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Meteorological drought features in northern and northwestern parts of Mexico under different climate change scenarios

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Abstract: Meteorological drought has been an inevitable natural disaster throughout Mexican history and the northern and northwestern parts of Mexico (i.e., the studied area), where the mean annual precipitation (MAP) is less than 500 mm, have suffered even more from droughts in the past. The aim of this study was to conduct a meteorological drought analysis of the available MAP data (1950–2013) from 649 meteorological stations selected from the studied area and to predict the drought features under the different IPCC-prescribed climate change scenarios. To determine the long-term drought features, we collected 1×10^4 synthetic samples using the periodic autoregressive moving average (PARMA) model for each rainfall series. The simulations first consider the present prevailing precipitation conditions (i.e., the average from 1950 to 2013) and then the precipitation anomalies under IPCC-prescribed RCP 4.5 scenario and RCP 8.5 scenario. The results indicated that the climate changes under the prescribed scenarios would significantly increase the duration and intensity of droughts. The most severe impacts may occur in the central plateau and in the Baja California Peninsula. Thus, it will be necessary to establish adequate protective measures for the sustainable management of water resources in these regions.

Keywords: meteorological drought; synthetic simulation; climate change; water stress; evapotranspiration

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1 Introduction

Meteorological drought has been well-documented to be one of the most powerful history makers (McIntosh and Tainer, 2000). Its powfulness was well demonstrated by many lines of archaeological evidence unearthed from the world's middle-latitude drylands (Liu and Feng, 2012). The best example came from the well-studied Mesopotamia domain where the Akkadian empire suddenly collapsed at ~4170 years ago (Weiss et al., 1993; Weiss and Bradley, 2001). Archaeological evidence documented widespread abandonment of the agricultural plains of Mesopotamia domain at ~4170 years ago. The stratigraphic level representing the collapse at Tell Leilan (northeast Syria) is overlain by a thick (~100 cm) accumulation of wind-blown silts, suggesting a sudden shift to much drier conditions at ~4170 years ago (deMenocal, 2001).

Mexico is generally characterized by dry climates due to the domination of the Subtropical High

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Pressure system (approximately from 15°N to 30°N) and also due to the topographic water-vapor barriers of two N-S striking mountains, the Sierra Madre Occidental and the Sierra Madre Oriental. The northern and northwestern parts of Mexico are even drier primarily due to limited access of the Intertropical Convergent Zone (ITCZ) and the mean annual precipitation is less than 500 mm. Consequently, meteorological drought has been an inevitable natural disaster throughout Mexican history. The most illustrative example is a prolonged drought that destroyed the well-known Mayan civilization in the 9th century (Gill, 2000). Severe droughts were also repeatedly documented in the historical records to have affected the colonial economies from the 16th to the early 19th century (Padilla et al., 1980). After the colonial time, several episodes of drought have been instrumentally recorded and the most significant ones that caused considerable economic losses include: 1948–1954, 1960–1964, 1970–1978 and 1993–1998 (CENAPRED, 2014). Furthermore, the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013) sternly warned that the world's middle-latitude drylands will become ever drier under the projected future warming. It means that in those drylands, the magnitude and frequency of drought will be enhanced and the associated water-resource shortage will be aggravated under a warming climate (Frich et al., 2002; Mishra and Singh, 2011; Kahil et al., 2015; Karabulut, 2015). In Mexico (especially in the northern and northwestern parts), an increase in drought frequency over the last 20 years was reported and primarily attributed to the temperature rising (Hernandez-Cerda and Valdez-Madero, 2004; Romero-Lankao et al., 2014; Curl et al., 2015).

Scientists and practicians have been persistently attempting to quantitatively estimate the socioeconomic effects of droughts, but they were unsuccessful because of the complexity of assessing the effects. First, drought always has a cumulative effect over a time period after a drought event, normally resulting in multi-year economic repercussions at local or regional scales (Lloyd-Hughes, 2014). Second, drought is a complex natural phenomenon that is difficult to define. For example, four types of drought commonly appeared in literature and they were sometimes used indistinguishably: meteorological drought, hydrological drought, agricultural drought, and socioeconomic drought (NDMC, 2016; Wang et al., 2016). This research particularly focused on meteorological drought that expresses the intensity and duration of a drought event in a specifiable region. The drought event refers to an episode of "below-average precipitation" and the average precipitation is the mean of at least 30-year rainfall data (Singh, 2006).

