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Recent Trends in Temperature and Precipitation in Al Jabal Al Akhdar, Sultanate of Oman, and the Implications for Future Climate Change

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Abstract

This article presents an analysis of recent trends and changes in temperature and precipitation for Al Jabal Al Akhdar, Sultanate of Oman; the first such analysis in this region. The objective is to assess the extent of observed climate change in this mountainous region over the last three decades using statistical tools, as well as providing a synthesis of future regional projections of climate change from global climate models (GCMs). A clear picture of climate change in the observed record is presented, with statistically significant increases in mean (+0.27°C/decade) and minimum (+0.79°C/decade) temperature coincident with a general decrease in precipitation (-9.42 mm/decade) from the 1979-2012 record. Climate change projections from various Intergovernmental Panel on Climate Change (IPCC) scenario families across a range of different models and time slices indicate a general increase in temperature and a decrease in precipitation over the present century. More climate change impact assessments are required to further assess the implications for environment and natural resources, especially water systems. This will better support policy- and decision-makers in evaluating and modifying existing policies in order to develop long-term strategic plans for climate change mitigation and adaptation.

Keywords: Al Jabal Al Akhdar; Climate change; Extremes; Mountains; Oman; Trends

Introduction

Analysis of observed climate data for a region bolsters assessments of future impacts associated with projected changes in climate [1] and variations in rainfall and temperature are key measures of a changing climate for any region. In their assessment report, Field et al. [2] concluded that "it is likely that anthropogenic influences have contributed to intensification of extreme precipitation at the global scale". The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change concluded that climate change impacts are projected to raise global average surface temperatures by 2.6-4.8°C by 2100 [3]. Such projected changes will have major impacts on the functioning of the world's ecosystems, and the services they provide including human society and natural systems [4,5]. The AR5 highlighted that, combined with increasing food demand, global temperature increases of 4°C or more would pose large risks to food security globally and regionally; and if temperatures increase by 3°C or more, agricultural adaptive capacity could be exceeded in regions closest to the equator [3].

Studies on the world's mountains have emphasized the sensitivity of mountain ecosystems to climate change, particularly for range-restricted species with limited dispersal abilities [6-8]. Climate change will also have increasingly net negative impacts on freshwater systems globally; by 2050, the area of land subject to increasing water stress due to climate change is projected to be more than twice that with decreasing water stress [9]. Higher water temperatures and changes in extremes, such as droughts, are projected to affect water quality and exacerbate many forms of water pollution, and thus to affect food availability, stability, access and utilization, especially in arid and semi-arid areas [10]. Results also indicate that more people will experience increased water scarcity under climate change [11]. Rockstrom et al. [12] indicate that, associated with a global mean temperature increase of ~2°C, around 59% of the world's population would be exposed to "blue water shortage" (i.e. irrigation water shortage). Despite the aridity and hence potential vulnerability of the Arab region, which extends from the Maghreb in Northwest Africa to the Arabian Peninsula, few climate change studies have been conducted. In part, this is because the region encompasses a diverse range of countries, and data quality and availability is variable [13]. A regional analysis of changes in climate extremes for the Middle East region indicates consistent changes, with a shift to more warm and less cold extremes and strong inter-annual variability in precipitation, with no significant trend [14]. Another study for the Middle East and North Africa found considerable variability in recent observations of atmospheric temperature and precipitation. However, when variability is filtered out and the underlying trend extrapolated, there is a general agreement between IPCC projections and estimates from statistical analyses [15]. Other studies on climate extremes have been undertaken in countries around the Arabian Peninsula (AP) such as Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates, and Yemen. Al Sarmi and Washington [16,17] and Al Mazroui et al. [18-20] all report warming trends in most of the meteorological station data analyzed. The region has already experienced an increase in extreme events such as warm spells, droughts, flash floods and storm surges [16]; projections indicate that, in the future, annual rainfall may decrease, and the frequency and intensity of extreme events are likely to increase [3]. Recent work by Al Sarmi and Washington [17] indicates trends of less severe cold temperature extremes and increasing warm temperature extremes from 1970-2008, and that precipitation trends were weak and insignificant; exceptions were for the annual count of days when precipitation exceeds 10 mm, which showed a significant decrease from 1986-2008. Al Mazroui et al.

