

Potential changes in the number of wet days and its effect on future intense and annual precipitation in northern Oman

Luminda Niroshana Gunawardhana, Ghazi A. Al-Rawas, Andy Y. Kwarteng, Malik Al-Wardy and Yassine Charabi

ABSTRACT

The changes in the number of wet days (NWD) in Oman projected by climate models was analyzed, focusing mostly on variation of precipitation intensity and its effect on total annual precipitation (PTOT) in the future. The daily precipitation records of 49 gage stations were divided into five regions. Of the five general circulation models studied, two of them were selected based on their performance to simulate local-scale precipitation characteristics. All regions studied, except the interior desert region of the country, could experience fewer wet days in the future, with the most significant decreases estimated in southern Oman. The contribution from the cold frontal troughs to the PTOT in the northeast coastal region would decrease from 85% in the 1985–2004 period to 79% during the 2040–2059 period and further decrease to 77% during the 2080–2099 period. In contrast, results depict enhanced tropical cyclone activities in the northeast coastal region during the post-monsoon period. Despite the decreases in the NWD, PTOT in all regions would increase by 6–29% and 35–67% during the 2040–2059 and 2080–2099 periods, respectively. These results, therefore, show that increases in precipitation intensity dominate the changes in PTOT.

Key words | cold frontal troughs, CMIP5, orographic precipitation, tropical cyclone

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INTRODUCTION

Precipitation regimes across a range of space-time scales have changed in many parts of the world. These variations at inter-annual and decadal scales have been detected in Asia (Naidu *et al.* 2015), America (Coopersmith *et al.* 2014), Europe (Haren *et al.* 2013), and the Arabian Peninsula (AlSarmi & Washington 2013). Increasing frequency of these climatic anomalies might have positive or disastrous consequences, especially for the countries suffering from water scarcity. Miguel *et al.* (2004) indicated that growth in gross domestic product in sub-Saharan African countries due to positive rainfall variations during the 1981–1999 period decreased the likelihood of civil war. The increase

or decrease in total precipitation is generally attributed to the changes in the number of wet days (NWD) and the proportion of total precipitation occurring during the wet days. A decrease in the NWD, which may result in prolonged periods of drought, is considered one of the major disasters in the Arab region (Swaireh 2009).

The Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC) concluded that the rise in the mean global surface air temperature by the end of the 21st century, relative to the pre-industrial period, is likely to be between 1.5 °C and 4.5 °C (Symon 2013). Global warming amplifies the water-holding

capacity of the atmosphere and, together with the enhanced evapotranspiration, this can increase the frequency and intensity of extreme precipitation events (Karl & Trenberth 2003). Burke *et al.* (2006) used the Hadley Centre global climate model with the Palmer Drought Severity Index and showed that the proportion of the land area in extreme drought will increase from 1% for the present climate to 30% by the end of the 21st century. In particular, their results predict drying over the Middle East and North Africa regions, with increasing severity continuing throughout the 21st century.

Land areas in most of the Arab countries in the Middle East region fall within the hyper-arid, arid, and semi-arid categories, and they receive up to 400 mm in annual rainfall on average. This value decreases substantially for the Arabian Peninsula, where the annual average precipitation reaches 130 mm over the region. The Sultanate of Oman occupies the southeastern coast of the Arabian Peninsula (Figure 1). This country has a series of rugged mountain ranges parallel to the densely populated coastal plain. In recent years, major extreme precipitation events have become common, generating flash floods with high frequencies (Al-Rawas & Valeo 2010). Climate change in the form of increased precipitation intensity would, therefore, have a significant impact on urban areas of the country.

AlSarmi & Washington (2013) have found that the rainfall in the Arabian Peninsula has become more intense, whereas the NWD with precipitation more than 10 mm significantly decreased. A study by Kwarteng *et al.* (2009) indicated that the annual average NWD for the whole of Oman is approximately 12.4, which shows a weak declining trend over the 1977–2003 period. The acute water scarcity and the increases in frequency of extreme rainfall have prompted the country to improve water management strategies and implement adaptation measures to cope with floods. A number of groundwater recharge dams and controlled river channels have been constructed and many others are expected to be built to enhance the groundwater recharge and reduce incoming flood peak. Climate change is expected to increase regional differences of rainfall regime even within the same country (Kazama *et al.* 2009). Consequently, impacts would be destructive in some regions and beneficial in others. The objectives of this study are, therefore, to evaluate potential changes in dry and wet days in the future compared with observations, and to examine what percentages of precipitation change in the future can be

attributed to the precipitation intensity change in different areas of the country. This study, to the best of our knowledge, is the first of its kind for Oman, analyzing the spatial and temporal variation of climate change effects across the country. Predicting potential changes in precipitation regime, particularly changes in the NWD and the precipitation intensity in different regions of the country, will be essential for decision-making processes in Oman for hazard mitigation through proper regional planning and implementation.

STUDY AREA AND DATA

Oman, located at the southeast tip of the Arabian Peninsula, is bordered by the United Arab Emirates to the north, by Saudi Arabia to the west, and by Yemen to the south (Figure 1). The 1,700 km long coastal plain stretches from the Strait of Hormuz in the north, to the borders of Yemen to the southwest, and is home to many urban cities such as Sohar, Sur and Salalah, including Muscat, the capital city of Oman. A series of rugged mountains (with the highest peak of 3,075 m above mean sea level) and the Ophiolite hills run parallel to most of the coast line. The interior of Oman occupies the area beyond the mountain range up to the borders with Saudi Arabia and Yemen. The interior region (IR) accounts for nearly 82% of the country and mainly consists of sandy wasteland deserts.

The climate in Oman varies mainly from semi-arid to hyper-arid. According to the records of 49 gage stations over the 1985–2004 period, PTOT ranges from 31 mm in the interior desert to 330 mm in the northern Oman mountain region (NOMR), with a station average of 129 mm/year. The NWD (precipitation more than 1 mm) over the same period varies between 2 and 32 days/year, with a station average of 12 days/year. Depending mainly on temperature, Oman has two distinct seasons: the summer season from May to October and the winter season from November to April.