Many researchers have assessed drought-related damages caused by different IPCC-prescribed climate change scenarios in order to develop adaption and mitigation strategies. In the AR5 (IPCC, 2013), the IPCC used four climate change scenarios known as the Representative Concentration Pathways (RCPs) to replace the previous scenarios of the Special Report on Emission Scenarios (SRES). Each of RCPs defines the trajectory of the alteration or change in the net irradiance (W/m^2) of the tropopause due to an increase in the concentration of greenhouse gases and other forcing agents for the year 2100. The four scenarios or RCPs include: a very low baseline emission scenario (RCP 2.6), a pre-2100 emission stabilization scenario (RCP 4.5), a post-2100 emission stabilization scenario (RCP 6.0) and a very high baseline emission scenario (RCP 8.5). It should be pointed out that regional-scale or local-scale impact assessments of meteorological anomalies under the IPCC-prescribed scenarios were normally done by downscaling global circulation model outputs to regional and local scales (Mishra and Singh, 2011).

The impact assessments for different IPCC-prescribed scenarios have been conducted in many parts of the world using different methods. For instance, Parry et al. (2004) employed a crop model to analyze the global consequences of crop yields and associated hunger risks resulted from the prescribed climate changes. Lehner et al. (2006) assessed the impact of the prescribed climate changes on drought frequencies across Europe using a non-climate-policy scenario. Loukas et al. (2007) evaluated drought features in Greece under different prescribed scenarios using the Standard Precipitation Index (SPI). Li et al. (2009) analyzed the drought risk of crop production under different prescribed scenarios using the Palmer Drought Severity Index (PDSI). Orlowsky and Seneviratne (2012) studied the global drought trends under different prescribed scenarios (i.e., four RCPs) using the global circulation model simulations.

To cope with the increases in drought frequency and probably also in drought intensity, the Mexican government is implementing several adaptive plans to maximize water storage capacities and minimize water losses. However, these plans need further scientifically clarification. The aim of this study was to analyze the meteorological drought in northern and northwestern parts of Mexico and assess the effects of different IPCC-prescribed climate change scenarios on water resources with a hope that existing adaptive plans can be improved.

2 Materials and methods

2.1 Study area

As aforementioned, Mexico is generally characterized by dry climates. But, the southern part of Mexico is relatively wet due to seasonal invasion of the Intertropical Convergent Zone (ITCZ). The northern and northwestern parts of Mexico are dominated by a high pressure system nearly throughout a year, resulting in a dry climate with the mean annual precipitation being less than 500 mm. Furthermore, nearly 70% of the rainfall falls between June and September, further exacerbating the problems related to water-resource availability and also to water-resource reallocation (CONAGUA, 2014).

The area devoted to agriculture in Mexico is approximately 21×10^6 hm^2, 31% (i.e., 6.5×10^6 hm^2) of which is irrigated and 69% (i.e., 14.5×10^6 hm^2) of which is rain fed (CONAGUA, 2014). Agriculture plays an important role in the economic development of the country, accounting for 8.4% of the gross domestic product and employing 23% of the economically active population. Irrigated agriculture contributes approximately 50% of the total value of agricultural production.

Again, drought has been an inevitable natural disaster throughout Mexican history. A recent three-year (2010–2012) drought in Mexico has resulted in $\$1.5\times10^9$ of economic damages, the damages include loss of 450×103 heads of cattle, and reduction in crop yields. The immediate consequence of these damages was the rising price of agricultural products, predominantly affecting the poorest sector of the society. It should be particularly noted that the greatest damage occurred in the northern and northwestern parts.