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[20] showed that warming during the dry season (June to September) is faster than warming during the wet season (November to April); and that the wet season temperature is highest over the western parts of the AP. They also found that available gridded datasets detect the dry zone over the world's largest sand desert, Rub Al-Khali (Empty Quarter), during the wet season and the existing distribution of seasonal rain belts Available gridded datasets for Saudi Arabia also accurately represent the very dry (40-80 mm) area over the Rub Al Khali, and the dry (80-150 mm) area over the middle to north of Saudi Arabia, and the wettest (>150 mm) region in the southwest of the AP [20]. For the Sultanate of Oman in the south-eastern corner of the AP, no in-depth analysis of changes of temperature and precipitation study has been done at the national or sub-national scale. However, some reports indicate that the country is likely to suffer from problems such as: increased aridity and soil salinity; recurrent drought and water scarcity due to higher average temperatures; less and more erratic precipitation; sea level rise; and desertification [21,22]. Analysis of rainfall data for 1977-2003 for various regions in Oman showed that days with light rainfall (<10 mm per day) dominate, accounting for 66-95% of rainfall; rain in excess of 50 mm per day is rare. This results in flash flooding and land degradation, with serious human impacts [23]. Analysis of precipitation series by Kwarteng et al. [23] indicates that Muscat and the surrounding areas are susceptible to tropical cyclones and catastrophic rainfall (>100 mm rainfall per day) approximately every 50 years. Nevertheless, in the past decade, the landfall of two recent tropical cyclones, Gonu (June 2007) and Phet (June 2010), resulted in loss of life and damage throughout Oman's coastal areas [24]. Oman's complex topography results in local climates ranging from hyper-arid conditions in the Rub Al Khali and along the coasts and plains, to arid conditions in the foothills and highlands, semi-arid conditions along the slopes and summits of the Hajar Mountains in the north, and moderate temperatures throughout the year in the southern Dhofar region [23]. Rainfall is the main source of fresh and renewable water, especially in the mountains where elevations range from 400-3000 m Above Sea Level (a.s.l), and the mean annual rainfall is about 250-400 mm. By comparison, the average rainfall in Muscat, situated on the coast, is 75 mm [23]. Mountain areas comprise ~15% of Oman's total land area (309,500 km^2) (Figure 1); they include the northern Oman or western Al Hajar Mountains and the Dhofar or Qara Mountains in the southwest. The former are approximately 700 km long, and stretch from Musandam in the north to the coast at Ras Al Hadd in easternmost Oman and range in width from 40 to 130 km [25]. For many arid regions, mountain areas are increasingly regarded as "water towers" with a vital role in providing the rainfall which supports food production for growing populations [26]. Rainfall in the mountains is the main source of fresh and renewable water, and both rainfall and temperature are key controls on water resources, determining water availability. Nonetheless, despite the high sensitivity of Oman's water resources to climate change, no attempt has been made to analyze changes in temperature and rainfall in the country's mountains. Addressing this is our primary objective, and we present an analysis of recent changes in key climate variables over the last 34 years in Al Jabal Al Akhdar, the highest part of the Al Hajar Mountains, and consider possible future trends. Oman is a 1,000-mile-long (1,700 km) coastal plain at the southeast tip of the Arabian Peninsula lying on the Arabian Sea and the Gulf of Oman. It is bordered by the United Arab Emirates, Saudi Arabia, and Yemen. The country is the size of Kansas [27].

The Study Area

Al Jabal Al Akhdar (Green Mountain) is the largest upland massif in the western Hajar Mountains of the Sultanate of Oman (Figure 1). Elevations range from 1500 to 3075 m a.s.l. at Jabal Shams; the Mediterranean climate and agricultural terraces enable the production of perennial fruits, especially pomegranate as well as date palm (grown at lower altitudes) and roses, and these are the primary source of income for local farmers [28]. The area also has a wide range of native habitats and flora and fauna that are not found elsewhere in Oman [29]. Average annual temperatures are 10-12°C lower than on the coastal plains. Mean monthly temperatures drop during winter to below 0°C and rise in summer to around ~22°C [30]. This cool climate and the availability of agricultural terraces have made Al Jabal Al Akhdar a place of special significance for the Omani people and an important tourist attraction. There are two distinct rainfall seasons: the winter season from mid-November through March, and the summer season from mid-June through mid-September. In winter, the prevailing air mass flow is from the north, with generally low moisture content. This general situation is occasionally interrupted by short-lived synoptic conditions when cyclonic fronts bring several days of widespread rainfall. Thus, seasonal total receipts fluctuate depending upon the frequency and intensity of these systems. In contrast, summer rainfall is associated with south-westerly airflows, resulting in heavy convective afternoon rainfall. These events are more intense than in winter, although the latter tend to last longer [30]. Rainfall is the main source of freshwater resources in the area, feeding groundwater, *aflaj*, and *wadis* [28]. Groundwater is accessed via wells established by a government agency which supplies the water to local communities through networks or water trucks. These wells are the main local source of water for drinking and domestic purposes (municipal, commercial). *Aflaj* (singular *falaj*) are surface or underground channels fed by groundwater, springs, or streams, built to provide water for agriculture [31]. Local people manage and distribute the *aflaj* water to farming areas; government agencies are not involved in these indigenous governance structures [31]. *Wadis* are seasonal

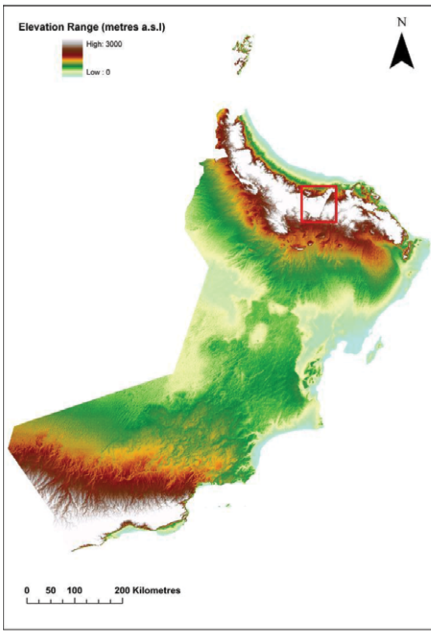

Figure 1: Digital elevation map of the Sultanate of Oman [45]. The Al Jabal Al Akhdar study area is shown in red.

valleys or dry ephemeral riverbeds that contain water only during times of rainfall or intermittent stream formation, and are intercepted by artificial surface storage dams. Water from *aflaj* and dams is mainly used for agriculture and livestock. The continued provision of fresh water to meet the demands of the domestic and agricultural sectors is the greatest challenge facing the study area. The total water consumption for the North Halfayn water catchment area (867 km^2), which includes Al Jabal Al Akhdar (404 km^2), is estimated to be 14 Million m^3/year, with agriculture accounting for 12.90 Million m^3/year and the remainder for urban use; the imbalance between supply and demand results in a water deficit of 9.69 Million m^3/year [32]. Al Jabal Al Akhdar has experienced rapid socioeconomic development and urbanization in recent decades. These changes have in turn impacted the water resources which support ecosystems and hence human well-being. Aside from the direct consequences of climate change, these impacts on provisioning ecosystem services and water resources have profound implications for the future sustainability of the region.