Influenced by its geographical location in the Arabian Sea and the diverse topography, substantial temporal and spatial differences in precipitation mechanisms are found in Oman. For the analysis in this study, precipitation data from 49 monitoring stations over the 1985–2004 period were obtained from the Ministry of Regional Municipalities, Environment, and Water Resources. These stations were then grouped into five

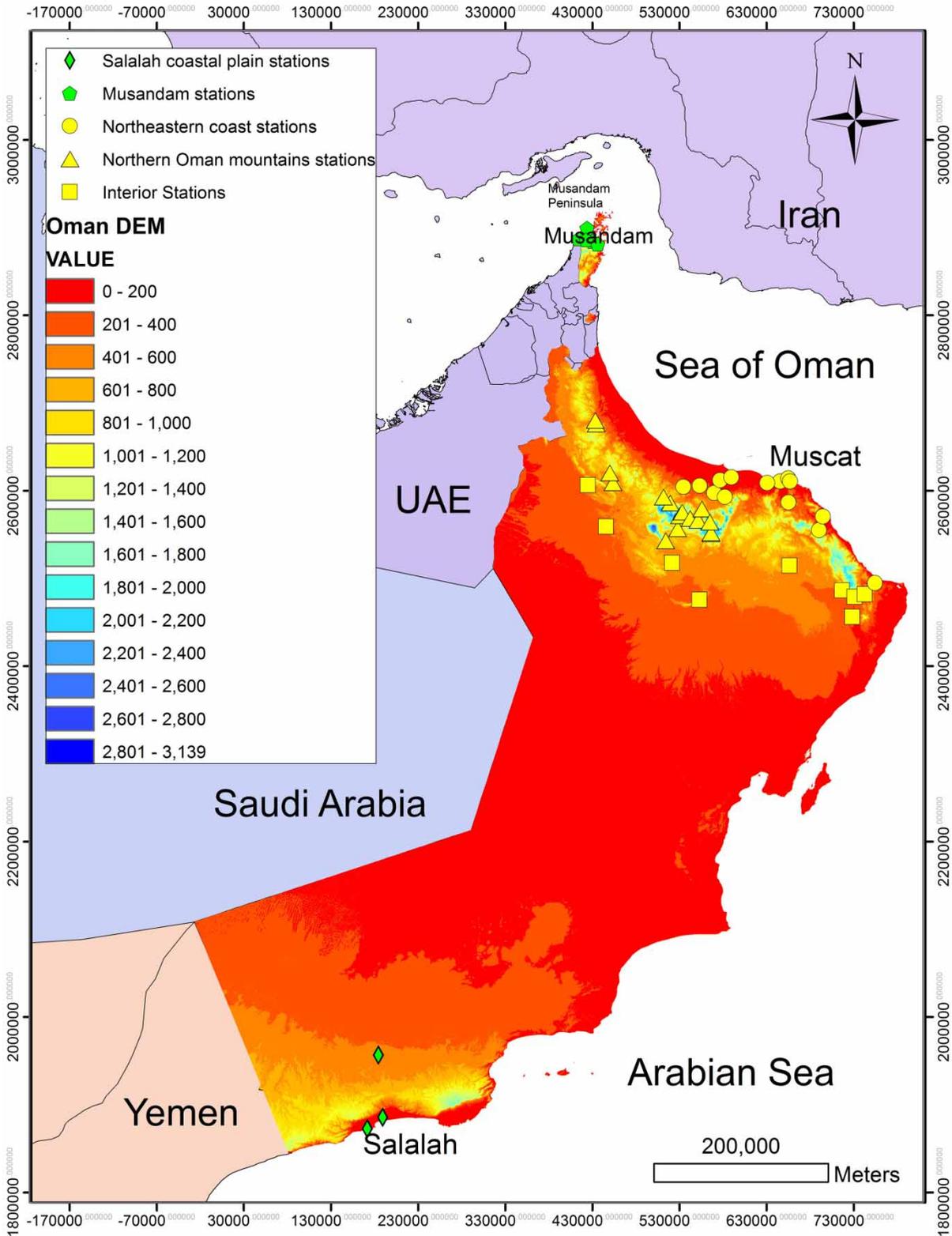


Figure 1 | Study area and the location of rain gage stations.

regions based on their geographical location, elevation, and dominant precipitation mechanism. Monitoring stations with long-term records are extremely rare in the middle and the IRs of the country, which mainly consist of sandy wasteland deserts. This study therefore mainly focused on the northern regions of the country. For comparison, an analysis in Salalah region located in southern Oman was also performed. A detailed description of these five regions is presented below.

Musandam region

The Musandam region (MR), located along the northern border of Oman, consists of seven monitoring stations (Figure 1). PTOT in the region is 178 mm and is second only to the rainfall in the NOMR. More than 95% of the PTOT in this region occurs from November to April (Figure 2(a)) via cold frontal troughs (horizontal variation

