Structure and Function of Chihuahuan Desert Ecosystem
The Jornada Basin Long-Term Ecological Research Site
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Climate and Climatological Variations in the Jornada Basin

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The purpose of this chapter is to review the climatic data for the Jornada Basin over the period for which instrumental records exist. Over this time period, up to 83 years in the case of Jornada Experimental Range (JER), we can deduce both the long-term mean characteristics and variability on a range of different spatial and temporal scales. Short-term variability is seen in individual rainstorms, whereas longer-term patterns are controlled spatially by factors such as large-scale circulation patterns and basin and regional orography and temporally by the large-scale fluctuations in atmospheric and oceanic circulation patterns. Variability can have significant impacts on the biogeography of a region (Neilson 1986) or its geomorphic processes (Cooke and Reeves 1976), which may set in motion a series of feedbacks, most important those referring to desertification (Schlesinger et al. 1990; Conley et al. 1992). Understanding the frequency and magnitude of such variability is therefore fundamental in explaining the observed landscape changes in areas such as the Jornada Basin.

The Instrumental Climate Record of the Jornada Basin

The patterns observed for different climatic variables within the available instrumental records for the Jornada Basin are defined in a hierarchical series of temporal scales, starting with the patterns that emerge from long-term average conditions and moving to seasonal and monthly, daily, and subdaily time scales. Two further analyses are made because of their potential importance to the hydrological and ecological characteristics of the basin, namely, the occurrence of extreme rainfall events and of longer-term changes. The effects of El Niño events in controlling the rainfall over decadal time scales will be addressed in particular. Spatial variability is an additional important concern, especially when characterizing dryland areas such as the Jornada Basin, where spatial variability tends to be high.

The overall climate of the basin can be defined according to the Köppen classification as being cool and arid, belonging to the midlatitude desert zone (BWk). However, interannual variability is important, and occasionally, the annual conditions are more characteristic of the semiarid steppe (BSk) zone. The higher rainfall rates in the higher altitudes of the basin are also more characteristic of semiarid conditions. Using the Thornthwaite approach, the basin is defined as arid (zone E) and only rarely crosses the threshold into semiarid in the higher altitudes. This spatial and temporal variability in classification probably explains the fact that previous overviews have placed the Jornada in both arid and semiarid zones.

Description of Data Available for the Jornada Basin

Instrumental climatic data for the Jornada Basin are available from these four sources: the Long-Term Ecological Research (LTER) project itself, the USDA JER, the New Mexico State University Chihuahuan Desert Rangeland Research Center (CDRRC), and the U.S. Geological Survey (USGS) (figure 3-1).

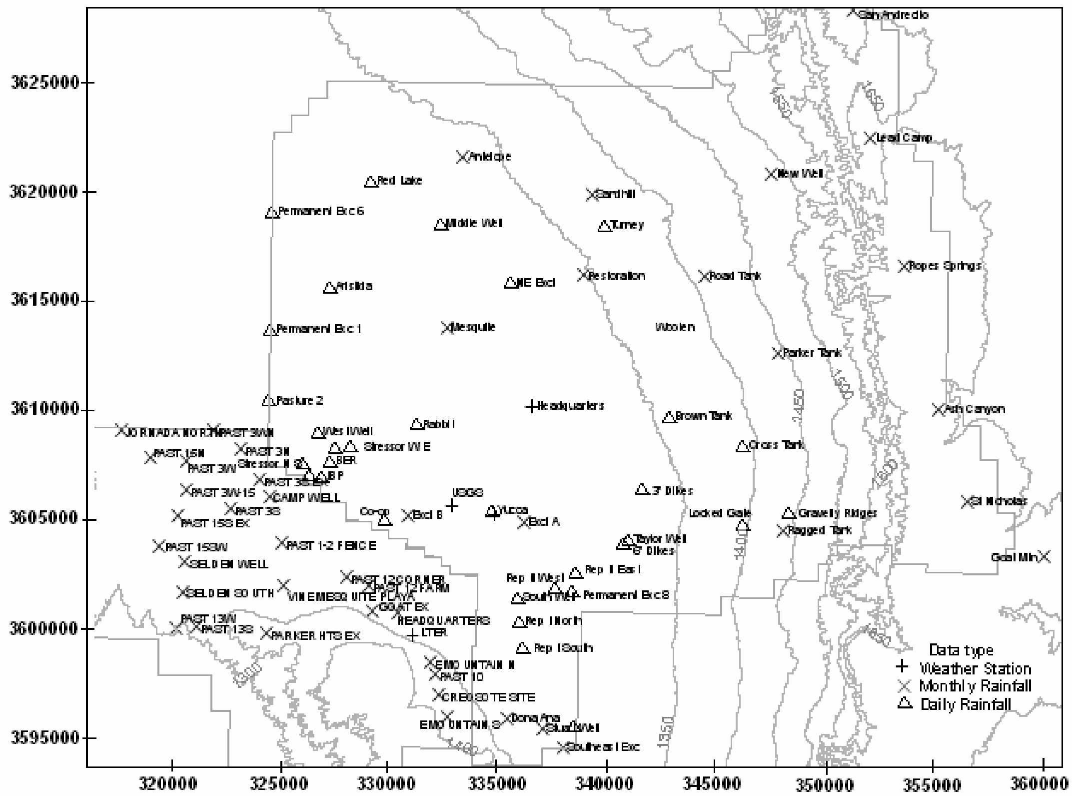


Fig. 3-1. Map of locations in the Jornada Basin at which climatic variables have been recorded.

The LTER data principally derive from the recording area weather station and the rain gauge at the base of Summerford Mountain (lower left of figure 3-1), which started in 1983 and 1981, respectively. The USDA data set contains the largest series of records, and those extend back over the longest period of time. Rainfall and temperatures have been recorded at the JER headquarters continuously since June 1914. Monthly pan evaporation was also recorded between January 1953 and August 1979. Rainfall data have also been recorded as monthly totals collected at 33 rain gauges, as well as at the headquarters, of which 23 have a record longer than 50 years. Daily rainfall data have been recorded at 58 locations since 1976, although most of these data do not cover the entire period since 1976. The CDRRC data are made up of monthly rainfall totals for 26 locations, the earliest being the CDRRC headquarters rain gauge, which was first operated in 1930. A number of these stations are discontinuous or have short records. The USGS data relate to the wind erosion project (described in chapter 9) in the central part of the basin and include daily records of temperature, precipitation, and wind speed since January 1990. Maximum rainfall intensities are recorded at a monthly level for durations of 15 minutes to 3 hours.

This impressive quantity of data makes it possible to look at temporal changes for most of the 20th century with a good temporal resolution for at least10 years. Spatial patterns are well represented over a50 year period in terms of monthly rainfall and over a 20 year period at a daily resolution. Comparisons of temperature and wind speed are much more restricted.

Annual Patterns

The long-term average rainfall for the Jornada headquarters between 1915 and 1995 is 245.1 mm with a standard deviation of 85.0 mm (table 3-1). The coefficient of variation is 34.7%. The minimum recorded value for a complete year is 77.0 mm, which occurred in 1953, with the maximum of 507.2 mm falling in 1984. The average annual temperature between 1915 and 1993 is 14.70°C with a standard deviation of 0.58°C. The minimum average annual temperature was 13.54°C in 1987, and the maximum average annual temperature of 16.25°C occurred in 1954. As already noted, measurements of evaporation were made over a shorter time period, between 1953 and 1979, with values ranging from

Table 3-1. Long-term (1915-1995) averages, minimums, and maximums for precipitation (P), ambient air temperature, potential evaporation (PE), and moisture balance (PE-P) as recorded at the instrumented station at the Jornada Experimental Range headquarters.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
precipitation mm													
average	12.80	9.76	7.66	5.78	10.94	16.01	46.66	50.05	35.61	23.79	11.85	17.65	245.09
std dev	11.52	9.30	9.17	9.14	15.26	22.24	29.54	33.24	28.76	20.73	14.47	18.72	85.58
std err	1.26	1.02	1.01	1.00	1.69	2.43	3.24	3.65	3.16	2.28	1.59	2.05	9.57
minimum	0.00	0.00	0.00	0.00	0.00	0.00	6.35	1.52	0.00	0.00	0.00	0.00	76.96
median	10.67	7.11	4.32	2.03	5.08	7.01	38.10	42.42	30.99	18.50	6.86	13.46	227.84
maximum	49.53	39.88	47.50	51.31	78.49	135.10	147.32	167.13	114.05	86.61	80.26	100.33	507.24
average temperature °C													
average	3.78	6.43	9.57	14.00	18.59	23.88	26.03	24.81	21.51	15.15	8.19	3.97	14.70
std dev	1.86	1.65	1.44	1.57	1.35	1.47	1.01	1.10	1.37	1.20	1.42	1.35	0.58
std err	0.21	0.19	0.17	0.18	0.16	0.17	0.12	0.13	0.16	0.14	0.17	0.16	0.07
minimum	-0.61	1.83	6.65	8.43	12.72	18.89	23.89	21.88	19.37	12.08	5.17	0.71	13.54
median	3.79	6.16	9.56	13.94	18.52	24.01	26.13	24.68	21.27	15.32	8.07	3.87	14.68
maximum	8.33	11.18	12.96	17.82	22.03	26.83	28.60	27.37	26.94	18.14	11.10	7.43	16.25
minimum temperature °C													
average	-5.99	-3.71	-0.94	3.24	7.67	13.10	17.11	16.08	12.17	4.98	-2.29	-5.46	4.70
std dev	2.56	2.35	1.84	2.03	1.75	2.12	1.47	1.68	1.93	2.10	2.02	2.88	1.03
std err	0.29	0.27	0.21	0.23	0.20	0.24	0.17	0.19	0.22	0.24	0.24	0.34	0.13
minimum	-13.17	-11.17	-6.77	-3.33	2.67	6.63	12.39	10.57	6.44	-1.34	-7.78	-10.11	1.51
median	-5.78	-3.56	-0.57	3.43	7.48	13.46	17.42	16.38	12.34	5.48	-2.37	-5.68	4.79
maximum	0.08	2.22	1.87	7.24	11.88	17.28	20.27	19.30	16.02	8.69	3.11	11.48	6.76
maximum temperature °C													
average	13.50	16.55	20.16	24.76	29.46	34.69	34.96	33.52	30.84	25.41	18.65	13.73	24.74
std dev	2.22	1.89	2.08	2.14	1.73	1.51	1.46	1.38	1.77	1.72	2.06	2.40	0.83
std err	0.25	0.22	0.24	0.24	0.20	0.17	0.17	0.16	0.21	0.20	0.24	0.28	0.10
minimum	6.61	12.18	13.79	15.98	20.76	30.11	31.59	30.46	27.35	21.04	13.28	8.53	22.17
median	13.36	16.30	20.31	24.91	29.63	34.69	35.00	33.49	30.63	25.56	18.49	13.79	24.76
maximum	17.94	20.99	24.83	28.41	32.58	38.06	38.15	36.31	36.67	28.96	22.32	23.52	26.45
Evaporation mm													
average	58.65	96.60	181.99	255.47	299.26	323.82	270.65	236.14	191.94	142.93	88.18	54.37	2204.05
std dev	25.69	39.72	41.97	38.90	38.14	34.56	38.51	35.45	34.94	25.43	27.92	29.64	279.04
std err	4.94	7.64	8.08	7.49	7.34	6.65	7.41	6.82	6.99	4.99	5.48	5.81	54.72
minimum	0.00	0.00	106.93	182.88	223.27	257.81	178.31	126.75	136.40	91.95	37.59	0.00	1565.15
median	57.15	91.19	174.75	246.63	301.50	321.56	280.92	245.62	185.17	140.21	86.61	56.77	2215.39
maximum	108.97	213.11	306.32	330.96	395.22	387.86	361.44	303.53	255.02	184.15	168.15	141.73	2832.61
moisture balance mm													
average	-47.5	-88.5	-175.1	-251.9	-293.3	-312.2	-220.5	-185.1	-157.3	-116.9	-76.7	-40.9	-1977.6
std dev	29.8	43.1	46.6	40.6	40.3	36.9	57.1	56.6	62.4	40.2	37.9	35.4	313.5
std err	5.7	8.3	9.0	7.8	7.8	7.1	11.0	10.9	12.5	7.9	7.4	6.9	62.7
minimum	-109.0	-213.1	-306.3	-329.9	-395.2	-384.6	-340.1	-280.2	-255.0	-184.2	-168.1	-127.3	-2637.0
median	-48.5	-85.9	-170.2	-242.3	-300.5	-316.7	-222.5	-193.8	-159.3	-125.5	-82.2	-43.7	-1992.4
maximum	3.0	17.3	-59.4	-172.7	-210.6	-224.8	-57.2	-31.0	-40.9	-39.4	26.2	40.9	-1289.1

1,565.2 mm (1976) to 2,832.6 mm (1971) and with a mean value of 2,204.1 mm and a standard deviation of 279.0 mm. There is a high interannual variability, particularly of rainfall and potential evaporation. On the annual time scale, there is always a large moisture deficit (evaporation minus precipitation) averaging 1,960.3 mm.