Materials and Methods

Station data series

A 34-year record of monthly minimum (T_{min}), maximum (T_{max}) and mean temperatures (T_{mean}), alongside the monthly precipitation record (Precip) for the period 1979-2012 from the only meteorology station in the area, at Saiq (1986 m a.s.l., part of Oman's national climate monitoring network), were analysed. The quality of data was carefully checked and any missing values documented. The monthly series were substantially intact with the exception of some missing values for Precip in November 2003; T_{min} in September and October 2003, T_{mean} in September-November 2003 and T_{max} in November 2003. No physically implausible data readings, e.g., negative rainfall or maximum temperature less than minimum temperature, were noted. After the quality control procedures, a number of Exploratory Data Analysis (EDA) protocols were applied. All the data series were checked for the normality or otherwise of the distribution of the monthly values. The Precip series for all months were strongly positively skewed; and although many of the monthly temperature series approximated a normal distribution, some months were negatively skewed. Monthly, seasonal and annual trends were calculated for each series based on the mean monthly values. In addition, linear trends were derived based on the monthly. Anomaly (relative to the series mean) data for T_{min}, $T_{max,}$ $T_{mean,}$ and Precip. A two sample t-test analysis of variance (ANOVA) was performed by splitting the data into two periods of 17 years each (1979-1995, 1996-2012); and a further two periods (1979-1996, 1998-2012) excluding 1997, a year with abnormally high precipitation. This analysis was extended by splitting the series into three decades (1979-1989, 1990-2000, and 2001-2012). In addition, and since the EDA indicated a departure from normality for some of the series (particularly Precip), non-parametric tests were conducted for the same analysis periods. This was important as t-tests assume that the observations in each group are normally distributed [33] and the sample sizes in each group, once the data series were split, were small. For all the between-period analyses, the statistical significance was set at 5% (α=0.05).

Climate change data projections for the region

To assess projections of future changes in surface air temperature and precipitation over the Sahara Region as defined by the IPCC, which incorporates projections for Oman, outputs from seven coupled atmosphere-ocean general circulation models (AOGCMs) were downloaded from the IPCC Data Distribution Centre [34]. Scenario outputs for the A2, B2, A1F1 and B1 families were used to describe the range of projected changes to temperature and precipitation.

Results

As part of the EDA, a series of waisted boxplots for each of the monthly data series were used to visualize the median and spread of the data, and to detect any outliers (Figure 2). As would be expected given the greater skew in the precipitation data, there were more outliers for all months, although some months for the temperature series also had outlying data points. A number of R-based routines (R Development Core Team 2013) were also used to conduct an exploration of the series via combined anomaly and smoothed plots for all the months available. These usefully summarized the characteristics of the series prior to a more detailed statistical analysis (Figure 3) as described in the following sections.

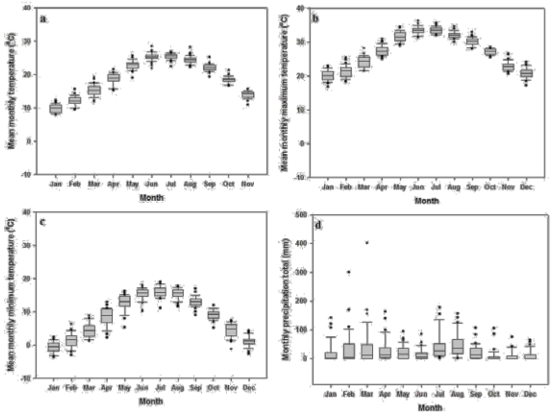

Figure 2: Boxplots for the Saiq temperature and precipitation monthly series. a) Mean monthly temperature (T_{mean}); b) Mean monthly maximum temperature (T_{max}); c) Mean monthly minimum temperature (T_{min}); d) Total monthly precipitation (Precip). Boxes: interquartile range; whiskers 5th and 95th percentiles.

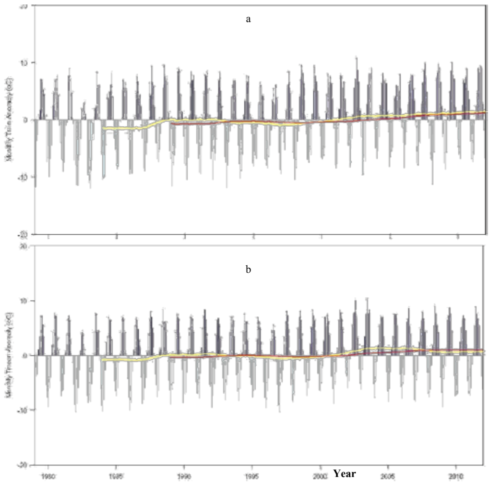

Figure 3: Anomaly plots for the Saiq temperature raw monthly series. a) Mean monthly minimum temperature (T_{min}); b) Mean monthly temperature (T_{mean}). Blue bars: monthly anomalies from series means. Yellow line: five year running mean for series. Red line: ten year running mean for series.