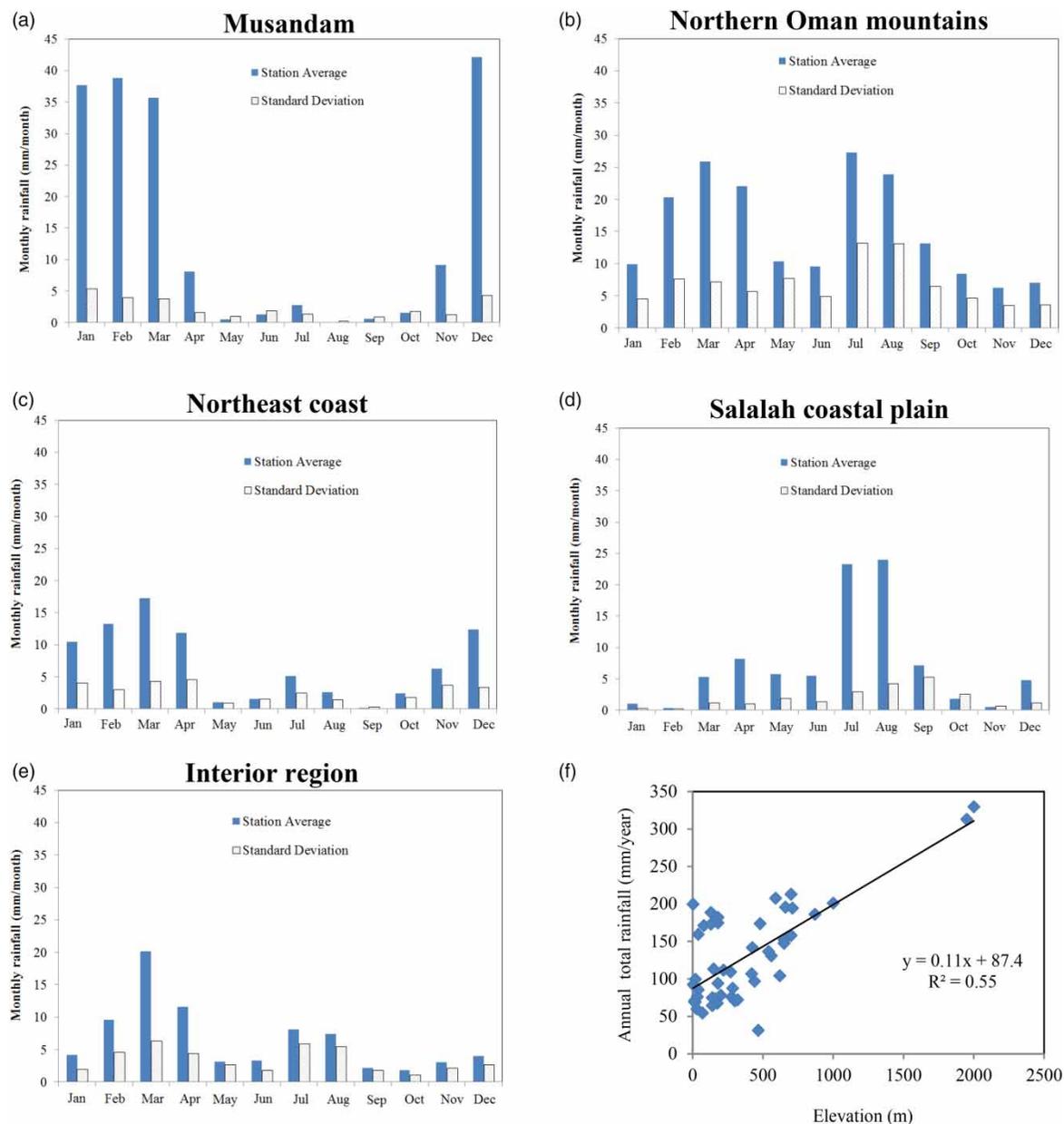


Figure 2 | (a)–(e) Monthly total rainfall average over the 1985–2004 period in different regions and (f) orographic precipitation effect in all regions.

of atmospheric temperature) originating from the North Atlantic or the Mediterranean Sea.

NOMR

There are 16 monitoring stations located in this region, with station elevations ranging from 420 m to 2,000 m. The PTOT is approximately 184 mm and is reasonably distributed throughout the year by two major precipitation mechanisms (Figure 2(b)). The cold frontal troughs bring nearly half of the total rainfall to the region during November to April, and orographic convective rain contributes significantly during July and August. Convective clouds are formed by the intense summer temperature (due to vertical stratification of atmospheric temperature) over the mountains, resulting in highly localized showers, thunder storms, and occasional hail.

Northeast coast

The PTOT average over 14 monitoring stations in this region is approximately 85 mm/year, which is approximately half of the PTOT in the MR and NOMR. Approximately 85% of the PTOT is received from November to April when the cold frontal troughs are active (Figure 2(c)). In addition, tropical cyclones originating from the Arabian Sea bring intense rainfall during the pre-monsoon (May/June) and post-monsoon (October/November) seasons. Although these cyclones are uncommon and their contributions are not apparent in long-term averages, they occasionally bring heavy rains to the coastal area, causing substantial damage. Hurricane Gonu in 2007 led to the worst natural disaster on record in Oman, with total rainfall reaching 610 mm near the coast.

Salalah coastal plain: SCP

In the Salalah and Dhofar governorates, in general, the period from June to September experiences the monsoon precipitation known locally as the Khareef. This precipitation is caused by cooling of the very humid warm south-westerly trade winds as they pass over the cold upwelling sea and are drawn over 900-m high mountains by the interior low pressure system. High humidity and drizzle

continue through the Khareef season. In total, 66% to 70% of the average annual rainfall in Salalah occurs during the Khareef period (Figure 2(d)). The average annual rainfall in Jabal Al-Qaraof at approximately 300 mm is reduced to 100 mm in the coastal plain and further decreases to as low as 50 mm in the Najd area in the heartland beyond the mountains.

IR

Located on the leeward side of the mountain range and triggered by the rain shadow effect, this region receives less precipitation compared with the NOMR located on the windward side of the mountain range. There are ten monitoring stations in this region, with station elevations ranging from 140 m to 467 m. The average PTOT over the stations is approximately 78 mm. The cold frontal troughs bring nearly 67% of total precipitation during November to April (Figure 2(e)). The monsoon mechanism also indirectly contributes to approximately 27% of the PTOT.

Orographic precipitation effect

Complex mountain geometry influences orographic precipitation, which occurs on the windward side and is further enhanced by a strong moisture source, such as the Arabian Sea in this study area. In these regions, a strong relationship was found between total annual rainfall and elevation (Figure 2(f)). According to the classic review by Houze (2012), precipitation over and near mountains is not caused by topography, but is rather caused by alternate or reorganized storms attributed to convective clouds, frontal systems, or tropical cyclones when they encounter topographic features. Depending on the height of the mountain range, heavy rain may occur on either the windward or leeward side. Station average precipitation in the NOMR is more than two-fold that in the two coastal plains and the IR located on the leeward side of the mountain range. Two stations located at approximately 2,000 m elevation level have precipitation of approximately 330 mm/year, which is more than three-fold that of the station with the highest individual rainfall in the other three regions.

METHODOLOGY

Increases in radiative forcing, as predicted by IPCC representative concentration pathways (RCPs), lead to atmospheric warming and likely amplify precipitation extremes (Karl & Trenberth 2003). The physical mechanism behind the link between global warming and stronger rainfall is explained by the Clausius–Clapeyron equation. As climate warms, saturation vapor pressure rises exponentially, and the water-holding capacity of the atmosphere increases by approximately 7% per 1 °C. As a result, the amount of moisture in the atmosphere increases. Trenberth *et al.* (2003) argued that, consequently, the rainfall intensity should also increase at approximately the same rate or can even exceed 7% per 1 °C. Increased rainfall intensity then must be compensated by decreases in duration or frequency of the precipitation events unless the total rainfall changes proportionally. In the absence of moderate precipitation, groundwater recharge would decrease, leading to enhanced surface and subsurface drying. The potential evapotranspiration rate in Oman is more than 2,000 mm/year (Siebert *et al.* 2007), which is approximately 16 times higher than the station average precipitation of 129 mm/year. Further increase in potential evapotranspiration attributed to global warming would increase the number of dry days leading to a long spell of droughts and increased risk of heat waves (Dahal *et al.* 2016).

