest in the non-monsoon region for the temperature extremes. The degree of agreement between extreme trends simulated and observed is very low for the monsoon region.

Table 5-6: Trends per decade for the regional average anomaly indices of DTR, TMAXmean, TMINmean, RX1day and TN10p extremes (values for trends significant at 5% level are shown in boldface while for 10% level are shown in italic)

Variable	time	All		NMON		MON	
		PRECIS	stations	PRECIS	stations	PRECIS	stations
DTR	Annual	**0.4**	0.1	**0.5**	0.1	0.2	0.0
	DJF	0.2	0.0	0.2	0.0	0.2	-0.1
	MA	**1.0**	**0.8**	**1.1**	**1.0**	**0.8**	0.6
	MJ	0.0	-0.3	0.1	-0.2	0.1	-0.5
	JAS	0.0	**-0.3**	0.0	-0.1	0.0	**-0.5**
	ON	0.1	-0.2	0.1	-0.3	-0.1	-0.4
TMAXmean	Annual	0.3	0.6	0.5	**0.6**	**0.3**	0.1
	DJF	0.2	0.2	0.3	0.3	0.3	0.3
	MA	**1.3**	**1.3**	**1.4**	**1.5**	**0.7**	0.5
	MJ	0.5	**0.7**	0.6	**0.9**	0.3	0.0
	JAS	**0.3**	**0.6**	0.4	**0.9**	0.1	0.1
	ON	0.1	**0.5**	0.2	**0.6**	0.2	-0.1
TMINmean	Annual	0.2	**0.6**	0.2	**0.7**	0.2	**0.5**
	DJF	0.0	0.3	0.0	0.3	0.0	0.3
	MA	0.3	**0.9**	**0.5**	**1.1**	0.2	0.5
	MJ	0.4	**1.0**	**0.5**	**1.2**	0.1	**0.6**
	JAS	**0.4**	**0.9**	**0.5**	**1.0**	0.1	**0.7**
	ON	0.0	**0.7**	0.0	**0.7**	0.2	0.5
RX1day	Annual	-11.142	-7.4	-10.3	-2.2	-8.4	-5.3
	DJF	-3.9	-2.1	**-3.6**	-2.3	-0.1	*-0.9*
	MA	-3.2	-3.4	-4.4	-4.7	-2.6	-1.3
	MJ	0.0	0.0	0.0	0.3	-0.3	-0.1
	JAS	0.0	-0.3	0.0	-0.5	0.4	-0.3
	ON	0.2	-0.2	-0.2	-0.3	0.8	-0.1
TN10p	Annual	-1.4	**-3.3**	-1.1	**-3.7**	-1.8	**-2.5**
	DJF	0.4	-0.9	0.9	-1.6	-0.8	-1.3
	MA	-2.0	**-3.0**	**-2.4**	**-4.5**	-1.2	-1.7
	MJ	**-2.9**	**-5.7**	**-2.0**	**-6.6**	-0.8	**-5.1**
	JAS	**-3.0**	**-5.8**	**-3.5**	**-6.9**	0.2	**-4.9**
	ON	-1.8	**-4.3**	-0.3	**-4.1**	-1.9	-3.7

Table 5-7: Trends per decade for the regional average anomaly indices of TN90p, TX10p, TX90p, TNx and TXx extremes (values for trends significant at 5% level are shown in boldface while for 10% level are shown in italic)

TN90p	Annual	1.2	**3.3**	0.9	**3.3**	1.7	**2.9**
	DJF	-0.2	1.7	-1.1	0.5	1.8	2.8
	MA	2.3	**3.6**	2.2	**3.8**	1.5	**3.6**
	MJ	2.4	**3.9**	1.8	**4.1**	**3.0**	**3.0**
	JAS	**2.1**	**4.9**	2.3	**4.9**	1.2	**4.5**
	ON	0.3	**3.3**	0.2	**3.2**	-0.4	1.8
TX10p	Annual	-2.9	-2.4	**-2.9**	**-2.6**	**-2.8**	-1.0
	DJF	-2.0	-0.4	-1.6	-3.4	-3.4	-1.5
	MA	**-5.5**	**-4.0**	**-6.6**	**-5.9**	**-4.8**	0.1
	MJ	**-3.5**	-2.4	**-4.0**	**-4.0**	-1.5	1.0
	JAS	**-2.9**	**-4.2**	**-2.9**	**-5.4**	-1.0	-0.7
	ON	-1.1	-2.1	-0.9	-2.5	-2.7	0.5
TX90p	Annual	**2.4**	**2.4**	**2.5**	**2.6**	**2.8**	2.6
	DJF	0.8	0.8	-0.3	0.5	**2.7**	1.4
	MA	**6.8**	**5.0**	**6.5**	**4.9**	**6.7**	**5.6**
	MJ	3.0	1.9	2.2	2.7	**4.7**	-0.1
	JAS	**2.2**	**2.8**	**2.2**	**3.3**	0.8	1.9
	ON	2.3	**3.2**	2.6	**2.9**	2.3	1.8
TNx	Annual	0.4	**0.9**	0.4	**0.9**	**0.4**	**1.0**
	DJF	0.0	0.5	-0.1	0.3	0.0	0.6
	MA	0.5	**1.1**	**0.6**	**1.1**	0.3	**0.6**
	MJ	**0.5**	**0.9**	**0.5**	**1.0**	**0.4**	**0.8**
	JAS	**0.5**	**0.9**	**0.6**	**1.1**	0.2	**0.8**
	ON	0.0	0.5	0.0	0.5	0.1	0.5
TXx	Annual	**0.3**	**0.5**	0.3	0.5	**0.4**	0.4
	DJF	0.3	0.5	0.3	0.4	**0.4**	0.6
	MA	1.2	**1.2**	1.4	**1.3**	0.6	0.9
	MJ	0.3	0.2	0.3	**0.6**	0.3	-0.1
	JAS	**0.4**	**0.6**	**0.5**	**0.9**	0.0	**0.5**
	ON	0.1	**0.6**	0.1	**0.7**	0.1	0.3

Table 5-8: Trends per decade for the regional average anomaly indices of SU40, TR25, R10, CDD, CWD, R95p and PRCPTOT extremes (values for trends significant at 5% level are shown in boldface while for 10% level are shown in italic)

Variable	time	All		NMON		MON	
		precis	stations	precis	stations	precis	stations
SU40	Annual	**5.4**	**9.5**	**7.2**	**13.2**	-1.1	2.5
TR25	Annual	**5.9**	**17.8**	6.8	**17.7**	2.7	**16.4**
R10	Annual	-0.7	-1.0	-1.0	-1.3	-0.5	-0.4
CDD	Annual	22.3	23.3	22.3	24.7	16.7	-30.1
CWD	Annual	-0.5	-0.3	**-0.7**	-0.4	0.0	-0.3
R95p	Annual	-19.8	-10.0	-23.7	-5.1	-19.9	-6.2
PRCPTOT	Annual	-26.9	**-36.8**	**-38.1**	-35.7	-34.5	**-56.7**

Taken together, the results show that PRECIS is capable of simulating warming in the extreme temperature statistics but with important caveats. Regional anomaly averages for all the AP stations and PRECIS (the area average obtained from the location of the stations) diurnal temperature range (DTR), very warm days (SU40), mean maximum temperature (TMAXmean), mean minimum temperature (TMIN mean), cold night frequency (TN10p), warm night frequency (TN90p), warmest night (TNx), very warm nights (TR25), cold day frequency (TX10p), warm day frequency (TX90p) and warmest day (TXx) all display trends consistent with warming (Figure 5-18). Of those indices four show the same sign of significant trends reported by PRECIS and the stations with some magnitude variations namely TX90p, TXx, SU40 and TR25. The precipitation extreme trends show trend patterns associated with decreasing precipitation total and increasing number of dry days with few indices reporting significant trends.

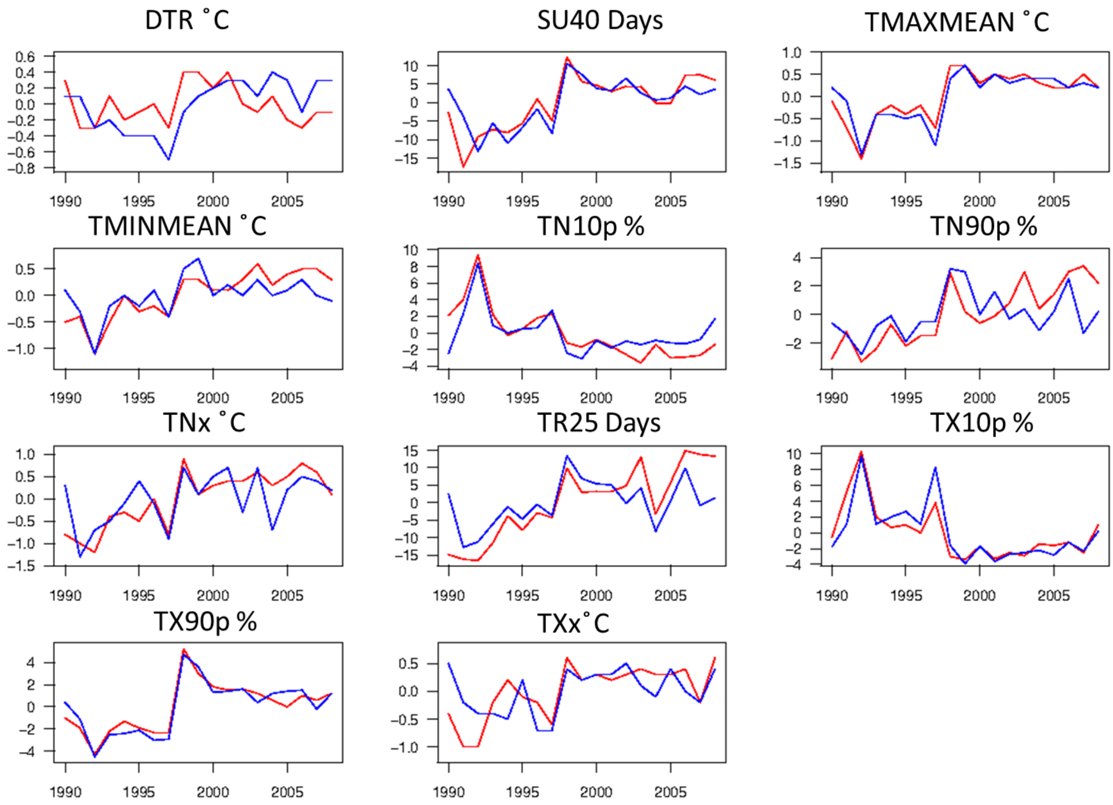

Figure 5-18: Annual All AP regionally averaged anomaly series (relative to the mean for 1990-2008) of temperature extreme indices for the stations (red) and PRECIS (blue).

For the day time temperature indices (TX10p, TX90p, TMAXmean, TXx, SU40), both PRECIS and the stations show significant trends over all and NMON regions during MA and JAS seasons. Only the TX90p index reported similarly significant positive trend for PRECIS and the stations over the MON region during MA season. In general the station trends are higher in these extremes during most seasons except MA season where the reverse is true. The annual count of days with very warm days (SU40) reported nearly two times higher trend magnitude in the stations than PRECIS over all and NMON regions.

Like the day time temperature indices, the significant trends of the night time temperature indices (TN10p, TN90p, TMINmean, TNx, TR25) for both PRECIS and the stations are reported over all and NMON regions. However these significant trends occur primarily in summer seasons (MJ and JAS). Over the MON region, both PRECIS and the stations reported significant positive trends in the TN90p and TNx during MJ season. The trend magnitudes of the PRECIS and stations show higher discrepancies for the night time temperature indices relative to the day time indices. The trends are a factor of 2 higher in the station data compared with PRECIS. PRECIS vastly underestimates the trend in warm nights over the monsoon region (2.7 compared with 16.4 days per decade).

The TMAXmean and TMINmean trends patterns lead to seasonal variations in the DTR trends especially in the stations dataset. The DTR has increased significantly in both the stations and PRECIS datasets in the MA season. However, the stations DTR trend turned significantly negative in the JAS season over all and the MON region.

In contrast to the temperature indices, there are few significant trends in the precipitation indices over the period 1990-2008. There is no report of significant similarly sign trends for both PRECIS and the stations. In general the AP region is characterized by large interannual variability in comparison to trends. Figure 5-19 shows the annual regionally averaged anomaly series (relative to the mean for 1990-2008) of precipitation extreme indices for the stations (red) and PRECIS (blue). The variability of both data sets look similar especially the sharp reduction of precipitation since 1999 but PRECIS shows higher values in 1997 affecting precipitation indices.

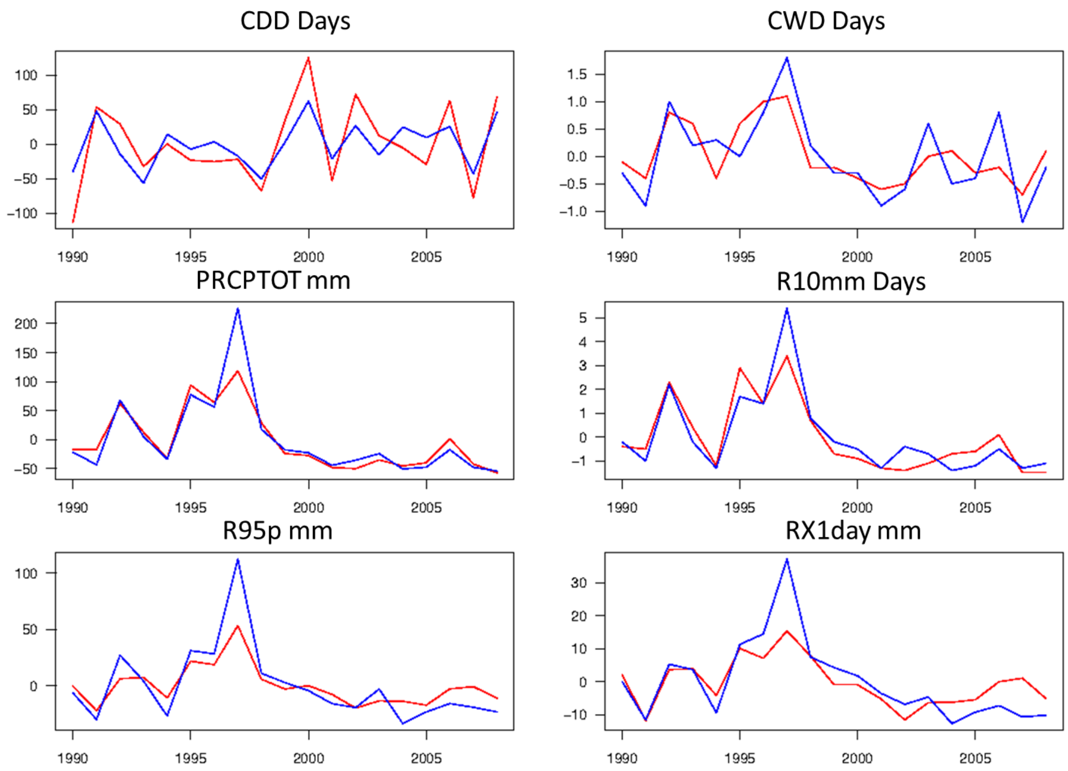

Figure 5-19: Annual All AP regionally averaged anomaly series (relative to the mean for 1990-2008) of precipitation extreme indices for the stations (red) and PRECIS (blue).

5.5. Discussion

The assessment of PRECIS's ability to simulate the annual and seasonal AP climate shows that the model captures the general mean climate patterns of the AP for both temperature and precipitation. PRECIS simulation patterns for the AP temperature and precipitation climatology are similar to other data sets results analysed for the region, including satellite derived rainfall and is therefore not confined to the observed data used in this study [*Almazroui, Nazrul Islam et al.*, 2012]. RCM fields however, have greater spatial and temporal detail, especially compared with the gridded data such as CRU where spatial interpolation may have smoothed details. Indeed, the added value of RCMs is mainly expected in the simulation of topography-influenced phenomena [*Flato et al*., 2013]. However, the model shows large biases in both temperature and precipitation variables.

In comparison with the station data, there is cold bias in northern and western AP but a large warm bias in the southern and eastern areas. The cold bias in northern AP has been noted by *Lelieveld et al*. [2012] who ran PRECIS model over the Eastern Mediterranean and the Middle East with 25 km resolution but the important warm bias has not been documented before. The model overestimates the precipitation over the southwestern areas while underestimating it over the southeastern areas.

The discrepancies between PRECIS and CRU are generally largest in regions with pronounced topography, indicating that the difference in resolution between the two datasets plays a role, and in desert regions where measurements are scarce [*Lelieveld et al.*, 2012]. *Tanarhte et al.* [2012] reported that uncertainties in observations should be considered when gridded data are used for numerical model evaluation. One problematic area they mention is the desert of Saudi Arabia due to their sparse station network where the gridded data should be used with caution. For example, using the case of Thumrait station in the Oman desert, PRECIS minus station summer maximum temperature is 0.2^{o}C. The CRU minus station summer maximum temperature difference is -10.3. The PRECIS minus CRU summer maximum temperature difference is 10.5^{o}C. We should point out that even at 25-km grid point spacing; the model resolution is probably still too coarse to fully capture the complexity of the AP topography especially at the southwestern and southeastern areas. For example the simulation indicates that the southwestern region of Saudi Arabia has the highest average annual rainfall (> 400 mm/year). The model tends to overestimate precipitation over the southwestern mountains of the AP which may well result from topography as represented by 25km spacing. Similar findings are reported over alpine mountains with 20-km resolution model [*Coppola and Giorgi*, 2010]. However the model also underestimates the annual totals over the AP southeast chain (Oman) where around 300 mm received per year based on the stations data (Saiq). One reason is the model topography underestimates Saiq elevation by 623 meters.

PRECIS simulates well the recent increase in daytime means and extremes in surface temperature over the AP. In general all the data sets agree that the significant warming is occurring in the spring and late summer. Spatially, PRECIS replicates the NMON region trends better than the MON trends, although the latter are not as spatially coherent in the observed either. The model matches the magnitude of the observed trends well in the spring but during late summer the trends are 50% relative to the CRU and the stations data set trends. More research is required to investigate PRECIS' underestimation of the late summer trends. One possible related issue might be the model cold bias detected over western and northern area as noted earlier.

The highest discrepancies between the observed station and model trends are seen in the nighttime means and extremes. Although the model shows good agreement with the stations when reporting significant trends during spring and summer (early and late), it underestimates the trends magnitude by nearly 50 % over the AP region and the NMON region. The model fails to simulate the large increase of nighttime temperature over the

MON region. The persisted large cold bias area over western (northwestern and southwestern) areas may play a role in lessening the trends magnitude and may be related to issues with cloud simulation in the model. The largest difference in trends between PRECIS and the stations over the MON region is for the very warm night's index where PRECIS trends are smaller by a factor of 6 compared with the stations.

The station trends show extensive spatial extent of warming especially in the northern areas while PRECIS is confined mostly to eastern areas of AP while CRU features warming from east to west along central Arabia. The station trends patterns look similar to those found in *AlSarmi and Washington* [2011] and *AlSarmi and Washington* [2013] but the trend magnitudes of this period 1990-2008 are much higher. The meridional aligned temperature trend gradients in the northern areas are warming more strongly than the southern areas and this is in line with *AlSarmi and Washington* [2011], *Lelieveld et al*. [2012] and *AlSarmi and Washington* [2013].

In the PRECIS simulations, the rainfall trend (Table 5-5) over all AP (-36.4 mm per decade) and to the NMON region (-42.6 mm per decade) is close to that reported by *Almazroui et al*. [2012] who found a significant decreasing trend (at 95% level) at a rate of 35.1 mm per decade during the period 1994–2009 over Saudi Arabia. *AlSarmi and Washington* [2011] reported that the recent increase of the maximum temperature over the AP during MA season might be due to the sensitivity of the maximum temperature to the decrease of the precipitation during this wet seasons. To investigate this, the PRECIS annual and seasonal trends of the specific humidity fields have been calculated (Figure 5-20). The plots show a clear significant reduction of the specific humidity over the region especially in MA season over the north and east/southeast AP. This supports the finding that dry lands have experienced a negative association between precipitation and temperatures, such that warmer (colder) years have been drier (wetter) [*Hulme*, 1996; *P. D. Jones and Reid*, 2001]. *Willett et al.* [2010] found that at smaller scales in water-limited regions, changes in specific humidity are strongly inversely correlated with total changes in temperature. Interestingly a small area of significant specific humidity increase is clearly located over the Empty Quarter desert which ties nicely with a similar area of significant increase of minimum temperature trends especially during MJ, JAS and ON seasons (Figure 5-15). Possible reasons for such localised specific humidity increase include change in the area dynamics and some unclear mesoscale topographical characteristics.