The states situated in northern and northwestern parts of Mexico include Aguascalientes, Baja California, Baja California Sur, Coahuila, Chihuahua, Durango, Nuevo León, San Luis Potosí, Sinaloa, Sonora, Tamaulipas, and Zacatecas (Fig. 1). These states cover a surface area of 1,193,134 km² and they had a total population of 32,281,464 in 2015 (INEGI, 2015), being 27% of the national total. It should be stressed that this region (i.e., studied area) is the one that the most severe droughts have occurred (Esparza, 2014). Topographically, the region is composed of a central plateau, two mountain ranges and a coast plain. The two mountain ranges, the Sierra Madre Occidental and the Sierra Madre Oriental, are separated by the central plateau and the coastal plain separates the Sierra Madre Oriental from the Atlantic Ocean. Climatologically, the northern and

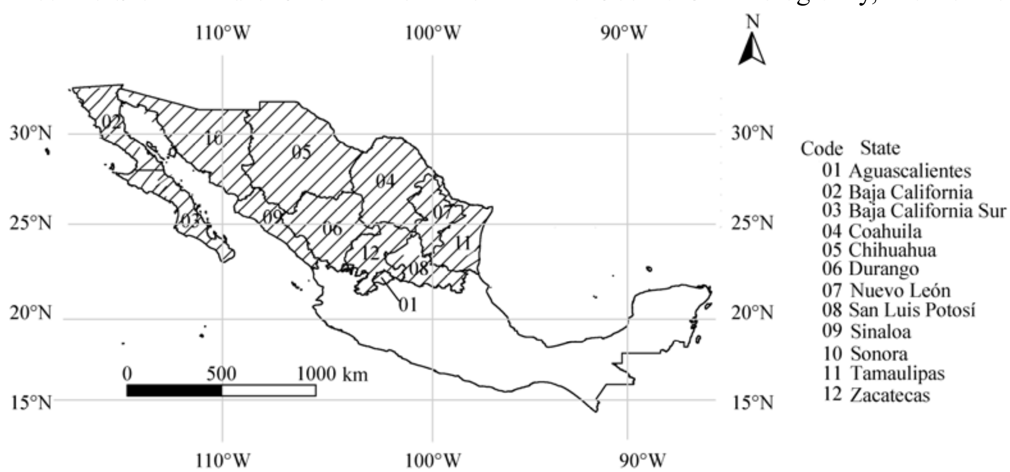

Fig. 1 The study area (shadow regions) and map of Mexico

northwestern parts of Mexico (i.e., studied area) are predominantly arid and semi-arid climates, covering 77% of the region's territory and consequently the states in northern and northwestern parts of Mexico are under water stress of varying degrees (Table 1).

Table 1 Water stress distribution in northern and northwestern parts of Mexico

State	Population	Water use (hm^3)	Average water availability (hm^3)	Water stress (%)
Aguascalientes	1,312,544	617	1051	59
Baja California	3,315,766	3001	2495	120
Baja California Sur	712,029	411	2505	16
Coahuila	2,954,915	1960	5308	37
Chihuahua	3,556,574	5065	12,493	41
Durango	1,754,754	1536	11,686	13
Nuevo León	5,119,504	2051	2478	83
San Luis Potosí	2,717,820	1383	7384	19
Sinaloa	2,966,321	9173	9788	94
Sonora	2,850,330	7519	7290	103
Tamaulipas	3,441,698	3885	13,586	29
Zacatecas	1,579,209	1484	7025	21
Northern Mexico	32,281,464	38,085	83,088	46

2.2 Data

According to Sirdas and Sen (2003), the annual time series method is suitable for assessing long-term drought features. This study thus adopted the method to assess long-term drought features based on the annual precipitation data of 64 years spanning from 1950 to 2013 obtained from 649 meteorological stations situated within the study area (Fig. 2). The only criterion for a meteorological station to be considered was that its recording period has to cover at least 85% of the total period of 64 years. In the present study, a feed-forward artificial neural network approach, similar to that proposed by Teegavarapu and Chandramouli (2005), was chosen for interpolation of missing rainfall data.