Comparisons with other sites in the basin are only possible with rainfall data. Because of the temporal variability, it is not possible to use all the available rain gauges to carry out this analysis. Thus, long series of data are derived from 37 sites for which there exist more than 30 years of data from the period since 1947. For those sites within this series that have longer sequences, there appear to be no significant differences between the total sequence and the sequence after 1947. Shorter sequences commencing after 1947 show an increasing divergence from the long-term values, and thus the sample cannot be assumed to be comparable. The average annual rainfall for these sites is 242.3 mm, which is close to the Jornada headquarters value of 247.1 mm since 1947 (compared to 245.1 mm for 1915–95). However, this average is made up of values ranging from 212.8 mm to 348.9 mm. Similarly, the values of the coefficient of variation range from 24.8% to 43.1%, with a median value of 36.5% (compare with 34.7% for Jornada headquarters). The variability is largely due to the altitude of the rain gauge (figure 3-2a–d). For example, the highest rainfall (348.9 mm) is recorded from the Rope Springs gauge (see figure 3-1 for gauge name and location) at an altitude of 1,725 m in the San Andres Mountains. Linear regression analysis shows that 77% of the variance in annual average rainfall is controlled by altitude. However, there is a great deal of scatter due to

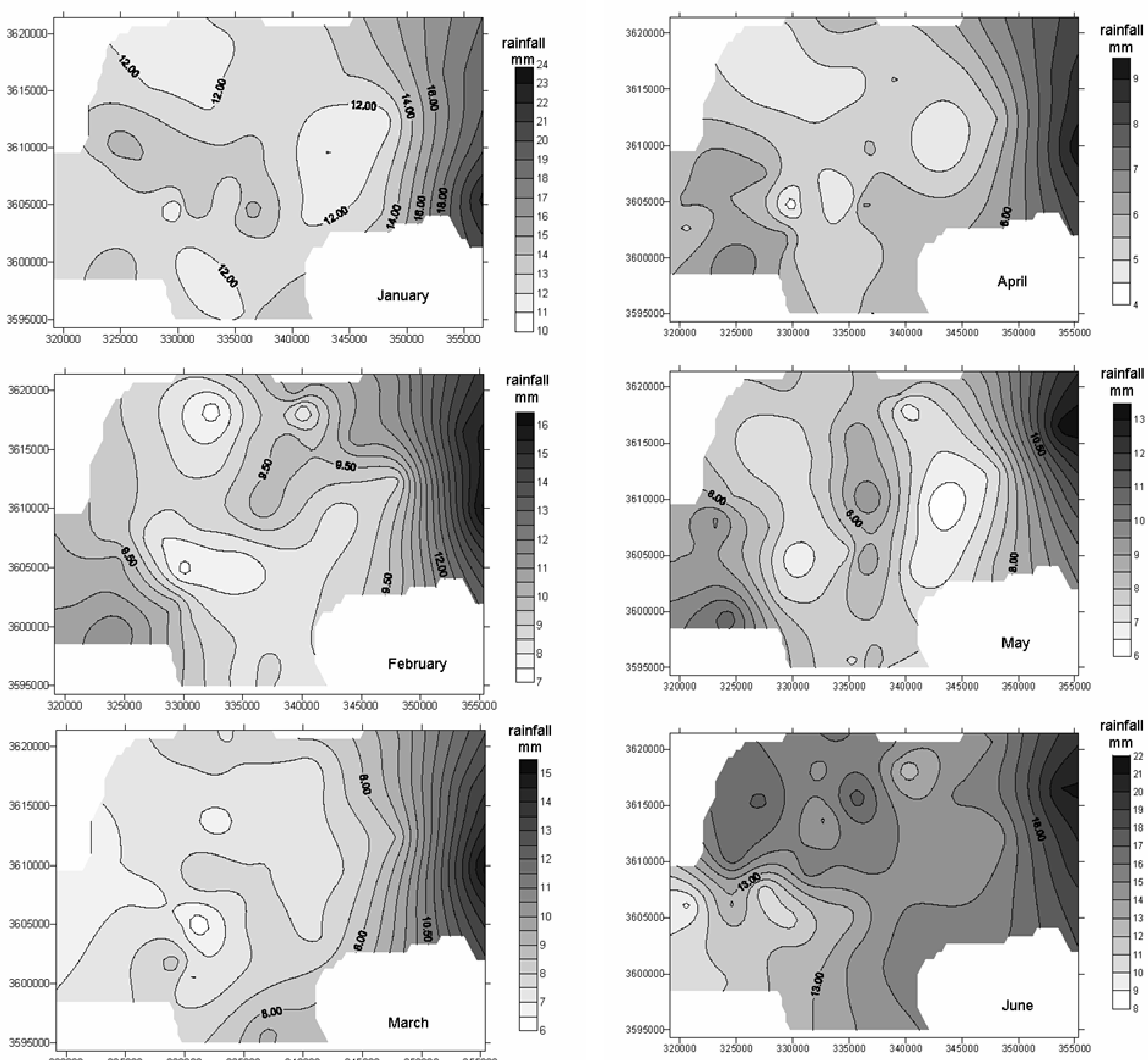
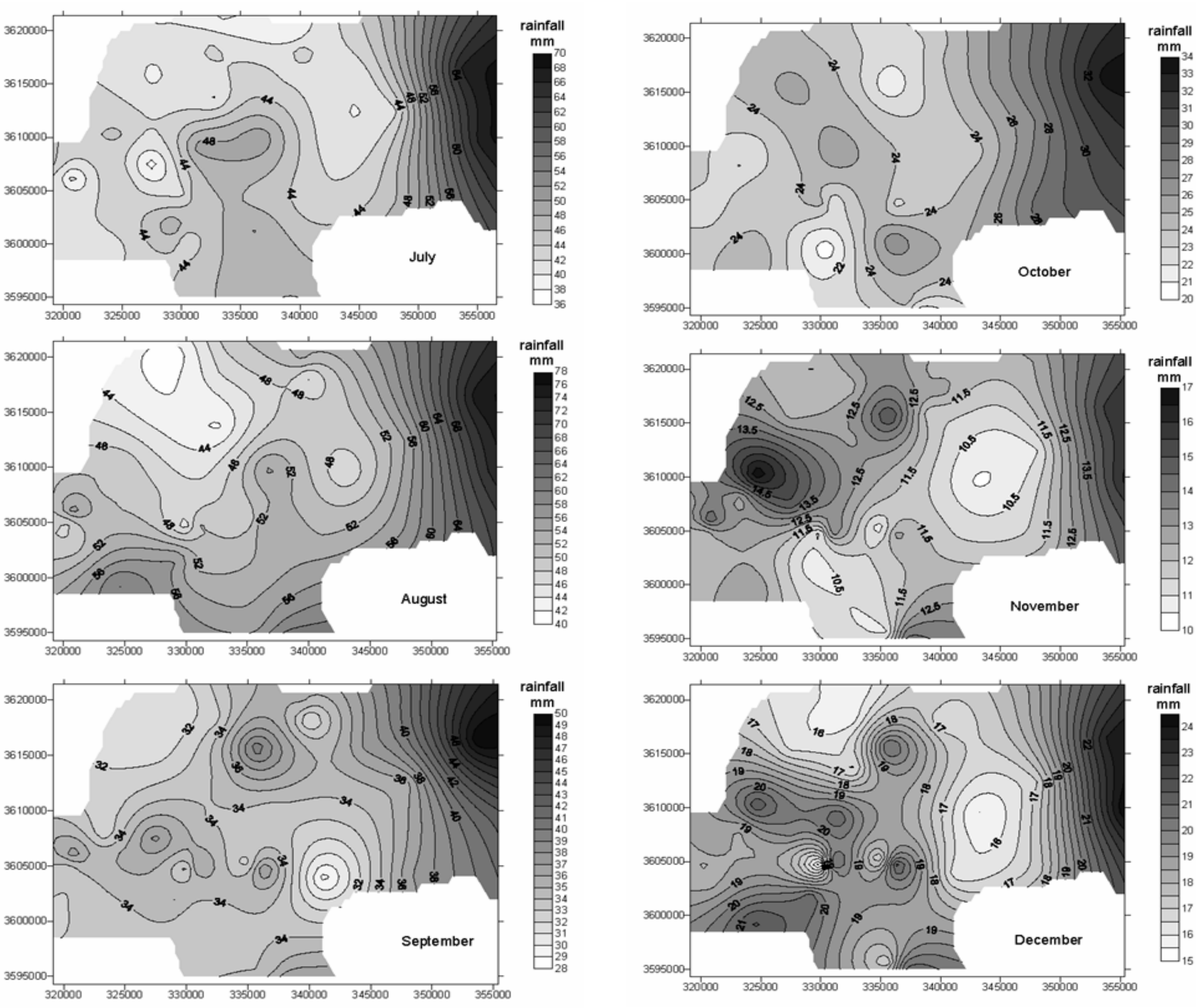


Fig. 3-2. Monthly distributions of precipitation in the Jornada Basin: a. January-March; b. April-June; c. July-September; d. October-December.


rainfall mm
July
October
August
November
September
December

two locational factors: (1) a general gradient of higher rainfall in the south of the basin, and (2) an increase away from the central north–south axis of the basin. Incorporating these two variables gives a general model for basin annual average rainfall since 1947 of

<EQ>(3-1) $r = 3{,}140.3 + 0.342z - 9.297 \times 10^{-4}y - 1.475 \times 10^{-3}d_m$,</EQ>

where r is mean annual rainfall (mm), z is altitude (m), y is the UTM northing (m), and d_m is the absolute distance from the medial N–S axis of the basin (m) in which 4.5% of the variance is explained by y and 2.7% by d_m. Similarly, there is a tendency for the variability of the annual average rainfall to increase with altitude, although this is countered by a decrease with distance from the north–south axis of the basin. This relationship is described by

<EQ>(3-2) $sd_r = -61.62 + 0.114z - 9.454 \times 10^{-4}d_m$</EQ>

in which sd_r is the standard deviation of the annual average rainfall (mm). The total variance explained by this relationship is 47.3%, of which 39.4% is explained by variations in altitude. It is likely that these relationships reflect the orographic control of the San Andres Mountains (right side of figure 3-1) on rainfall and the distance from the source of the rainfall (i.e., from the Gulf of Mexico). It is possible that the decrease in rainfall and its variability reflects a vegetation feedback on precipitation with the bare central areas of the basin leading to more atmospheric uplift. Associated convective rainfall activity might then be reflected in the decreasing variability away from the center of the basin.

Monthly and Seasonal Patterns

Within the annual patterns described, there are important variations at the monthly and seasonal level. The Jornada headquarters data show a peak in rainfall between July and

October, the maximum being in August, with a much smaller secondary peak in November to February (table 3-1). This seasonality is related to the different source of rainfall. In the summer months, rainfall is monsoonal in origin with moisture derived from the Gulf of Mexico. These months are characterized by thunderstorm activity, which frequently leads to relatively large precipitation events in the basin. The rainfall in the winter months tends to be more frontal in character, and moisture largely comes from the Pacific coast. Therefore, both because of the lower intensity rainfall and the greater rain shadow effect, rainfall tends to be lower in total. There is important variability in the monthly totals with minimum values of zero in all but July and August. Maximum monthly rainfalls exceeding 100 mm have been recorded in July, August, September, and December. The maximum recorded monthly rainfall was 167.1 mm, which occurred in August 1984.

Average temperatures are at their lowest in January with a mean value of 3.78°C. The lowest recorded value of –0.61°C occurred in January 1919, whereas the following January the average temperature reached its maximum of 8.33°C. Apart from the month of March, the first six months of the year tend to show greater variability, which is seen not in the standard deviation but in the recorded extremes. Peak average monthly temperatures occur in July when the average is 26.03°C, with a minimum recorded value of 23.89°C (1962) and a maximum of 28.60°C (1951). Minimum and maximum temperatures follow the same cycle. Average January minimum temperatures are –5.99°C, the lowest recorded value being –13.17°C in 1963. Indeed, on only one occasion since 1915 has the January minimum temperature averaged above freezing. That was in 1916 when the value of 0.08°C was recorded. Maximum daytime temperatures average

13.5°C in January with a range from 6.61°C (1919) to 17.94°C (1920) and rise to an average of 34.96°C in July. The coldest July on record was in 1916, when the maximum daytime temperature only reached 31.59°C, and the warmest July saw mean daytime temperatures of 38.15°C in 1980. Minimum temperatures peak at 17.11°C in July, although the observed range of values is from 12.39°C (1963) to 20.27°C (1935).

The onset of frosts starts on average on October 22, although dates as early as September 14 (1959) and as late as December 1 (1932) have been recorded. There is a similar variability in the last frost of the year. The average date is April 29, the earliest date is March 20 (1990), and the latest is June 10 (1963). The average period with frosts (i.e., the length of time between the first frost in one year and the last frost the next) is 188 days, although the range of values recorded varies from 145 (1922–23) to 244 (1962–63). The actual number of days with frost per year is again somewhat shorter, averaging 128 days, but again with a wide range from 97 (1940–41) to 186 days (1929–30). There is a weak linear correlation between the length of the period with frosts and the actual number of days with frost ($r = 0.49$).