In this study, a dry day is defined as a day with precipitation less than 1 mm/day. Pierce *et al.* (2013) presented a method to estimate the effect of changes in dry days on annual precipitation. Polade *et al.* (2014) applied this method to decouple the projected changes in annual precipitation in different regions in the world. This methodology was adopted to estimate the contribution of precipitation intensity change to the changes in PTOT in the future in Oman. The methodology is outlined as follows. Daily precipitation during the 1985–2004 period was sorted on a monthly basis. Average monthly total precipitation and the NWD for each month were calculated and then they were used to estimate daily precipitation intensity on a wet day. Similarly, average monthly total precipitation and the NWD in the future for each month were calculated. The effect of a change in the NWD in a given month in

the future is calculated by multiplying the change in the NWD between two periods by the daily precipitation intensity on a wet day estimated for that particular month. Here, precipitation reduction due to an additional dry day in the present climate in a particular month is considered to be the same as in the future. The result is then subtracted from the monthly total precipitation change to obtain its change due to changes in daily precipitation intensity. The baseline period of observations (1985–2004) does not include recent records but ends at year 2004 because the base line period of general circulation model (GCM) results extends up to the year 2005 only.

When predicting the future climate, a substantial level of variability arises due to uncertainties in the future emissions of greenhouse gases and the incomplete representation of the climate system in the models. As such, a plausible range of precipitation scenarios was developed based on two emission scenarios used in IPCC AR5. These emission scenarios, known as the RCPs, have been defined by their total radiative forcing expressed in watts per square meter. Accordingly, the RCP4.5 (moderate scenario) and RCP8.5 (worst case scenario) used in this study represent pathways that result in radiative forcings of 4.5 and 8.5 W/m² in 2100 (Moss *et al.* 2010). The Coupled Model Intercomparison Project Phase 5 (CMIP5) comprises a set of state-of-the-art GCMs that use RCPs to produce a wide range of climate scenarios. Based on the data availability at all 49 stations, the years 1985–2004 were selected as the base line period. Two future periods, each encompassing 20 years, were also defined: 2040–2059 and 2080–2099.

Due to the orographic effect, precipitation varies substantially even within short distances. Therefore, the horizontal resolutions of GCMs are still too coarse to capture local-scale variability in precipitation events (Herath *et al.* 2016). In this study, LARS-WG5.5 (Semenov & Stratonovitch 2010) was used to downscale GCM precipitation records to the local scale. In this program, future precipitation scenarios are generated based on the probability distributions fitted for different characteristics of precipitation observations (e.g., length of the wet and dry periods, total precipitation, etc.) in the base line period and the relative changes in magnitude of the corresponding characteristics predicted by the future GCM scenario

(detailed information can be found in [Semenov & Stratonovitch 2010](#)). To evaluate the performance of LARS-WG5.5, the two-tailed Kolmogorov–Smirnov goodness-of-fit test is applied to compare the probability distributions of the original and synthetic time series.

In total, five GCMs and two scenarios were used to evaluate precipitation variations. The ability of the GCMs and downscaling model to produce reliable projections was examined by comparing downscaled results with observations. The basic assessment principles are the NWD, annual total rainfall, and the Kolmogorov–Smirnov test statistics for the match between observed and simulated time series. The station with the longest observation period (at least 25 years) from each region was selected for the validation. Approximately half of the data set (1977–1990) was used for the model calibration, while the other half was used for the verification (1991–2004).

RESULTS AND DISCUSSION

This study evaluates potential changes in precipitation in the future in Oman and attributes them to the projected dry/wet day change and precipitation intensity change. Daily precipitations from five GCMs were downscaled using LARS-WG and compared results with the observations in the 1991–2004 period. This was guided to select GCMs whose results best match with the precipitation characteristics in the study area.

[Table 1](#) shows the estimated p -values from the K-S test applied for observed and downscaled precipitation time series. The K-S test is designed to test the null-hypothesis of no difference between observed and predicted distributions. The p -value reports the probability of incorrectly rejecting

the null-hypothesis. A lower p -value therefore suggests stronger evidence for rejecting the null hypothesis. Of the five GCMs considered in five regions, the MIROC5 and INM-CM4 models produce p -values smaller than 0.05 for four regions, suggesting a statistically significance difference between downscaled and observed distributions. The MRI-CGCM3 model depicts comparatively better results with estimated p -values more than 0.05 in all regions except in the IR. The results of the CNRM-CM5 and HadGEM2-ES models suggest statistically no significance different between observed and downscaled time series in all five regions. Furthermore, the annual total rainfall and the NWD between observed and downscaled time series were examined in all regions. A sample result is shown in [Figure 3](#) for Muscat, the capital city of Oman. According to the similar results in all five regions, the HadGEM2-ES model depicts significant difference in NWD compared to observations. The CNRM-CM5 and MRI-CGCM3 models show good agreement in all aspects. Therefore, these two models were selected for further studies. Precipitation time series were downscaled for CNRM-CM5 and MRI-CGCM3 models under RCP4.5 and RCP8.5 scenarios, which altogether produced four precipitation scenarios in two future periods (2040–2059 and 2080–2099) to compare with the observations at 49 stations during the 1985–2004 period.

Potential changes in precipitation characteristics in the MR

Climate scenarios are not consistent regarding whether future precipitation will increase or decrease over the five regions considered in this analysis. According to the four projected time series examined at each station in the MR, PTOT will increase, with a mean change of –9–36% and 4–49% mm/year in the 2040–2059 and 2080–2099 periods, respectively. In contrast, at least three out of four scenarios in all stations predict that the NWD will decrease, with a mean reduction of 2.1 days/year in the 2040–2059 period. However, no statistically significance difference in NWD is calculated in the 2080–2099 period. The net result of this is that enhanced precipitation intensity will contribute to increasing PTOT by 19–54% in the 2040–2059 period and by 14–64% in the 2080–2099 period among seven stations in the MR.