Fig. 2 Locations of the meteorological stations selected for this study

2.3 Methods

The theory of runs proposed by Yevjevich (1967) was used to obtain the meteorological drought features for each time series (Fig. 3). A negative run, d^*, occurs when the precipitation, X_t, is consecutively less than X_0 during one or more time intervals (years). Similarly, a positive run occurs when X_t is consecutively greater than X_0. We focused only on negative runs because they are related to drought features. A run can be determined by its duration D (years), and its severity (S) or the accumulated deficit is the sum of the differences between the threshold and the precipitation in the time (in mm). The drought intensity $I=S/D$ (in mm/a). The time span between two runs is known as drought periodicity, P. For this study, an additional drought feature was estimated, i.e., the available rainfall in an average drought period, which is actually the difference between the threshold and the average run severity.

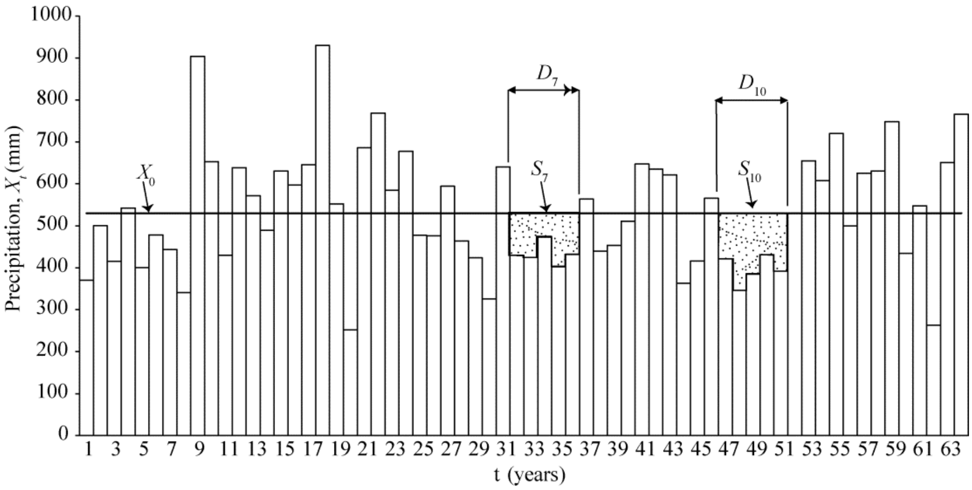

Fig. 3 Meteorological drought properties defined for a threshold X_0 (7th and 10th runs)

To obtain the long-term meteorological annual drought features, we generated 10×10^3 synthetic monthly samples for each rainfall series. The periodic autoregressive moving average (PARMA) model was used for this purpose (Salas et al., 1988):

$$Y_{\nu,\tau} = \Sigma\phi_{1,\tau} Y_{\nu,\tau-i} + \varepsilon_{\nu,\tau} - \Sigma\theta_{1,\tau}\, \varepsilon_{\nu,\tau-j}. \qquad (1)$$

Where $Y_{\nu,\tau}$ represents the precipitation process for year ν and season τ. For each season τ, this process is normally distributed with a mean of zero and variance $\sigma_\tau^2(Y)$. $\varepsilon_{\nu,\tau}$ is the uncorrelated noise term which is normally distributed for each season with a mean of zero and variance $\sigma_\tau^2(Y)$. $\{\phi_{1,\tau}, \ldots, \phi_{p,\tau}\}$ includes the periodic autoregressive parameters and $\{\theta_{1,\tau}, \ldots, \theta_{p,\tau}\}$ includes the periodic moving average parameters. Although this model has a limited ability to capture non-stationarity and non-linearity in data, it has been generally accepted by practitioners.

In Mexico, the "National Institute of Ecology and Climate Change" performed a regional climatic analysis using projections from 15 global circulation models (Table 2) of the Coupled Model Intercomparison Project Phase 5 (CMIP5) under the prevailing conditions of the RCP 4.5, RCP 6.0 and RCP 8.5 scenarios for the near future (2015–2039) and also for the far future (2075–2099). Each model employed a grid between latitudes 5.25°N and 34.75°N and longitudes 74.75°W and 121.25°W. The annual anomalies of the four output variables (precipitation, maximum, minimum and average temperature) for each RCP scenario were presented in a 0.5°×0.5° grid (INECC, 2014).