Analysis of temperature series and trends

Analysis of temperature series from 1979 to 2012 showed increases in minimum, mean, and maximum temperatures (Figure 4); the rates of increase were 0.79, 0.27 and 0.15°C per decade, respectively. The analysis also shows February to April temperature ranges of 12.1-18.7°C and ~25°C during July and August. Minimum temperatures range from -0.6°C in January to 15.9°C in July, and maximum temperatures range from 20.3°C in January to 33.5°C in July. A comparison of the data for 1979-1995 and 1996-2012 showed highly significant differences ($p<0.05$) in annual mean (Table 1) and minimum (Table 2) temperatures and for some months; no significant differences were found between these two periods with regard to maximum temperature. A comparison of the data between the three decades (1979-1989, 1990-2000, 2001-2012) showed highly significant differences ($p<0.05$) in annual mean temperature between the first and third decades and for monthly mean temperature in February, March, May, July, September and November (Table 3). Highly significant differences in annual mean temperatures were also observed between the second and third decades and for monthly mean temperature in March, September and October. There were significant differences in the annual minimum temperatures between the first and third decades, but not between the second and the third decades (Table 4). Significant differences ($p<0.05$) were also found in monthly minimum temperatures for April, September and November between the first and third, and the second and third decades. Maximum temperatures were not significantly different between the three decades, other than for annual temperature between the first and second decade and the month of July ($p<0.05$). The t-test analysis statistically confirmed increases in both minimum and mean temperatures, which reflect global [3,35] and national [36] trends.

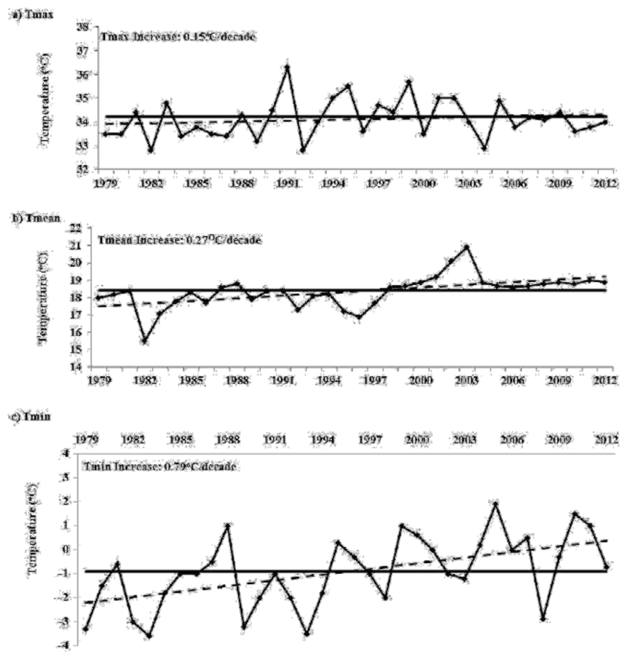

Figure 4: Saiq time series plots 1979-2012 for a) maximum, b) mean, and c) minimum temperatures. Solids lines and diamonds denote annual means; linear dashed lines denote the trends.

Month	Period	Mean	Std. Deviation	Minimum	Maximum	p-Value
Feb	1979-1995	11.46	1.31	9.40	14.30	0.004
	1996-2012	12.76	1.17	10.90	15.60	
	Total	12.11	1.39	9.40	15.60	
Mar	1979-1995	14.58	1.67	120.00	18.70	0.024
	1996-2012	15.88	1.52	13.20	19.20	
	Total	15.23	1.71	120.00	19.20	
Apr	1979-1995	180.09	1.65	15.20	20.50	0.027
	1996-2012	19.31	1.40	15.50	21.60	
	Total	18.70	1.63	15.20	21.60	
May	1979-1995	22.22	10.09	190.00	23.70	0.005
	1996-2012	23.44	1.26	20.80	25.70	
	Total	22.83	1.31	190.00	25.70	
Jul	1979-1995	250.00	0.89	22.50	26.40	0.005
	1996-2012	25.82	0.71	23.80	26.90	
	Total	25.41	0.90	22.50	26.90	
Aug	1979-1995	24.11	0.92	22.20	25.30	0.034
	1996-2012	24.94	1.23	22.70	28.20	
	Total	24.52	1.15	22.20	28.20	
Sep	1979-1995	21.56	0.93	19.30	23.10	0.001
	1996-2012	22.70	0.89	21.50	25.20	
	Total	22.11	10.07	19.30	25.20	
Oct	1979-1995	17.97	0.84	16.60	19.50	0.007
	1996-2012	18.88	0.94	170.00	21.30	
	Total	18.43	0.99	16.60	21.30	
Nov	1979-1995	13.53	10.09	10.90	15.60	0.011
	1996-2012	14.44	0.79	12.70	15.70	
	Total	13.97	10.05	10.90	15.70	
Annual	1979-1995	17.88	0.78	15.50	18.80	0.001
	1996-2012	18.84	0.84	16.90	20.90	
	Total	18.36	0.94	15.50	20.90	

Table 1: Summary of the statistical analysis between the two periods: 1979-1995 and 1996-2012, and associated significance (p-values) for mean monthly temperature. Statistically insignificant months are excluded.