Table 1 | P -values estimated from the two-sample Kolmogorov–Smirnov test

GCM	Musandam	NOMR	Northeast coast	SCP	IR
MIROC5	0.009	0.003	0.034	0.000	0.464
MRI-CGCM3	0.125	0.072	0.532	0.835	0.047
INM-CM4	0.000	0.000	0.012	0.014	0.234
CNRM-CM5	0.670	0.058	0.253	0.070	0.618
HadGEM2-ES	0.347	0.204	0.066	0.069	0.076

Models that pass the K-S test at 95% confidence level are in bold font.

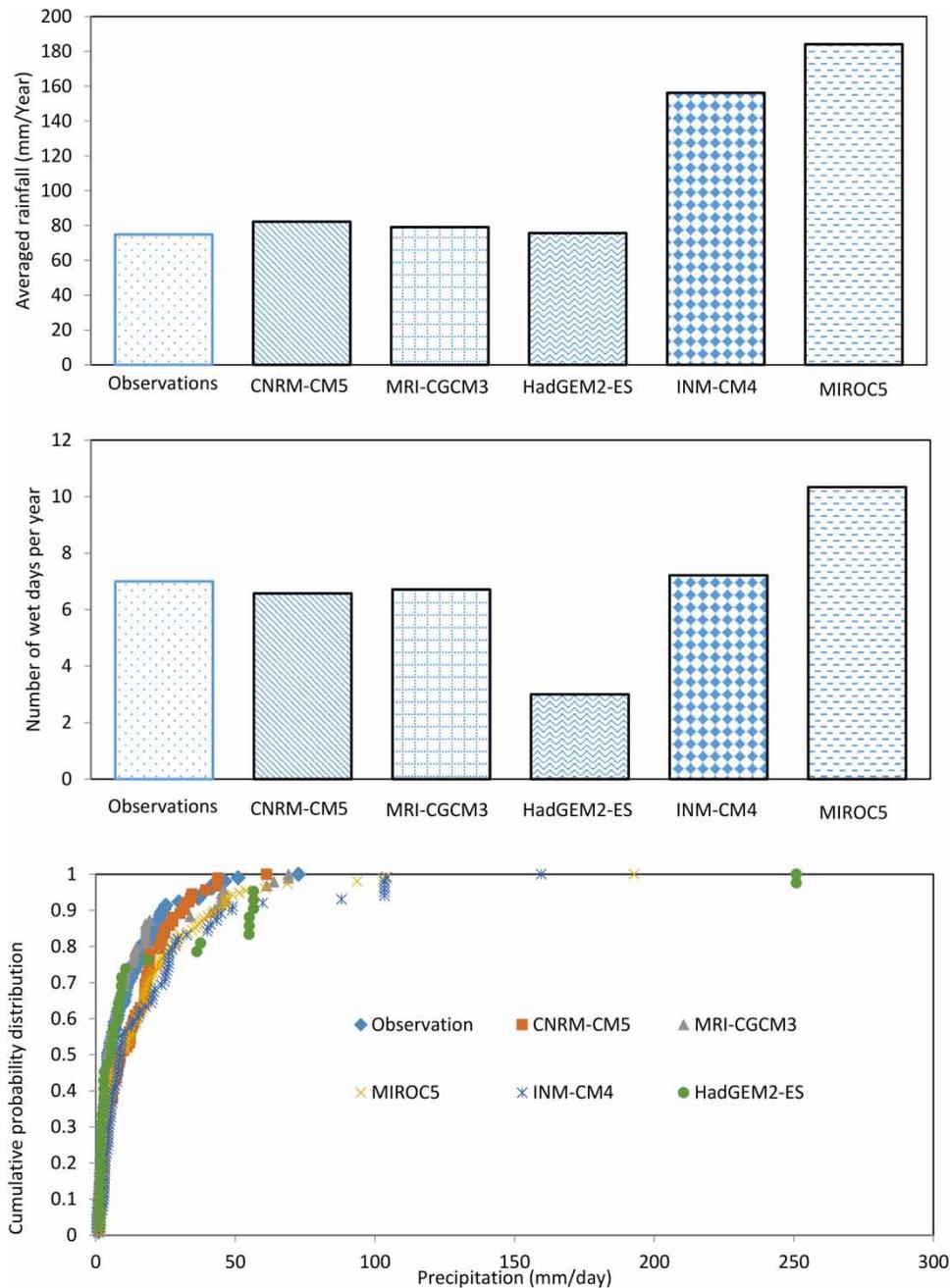


Figure 3 | The observed and downscaled precipitation characteristics in Muscat (northeast coast).

The objective of this study is to determine which fraction of the PTOT change can be attributed to the changes in the number of wet/dry days. As precipitation is highly variable and different mechanisms are involved, potential changes at the local scale could be rather different in the different regions considered. Figure 4(a) and 4(b) show the

contributions of changes in the NWD and changes in precipitation intensity in monthly total rainfall in two future time periods. No major shift in precipitation mechanism is observed, because more than 80% of the PTOT will occur from November to April by the cold frontal troughs in both future time periods. However, precipitation is