Table 2 Coupled Model Intercomparison Project Phase 5 global circulation models

1 Max Plank Institute (MPI-ESM-LR)	6 Beijing Climate Centre (BCC-CSM1-1)	11 Atmosphere and Ocean Research Institute (MIROC5)
2 Institute for Numerical Mathematics (INM)	7 Institute Pierre-Simon Laplace (IPSL-cm5a-Ir)	12 Met Office Hadley (MOHC)
3 Norwegian Climate Centre (NorESM1)	8 NASA Goddard Institute for Space Studies (GISS-E2-R)	13 Meteorological Research Institute (MRI-CGCM3)
4 Canadian Centre for Climate Modelling and Analysis (CanESM2)	9, 10 Japan Agency for Marine-Earth Science and Technology (MIROC.-esm-chem)	14 Geophysical Fluid Dynamics Laboratory (GFDL-CM3)
5 Centre National de Recherches Meteorologiques (CNRM-CM5)	10 Japan Agency for Marine-Earth Science and Technology (MIROC-esm)	15 Australian Commonwealth Scientific and Industrial Research Organization (CSIRO-MK3-6)

This study analyzed the responses of the meteorological drought features in northern and northwestern parts of Mexico to the IPCC-prescribed RCP 4.5 scenario (i.e., a pre-2100 emission stabilization scenario) for the near future (2015–2039) and also to the IPCC-prescribed RCP8.5 scenario (i.e., a very high baseline emission scenario) for the far future (2075–2099).

3 Results

Long-term meteorological drought features were estimated for 10×10^3 synthetic samples. The first simulated scenario, "Normal Conditions", considered no significant deviations of rainfall patterns from the present patterns (1950–2013). The other two considered the possible alterations in rainfall patterns according to the projections of two climate change scenarios: "emission stabilization (RCP 4.5) for the near future (2015–2039)" and "very high baseline emission RCP 8.5 for the far future (2075–2099)".

3.1 Normal conditions

Spatial analysis of the mean annual precipitation (MAP) allows us distinguish the "dry areas" from the "wet areas" (Fig. 4). The "dry areas" include the entire Baja California Peninsula (MAP≤400 mm), the Sonora (MAP≤375 mm), and the central plateau (MAP≤250 mm). The "wet areas" are situated in the eastern part of the region, including the states of San Luis Potosí, Tamaulipas, the south-eastern zone of Nuevo León, and also some regions in the states of Sinaloa, Chihuahua and Durango. Due to orographic effect, the mean annual precipitation (MAP) in the highlands of the eastern mountain ranges (i.e., Sierra Madre Oriental) reaches a value of 1350 mm.

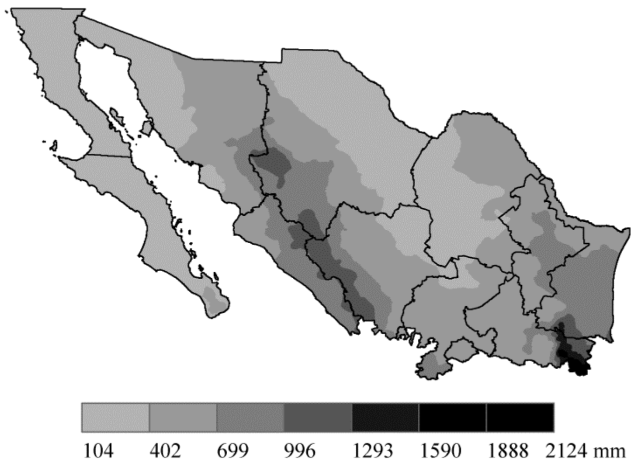

Fig. 4 Spatial distribution of the mean annual precipitation (mm) in northern and northwestern Mexico based on the available data (1950–2013)

The long-term drought features under normal conditions (the average between 1950 and 2013) were estimated from 10×10^3 synthetic samples generated from the mean annual precipitation data of all selected meteorological stations. The results reveal that the region suffered a drought on average every 4.1 years with a mean duration of 2.2 years and with an intensity of 143 mm/a (24.2% below the average). The mean annual precipitation in drought episodes is only 447 mm (Fig. 5), whereas the mean annual precipitation during the data-available period (1950–2013) is 590 mm (Fig. 4).