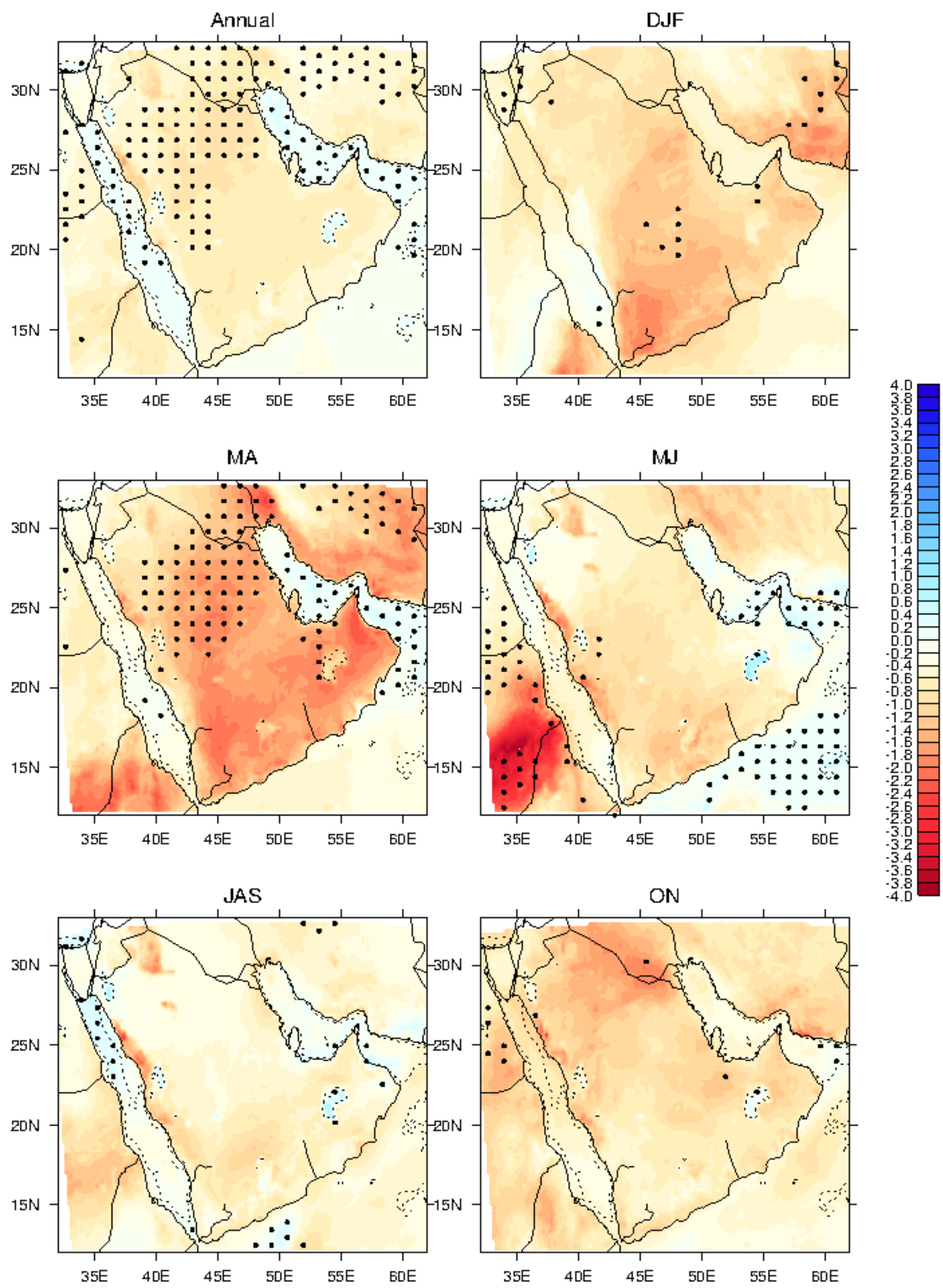

Figure 5-20: Specific humidity annual and seasonal trends plots of PRECIS for the period 1990-2008 (grids of trends significant at 5% level are shown with black dots). The dashed line represents the zero value.

The station extremes indices patterns suggest the sensitivity of these trends to seasons. During MA season the extreme indices trends are higher in the day time relative to night time indices. However during summer seasons (MJ and JAS) and in many cases autumn, the night time indices trends are higher than day time indices trends. The stations trends are notable in the night time extremes especially over the MON region. The change of the stations regional average DTR trend from positive (significant) during MA season to negative (significant) during JAS season is consistent with the increase of the minimum temperature and the lower increase 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, may itself be a response to warming. To investigate this, annual and seasonal Mean Sea Level pressure (MSLP) trends over the AP were obtained from PRECIS simulation for the period 1990-2008 (Figure 5-21). In general the pressure is falling during most of the seasons but particularly in the early summer (MJ) season which reported the highest number of grid points with large and significant MSLP decrease, as might be expected from a deepening of the heat low. This alone would change the pressure gradient over southern Arabia coast. For sake of comparison the ERA-Interim MSLP annual and seasonal fields have been obtained for the period 1990-2008 and trends fields calculated (Figure 5-22). The trends plots of ERA-Interim data show good agreement with PRECIS simulation trends as the pressure fall in all seasons especially the summer seasons over

AP. One striking different is that the number of grids with significant MSLP fall is higher in ERA-Interim than PRECIS especially during JAS and ON seasons. The SST trend plots indicate that significant cooling has occurred during 1990-2008 over south AP coast especially in MA, MJ and JAS seasons (Figure 5-23).

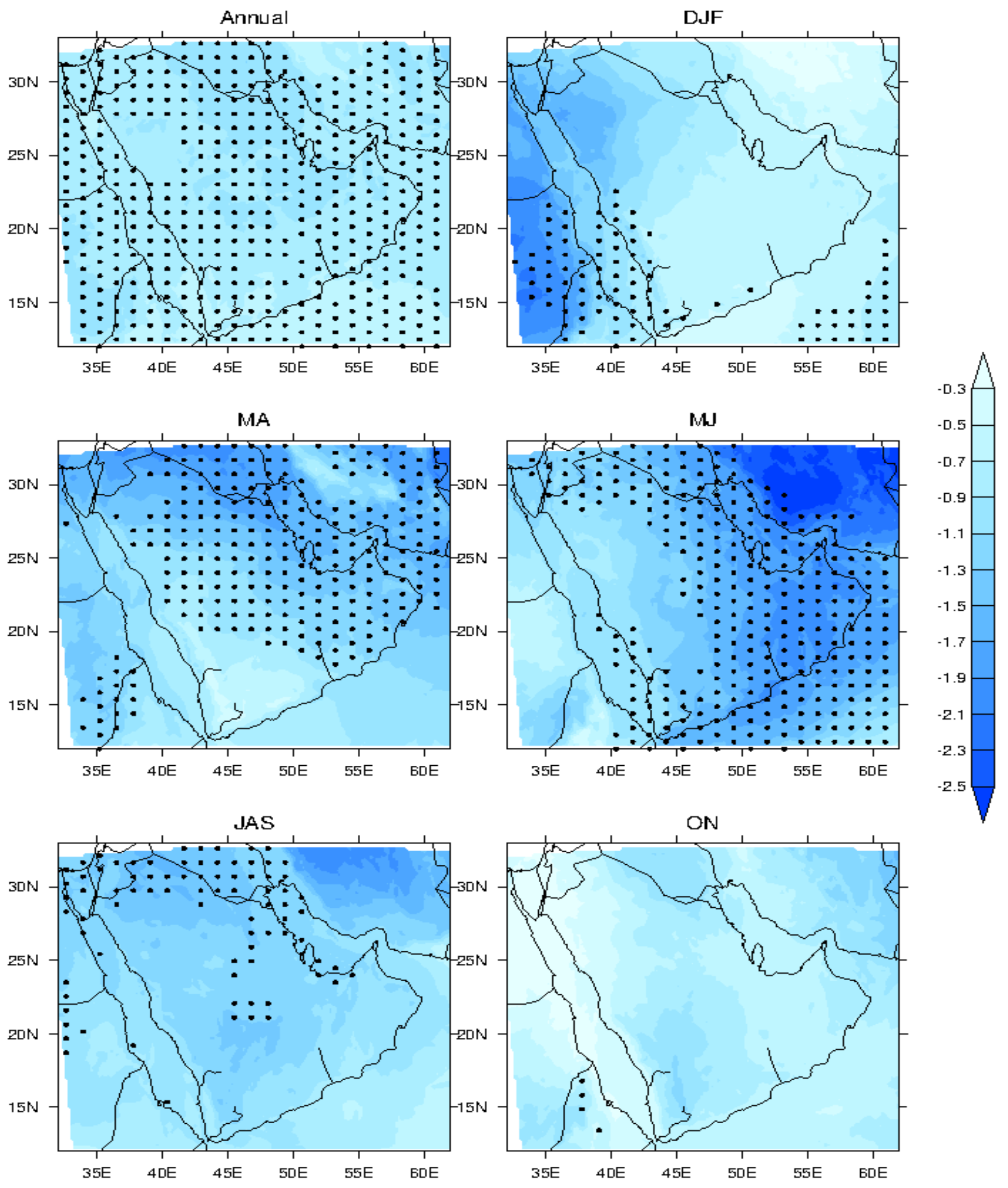

Figure 5-21: Mean Sea Level Pressure annual and seasonal trends plots of PRECIS for the period 1990-2008 (grids of trends significant at 5% level are shown with black dots).

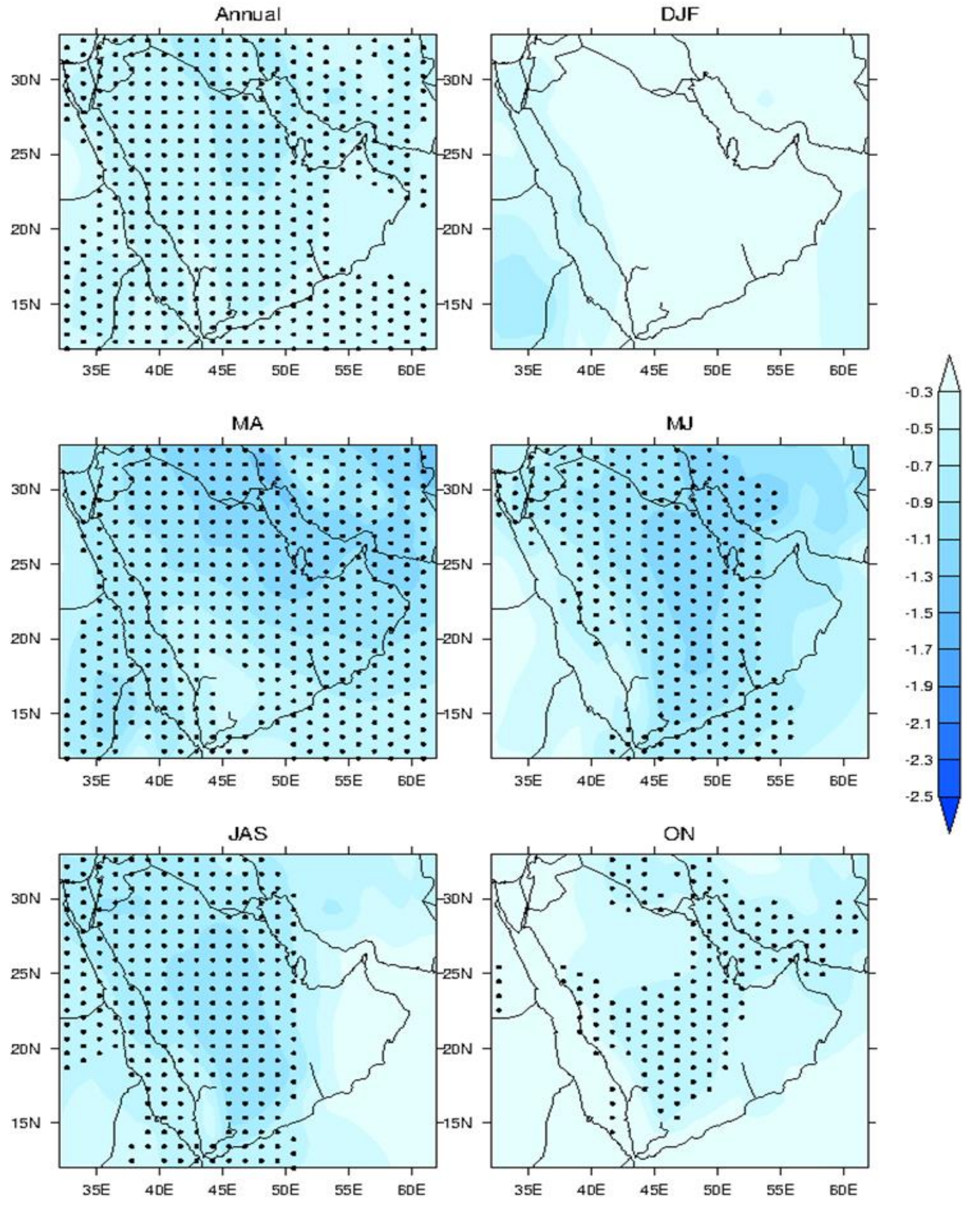

Figure 5-22: Mean Sea Level Pressure annual and seasonal trends plots of ERA-Interim for the period 1990-2008 (grids of trends significant at 5% level are shown with black dots).

Based on the station data sets, the minimum temperature highest significant warming occurs over the AG and Oman coast especially in the MA, MJ, JAS and ON seasons. In general PRECIS agrees with the stations more than with CRU. It is worth to mention that the area averages obtained for the stations, PRECIS and CRU datasets are all based on the station locations. To investigate whether the semi closed AG Sea Surface Temperature (SST) has an influence on the air temperature over the stations surrounding it, the PRECIS SST annual and seasonal fields trends have been analysed (Figure 5-19). The plots indicate that the AG has warmed significantly during 1990-2008 in the MJ and JAS seasons. During ON season, the significant warming concentrated over Oman coast and northern AG. The highest SST in the world is found in the Arabian Gulf with summer maxima of 36.0℃ or more [*Jackson*, 1988]. The AP region is bounded by four adjacent seas; Arabian Sea (AS), Red Sea (RS), Gulf of Oman (GoO) and Arabian Gulf (AG) so any variations in these SSTs might cause changes in the regional climate system. In addition, the fact that the AG is being shallower than other seas as the AS and the RS makes the AG SSTs to warm much faster. Other possible mechanism which might influence both the region SSTs and the coastal stations is related to the recent decrease of total clouds amount as simulated by PRECIS (not shown). This might lead to an increase in both SSTs and air temperature. These possible mechanisms might explain why the minimum air temperature trends over AG during 1990-2008 reported the highest significant values in the region.

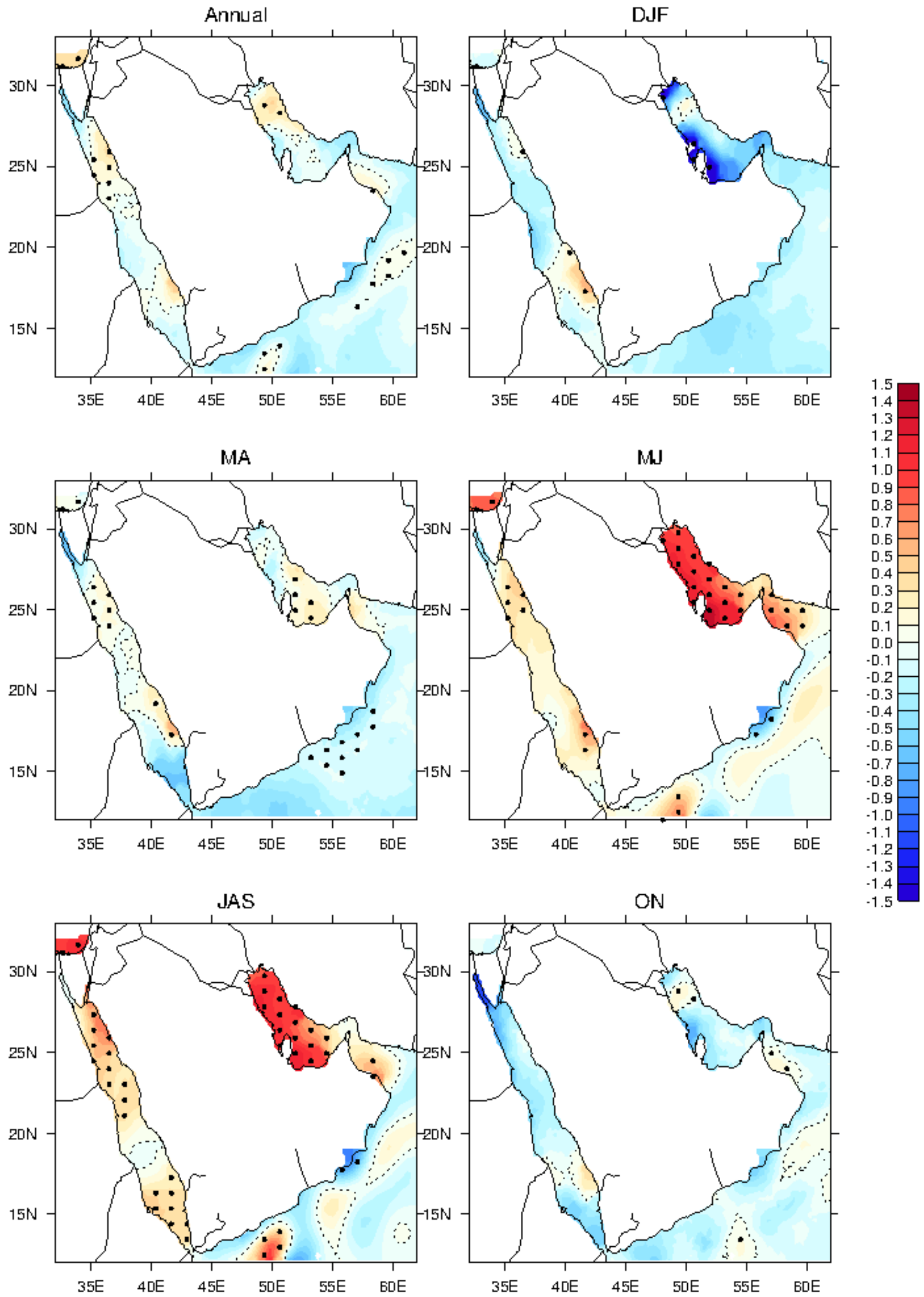

Figure 5-23: Sea Surface Temperature annual and seasonal trends plots of PRECIS for the period 1990-2008 (grids of trends significant at 5% level are shown with black dots).). The dashed line represents the zero value.

5.6. Conclusion

This study examined the performance of a regional climate model, based on PRECIS, over the Arabian Peninsula for the period 1990-2008 using ERA-Interim boundary conditions. Evaluation of PRECIS against gridded observational dataset (CRUTS3.2) and the available AP meteorological stations of temperature and precipitation found that PRECIS appears to generally reproduce the regional mean climate, the temporal evolution of the regional temperature and precipitation and the temporal evolution of the regional extremes. However there are large biases in relation to some observed data sets.

The results show widespread significant increasing trend of temperature associated with widespread decreasing trend in precipitation. All datasets agree in direction but often not in magnitude. Similar findings reported over East Mediterranean and the Middle East [*Tanarhte et al.*, 2012]. PRECIS displays a negative bias in temperature thought the year mostly over southwest, west and northwest AP. It displays positive bias over the southeast and south AP relative to both stations and CRU datasets. For the precipitation, PRECIS overestimate the precipitation over the southwestern mountains. However, it underestimates the precipitation over the southeastern mountains. These bias likely relate to the model topography in areas of steep topography [*Evans*, 2010].

The station data, CRU and PRECIS data agree on the meridional gradient patterns of the daytime (maximum) temperature trends where the northern areas trends are higher and more significant than the southern areas. The nighttime (minimum) temperature trends show more variations among the three datasets especially PRECIS being uniquely colder. However, the significant increase of the AG SST during MJ and JAS as apparent from PRECIS SST trends could explain why the stations minimum temperature trends are high and significant in theses seasons.

PRECIS simulates well the daytime extremes indices significant increase during MA seasons but underestimate the trends during late summer (JAS). For the nighttime extreme indices, PRECIS underestimates the trends magnitude by nearly 50% over the AP region and the NMON region. The model fails to simulate the large increase of nighttime temperature over the MON region.

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We wish to express our gratitude to all the AP NMSs for providing the climate data. Special thanks to the Ministry of Transport and Communication in the Sultanate of Oman for sponsoring the lead author's doctorate degree of the Arabian climate trends, variability and change. The authors encourage the research community to contact directly the relevant AP NMSs in order to obtain the data.

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Chapter 6: Circulation changes over the Arabian Peninsula associated with recent climate change

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Submitted to *Global and Planetary Change*

Abstract

This study investigates links between local atmospheric circulation and Sea Surface Temperature (SST) and teleconnections associated with recent climate extremes changes in the Arabian Peninsula (AP). A high resolution (25 km) Providing Regional Climates for Impact Studies (PRECIS) model forced by ERA-Interim reanalysis is used to derive a set of composite difference maps for some surface and upper level atmospheric circulation parameters and SSTs of the adjacent seas between two periods 1990-1997 and 1998-2008. The AP experienced a climate jump in 1998 associated with abrupt increase of the regional temperature and a decrease in precipitation. The drier conditions which have occurred over much of Arabia in winter and spring are associated with significant increases in the 500 hPa height and associated significant increase in subsidence at the same level, both of which could be expected to decrease conditions favourable for precipitation. Additionally, changes in low level circulation at 925 hPa leads to drier air advection from west Asia and northern Arabia. This could be argued to inhibit cloud formation, leading to below average precipitation and, as a consequence, increase daytime temperature extremes, consist with the observed especially in spring. The composite difference maps of the SST and specific humidity show parallel increase

over the adjacent seas especially the Arabian Gulf (AG) and Red Sea (RS) could be responsible for increasing the nighttime temperature over the AG during summer. It appears that both local and remote changes play roles in influencing the climate variability and trends during the last few decades. We show that the relationships of the climate extremes with El Niño/Southern Oscillation (ENSO) are stronger than North Atlantic Oscillation (NAO), North Atlantic Caspian Sea Pattern (NCP) and Indian Ocean Diploe (IOD), with the exception of winter when NCP relationships are stronger.

6.1. Introduction

Anticipating the impact of climate change on a region involves many steps, not least in the climate science sphere. Whilst extensive parts of North America and Europe have benefited from analyses of the nature of observed climate change [*Freiwan and Kadioglu*, 2008] which often marks out the first step in such regionally-based research, work has only recently begun in the case the Arabian Peninsula (AP). A key step in the process of understanding climate change has been the analysis of observed monthly climate parameters, such as rainfall and temperature [*Kwarteng et al*., 2009; *AlSarmi and Washington*, 2011; *Almazroui et al.*, 2012; *Almazroui, Nazrul Islam et al*., 2012]. This, in turn, has evolved into analyses of how observed extreme climate parameters are changing [*Zhang et al., 2005; AlSarmi and Washington*, 2013; *Donat et al*., 2013] and the capability of regional models, thought to be important to climate change scenario development [*Coppola and Giorgi*, 2010] in reproducing that observed change.

Key results emerging from this work are the general pattern of the AP temperature parameters trend during the last few decades is one of warming. The highest significant increase has occurred in the minimum temperature over the AG coastal stations. The highest significant increase for both maximum and minimum temperatures has occurred in spring and summer. The precipitation trends are generally decreasing with few significant values [*AlSarmi and Washington*, 2011]. Furthermore, the results indicate a general decreasing trend of cold temperature extremes and increasing trends of the warm temperature extremes [*AlSarmi and Washington*, 2013]. The PRECIS model simulation captures the mean climatic conditions and patterns, the increasing temperature tendency, as well as the decreasing precipitation observed in the last two decades [*AlSarmi and Washington*, 2014]. However, the model suffers large biases. There is a clear need to understand the circulation anomalies associated with the documented changes in the AP climate. Doing so provides insights into the mechanisms responsible for the change and the extent to which such mechanisms link with known patterns of natural variability. *Alsarmi and Washington* [2011; 2013] have documented a notable inverse relationship between a region wide index of AP rainfall and temperature. This relationship is evident also in the correlation between mean annual AP maximum temperature and rainfall (Figure 6-1) which shows a distinct jump in 1998. The shift is also evident in homogeneity tests of station data [*AlSarmi and Washington*, 2011; *AlSarmi and Washington*, 2013].