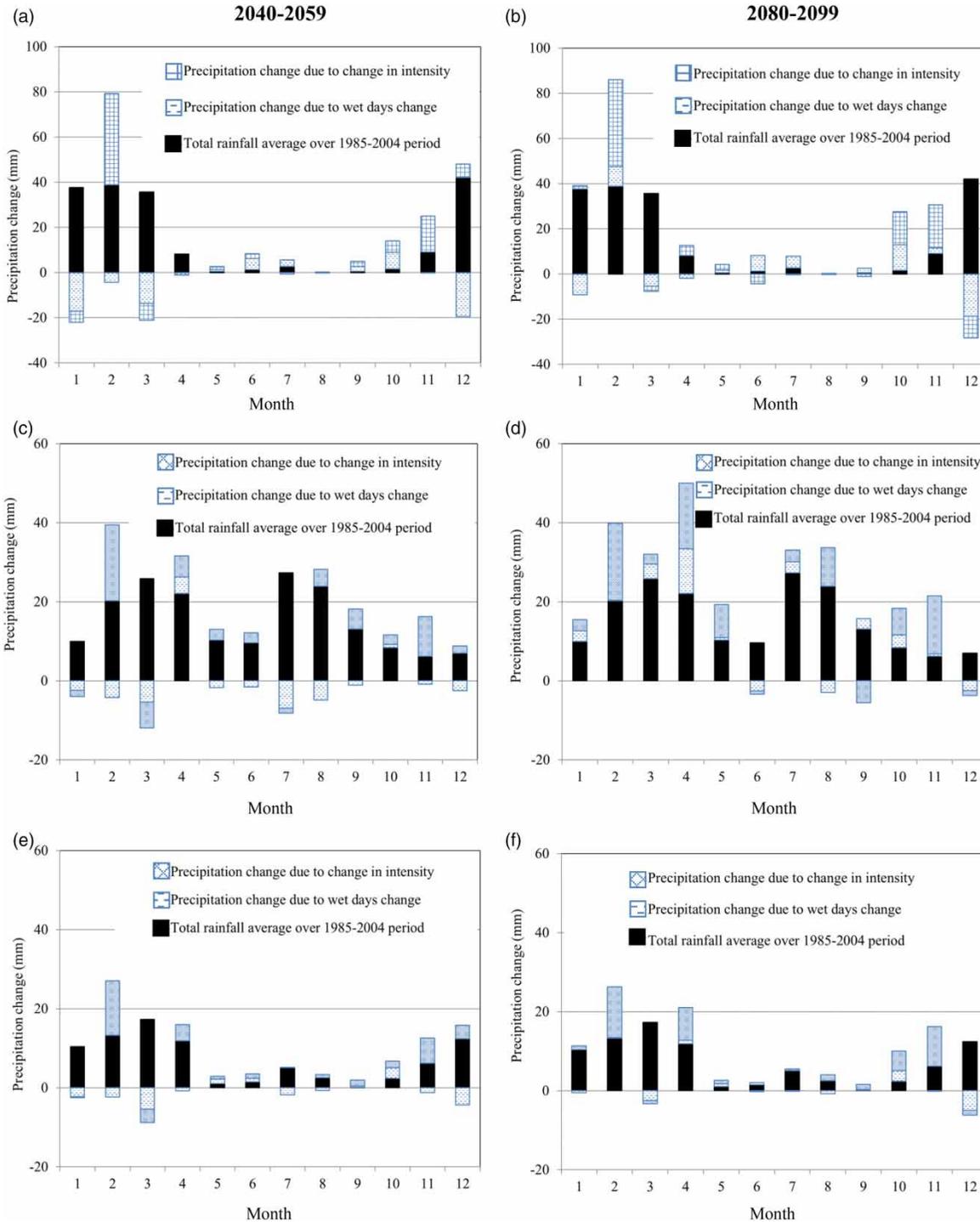


Figure 4 | Contributions of changes in the NWD and changes in precipitation intensity to total rainfall: (a) and (b) MR, (c) and (d) northern Oman mountain region, and (e) and (f) northeast coast.

projected to decline significantly due to decreases in the frequency of wet days especially in the 2040–2059 period. This effect on PTOT is then compensated by the increases in

precipitation intensity, especially in the months of November and February. Consequently, this interplay between changing precipitation intensity on wet days and the

frequency of wet days will increase PTOT by 13% and 37% in the MR in the 2040–2059 and 2080–2099 periods, respectively.

Potential changes in precipitation characteristics in the NOMR

All 16 stations studied in the NOMR agree that PTOT will increase, with mean changes of 4–21% and 18–76% mm/year in the 2040–2059 and 2080–2099 periods, respectively. Similar to the projections of the MR, the NWD among stations will decrease in the range of 0.4–8.8 days/year in the 2040–2059 periods. However, the change in the NWD is not consistent across the region in the 2080–2099 period. Of the 16 stations, 13 of them are projected to increase the NWD in a range of 0.3–4.8 days/year. In the other three stations, the NWD will decrease by 0.1–3.2 days/year. On the other hand, increased precipitation intensity will account for 14–37% of PTOT in the 2040–2059 period and 15–56% in the 2080–2099 period in this region. As a result of these changes in precipitation intensity and the NWD, PTOT is expected to increase by 9% in the 2040–2059 period and by 51% in the 2080–2099 period. This clear difference in PTOT change between two time periods can be attributed to the effect of increases in NWD in the 2080–2099 period.

Precipitation in the NOMR is influenced by two major precipitation mechanisms: cold frontal troughs and convective rainfall (Figure 2(b)). As shown in Figure 4(c) and 4(d), no major shift in precipitation mechanisms or their contribution to the PTOT is observed. Approximately 54% of the precipitation is projected to be received during November to April by the cold frontal troughs, and approximately 21% can be expected during the months of July to August from the convective rains. Figure 4(c) and 4(d) also show that, irrespective of the precipitation mechanisms, the contribution from the increased precipitation intensity to the PTOT increased in most of the months.

Potential changes in precipitation characteristics in the northeast coast

Approximately 85% of the PTOT during the 1985–2004 period was received from November to April. According to

future predictions, this will be reduced to 79% during the 2040–2059 period and will be further reduced to 77% during the 2080–2099 period. In contrast, significant changes in precipitation are predicted during the post-monsoon period (Figure 4(e) and 4(f)). Tropical cyclones are generally active during the post-monsoon period, even though their effect on long-term average precipitation is not clear during the observation period (Figure 2). Increases in sea surface temperature under global warming would enhance the cyclone development. For example, Balaguru *et al.* (2014) found an increase in the intensity of tropical cyclones over the Bay of Bengal during the 1981–2010 period.

As the potential increase in precipitation during the pre-monsoon period cannot be directly attributed to the intensification of tropical cyclones in the region, the occurrence of extreme events was examined. The 90th percentile of the daily precipitation during the 1985–2004 period was estimated and considered as the threshold for the extreme events. Figure 5 shows the number of extreme rainfall events observed and predicted from September to November during the observation period and two future periods. When averaged over different stations in the region, the number of extreme events in the observation period is approximately two (0–6 at different stations), which is projected to increase to 4.4 and 7.0 in the 2040–2059 and 2080–2099 future periods, respectively. Accordingly, this result may suggest a possible link between the increased precipitation and intensified tropical cyclone activities in this region in the future.