Measured evaporation rates range from a minimum average of 54.37 mm in December (with a range from zero in 1975 and 1977) to a maximum of 141.73 mm in 1970. Evaporation rises rapidly in the first half of the year, peaking at average figure of 323.82 mm in June, before falling more slowly in the second half of the year. Evaporation thus peaks before either temperature or rainfall. June values range from a minimum of 257.81 mm recorded in 1976 to a maximum of 387.86 mm two years previously in 1974. However the maximum recorded value is 395.22 mm, which occurred in May 1971. Patterns of moisture balance generally follow the trend in evaporation because this variable dominates over precipitation. On the other hand, the decrease in the deficit in July to August is more marked than the decrease in evaporation because of the high summer rainfall. Only the months of November to February have recorded positive moisture balances, the maximum being 40.9 mm in December 1960. A positive water balance only occurred for seven months in the recording period from January 1953 to August 1979.

Wind patterns have only been recorded over much shorter periods. At the USGS site (5.9 km southwest of Jornada headquarters), daily records have been analyzed for the period from January 1990 to August 1996 to give monthly summaries. Average monthly wind speeds are highest in April with a value of 12.4 km/h, declining to a value of 7.9 km/h in August (figure 3-3). There is a second maximum of 8.8 km/h in November. The least windy month is December, when the average velocity is 7.6 km/h. In terms of the average peak gust, there is a less well-defined annual pattern, although peaks occur in April (78.6 km/h) and July (78.8 km/h). Thus the summer months have lower average wind speeds, but they have important gusts, usually relating to local atmospheric convection in the afternoons, leading to the characteristic dust devils, which can commonly be seen tracking along the center of the basin. The dominant direction of the

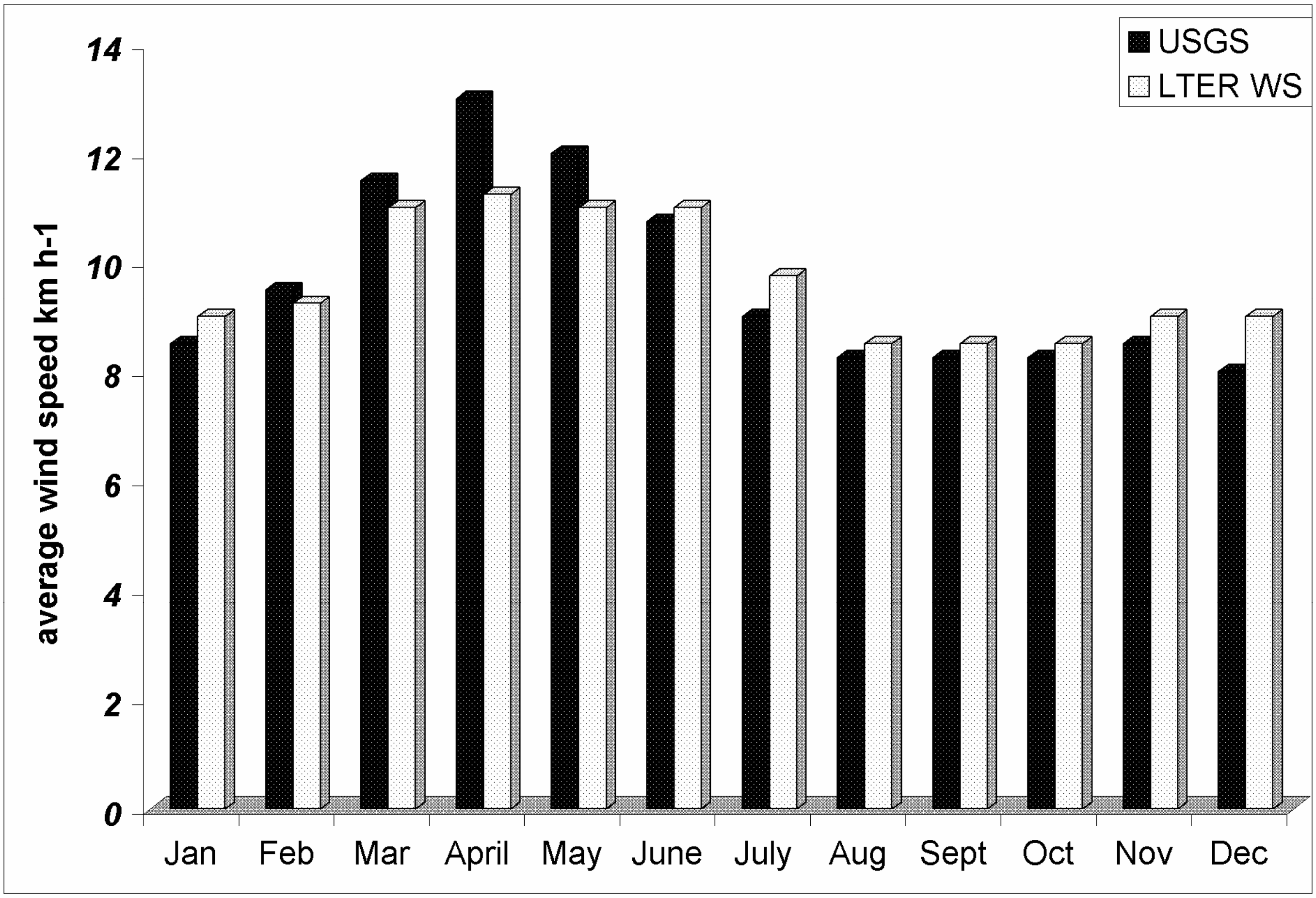


Fig. 3-4. Comparison of average wind speed as recorded at the Long Term Ecological Research (LTER) weather station (1983-1997) and the US Geological Service (USGS) weather station (1990-1996).

peaks gusts is from the WSW, which occurs in seven months from the end of October through May. January and April have similar directions with peaks arriving from the west and southwest, respectively. In the summer months the direction shifts distinctly so there is no dominant wind direction throughout the month of July. These shifts are due to the onset of monsoonal activity derived from the Gulf of Mexico.

For the shorter time period between 1983 and 1997, the LTER weather station on the Summerford Mountain bajada presented a more detailed record of climate (see data sets available online at http://jornada-www.nmsu.edu). Temperature patterns illustrate that dew temperatures are rarely reached, and the soil temperature at a depth of 5 cm lies midway between the average and maximum air temperature. Wind velocities show a major peak between March and June and a smaller peak in November. Relative humidity decreases during the early part of the year to a minimum in June, when the average minimum is 13.5% and the average maximum 45.6%. Relative humidity then increases rapidly during the onset of the monsoonal season, reaching a peak in August. The minimum values stay relatively constant until reaching a peak with the winter rainfall season in December (average 35.9%). The maximum values decline over the same period but again rise in December (average 75.7%).

Solar radiation is asymmetrically distributed through the year, rising rapidly to a peak value in May (671.1 MJ/m^2) and then declining more slowly to a minimum in December (244.5 MJ/m^2). The average annual solar radiation received at the LTER weather station is 6,250.1 MJ/m^2.

Spatial Patterns

Spatial patterns of monthly rainfall can be reconstructed for the Jornada Basin using 37 gauges. At the monthly time scale, most months show spatial patterns similar to those described for the annual time scale. However, there are some notable variations (figure 3-2a–d). There are greater altitudinal gradients in the months of July and August compared to the other months. Higher rainfall occurs locally in the west and central parts of the basin in November and December, whereas in May, June, and October there are central bands of higher rainfall trending either north–south or northwest–southeast. There is a localized peak in rainfall to the north of Summerford Mountain in February, May, and December. These different patterns probably reflect the different orographic effects of the different mountain ranges surrounding the basin, as they affect moisture arriving in the basin from difference sources. Semivariograms of the monthly and seasonal patterns follow a Gaussian pattern with semivariance generally increasing rapidly beyond a lag distance of around 20 km.

The spatial variability of temperatures can be seen with reference to the LTER, Jornada headquarters, and USGS weather station data (figure 3-4). There is a consistent ordering of the average monthly temperatures, with the highest values at the LTER weather station, followed by the USGS, and the lowest values at Jornada headquarters. Temperatures at the LTER site are between 0.4°C and 2.8°C warmer than at the USGS site, which is in turn between 0.3°C and 1.5°C warmer than at Jornada headquarters. These patterns relate to the fact that minimum monthly temperatures are much higher at the LTER site than the other two (2.7–5.0°C warmer than USGS and 3.6–5.9°C warmer than JER headquarters). The LTER weather station has the lowest maximum temperatures of the three locations in every month except May (0.9–2.7°C cooler than USGS and 1.1°C cooler to 0.1°C warmer than Jornada headquarters), and there tends to be less diurnal variability at the LTER site. Wind data can be compared between the LTER and USGS weather stations, although due to differences in the way these data are recorded, the comparison is limited to average wind speeds. The average wind speed

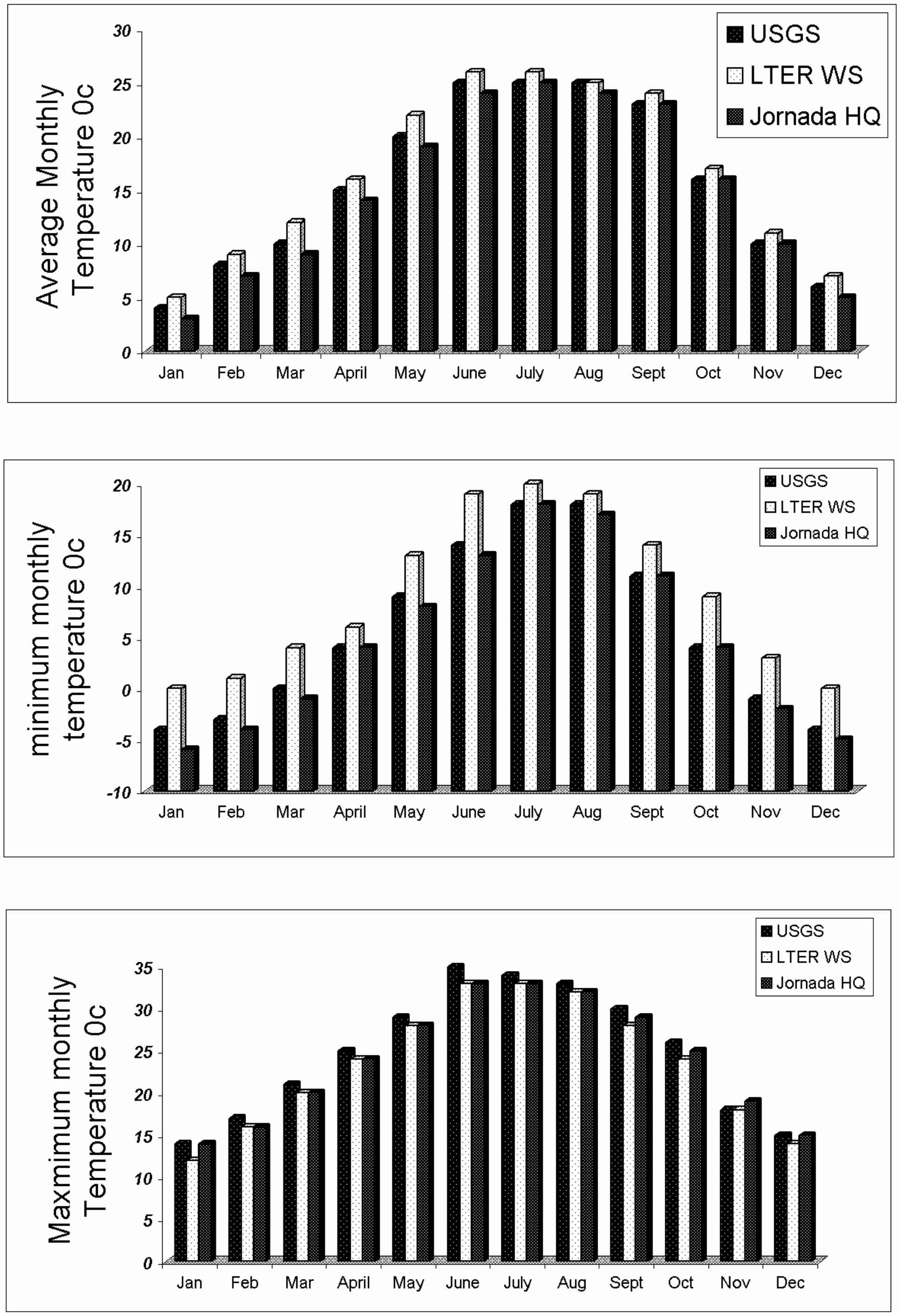


Fig. 3-3. Comparisons of temperature records at the Long Term Ecological Research (LTER), US Geological Service (USGS) and Jornada Experimental Range (JER) headquarters weather stations: a. average monthly temperature; b. minimum monthly temperature; and c. maximum monthly temperature.

tends to be higher at the LTER weather station between the months of June and January (figure 3-3). The change in June coincides with the change from the modal direction at the LTER weather station from SSW to S, although the modal direction reverts to SSW in October.

