Climate and Climate Change Scenarios in the Indian Thar Region

Surendra Poonia and A. S. Rao

Contents

Abstract

The Thar Desert region of India, which extends in more than 2.0 lakh sq. km area, experiences variable rainfall from 100 mm to 450 mm in a year. Frequent drought, which occurs once in 2 or 3 years in the region, causes extreme stress to fauna due to limited seasonal grazing resources. Besides the xerophytic type of ecosystem, the fauna in the Thar Desert is subjected to extreme diurnal and seasonal variation in temperatures ranging as low as −5 °C in winter to a high of +49 °C in summer,

S. Poonia (✉)
ICAR-Central Arid Zone Research Institute, Jodhpur, Rajasthan, India
e-mail: poonia.surendra@gmail.com

A. S. Rao
ICAR-Central Research Institute for Dryland Agriculture, Hyderabad, India
e-mail: ashivrao@gmail.com

W. Leal Filho (ed.), *Handbook of Climate Change Resilience*,
https://doi.org/10.1007/978-3-319-71025-9_12-1

causing thermal stress to the fauna. The Intergovernmental Panel on Climate Change (IPCC 2007) projected for hotter days and warm nights and a reduction in rainfall in the Thar region by the twenty-first century. Such projected climate change results in shifting rainfall pattern, higher temperatures, and more demand for water and will be significant driver of biodiversity with changing life cycles, loss, migration, and invasion of new habitat in the Thar region. The present study on annual rainfall and temperature for the Thar region showed, by the end of the twenty-first century, an increase in temperature by +3.3 °C at Bikaner, +3.4 °C at Jaisalmer, +2.9 °C at Jodhpur, and +2.3 °C at Pali, if the present rate of warming continues. Similarly, though there was no significant rise (at 0.56 mm/year) in the annual rainfall of 12 arid districts of western Rajasthan, the annual rainfall is likely to be increased by +100 mm at Bikaner, +124 mm at Jaisalmer, −40 mm at Jodhpur, and +21 mm at Pali. The spatial and temporal variation in potential evapotranspiration requirement of the Thar region ranged from 2.1 mm/day to 12.2 mm/day and on an annual basis between 1500 mm and 2220 mm. Further, due to global warming, if the projected temperatures rise by 4 °C, by the end of the twenty-first century, water requirement in arid Rajasthan increases from the current level, by 12.9% for pearl millet and cluster bean, 12.8% for green gram, 13.2% for moth bean, 17.1% for wheat, and 19.9% for mustard.

Keywords
Climate change · Thar Desert region · Crop water requirement · Drought · Elevated air temperature · Rainfall

Climate Variability

The hot arid zone of India, which is located in northwest India, is spread in 3,17,000 km^2 and is characterized by limited and erratic nature of rainfall, extreme temperatures with large diurnal and seasonal variation, strong solar radiation, and wind regime resulting in the demand for high water requirements (Rao and Roy 2012). The weather conditions, even in normal years, for most part of the year remain too dry and inhospitable for human and livestock.

Rainfall and Its Distribution

The mean annual rainfall in arid Rajasthan varies from 185 mm at Jaisalmer to more than 467 mm at Sikar (Table 1 and Fig. 1). About 80–90% of the annual rainfall is received during southwest monsoon period from west southwesterly moving depressions which are the main source for *kharif* crops. The westerly moist wind from the Arabian Sea during May or early June move in east-northeasterly direction and cause rainfall, but such events occur with a lesser frequency of once in 2 or 3 years. The western disturbances during winter also cause precipitation particularly in the northern districts favoring *rabi* crops. The high interannual variability in rainfall

Table 1 Normal rainfall (mm) and its coefficient of variation (%) in arid Rajasthan

Month	Winter (Dec–Feb)	Summer (Mar–May)	Monsoon (Jun–Sept)	Post-monsoon (Oct–Nov)	Annual mean	Coefficient of variation
Barmer	6.8	12.5	242.6	4.8	266.7	63
Bikaner	13.5	23.5	243.1	8.0	290.6	47
Churu	19.7	21.6	314.4	9.5	365.7	37
Ganganagar	21.0	26.8	204.6	2.8	255.1	53
Hanumangarh	18.9	19.5	207.2	4.9	250.5	56
Jaisalmer	9.1	12.3	161.4	2.9	185.3	65
Jalore	17.9	14.9	349.1	10.1	381.0	52
Jodhpur	7.1	27.9	332.2	12.0	379.2	46
Jhunjhunu	21.5	28.4	340.4	11.7	402.0	36
Nagaur	15.0	20.9	285.1	6.7	327.7	53
Pali	5.8	17.0	384.4	16.9	424.1	50
Sikar	22.0	25.5	410.5	9.4	467.4	42
Wes. Rajasthan	15.3	19.4	290.6	7.7	332.3	50

causes the high degree of coefficient of variation ranging from 36% in eastern parts to 65% in western parts of arid Rajasthan. Thus, the variability in annual rainfall is the most important factor influencing crop and pasture yields in this region.