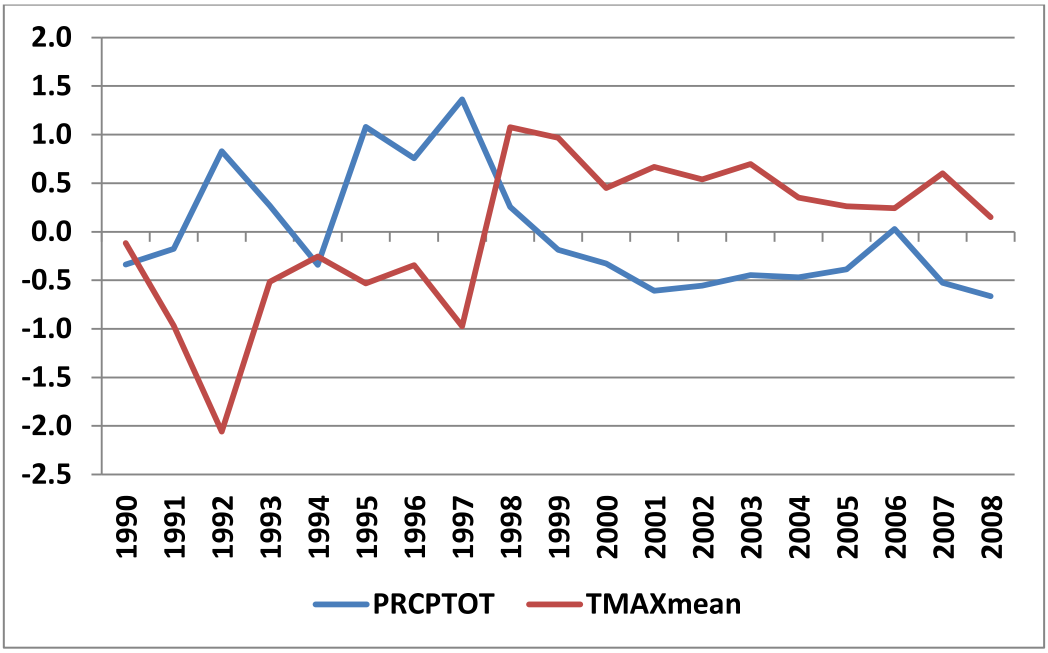

Figure 6-1: All Arabian Peninsula standarized annual time series for both TMAXmean and total precipitation for the period 1990–2008**.**

The first aim of this work is to analyse the circulation anomalies associated with the 1998 climate jump. In particular, we consider mid-tropospheric circulation changes as revealed by 500 hPa geopotential and vertical velocity fields. We go on to analyse low level (925 hPa) winds, specific humidity and total cloud, SST and Mean Sea Level Pressure (MSLP). Data from a high resolution (25 km grid spacing) regional model, PRECIS, forced with boundary conditions from ERA-Interim over the period 1990 to 2008, are used as the basis for studying the circulation changes. The second aim of this paper is to provide insights into the association between the AP climate extremes indices and key modes of climate variability, such as El Niño Southern Oscillation (ENSO), which experienced the largest observed phase of El Niño in the year of the climate shift, namely 1998 and the Indian Ocean Dipole (IOD). Additionally, the association with two mid-latitudinal modes, North Atlantic Oscillation (NAO) and North Atlantic Caspian Sea Pattern (NCP) will be considered.

The paper is organized as follows: in section 2 the data used for the analysis are presented, while in section 3 there is a description of methodology. Section 4 illustrates the main results and section 5 discusses the analysis findings and section 6 provides the conclusion.

6.2. Data

The AP meteorological stations records of daily and monthly precipitation and temperature (maximum, minimum and mean) during the period 1990-2008 were provided by the Meteorological Services of most the AP countries. Oman provided 24 stations, Saudi Arabia 11, UAE 4 with 1 station from each of Qatar, Bahrain and Kuwait. These data have recently been analysed by *Alsarmi and Washington* [2011; 2013].

6.2.1. Quality Control of station data (QC) and homogeneity test

Data were quality controlled for false values and outliers using the methods described in detail in *Alsarmi and Washington* [2011; 2013]. 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 and Sur [*AlSarmi and Washington*, 2011] and the region as a whole. We decided to exclude Seeb station due to the station relocation in 1994 following *AlSarmi and Washington* [2013]. Although Seeb temperature variables have been excluded from the analysis but we used Seeb precipitation data as they deemed to be correct and homogeneous.

Homogeneity testing of the station data used in this paper has been reported in *Alsarmi and Washington* [2013]. Here we focus particularly on the homogeneity jump in 1998 which is key to the sampling period used in the regional model circulation data analysis. Table 6-1 summarizes significant changepoints for 1998 the strongest El Niño year on record, namely 1998.

Table 6-1: Details of significant detected changepoints during the year 1998 showing stations, variables and dates.

Year	Station	Variable	Date (year.month)
1998	Dubai	maxT	19980100
	Ras Alkhaimah	maxT	19980200
	Sharjah	maxT	19980200
	Riyadh	maxT	19980500
	Al-Taif	maxT	19980400
	Hail	maxT	19980400
	Khamis Mushait	maxT	19980200
	Bahrain	meanT	19980100
	Dubai	meanT	19980100
	Hail	meanT	19980500
	Bahrain	minT	19980500
	Khasab	Precip	19980300
	Ras Alkhaimah	Precip	19980300
	Doha	Precip	19980100

After quality control and the homogeneity testing evaluations, 10 stations were retained from Saudi Arabia, 8 stations from Oman (the remaining 16 stations were mainly excluded because of short record), 3 from UAE, and 1 station from Qatar, 1 from Bahrain and 1 from Kuwait. The final list of stations is summarized in Table 6-2 where details of station locations, name and missing percentage (%) during the period 1990-2008 are listed. The total number of stations used for this analysis is 23 (24 for precipitations including Seeb). The stations locations are shown in Figure 6-2. To better represent the different geographical conditions of the AP, the variables were standardized, using the period 1990–2008 as reference.

Table 6-2: Stations location, name, elevation and missing percentage (%) during the period 1990-2008

Country	Station	WMO	Latitude	Longitude	Elevation(m)	Variable			
						MaxT	MinT	MeanT	Precipitation
Oman	Khasab	41240	26 20	56 23	33	3.5	3.5	1.8	2.2
	Sohar	41246	24 28	56 38	3.6	0	0	0	0
	Saiq	41254	23 04	57 38	1755	0.4	0.4	1.3	0.4
	Seeb	41256	23 35	58 17	8.4	nil	nil	nil	0
	Sur	41268	22 32	59 28	14	0	0	0	0
	Masirah	41288	20 40	58 54	19	0	0	0	0
	Thumrait	41314	17 40	54 01	467	0	0	0	0
	Salalah	41316	17 02	54 05	22	0	0	0	0
UAE	Ras Alkhaimah	41184	25 37	55 56	31	0	0	0	0
	Dubai	41194	25 15	55 20	5	0	0	0	0
	Sharjah	41196	25 20	55 31	33	0	0	0	0
Bahrain	Bahrain	41150	26.16	50.39	2	0	0	0	0
Qatar	Doha	41170	25.15	51.34	11	0	0	0	0
Kuwait	Kuwait	40582	29.22	47.59	6.1	5.3	0	4.8	5.7
Saudi Arabia	Tabuk	40375	28 23	36 36	768.1	0	0	0	0
	Hail	40394	27 26	41 41	1001.5	0	0	0	0
	Dhahran	40416	26 16	50 10	16.8	0	0.9	0	0
	Al-Madinah	40430	24 33	39 42	635.6	0.9	1.8	0.9	0.9
	Riyadh	40438	24 42	46 44	619.6	0	0.4	0.4	0.4
	Jeddah	41024	21 42	39 11	16.9	0.4	0.4	0.4	0.4
	Al-Taif	41036	21 29	40 33	1452.8	0.9	0.9	0.9	0.9
	Bisha	41084	19 59	42 38	1162	0	0	0	0
	Khamis Mushait	41114	18 18	42 48	2055.9	0	0	0	0
	Gizan	41140	16 53	42 35	7.2	0.4	0.4	0.4	0.4

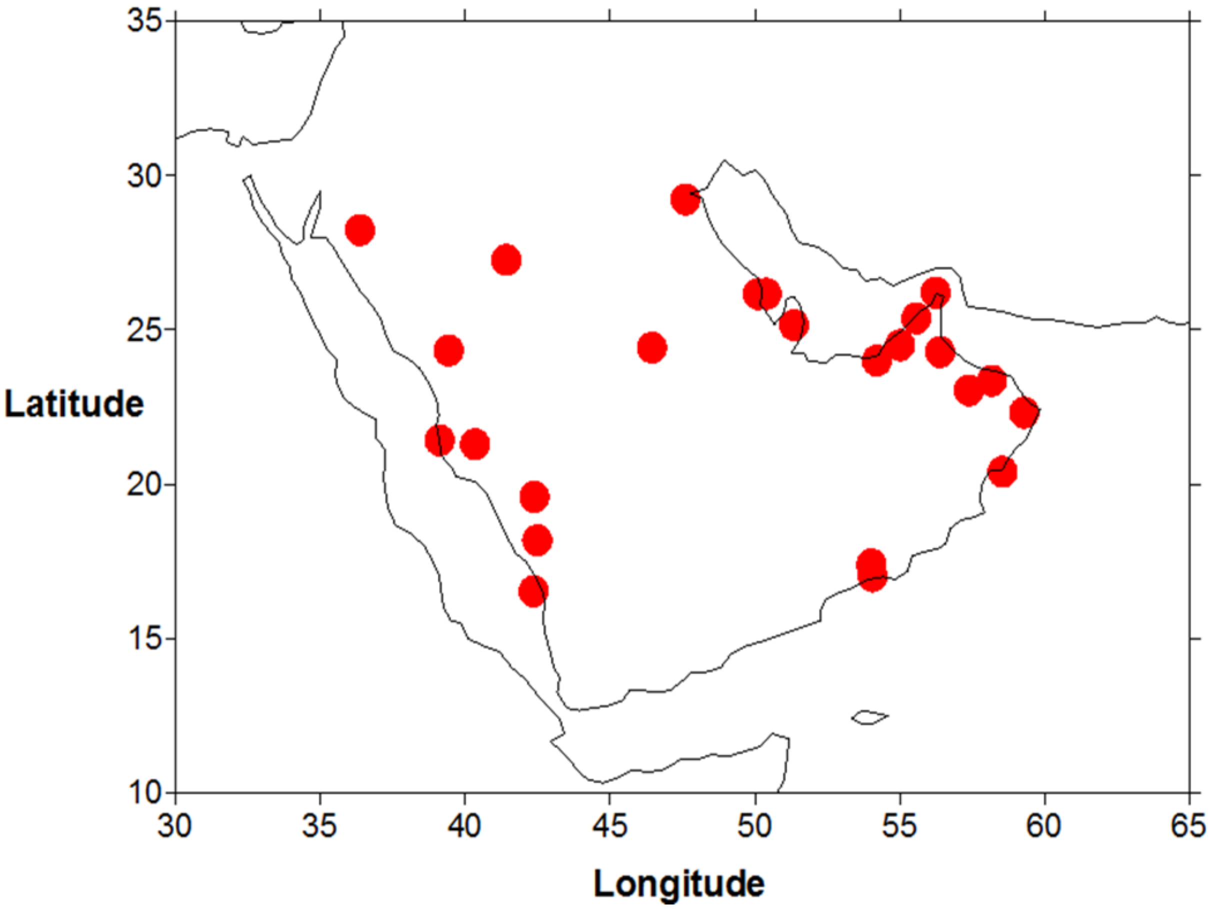

Figure 6-2: The distribution of 24stations used in this study in the Arabian Peninsula.

6.2.2. PRECIS simulations

Simulations of the AP climate were performed using the PRECIS regional climate model HadRM3P model [*Jones et al*., 1995] for the period 1990-2008 in order to investigate the regional climate associated with the apparent change in the AP climate.

PRECIS applies the same formulation of the climate system as its parent AOGCM which is HadCM3. The PRECIS climate model is an atmospheric and land surface model of limited area and high resolution which is locatable over any part of the globe. More details about the model could be found in *Jones et al.* [2004]. HadRM3P has been used with horizontal grid spacing of 25 km with 19 levels in the atmosphere (from the surface to 30 km in the stratosphere) and four levels in the soil. For the model SSTs, the Hadley Centre has used the observed SSTs and sea-ice (on a 1° grid) with an atmosphere-only GCM for the present-day simulation (which then provides lateral boundary conditions for the RCM present-day simulation). The SSTs and sea-ice fractions are taken from a combination of the monthly HadISST4.3 and weekly NCEP4.4 observed datasets.

More realistic land-sea mask topography is expected at 25km resolution. The models capture the basic features of the main AP mountain chains (the W/SW and SE) and shape, although this is still generally smoothed especially over Oman Mountains (Figure 6-3). Table 6-3 summarizes the elevation bias of the model relative to the actual stations elevations. Most of the elevation bias either positive or negative occurred in the range from 10 to 100 metres. The highest bias values occurred either over the high lands stations or those close to them. The highest positive elevation bias with value more than 200 metres occurs over Oman (Salalah and Sur) and over Saudi (Al-Taif and Bisha) while the highest negative elevation occurred over Oman mountains (Saiq, -623.1 metres). The performance of PRECIS over the AP has been investigated by *AlSarmi and Washington* [2014].

Table 6-3: Elevation bias of the PRECIS model (25 km resolution) and the actual stations elevations in metres.

Country	Station	Elevation bias (m)
Oman	Khasab	61.219
	Sohar	81.339
	Saiq	-623.1
	Seeb	57.784
	Sur	324.35
	Masirah	-19
	Thumrait	34.43
	Salalah	232.34
UAE	Ras Alkhaimah	-9.594
	Dubai	16.189
	Sharjah	-11.811
Bahrain	Bahrain	-2
Qatar	Doha	28.172
Kuwait	Kuwait	133.65
Saudi Arabia	Tabuk	142.58
	Hail	-28.31
	Dhahran	-3.163
	Al-Madinah	18.3
	Riyadh	197.49
	Jeddah	47.509
	Al-Taif	239.7
	Bisha	453.6
	Khamis Mushait	140.2
	Gizan	-7.24

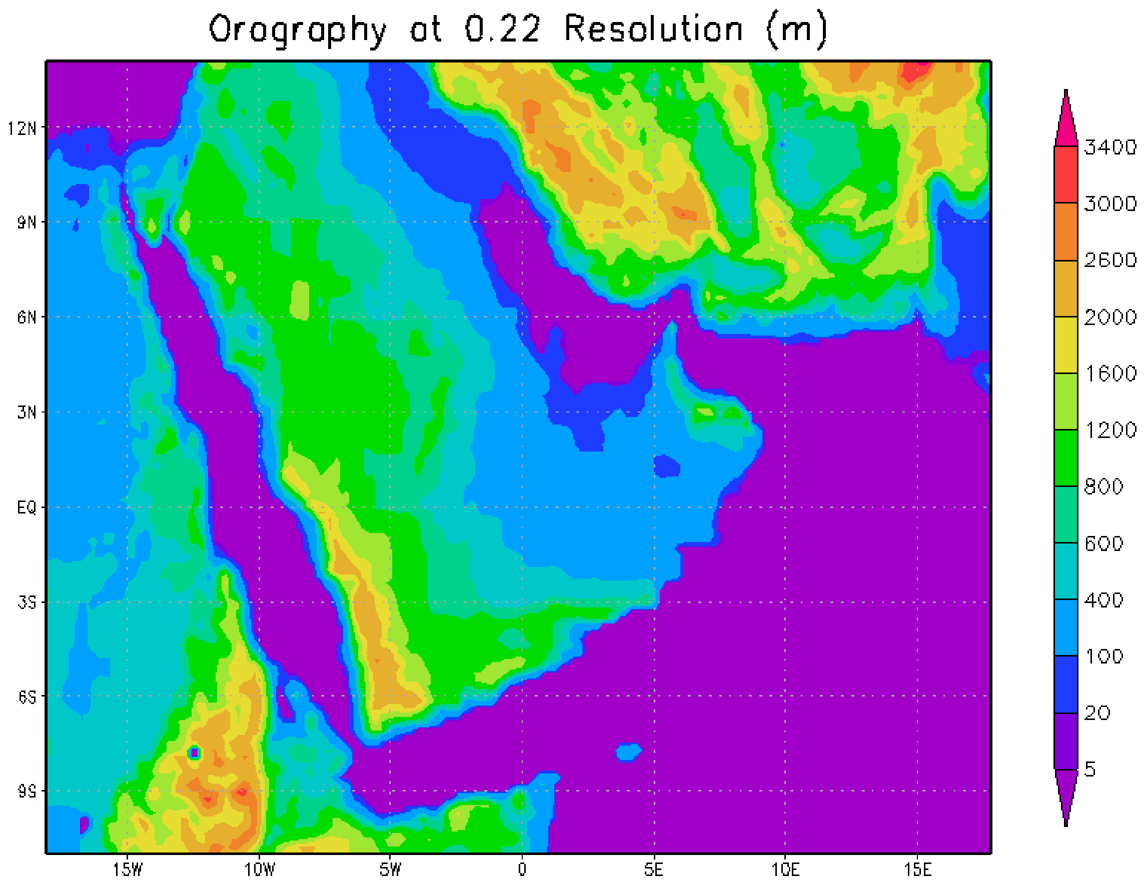

Figure 6-3: PRECIS topography (m) of the Arabian Peninsula at 25 km resolution.

6.2.3. Climate variability modes

For the NAO and ENSO (Nino3.4) indices, we use the monthly timeseries over the period 1970-2008 which are compiled by the Climate Prediction Centre of National Oceanic and Atmospheric Administration (NOAA) USA and freely available on the web at the URL http://www.cpc.noaa.gov/data/indices. The IOD monthly timeseries were obtained from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC, http://www.jamstec.go.jp/frsgc/research/d1/iod/). The NCP monthly timeseries have constructed following the study by *Kutiel et al.* [2002]. For all the four indices, the monthly anomalies were computed by subtracting the monthly climatological means based on the 1990–2008 climatology from the values, and normalized by dividing each record by the corresponding monthly standard deviation. Annual and seasonal standardized timeseries were then computed.

6.3. Methods

6.3.1. Extremes indices calculations

RClimDex software was used to calculate climate indices from the daily observed station data with an emphasis given to high temperatures and heavy rainfall. Two precipitation indices and ten temperature indices were calculated following *AlSarmi and Washington* [2013]. Table 6-4 summarizes the temperature and precipitation climate extreme indices used in this study. A base period of 1990-2008 has been used for calculating the percentile based indices. Stations to be included in the analysis have at least 18 years of data within this base period and pass the QC and homogeneity tests.

Table 6-4: List all the ETCCDI climate indices calculated by RClimDex used in this study.

ID	Descriptive name	Definitions	UNITS
SU40	Very warm days	Annual count when TX(daily maximum)>40ºC	Days
TR25	Very warm nights	Annual count when TN(daily minimum)>25ºC	Days
TXx	Warmest day	Monthly maximum value of daily maximum temperature	^{o}C
TNx	Warmest night	Monthly maximum value of daily minimum temperature	^{o}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	^{o}C
TMINmean	Mean minimum	Monthly mean value of daily minimum temperature	^{o}C
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR>=1mm)	mm

6.3.2. Standardized Area Averaging

Regionally standardized series for each extreme index has been derived by first normalizing each temperature and precipitation station, and then averaging all temperature and precipitation records for the time period 1990–2008. The data were normalized to minimize the probable topographical effects. Furthermore, in addition to the calculation of all the region time averages, two more subregional time series were produced, namely the nonmonsoonal region (north of 20°N) and the monsoonal region (south of 20°N) following *AlSarmi and Washington* [2011]. The regional average indices time series over 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 1990-2008 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.

6.4. Results

Figure 6-1 presents the time series of the annual regional standardized TMAXmean and PRCPTOT extreme indices departures for the period 1990–2008. There is a clear negative correlation ($r=-0.62$, $p<0.01$) as reported by *Alsarmi and Washington* [2011]. Also evident is the jump from mostly negative TMAXmean anomalies to positive TMAXmean anomalies in 1998, coincident with the switch in total precipitation anomalies from strongly positive to weakly positive or negative and coincident with 58% of the significant changepoints in the homogeneity test reported earlier.

6.4.1. PRECIS atmospheric circulation composite difference maps

To investigate this further, we first analyse the regional model circulation differences between the periods 1990-1997 inclusive and 1998-2008 inclusive. Atmospheric circulation and SST difference composite maps.

6.4.1.1. 500 hPa Geopotential height and vertical velocity

The mean difference composites of annual, DJF and MA 500 hPa geopotential height between the period 1990-1997 and 1998-2008 (Figure 6-4), shows significant increase in the pressure over almost all the AP except the southern part of the Arabian Sea (AS) for the latter period compared with the former. The largest differences (>24 gpm) occur over northern, northeastern and northwestern AP during both DJF and MA. In MJ, an area of significant increase of geopotential height develops over Iran, with a ridge extending over most the AP especially at the eastern and northeastern areas. An area of increasing geopotential height of limited spatial extent in terms of significance develops over northern

AP in the JAS. In Autumn (ON) the pressure increases over most of the domain but is significant only over the Sudan.

Figure 6-5 shows the annual and seasonal mean difference of the 500 hPa vertical velocity field in ms^{-1}. It is evident that subsidence at 500 hPa increases significantly over most Arabia during the annual, winter and spring seasons especially over the southern half of the region. Most of the significant subsidence occurs in MA over Oman and Emirates with values exceeding -0.0004 ms^{-1}. A pronounced difference is clearly seen in the MJ season where areas located south of 20° N (mostly Oman) witness significant enhanced uplift of more than 0.0002 ms^{-1}. During JAS and ON there is no significant difference in this field other than a small area located north Saudi and Jordan where air is significantly rising during JAS season.