In a number of climate variables, but most dominantly precipitation, there is a major shift in the climatic character of the basin for June through September, associated with the onset and development of the summer monsoonal system. For example, at the JER headquarters, on average, 61% of the annual rainfall occurs in these summer months. Precipitation increases and a change in the dominant wind direction are associated with changes in the other variables observed. Thus, a bipartite division of the Jornada climate has been made, with summer conditions relating to the June through September period and winter conditions referring to the October through May period. The difference in rainfall between these periods is clearly marked in terms of quantity of rainfall and, to a lesser extent, in terms of rainfall variability (figures 3-5a and 3-5b).

This division contrasts with that of Conley et al. (1992) who used a tripartite division of winter (November–March), spring (April–June), and summer (July–October). Although this allows more detail for the winter period, it is thought that this is of little significance in terms of application to understanding plant growth patterns (Reynolds et al. 1999b).

Daily Patterns

Specific daily climatic patterns of interest include distributions of rainfall events, diurnal ranges of temperature, and relative humidity. The occurrence of extreme rainfall events

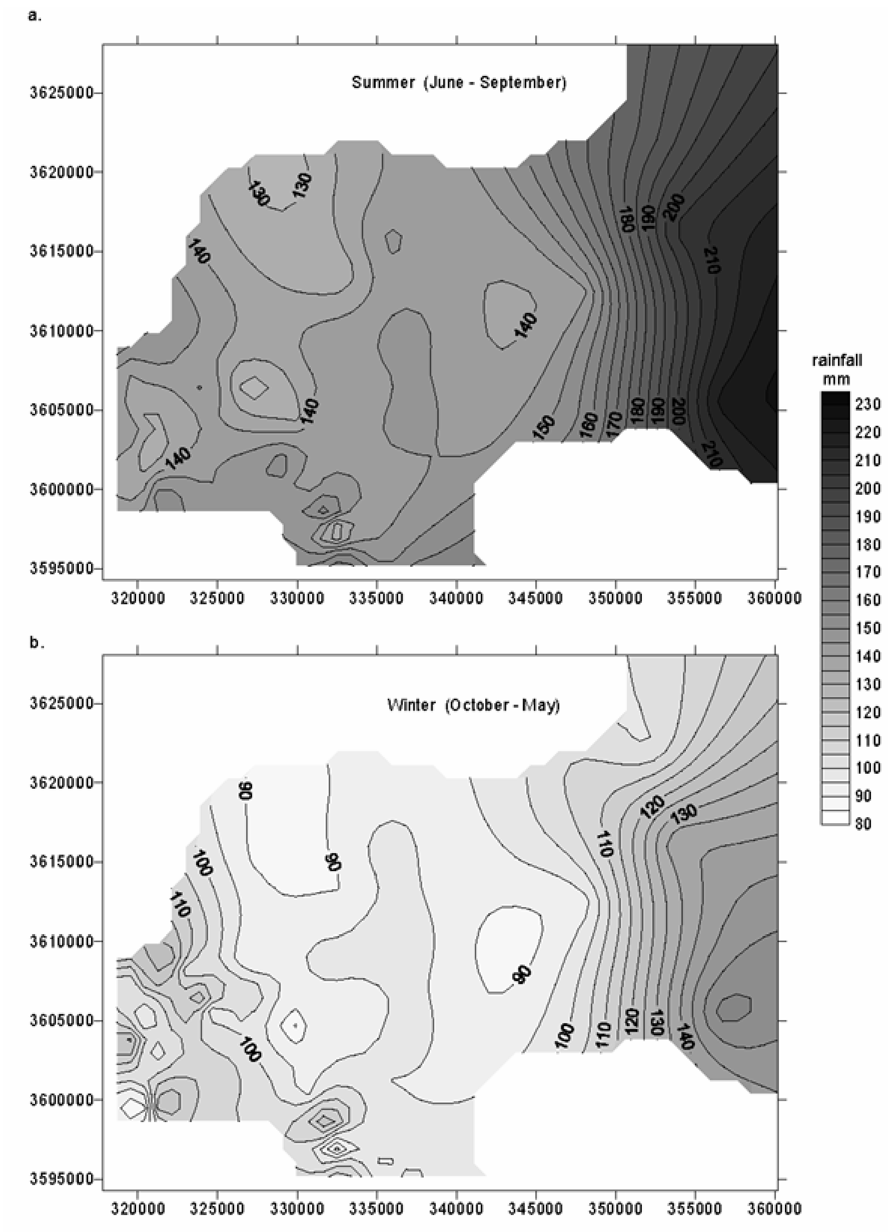


Fig. 3-5. Seasonal patterns of precipitation in the Jornada Basin: a. summer (June-September); and b. winter (October-May).

and their spatial and temporal distributions will be considered separately in the next section.

The mean number of rain days recorded at Jornada Experimental Range headquarters is 42.6, and at the LTER weather station the value is 50.7. These values are predominantly composed of rain days in July and August during the peak of the monsoon. The winter peak in rainfall is dominated by the three to five rain days in December and January, with a steady decline until the minimum in April. Across the basin, the number of rain days ranges from a minimum of 41.6 to a maximum of 51.1 (median 45.2). The spatial pattern of the number of rain days is different from that of the annual average rainfall, with higher values occurring on the higher ground to the north, northeast, and southwest and the lowest values in the north-central and southeastern parts of the basin. The seasonal number of rain days does not differ substantially between summer—with a minimum if 21.3, median of 23.4, and maximum of 29.1 across the basin—and winter—minimum 19.7, median 21.2, maximum 24.9. This pattern reflects the typically much lower intensity event in the winter months.

An important parameter of rainfall is its persistence (table 3-2). Where runoff production, sediment transport, or plant growth are involved, the occurrence of repeated rainfall events can be significant. Conversely, the persistence of days without rain can signal drought conditions. One way of observing such persistence is to calculate Markov transition probabilities for the occurrence of days with rain followed by a second day of rain, and similarly for days without rain followed by a second day without rain. Higher orders of persistence can be observed by repeating the calculation for three successive days, and so on.

Table 3-2. Measured and predicted probabilities for the Jornada Experimental Range (JER) headquarters and the Jornada Basin Long-Term Ecological Research (LTER) weather station locations for persistence (successive days) of 2, 3, or 4 successive dry days (dd, ddd, or dddd, respectively) or 2, 3, or 4 successive days with precipitation (ww, www, or wwww, respectively).

	Measured probabilities						Predicted probabilities					
	annual		summer		winter		annual		summer		winter	
Location	p_{dd}	p_{ww}	p_{dd}	p_{ww}	p_{dd}	p_{ww}						
JER HQ	0.76	0.04	0.31	0.01	0.96	0.05						
LTER	0.69	0.05	0.29	0.02	0.83	0.06						
	p_{ddd}	p_{www}	p_{ddd}	p_{www}	p_{ddd}	p_{www}	p_{ddd}	p_{www}	p_{ddd}	p_{www}	p_{ddd}	p_{www}
JER HQ	0.668	0.011	0.280	0.0044	0.831	0.0139	0.578	0.0016	0.0961	0.0001	0.9216	0.0025
LTER	0.598	0.015	0.260	0.0033	0.719	0.0200	0.476	0.0025	0.0841	0.0004	0.6889	0.0036
	p_{dddd}	p_{wwww}	p_{dddd}	p_{wwww}	p_{dddd}	p_{wwww}	p_{dddd}	p_{wwww}	p_{dddd}	p_{wwww}	p_{dddd}	p_{wwww}
JER HQ	0.585	0.0040	0.256	5.5×10^{-4}	0.724	0.00932	0.439	6.4×10^{-5}	0.0298	1.0×10^{-6}	0.885	1.3×10^{-4}
LTER	0.521	0.0066	0.236	0.00210	0.622	0.00472	0.329	1.3×10^{-5}	0.0244	8.0×10^{-6}	0.572	2.2×10^{-4}

The probability for two successive wet days at the annual level is 0.04 at the Jornada headquarters and 0.05 at the LTER weather station, whereas the respective probabilities for two successive dry days are 0.76 and 0.69. At the seasonal level, the wet-wet probability increases in the summer months to 0.06 at the Jornada headquarters and 0.08 at the LTER weather station. In other words, as might be expected, there is much greater persistence of dry than wet periods. The annual probability of three successive wet days is 0.011 at the Jornada headquarters and 0.015 at the LTER weather station. Based on the probabilities for two successive dry days, we can calculate the probability of having three successive events by chance, assuming independence of events. This probability is simply the square of the first probability. The calculated probabilities are 0.0016 for the Jornada headquarters and 0.0025 at the LTER weather station. The fact that these are lower than the measured transition probabilities suggests much stronger persistence of wet episodes. Extending this analysis to four successive wet days gives predicted probabilities of 0.000064 for the Jornada headquarters and 0.000125 at the LTER weather station compared to measured transition probabilities of 0.004 and 0.00657, respectively. Repeating this analysis for sequences of dry periods and for both wet and dry periods according to season shows a similar result, except for the sequences of dry periods in winter. Thus persistence is a feature of both dry and wet periods. This conclusion contrasts with the results of Chin (1977) who suggested that rainfall at El Paso, Texas, 80 km to the south, was only first-order dependent in summer and second-order dependent in winter. An additional difference is seen in comparing persistence at different temporal scales. Whereas persistence seems to be an important feature at the daily scale, it has already been seen to be far less significant at an interannual scale.

The intensity of rainfall is significant in producing runoff and therefore in its role in distributing water through the basin catchment. Relative to soil infiltration rates, the rainfall intensity determines the extent of runoff during rainfall events of the same magnitude. Because most rainfall events at Jornada last for much less than one day due to their convective nature, daily rainfall data do not give good estimates of rainfall intensities. Data that can provide a better indication occur at the LTER weather station, where hourly intensities have been recorded since 1992, and at several tipping-bucket rain gauges employed within the LTER project. Peak intensities for time periods between 5 and 180 minutes are also included in the USGS summaries on a monthly basis.

The majority of events (55%) recorded at the LTER weather station last for an hour or less, with an exponential decline in the length of event. The mean event is 2 hours long. The longest event took place in 1994, when 19.8 mm of rain fell in 19 hours between 1000 on December 5 and 0500 on December 6. The median hourly rainfall intensity is 0.76 mm/h, with an average of 1.7 mm/h. The maximum value of 25.2 mm/h fell at 1900 on July 24, 1992, although this may be an underestimate of the true peak intensity as this whole event took place within a single hour.

Data from three tipping-bucket rain gauges also show an exponential decline in intensities (figure 3-6).

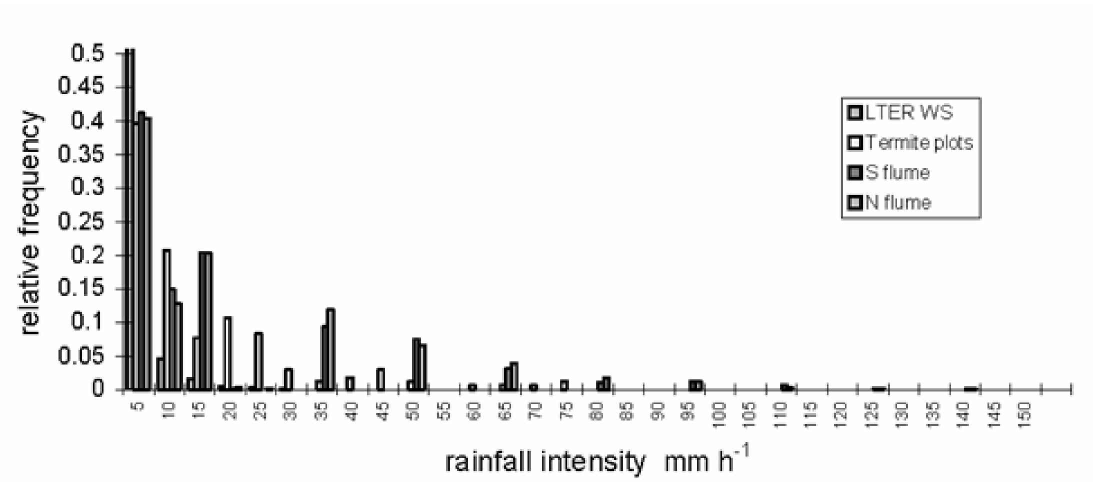


Fig. 3-6. Rainfall intensities recorded at three tipping-bucket raingauges (Termite plots, S flume, and N flume) on Long Term Ecological Research (LTER) sites on the Summerford Mountain bajada, compared with hourly intensities as recorded at the LTER Weather Station (LTER WS).

Maximum intensities recording by the tipping-bucket gauges are 137.3 mm/h, although this intensity was only maintained for 1 minute (on two occasions, June 26 and September 14, 1996). During the June 26 event, the peak 5-minute intensity was 100.6 mm/h; the peak 10-minute intensity, 75.3 mm/h; the peak 30-minute intensity, 48.2 mm/h; and the peak hourly intensity, 36.3 mm/h. The September 14 event had corresponding 5-, 10-, 30-minute, and hourly values of 82.3 mm/h, 50.6 mm/h, 40.3 mm/h, and 38.6 mm/h, respectively. These values compare with the maximum recorded hourly rainfall at LTER weather station, which is 25.2 mm/h.