Analysis of precipitation series and trends

The analysis of Precip data from 1979 to 2012 showed an overall decrease in rainfall, at a rate of 9.42 mm per decade. Over this period, the average annual rainfall was 296.7 mm, with the highest total (901 mm) recorded in 1997 (Figure 5). The plot of 5-year moving averages of annual rainfall indicates a general decrease from 355.20 mm in 1982 to 263.40 mm in 1988, followed by an increase to 502.28 mm in 1998; and then an almost continual decrease, to 176.4 mm in 2012 (Figure 5). The boxplot showed that the monthly precipitation data are not normally distributed, with the presence of several outliers. Over the entire period, the three wettest months are February to April; on average, these have more than 36% of the total annual rainfall. A second relatively wet period occurs during July and August, accounting for a further 30% on average. From 1979 to 2012, the highest monthly averages were 45.8 and 42 mm during August and July; the lowest were 8.8 and 8.2 mm during October and November, respectively. However, in recent years, the winter (February to April) maximum has almost disappeared. A comparison of data for 1979-1995 (average rainfall: 340 mm) and 1996-2012 (average rainfall: 253 mm) showed no significant differences in annual and monthly rainfall. However, when the highest annual rainfall of 901 mm in 1997 was excluded, there were highly significant differences ($p<0.01$) in the annual rainfall between 1979-1996 (average rainfall: 341 mm) and 1998-2012 (average rainfall: 203 mm). The August rainfall also showed significant difference between these two periods ($p<0.05$). A comparison of the rainfall data between the three decades – 1979-1989, 1990-2000 (including 1997) and 2001-

Month	Period	Mean	Std. Deviation	Minimum	Maximum	p-Value
Jan	1979-1995	-1.47	1.48	-3.60	10.00	0.000
	1996-2012	0.36	1.20	-20.00	2.40	
	Total	-0.55	1.62	-3.60	2.40	
Feb	1979-1995	0.52	1.98	-30.00	4.80	0.018
	1996-2012	2.22	20.02	-2.90	6.30	
	Total	1.37	2.15	-30.00	6.30	
May	1979-1995	11.66	2.61	5.30	150.00	0.008
	1996-2012	13.74	1.58	100.00	16.20	
	Total	12.70	2.37	5.30	16.20	
Aug	1979-1995	14.82	1.66	11.50	170.00	0.020
	1996-2012	160.04	1.22	13.30	17.70	
	Total	15.43	1.56	11.50	17.70	
Sep	1979-1995	12.24	1.35	90.00	140.00	0.001
	1996-2012	13.94	1.39	120.00	170.00	
	Total	130.06	1.60	90.00	170.00	
Oct	1979-1995	8.44	1.28	5.20	100.00	0.001
	1996-2012	9.89	10.06	80.00	120.00	
	Total	9.17	1.37	5.20	120.00	
Nov	1979-1995	3.16	1.94	-1.20	60.00	0.000
	1996-2012	5.74	1.47	2.70	7.40	
	Total	4.45	2.14	-1.20	7.40	
Annual	1979-1995	-1.68	1.35	-3.60	10.00	0.002
	1996-2012	-0.16	1.24	-2.90	1.90	
	Total	-0.92	1.49	-3.60	1.90	

Table 2: Summary of the statistical analysis between the two periods: 1979-1995 and 1996-2012, and associated significance (p-values) for minimum monthly temperature. Statistically insignificant months are excluded.

2012 – showed highly significant differences ($p<0.01$) in the annual rainfall between the second decade (average rainfall: 422 mm) and third decade (average rainfall: 176 mm). There were highly significant differences ($p<0.05$) in August rainfall between the second decade (1990-2000) and the third decade (2001-2012).

Implications for future climate change

The range of projected changes for standard climatological seasons – December-February (DJF), March-May (MAM), June-August (JJA), September-November (SON) – are summarized for three future time slices (2010-2039, 2040-2069, 2070-2099) relative to the 1961-1990 climatological baseline period (Appendices, Figures A1-A4). Projections from different GCMs for the region using IPCC A2, B2, A1F1 and B1 scenarios for 2020, 2050 and 2080 indicate mean annual temperature increases from 1.32°C in 2020 to 4.12°C in 2080. The range of projected temperature increases are 1.98-3.43°C, 1.74-2.92°C, 2.44-3.80 and 1.45-2.61°C for the A2, B2, A1F1 and B1 scenarios respectively. A comparison between seasons for these scenarios showed that the temperature changes ranged from 0.60-6.11°C, 0.82-7.47, 0.90-6.72°C and 0.75-6.92°C for winter, spring, summer and autumn, respectively (Table 5).

For the same future periods, projected precipitation changes varied considerably in both magnitude and direction between scenarios, ranging from -15.70 to 91.26% (A2), -16.45 to 72.50% (B2), -19.59 to 109.38% (A1F1), and -12.04 to 60.49% (B1). Projected seasonal precipitation changes ranged from -51.67 to 66.41%, -75.86 to 55.86, -31.97 to 411.00% and -34.13 to 528.70% for DJF, MAM, JJA and SON, respectively (Table 5).