Solar Radiation and Duration of Sunshine

Solar radiation is generally high in arid Rajasthan throughout the year. During winter, it varies between 15.12 and 17.71 MJ/m^2/day, and in summer months, the values range from 22.79 to 26.50 MJ/m^2/day with a mean of 22 MJ/m^2/day (Table 2). The daily duration of bright sunshine hours in the area remains above 10 h/day in May, reduces to 6.6 h/day in July and August, and is above 8.8 h/day in the winter season.

Air Temperatures

The western Rajasthan experiences high extreme air temperatures considerably influencing the vegetation and crops and demanding higher water requirements. During winter, mean monthly maximum air temperature in the region varies from 22.4 °C to 29.0 °C and minimum temperatures between 4.1 °C and 14.3 °C (Table 3). Air temperatures increase sharply from April onward and stand highest during May till pre-monsoon showers set in the area. Summer air temperatures vary between 31.2 °C and 42.0 °C with peak values as high as 50 °C in summer and −5.7 °C during winter months. Temperatures fall during the monsoon period (June

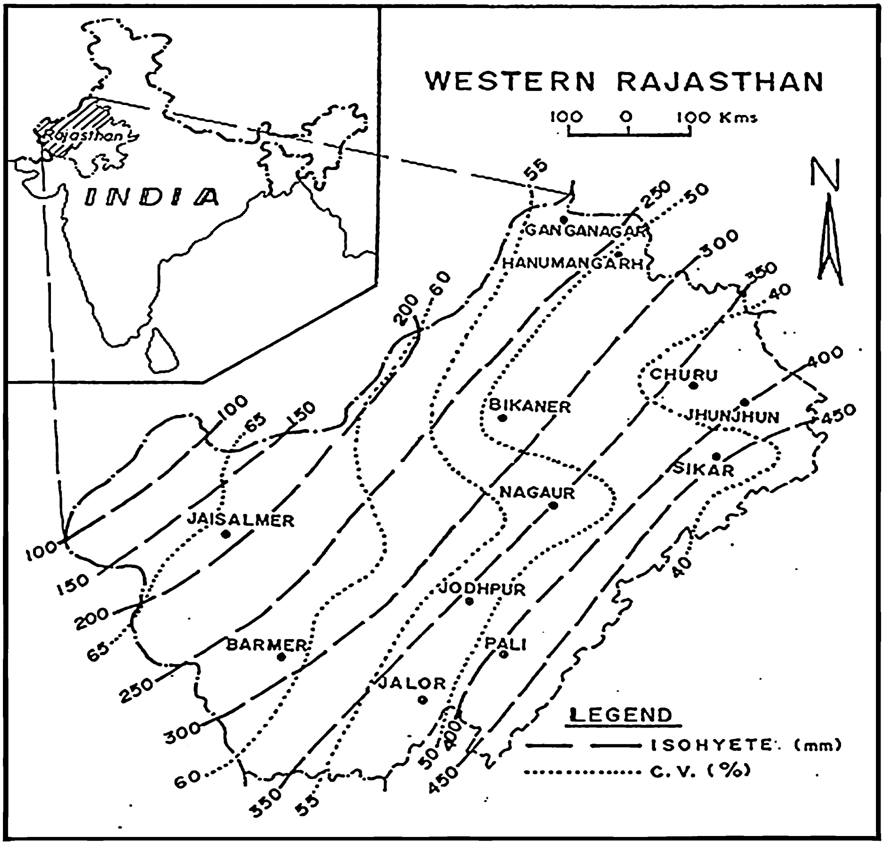

Fig. 1 Spatial distribution of annual rainfall

Table 2 Solar radiation (MJ/m^2/day) over arid Rajasthan

Station	Winter (Dec–Feb)	Summer (Mar–May)	Monsoon (Jun–Sept)	Post-monsoon (Oct–Nov)	Annual average
Barmer	17.71	26.50	24.55	20.05	22.18
Bikaner	16.81	26.39	26.17	19.37	22.18
Hanumangarh	15.12	22.79	21.96	20.16	19.98
Jaisalmer	17.42	26.49	26.60	19.87	22.57
Jodhpur	17.71	24.94	23.15	19.87	21.31

to September) but however rise after recession of the monsoon by about 3–5 °C and again start falling from December onward due to winter conditions.