Diurnal temperature ranges have been calculated for the long sequence at the Jornada headquarters (1914–95), as well as for the shorter LTER weather station (1983–

97) and USGS (1990–96) sites. On average, the LTER weather station diurnal range is 14.6°C, which is significantly lower than either the Jornada headquarters (20.0°C) or the USGS (20.1°C) sites. A similar difference is also noted for monthly averages. The most likely explanation for this difference is the more exposed location of the Jornada and USGS sites toward the central part of the basin. In all cases, there is a seasonal pattern with low values in December and January, an increase to May or June, followed by a decrease to the annual minimum in August, with a second cycle peaking in October.

The diurnal range of relative humidity at the LTER weather station shows a single oscillation through the year, with a rapid rise to a peak corresponding to the onset of the monsoonal rains, followed by a more gradual decrease. Low ranges are typically recorded for the months of April to June after the end of the main winter rains, although in certain years, such as 1992, high values have been recorded in May.

Occurrence of Extreme Events

Maximum daily rainfall shows significant variation through the basin (figure 3-7). For those sites with data for 10 years or more, the maximum recorded values range from 47 mm to 105 mm. There is no significant relationship between the maximum daily rainfall and the mean average rainfall ($r = 0.19$, $p = 0.29$), or with the altitude of the rain gauge ($r = 0.17$, $p = 0.35$). The larger recorded events seem to cluster around the central, northwestern, and southeastern part of the basin.

Intensity-duration-frequency values demonstrate the importance of relatively frequent high-intensity rainfalls, albeit lasting for relatively short periods (table 3-3).

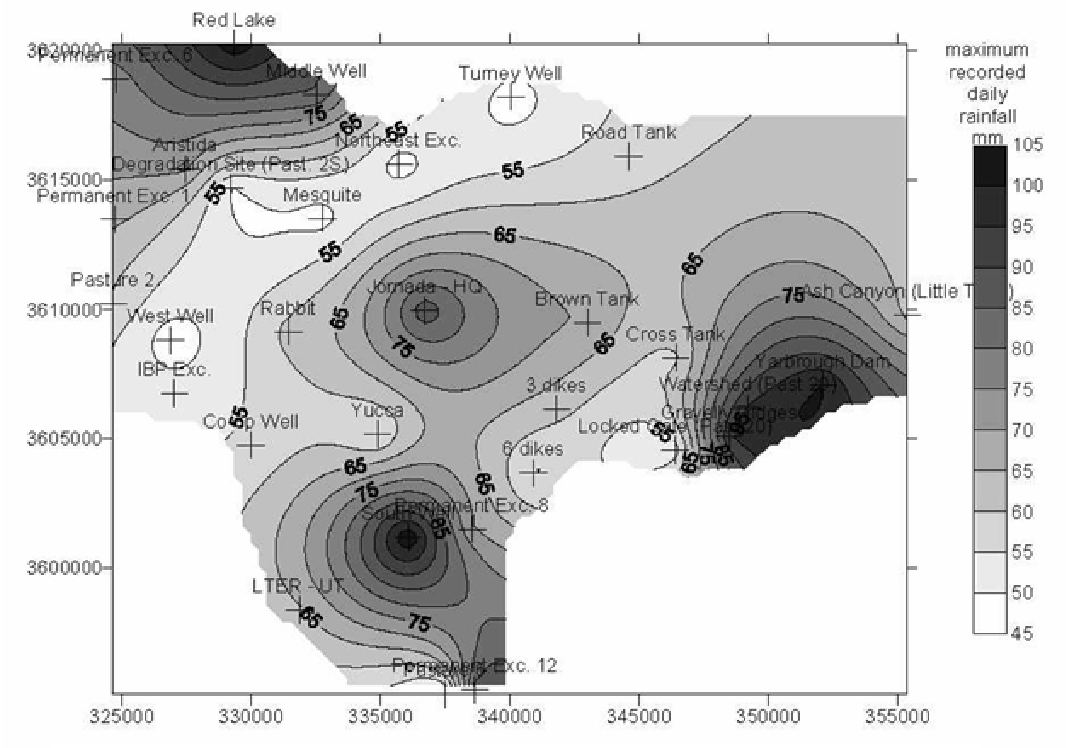


Fig. 3-7. Patterns of daily rainfall throughout the Jornada Basin. Patterns are displayed within the UTM grid.

Table 3-3. Intensity (mm/h) of precipitation events observed for different storm durations over different time intervals (years).

storm	rainfall intensity in mm/h for given return interval					
duration	2 year	5 year	10 year	25 year	50 year	100 year
5 min	86.6‡	97.5	109.7	135.7	161.2	189.6
10 min	68.7‡	80.6	90.8	106.9	131.8	156.4
15 min	57.2‡	67.6	79.5	95.5	110.4	130.5
30 min	38.6‡	48.1	55.7	69.0	80.4	96.0
60 min	24.0‡	27.9†	31.7†	35.6†	40.6†	45.9†
6 hr	5.67‡	6.77†	7.62†	9.52†	10.58†	12.28†
24 hr	1.72‡	1.96†	2.38†	2.91†	3.39†	3.81†

† Values based directly on Miller et al. (1973) and should be considered as underestimates.

‡ Values derived from Jornada Basin LTER weather station data using Chen (1983) method, but may still be underestimates due to the length of available record.

Because of the convective character of the rainfall, these high intensities are rarely sustained for more than 30 minutes. Because only hourly data were available for short time periods from the LTER weather station, it was not possible to carry out a more detailed analysis for the Jornada Basin itself, beyond that proposed by the National Oceanographic and Atmospheric Administration (NOAA) (Miller et al. 1973). A comparison for short return periods using the method of Chen (1983[a]) showed a correspondence with the figures given in Miller et al. (1973) for return periods of less than 10 years, so in these cases the LTER figures are presented. However, because of extrapolation from a short data set, the intensity of the lower frequency events was lower, and other means were used to estimate these values.

Return periods for daily rainfall have also been calculated, using standard Gumbel analysis, for each of the daily rain gauges in the basin to explore spatial patterns of large events. Daily rainfall within the basin varies between 27.5 and 38.5 mm for a 2-year return period, between 35.8 and 57.6 mm for a 5-year return period, between 41.3 and 70.2 mm for a 10-year return period, between 47.2 and 87.4 mm for a 25-year return period, between 51.5 and 100.3 mm for a 50-year return period, and between 55.8 and 113.1 mm for a 100-year return period. Three peaks of generally higher rainfall tend to appear in these calculations in the northwest, southwest, and southeast of the basin area studied. There is a relatively complex pattern in the central part of the basin, which varies according to the length of the return period, although this may, in part, be due to the generally shorter record lengths (albeit > 10 years) of the gauges in this part of the basin.

A sample of extreme events was selected by examining the rainfall across the basin for the largest recorded event at each rain gauge. The spatial pattern of these events can be divided into three broad groups. First, there are a small number of events that have

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[a] Chen 1983 not found in References. Please add it. (Added)

a single center but may be more or less continuous across the basin. The maximum rainfall at the center of these events may still be large, for example the event of July 4, 1988, when 103.6 mm of rain was recorded at the Middle Well and Red Lake gauges. Only 3 out of 32 of the sampled events fell into this category. Second, there are 11 events that have multiple centers but that have a discontinuous cover over the basin. The third type contains multiple cells that cover the entire basin and makes up the majority of the sampled storm events (17 out of 32). There appears to be no correlation with the type of extreme event and the time within the monsoonal season at which it occurred in the chosen sample. There are, on the other hand, a significant number of events where the third pattern occurred outside the main monsoonal season (e.g., May 3, 1980; April 29, 1981; December 9, 1982; November 2, 1983; November 2, 1986; and, May 22, 1992), producing significant rainfalls.

Longer Term Changes and the Effects of El Niño and Other Large-Scale Atmospheric Phenomena

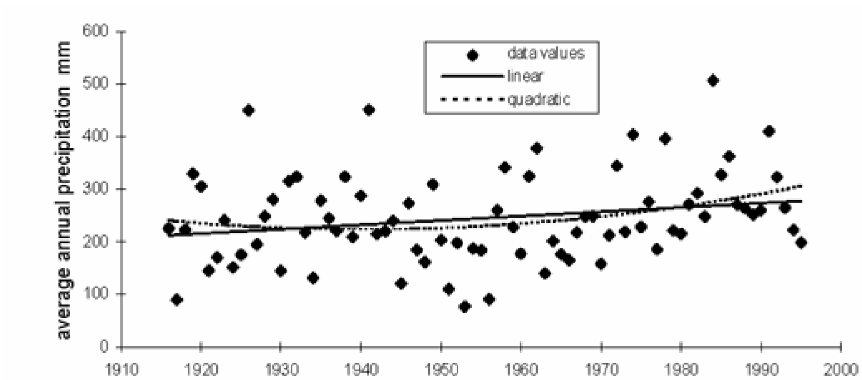
The analysis of the longer term records from the Jornada Basin to observe any significant trends through time is composed of two parts. First, the records are assessed for any statistically significant patterns that may relate to climatic variability or change at moderate to long time scales. Second, the records are subdivided to allow the impact of El Niño events to be assessed. For the most part, these analyses have been carried out at the annual and seasonal level.

Conley et al. (1992) used regression and autocorrelation analysis to examine trends in the rainfall and temperature at the Jornada headquarters station as well as nearby sites in Las Cruces. They found no significant linear or quadratic trends for the annual precipitation data (1914–84) but a significant quadratic relationship for mean temperature. Analyses for trends have been carried out in the same way here, except that the sequence of data are now extended to cover the period until 1996; the minimum, maximum, and average annual temperatures have been analyzed separately; and the evaporation data from 1953–78 have also been analyzed (table 3-4). Outliers have not been ignored, as in the analysis of Conley et al. (1992), but years for which data are incomplete (which is often the cause of major outliers) have been excluded from the analysis.

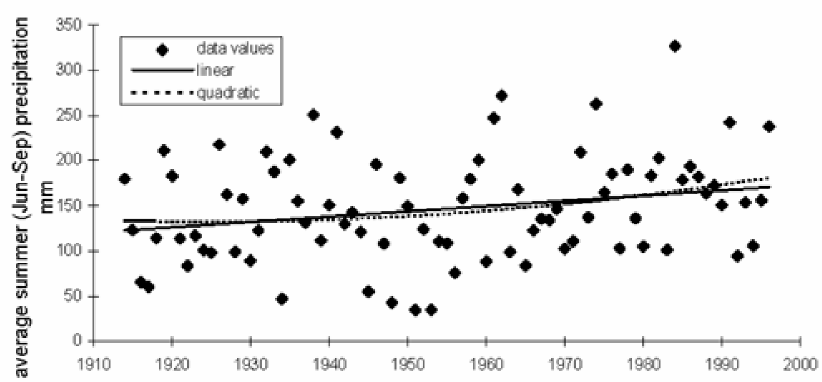
The average temperature data at the Jornada headquarters station show significant linear, quadratic, and quartic trends; however, the implications of the different models are important. The linear model describes a general decrease of the average temperature of 0.0092°C per year, whereas the quadratic model shows a slight increase of temperature from 1914 to around 1940, when a more rapid decrease takes place. On the other hand, the third-order polynomial model shows a similar but more rapid increase in the earlier time period followed by a more gradual decrease until the mid-1980s when the trend starts to reverse A similar general pattern is observable with the average minimum temperature, albeit with a much stronger upturn since the mid-1970s. In the case of average maximum temperatures, only the quadratic and third-order models are significant, both of which suggest a general increase in the first half of the century followed by a subsequent marked decrease. Annual average precipitation seems to increase slightly over the period (figure 3-8a).

Table 3-4. Results of regression analyses of long-term records from the Jornada Experimental Range headquarters for temperature, precipitation, evaporation, and frost days. Results are graphed in Fig. 3-8, 3-9, and 3-10.