Drought duration throughout the region varied from 2.0 to 2.8 years. The intensity of drought also varied across the region. The driest places (e.g., the California Desert) experienced droughts with intensities ranging from 35% to 50% below the average and less dry places (e.g., the Sonoran Desert and central plateau) experienced droughts with intensities varying from 25% to 35% below the average. The intensity was considerably lower in the mountain ranges (15% to 25% below the average) and also in the southern part (i.e., Zacatecas and Aguascalientes) of the studied area (10% to 20% below the average).

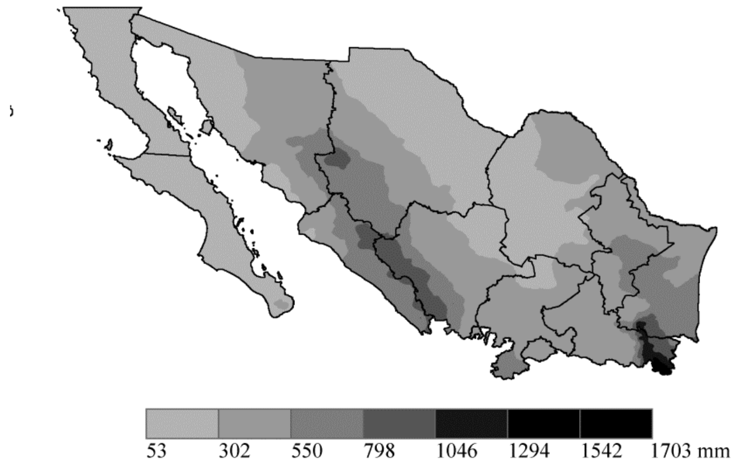

Fig. 5 Spatial distribution of the mean annual precipitation (mm) in northern and northwestern Mexico under drought episodes occurred during the data-available period (1950–2013)

3.2 Meteorological drought features under different climate change scenarios

The RCP 4.5 (2015–2039) scenario-simulation results indicate that the region would suffer from a drought every 4.3 years in the near future (2015–2039) with an average duration of 2.7 years and with an intensity of 165 mm/a (28% below the average) and that the regional mean annual precipitation would be only 425 mm (Fig. 6). The RCP 8.5 (2075–2099) scenario-simulation results indicate that the region would suffer from a drought every 4.7 years in the far future (2075–2099) with an average duration of 3.2 years and with an intensity of 182 mm/a (30.8% below the average) and that the regional mean annual precipitation would be only 408 mm (Fig. 7).

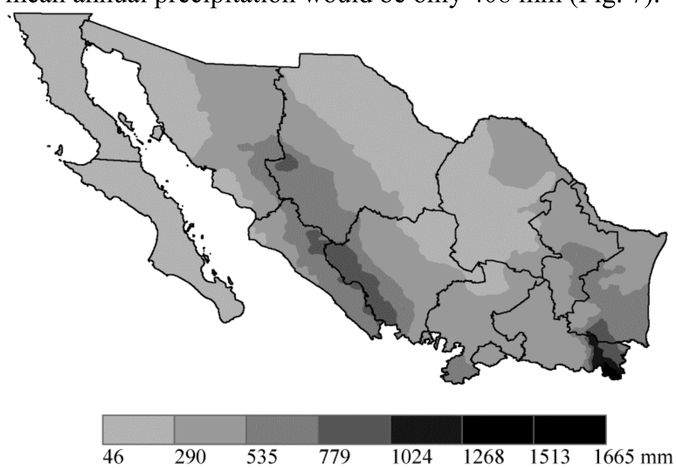

Fig. 6 Spatial distribution of the mean annual precipitation (mm) in northern and northwestern Mexico during droughts for the RCP 4.5 (2015–2039) scenario

In the RCP 4.5 (2015–2039) scenario, the projected drought duration would continue to be spatially homogeneous across the region, varying from 2.5 to 3.0 years. The longest drought durations would occur in central Sonora and Baja California, ranging from 3.0 to 3.5 years. In the RCP 8.5 (2075–2099) scenario, the projected drought duration would vary from 3.0 to 3.5 years in the eastern part (i.e., Nuevo León, San Luis Potosí, Tamaulipas and eastern Coahuila and Zacatecas) and from 2.5 to 3.0 years in the central part (i.e., Durango, eastern Chihuahua and western Coahuila). The drought durations would be up to 4 years in southern Zacatecas and up to 5 years in central Sonora. The duration would vary from 2.5 to 3.0 years in the remaining areas (e.g., the Baja California Peninsula).