Table 3 Seasonal variation in air temperatures over arid Rajasthan

Month		Winter (Dec–Feb)	Summer (Mar–May)	Monsoon (Jun–Sept)	Post-monsoon (Oct–Nov)	Annual mean
Barmer	Max	25.4–29.0	34.6–42.0	34.9–40.3	35.9–39.6	34.5
	Min	10.6–13.3	19.0–26.7	24.6–27.3	16.6–22.1	20.7
Bikaner	Max	22.7–26.3	32.3–41.7	36.6–41.7	30.5–35.8	33.8
	Min	05.0–08.6	14.0–26.3	24.9–29.0	11.1–19.0	18.4
Churu	Max	22.4–25.6	31.6–40.9	35.4–41.1	29.4–34.7	32.9
	Min	04.1–07.4	19.4–24.3	23.2–27.9	10.0–17.3	17.1
Ganganagar	Max	21.1–24.2	24.9–40.6	36.6–41.9	29.2–35.1	32.8
	Min	05.3–06.3	13.4–23.9	23.0–28.2	10.8–17.9	17.6
Jaisalmer	Max	23.6–27.3	32.7–41.5	36.2–40.8	30.9–36.0	33.9
	Min	07.1–10.2	16.0–25.2	23.9–26.8	13.0–19.8	18.6
Jalore	Max	25.9–28.1	34.4–41.1	33.4–39.1	32.2–36.2	34.1
	Min	10.1–14.3	20.1–28.5	25.6–28.9	17.8–23.7	21.6
Jodhpur	Max	24.6–27.9	33.3–41.6	33.2–40.1	31.6–35.7	33.6
	Min	09.5–12.0	17.1–27.3	24.1–28.5	13.9–19.6	19.8
Nagaur	Max	23.6–26.7	32.7–41.2	3475–40.6	30.3–35.7	33.4
	Min	06.0–09.6	15.2–25.2	23.6–27.6	13.1–18.7	18.2
Sikar	Max	22.5–25.7	31.2–39.6	33.7–39.2	29.1–33.7	32.0
	Min	05.1–07.9	13.5–23.5	22.4–26.7	10.0–16.6	16.7

Relative Humidity

Relative humidity in arid Rajasthan is often less than 30% during the summer months, but gradually increases up to 80% by monsoon season, and then again decreases from October onward following withdrawal of the monsoon. Low humidity combined with strong wind regime leads to advection, a phenomenon which causes evaporation losses more than the energy actually available through solar radiation.

Wind Regime

The winds over arid Rajasthan blow in southwesterly direction during monsoon and in northeasterly direction during winter season. Though winds during winter are low, a strong wind regime builds up along with the temperature regime from April onward. Strong winds of the rate 15–18 kmph are observed during June, but the average winds during summer vary from 9 to 13 kmph. Peak winds occasionally reach as high as 60–80 kmph during a severe dust storm period. Strong wind regime during May and June cause wind erosion depleting soil fertility particularly during drought years.

Table 4 Potential evapotranspiration (mm/day) over arid Rajasthan

Station	Winter (Dec–Feb)	Summer (Mar–May)	Monsoon (Jun–Sept)	Post-monsoon (Oct–Nov)	Annual average
Barmer	2.3–3.5	5.2–8.4	5.5–8.0	3.1–4.7	5.1
Bikaner	1.6–2.6	4.3–7.6	5.9–8.6	2.3–4.0	4.9
Ganganagar	1.3–2.3	3.7–7.0	5.4–7.3	2.0–3.7	4.6
Jaisalmer	2.1–3.2	4.9–8.4	6.4–10.6	2.8–4.8	5.7
Jodhpur	2.5–3.5	5.0–8.5	5.2–8.7	2.9–4.3	5.0
Phalodi	2.1–3.0	5.1–9.5	6.2–9.8	3.5–4.3	5.6

Evapotranspiration Rates

The extreme climatic conditions in the region result in high evapotranspiration rates. The potential evapotranspiration rates were 1.3–3.5 mm/day in winter months of December and January; as the summer temperatures increase by May, the values increase to 3.7–9.5 mm/day. During monsoon period, the evapotranspiration rates were 5.2–10.6 mm/day but again decrease from October onward till December (Table 4). The annual potential evapotranspiration ranges from 1400 mm in eastern parts to more than 2000 mm/year in the western parts of arid Rajasthan.

Drought Scenarios in the Thar Region

The arid Rajasthan is frequently prone to severe drought due to low and erratic nature of rainfall of the region. Failure of monsoon leaves the arid region totally dependent for food and fodder on buffer stocks to sustain its 19.8 million human and 48 million livestock population.

According to a classification given by Ramana Rao et al. (1981), the frequency of agricultural drought (Table 5) in arid Rajasthan indicated that out of 112 years (1901–2012), the region experienced agricultural drought in one part or the other in 49–60 years, which suggests drought occurs in the region once in 3 years to every alternate year. Jaisalmer district is the most prone region to drought. During 1901–2012, the agricultural drought in the region occurred in 70% of the years, out of which drought in 43% years was of severe nature and in 27% years moderate, thus considerably affecting the crop and fodder production. Next to Jaisalmer district, the Barmer district experienced severe drought in 30% years and moderate drought in 20% years. Bikaner district experienced severe agricultural drought in 23% years and moderate in 25% years, whereas Jodhpur district experienced severe drought in 17% years and moderate drought in 28% years.