Discussion

Detected changes in climate and comparisons with other work

The t-test results confirmed statistically significant increases in both minimum and mean temperatures, with the greatest warming detected in recent decades (1998-2012). This recent significant warming is in agreement with observations globally [3,37], for other arid countries, regionally for the Arabian Peninsula (AP) [16-20] and for other locations in Oman [23,36]. The temperature increase in the study area is also in line with greater increases inland compared to coastal regions; over the past two decades, land surfaces have warmed at about 0.27°C per decade versus 0.13°C over the oceans [37]. Our station data analysis of mean surface temperature for 1979 to 2012 showed exactly the same trend of 0.27°C/decade. Overall, Al Sarmi and Washington [16] concluded that trends at Saiq were ~1.5 to 3.5 times greater than global land mean trends. An analysis of 21 meteorological stations across the AP found statistically significant trends in mean annual temperature, with the highest rate of winter warming (0.85°C/decade) at Saiq from 1980-2008 [16,17]. However, the rate of change at this station was least significant for mean annual maximum temperature (0.27°C/decade); for mean annual minima, warming trends exceeding 1.00°C/decade were recorded for 1989-2008 [16]. Significant warming of 1.20°C/decade was also recorded for Saiq in December, January and February. Al Sarmi and Washington [16] also report that the warming trends for mean annual minima in the AP are significant and more spatially coherent across the 21 stations, including Saiq, than those for annual maxima and mean temperatures. For example, the December, January and February warming at Saiq of 0.85°C/decade may be compared to a rate of 0.70°C/decade for Khamis Mushait station at 2000 m a.s.l in Saudi Arabia; compared to the lowland Sohar station (3.6 m a.s.l.) in Oman, the rate of late summer warming is five times greater. Almazroui et al. [19,20] analyzed annual and seasonal temperature over the AP and Saudi Arabia for 1978-2009 and showed significant increases in the annual maximum, mean and minimum temperature trends, at rates of 0.71, 0.60 and 0.48°C/decade, respectively. Also for Saudi Arabia, but for 1979-2008, Athar [38] reported a greater increase in the frequency of high temperature extremes than for cold temperature extremes. The temperature-based indices were statistically more significant for decadal trends than the precipitation-based indices [39]. Compared with temperature, the trends for precipitation in the study area are statistically insignificant when the two periods 1979-1995 and 1996-2012 are compared. However, there was a decrease in precipitation from 1979 to 2012. Al Sarmi and Washington [16,17] also recorded a general decrease in precipitation over the AP; Almazroui et al. (2012a) identified a decrease in precipitation of 47.8 mm/decade from 1994 to 2009 for the AP and Saudi Arabia; Kwarteng et al. [23]. Observed negative trends in general, but statistically insignificant rainfall trends in Oman from 1977 to 2003. Al Sarmi and Washington [16] reported statistically significant decreases in total annual precipitation at a rate of ~67.71 mm/decade, with the greatest monthly decreases in March and April (~10.23 mm/decade). Overall, the results for precipitation trends here are presented at a lower level of statistical significance and hence confidence than temperature changes. However, we only had one station series at the limited resolution of monthly data for a climatic variable which generally exhibits high space-time variability. It is therefore unlikely to be representative of overall precipitation in a topographically diverse arid mountain area. The annual mean temperature and total annual precipitation regimes of the study area are very closely correlated ($r=-0.60$, $p<0.01$). Sustained negative precipitation anomalies are matched by sustained positive temperature

Month	Decade	Mean	Std. Deviation	Minimum	Maximum	p-Value		
						1&2	1&3	2&3
Feb	**1.** 1979-1989	11.40	1.53	9.40	14.30	0.643	00.022	0.159
	2. 1990-2000	11.91	10.03	10.40	13.80			
	3. 2001-2012	12.95	1.18	11.20	15.60			
	Total	12.11	1.39	9.40	15.60			
Mar	**1.** 1979-1989	14.78	1.83	12.30	18.70	0.797	00.04	00.008
	2. 1990-2000	14.35	1.29	120.00	16.20			
	3. 2001-2012	16.43	1.27	14.60	19.20			
	Total	15.23	1.71	120.00	19.20			
May	**1.** 1979-1989	22.15	1.24	190.00	23.70	0.732	00.01	00.065
	2. 1990-2000	22.54	1.22	20.80	25.10			
	3. 2001-2012	23.72	10.01	21.70	25.70			
	Total	22.83	1.31	190.00	25.70			
Jul	**1.** 1979-1989	24.95	0.99	22.50	26.20	0.659	00.021	0.146
	2. 1990-2000	25.27	0.87	23.80	26.40			
	3. 2001-2012	25.96	0.53	250.00	26.90			
	Total	25.41	0.90	22.50	26.90			
Sep	**1.** 1979-1989	21.60	10.05	19.30	23.10	0.878	00.007	00.024
	2. 1990-2000	21.80	0.72	20.50	22.90			
	3. 2001-2012	22.94	0.94	21.60	25.20			
	Total	22.11	10.07	19.30	25.20			
Oct	**1.** 1979-1989	18.12	0.95	16.70	19.50	0.972	00.056	00.029
	2. 1990-2000	180.03	0.76	16.60	190.00			
	3. 2001-2012	19.10	0.95	17.90	21.30			
	Total	18.43	0.99	16.60	21.30			
Nov	**1.** 1979-1989	13.44	1.28	10.90	15.60	0.654	00.017	0.121
	2. 1990-2000	13.81	0.84	12.70	14.90			
	3. 2001-2012	14.66	0.56	13.50	15.70			
	Total	13.97	10.05	10.90	15.70			
Annual	**1.** 1979-1989	17.85	0.91	15.50	18.80	0.841	00.001	00.007
	2. 1990-2000	180.04	0.67	16.90	18.90			
	3. 2001-2012	19.13	0.68	18.60	20.90			
	Total	18.36	0.94	15.50	20.90			