Variable	constant	year	$year^2$	$year^3$	$year^4$	r^2	p
Average	32.68	-0.0092				0.124	0.005
Annual	-914.083	0.9590	-0.00024			0.161	0.006
temperature	-89327.9	136.61	-0.0696	1.183×10^{-5}		0.195	0.006
average	36.49	-0.0162				0.122	0.006
minimum	895.71	-0.8949	0.00022			0.131	0.017
temperature	-267769.5	411.325	-0.21059	3.593×10^{-5}		0.229	0.002
average	28.91	-0.0021				0.003	0.661
maximum	-3003.03	3.0982	-0.00079			0.190	0.002
temperature	81326.70	-126.293	0.06537	-1.128×10^{-5}		0.205	0.003
average	-1378.65	0.8303				0.051	0.044
Annual	103402.5	-106.350	0.02740			0.074	0.051
precipitation	-2.216×10^{6}	3452.82	-1.79283	0.00031		0.076	0.111
average	-994.411	0.58379				0.059	0.027
summer	35471.71	-36.7273	0.00954			0.066	0.065
precipitation	-4.526×10^{5}	712.361	-0.37365	6.534×10^{-5}		0.066	0.142
average	-643.444	0.38030				0.036	0.089
Winter	95811.9	-98.3069	0.02524			0.107	0.012
precipitation	-4.724×10^{6}	7298.935	-3.75863	0.00065		0.126	0.015
	-9.551×10^{6}	17186.77	-11.354	0.00324	-3.319×10^{-7}	0.127	0.034
average	-14774.96	8.63852				0.056	0.244
Annual	-1.114×10^{6}	1126.99	-0.28449			0.059	0.498
evaporation	1.936×10^{9}	-2.956×10^{6}	1504.089	-0.25513		0.336	0.027
first frost day	467.234	-0.08780				0.025	0.159
last frost day	-149.518	0.13750				0.050	0.047
	-23322.2	23.847	-0.00606			0.091	0.025
	1.5767×10^{6}	-2431.71	1.25005	-0.00021		0.113	0.027
	-9.567×10^{6}	20375.0	-16.2533	0.00576	-7.635×10^{-7}	0.116	0.053
number of	-770.78	0.45485				0.138	7.5×10^{-4}
frost days	-48878.7	49.6773	-0.01259			0.185	4.2×10^{-4}
	-4.510×10^{5}	666.89	-0.32832	5.383×10^{-5}		0.186	1.4×10^{-3}



b.



c.

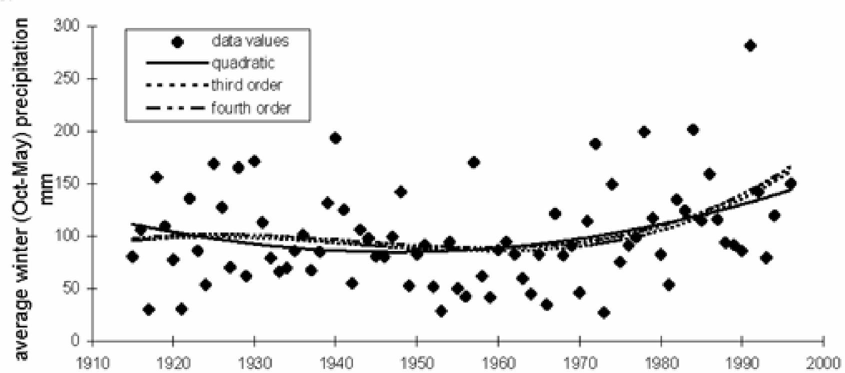


Figure 3-8. Trends in temperature data from Jornada (headquarters): (a) average annual; (b) average summer (June-September); and (c) average winter (October-May).

Subdivision into summer and winter precipitation suggests that both summer and, more recently, winter precipitation have contributed to this increase (figure 3-8b and 3-8c). The results of these analyses suggest that the period of drought experienced in the 1930s was a result of higher temperatures, but the drought of the 1950s was in response to lower precipitation levels. Evaporation shows a strong oscillation and thus only shows significant trends with third- and fourth-order polynomials (figure 3-9).

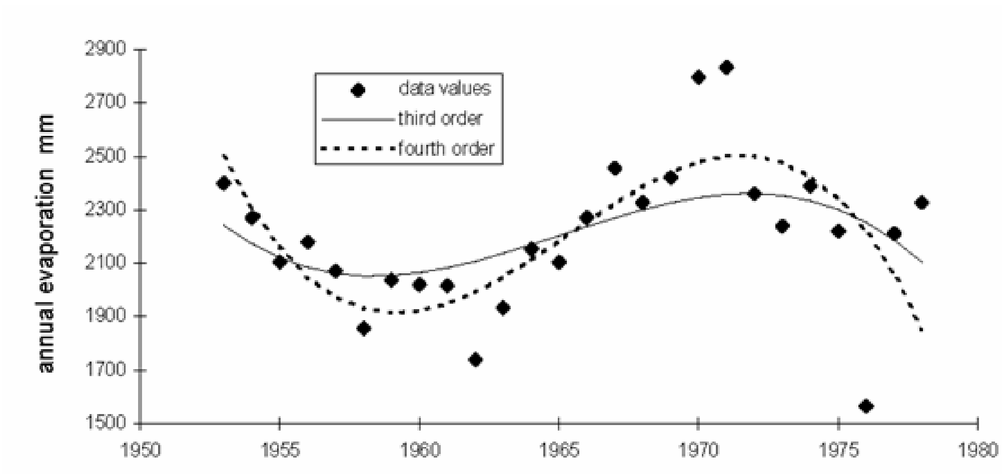


Figure 3-9. Trends in evaporation data from JER headquarters

The monthly trends in evaporation show the oscillation occurred in all months, albeit more markedly in April to June and September to December. It is likely that the oscillation is a function of two factors, the generally lower minimum temperatures in the years just before and after 1960 and followed by an increase around 1970 and, to a lesser extent, the slight increase in maximum temperatures during the latter period. There is no significant trend in the day of the occurrence of the first frost, but both the date of the last frost and the total number of frost days show similar patterns. Linear models suggest continuous increases in frost occurrence (i.e., longer periods with frost with more frost days), but higher order models suggest an increase until the mid-1960s followed by a subsequent decrease (figure 3-10a–c).

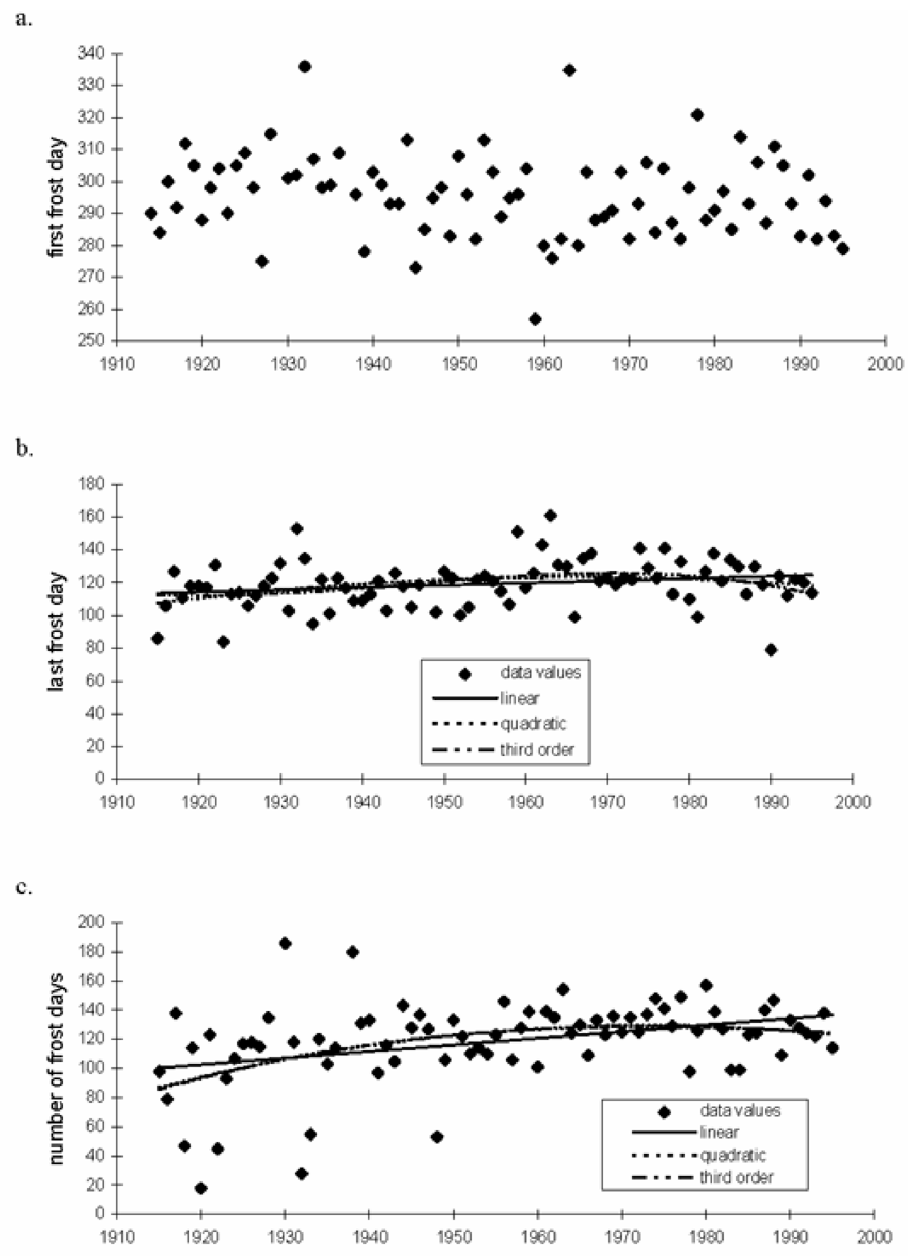


Fig. 3-11. Trends in frost-day data from (JER) headquarters (a) Julian day of first frost; (b) Julian day of last frost; and (c) number of days with frost.

Removing the linear trend from each of these sequences allows analysis of higher frequency changes using Fourier analysis. The average temperature shows spectral peaks at periods greater than 40 years (supporting the existence of the longer term oscillations shown by the regression analysis), as well as between 11 and 20 years. There are a number of strong peaks at periods of between two and five years. The minimum and maximum temperature signals are similar, except that both have a relatively stronger long-term cyclicity compared to the 11–20-year peaks. The minimum temperature signal shows no two-year cyclicity but has an extra peak at seven years, whereas the maximum temperature has an extra peak at around nine years. The annual precipitation has a strong spectral response through its range, although decomposition into the summer and winter rainfall suggests this is due to the interplay of seasonal factors that occur at difference frequencies. The summer rainfall shows stronger peaks at frequencies of around 3, 6, 12, and 30 years. As well as the 3- and 6-year signals, the winter rainfall has a stronger response at 7, 9, and 18 years, as well as over periods of more than 40 years (again supporting the regression analysis). The three- and six-year cycles may relate to the El Niño phenomenon (see further analysis to follow). Persistence in these sequences was also tested by means of runs tests, but only the strong oscillation in the evaporation data showed any significant persistence at the 95% confidence level.

It is also interesting to compare long-term trends in the precipitation at other sites in the basin for which there are long data records. A total of 28 gauges, including the Jornada headquarters, were selected for this analysis on the basis of having data series starting before 1940, with more than 40 years of total records. Of these sites, 14 had significant linear trends, 19 significant quadratic trends, and 21 significant third-order polynomial trends at a 95% confidence level (table 3-5).

Table 3-5. Long-term (>40 years) trends in annual precipitation for 28 permanent recording stations in the Jornada Basin.

	constant	year	year2	year3	r^2	p
Antelope	-3928.369	2.113191			0.139	0.004
	260031.64	-266.295	0.0682		0.172	0.005
	63189540	-96252.8	48.869	-0.00827	0.281	0.000
Aristida	-1839.956	1.050213			0.063	0.036
	191951.5	-196.566	0.0504		0.111	0.020
	13354648	-20330.7	10.316	-0.001744	0.128	0.027
Ash Canyon	-3437.851	1.92424			0.095	0.018
	342116.01	-349.534	0.0894		0.144	0.013
	57993213	-88310.6	44.823	-0.007583	0.224	0.003
Brown Tank	-973.2359	0.611896			0.024	0.205
	271621.79	-277.417	0.0709		0.128	0.011
	16778778	-25530.8	12.948	-0.002189	0.159	0.010
Co-op Well	-1761.779	1.005324			0.050	0.086
	148886.31	-152.221	0.039		0.068	0.134
	37273746	-56793.4	28.843	-0.004883	0.133	0.044
Dona Ana	-1723.753	1.000714			0.062	0.036
	143941.81	-147.578	0.0379		0.092	0.037
	26162753	-39957.2	20.34	-0.003451	0.173	0.005
Headquarters	-1398.13	0.839842			0.054	0.037
	93343.455	-96.0964	0.0248		0.075	0.049
	-3578673	5539.678	-2.858	0.0004916	0.078	0.098
Mesquite	-3876.88	2.082954			0.160	0.002
	233566.52	-239.424	0.0614		0.194	0.002
	56849959	-86618.8	43.989	-0.007446	0.307	0.000
Middle Well	-966.313	0.60782			0.018	0.268
	271046.68	-276.845	0.0707		0.098	0.030
	30052639	-45843.6	23.309	-0.00395	0.180	0.004
New Well	-1495.99	0.902292			0.040	0.101
	262057.52	-267.899	0.0685		0.114	0.018
	19957452	-30397.5	15.431	-0.002611	0.149	0.014
Rabbit	-2505.238	1.399172			0.101	0.007
	165194.06	-169.61	0.0436		0.133	0.008
	34235808	-52285.3	26.615	-0.004515	0.241	0.000
Ragged Tank	-777.5242	0.530026			0.017	0.266
	175173.13	-179.125	0.0459		0.064	0.091
	11031231	-16806.5	8.5341	-0.001444	0.081	0.108
Red Lake	-2198.286	1.231195			0.096	0.005
	264237.69	-271.096	0.0696		0.224	0.000
	5459924.8	-8237.17	4.1405	-0.000693	0.229	0.000
Restoration	-3383.717	1.839516			0.139	0.003
	126096.21	-129.958	0.0335		0.151	0.007
	57350419	-87504.3	44.501	-0.007543	0.308	0.000
Road Tank	-1517.61	0.897357			0.039	0.097
	201341.32	-206.019	0.0528		0.085	0.049
	44273092	-67637.2	34.441	-0.005845	0.267	0.000
Rope Springs	-2039.815	1.21825			0.067	0.023
	135637.64	-139.501	0.036		0.091	0.028
	-5745201	8877.176	-4.572	0.0007849	0.095	0.058
Sand Hill	-1889.168	1.082622			0.051	0.064
	184666.37	-189.204	0.0485		0.084	0.058
	40301082	-61567.9	31.35	-0.005321	0.203	0.002
South Well	-2204.621	1.246951			0.104	0.004
	101578.42	-104.803	0.0271		0.124	0.007
	9548720.6	-14585.5	7.4252	-0.00126	0.140	0.010
Stuart Well	-1693.325	0.995332			0.051	0.058
	191521.94	-196.084	0.0502		0.095	0.033
	24568102	-37493	19.071	-0.003233	0.154	0.010
Taylor Well	-2284.302	1.278477			0.082	0.026
	189958.25	-194.254	0.0497		0.112	0.034
	60978251	-92938.6	47.214	-0.007995	0.289	0.000
West Well	-385.0251	0.311672			0.007	0.451
	90054.882	-92.128	0.0236		0.025	0.381
	2156024.7	-3259.69	1.6423	-0.000276	0.026	0.574
Yucca	-977.9326	0.615654			0.024	0.195
	218039.66	-222.782	0.057		0.094	0.035
	21709147	-33104.9	16.826	-0.00285	0.151	0.012
Pasture 15N	-2269.145	1.275022			0.068	0.049
	219491.06	-224.272	0.0573		0.100	0.056
	45078904	-68669.8	34.867	-0.005901	0.178	0.014
Pasture 15S	-1478.611	0.867952			0.037	0.149
Exclosure	177008.01	-180.671	0.0462		0.061	0.178
	44730372	-68157.3	34.616	-0.00586	0.153	0.029
Camp Well	-1760.727	1.019452			0.047	0.087