Often, drought persists continuously for 2–6 years. Such prolonged droughts were experienced by this region during 1903–1905, 1957–1960, 1966–1970, 1984–1987, and 1997–2002. Century's worst drought conditions were recorded during the years 1918 and 2002. Prolonged drought puts tremendous stress on natural resources and leads to severe scarcity of food, fodder, and water (Rao

Table 5 Frequency of different intensities of meteorological droughts in arid Rajasthan

District	Period	Mild	Moderate	Severe	Total years	% years
Ganganagar	1926–2012	20	13	15	48	57
Churu	1906–2012	34	17	05	58	55
Hanumangarh	1906–2012	17	16	19	52	49
Jalore	1901–2012	31	17	16	64	58
Nagaur	1901–2012	29	23	14	66	60
Jhunjhunu	1901–2012	28	21	09	58	53
Jodhpur	1901–2012	24	23	16	63	57
Sikar	1901–2012	23	21	15	59	54
Barmer	1901–2012	22	18	22	62	56
Bikaner	1901–2012	22	21	13	56	51
Pali	1901–2012	18	30	11	59	54
Jaisalmer	1901–2012	15	23	23	61	55

1997; Rao et al. 1997; Rao and Boken 2005). However, the western Rajasthan sometimes gets normal to above normal rainfall in subsequent drought years like the years of 1988 to 1996, which followed the 1987 severe drought, leaving ample scope for harvesting and reuse it during scarce periods.

Climate Change Impacts on the Thar Region

The Intergovernmental Panel on Climate Change (IPCC 2007) projected that the likely impact of climate change will be higher in arid regions than in semiarid or subhumid regions of India. Arid Rajasthan, which spreads in 12 western districts of the state covering 19.61 million ha, is very fragile and is subjected to excessive stresses due to frequent drought and low rainfall. The arid phase of northwest India has a history of about 3000 years (Pant and Maliekal 1987). In the northwest India covering Punjab, Haryana, west Rajasthan, and west Madhya Pradesh, there was a marginal increase in the rainfall by 141 mm and fall in air temperature by -0.52 °C in the past 100 years (Pant and Hingane 1988) and more so in irrigated belts of Sri Ganganagar region particularly during the past three decades (Rao 1996). The studies for Jodhpur region showed that the changes in rainfall and air temperatures were not alarming, but the increase in human population (by 400%) and livestock (by 127%) during the twentieth century resulted in a major shift in land use pattern and put tremendous pressure on surface and groundwater resources (Rao 1996; Rao and Miyazaki 1997). The desertification process may continue due to increased biological activity as a result of overgrazing and loss of vegetation cover with consequent more radiant energy loss and reduction in convective activity. Soil degradation and vegetation loss impact the thermodynamic balance in the north-western India, and expansion of the Thar Desert can lead to a pronounced and large-scale impact on summer monsoon hydroclimate of the northwestern region of India. The Thar Desert is very rich in biodiversity with arid climatic conditions of the region suitable for adaptation of different species in the region. But extreme weather conditions like low and erratic rainfall, high temperatures, strong winds, and low humidity make it inhospitable to different habitats leaving to migration and loss of habitats in the region (Rao 1992, 2005 and 2009).

Climate Change Scenarios for Arid Western Part of India

According to PRECIS model, the simulated future climate of India under A_2 scenario indicates that by the last quarter of the present century, the mean annual temperature in the country will most likely increase by 3–5 °C. The annual spatially average rainfall is increase during the period is expected to be 7–10% (Rupa Kumar et al. 2006). The model also predicted in high variability in the changes in distribution of rainfall and temperature. North India is expected to be warmer than the south, but more importantly, night temperature and winter temperature would register higher of 5 °C increases over the most part. The rainfall trend during the last 100 years revealed that the summer monsoon rainfall, which contributes more than 85% of the total annual rainfall in the region, has increased marginally (< 10%) in the southern and eastern parts of the Thar Desert but has already declined by 10–15% in its northwestern part. Earlier studies on changes in rainfall and air temperatures of northwest India showed that the rainfall increased marginally by 141 mm in the past 100 years (Pant and Hingane 1988), especially in the irrigated belt of Ganganagar region particularly during the past three decades (Rao 1996).

Secular Trends in Annual Rainfall

The long-term rainfall trends in annual rainfall of 12 arid districts in Rajasthan showed that there was no significant change in annual rainfall during 1901 to 2012 (Fig. 2). Severest drought occurred in arid Rajasthan during 1917 and 2002, and the wettest year was in 1918. The rainfall (1960–2008) analysis at tehsil-wise locations of arid Rajasthan shows that the rainfall of June increased at 58 out of 65 locations, whereas the scenario for subsequent monsoon months is different as it decreased during July, August, and September. The rainfall was decreasing at 36 out of 65 locations in July, 49 in August, and 45 in September indicating larger arid area is under reduction in monsoonal rainfall of July, August, and September. The seasonal rainfall was decreasing at 37 locations during monsoon (JJAS), 7 in post-monsoon (ON), 16 in winter (DJF), and 15 during summer (MAM) (Rao and Roy 2012).