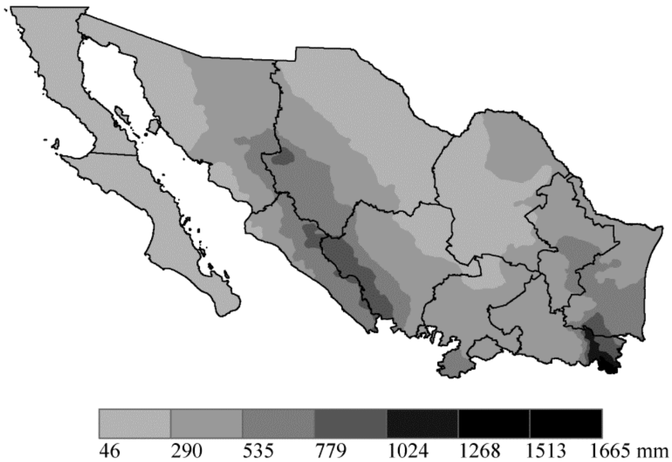

Fig. 7 Spatial distribution of the mean annual precipitation (mm) in northern and northwestern Mexico during droughts for the RCP 8.5 (2075–2099) scenario

The spatial distribution of the intensity under different scenarios would follow the same pattern as under normal conditions and the presently driest places would have the most intense droughts. The California Desert would experience droughts with an intensity ranging from 47% to 57% below the average. Similarly, the Sonoran Desert and central plateau would experience drought with intensities ranging from 30% to 45%. In the highlands of the mountain ranges the intensity would vary between 20% and 30% below the average, and in the southern tip of the region the intensity would be approximately 15% below the average.

4 Discussion

4.1 Expected water stress

Due to the naturally arid conditions in northern and northwestern Mexico, the water resources in the region are already stressed under the current socioeconomic status (see Table 1), and the continuation of the rapid population growth would definitely aggravate the water stress level (CONAPO, 2015). Magaña-Rueda (2006) suggested that the water stress levels would further increase by 7%–17% above the current levels for northern and northwestern Mexico in the year 2030, considering water-demanding factors including population, gross domestic product, water and food demand and other factors. Furthermore, if the RCP 4.5 scenarios for the near future (2015–2039) and the projected population for the year 2030 are taken into consideration (CONAPO, 2015), the water stress levels would become much worse and the water stress levels for the studied area would further increase by nearly 30% above the current levels (Table 3).

4.2 Expected impacts on agriculture

A lack of rainfall mainly affects the crops of rain-fed agriculture. The rain-fed agriculture is 2-fold greater than that of irrigated agriculture in terms of areal extents in northern and northwestern Mexico (SIAP, 2015). In the most recent drought year (i.e., 2011), rain-fed bean production (224×10^3 tons) and rain-fed maize production (505×10^3 tons) were considerably lower than expected, and the drought-resulted economic loss was as high as \$363 million. The most affected states were Zacatecas, San Luis Potosí and Durango and the losses amounted for 79% of the total losses in the region (SIAP, 2015). In the same year, some states, such as Baja California Sur and Zacatecas, did not suffer from the drought, but the groundwater extractions for irrigation were 54% and 40% higher than the averages between 2006 and 2010 (INEGI, 2015). During the period from 1980 to 2013, the average annual rain-fed agricultural lands were 2,428,245 hm^2 in total and the average annual drought-damaged agricultural lands accounted for 19% of the total (SIAP, 2015). To

Table 3 Water stress in northern and northwestern Mexico under drought conditions for the RCP 4.5 (2015–2039) scenario