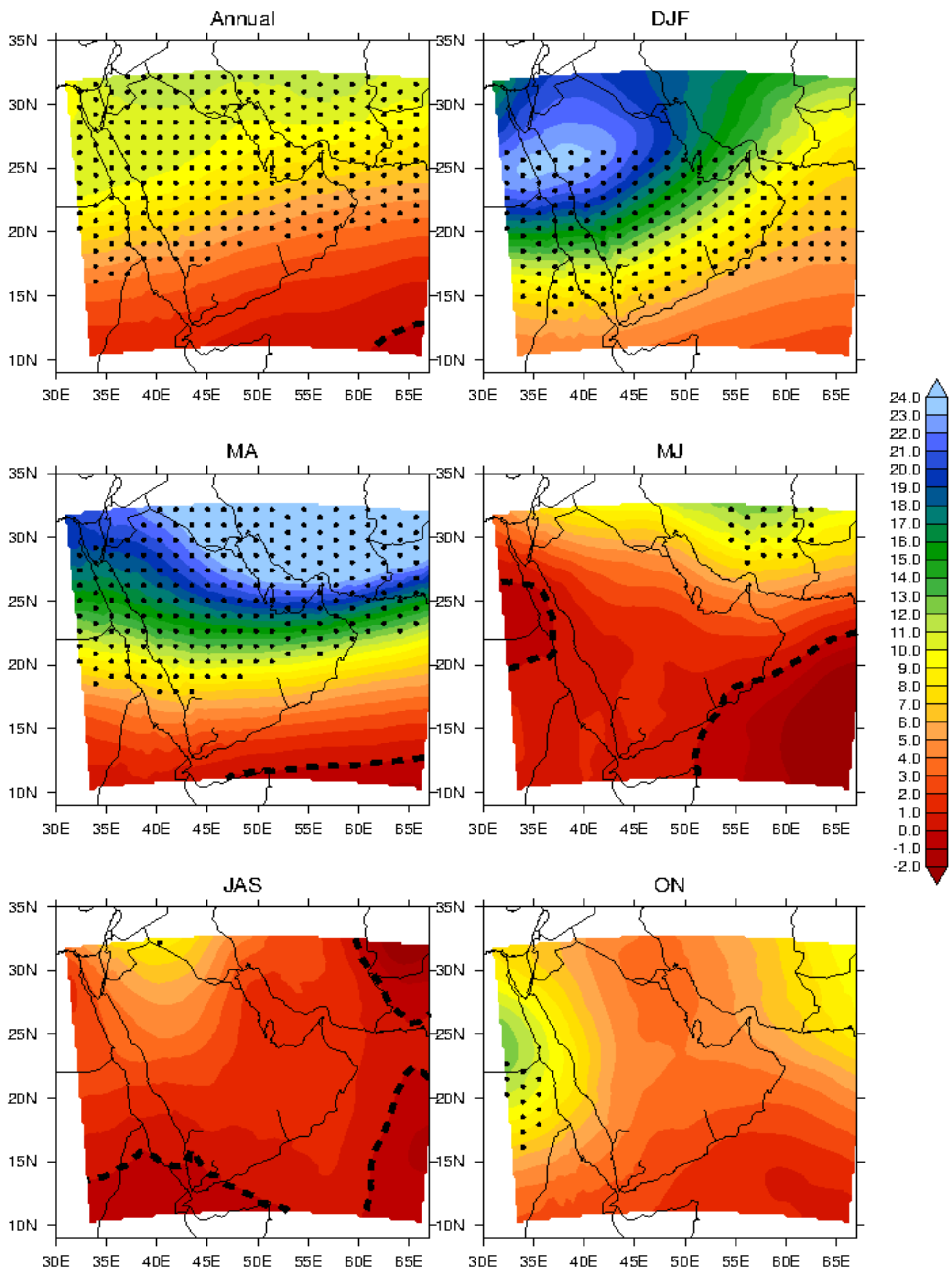

Figure 6-4: PRECIS Differences (m) between geopotential height at 500 hPa in annual, DJF, MA, MJ, JAS and ON seasons, 1998-2008 composite mean minus 1990-1997 composite mean (grids of significant difference at 5% level are shown with black dots).

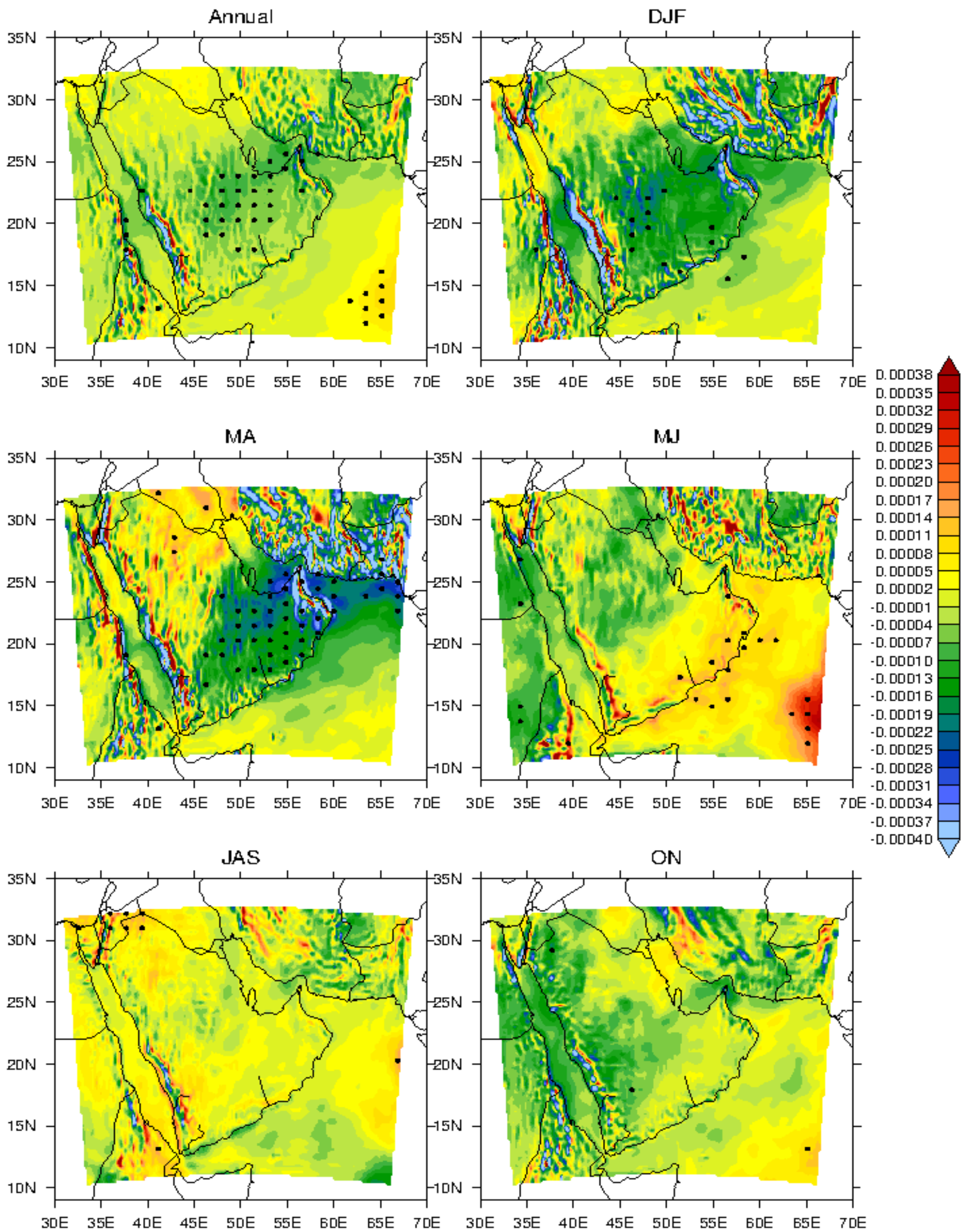

Figure 6-5: Same as Figure 4 but for vertical velocity (ms^{-1}) at 500 hPa.

6.4.1.2. 925 hPa winds and specific humidity

The mean differences in annual and seasonal 925 hPa vector wind and specific humidity (gkg^{-1}) between 1998-2008 and 1990-1997 are shown in Figure 6-6 and 6-7 respectively. The annual mean difference shows significant enhanced southwesterly winds over the Arabian Sea (AS) while the specific humidity decreases significantly over most large parts of northern and central Arabia. The season of greatest change in winds is MJ which shows a widespread region of strengthened monsoon flow over the AS which appears to be responsible for much of the annual average change. JAS features an anomalous southerly flow over the central area of the AP, but this is sparsely significant. Key changes in specific humidity occur in MA with widespread drying over central and eastern AP. This continues in MJ over central AP in a band aligned from southwest to northeast.

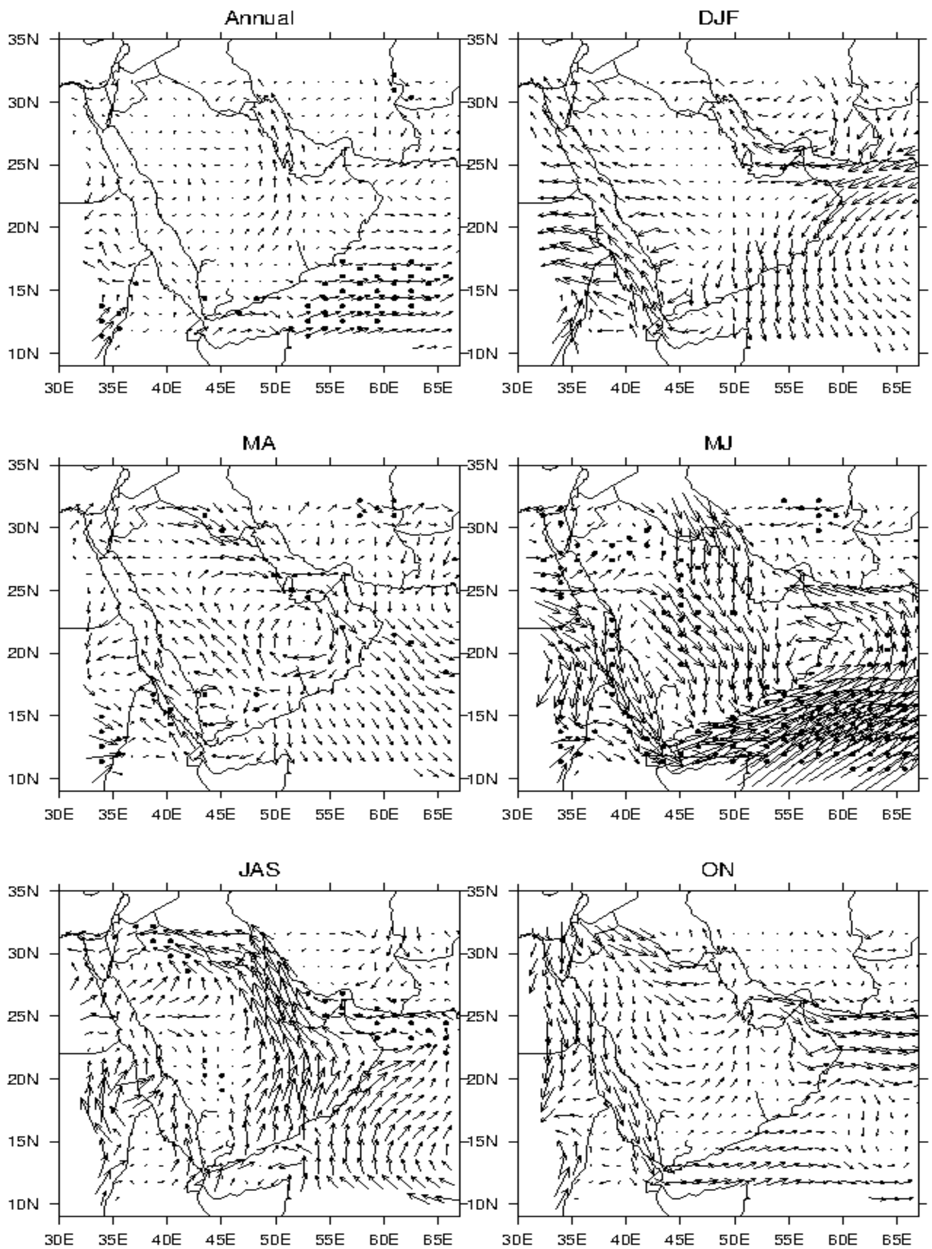

Figure 6-6: Same as Figure 4 but for vector wind at 925 hPa.

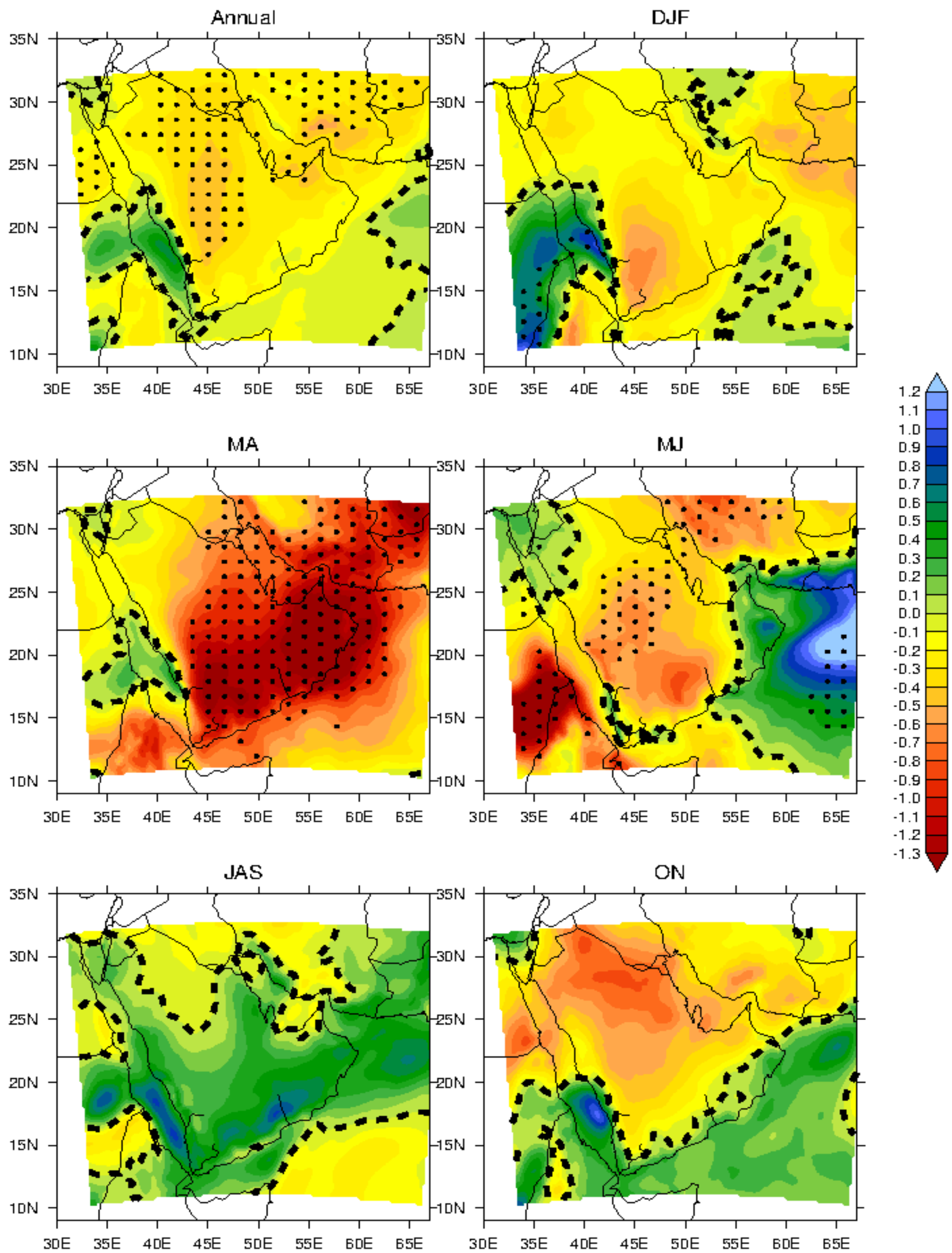

Figure 6-7: Same as Figure 4 but for specific humidity (gkg^{-1}) at 925 hPa.

6.4.1.3. Clouds

Significant decreased cloud formation is found in the annual mean difference composites of total cloud cover especially in the eastern and northern areas (Figure 6-8). A line of significant decreasing cloud is evident over eastern Arabia and beyond in the MA and, to a lesser extent in MJ season where there is a pronounced increase in cloudiness over eastern Oman. Changes in the remaining seasons are muted.

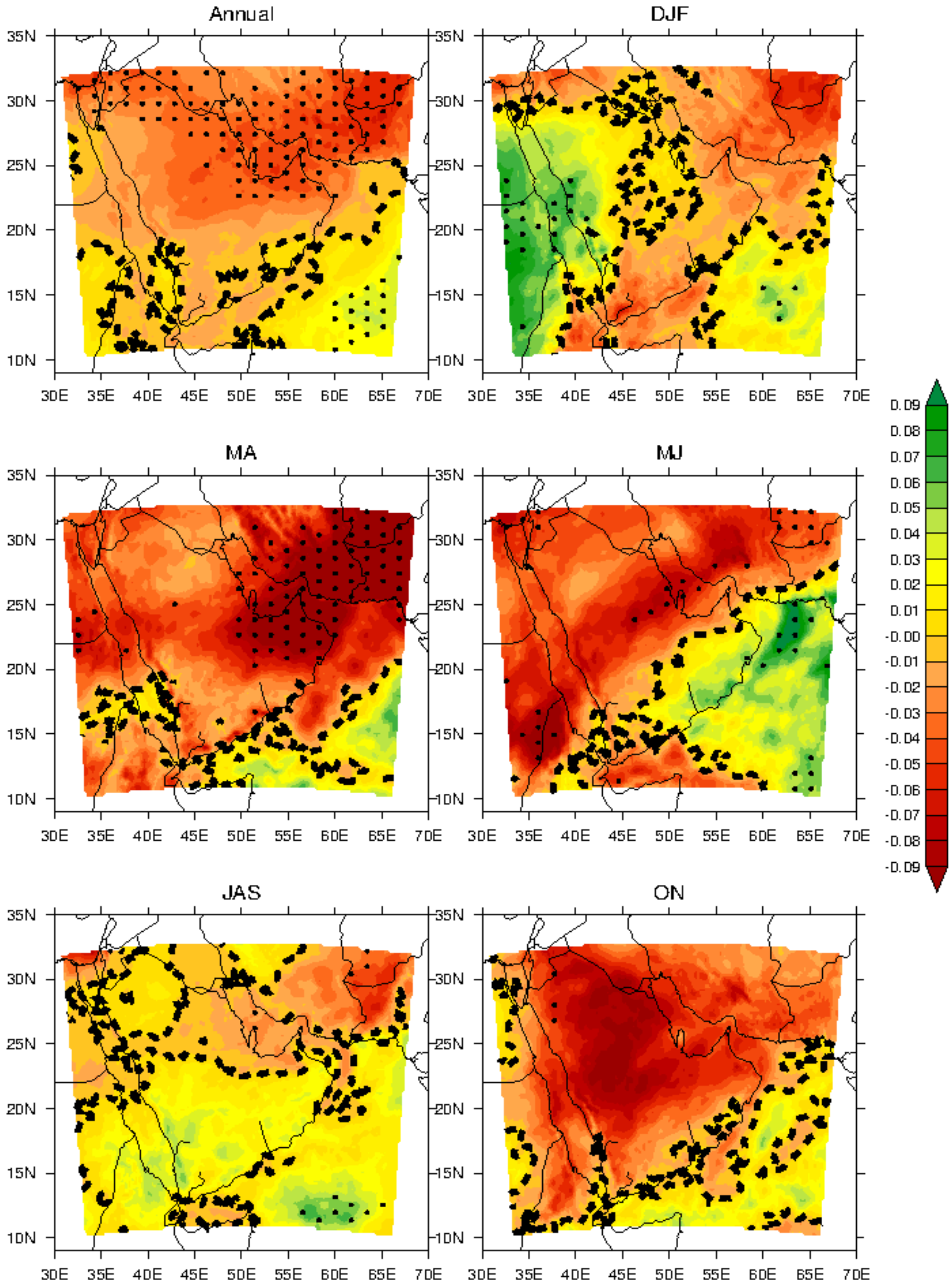

Figure 6-8: Same as Figure 4 but for total clouds.

6.4.1.4. SST

The mean difference composites of annual and seasonal SST between 1998-2008 and 1990-1997 are shown in Figure 6-9. Most of the SST of the adjacent seas to the AP (especially the Arabian Gulf (AG) and Red Sea (RS)) experienced remarkable significant increase of nearly 1.0 to 1.2℃ or more. The AG SSTs show higher increase relative to the RS which could be related to the shallowness of the former sea. However, the southern coast (mostly Oman eastern coasts) has decreased somewhat. During DJF, the significant increase of the SST has occurred over the southern RS, some areas over west AS and at the top north of AG. All seas have dramatically and significantly warmed in spring (more than 1.1℃) with less warming over Yemen coasts. The warming is more evident in MJ over the AG, Yemen coast and south and north RS, however this season also witnesses the highest significant cooling pattern occurred over Oman eastern coasts. The warming patterns in JAS season look similar to MJ season but the cooling over eastern Oman coast is less significant. In autumn, all the seas have warmed with the highest significant anomaly have occurred over Oman coasts, Yemen coast and south RS and the AG.