Changes and Shift in Rainfall

Twelve arid districts of western Rajasthan constitute 61% area of Indian hot arid zone, where the annual rainfall varies from 100 mm in the extreme west to 400 mm

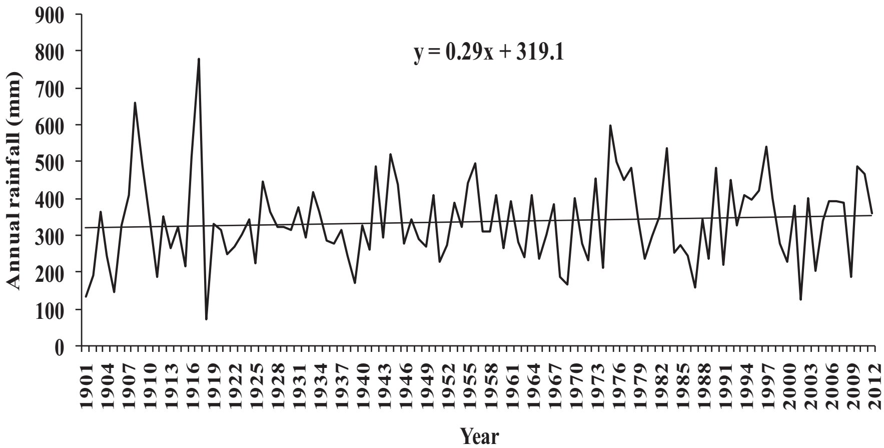

Fig. 2 Long-term annual rainfall trend of arid Rajasthan

toward eastern part of the region. The coefficient of annual rainfall varies from 40 in the east to 70% in the west of the region, causing larger interannual variability in rainfall influencing crop production. According to a classification given by Ramana Rao et al. (1981), the frequency of agricultural drought in arid Rajasthan indicated that out of 109 years (1901–2011), the region experienced agricultural drought in one part or the other in 54–62 years, which suggest drought occurs in the region once in 3 years to alternate year. Jaisalmer district is most prone to drought. During 1901–2011, the agricultural drought in the region occurred in 70% of the years, out of which drought in 44% years was of severe in nature and in 29% years moderate, thus drought affecting considerably the crop and fodder production. Bikaner district experienced severe agricultural drought in 24% years and moderate in 26% years, whereas Jodhpur district experienced severe drought in 18% years and moderate drought in 29% years.

The overall regional trend in annual rainfall (1960–2011) for Thar showed no significant rise (at 0.56 mm/year) in the rainfall; however, the rainfall trend at different locations showed that the annual rainfall is likely to increase by +100 mm at Bikaner, +124 mm at Jaisalmer, −40 mm at Jodhpur, and +21 mm at Pali (Fig. 3). Thus, the projected rainfall is likely to increase from 252 mm to 308 mm at Bikaner, from 176 mm to 234 mm at Jaisalmer, and from 487 mm to 613 mm at Pali, whereas in Jodhpur the rainfall is likely to be decreased from 325 mm to 275 mm. Thus, in Jodhpur region, long-duration crops like pearl millet and sorghum are likely to be replaced with short-duration and traditional crops like cluster bean, moth bean, and green gram where rainfall is expected to decrease by the twenty-first century (Rao and Purohit 2009). To cope up with the delayed monsoon conditions, crop contingency plans (Joshi and Kar 2009) should be adopted. Adoption of traditional agroforestry systems in arid region buffers against climate