State	Population (2030)	Water use (hm^3)	Average water availability in drought (hm^3)	Water stress (%)
Aguascalientes	1,403,549	730.94	460.7	158.65
Baja California	3,838,573	3652.01	1953.6	186.94
Baja California Sur	935,908	603.37	1732.0	34.84
Coahuila	3,203,950	2284.68	3192.8	71.56
Chihuahua	3,955,472	5880.78	8830.2	66.60
Durango	1,880,903	1769.12	8300.8	21.31
Nuevo León	5,604,167	2470.19	2739.7	90.16
San Luis Potosí	2,914,568	1558.81	6391.1	24.39
Sinaloa	3,154,280	10,454.24	7236.3	144.47
Sonora	3,213,165	9074.49	5686.0	159.59
Tamaulipas	3,818,219	4538.79	7950.9	57.09
Zacatecas	1,656,459	1649.53	4737.6	34.82
Northern Mexico	35,579,213	44,666.95	59,211.8	75.44

estimate the drought-damaged percentages of the rain-fed agricultural lands during the data-available period (1950–2013) for each state, we established a statistical relationship between the damaged percentages of agricultural lands and the mean annual precipitation amounts. Our estimates suggest that the mean annual precipitation (MAP) during a drought episode is 416 mm and the possible damaged percentages of rain-fed agricultural lands reaches 56% under current conditions (i.e., 1950–2013) in Aguascalientes. The damaged percentage increases to 60% in the near future (2015–2039) for the RCP 4.5 scenario and up to 65% in the far future (2075–2099) for the RCP 8.5 scenario. Table 4 presents the expected percentage of the damaged agricultural lands for the remaining states in the central plateau and Baja California Peninsula. It should be noted that Baja California Sur is an exception because no rain-fed agriculture is practiced there.

Table 4 Expected percentage of damaged rain-fed agricultural lands under drought conditions for different climate scenarios

State	Average area of annual sowing of rain-fed land (hm^2)	Current condition (1950—2013) (%)	RCP 4.5 (2015–2039) (%)	RCP 8.5 (2075–2099) (%)
Baja California	35,909	54	59	60
Chihuahua	654,890	27	29	30
Coahuila	54,055	28	29	30
Durango	523,051	18	21	23
Zacatecas	1,059,254	21	24	29

5 Conclusions

Under the current conditions (during the data-available period from 1950 to 2013), the studied area, northern and northwestern parts of Mexico, suffers a drought on average every 4.0 years with a duration of 2.2 years and with an intensity of 143 mm/a (24% below the average). The mean annual precipitation (MAP) during the data-available period (1950–2013) is 590 mm and the MAP during drought episodes is 447 mm. Under the RCP 4.5 scenario, the region would suffer from a drought every 4.3 years in the near future (2015–2039) with an average duration of 2.7 years and with an intensity of 165 mm/a (28% below the average) and that the regional mean annual precipitation would be only 425 mm during drought episodes. Under the RCP 8.5 scenario, the region would suffer from a drought every 4.7 years in the far future (2075–2099) with an average duration of 3.2 years and with an intensity of 182 mm/a (30.8% below the average) and that the regional mean annual precipitation would be only 408 mm during drought episodes.

Spatial analysis of meteorological drought features further promotes the notion that drier areas will become more vulnerable to future rainfall shortages under different climate change scenarios. In northern and northwestern parts of Mexico, the annual average damaged percentages of rain fed agricultural lands will definitely increase under different scenarios and the food requirements of a growing population will also increase significantly. Consequently, the demand for water resources will increase rather dramatically. All in all, the lack of water resources will have negative impacts not only on agriculture but also on domestic uses. Based on the projected population growth in northern and northwestern parts of Mexico, the water demand in cities will increase by 18% for the period between 2015 and 2030. The most important effect will take place in the state of Baja California Sur where an expected increase of 223,879 inhabitants will demand 47% more water above the current level. Admittedly, our approach in this study was just one step further towards a comprehensive understanding of the drought features for developing mitigation strategies. Surely, the need is pressing to further explore the temporal trends and spatial patterns of water-resource availability on other hand and water-resource consumption on the other under different climate change scenarios.

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