	constant	year	year2	year3	r^2	p
	109832.49	-112.655	0.0289		0.058	0.165
	18386505	-28042	14.255	-0.002415	0.079	0.178
College	-2621.301	1.457836			0.095	0.029
Ranch	238243.41	-243.801	0.0624		0.143	0.027
Headquarters	31969217	-48761.2	24.789	-0.0042	0.188	0.021
Parker	-2245.223	1.2707			0.079	0.072
Heights	-34654.55	34.22995	-0.008		0.079	0.201
Exclosure	46136172	-70436.2	35.843	-0.006079	0.166	0.072
Selden Well	-1596.798	0.928175			0.043	0.099
	62659.448	-64.5265	0.0167		0.047	0.229
	16232470	-24774.3	12.603	-0.002137	0.066	0.250

The linear trend is always positive. Only the areas in the southern, north-central, and eastern portions of the basin show significant linear trends, although there is no clear spatial pattern. Quadratic trends reinforce the pattern from Jornada headquarters, suggesting an increase in the rate of change in recent years. Third-order polynomial trends suggest a different pattern, in that only the Rope Springs gauge follows the same trend as Jornada headquarters, whereas all of the other gauges suggest an oscillation, with rainfall decreasing until the mid-1950s, increasing until the mid-1980s, and decreasing again thereafter. These results suggest that although there are general patterns of long-term variability in the rainfall data, the trends have a complex spatial pattern.

Again, the linear trend was removed from these rainfall sequences to observe whether any shorter term oscillations are present. The results obtained show strong spatial variability in these data. Oscillations on a 3-year cycle are the most common, followed by the 64-year cycle, then the 16, the 6, the 9, and the 32. The 2-, 11-, and 13-year cycles are the least well represented. Only 7 out of the 26 available gauges showed a significant persistence in annual rainfall using a runs test. Although these gauges are located for the main part on the edge of the central part of the basin, again there is no definite spatial pattern. Observation of these series suggests that the main pattern of persistence is the period starting about 1943 or, more usually, 1945 and continuing until

1956 or 1957 when conditions were generally drier than the detrended, long-term median rainfall. This pattern of general aridity is seen in many of the rainfall sequences and is discussed as the drought of the 1950s by Conley et al. (1992). It possibly also includes the drier conditions of the early 1930s. Several of the seven sites also show some persistence of wetter conditions in the late 1930s, early 1940s, late 1960s, and early 1970s. It is likely that these secondary patterns of persistence cause the significance in the runs test in conjunction with the more widespread late 1940s to early 1950s phenomenon. At a seasonal level, only six sites show persistence in values of summer rainfall and four sites in values of winter rainfall. It could thus be concluded that although persistence is important at specific points in space and time, it is not a dominant feature of the Jornada rainfall record over the past 80 years.

Effects of the El Niño–Southern Oscillation

A further climatic phenomenon which has been shown to be a significant factor in variability in the region is that of El Niño (see Trenberth 1976; Rasmussen and Wallace 1983; Rasmussen 1985; Nicholls 1988; Diaz and Kiladis 1992 for details on the mechanisms). At the Sevilleta LTER site in New Mexico, Dahm and Moore (1994) found significant differences in winter (October to May) rainfall, with El Niño years having about 1.5 times the medial rainfall and La Niña years having about 0.5 times the medial rainfall. Only La Niña years showed a significant difference at the annual level (~ 0.7 times medial rainfall), although El Niño years had a higher annual rainfall than medial years. There was no significant difference observed in summer (June to September) rainfall in either case.

The patterns of rainfall differences have been assessed for the Jornada using the same definition of El Niño years (1919, 1926, 1940, 1941, 1942, 1952, 1958, 1964, 1966, 1973, 1978, 1983, 1987, 1992, and 1993) and La Niña years (1918, 1939, 1950, 1951, 1956, 1971, 1974, 1976, and 1989) as Dahm and Moore (1994). Of the 47 gauges with sequences sufficiently long to allow analysis, only 5 sites show significantly higher rainfall in El Niño years, and only 8 have significantly lower rainfall in La Niña years, compared to medial years of annual rainfall (table 3-6).

In the case of winter (October to May) rainfall, the pattern is much clearer, with 42 sites with significantly higher rainfall in El Niño years and 33 sites with significantly lower rainfall in La Niña years compared to medial years. On the other hand, only seven sites show significantly higher summer rainfall in El Niño years, and three sites show significantly lower rainfall in La Niña years compared to medial years. These results support the conclusion drawn by Dahm and Moore (1994) that El Niño affects the climate in the area by affecting the moisture supply. Thus it is only really significant in the winter months when rainfall is dominantly drawn from the Pacific Ocean. On average, El Niño years have 1.13 times and La Niña years 0.84 times the annual rainfall in medial years. The respective ratios for winter rainfall are 1.59 and 0.63 and for summer rainfall, 1.02 and 0.84. It is possible that the La Niña events in 1950, 1951, and 1956 were at least partly responsible for the period of dry weather in the 1950s, although the earlier onset (as discussed) suggests that it was probably not the principal mechanism. There seems to be a spatial pattern in the extent to which El Niño and La Niña events affect the rainfall within the basin. The effects in El Niño years are particularly pronounced in the higher altitude sites in the east and northeast of the basin, whereas the La Niña years seem to

Table 3-6. Annual rainfall (mm) for 47 long-term precipitation-recording locations in the Jornada Basin analysed for La Niña years (1918, 1939, 1950, 1951, 1956, 1971, 1974, 1976, and 1989), El Niño years (1919, 1926, 1940, 1941, 1942, 1952, 1958, 1964, 1966, 1973, 1978, 1983, 1984, 1992, and 1993), and medial years (all others between 1915 and 1995). Values with the same letter in each period (annual, winter, or summer) are not different P≤0.05)

	Annual rainfall (January-December)			**Winter rainfall (October-May)**			**Summer rainfall (June-September)**		
rain gauge	El Niño	Medial	La Niña	El Niño	Medial	La Niña	El Niño	Medial	La Niña
Antelope	270.33[a]	224.17[a]	179.46[a]	136.50[d]	86.69[e]	49.65[f]	151.48[g]	136.53[g]	113.11[g]
Aristida	250.74[a]	218.96[a]	176.73[a]	134.87[d]	81.99[e]	55.64[f]	132.61[g]	135.77[g]	108.33[g]
Ash Canyon	388.12[a]	343.42[a]	288.53[a]	206.08[d]	133.24[e]	80.98[f]	199.13[g]	213.71[g]	171.96[g]
Ber	208.56[a]	241.38[a]	228.95[a]	126.94[d]	94.28[d]	66.53[d]	108.31[g]	144.23[g]	134.40[g]
Brown Tank	263.28[a]	222.93[a,b]	189.98[b]	135.59[d]	79.38[e]	58.16[e]	148.18[g]	139.32[g]	116.53[g]
Co-op Well	251.93[a]	208.53[a]	187.95[a]	125.48[d]	76.61[e]	50.40[f]	145.96[g]	129.43[g]	120.14[g]
Dona Ana	291.71[a]	227.01[b]	217.10[a,b]	136.53[d]	85.71[e]	53.43[f]	166.74[g]	142.04[g]	140.39[g]
Exclosure A	238.23[a]	244.89[a]	281.38[a]	145.80[d]	92.38[d]	66.20[e]	123.13[g]	150.92[g]	178.98[g]
Exclosure B	253.39[a]	226.70[a]	258.00[a]	142.88[d]	86.42[d]	58.38[e]	135.34[g]	140.76[g]	162.90[g]
Goat Mountain	334.07[a]	387.21[a]	350.65[a]	237.90[d]	137.71[e]	84.18[e]	198.28[g]	243.69[g]	211.35[g]
Headquarters	290.18[a]	235.90[b]	216.18[a,b]	145.05[d]	93.59[e]	59.88[f]	159.75[g]	144.79[g]	131.37[g]
IBP	235.13[a]	230.68[a]	204.40[a]	162.98[d]	99.42[d,e]	61.63[e]	101.80[g]	131.03[g]	113.08[g]
Mesquite	256.65[a]	214.25[a]	182.83[a]	130.59[d]	83.40[e]	53.73[f]	145.81[g]	128.84[g]	113.31[g]
Middle Well	261.14[a]	223.84[a]	174.39[a]	130.48[d]	84.68[e]	51.46[f]	138.36[g]	137.84[g]	111.25[g]
New Well	316.44[a]	272.35[a,b]	215.63[b]	163.32[d]	99.41[e]	66.65[f]	173.77[g]	172.07[g]	128.70[g]
Northeast Exclosure	235.20[a]	237.52[a]	274.10[a]	140.26[d]	92.04[d,e]	62.53[e]	121.10[g]	144.83[g]	183.15[g]
Parker	263.91[a]	229.93[a]	204.51[a]	140.14[d]	84.02[e]	66.77[e]	151.53[g]	144.10[g]	119.70[g]
Pasture 2	246.97[a]	250.81[a]	218.93[a]	155.13[d]	95.30[d,e]	63.40[e]	114.76[g]	154.14[g]	128.80[g]
Rabbit	273.63[a]	236.65[a]	199.21[a]	145.42[d]	89.88[e]	62.69[f]	147.68[g]	144.98[g]	121.84[g]
Ragged Tank	327.09[a]	247.38[b]	233.64[b]	153.41[d]	96.75[e]	65.59[f]	188.41[g]	151.55[h]	141.33[g,h]
Red Lake	253.40[a]	207.43[a,b]	163.59[b]	132.42[d]	79.56[e]	47.78[f]	135.76[g]	126.46[g]	104.28[g]
Restoration	270.49[a]	226.57[a]	189.56[a]	141.61[d]	83.04[e,f]	60.60[f]	152.46[g]	139.99[g]	115.51[g]
Road Tank	285.87[a]	231.78[a]	228.81[a]	141.47[d]	90.82[e]	58.78[f]	156.28[g]	141.27[g]	148.09[g]
Rope Springs	403.81[a]	338.63[b]	276.46[b]	218.58[d]	128.62[e]	74.56[f]	207.50[g]	211.90[g]	163.16[g]
Sand Hill	275.68[a]	223.41[a]	224.40[a]	147.72[d]	85.93[e]	55.31[f]	153.43[g]	134.80[g]	149.23[g]
South Exclosure	248.00[a]	252.08[a]	278.70[a]	136.43[d]	88.44[e,f]	71.05[f]	136.54[g]	163.02[g]	173.70[g]
South Well	268.87[a]	229.08[a]	224.74[a]	145.56[d]	87.09[e,f]	59.90[f]	146.29[g]	141.45[g]	138.40[g]
St Nicholas	315.07[a]	394.54[b]	382.28[a,b]	203.95[d]	154.80[d,e]	92.85[e]	167.14[g]	243.67[h]	210.13[g,h]
Stuart Well	300.36[a]	249.20[a]	242.38[a]	154.18[d]	95.07[e,f]	66.65[f]	161.15[g]	154.34[g]	149.58[g]
Taylor Well	257.35[a]	227.39[a]	196.96[a]	133.95[d]	81.62[e,f]	59.76[f]	148.03[g]	142.43[g]	119.00[g]
West Well	264.58[a]	222.66[a,b]	172.62[b]	132.58[d]	83.58[e]	53.25[f]	144.00[g]	138.41[g]	106.91[g]
Yucca	272.61[a]	221.61[a]	201.19[a]	136.21[d]	82.79[e]	55.88[f]	149.54[g]	137.60[g]	129.26[g]
Pasture 15N	270.49[a]	241.09[a]	160.26[b]	140.85[d]	90.83[e]	50.00[f]	156.35[g]	144.05[g]	91.56[h]
Pasture 15S Exclosure	260.06[a]	230.98[a]	163.24[b]	139.01[d]	89.38[e]	53.69[f]	146.71[g]	140.08[g]	87.99[h]
Pasture 3N	269.79[a]	241.56[a]	164.16[b]	143.65[d]	91.65[e]	47.63[f]	149.92[g]	147.57[g]	89.77[h]
Pasture 3S	255.82[a]	261.26[a]	215.10[a]	176.15[d]	104.88[d,e]	55.48[e]	117.82[g,h]	151.69[g]	110.40[h]
Pasture 3W-15	228.04[a]	251.74[a]	106.85[a]	149.42[d]	92.68[d]	63.40[d]	128.53[g]	147.85[g]	69.75[g]
Pasture 3W	278.22[a]	270.62[a]	206.68[b]	182.68[d]	114.70[d]	59.73[e]	130.48[g,h]	158.19[g]	104.55[h]
Camp Well	265.82[a]	243.30[a]	180.43[b]	142.82[d]	89.70[e]	47.50[f]	150.59[g,h]	149.60[g]	111.11[h]
Creosote Site	254.93[a]	214.98[a]	155.57[a]	120.23[d]	77.88[d]	41.03[e]	153.28[g]	134.19[g]	111.03[g]
College Ranch Headquarters	273.68[a]	235.49[a]	161.52[a]	142.93[d]	84.25[e]	57.92[d,e]	168.53[g]	138.98[g]	104.32[g]