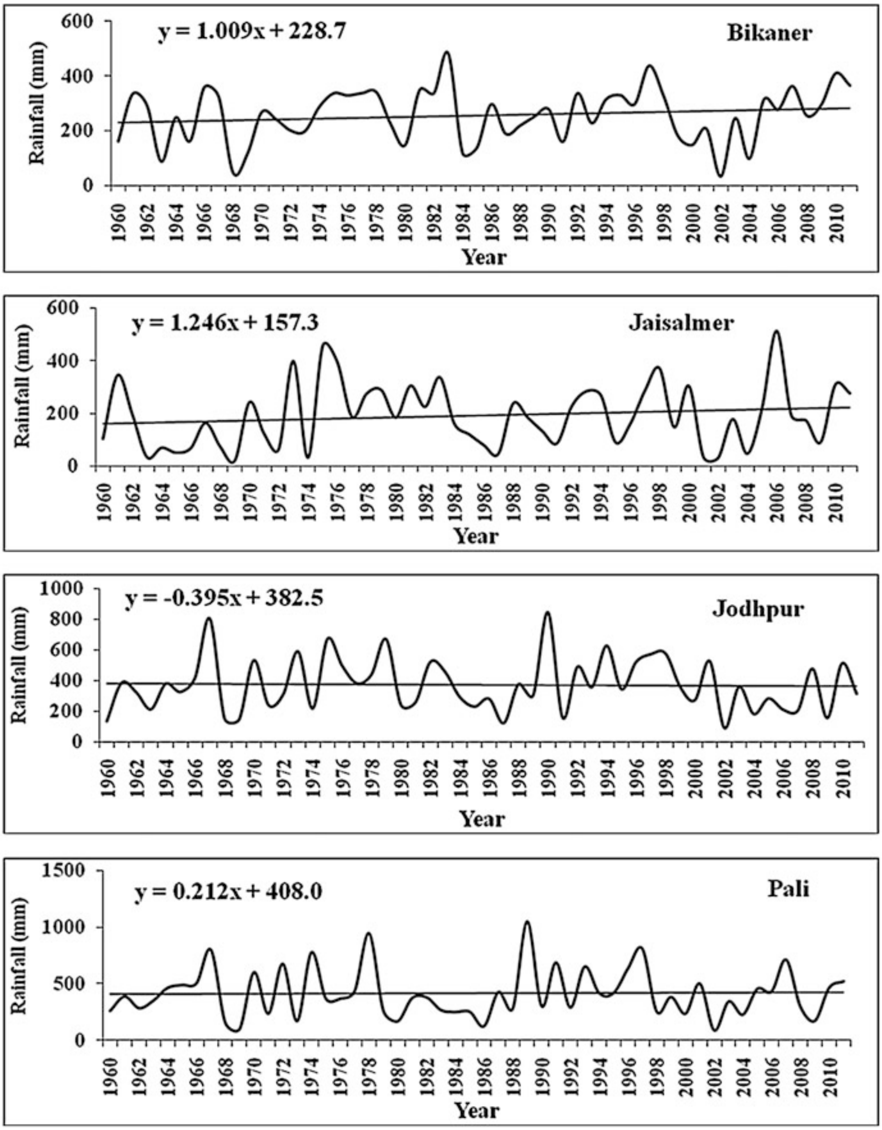

Fig. 3 Long-term trends in annual rainfall in the Thar region

variability, improves carbon sequestration, and also provides improved livelihood to the people (Roy et al. 2011 and Poonia and Rao 2013).