Table 3: Summary of the statistical analysis between the three decades: 1979-1989, 1990-2000 and 2001-2012, and associated significance (p-values) for mean monthly temperature. Statistically insignificant months are excluded.

anomalies, especially from 1998 to 2012. This matches results for other arid regions where negative associations between precipitation and temperature regimes have been detected, with warmer years being drier and vice versa [40]. Although the results for mean and minimum temperatures are statistically significant, this is not the case for maxima. Al Sarmi and Washington [16] also report no significant increase in maxima for two of the mountain stations in their AP study. Reasons for the behaviour of maximum temperature trends are unclear, whereas the trend in the mean temperature for our study is linked to the increase in minima and reflects a commonly detected pattern (e.g. Zhang et al. [14]; Labraga and Villalba [41]). Since changes in rainfall and temperature over 30 years are considered a reasonable baseline over which to gauge a changing climate [42,43], this study indicates that the changes in the climate of Al Jabal Al Akhdar parallel changes reported from other locations around the AP. The changes in the temperature and precipitation of the study area detected through our analyses are also in line with global and national projections. For example, Alexander et al. [35] reported globally widespread significant changes in temperature extremes, with wider warming over the 20th century, especially for minima; while maxima showed similar changes, the magnitudes were smaller. Precipitation changes also showed widespread and significant increases, but these were much less spatially coherent than changes in temperature.

Climate change projections for the region

The projected trends of an increasing temperature and a general decrease in precipitation for the study area are in agreement with other projections in the AP. A dynamically downscaled projection for the ECHAM5 A1B scenario output for 2021-2070 via the regional climate model (RCM) PRECIS indicates a mean temperature increase of ~0.65°C/decade [18]. PRECIS results are in good agreement with the IPCC precipitation projection for the AP; the northern and central areas tend to become drier, and the southeastern parts to become wetter, which may lead to an increase in the extreme events. The results also indicate more extreme rainfall events in the coastal areas along the central parts of the Red Sea and the south-south western areas of Saudi Arabia, and that the northern and central parts of the country may experience increased [18]. In an application of the MIROC GCM integrating four Representative Concentration Pathways (RCPs) for a 2080-2099 time slice, projected mean warming ranged from 0.93°C for the lowest RCP to 3.1°C for the highest RCP [44]. For the same model and RCP projections, precipitation totals indicate a decrease by around -36% during the periods 2080-2099 compared to the 1986-2005 baseline data for Muscat airport meteorological [44]. Based on an IPCC A1B scenario for 2011-2040 and 2041-2070, maximum temperature is projected to increase by1-2°C for Oman as a whole by 2040 and 2-3°C

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Month	Decade	Mean	Std. Deviation	Minimum	Maximum	p-Value		
						1&2	1&3	2&3
Jan	**1.** 1979-1989	-1.61	1.51	-3.60	10.00	0.326	00.003	0.107
	2. 1990-2000	-0.71	1.52	-3.50	1.50			
	3. 2001-2012	0.56	1.11	-1.20	2.40			
	Total	-0.55	1.62	-3.60	2.40			
Mar	**1.** 1979-1989	4.53	2.20	1.40	8.20	0.343	0.548	00.044
	2. 1990-2000	3.27	1.14	1.70	4.60			
	3. 2001-2012	5.44	2.33	1.20	8.90			
	Total	4.44	2.12	1.20	8.90			
Apr	**1.** 1979-1989	7.60	30.09	2.30	12.90	0.978	00.04	00.025
	2. 1990-2000	7.39	20.08	3.20	9.50			
	3. 2001-2012	10.16	1.49	6.70	12.10			
	Total	8.44	2.57	2.30	12.90			
May	**1.** 1979-1989	11.13	30.04	5.30	150.00	0.338	00.002	00.061
	2. 1990-2000	12.39	1.25	100.00	14.80			
	3. 2001-2012	14.43	10.09	12.40	16.20			
	Total	12.70	2.37	5.30	16.20			
Sep	**1.** 1979-1989	12.45	1.44	90.00	140.00	1	00.016	00.016
	2. 1990-2000	12.45	1.21	100.00	140.00			
	3. 2001-2012	14.27	1.49	120.00	170.00			
	Total	130.06	1.60	90.00	170.00			
Oct	**1.** 1979-1989	8.38	1.57	5.20	100.00	0.492	00.018	0.185
	2. 1990-2000	90.03	1.19	7.50	120.00			
	3. 2001-2012	100.02	0.86	80.00	110.00			
	Total	9.17	1.37	5.20	120.00			
Nov	**1.** 1979-1989	3.13	20.09	-1.20	5.50	0.557	00.001	00.02
	2. 1990-2000	3.95	1.96	1.50	70.00			
	3. 2001-2012	6.13	1.11	40.00	7.40			
	Total	4.45	2.14	-1.20	7.40			
Annual	**1.** 1979-1989	-1.68	1.45	-3.60	10.00	0.577	00.031	0.246
	2. 1990-2000	-10.06	1.36	-3.50	10.00			
	3. 2001-2012	-00.08	1.30	-2.90	1.90			
	Total	-0.92	1.49	-3.60	1.90			

Table 4: Summary of the statistical analysis between the three decades: 1979-1989, 1990-2000 and 2001-2012, and associated significance (p-values) for minimum monthly temperature. Statistically insignificant months are excluded.

by 2070 [36]. The A1B scenario indicates that minimum temperatures will increase most and that, by 2070, most of the land south of the Hajar Mountains from the United Arab Emirates border to the Arabian Sea will experience an increase in average minimum temperature of about 3°C [36]. Precipitation change projections for the same scenario indicate that most of Oman will become drier, with large portions of the Al Hajar Mountains receiving up to 40 mm less annual rainfall than at present [36]. If realized, these changes will accelerate and amplify the trends we detect for the Al Jabal Al Akhdar region. Our work and results here also lend credence to many of the GCM- and RCM-projected changes for the region, insofar as the projections appear to support a continuation of the detected changes in climate already underway.