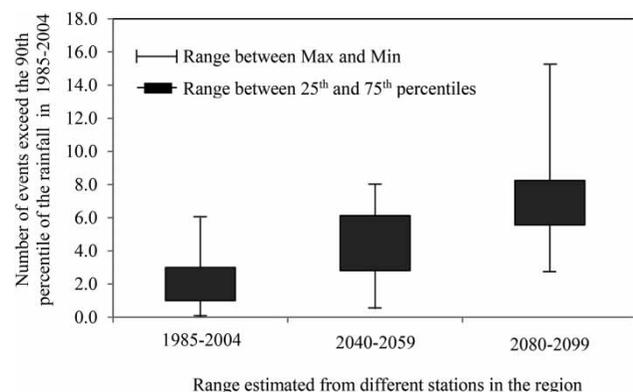


Figure 5 | The number of extreme rainfall events estimated in the observation period and two future periods. The range of values here represents the variation of the extreme events at different stations.

Potential changes in precipitation characteristics in the SCP

In Salalah, PTOT is projected to increase by 6% in the 2040–2059 period and by 35% in the 2080–2099 period. However, all scenarios agree that the NWD will decrease on average by 7.3 days and 3.3 days in the 2040–2055 and 2080–2099 periods, respectively. Consequently, 22% of precipitation in the 2040–2059 period and 9% in the 2080–2099 period will decrease due to the decrease in the NWD. The impact of this will mostly affect the monsoon period. Approximately 66–70% of the total precipitation occurred during the monsoon period in the 1985–2004 period. Figure 6(a) and 6(b) show that the precipitation reduction due to changes in the NWD is quite significant in the months of July and August. Figure 6 also shows that increases in PTOT when

NWD decreases will occur by increasing precipitation intensity in all months throughout the year. Accordingly, the enhanced precipitation intensity will contribute to increase total annual rainfall by 28% in the 2040–2059 period and by 41% in the 2080–2099 period.

Potential changes in precipitation characteristics in the IR

Most of the stations in the IR are located on the leeward slope of the mountain range and thus receive relatively low rainfall. The NWD averaged over ten stations in the 1985–2004 period is 7.9, which is significantly smaller than the 17.7 wet days averaged over the windward side of the mountain area. No significant change in the NWD during the 2040–2059 period is estimated. Similarly, the

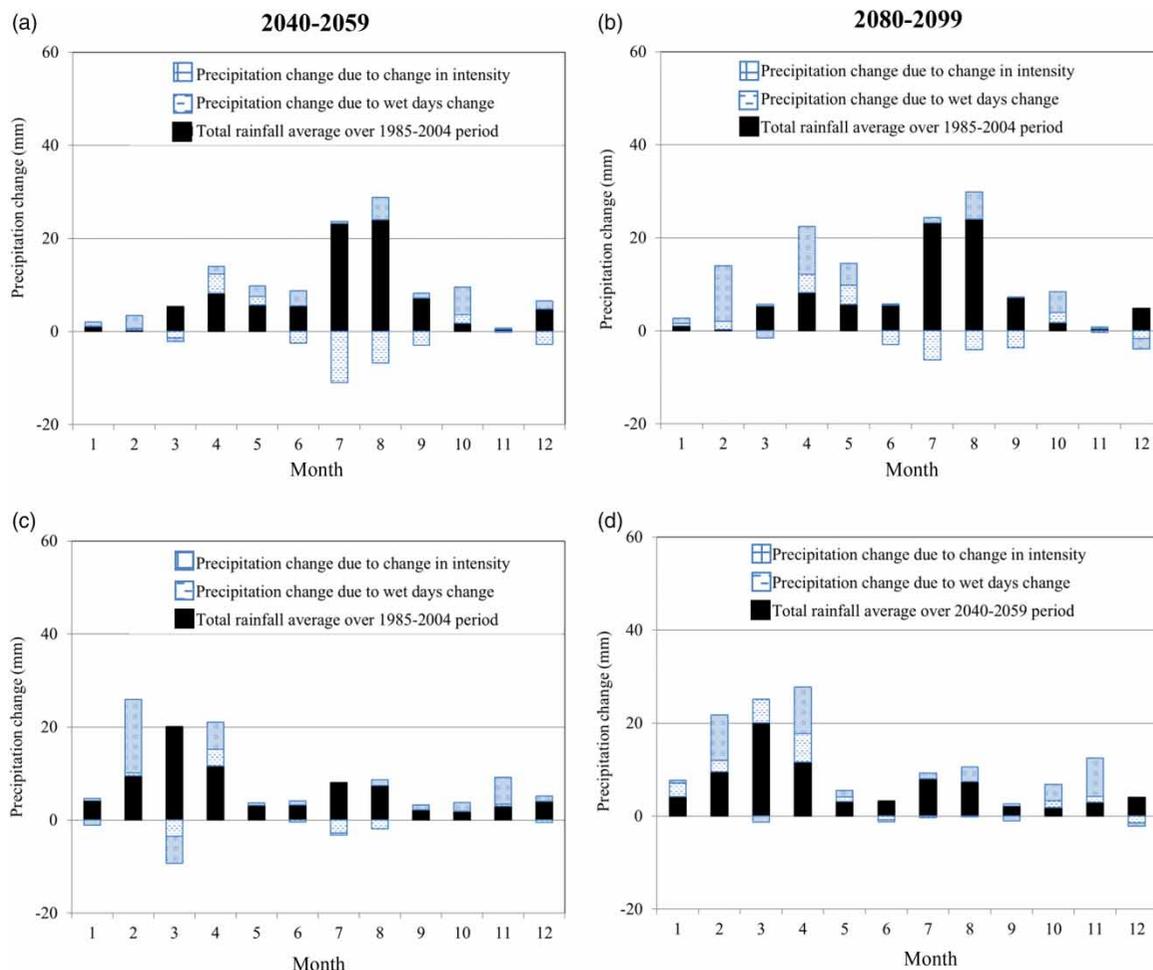


Figure 6 | Contributions of changes in the NWD and changes in precipitation intensity to total rainfall: (a) and (b) SCP and (c) and (d) IR.

NWD is projected to increase in the 2080–2099 period, but only by 1 day and not consistently among the various scenarios. As such, Figure 6(c) and 6(d) show that precipitation change due to changes in the NWD is smaller compared with other regions. However, PTOT in the region is expected to increase by 29% in the 2040–2059 period and further increase by 67% in the 2080–2099 period. Figure 6(c) and 6(d) show that the effect of the precipitation intensity has grown in most months in both future periods. As a result, approximately 44% of the projected annual precipitation in the 2040–2059 period and approximately 34% in the 2080–2099 period can be attributed to increases in daily precipitation intensity.