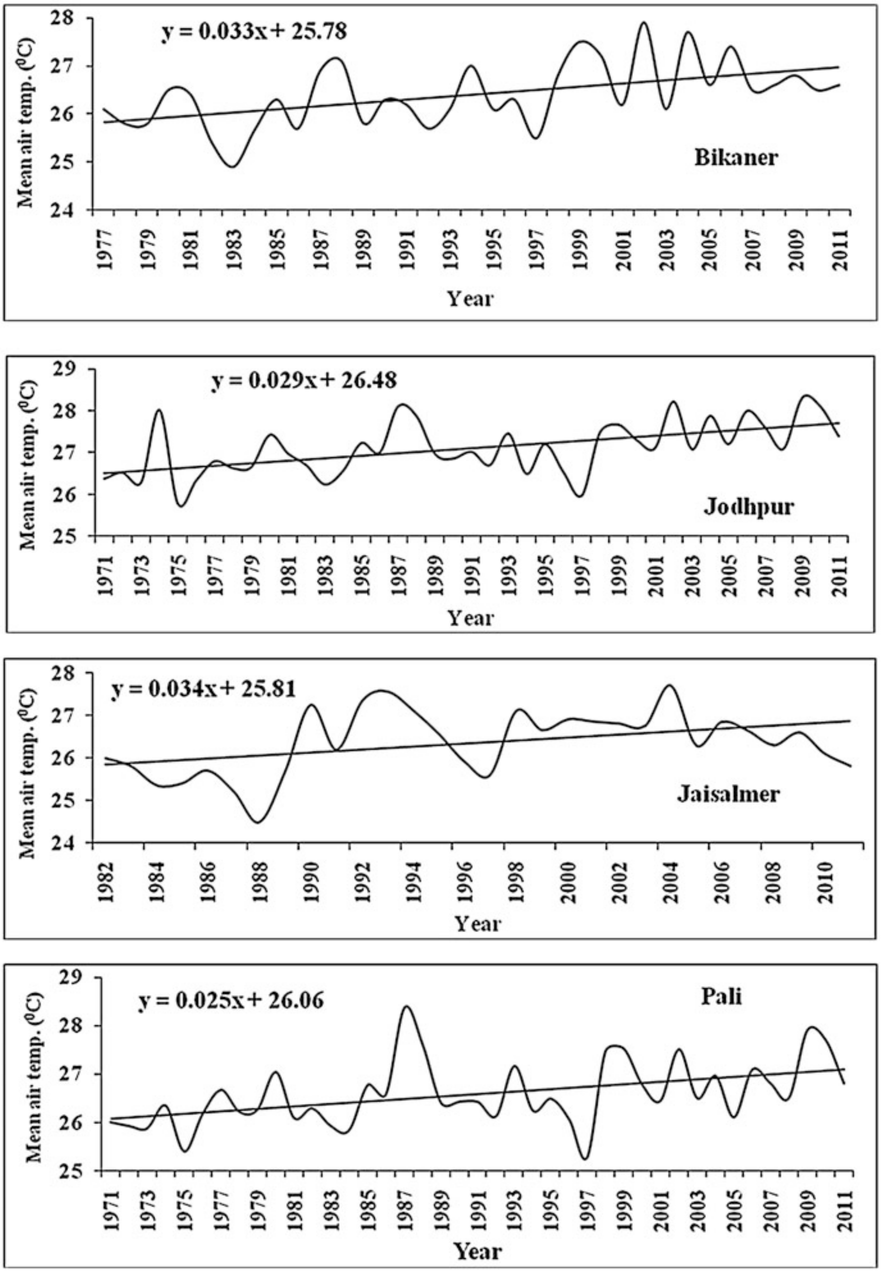

Fig. 4 Long-term trends in annual mean air temperatures in the Thar region

Changes in Air Temperatures

Poonia and Rao (2013) studied the long-term trends in mean air temperature (1971–2011) for the Thar region and showed, by the end of the twenty-first century, an increase in temperature by +3.3 °C at Bikaner, +3.4 °C at Jaisalmer, +2.9 °C at Jodhpur, and +2.5 °C at Pali if the present rate of warming continues (Fig. 4). Jodhpur experienced highest day temperature of 48.3 °C on June 8, 2011, and warmest winter in 2008–2009 surpassing all past 50 years of extreme hot summer and warm winters in the region. Desert fauna suffers causality during severe drought years, reducing population, but multiplies during consecutive good rainfall years when adequate feed is available. The Thar region experienced severe drought during 1918, and 1987, 2002, and 2009 were most severe, when rainfall departure from the normal was −81%, −65%, and −70%, respectively. In 2009, a rainfall deficiency of 40% from its normal rainfall caused drought affecting desert fauna due to scarcity for feed and drinking water. Drought followed by high temperatures touching 45–49 °C during late summer period of June 2010 resulted in a casualty of chinkaras and black bucks in Barmer, Churu, and Jodhpur districts of the Thar region. It was reported in local newspapers more than 177 chinkaras and black bucks died in villages of Bhacharna, Guda Vishnoi, Janguwas in Jodhpur district, Chawa in Barmer district, and Tal Chhapar in Churu. Soil fauna is not going to be affected directly by high temperatures due to their habit of living in burrows where the subsurface temperatures are not greatly influenced by high air temperatures (Poonia and Rao 2013).

Impact of Rising Temperatures on Crop Water Requirements

Rao and Poonia (2011) studied the impact of projected climate change by the twenty-first century on water requirements of rain-fed monsoon and irrigated winter crops of arid Rajasthan. Crop water requirements were estimated by them from daily potential evapotranspiration at ambient and projected air temperature by 2020, 2050, 2080, and 2100 using modified Penman-Monteith equation and then by multiplying with crop coefficients. The spatial variability in annual PET over arid Rajasthan shows that high PET prevails in the extreme western districts of Bikaner (2066 mm) and Jaisalmer (2221 mm) and low PET in northern districts of Ganganagar (1712 mm) and Hanumangarh (1736 mm). The northern districts are fed with canal irrigation from Beas and Sutlej rivers and find lower impact due to raising crop water requirements. However, the western districts of Jaisalmer and Bikaner are often prone to drought on an average every alternate year, thus causing frequent crop failures. PET isolines follow reverse trend to the rainfall isohyets in the arid Rajasthan. Crop water requirements in the region varied from 308 to 411 mm for pearl millet, 244 to 332 mm for cluster bean, 217 to 296 mm for green gram, 189 to 260 mm for moth bean, 173 to 288 mm for wheat, and 209 to 343 mm for mustard. Further, due to global warming, if the projected temperatures rises by 4°C, by the end of the twenty-first century, water requirement in arid Rajasthan increases from the current level by 12.9% for pearl millet and cluster bean, 12.8% for green gram,