Conclusions and Recommendations

During the past three decades, a significant increase in mean annual temperatures has been recorded at the Saiq meteorology station in Al Jabal Al Akhdar; these are primarily linked to increases in minimum temperatures. The increase in temperatures is statistically significant and is increasing more for maximum temperatures. Broadly, the detected changes in temperature and precipitation and their trends are in agreement with rate and magnitude of climate change projections for the region from various GCMs and RCMs. The differences in the precipitation projections between the models and scenarios are much more variable than the consistent increases projected for temperatures. These findings could be further improved by applying more GCMs,

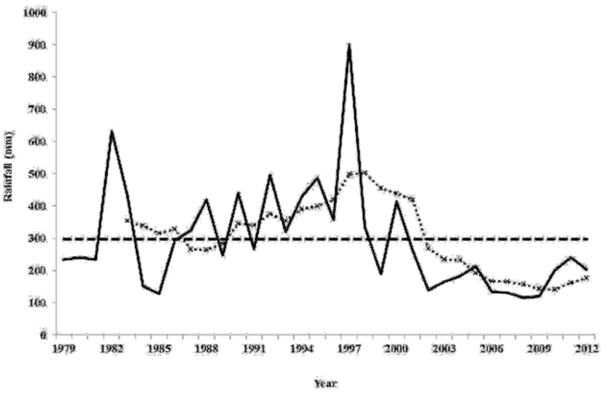

Figure 5: Annual observed precipitation for Saiq 1979-2012. The solid line denotes annual totals relative to the series annual mean (dashed line). The dotted line and crosses denote the 5-year moving average.

Scenario	Season	Tmean Range (°C)			Precipitation Range (%)		
		Min	Mean	Max	Min	Mean	Max
A2	**DJF**	0.60	2.60	5.76	-41.34	0.73	66.41
	MAM	1.14	2.79	6.85	-60.68	-6.51	43.30
	JJA	0.90	2.87	5.34	-25.58	45.75	256.59
	SON	10.01	2.96	5.49	-27.30	50.94	346.83
B2	**DJF**	0.94	2.29	4.46	-36.67	-8.40	17.92
	MAM	0.89	2.39	4.85	-57.18	-8.78	510.05
	JJA	1.16	2.44	4.13	-16.89	42.16	170.41
	SON	10.01	2.50	4.25	-16.29	43.31	229.30
A1F1	**DJF**	10.05	3.29	6.11	-51.67	-130.05	25.96
	MAM	1.25	3.46	7.47	-75.86	-190.09	55.86
	JJA	0.98	3.44	6.72	-31.97	710.03	4110.00
	SON	0.89	3.41	6.92	-34.13	78.14	528.70
B1	**DJF**	0.81	20.00	3.69	-32.26	-16.61	40.00
	MAM	0.82	2.14	4.32	-44.13	-12.67	41.35
	JJA	10.00	2.13	3.63	-17.28	44.96	167.90
	SON	0.75	2.12	3.57	-13.19	53.44	240.68

Table 5: Projected seasonal temperature and precipitation changes over the Sahara Region for 2020, 2050 and 2080 time slices based on IPCC A2, B2, A1F1 and B1 scenarios for GCM models.

which may project potential changes over a more consistent range. This study represents the first complete analysis of long-term temperature and precipitation data (more than 30 years) in the mountains of Oman, which should help inform future climate change impact studies at a local scale. However, further analysis of the possible differential impacts of climate change between the upland and lowland regions of Oman is needed. Greater rainfall variability and longer drought periods may adversely impact the area's fragile and vulnerable mountain ecosystems, and there is future scope for the results of this study to be integrated with hydrological models so that drought scenarios can be developed for future time periods. There is also considerable scope for integrating statistically or dynamically downscaled output from various GCM and RCM combinations in order to refine projections for the region. As for other mountain regions globally, especially those in arid regions [26], there is a pressing need to assess and refine climate change projections for this and other mountainous regions in Oman. In particular, there is an urgent need to understand how climate extremes will change, in order to assess the future implications for vulnerable ecosystems and a water resource infrastructure already under considerable pressure. With climate change, it is reasonable to expect that preventing groundwater degradation and balancing supply and demand will become even greater challenges, adding uncertainty and further complexity to the planning and the management of water resources in the region. Therefore, one key recommendation to policy and decision-makers is to implement an integrated water resources management approach alongside policies to effectively implement national adaptation and mitigation measures. A specific action plan for adaptation, with a focus on the challenge of sustaining a unique mountain ecosystem under climate change, is also required. This needs to be based on more detailed analysis of data characterizing the changing climate, not only at a monthly resolution, but also at a finer temporal resolution and addressing extreme events.

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