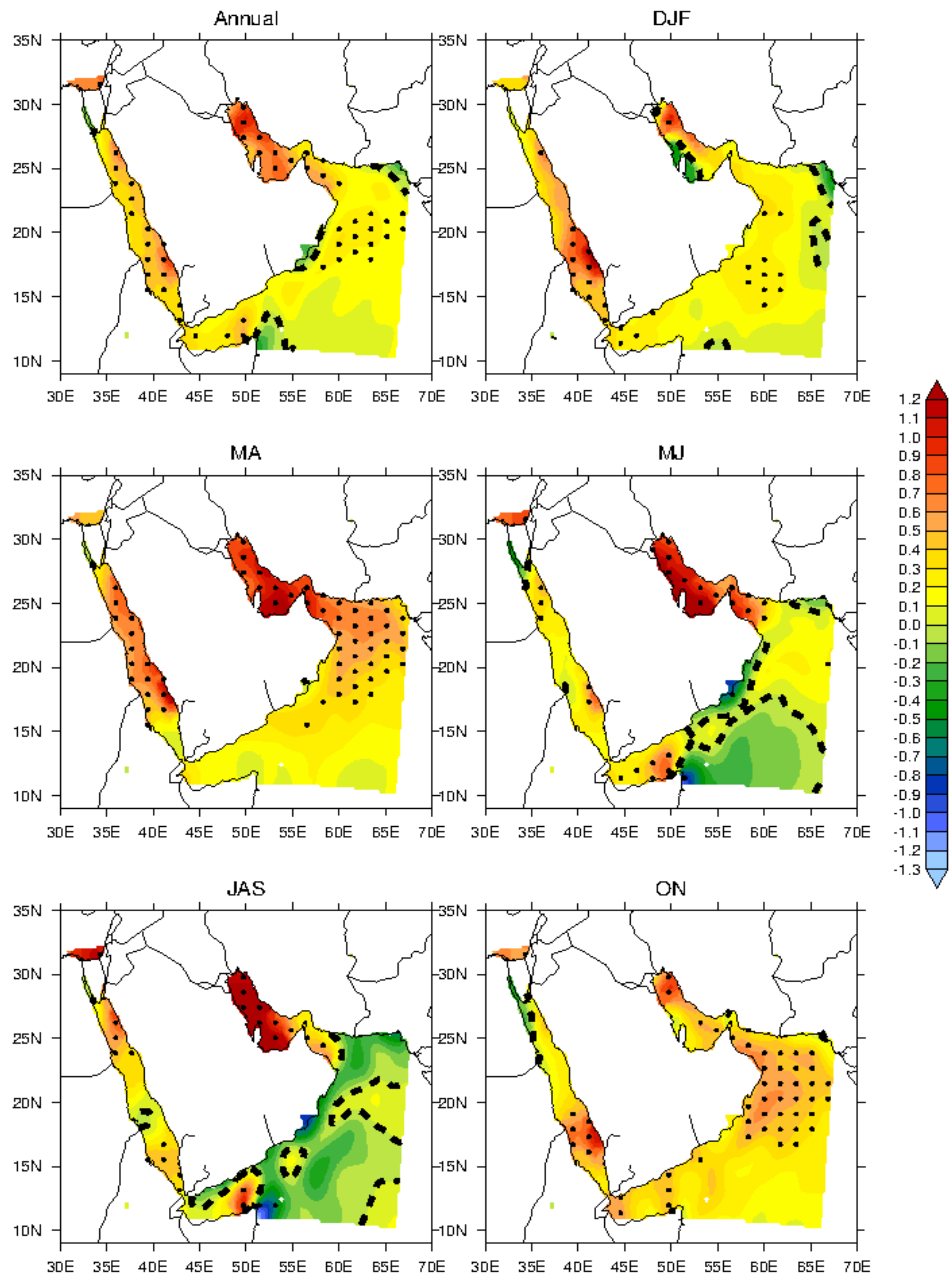

Figure 6-9: Same as Figure 4 but for sea surface temperature (℃).

6.4.1.5. MSLP

The mean difference composites of annual and seasonal MSLP between 1998-2008 and 1990-1997 are shown in Figure 6-10. The annual MSLP has decreased significantly over large parts of the AP in all seasons except DJF. Most of annual significant decrease has occurred during MA and MJ seasons. In JAS, the significant decrease has occurred over northern areas. The anomalous significant pressure decrease over Iran during autumn extends to cover most the eastern half of Arabia.

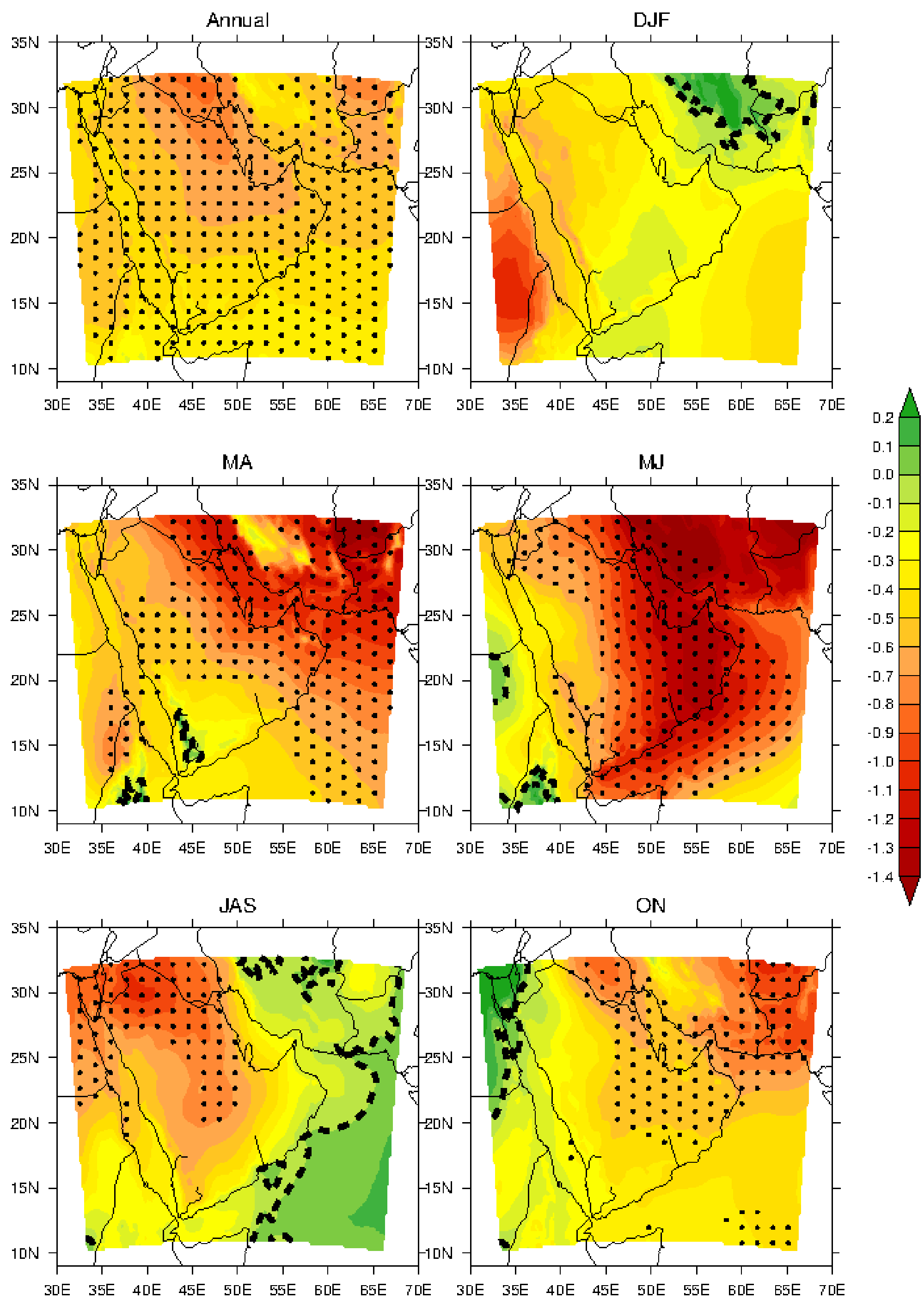

Figure 6-10: Same as Figure 4 but for mean sea level pressure (hpa).

6.4.2. Links to Modes of Variability: Correlation

The primary focus of this section is to establish and quantify the regional extent of climate extremes associated with four key modes of variability, namely the NAO, NCP, ENSO and IOD. Correlations have been computed for two periods 1990-2008 and 1970-2008, for individual stations, regional averages and for each season and for each of the extreme indices. The correlations were calculated using Spearman's rank method and the climate extreme indices were detrended prior the correlation calculation following *Donat et al.* [2013]. It is worth to mention that the second period 1970-2008 has only temperature data from nine stations (11 stations for precipitation) located at north of the AP. These are less representative for the whole region.

6.4.2.1. DJF

For the period 1970-2008 and during winter both NCP and NAO show the strongest association on interannual timescales with regional average temperature extreme indices. None of the teleconnections have significant link with any regional average precipitation extremes. The NAO shows a significant negative correlation during 1970-2008 with the TX90p index ($r=-0.6$, $p=<0.05$). The negative (positive) NAO mode is associated with higher (lower) warm day frequency. Table 6-5 summarises the extremes indices regional area average with the NAO during DJF season.

Table 6-5: Correlation coefficients with two periods 1990-2008 and 1970-2008 between the DJF standardized regional average temperature and precipitation extreme indices and NAO (coefficients significant at 0.05 level are in bold and to 0.1 level in italic).

	1990-2008			1970-2008
	All	NMON	MON	extremes_11
PRCP_Mon	-0.35	-0.28	-0.28	0.03
RX1day	-0.23	-0.15	-0.29	0.03
TMAXmean	0.00	0.06	0.03	**-0.46**
TX10p	-0.01	-0.06	0.08	0.32
TX90p	0.26	0.31	0.26	**-0.60**
TXX	0.19	0.20	0.15	-0.34
TMINmean	-0.25	-0.10	-0.32	*-0.43*
TN10p	0.19	0.15	0.36	0.38
TN90p	-0.18	-0.10	-0.23	**-0.49**
TNX	-0.16	-0.10	-0.28	-0.35

During both periods, generally the NCP is significantly negatively correlated with warm extremes (TMAXmean, TX90p) while it is significantly positively correlated with some cold extremes (Tx10p and TN10p) (Table 6-6).

During the period 1990-2008, the station correlations with the NCP mode results (Table 6-7) indicate that the highest number of stations reporting significant (at 0.05 level) negative correlation (17 stations) do so for the TMAXmean index (Saiq the highest r=-0.67) while, 14 stations report for significant positive correlations for the TX10p index (the highest Dhahran r=0.8).

Table 6-6: Correlation coefficients with two periods 1990-2008 and 1970-2008 between the DJF standardized regional average temperature and precipitation extreme indices and NCP (coefficients significant at 0.05 level are in bold and to 0.1 level in italic).

		1990-2008		1970-2008
	All	NMON	MON	extremes_11
PRCP_Mon	0.24	0.30	0.09	0.19
RX1day	0.31	0.32	0.17	0.16
TMAXmean	**-0.60**	**-0.62**	**-0.56**	**-0.71**
TX10p	**0.69**	**0.70**	**0.58**	**0.73**
TX90p	**-0.51**	**-0.50**	**-0.55**	-0.35
TXX	-0.37	-0.31	*-0.45*	-0.37
TMINmean	-0.24	-0.35	0.15	-0.27
TN10p	**0.47**	**0.49**	0.26	0.33
TN90p	0.04	-0.07	0.33	0.03
TNX	0.09	0.07	0.29	-0.07

Table 6-7 summarises the DJF significant stations correlations of some extreme indices with both NAO and NCP teleconnections. The results clearly indicate the strong influence of the NCP mode on the AP surface temperature during winter. The strong relationship is strong and robust during the two periods.

Table 6-7: Correlation coefficients with two periods 1990-2008 and 1970-2008 between some DJF standardized station temperature and precipitation extreme indices and both NAO and NCP (coefficients significant at 0.05 level are in bold and to 0.1 level in italic).

Index	1990-2008				1970-2008			
	NAO		NCP		NAO		NCP	
	station	cor	station	cor	station	cor	station	cor
PRCP_Mon	Bisha	**-0.60**	Ras Alkhaimah	**0.47**	Al.Al-Taif	**-0.51**	Kuwait	*0.38*
	Dubai	*-0.41*	Dubai	**0.52**				
	Sohar	*-0.41*	Khasab	*0.41*				
	Saiq	**-0.49**						
TMAXmean	Sohar	**0.53**	Bahrain	**-0.54**	Bahrain	**-0.48**	Dhahran	**-0.70**
			Kuwait	**-0.50**	Dhahran	*-0.42*	Riyadh	**-0.56**
			Dhahran	**-0.55**			Hail	**-0.59**
			Riyadh	**-0.59**			Al-Madinah	**-0.67**
			Hail	**-0.51**			Jeddah	**-0.60**
			Tabuk	**-0.46**			Al-Taif	*-0.46*
			Al-Madinah	**-0.58**				
			Jeddah	**-0.63**				
			Al-Taif	**-0.56**				
			Khamis Mushait	**-0.57**				
			Gizan	*-0.45*				
			Doha	**-0.50**				
			Ras Alkhaimah	**-0.54**				
			Sharjah	**-0.60**				
			Khasab	**-0.56**				
			Sohar	**-0.57**				
			Saiq	**-0.67**				
			Masirah	**-0.54**				
TMINmean	Dhahran	*-0.40*	Bahrain	**-0.52**			Dhahran	*-0.42*
	Gizan	*-0.39*	Hail	**-0.51**			Riyadh	*-0.49*
			Tabuk	**-0.47**			Bisha	**0.56**
			Al-Madinah	**-0.51**				
			Jeddah	**-0.46**				
			Doha	*-0.44*				
			Khasab	**-0.49**				
TX10p	Sur	**-0.54**	Bahrain	**0.58**	Riyadh	**-0.56**	Bahrain	**0.75**

Index	1990-2008				1970-2008			
	NAO		NCP		NAO		NCP	

TX10p (con)	station	cor	station	cor	station	cor	station	cor
			Kuwait	**0.54**	Jeddah	*-0.43*	Kuwait	**0.77**
			Dhahran	**0.75**	Bahrain	**-0.51**	Dhahran	**0.74**
			Riyadh	**0.65**	Kuwait	**-0.55**	Riyadh	**0.76**
			Hail	**0.60**	Al-Madinah	*-0.49*	Hail	**0.75**
			Al-Madinah	*0.44*			Al-Madinah	**0.77**
			Jeddah	*0.42*			Jeddah	**0.50**
			Al-Taif	**0.48**			Al-Taif	**0.59**
			Bisha	*0.41*				
			Gizan	**0.61**				
			Doha	**0.49**				
			Ras Alkhaimah	**0.57**				
			Dubai	**0.66**				
			Sharjah	**0.58**				
			Khasab	*0.44*				
			Sohar	**0.66**				
			Saiq	**0.70**				
			Sur	*0.46*				
			Masirah	**0.66**				
TN10p	Doha	*0.41*	Bahrain	**0.56**	Kuwait	**0.47**	Bahrain	**0.49**
			Riyadh	**0.50**	Dhahran	*0.44*	Kuwait	*0.44*
			Hail	**0.61**			Dhahran	**0.57**
			Tabuk	**0.49**			Riyadh	**0.55**
			Al-Madinah	**0.49**			Hail	**0.51**
			Jeddah	**0.57**			Bisha	*-0.49*
			Al-Taif	*0.43*				
			Doha	*0.44*				
			Khasab	**0.60**				
			Saiq	**0.42**				
			Thumrait	**0.54**				

6.4.2.2. MA

During 1990-2008, ENSO has a positive correlation with the regional average precipitation and RX1day over the Monsoon area. The highest ENSO correlation reported in RX1day index is over Jeddah (r=0.6). During the period 1970-2007, the NAO is significantly positively correlated with the precipitation and the cold extremes (TX10p and TN10p). The highest positive NAO correlation was reported in the TX10p index over Riyadh (0.6). Table 6-8 summarises the MA significant stations correlations of some extreme indices with both NAO and ENSO teleconnections. During the period 1990-2008, ENSO has strong influence on the region temperature. During the ENSO positive phase cooler daytime air is expected. The NAO mode influence is dominant on the period 1970-2008 especially on the TX10p index.

Table 6-8: Correlation coefficients with two periods 1990-2008 and 1970-2008 between some MA standardized station temperature and precipitation extreme indices and both NAO and ENSO (coefficients significant at 0.05 level are in bold and to 0.1 level in italic).

Index	1990-2008				1970-2008			
	NAO		ENSO		NAO		ENSO	
	station	cor	station	cor	station	cor	station	cor
PRCP_Mon	Bahrain	*-0.41*	Jeddah	**0.56**	Bahrain	**0.49**	Al-Madinah	*-0.45*
	Tabuk	**-0.68**	Seeb	*0.39*	Al-Madinah	0.41	Masirah	**0.52**
	Ras Alkhaimah	*-0.43*					Salalah	**0.45**
	Khasab	**-0.46**						
TMAXmean	Al-Taif	*-0.41*	Kuwait	**-0.58**	Bahrain	*-0.39*		
	Khasab	*-0.44*	Riyadh	**-0.44**	Kuwait	*-0.41*		
			Khasab	**-0.50**	Hail	*-0.41*		
			Sur	*-0.42*	Al-Madinah	**-0.50**		
			Masirah	**-0.51**				
TMINmean	Al-Madinah	*-0.39*	Salalah	*0.40*	Bahrain	*-0.42*		
	Bisha	*-0.42*			Jeddah	*-0.44*		
	Khamis Mushait	*-0.40*						
	Gizan	*-0.40*						
TX10p	Al-Taif	**0.51**	Kuwait	**0.48**	Bahrain	*0.43*		
	Khamis Mushait	*0.42*	Hail	**0.57**	Kuwait	*0.38*		
	Gizan	*0.45*	Gizan	**0.51**	Dhahran	**0.53**		
			Khasab	**0.62**	Riyadh	**0.58**		
			Saiq	**0.47**	Al-Madinah	**0.48**		
			Masirah	**0.53**				
TN10p	Al-Madinah	*0.42*	Thumrait	**-0.52**	Bahrain	*0.41*		
	Jeddah	*0.41*	Salalah	**-0.50**	Hail	*0.44*		
	Gizan	**0.48**			Al-Madinah	*0.46*		
					Jeddah	*0.39*		

6.4.2.3. MJ

In early summer and during 1990-2008, ENSO is significantly negatively correlated with regionally average warm extremes (TMAXmean, TMINmean) and is significantly positively correlated with regionally average cold extremes (TX10p, TN10p). Surprisingly during 1970-2008, both NAO and NCP have significantly negative correlations with the regionally average precipitation and RX1day index. Table 6-9 shows that during 1990-2008, the highest positive ENSO correlation with the stations is reported in the TX10p index over Al-Madinah (r=0.68) while the highest negative is reported in the TMAXmean over Kuwait (r=-0.62). For the NCP the highest negative correlation is reported in the precipitation over Tabuk (r=-0.55). During 1970-2008, Al-Taif reported the highest correlation of -0.55 which correlate the MJ station precipitation with the NCP.

Table 6-9: Correlation coefficients with two periods 1990-2008 and 1970-2008 between some MJ standardized station temperature and precipitation extreme indices and both NCP and ENSO (coefficients significant at 0.05 level are in bold and to 0.1 level in italic).

Index	1990-2008				1970-2008			
	NCP		ENSO		NCP		ENSO	
	station	cor	station	cor	station	cor	station	cor
PRCP_Mon	Tabuk	**-0.55**			.Al-Madinah	*-0.43*	Al-Taif	*0.40*
					Al-Taif	**-0.55**	Salalah	**0.47**
					Salalah	**-0.49**		
TMAXmean	Tabuk	**-0.55**	Kuwait	**-0.62**	Al-Taif	*0.41*		
	Doha	*0.39*	Riyadh	*-0.44*	Bisha	*0.46*		
	Sohar	**0.55**	Hail	**-0.46**				
	Sur	*0.47*	Tabuk	**-0.51**				
			Al-Madinah	**-0.47**				
			Al-Taif	**-0.55**				
			Bisha	*-0.41*				
TMINmean	Al-Madinah	*-0.44*	Kuwait	*-0.40*			Bahrain	**0.52**
	Doha	*0.44*	Dhahran	*-0.39*			Riyadh	*0.45*
	Masirah	**-0.62**	Hail	*-0.39*				
			Tabuk	**-0.60**				
			Doha	**-0.48**				
			Khasab	*-0.45*				
TX10p	Kuwait	**0.49**	Kuwait	**0.53**	Al-Taif	*-0.44*	Jeddah	*-0.40*
	Doha	**-0.50**	Riyadh	*0.43*	Bisha	*-0.41*		
	Sur	**-0.48**	Hail	*0.41*				
			Tabuk	**0.61**				
			Al-Madinah	**0.68**				
			Al-Taif	**0.58**				
			Saiq	*0.42*				
TN10p	Kuwait	*-0.41*	Hail	**0.60**	Bisha	**-0.48**	Bahrain	*-0.44*
			Tabuk	**0.64**			Hail	*-0.41*
			Al-Madinah	**0.57**				
			Khasab	**0.57**				

6.4.2.4. JAS

During late summer ENSO seems to have the strongest impact over the region for the period 1990-2008. It mostly influences the warm temperature extremes which are significantly negatively correlated. Table 6-10 summarizes the late summer ENSO correlation with the regionally average extreme indices. It is clear that the influence is only in the period 1990-2008. During 1970-2008, only NAO exhibits significant correlation which is negative with the TMAXmean index and positive with the TX10 index.

Table 6-10: Same as table 4 but the correlation coefficients for Nino3.4 teleconnection during JAS season.

		1990-2008		1970-2008
	All	NMON	MON	extremes_11
PRCP_Mon	-0.25	-0.34	-0.11	-0.13
RX1day	-0.29	-0.28	-0.12	-0.03
TMAXmean	*-0.41*	**-0.51**	-0.14	0.08
TX10p	*0.39*	0.37	0.35	-0.18
TX90p	*-0.39*	**-0.49**	-0.06	-0.20
TXX	**-0.49**	**-0.56**	-0.20	-0.07
TMINmean	**-0.48**	**-0.51**	0.01	0.03
TN10p	0.24	0.32	-0.13	-0.13
TN90p	-0.61	-0.55	-0.14	-0.28
TNX	*-0.44*	-0.53	0.06	-0.20

For the station correlations, Table 6-11 shows that many stations reported high strong negative correlations of ENSO with the night extreme indices such as the TMINmean and TN10p. The highest negative correlation reported in the TMINmean index over Bahrain (r=-0.75) while the highest significant positive correlation reported in the TN10p over

Bisha (r=0.61). One striking correlation finding with the NCP index is that although the precipitation regional average shows no correlation, the stations indicate two opposite significant correlations centers. Some northern stations show negatively significant correlations while some Omani stations (southern AP) show positively significant correlations. Similar findings are seen in some temperature extreme indices as TMAXmean, TX90p and TN90p. The NCP shows some influence on some stations during 1970-2008 especially in the precipitation and cool days percentage indices.