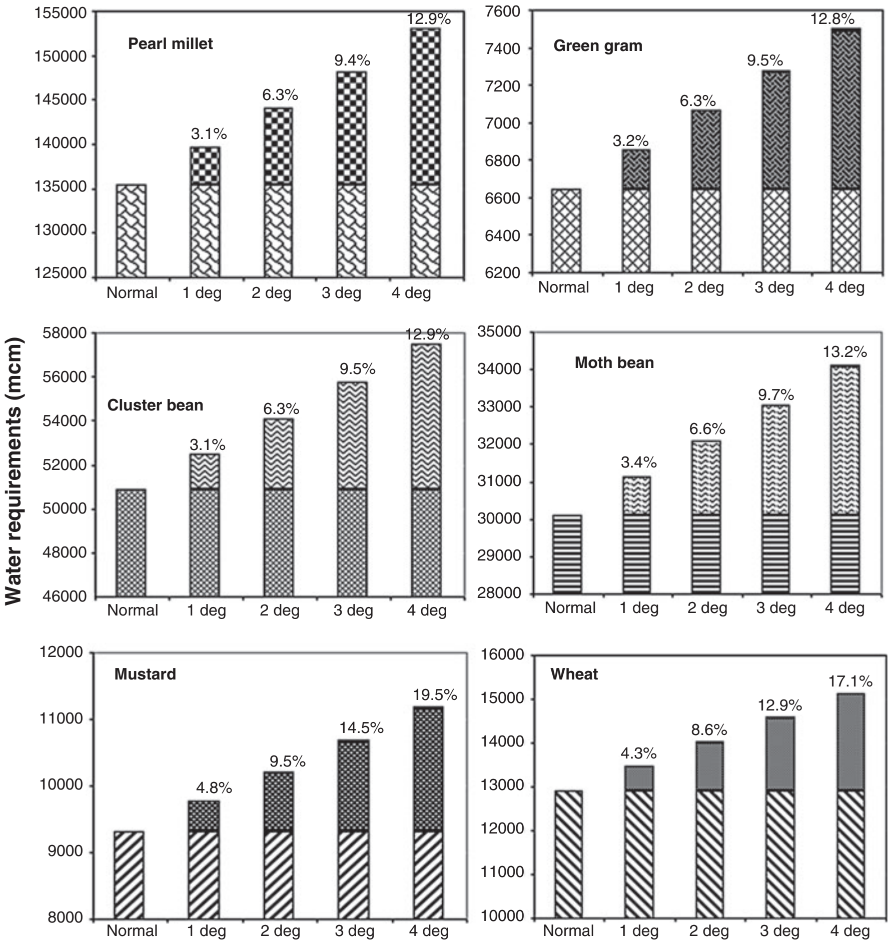

Fig. 5 Seasonal crop water requirements of *kharif* and *rabi* crops at elevated temperatures

13.2% for moth bean, 17.1% for wheat, and 19.9% for mustard (Rao and Poonia 2011; Fig. 5). Their study reveals that the impact will be more severe on *rabi* crops than *kharif* crops, the *rabi* crops being dependent on depleting ground water resources in the region.

The western districts of Barmer, Bikaner, and Jaisalmer which are already in low rainfall zone form hot spots due to the impact of projected rise in temperature leading to higher crop water demand, whereas in the districts Sri Ganganagar and Hanumangarh having canal water facility for irrigation, the impact due to climate change in these areas is likely to be less.

References

IPCC, Cambridge (2007) Climate change 2007: the physical science basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Contribution of the working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK/New York 996 pp

Joshi NL, Kar A (2009) Contingency crop planning for dryland areas in relation to climate change. Indian J Agro 54(2):237–243

Pant GB, Hingane LS (1988) Climatic changes in and around the Rajasthan desert during the 20th century. J Clim 8:391–401

Pant GB, Maliekal JA (1987) Holocene climatic changes over north-west India. An appraisal. Clim Chang 10:183–194

Poonia S, Rao AS (2013) Climate change and its impact on Thar desert ecosystem. J Agric Phys 13(1):71–79

Ramana Rao BV, Sastri ASRAS, Ramakrishna YS (1981) An integrated scheme of drought classification as applicable to Indian arid region. Idojaras 85:317–322

Rao AS (1992) Climate, climatic changes and paleo-climatic aspects of Rajasthan. In: Sharma HS, Sharma ML (eds) Geographical facets of Rajasthan. Kuldeep Publications, Ajmer, pp 38–44

Rao AS (1996) Climatic changes in the irrigated tracts of Indira Gandhi canal region of arid western Rajasthan, India. Ann Arid Zone 38(2):111–116

Rao AS (1997) Impact of droughts on Indian arid ecosystem. In: Singh S, Kar A (eds) Desertification control in the arid ecosystem of India for sustainable development. Agro Botanical Publishers (India), Bikaner, pp 120–130

Rao AS (2005) Impact of introduction of IGNP canal irrigation on micro- and secular changes in climate of Thar desert region. In: Tyagi BK, Baqri QH (eds) Changing faunal ecology in the Thar desert, vol 3. Scientific Publishers, Jodhpur, pp 37–44

Rao AS (2009) Climate and microclimate changes influencing the fauna of the hot indian arid zone. In: Sivaperuman C, Baqri QH, Ramaswamy G, Naseema M (eds) Faunal ecology and conservation of the great Indian desert. Springer-Verlag, Heidelberg, pp 13–24

Rao AS, Boken VK (2005) Agricultural drought monitoring and management in India (Chapter 23). In: Boken VK, Cracknell AP, Heathcote RL (eds) Monitoring and prediction of drought: a global study. Oxford University Press, New York, pp 297–312

Rao AS, Miyazaki T (1997) Climatic changes and other causative factors influencing desertification in Osian (Jodhpur) region of the Indian arid zone. J Arid Land Stud 7(1):1–11

Rao AS, Poonia S (2011) Sensitivity of crop water requirements to elevated temperatures in arid Rajasthan. Ann Arid Zone 50(2):131–138

Rao AS, Purohit RS (2009) Spatial variability and shifts in rainfall patterns of arid Rajasthan, India. In: Proceedings international conference on "Nurturing arid zone for people and the environment: issues and agenda for the 21st century." Central Arid Zone Research Institute, Jodhpur, pp 9

Rao AS, Roy MM (2012) Weather variability and crop production in arid Rajasthan. Central Arid Zone Research Institute, Jodhpur 70p

Rao AS, Gupta JP, Faroda AS (1997) Changing climatic scenarios and strategies for drought management in the Indian arid region. Drought Netw News 9(1):8–11

Roy MM, Tewari JC, Ram M (2011) Agroforestry for climate change adaptations and livelihood improvement in Indian hot arid regions. Int J Agric Crop Sci 3(2):43–54

Rupa Kumar K, Sahai AK, Krishna Kumar K, Patwardhan SK, Mishra PK, Revadekar JV, Kamala K, Pant GP (2006) High-resolution climate change scenarios for India for the 21st century. Curr Sci 90:334–345