Comparison of the results between two scenarios

Regarding results, both scenarios depict a clear increase in extreme precipitation events in both 2040–2059 and 2080–2099 periods while the RCP8.5 effect in all regions is of a greater magnitude compared to that of RCP4.5 (Figure 7). Two RCP scenarios predict distinctly different warming rates in the future. According to the RCP4.5 scenario,

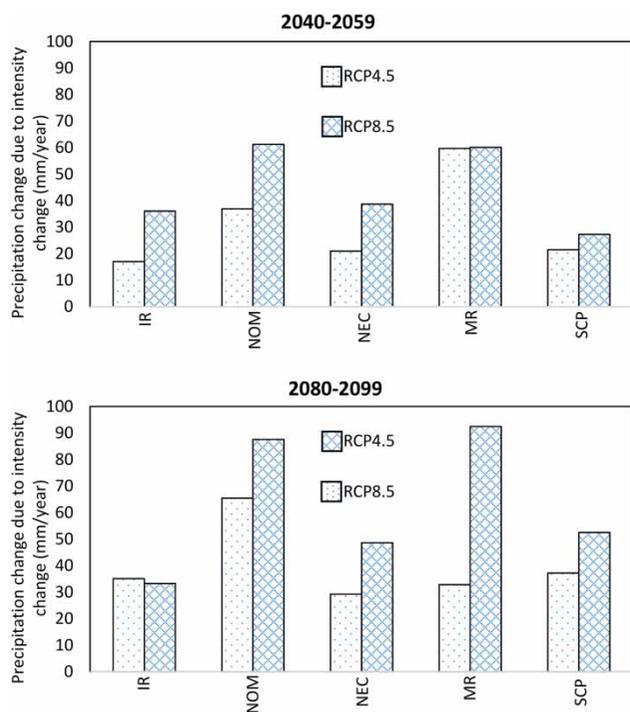


Figure 7 | Precipitation change due to increases in intensity as predicted by two scenarios in different regions.

radiative forcing reaches 4 W/m^2 limit by 2050 and then slowly increases and stabilizes at approximately 4.5 W/m^2 level after 2100. In contrast, RCP8.5 is representative of high energy demand and GHG emissions in the absence of climate change policies. RCP8.5 thus corresponds to the pathway with the highest greenhouse gas emissions (Riahi *et al.* 2011). In line with corresponding warming rates, Fix *et al.* (2016) showed that the change of extreme rainfall projections is comparatively higher for the RCP8.5 scenario than the projected changes with the RCP4.5 scenario. In principle, greater warming as predicted by the RCP8.5 scenario also increased the saturated amount of water in the lower troposphere and thus increased the intensity of the precipitation events. For example, Lenderink & Van Meijgaard (2008) showed that, when warming rate increases, the sub-daily extreme precipitation events increase at a rate twice the amount predicted by the Clausius–Clapeyron equation. This monotonic increase in precipitation intensity with atmospheric warming as explained by the Clausius–Clapeyron relationship however can be different in arid and semi-arid regions. Berg *et al.* (2009) found that water availability rather than water-holding capacity is the controlling factor to increase precipitation intensity in warmer climate conditions. Figure 7 shows that the precipitation change due to intensity change is higher in the MR and the NOMR than the other three regions. Figure 2 shows that the annual total rainfall is also higher in the MR and NOMR than the other three regions. In particular, orographic precipitation effect, as shown in Figure 2(f), causes wetter conditions in the NOMR throughout the year than in other regions. This would lead to an enhanced increase in extreme precipitation in high altitude areas and the northern region in Oman.

CONCLUSIONS

Daily precipitation data for the 1985–2004 period at 49 stations in five regions in Oman and two CMIP5 GCMs forced by the RCP4.5 and RCP8.5 radiative forcing scenarios in the 2040–2059 and 2080–2099 periods were used to estimate potential changes in the NWD and in precipitation intensity, as well as the net effect of these on PTOT. Seasonal and spatial precipitation variations among

different regions can be ascribed to four precipitation mechanisms, namely the cold frontal troughs, convective precipitation, tropical cyclones, and southwesterly monsoon that dominate a particular region in a certain time period. Moreover, the mountain ranges run parallel to the coast, creating a pronounced orographic precipitation effect.

In all regions studied, except the interior desert region of the country, the NWD is projected to decrease. The most significant impact was projected in Salalah during the monsoon period, where the NWD could decrease by 7.3 days and 3.3 days on average in the 2040–2059 and 2080–2099 periods, respectively. On the other hand, the precipitation received from amplified precipitation intensity will account for 28% and 41% of the annual precipitation in the 2040–2059 and 2080–2099 periods, respectively. Salalah city and the surrounding area in the Dhofar governorate are famous tourist destinations in the monsoon months due to hills that turn into lush greenery surrounded by white fog and cool air produced by light drizzling. Potential changes, as predicted in this study, could have a significant impact on altering this well-known fine climate and thereby the tourism in the region.

The contribution from the cold frontal troughs in the northeast coastal region account for 85% of the PTOT in the 1985–2004 period, which could decrease to 79% during the 2040–2059 period and further decrease to 77% during the 2080–2099 period. In contrast, a marked increase in the number of extreme rainfall events was predicted during the post-monsoon period. Generally, the northeast coastal region is affected by tropical cyclones during the post-monsoon period. Thus, further research in the context of tropical cyclone frequency under changing climate in the Arabian Peninsula is recommended.

Despite the decreases in the NWD, the PTOT in all regions would increase by 6–29% and 35–67% during the 2040–2059 and 2080–2099 periods, respectively. These results, therefore, show that increases in precipitation intensity dominate the changes in PTOT. Increased precipitation intensity results in greater river flow, which could worsen the flash flood disasters that are common in Oman. Consequently, exclusive use of climatic normals derived from historical data may no longer be appropriate and could render infrastructure vulnerable by leading to design with insufficient capacity, or by taking policy measures that

become difficult to practice over time. In order to avoid or, at the very least, to reduce the risks of floods and damage, potential changes of the precipitation regime need to be incorporated in intensity–duration–frequency curves. Nevertheless, the additional river flow that will be generated by increased precipitation will not alleviate water scarcity problems in these regions if the extra water cannot be stored. Groundwater recharge dams and controlled river channels are used in arid countries, including Oman, to enhance the groundwater recharge. Incorporation of climate change projections, as presented in this study, into future designs and management strategies can improve the efficiency of the controlled recharge practices.

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