	Annual rainfall (January-December)			Winter rainfall (October-May)			Summer rainfall (June-September)		
Pasture 12 Farm	281.68[a]	263.80[a]	145.10[b]	154.59[d]	89.20[e]	64.25[d,e]	168.61[g]	160.87[g,h]	89.35[h]
Pasture 13W	295.94[a]	221.54[a]	133.27[b]	116.08[d]	79.43[d]	41.53[d]	177.53[g]	132.21[g]	90.80[g]
Pasture 10	302.23[a]	188.26[a]	161.45[a]	129.83[d]	98.45[d]	44.35[d]	195.33[g]	93.66[h]	102.35[g,h]
Parker Heights Exclosure	319.39	247.09	148.10	159.80[d]	97.98[e]	61.46[d,e]	177.33[g]	142.50[g]	90.24[h]
Seldon Well	267.39[a]	224.04[a,b]	165.48[b]	137.42[d]	90.18[e]	53.05[f]	153.93[g]	134.20[g]	89.81[h]
Seldon South	276.56[a]	236.31[a]	138.93[b]	160.64[d]	96.56[d,e]	59.10[e]	153.43[g]	131.23[g,h]	84.37[h]

have a stronger effect in the west of the basin, particularly in the summer months. These differences probably also relate to the differences in the moisture supply and the rainfall mechanisms through the year.

More detail on the relationship between El Niño and the rainfall pattern can be obtained by comparing monthly rainfall values with values of the Southern Oscillation Index (SOI). The values of the SOI covering the period of record in the Jornada Basin were obtained from the Climatic Research Unit at the University of East Anglia (available online at fttp://daac.gsfc.nasa.gov) and compared with the monthly rainfall at the Jornada headquarters. Cross-correlation of these two data series from November 1915 to January 1996 shows a weak but significant negative correlation at lags of –2 to 4 months and at 9 months. In other words, the Jornada headquarters' rainfall leads the response of SOI by two months and continues to respond until four months later. Analysis of the other long sequences shows again that the pattern of response is relatively complex. Lags of –3, –2, –1, 3, and 9 months dominate the response within the basin, whereas the direct response at lag 0 is recorded in only a few cases. A number of sites concentrated in the CDRRC area in the west of the basin also show a response between lags of six and nine months. It is possible that the atmospheric fluctuations that tend to precede the El Niño–Southern Oscillation (ENSO) events (Rasmussen 1985; Diaz and Kiladis 1992) also cause the rainfall patterns at Jornada to precede the changes in the SOI. The delayed response at lags of six to nine months is most likely to be related to the change in the source of moisture in the summer months followed by the return to Pacific moisture sources in the next winter rainfall season. Similar correlations between SOI fluctuations and rainfall in southern New Mexico have been demonstrated by a number of authors (Rasmussen 1985; Ropelewski and Halpert 1986, 1987; Andrade and Sellers 1988; Nicholls 1988; Kiladis and Diaz 1989; Molles and Dahm 1990; Redmond and Koch 1991; Diaz and Kiladis 1992; Kahya and Dracup 1993). The impact of major episodic fluctuations in precipitation has been demonstrated by Swetnam and Betancourt (1990, 1992) in terms of its correlation with major episodes of wildfires across large parts of the American Southwest, which has important implications for vegetation patterns.

The other climatic data for Jornada headquarters have also been analyzed to test for significant differences related to El Niño events. The results of this analysis suggest that El Niño events have a small impact on the temperature and evaporation characteristics of the basin. In El Niño years, only February has significantly colder average air temperatures, and January and February have significantly colder maximum air temperatures when compared to medial years. March average temperatures are significantly higher in La Niña years than in medial years, March and June have significantly higher maximum temperatures, and February has significantly lower maximum temperatures. Although Diaz and Kiladis (1992) showed that there was a significant decrease in December–February temperature in parts of New Mexico and Texas relating to ENSO events, the Jornada Basin is on the edge of the zone they delimited as being significant. In contrast, Redmond and Koch (1991) found no significant correlation for October–March temperatures in southern New Mexico. The relationship between SOI and temperature is also very weak in this region according to the analyses of Ropelewski and Halpert (1986); they suggest this is due to the more complex teleconnections associated with the development of the Pacific–North America ridge.

Effects of Other Large-Scale Circulation Patterns

The impact of the North Atlantic Oscillation (NAO) was assessed because of its potential link to fluctuations in summer moisture supplies from the Gulf of Mexico. Long-term trends in the NAO were presented by Trenberth and Hurrell (1995) and also by the University of East Anglia Climate Research Unit and NOAA. These data show no major differences between years with high positive or negative deviations from the NAO and annual precipitation at the Jornada. There are, however, a series of linkages demonstrated by cross-correlation analysis at the monthly level. For the Jornada headquarters' precipitation data from 1914, there are weak but significant negative correlations at a lag of –3 months (i.e., precipitation leading NAO) and at lag 4 months. This would tend to suggest that the effects of the NAO signal occur more in the autumn and spring, rather than in the summer, as originally hypothesized. This may relate more to the generation of anomalous airflow patterns during these periods bringing moisture from the Gulf of Mexico during the winter rainfall season (Trenberth and Hurrell 1995). No significant correlations were found with the temperature or these evaporation data.

The Pacific–North America Index (PNA), defined in terms of pressure anomalies between the Aleutians and the Gulf of Mexico, illustrates the effects of other Pacific circulation patterns. In this case, there are significant positive correlations with the Jornada headquarters' precipitation at lags of –3, –2, and 8 months. The minimum, maximum, and average temperatures have significant positive correlations at lags of –2, –1, and 10 months. The 10-month lag positive correlation is also present in these evaporation data. Redmond and Koch (1991) examined the relationship between October–March PNA and temperature and precipitation at a regional scale. They found an insignificant positive correlation for precipitation and a significant negative correlation ($p < 0.05$) for temperatures. Although the Jornada data do have negative correlations for temperatures at lags 1–7, which would correspond to the signal observed by Redmond and Koch, in no case are they significant.

Implications of Changes within the Instrumental Climate Record

The instrumental record at Jornada shows that there have been significant fluctuations in temperature, precipitation, and by extension, the number of frost days and evaporation. These fluctuations exist on cycles extending from 3 to 64 years. Precipitation fluctuations are reinforced by the occurrence of ENSO events, with significant increases in winter precipitation in El Niño and significant decreases in La Niña years. To a certain extent, these fluctuations are reinforced by teleconnections with the NAO and PNA signals. The coincidence of these larger scale teleconnections with other cycles in the climate may serve to amplify the variations, for example, the repeated La Niña events in the 1950s superimposed on the preexisting drought signal. Reynolds et al. (1999a) show how shrubs on the Jornada can withstand drought by switching growth activity between seasons, which would allow a certain degree of tolerance of such fluctuations. Neilson (1986) suggested that black grama (*Bouteloua eriopoda*) seedling production occurred preferentially when winter drought was followed by high summer rainfalls. In that the summer rainfall has no significant relationship with the large-scale circulation patterns analyzed, such conditions may develop when La Niña events occur in association with otherwise wetter than average cycles. It is possible, then, that longer term fluctuations in vegetation may be triggered by combinations of the various climatic conditions, controlled in the winter season by the ENSO, PNA, and NAO signals and in the summer by the movements of the Intertropical

Convergence Zone[b] and the development of monsoonal conditions and their interplay with auto variations in the local climate.

Conclusions

Although there are some elements of persistence in the Jornada climate at the daily scale, the general climate in the basin is characterized by variability at all spatial and temporal scales. There is a clear seasonality, relating to the development of the summer monsoonal system, that controls the amount of rainfall received. The general fluctuations within the years and between years can be ascribed to the highly variable nature of the convective rainfall generated by such systems. As well as such apparently random variability, there are a number of fluctuations that occur on a cyclic basis, with measured cycles of up to 64 years in length present in the instrumental records. Although the mechanisms behind most of these remain unexplained, there is evidence for important quasi-periodic fluctuations relating to variability in global circulation patterns, particularly those represented by the Southern Oscillation and to a lesser extent the NAO and the PNA signal. The Southern Oscillation is particularly important in controlling the amount of winter precipitation, with significantly wetter conditions occurring in El Niño years and significantly drier conditions occurring in La Niña years. According to Neilson (1986), the El Niño years should thus favor shrub vegetation and the La Niña years grass vegetation. The more frequent occurrence of El Niño events at the end of the last century and in the first half of the present century (Anderson et al. 1992) may thus have provided favorable conditions for the increase of shrubland in the light of other land use and environmental changes.

[b] ITCZ has not been spelled our defined (or even mentioned) elsewhere in this chapter. Please at least spell it out here (parenthetically, if necessary). (Added)

Wainwright (2005) reviews evidence that suggests that this climatic regime seems to have been in place for around the last 4,500 years, albeit with a number of smaller scale oscillations. The longer term variability related to the Southern Oscillation phenomena was well established over this time period, suggesting that both the general trend and shorter timescale variability has been in operation over at least this time scale. There also appear to have been a number of episodes of shorter time scale variability over the last millennium, which are well documented by tree ring analysis. The climate seems to have oscillated between extremes of wet and dry conditions over this time period, although some of the records suggest that the present century has seen the largest magnitude extremes. Before this time period, there is a phase where conditions were warmer than present, again lasting for up to 4,000 or 5,000 years. This broadly corresponds to the early Holocene peak of insolation. Vegetation evidence as well as global change model[c] experiments suggests that this period saw enhanced monsoonal activity, which seems to have led to generally wetter conditions than present. There is evidence for oscillations of even wetter conditions superimposed on this increase both in the Jornada Basin and elsewhere in the Southwest, although this seems to have been more pronounced in the Sonoran Desert than the Chihuahuan Desert. The mechanisms of these changes are unknown. It has been suggested that the Southern Oscillation phenomena were not operative during these periods of warmer conditions, but it is not known to what extent other large-scale phenomena could have controlled such variability. The vegetational evidence suggests continual changes and migrations of the plant species that now characterize these areas throughout this period in response to such changes.

[c] GCM has not been spelled our defined (or even mentioned) elsewhere in this chapter. Please at least spell it out here (parenthetically, if necessary). (Done)

Given the control of the monsoonal circulation patterns on the climate, it is probable that the modern patterns have been in place for the major part of the Pleistocene, although soil carbonate and geomorphic data suggest that there was a gradual transition until around 700 ka B.P., when these cycles became fully established. Glacial periods were probably characterized by generally pluvial conditions, although this term should also be understood with respect to available moisture under cooler than present conditions. Estimates of temperature change vary from about 2°C to 6°C cooler than present at the late glacial maximum. It is likely that the patterns of seasonality were highly different from those at present, due to the absence of the summer monsoonal patterns and the Equatorward displacement of the polar jet stream. Summer rainfall was probably slightly less than at present, and winter rainfall was probably substantially higher. Expanded analyses beyond the scope of this chapter (Wainwright 2005) can be viewed at www.ambiotek.com/advances/advemma/indivs/wainwright.pdf.