Table 6-11: Correlation coefficients with two periods 1990-2008 and 1970-2008 between some JAS standardized station temperature and precipitation extreme indices and both NCP and ENSO (coefficients significant at 0.05 level are in bold and to 0.1 level in italic).
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Index	1990-2008				1970-2008			
	NCP		ENSO		NCP		ENSO	
	station	cor	station	cor	station	cor	station	cor
PRCP_Mon	Bahrain	**-0.65**			Bahrain	**0.53**	Nil	
	Riyadh	**-0.57**			Dhahran	**0.54**		
	Hail	*-0.42*						
	Jeddah	**-0.52**						
	Ras Alkhaimah	*-0.41*						
	Sur	**0.56**						
	Masirah	**0.61**						
	Thumrait	**0.56**						
TMAXmean	Bahrain	**-0.49**	Bahrain	**-0.46**	Dhahran	**-0.55**	Jeddah	*0.42*
	Kuwait	**-0.75**	Dhahran	**-0.58**				
	Dhahran	**-0.59**	Riyadh	**-0.48**				
	Riyadh	**-0.45**	Tabuk	**-0.45**				
	Doha	*-0.39*	Ras Alkhaimah	**-0.60**				
	Ras Alkhaimah	**-0.58**	Dubai	**-0.58**				
	Dubai	**-0.61**	Sharjah	**-0.54**				
	Sharjah	**-0.59**	Khasab	*-0.41*				
	Khasab	**-0.86**						
	Sur	**-0.68**						
	Thumrait	**0.64**						
TMINmean	Bahrain	**-0.46**	Bahrain	**-0.75**	Bisha	**0.57**		
	Khasab	**-0.55**	Riyadh	**-0.67**				
			Hail	**-0.62**				
			Tabuk	**-0.63**				
			Al-Madinah	**-0.44**				
			Jeddah	**-0.53**				
			Bisha	**-0.59**				
			Doha	**-0.71**				
TX10p	Kuwait	**0.61**	Riyadh	**0.53**	Dhahran	**0.50**	Jeddah	*-0.45*
	Riyadh	**0.47**	Tabuk	*0.41*	Jeddah	**0.47**		
	Ras Alkhaimah	*0.39*	Doha	*0.39*				
	Sharjah	*0.42*	Ras Alkhaimah	*0.42*				
	Khasab	**0.80**	Thumrait	*0.43*				
	Sur	**0.58**						
TN10p	Dhahran	*0.41*	Bahrain	**0.54**	Bisha	**-0.61**		
	Sohar	**-0.66**	Dhahran	**0.53**				
	Saiq	*0.43*	Riyadh	**0.47**				
			Hail	*0.40*				
			Tabuk	**0.46**				
			Bisha	**0.61**				
			Doha	**0.46**				

6.4.2.5. ON

Autumn season witnesses a wide variation of impacts from many teleconnections on different extreme indices. During 1990-2008, the autumn regionally averaged precipitation is negatively correlated with the NAO and NCP over both the all and NMON regions. However, it is positively correlated over the NMON region with the ENSO index. The warm nighttime extreme indices show high significant positive correlation (TMINmean, TN90p and TNx) with both IOD and ENSO and it is vice versa with the cold nighttime extreme indices (TN10p). Detailed correlation results of the autumn ENSO correlation with the regional average extreme indices are summarized in Table 6-12 and with the IOD in Table 6-13.

Table 6-12: Same as table 4 but the correlation coefficients for Nino3.4 teleconnection during ON season.

		1990-2008		1970-2008
	All	NMON	MON	extremes_11
PRCP_Mon	0.31	**0.48**	0.14	**0.45**
RX1day	0.35	**0.50**	0.00	*0.38*
TMAXmean	-0.10	-0.26	-0.09	0.11
TX10p	0.21	0.17	0.29	-0.15
TX90p	-0.10	-0.16	0.00	0.34
TXX	-0.31	-0.29	-0.27	0.28
TMINmean	**0.53**	**0.70**	*0.41*	**0.51**
TN10p	**-0.51**	**-0.60**	*-0.36*	*-0.44*
TN90p	**0.58**	**0.70**	0.26	**0.70**
TNX	**0.49**	**0.49**	0.19	**0.63**

Table 6-13: Same as table 4 but the correlation coefficients for IOD teleconnection during ON season.

		ON		
		1990-2008		1970-2008
	All	NMON	MON	extremes_11
PRCP_Mon	0.20	0.29	0.21	0.14
RX1day	0.24	0.28	0.13	0.18
Tmaxmean	0.07	-0.03	0.04	-0.04
TX10p	0.00	-0.04	0.06	-0.05
TX90p	0.10	0.08	0.10	0.02
TXX	-0.16	-0.12	-0.14	0.02
Tminmean	**0.67**	**0.83**	*0.44*	0.20
TN10p	**-0.71**	**-0.78**	**-0.45**	-0.22
TN90p	**0.66**	**0.84**	0.26	0.28
TNX	**0.65**	**0.70**	0.16	0.36

During 1990-2008, the NCP index has positive correlation with only one temperature extreme index over all and the NMON regions which is TXx. However, during 1970-2008, NCP exhibit negative correlation with the warm extreme indices and positive correlation with the cold extreme indices. The ENSO correlation is robust in autumn during both periods.

Table 6-14 summarises the ON significant stations correlations of some extreme indices with both ENSO and IOD teleconnections During 1990-2008, the index with highest number of stations having significant positive correlation with IOD and ENSO is the TMINmean. Many stations reported high significant positive correlation between r=0.55 and r=0.83. In contrast the index with the highest number of significant negative correlation with IOD and ENSO is the TN10p index with correlation value between r=-0.50 and r=-

0.72. In general the nighttime temperature indices are influenced dramatically in this season. Many stations reported high positive significant correlation of r=0.46 or higher between precipitation and ENSO as in Kuwait, Hail, Al-Taif and Khamis Mushait. During 1970-2008, ENSO shows similar strong influence on the region precipitation and temperature as during 1990-2008.

Table 6-14: Correlation coefficients with two periods 1990-2008 and 1970-2008 between some ON standardized station temperature and precipitation extreme indices and both ENSO and IOD (coefficients significant at 0.05 level are in bold and to 0.1 level in italic).

Index	1990-2008				1970-2008			
	ENSO		IOD		ENSO		IOD	
	station	cor	station	cor	station	cor	station	cor
PRCP_Mon	Bahrain	*0.42*	Dubai	*0.42*	Kuwait	**0.59**	Al-Taif	*0.41*
	Kuwait	**0.46**			Riyadh	**0.53**		
	Hail	**0.48**			Al-Taif	*0.45*		
	Al-Madinah	*0.40*			Bisha	**0.50**		
	Al-Taif	**0.51**						
	Khamis Mushait	**0.46**						
	Khasab	*0.42*						
TMAXmean	Al-Madinah	**-0.47**	Nil		Nil	Nil		
	Ras Alkhaimah	**-0.45**						
TMINmean	Kuwait	**0.67**	Bahrain	*0.40*	Bahrain	**0.45**	Dhahran	**0.48**
	Riyadh	**0.47**	Kuwait	**0.70**	Dhahran	**0.69**		
	Hail	**0.74**	Dhahran	**0.68**	Riyadh	*0.47*		
	Al-Madinah	**0.49**	Riyadh	**0.55**	Jeddah	*0.44*		
	Jeddah	**0.74**	Hail	**0.83**	Al-Taif	**0.47**		
	Al-Taif	**0.48**	Al-Madinah	**0.55**	Bisha	**0.52**		
	Bisha	**0.52**	Jeddah	**0.67**				
	Khamis Mushait	**0.64**	Al-Taif	**0.53**				
	Gizan	**0.55**	Bisha	**0.57**				
	Ras Alkhaimah	**0.45**	Khamis Mushait	**0.59**				
			Gizan	**0.33**				
			Ras Alkhaimah	**0.55**				
			Sohar	**0.49**				
			Sur	*0.41*				
TX10p	Al-Madinah	*0.45*						
TN10p	Kuwait	**-0.53**	Bahrain	**-0.54**	Bahrain	**-0.54**	Bahrain	
	Dhahran	**-0.46**	Kuwait	**-0.57**	Kuwait	**-0.45**	Dhahran	
	Riyadh	**-0.59**	Dhahran	**-0.72**	Dhahran	**-0.62**		
	Hail	**-0.50**	Riyadh	**-0.66**	Jeddah	*-0.39*		
	Jeddah	**-0.61**	Hail	**-0.72**				*-0.41*
	Al-Taif	*-0.41*	Al-Madinah	*-0.44*				**-0.56**
	Bisha	*-0.41*	Jeddah	**-0.54**				
	Khamis Mushait	**-0.63**	Al-Taif	**-0.45**				
	Gizan	**-0.46**	Bisha	**-0.58**				
			Khamis Mushait	**-0.65**				
			Sohar	**-0.53**				
			Sur	*-0.42*				

6.4.2.6. Correlations of stations with longer data (1950-2008)

To check the stability of the relationships between the extreme indices and the teleconnections, correlations of longer timeseries stations (Bahrain, Kuwait, Salalah and Masirah) which having data from 1950-2008 have been calculated. Focus is given into two seasons the DJF season where NAO and NCP are dominant (Table 6-15) and ON season where ENSO and IOD are dominant (Table 6-16). In general the correlations of the teleconnections with temperature are stronger and more significant relative to precipitation during all periods. The NCP has stronger and robust influence on Bahrain and Kuwait temperature during DJF season relative to NAO. The influence is limited over Salalah (south of Arabia). During ON season, ENSO and IOD have strong relationships with Kuwait precipitation and nighttime temperature. The same influence is seen over Bahrain but to a lesser extent. Positive ENSO phase is associated with wet conditions over Kuwait and Bahrain, higher nighttime temperatures and lower daytime temperatures (insignificant).

Table 6-15: Correlation coefficients with three periods 1990-2008, 1970-2008 and 1950-2008 between some DJF standardized station temperature and precipitation extreme indices and both NAO and NCP (coefficients significant at 0.05 level are in bold and to 0.1 level in italic). Correlations which could not be obtained due to missing data are in blank boxes.

		Bahrain		Kuwait		Salalah		Masirah	
		NAO	NCP	NAO	NCP	NAO	NCP	NAO	NCP
RCP_Mon	1990-2008	-0.24	0.22	-0.12	-0.10	-0.38	0.03	-0.05	0.09
	1970-2008	0.31	0.28	0.13	*0.38*	0.05	-0.16	0.02	-0.13
	1950-2008	0.01	**0.26**	0.10	0.09	**-0.34**	0.11	0.11	*0.22*
TMAXmean	1990-2008	-0.08	**-0.54**	-0.26	**-0.50**	-0.06	-0.18	0.23	**-0.54**
	1970-2008	**-0.48**	**-0.66**	-0.38	**-0.83**				
	1950-2008	-0.17	**-0.45**	*-0.27*	**-0.63**	**0.32**	-0.03		
TMINmean	1990-2008	-0.11	**-0.52**	-0.34	0.02	-0.31	0.15	-0.29	-0.21
	1970-2008	**-0.51**	-0.35	**-0.55**	-0.36				
	1950-2008	**-0.36**	**-0.56**	**-0.34**	**-0.31**	**0.37**	0.22		
TX10p	1990-2008	0.14	**0.58**	0.30	**0.54**	0.15	0.06	-0.05	**0.66**
	1970-2008	*0.39*	**0.75**	0.22	**0.77**				
	1950-2008	0.08	**0.46**	0.14	**0.68**	-0.25	0.02		
TX90p	1990-2008	0.09	-0.36	0.03	-0.13	-0.15	**-0.47**	*0.43*	**-0.58**
	1970-2008	*-0.44*	-0.23	**-0.53**	*-0.43*				
	1950-2008	-0.17	**-0.32**	**-0.37**	**-0.40**	0.12	-0.14		
TN10p	1990-2008	0.19	**0.56**	0.31	0.12	0.34	0.09	0.35	0.28
	1970-2008	0.29	**0.49**	**0.47**	*0.44*				
	1950-2008	0.19	**0.55**	*0.26*	**0.34**	**-0.43**	-0.11		
TN90p	1990-2008	0.03	-0.27	-0.29	-0.03	-0.09	0.16	-0.10	-0.06
	1970-2008	**-0.69**	-0.33	**-0.48**	-0.16				
	1950-2008	**-0.43**	**-0.49**	**-0.33**	*-0.28*	0.17	0.21		

Table 6-16: Correlation coefficients with three periods 1990-2008, 1970-2008 and 1950-2008 between some ON standardized station temperature and precipitation extreme indices and both ENSO and IOD (coefficients significant at 0.05 level are in bold and to 0.1 level in italic). Correlations which could not be obtained due to missing data are in blank boxes.

		Bahrain		Kuwait		Salalah		Masirah	
		ENSO	IOD	ENSO	IOD	ENSO	IOD	ENSO	IOD
PRCP_Mon	1990-2008	*0.42*	0.29	**0.46**	0.39	-0.17	0.01	0.12	0.12
	1970-2008	0.03	-0.04	**0.59**	0.27	0.25	0.03	0.02	-0.13
	1950-2008	**0.26**	**0.32**	**0.51**	**0.38**	-0.01	-0.01	0.19	0.08
TMAXmean	1990-2008	0.00	0.13	-0.27	0.04	-0.15	0.00	-0.21	-0.04
	1970-2008	0.29	0.11	-0.17	-0.12				
	1950-2008	*0.23*	*0.23*	-0.06	0.04	*0.25*	0.11		
TMINmean	1990-2008	0.02	*0.40*	**0.67**	**0.70**	0.17	0.33	0.13	0.20
	1970-2008	**0.45**	0.05	0.28	-0.12				
	1950-2008	*0.24*	*0.23*	**0.43**	**0.34**	**0.31**	0.17		
TX10p	1990-2008	-0.03	-0.24	0.14	-0.15	-0.10	-0.28	0.20	-0.05
	1970-2008	-0.31	-0.13	0.13	0.22				
	1950-2008	**-0.27**	*-0.27*	-0.06	-0.07	**-0.34**	-0.24		
TX90p	1990-2008	0.32	*0.39*	-0.26	-0.07	-0.36	-0.20	-0.11	-0.13
	1970-2008	**0.54**	0.09	-0.03	0.00				
	1950-2008	0.21	*0.26*	-0.01	0.03	0.06	0.07		
TN10p	1990-2008	-0.20	**-0.54**	**-0.53**	**-0.57**	-0.08	-0.12	-0.15	-0.25
	1970-2008	**-0.54**	*-0.41*	**-0.45**	-0.25				
	1950-2008	**-0.31**	**-0.47**	**-0.49**	**-0.46**	**-0.34**	-0.15		
TN90p	1990-2008	0.14	*0.38*	**0.67**	**0.74**	0.05	0.27		
	1970-2008	0.34	-0.01	**0.67**	**0.74**	-0.06	0.02	0.21	-0.04
	1950-2008	0.17	0.18	**0.39**	0.23	0.03	-0.09		

6.4.3. The physical mechanisms composites

Here we examine the circulation mechanisms behind the strong statistical links of some teleconnections with some extreme indices in particular season through deriving composite mean anomaly maps of atmospheric circulation variables from the PRECIS regional model runs and SST for the years associated with the teleconnection dominant phases sign (negative or positive). The years of positive and negative phases were defined based on the standardized seasonal departure from the long-term mean (i.e., the mean over 1990-2008). Years with normalized index departure greater than 0.5 of the standard deviation were classified as positive composites, and years with index departure less than -0.5 of the standard deviation as negative composites. The composite analysis cover the period 1990-2008 and has included all the seasons (DJF, MA, MJ, JAS and ON).

6.4.3.1. DJF

During winter the NCP correlation is significantly negative with the warm extremes and significantly positive with the cold extremes. The NCP timeseries shows a decreasing trend in DJF with negative phases in the following years 1994, 1995, 1999, 2000, 2001, 2002 and 2004. The composite mean anomalies maps for 500 hPa height, 500 hPa vertical velocity, 925 hPa wind and total cloud during negative winter NCP years are shown in Figure 6-11. The maps show an increase of geopotential height at 500 hPa over most AP especially the northern area accompanied with strong subsidence at the same level over the middle, eastern and southeastern areas. This subsidence extends over Iran and Pakistan. The low level wind at 925 hPa brings cool dry air over the region especially those areas located at the east/southeast. Stable air aloft and dryer air advection at lower levels inhibits cloud formation as is evident from the total cloud composite map. As the NCP index is decreasing during 1990-2008 and the correlation of the NCP is negative with the daytime warm extremes (TMAXmean and TX90p) and positive with the cold extremes (TX10p and TN10p), an increase of warm indices and a decrease in the cold extremes is expected.

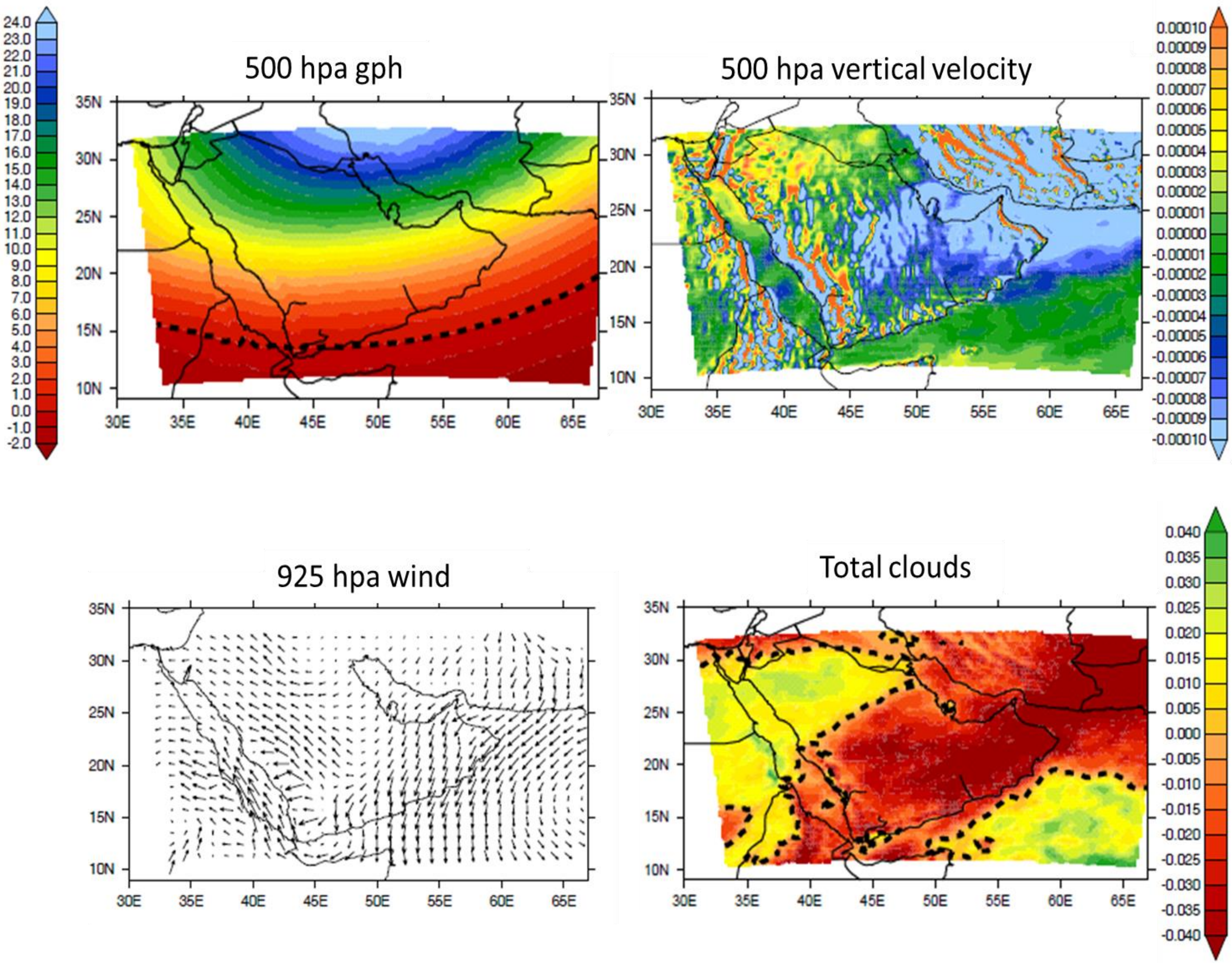

Figure 6-11: Composite mean anomalies of DJF geopotential height at 500 hPa (m), vertical velocity (ms^{-1}) at 500 hPa, vector winds at 925 hPa and total clouds for the negative NCP years. Dashed line represents the zero value.

6.4.3.2. MA

During MA season ENSO is significantly positively correlated with the MON precipitation. The years of negative ENSO (La Niña) are 1996, 1999, 2000, 2001, 2006 and 2008. Figure 6-12 depicts the composite mean anomalies maps for 500 hPa height, 500 hPa vertical velocity, 925 hPa wind and SST and total cloud during negative ENSO phases. It shows clearly an increase of geopotential height at 500 hPa associated with stronger subsidence. The air is likely to be dry at lower level (925 hPa) because the wind originates from north/northeasterly direction (not shown). The SST is colder over the AS but warmer over rest of the ocean.

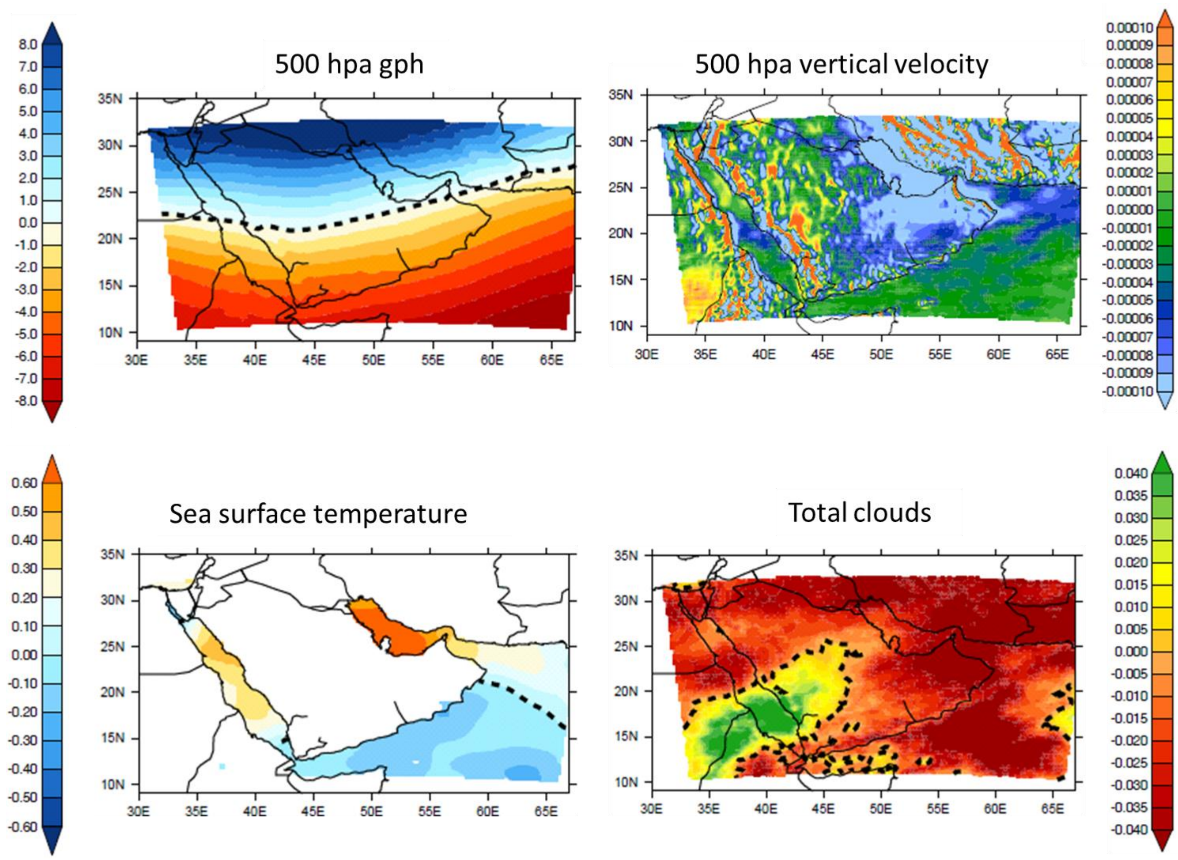

Figure 6-12: Composite mean anomalies of MA geopotential height at 500 hPa (m), vertical velocity (ms^{-1}) at 500 hPa, SST (℃) and total clouds for the negative Nino3.4 years. Dashed line represents the zero value.

6.4.3.3. MJ

In MJ season, the correlation is significantly negative between ENSO and TMAXmean (positive with TX10p). During 1990-2008, similar to spring the dominating phase of ENSO is negative. ENSO negative years are as follow 1996, 1999, 2000, 2003, 2007 and 2008. Figure 6-13 shows enhanced vertical air motion over the southern half of Arabia because of the decrease of 500 hPa while the increase of geopotential height in the north causes subsidence especially in the area from west to northeast Arabia. The southeasterly low level winds at 925 hPa over southeastern areas (not shown) advect moisture from the AS as is evident in the specific humidity composite. The SST over the AG is increasing remarkably while cooling is occurring over the Omani eastern coasts.

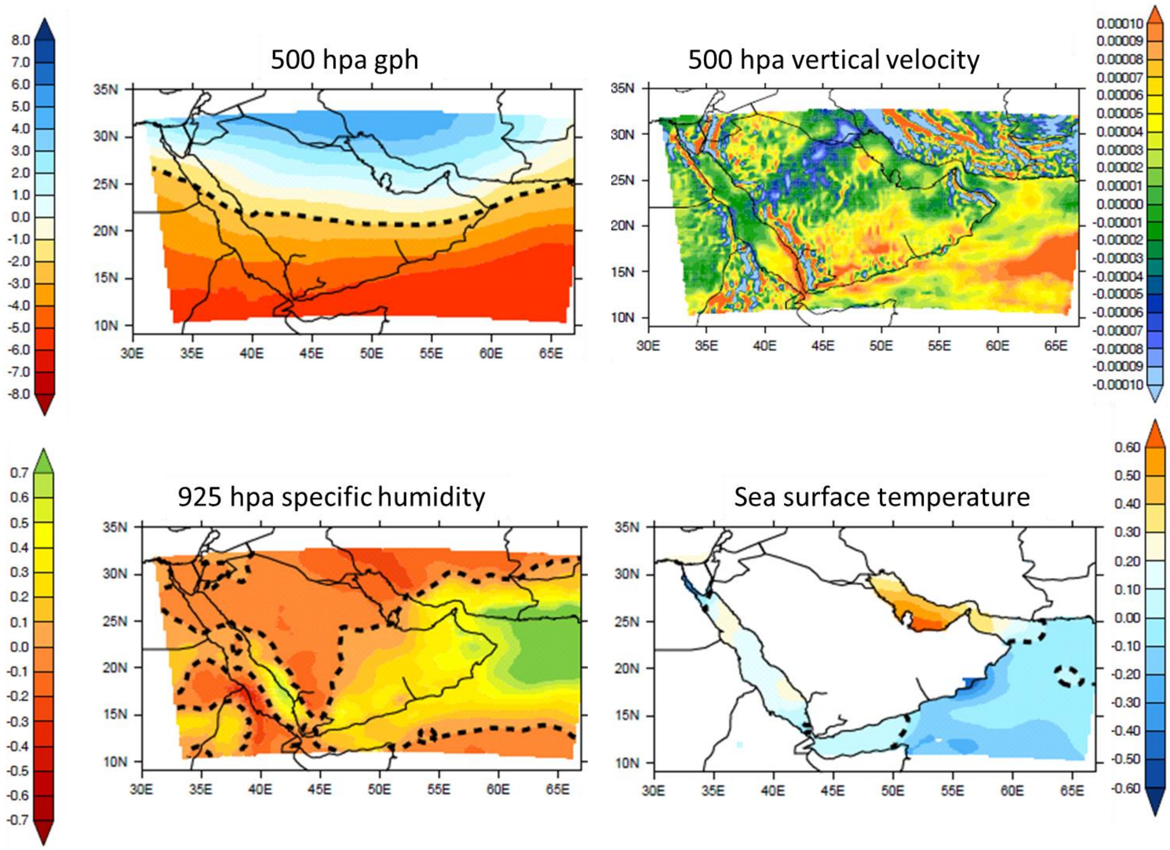

Figure 6-13: Composite mean anomalies of MJ geopotential height at 500 hPa (m), vertical velocity (ms^{-1}) at 500 hPa, specific humidity (jkg^{-1}) and total clouds for the negative Nino3.4 years. Dashed line represents the zero value.

6.4.3.4. JAS

The correlation is negative between ENSO and the warm extremes TMAXmean, TX90p, TXX, TMINmean, TN90p, TNX (positive with TX10p) in the JAS season. The negative phases ENSO year in the JAS season are 1995, 1996, 1998, 1999, 2000 and 2007. Figure 6-14 demonstrates the upper and lower atmospheric circulation mean anomalies of the years with negative ENSO phase. The decrease of 500 hPa height over Iran/Pakistan/Afghanistan and its extended trough over most of Arabia especially the south will likely be associated with instability. The 925 hPa wind is anomalously southeastly over most Arabia especially over the eastern/southeastern areas advecting moisture to these areas. The MSLP composite mean anomalies map supports such moisture advection as the development of anomalously low to the west of Arabia and an anomalously high pressure over Iran lead to the prevailing of the southeasterly flow. The SST is colder over Oman eastern coast while elsewhere is warmer especially over AG.

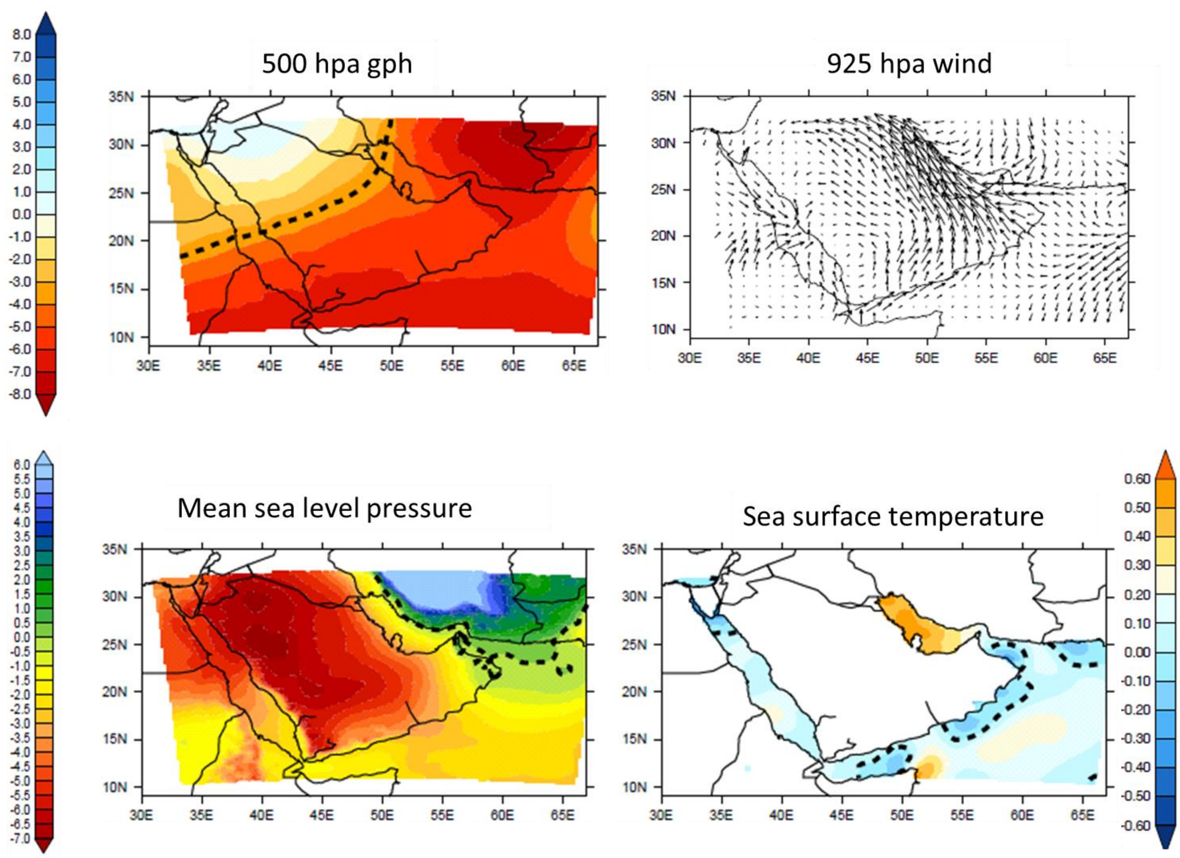

Figure 6-14: Composite mean anomalies of JAS geopotential height at 500 hPa (m), vector winds at 925 hPa, MSLP (hPa) and SST (℃) for the negative Nino3.4 years. Dashed line represents the zero value.

6.4.3.5. ON

During ON season, the correlation of ENSO is significantly positive with NMON precipitation, with nighttime warm extremes and negative with TN10p. The negative years are 1995, 1998, 1999, 2000, 2007 and 2008. The composite mean anomalies plots (Figure 6-15), depicts an increase of geopotential height at 500 hPa over northern areas and an anomalous height decrease over the AS with extended trough over south Arabia. The 500 hPa vertical velocity clearly shows major subsidising air over most areas especially the north while the southern region is influenced by uplift. The SST and total cloud composite maps show relatively warmer north AS, south RS and the AG with higher amount of cloud over the southern Arabia. ENSO is decreasing in ON season. As the correlation is positive with NMON precipitation then we expect decreasing precipitation. However, the correlation is positive with nighttime warm extremes and negative with TN10p.

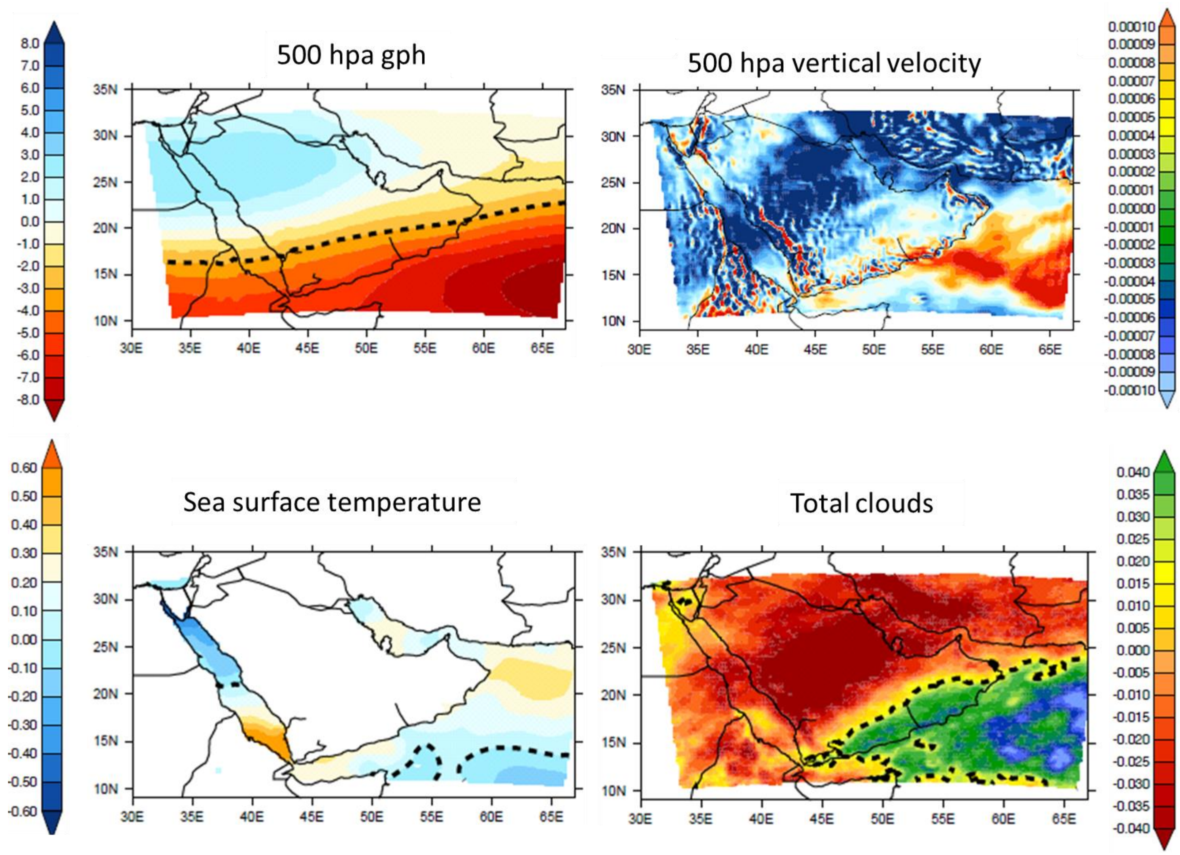

Figure 6-15: Composite mean anomalies of ON geopotential height at 500 hPa (m), vertical velocity (ms^{-1}) at 500 hPa, SST (℃) and total clouds for the negative Nino3.4 years. Dashed line represents the zero value.

6.5. Discussion

The AP experienced a climate jump in 1998 associated with abrupt increase of the regional temperature and a decrease in precipitation (Figure 1). *AlSarmi and Washington* [2011] reported that sustained negative precipitation anomalies are matched by sustained positive temperature anomalies since 1998 over the AP. The jump is evident in several variables but notably maximum temperature. *Mitchell et al*. [1966] defined a climate jump or a discontinuity as ‘‘a climate change that consists of a rather abrupt and permanent change during the period of record from one average value to another’’.

Recent temperature and precipitation trends and variability over the AP has been studied by *AlSarmi and Washington* [2011; 2013] and *Almazroui et al.* [2012a; 2012b]. It was proposed by *AlSarmi and Washington* [2011; 2013] that some changes in climate parameters might be explained by temporal changes of local atmospheric/oceanic variables and patterns of variability at the regional and hemispheric scale. The investigation in this paper, based on a regional climate model simulation and the analysis of statistical links between established large-scale modes of climate variability, does provide evidence that the observed climate trends exist for reasons discernible in other, independent data sets.

The drier conditions which have occurred over much of Arabia in winter and spring are associated with significant increases in the 500 hPa height and associated significant increase in subsidence at the same level, both of which could be expected to decrease conditions favourable for precipitation. Additionally, changes in low level circulation at 925 hPa leads to drier air advection from west Asia and northern Arabia. This could be argued to inhibit cloud formation, leading to below average precipitation and, as a consequence, increase daytime temperature extremes, consist with the observed especially in spring. *Larsen* [2008] has noted that the observed reductions in rainfall over Australia associated with the expanded influence of the high pressure system. A similar set of conditions may apply also over Arabia. The maximum temperature appears to be particularly closely linked to the decrease of precipitation in the highest rainy months/seasons as in MA season [*AlSarmi and Washington*, 2011].

There is a remarkable increase of nighttime temperature over the AP, especially during the last decade [*AlSarmi and Washington*, 2011; *AlSarmi and Washington*, 2013]. A potential link to the nighttime temperatures might lie in the sea surface temperatures of surrounding seas. *Jackson* [1988] reported that the highest SST in the world are found in the AG with summer maxima of 36.0℃ or more. Over the AG air, particularly so near the coasts, and water temperature track each other strongly [*Sheppard and Loughland*, 2002]. The composites difference maps of the SST and specific humidity show parallel increase over the adjacent seas especially the AG and RS could be responsible for increasing the nighttime temperature over the AG during summer.

The relationships between the teleconnections patterns and climate extreme indices are generally stronger for temperature indices than for the precipitation indices. In addition, the associations are stronger for the seasonal than the annual timeseries. This is in line with a similar study by *Donat et al.* [2013]. *Charabi and Al-Hatrushi* [2010] studied the link of Oman winter precipitation with the NAO during the period 1984-2007 showing that there are two factors that complicate the evaluation of Oman winter precipitation links with NAO. One is the short and erratic nature of the rainy season, as reflected by the high intra-seasonal variability. The other is related to the local effects, such as the year-to-year differences in the amount of heat released by the winter cooling of the upper layers of Mediterranean water. Precipitation is a climate element strongly influenced by local factors. Precipitation signals are therefore difficult to detect clearly and difficult to assign to corresponding underlying physical processes.

During winter the NCP correlation is significantly negative with the warm extremes and significantly positive with the cold extremes. This is in line with *Ghasemi and Khalili* [2008b] who found that the NCP has a strong negative correlation with the winter temperature in Iran. *Kutiel et al*. [2002] reported that the NCP is positively correlated with below normal temperatures and above normal precipitation in Palestine, the Balkans and the Middle East. They concluded that the NCP teleconnection is the strongest in terms of differentiating between below and above normal temperature. The composite mean anomalies of the NCP years with negative phase are consistent with the decrease of precipitation because of strong positive anomalies and induced subsidence at 500 hPa height, lower level dry air and lower cloud amount. The stations correlation with NCP teleconnection shows opposite signs between north and south Arabia during JAS season. It is negatively correlated with precipitation and warm day extremes in the north and positively correlated in the south. This indicates different atmospheric and dynamic controls affecting each region.

During the MA season ENSO is significantly positively correlated with the MON precipitation. The La Niña phase of ENSO is dominant during 1990-2008. The atmospheric circulation and SST composite mean anomalies of La Niña years partly explains the reduction in precipitation over the region. Associated with this phase of ENSO are strong positive anomalies of 500 hPa height and subsidence which, together with the anomalous northerly flow at lower level (925 hPa), and the presence of cold SST over west AS, appears to have stabilised the atmosphere. Elements of these circulation anomalies have been noted for nearby regions, such as *Ghasemi and Khalili* [2008a] who found that during anomalously dry conditions over Iran, there was a prevalence northerly and the northeasterly winds and below normal anomaly SST over the northwestern Indian Ocean.

In MJ season, the correlation is significantly negative between ENSO and TMAXmean and positive with TX10p. Recently *AlSarmi and Washington* [2013] found that the regional TMAXmean has increased significantly and the regional TX10p has significantly decreased over the AP. The composite mean anomalies of atmospheric circulation and SST of the negative ENSO phase years (the dominant phase) suggest that possible mechanisms could relate to the strong positive 500 hPa anomalies and associated subsidence over the northern areas with drier air at lower level. In addition the composites could explain the weak warming over the eastern stations of Oman [*AlSarmi and Washington*, 2013] where an increase of humidity is evident associated with an extension of moist air located over northern AS. Other possible reasons for the reduced warming over Oman eastern stations may lie in a reduction in the SSTs due to enhanced upwelling. *Murtugudde et al.* [2007] found that the western AS coastal upwelling is shown to be demonstrably stronger for strong monsoons leading to significant surface cooling, shallower thermoclines, and deeper mixed layers.

The correlation is negative between ENSO and the warm extremes TMAXmean, TX90p, TXX, TMINmean, TN90p, TNX (positive with TX10p) in the JAS season. From the composite mean anomalies of negative JAS ENSO years, the atmospheric/oceanic patterns look similar to MJ. The correlation is more negative and stronger in TMINmean than the TMAXmean because the anomalous southeasterly flow is stronger in the JAS, advecting more humidity over the region leading to higher increase in the TMINmean than TMAXmean [*AlSarmi and Washington*, 2011]. Lower warming/cooling over Oman eastern coast station could be attributed mostly to the SST decrease as in the MJ season. An inverse relationship between summertime temperatures and ENSO is also found at 17 stations over Egypt over the period 1979–2000 [*Hasanean and Basset*, 2006].

During ON season, the correlation between ENSO NMON precipitation is significantly positive, this is in line with *Raziei et al*. [2009] who found a negative relationship between the SOI and Iran autumn precipitation. The correlation is also significantly positive with nighttime warm extremes and significantly negative with nighttime cold extremes. *AlSarmi and Washington* [2011] reported a high significant increase in the minimum temperature which reaches approximately 3-6˚C in October in both urban and rural stations over the period 1980 to 2008. The ON ENSO negative phases composite mean anomalies support the decrease of precipitation over the NMON region through the strong positive anomalies at the 500 hpa height which induces subsidence and the presence of drier air in the northern areas. The increase of nighttime warm extremes is consistent with the increase of SST in the adjacent seas as evident from the SST difference composites (Figure 6-9). In the case of ON season, it seems that the local SST changes influence is far stronger than the remote signal. More detailed studies of how ENSO and IOD phases control the Arabian climate are necessary.

The year 1998 marks a clear shift in the climate regime of AP. Given the strong links between ENSO and the climate of the AP, it is tempting to suggest that the event of 1997/1998, the largest of the observational record, marked or perhaps even induced a shift in conditions over AP. This paper finding agrees with *Donat et al.* [2013] that ENSO has a stronger effect on extremes in the eastern Arab world than in the west but it disagree that boreal winter witnesses the strongest correlation values. Reasons for this disagreement could be the number of stations comprising the area average and the data time period of the stations used.

6.6. Conclusion

With a view to understanding the circulation mechanisms of recent AP climate change, this study has analysed local changes of sea surface and atmospheric circulation over the AP using regional climate model (PRECIS) at 25 km. In an analysis of the homogeneity of standard meteorological parameters, such as mean, maximum and minimum temperatures from stations within the AP, the year 1998 stands out as a significant changepoint accounting for nearly half of all the identified significant changepoints over the period

1990-2008 inclusive. Composite difference maps between 1990-1997 and 1998-2008 give evidence for significant changes in the atmospheric circulations at the surface and upper level and the adjacent SSTs. Relative to the former period, there is an increase of 500 hPa height, enhanced subsidence and advection of northerly drier air at low level (925hpa) which seems related to a reduction in cloud formation. As a consequence temperature increases significantly especially over central, eastern and southeastern AP. The significant increase of the nighttime temperature during the later decade could be attributed to the increase of the SSTs and humidity especially over the AG during spring and summer.

Second, we assess the possible remote influence of four known global/regional teleconnections; two midlatitudinal (NAO and NCP) and two tropical (ENSO and IOD) on the recent AP climate variability and trends through examining the simultaneous seasonal rank correlation between these indices and the detrended climate extreme indices. ENSO is most strongly associated with the extreme indices, especially in the case of the temperature extremes in all the seasons except winter. NCP seems to have the strongest influence on temperature extremes during winter.

We also investigate the possible circulation mechanisms of ENSO and the NCP signal on the AP climate through composite analysis of the teleconnections during the period 1990-2008. La Niña years dominate the period 1990-2008. The composites of 500 hPa height and vertical velocity, the low level 925hpa circulation and specific humidity and the SSTs during the negative phases of both ENSO (La Niña) and NCP are all in phase with the decrease of precipitation, significant increase of the daytime extreme indices, the increase of the SSTs and the increase of the nighttime extreme indices.

The significant observed climate jump of 1998 over the AP and the associated abrupt increase of surface temperature and decrease in precipitation is of concern given that this trend may continue in the future and could be an expression of the enhanced greenhouse effect. Further model experiments are necessary in order for clarity of these respective roles to emerge.

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Chapter 7: Conclusions

7.1. Overview

Detailed knowledge of the spatial distribution of observed climate change and the climate parameters undergoing change over land areas of the planet is remarkably patchy with most of the existing research having been done for Europe and North America. The AP is one region of the world where such detailed studies have been absent. Knowledge of recent climate change signals on the AP and the processes that drive these changes is essential if we are to predict the future, assess the impacts and vulnerability and suggest adaptation policies. Given the dearth of climate change studies over the AP, owing mainly to limited data availability and quality, this thesis set out to obtain up-to date meteorological data from the in-situ meteorological stations across the AP, testing the quality and the homogeneity of the data, quantifying trends of the temperature and precipitation means and extremes and linking these to local atmospheric/oceanic variables and features of the larger-scale atmospheric/oceanic circulation.

The scope of the work was as follows:

• Quantification of recent observed trends of monthly temperature and precipitation during the past few decades and identification of most significant regions and seasons;

• Calculation of extreme indices timeseries of temperature and precipitation and quantification of trends of the most relevant indices to the AP climate;

• Evaluation a 25km regional model (PRECIS) simulation over the AP during 1990-2008 using ERA-Interim boundary condition data;

• Identification of local and remote atmospheric/oceanic controls on interannual and seasonal climate extremes variability and trends.

This concluding chapter summarises the results presented in the preceding research chapters, focusing specifically on how these address each of the research aims proposed in section 1.2. These results are drawn together to form broader conclusions in the context of the existing work in this area. Caveats and limitations to the analyses are discussed, before finally outlining the steps in the future progression of this work.

7.2. Summary of results

7.2.1. Trends of monthly AP temperature and precipitation and identify the most significant seasons and regions.

Trends of monthly temperature and precipitation are quantified using a sound non-parametric robust method. Monthly mean temperature, maximum temperature, minimum temperature and precipitation data from 21 stations at the AP's 7 countries namely Oman, UAE, Qatar, Bahrain, Saudi Arabia, Kuwait and Yemen have been quality controlled and tested for homogeneity to calculate trends during the period 1980-2008. In addition the analysis covers three stations with longest data record of more than 50 years during the period 1943-2008, namely Bahrain, Masirah and Salalah. The general pattern of the AP temperature parameter trend is one of warming, with 14 of 21 stations show statistically significant warming at 0.05 level and most at 0.01 level. The highest statistically significant mean annual warming trends are found in Oman (Sur=1.03°C $decade^{-1}$) and Emirates (Dubai=0.81°C $decade^{-1}$). The season of maximum warming in mean temperature is March to April. There is a broad statistically significant increase in mean annual maximum temperature in AP in 12 out of 21 stations with the highest trends in central and eastern/southeastern AP. Only SW AP and the Gulf of Oman do not show warming. For minimum temperature, 16 out of 21 stations show statistically significant warming trends, with the highest annual trends observed in the Emirates (Dubai=1.24°C $decade^{-1}$), northwest Oman (Sohar=1.17°C $decade^{-1}$) and Qatar (Doha=1.13°C $decade^{-1}$). The highest significant increase has occurred over the AG coastal stations. The highest monthly minimum temperature warming rate occurred in October. The general mean annual diurnal temperature range trend is negative in the AP with 6 out of 21 stations show statistically significant negative trends while 3 stations show statistically significant positive trends. Trends in mean annual precipitation are significant at only two stations which show a decrease in precipitation. In general the temperature trends are higher in the northern areas relative to the southern ones. In some cases the mountain stations reported higher significant trends than the ground stations. One striking finding is the significant regional climate jump that occurred in 1998 characterized by an increase of temperature and decrease of precipitation.

7.2.2. Temperature and precipitation related extremes and trends during the past 2-4 decades.

The trend magnitudes and significance of the recent AP temperature and precipitation related extremes have been calculated using stations records of daily precipitation, maximum temperature and minimum temperature. The data have been obtained from 6 countries of the AP namely Oman, UAE, Qatar, Bahrain, Saudi Arabia and Kuwait. The analysis will cover 3 periods, the period longer than 1970-2008 will use data from 4 stations (each of different length); the period 1970-2008 will use data from 9 stations (11 stations for precipitation) while 1986-2008 will use data from 23 stations (24 for precipitation). 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. For example the annual count when TN (daily minimum)>25ºC has increased significantly with a rate of 15.1 days decade^{-1} over the whole region, 14.7 days decade^{-1} over the NMON region and 15.3 days decade^{-1} over the MON region. 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. These changes may relate to the influence of Indian Ocean sea surface temperature on the nearby coastal stations. Most of the precipitation indices trends are weak and insignificant. However the rainfall in the AP has become more intense with longer dry spells between the more intense events. The deepening of the early summer heat low and the enhanced upwelling could explain less warming over the southern AP coastal stations. The increase in dew point temperatures over central/southwest AP could partly explain increasing nighttime temperature. It is noted that although dew point is decreasing in the southeast/south AP, nighttime temperature is increasing especially in spring and summer.

7.2.3. How accurate is a 25km regional model (PRECIS) in simulating the recent AP climate mean and extremes during 1990-2008

A PRECIS model (25km resolution) simulation forced by ERA-Interim data (1990-2008) has been run over the AP. PRECIS annual and seasonal means and extremes have been evaluated against gridded observational dataset (CRUTS3.2) and the available AP meteorological stations of temperature and precipitation. The results show that PRECIS appears to generally reproduce the regional mean climate, the temporal evolution of the regional temperature and precipitation and the temporal evolution of the regional extremes. However there are large biases in relation to some observed data sets. The results show widespread significant increasing trend of temperature associated with widespread decreasing trend in precipitation. PRECIS displays a negative bias in temperature throughout the year mostly over southwest, west and northwest AP. It displays a positive bias over the southeast and south AP relative to both stations and CRU datasets. PRECIS overestimates the precipitation over the southwestern mountains. However, it underestimates the precipitation over the southeastern mountains. These biases likely relate to interactions with the model topography in areas of steep topography. The model captures the meridional gradient patterns of the daytime (maximum) temperature trends where the northern area trends are higher and more significant than the southern areas. PRECIS simulates well the daytime extremes indices increase during the MA season but underestimates the trends during late summer (JAS). For the nighttime extreme indices, PRECIS underestimates the trend magnitude by nearly 50 % over the AP region and the NMON region. The model fails to simulate the large increase of nighttime temperature over the MON region.

7.2.4. What role do the atmospheric/oceanic variables play in influencing the recent climate extremes variability and trends over the AP

PRECIS model (25km resolution) has been used to run a simulation for the AP climate during 1990-2008 forced by ERA-Interim reanalysis data. Composite difference maps for atmospheric circulations at the surface and upper level and the adjacent SSTs between 1990-1997 and 1998-2008 are obtained to understand the mechanisms behind the 1998 climate jump over the AP. These composite maps give evidence for significant changes. Relative to the former period, there is an increase of 500 hPa height, enhanced subsidence and advection of northerly drier air at low level (925hpa) which seems related to a reduction in cloud formation. As a consequence temperature increases significantly especially over central, eastern and southeastern AP. The significant increase of the nighttime temperature during the later decade could be attributed to the increase of the SSTs and humidity especially over the AG during spring and summer. Teleconnections between the regional extreme indices and four known global/regional teleconnections; two midlatitudinal (NAO and NCP) and two tropical (ENSO and IOD) have been calculated to assess the possible remote influence of these modes on the recent extreme changes over the AP. ENSO is most strongly associated with the extreme indices, especially in the case of the temperature extremes in all the seasons except winter. NCP seems to have the strongest influence on temperature extremes during winter. The physical mechanisms behind the strong relationships of ENSO and NCP with the extreme indices have been studied which indicate that these mechanisms are physically reasonable.

7.3. Overall conclusions

Conclusions have already been made at the end of each chapter in this thesis. However, some summarising remarks will now be collated in order to present a clear picture of the outcome of this work. The work provides the first comprehensive regional synthesis of trends in monthly and daily based extremes for the AP during the recent few decades. It suggests mechanisms that might be responsible for such changes based on high resolution model simulation. Focusing on the AP region where there is a dearth of climate studies, this thesis has brought together several areas of climate science, and contributed to a number of contemporary subjects in the field. In particular it has attempted to reveal the recent AP climate changes patterns and the mechanisms behind these changes by using the up-to date regional meteorological data.

The results of this thesis provide clear evidences that the AP climate has changed during the last 30-50 years. The significant changes are associated more with the temperature parameters than with the precipitation ones. This is in broad agreement with the recent findings obtained either over the AP or nearby regions [*Almazroui et al*., 2012; *Almazroui et al.*, 2012; *Athar*, 2012; *AlSarmi and Washington*, 2013; *Donat et al.*, 2013; *Hartmann et* *al*., 2013; *Zarenistanak et al.*, 2014]. The trends pattern varies between the north and south of the AP where higher significant trends are noted in the north relative to the south. In addition, the daytime extremes show larger trends in the north while the nighttime extremes are more significant in the south. This is an aspect of the trends in climate over AP that has not previously been explored.

The AP regional climate jump on 1998 is a robust finding. This is because this jump is clearly identified in the timeseries of many temperature parameters (i.e. monthly or extremes) and different time periods (1980-2008 or 1970-2008) for several stations. The increase of nighttime temperature over the AP is remarkable especially during the last 2 decades. The increase is significant over both urban and rural stations which suggest the need for a regional climate change attribution experiments. Seasonality is also an issue to consider when studying the climate changes in the AP, for example during the recent 2 decades the increase of mean maximum temperature during MA season is higher than the mean minimum which leads to a positive DTR. The opposite is true during the summer seasons (MJ and JAS).

The high resolution PRECIS experiment presents (to a large extent) evidence of the ability of this model to reproduce the regional mean climate, the temporal evolution of the regional temperature and precipitation and the temporal evolution of the regional extremes. The results indicate that the model temperature and precipitation bias is associated with its topographical elevations errors. It appears that the 25-km resolution is not sufficient to capture these complex variations. PRECIS is less reliable in computing changes in precipitation than of temperature [*Lelieveld et al*., 2012]. Nevertheless, the strengths of the PRECIS simulations do depend on which variable, season and area is being considered. The results of the simulation experiment provide the necessary products for studying the possible circulation changes which occurred during the last 2 decades in different atmospheric and oceanic variables that proved to be important in the AP climate variability. The model simulation points to the feasibility of using high resolution climate models to investigate the physical mechanisms responsible for the recent climate changes. In addition this thesis results shows that remote modes of variability such as ENSO and NCP have contributed to the recent observed changes.

7.4. Caveats/limitations

Below the significance of data problems to the overall results and conclusions of this thesis are considered. Many of the caveats/limitations outlined in this section revolve around a lack of observational data from the AP region. It is essential to address these limitations for the future researchers to be more motivated in spending more time solving and looking for more data sources.

7.4.1 Sparse meteorological stations data and difficulties to obtain these data

In additional to the fact that much of the AP region is desert and there are very few sites with instrumental data, the region is typically affected by both the lack of high quality data and the yet relatively modest interest by the climate research community. It would be highly desirable to increase the research efforts and the number of measurement stations, make available all existing meteorological data sets and invest into quality control procedures [*Tanarhte et al*., 2012]. *Kwarteng et al*. [2009] state that long-term rainfall data and their analysis are limited in Oman and most of the Arabian Peninsula. The region covers a broad range of countries, some of which have poor data availability, quality and consistency [*Nasrallah and Balling Jr*., 1993; *Zhang et al*., 2005; *Kwarteng et al*., 2009]. Gathering the stations data for this work shows that the above problems are still present especially in the matter of obtaining the existing meteorological data. For some countries like Yemen, there is a governmental restriction of providing monthly data more than 10 years period and there is no way to obtain the daily data. Even in a more modern country like Qatar, there is a strict rule preventing sharing of daily data of more than 20 years. The current regional data sharing policy creates some difficulties in understanding the AP climate change patterns and prevents the research community obtaining the data needed for climate change analysis. If such policy continues in the future, the AP countries will fail in delivering inputs to the IPCC meetings and they will face problems in proposing suitable climate change adapting strategies.

7.4.3 PRECIS and ERA-Interim reanalysis

Although the regional model PRECIS was run at 25 km to simulate the recent AP climate during 1990-2008, the results show that in regions of complex topography the model suffers from large biases. Most of these biases occur close to the mountain ranges in the southwestern, southeastern and southern AP. This leads to positive and negative biases in both temperature and precipitation. It appears that the 25-km resolution is not sufficient to capture these complex variations. PRECIS is less reliable in computing changes in precipitation than of temperature [*Lelieveld et al*., 2012]. Even with 25 km resolution, the model does not represent atmospheric features known to affect the regional atmosphere. These include sea and land breezes, topography and convection. In addition the ERA-Interim boundary condition data are less reliable where observations networks are sparse. This is true for the AP. Many falsely believe that reanalyses represent 'observed' data. While they do incorporate more observations than would have been available at the time of the original analysis, they are nonetheless essentially model data over data sparse regions.

7.5. Future work

The results of this thesis show opportunities for future research for both the observed and the projected AP climate. The recent regional significant increase of temperature especially the nighttime temperature suggests the need for regional climate change attribution experiments. Furthermore when looking into the site specific total temperature increase, the minimum temperature increases reach approximately 3-6˚C in October in both urban and rural stations over the period 1980 to 2008. Overall, these observational data underscore the concerns about global climate change with the projections, as summarized by IPCC, having not exaggerated but in some respects actually underestimated the change [*Rahmstorf et al*., 2007]. These changes need attention by the AP communities to enable planning and adaptation. Minimum temperature is increasing faster than maximum temperature – which is a widespread finding [*Manton et al*., 2001; *Aguilar et al*., 2005; *Zhang et al*., 2005; *You et al*., 2008]. The results of Chapter 3 points to a possibility of urbanization effect on minimum temperature over the large cities during late summer. Any urban warming signal should be most evident in summer, when urban heat islands are stronger owing to greater storage of solar heat in urban structures [*Parker*, 2004]. Further work on urbanization could lead to better quantification of its contribution to the recent large significant minimum temperature increase. However the possible effects of urbanization on the rise of air temperature in Saudi Arabia for the period 1981-2010 have been investigated by *Almazroui et al*. [2013]. They found no link between the temperature increase and population increase nor with elevation at the 24 sites which are mostly located in the urban effected area but not at the city centers. This suggests that the rise in air temperature is not likely due to urbanization changes resulting from the population increases.

The roles of the seas adjacent to AP emerge as a point of interest in this research. The regional SST plots discussed in Chapters 5 & 6 provide support that further work needs to be focused on these oceanic changes. The AP atmosphere and seas are linked strongly and each component has an influence on the other. In the past two decades, rapid increases of the AG sea surface temperature have been observed, dominated by changes in summer. This corroborates the model results indicating that temperature rise are more pronounced in summer than in winter [*Lelieveld et al*., 2012]. The homogeneity results together with the relationships correlation coefficients suggest that ENSO has major role in influencing the AP climate. It might be interesting to look again in more detail at the role of ENSO in the AP seasonal climate variation. The global monthly mean surface temperature SSTs anomaly relative to 1961–1990 climatology from satellites (ATSRs) and in situ records

(HadSST3) [Hartmann et al., 2013] are shown if Figure 7-1. Black lines: the 100-member HadSST3 ensemble. Red lines: ATSR-based nighttime subsurface temperature at 0.2 m depth (SST0.2m) estimates from the ATSR Reprocessing for Climate (ARC) project. The SSTs timeseries variability shows a significant step change in the 1997/98 El Niño which looks similar to Figure 3-12. Examining the relation between the AP temperature parameters and the adjacent seas could lead to greater understanding of the cause behind the AP 1998 climate jump

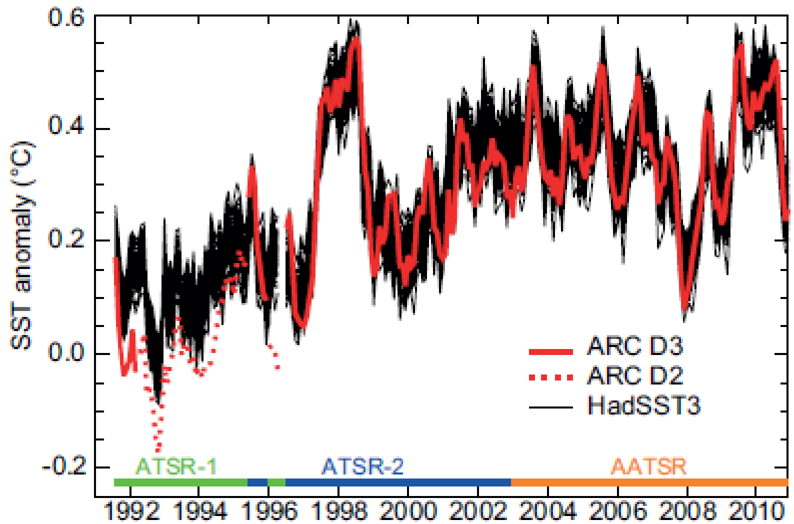

Figure 7-1: The global monthly mean surface temperature SSTs anomaly relative to 1961–1990 climatology from satellites (ATSRs) and in situ records (HadSST3). Black lines: the 100-member HadSST3 ensemble. Red lines: ATSR-based nighttime subsurface temperature at 0.2 m depth (SST0.2m) estimates from the ATSR Reprocessing for Climate (ARC) project [Hartmann et al., 2013] .

Recently *Annamalai et al.* [2013] found that the SST over the Indo-Pacific warm pool has risen during the last 5 to 6 decades. This has changed the atmospheric circulation leading to enhanced dry and cool northeasterly air advection over south Asia [*Christensen et al*., 2013]. The results of Chapters 3 & 4 confirm that the AP climate is significantly changing especially after the 1998 climate jump. Most of the daytime significant changes occur during spring while the nighttime significant changes are occurring during summer. Possible atmospheric/oceanic variable links for this have been suggested in Chapters 5 and 6. An obvious next step for this work would be to explore the future climate projections using climate models. One important task of this work would be to assess the ability of climate models to simulate processes important to the AP. Overall this research would introduce new knowledge resources for the regional community in terms of the probable shape of future climate over the region and, importantly, the degree to which the future climate results from mechanisms which are also responsible for observed climate trends. This will help in studies related to vulnerability and adaptation. A reasonable work progression is to continue using PRECIS for the climate projection work. The new version PRECIS 2.0 will include the ability for PRECIS to be driven by a subset of CMIP5 GCM experiments (GCMs which will inform the upcoming IPCC Fifth Assessment Report). The first CMIP5 model to be made available for use with PRECIS 2.0 will be HadGEM2-ES, the earth-system model from the Met Office Hadley Centre. Other CMIP5 models will be made available in due course, allowing users to select and downscale a sub-set of the ensemble. Version 2.0 will also feature a faster regional model executable and an improved user interface (http://www.metoffice.gov.uk/precis/newsletter-april-2013).

As the present study is considered as the first regional synthesis of recent AP climate trends and mechanisms of change, the results should be critical and important for the AP people. The significant observed climate jump of 1998 over the AP associated with an increase of surface temperature and a decrease in precipitation leads to a concern that such trend will continue in the future and could itself be an indication of the enhanced greenhouse impacts. These recent climate changes are alarming signals which call on the policymakers for immediate actions. Impact and adaptation studies should be arranged and the governments should play a major role in addressing the climate change challenge with coordination with all parties concerned including the scientific community.

7.6. References

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